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FIELD TRIP GUIDEBOOK TO STRATABOUND SULPHIDE DEPOSITS, BATHURST AREA, N.B., CANADA AND WEST-CENTRAL NEW ENGLAND, U.S.A.

Editor: D.F. Sangster

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CORRELATION
OF CALEDONIAN
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SULPHIDES

1983

Miscellaneous Report 36

IGCP-CCSS SYMPOSIUM

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FIELD TRIP GUIDEBOOK TO STRATABOUND SULPHIDE DEPOSITS, BATHURST AREA, N.B., CANADA AND WEST-CENTRAL NEW ENGLAND, U.S.A.

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INTRODUCTION

This guidebook was prepared for field trips associated with the 8th International Working Group Symposium of International Geological Correlation Program (IGCP) Project 60 — Correlation of Caledonian Stratabound Sulphides (CCSS). The Symposium was held in Ottawa, Canada, Sept. 16-17, 1983.

Stratabound sulphide deposits described herein are representative of those which were the subject of CCSS research. Davies, Fyffe, and McAllister guide the reader through the famous Bathurst area, New Brunswick, site of the largest known concentration of stratabound sulphide deposits in the Caledonian(-Appalachian) orogen. All three currently-operating mines in the district are described as well as the Turgeon prospect, the most recent discovery in the Bathurst region. In west-central New England, Slack and co-workers describe the old Elizabeth deposit, one of the more renowned Paleozoic stratabound sulphide deposits in the U.S. Appalachians. The authors also entice the reader with new interpretations relating stratabound Mn(-Fe) deposits to nearby stratabound Cu-Zn deposits, a relationship well-documented in the Bathurst district. The road-log through New England invites the reader to conduct a do-it-yourself field trip to these now-defunct mines and occurrences and to enjoy the famous New England scenery as a bonus.

Texts for the guidebook were prepared in camera-ready form following, to the extent feasible, normal Geological Survey of Canada editorial requirements. An exception was made in the units used for certain measurements. Geological Survey of Canada publications normally use the Système International (SI) metric system. However, inasmuch as part of this guidebook was prepared in the United States, where the SI system is not in effect, units of measurement used by these authors were accepted as submitted. Conversion factors are as follows:

short tons X 0.90718 = metric tons (tonnes)
tonnes X 1.1023 = short tons
Troy oz/short ton X 34.2857 = grams/tonne

statute miles X 1.6093 = kilometres
kilometres X 0.62137 = statute miles
feet X 0.3048 = metres
metres X 3.2808 = feet

The editor's task was made easier by the willing co-operation of all authors in meeting submission deadlines and careful adherence to format instructions. The editor also wishes to acknowledge with thanks the assistance of M. Kiel, Geological Information Division, G.S.C., in preparing the layout of this report.

D. F. Sangster
D.F. Sangster
Editor

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GEOLOGY AND MASSIVE SULPHIDES OF THE BATHURST AREA, NEW BRUNSWICK

J.L. Davies

New Brunswick Department of Natural Resources
Bathurst, New Brunswick
E3B 5H1

L.R. Fyffe

New Brunswick Department of Natural Resources
Bathurst, New Brunswick
E3B 5H1

A.L. McAllister

Department of Geology
University of New Brunswick
Fredericton, New Brunswick
E3B 5A3

INTRODUCTION

This field trip, in the Bathurst area of northern New Brunswick, is concerned with the geology and sulphide deposits of the Tetagouche Group of the Miramichi Massif and Fournier Group of the Elmtree Inlier (Figures 1 and 2).

Sulphide deposits of the Bathurst area are found in two distinct settings. Approximately three dozen known stratabound Zn-Pb-Cu-Ag sulphide deposits occur within Ordovician felsic volcanic rocks and interbedded sedimentary rocks of the Tetagouche Group. Many of these deposits have features similar to "Kuroko-type" deposits located in island arc environments at consuming plate margins. In contrast, a Cu-Zn sulphide deposit within mafic volcanic rocks of the Fournier Group ophiolitic suite resembles "Cyprus-type" deposits of accreting plate margins.

REGIONAL GEOLOGIC SETTING

New Brunswick can be divided into five pre-Carboniferous tectonostratigraphic zones (Fyffe *et al*. 1981). These are, from southeast to

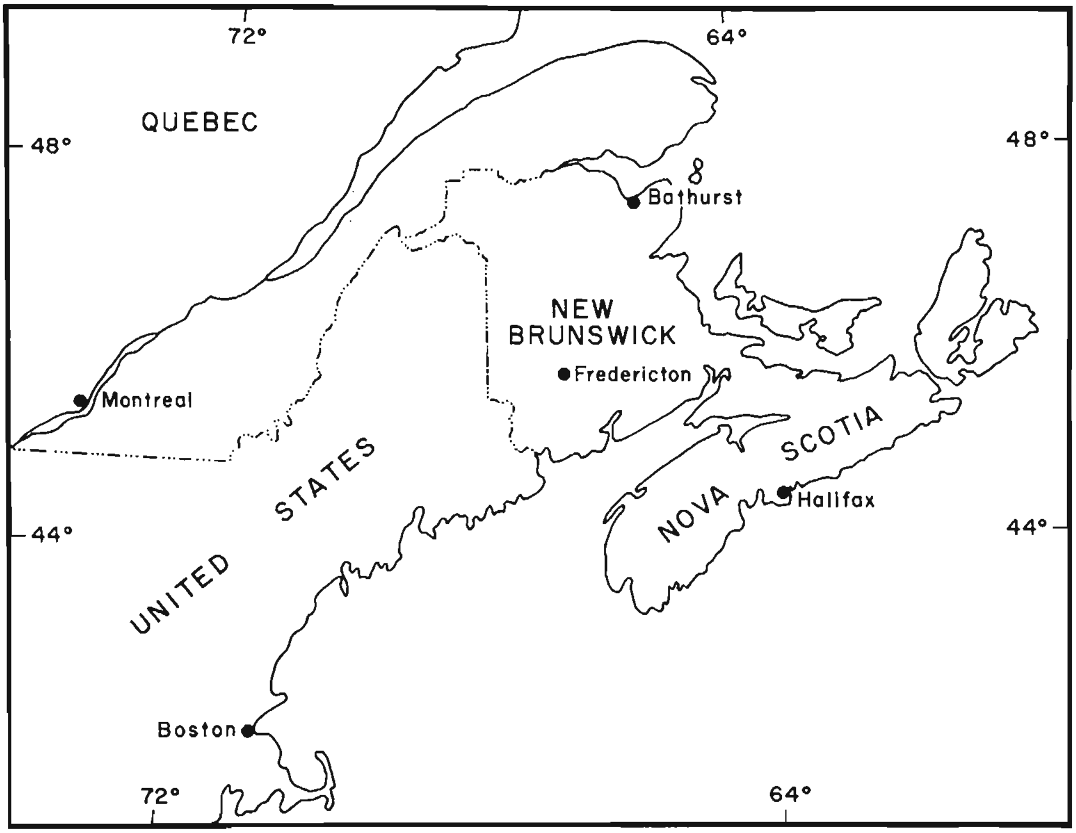


Fig. 1. Location Map

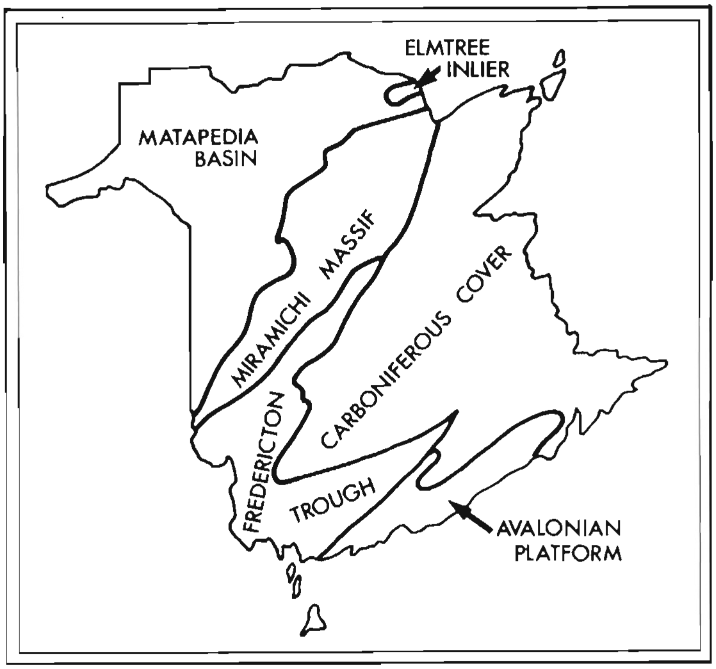


Fig. 2. Tectonostratigraphic Zones of New Brunswick

northwest: the Avalonian Platform, the Fredericton Trough, the Miramichi Massif, the Elmtree Inlier, and the Matapedia Basin (Figure 2). Faults generally mark the boundary of the zones.

Avalon Platform

Biotite - hornblende - quartz - feldspar gneiss, termed the Brookville Gneiss, forms a Precambrian (Aphebian) basement to the Avalonian Platform (Currie et al. 1981). Stromatolite-bearing marble, quartzite and siltstone of the Greenhead Group constitutes a Precambrian (Helikian) platform sequence over the gneiss. Felsic and mafic volcanics of the Precambrian (Hadrynian) Coldbrook Group are in fault contact with the Greenhead Group. Hadrynian plutons intruding the above sequences are predominantly of granodioritic composition. The Saint John Group, consisting of continental Lower Cambrian conglomerate and quartzite and marine Middle Cambrian to Lower Ordovician siltstone, shale, and minor limestone, unconformably overlies the Coldbrook Group.

Fredericton Trough

The Fredericton Trough is underlain by a thick, tightly folded Silurian greywacke sequence. Silurian and Lower Devonian mafic and felsic volcanic rocks are present along the southeastern margin of the Trough. Shallow-water Upper Silurian clastic sedimentary rocks overlie an inlier of Cambro-Ordovician quartzite and graphitic slate in the southwest (Pickerill 1976). These Cambro-Ordovician rocks represent a continental rise prism formed off the Avalonian Platform (Schenk 1971).

Miramichi Massif

Cordierite-bearing psammite interbedded with sillimanite-bearing pelite and minor amphibolite occur in the central part of the Massif and possibly represent the oldest rocks of the Tetagouche Group (Rast et al. 1976a). These high grade metamorphic rocks grade into a thick sequence of greenschist grade quartz wacke, quartzite and slate which underlies a thin calcareous slate containing an early Ordovician fauna (Neuman 1968; Fyffe 1976). The quartzose rocks have been interpreted as an Hadrynian marine apron off the northwest margin of the Avalonian volcanic belt (Rast et al. 1976b). However, others have interpreted them as a Cambrian to early Ordovician rift facies (Poole 1976; Ruitenberg et al. 1977).

The Lower Ordovician calcareous slate of central New Brunswick is overlain successively by red ferromanganiferous slate, Middle Ordovician black slate, and a thick upper unit of greywacke (Poole 1963). Minor intercalations of predominantly mafic volcanic rocks are found below the greywacke.

In northern New Brunswick, the Lower Ordovician slate is overlain by a thick succession of felsic volcanic rocks and a younger Middle Ordovician sequence of mafic volcanic rocks and greywacke (Helmstaedt 1971; Fyffe 1976). The broadly circular distribution of the felsic volcanic rocks of the Tetagouche Group in this area (Fig. 3) suggests a large caldera complex (Davies 1966; Harley 1979).

The abundance of felsic volcanic rocks and associated pervasively deformed granites (Fyffe et al. 1977) suggests that continental crust underlies much of the Ordovician volcanic terrain. The volcanism is interpreted to have been caused by the southeast subduction of oceanic crust along a continental margin represented by the northwestern border of the Miramichi Massif.

The rocks of the Massif were polydeformed and metamorphosed from subgreenschist to amphibolite grade and uplifted during the Taconic Orogeny as a result of the closure of the Iapetus Ocean (Bird and Dewey 1970). During the Acadian Orogeny, the Massif was intruded by a large volume of magma, mainly of granitic composition.

Elmtree Inlier

An uplifted block to the north of the Miramichi Massif (Fig. 2) consists of deformed gabbro, amphibolite, sheeted dykes, peridotite, plagiogranite, and pillow basalt of the Fournier Group (Rast and Stringer 1980). Ordovician feldspathic and quartzose turbidites of the Elmtree Group overlie the basalt and in turn are overlain

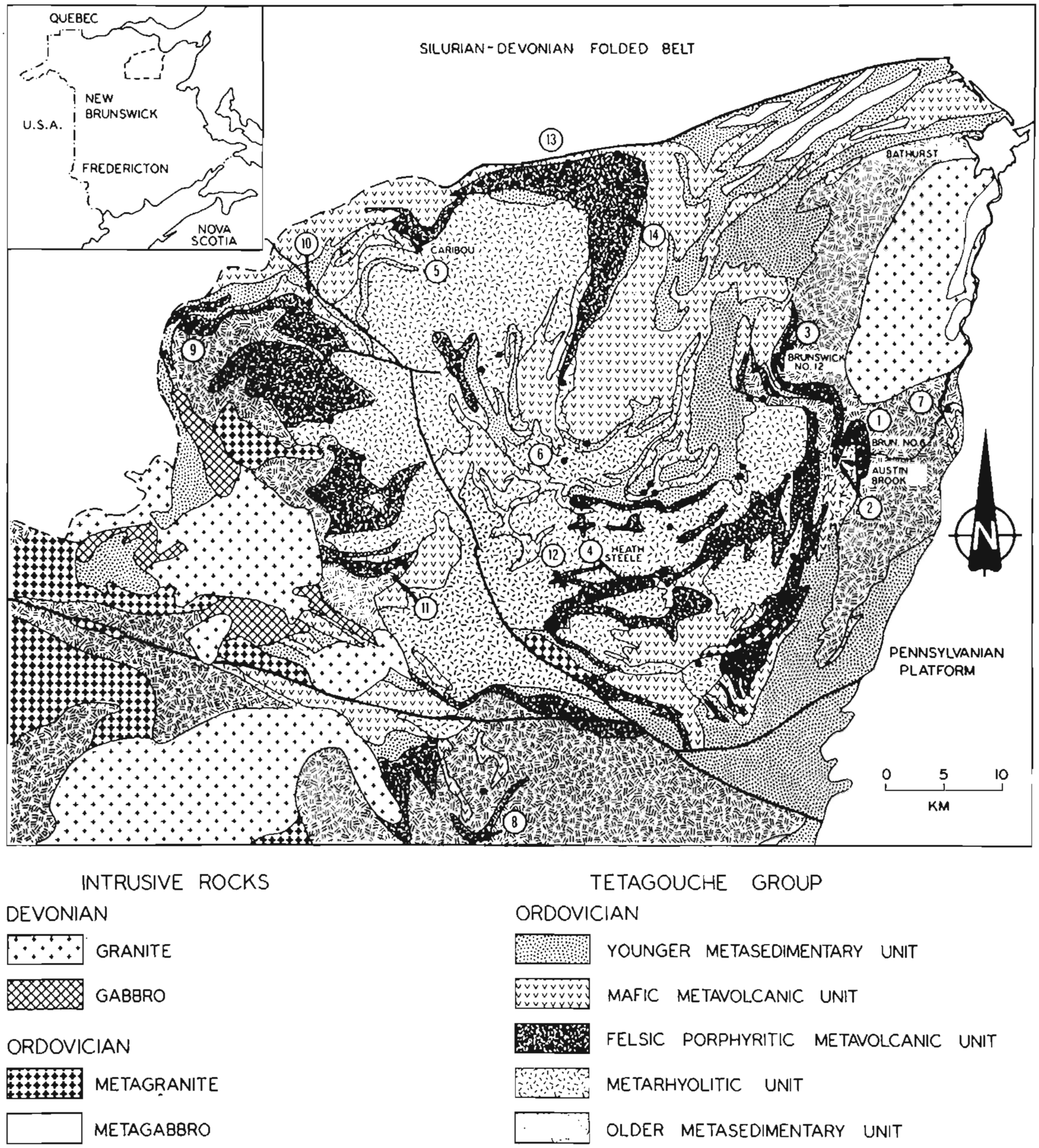


Fig. 3. General geology of the northern part of the Miramichi Massif (Bathurst area) with black dots showing the location of most sulphide deposits. The more important are numbered as follows:

No. 1. Brunswick Mine No. 6
No. 2. Austin Brook
No. 3. Brunswick No. 12.
No. 4. Heath Steele
No. 5. Anaconda-Caribou
No. 6. Wedge
No. 7. Key Anacon
No. 8. Chester
No. 9. Restigouche
No. 10. Murray Brook
No. 11. Half Mile Lake
No. 12. Cominco-Stratmat
No. 13. Orvan Brook
No. 14. Armstrong

unconformably by Lower Silurian conglomerate.

The Fournier Group ophiolite suite represents a remnant of the Ordovician Iapetus Ocean (Pajari et al. 1977).

Matapedia Basin

The lowermost rocks exposed within the deeper parts of the Matapedia Basin are Middle to Upper

Ordovician greywacke and slate of the Grog Brook Group (St. Peter, 1978). The Grog Brook Group grades laterally into, and is overlain by, Upper Ordovician to Lower Silurian calcareous slate and aphanitic limestone of the Matapedia Group.

The Matapedia Group is overlain by ferromanganiferous slate, limestone, calcareous sandstone, and conglomerate of the Silurian Perham Group in the southwest and northwest. To the northwest, a thick sequence of Lower Devonian siltstone and slate of the Temiscouata Formation overlies the Perham Group. Lower Devonian volcanic rocks, sandstone and conglomerate of the Tobique Group overlie the Perham Group along the southeastern border of the Basin.

In the northeast, Silurian calcareous sandstone and siltstone of the Chaleur Group conformably overlie the Matapedia Group. Locally, the Chaleur Group begins with a Lower Silurian conglomerate resting unconformably on deformed rocks of the Elmtree Inlier. Middle Silurian nodular limestone succeeds the conglomerate and is overlain by Upper Silurian and Lower Devonian volcanic rocks (Greiner 1970).

THE TETAGOUCHE GROUP

The supracrustal rocks of the Miramichi Massif (Skinner, 1956, 1974), consists of five lithologic units; two metasedimentary, two felsic metavolcanic and one mafic metavolcanic all assigned to the Tetagouche Group. The felsic volcanic units, with their contained orebodies, form a roughly circular structure, about 50km across, surrounded by an envelope of metasedimentary rocks (Fig. 3).

The stratigraphic succession continues to be the subject of much speculation due to lack of outcrop, complex and rapid facies changes in volcanic units, polyphase deformation, and the lack of well defined contacts of the units, which are identified by gradual changes in the nature and abundance of the volcanic rocks. Geological mapping over the last 10 years, however, has established general stratigraphic relations between the five lithological units. In the northeast, along the Tetagouche River (Fyffe, 1975), the stratigraphic order is:

5 Feldspathic metagreywacke, graphitic schist, phyllite
4 Pillow basalt, basaltic tuff, limestone, phyllite
3 Pillow basalt, manganiferous red and grey slate, metagreywacke
2 Felsic metavolcanic rocks, manganiferous slate, fossiliferous calcareous slate and crystalline limestone
1 Quartzose metagreywacke, slate

In the northwest part of the Massif near the Restigouche deposit (no. 9, Figure 3) the stratigraphic succession is; (Helmstaedt, 1971).

5 Metabasalt, minor argillaceous metasedimentary rocks
4 Slate, chert, metabasalt
3 Felsic metavolcanic rocks
2 Slate, metasiltstone, metagreywacke
1 Quartzose metasedimentary rocks

Between the two areas, the felsic volcanic complex occupies essentially the same stratigraphic position, viz. a transition zone separating older, quartzose, metasedimentary rocks from younger, argillaceous, metasedimentary rocks with mafic flows becoming progressively more dominant near the top.

Tetagouche Sedimentation

The older, quartzose metasediments are thin bedded, intercalated, fine-grained, quartzose metagreywackes and phyllites (locally graphitic). Primary features are generally obliterated by recrystallization and intense deformation, but in a few places graded bedding and cross bedding can be seen. The clastic fraction in most arenaceous rocks is sand to silt size, sub-rounded to rounded quartz grains with few (>5%) feldspar clasts. The matrix is largely granoblastic quartz with sericite, chlorite and biotite which define foliations. No reliable estimate of thickness of this unit can be made.

The age of the older metasediments in northern New Brunswick is based on a single fossil locality 10km west of Tetagouche Falls (Fyffe, 1975, 1976) that yielded Arenigian (early Ordovician) brachiopods.

The younger metasediments are mainly grey slate, graphitic and siliceous phyllites, and intercalated metagreywacke. The metagreywacke is poorly sorted and beds are locally graded. This unit also includes distinctive red, purple and maroon, siliceous meta-argillite and slate, and jasper which in places are intercalated with mafic and felsic metavolcanic rocks. At Tetagouche Falls, manganiferous slates have been the object of mining interest for over 120 years.

Graptolites found in the Tetagouche River valley within the City of Bathurst, and trilobites and conodonts found near the Murray Brook sulphide deposits (no. 10, Figure 2) indicate a Middle Ordovician age for the younger metasediments and associated mafic volcanic rocks. Fossils more recently discovered (Gummet et al. 1978) in beds interbedded with acidic volcanic rocks near sulphide horizons have been tentatively identified as most likely late, or possibly late-Middle Ordovician in age.

The older sedimentary rocks are thought to represent platformal deposition in a relatively stable tectonic environment, whereas the argillaceous and poorly sorted arenaceous sediments, and intercalated lavas and pyroclastics represent an unstable tectonic regime accompanying volcanism.

Tetagouche Volcanism

According to the foregoing discussion, felsic volcanism in the Miramichi Zone occurred in Middle or late Ordovocian time. Evidence gathered to date indicates that the early volcanism was of a felsic nature and accompanied by relatively minor extrusions of mafic rock. The proportion of mafic volcanic rocks increases toward the top of the pile, which is capped by massive, commonly pillowed basalt, basaltic tuff, and metagabbro intercalated with argillaceous metasediments (Rankin, 1981).

The schistose and massive metarhyolitic rocks (Figure 3) represent coalescing piles of rhyolitic tuff, breccia, agglomerate, and flow banded lavas apparently extruded from a number of sources. In places in the northern and eastern parts of the volcanic complex, microfelsic, spherulitic, vesicular, and pisolitic textures and remnant shards are recognizable. Some massive, rhyolitic bodies associated with agglomerate, tuff and iron formation may represent remnant intrusive domes. Good examples occur in the Nine Mile Brook area west of Brunswick No. 6 (no. 1, Figure 3) and west and south of the Heath Steele deposits (no. 4, Figure 3).

The felsic porphyritic metavolcanic unit (augen schist, "Bathurst" porphyry, etc.) consists of quartz and/or relict feldspar phenocrysts and crystal fragments set in a schistose (rarely microfelsic) or granoblastic matrix of quartz, sericite, feldspar, chlorite and biotite. In most places these rocks are intercalated with thin layers of metasedimentary rocks, and mafic metavolcanic rocks, indicating they may be submarine ash flows or ignimbrites that flowed into water. No concrete evidence of subaerial volcanism has yet been documented.

The mafic metavolcanic rocks can be divided into two general varieties (Skinner, 1956, 1974): (1) spilite, consisting of albite, clinopyroxene, chlorite, ilmenite, leucoxene, magnetite and stilpnomelane, and characterized by an igneous texture, and (2) greenstone, characterized by massive banded and schistose textures and strictly metamorphic mineral assemblages.

Recent mapping (Rankin, 1981) indicates that spilite, massive greenstone, and intercalated tuffs form the youngest volcanic unit of the Tetagouche Group. Extensive occurrence of pillows leaves little doubt that these rocks represent submarine flows. Types distinguished by a better developed schistosity and in association with foliated felsic metavolcanics, appear to be older (Fyffe, 1971). Some of the older mafic rocks have been described as andesites but this classification is not supported by petrographic or chemical data.

Intrusive rocks emplaced prior to late Ordovician deformation and metamorphism consist of cataclastic or foliated granite and foliated and metamorphosed gabbro. The felsic plutons dated at about 479 my (Fyffe et al., 1977) intrude the older metasedimentary and felsic metavolcanic units but not the younger metasediments. Post-orogenic Devonian granitic rocks occur as batholiths along the western part of the Miramichi Massif and as isolated stocks in the northeast.

Available chemical data indicate that the Tetagouche volcanic rocks,especially those of felsic composition, have been profoundly altered since extrusion. Such alteration can be attributed to reaction with sea water, weathering, hydrothermal alteration and regional metamorphism. Hence the use of geochemical parameters in rock classification and determination of tectonic setting of Tetagouche volcanism is limited. Frequency distribution of SiO_2 reveals the Tetagouche suite is essentially bimodal. Felsic volcanic rocks are generally depleted in alkalies and K_2O/Na_2O ratios are high.

Tetagouche volcanism is thought to be attributable to island arc development related to the closing of the Proto Atlantic (Wilson, 1966). Bird and Dewey (1970), in the context of a global approach, favour this interpretation, as does Helmstaedt (1971). The shape of the Tetagouche volcanic complex was interpreted by Davies (1966, 1972a) as indicative of a deformed volcanic-tectonic depression (large caldera), a view recently revived by Harley (1979). Such a structure, together with the bimodal character of the volcanic rocks, suggests an origin during a local rifting in continental crust. The trend of volcanism probably followed the sequence of local doming, extrusion, deflation and subsidence, although there is no evidence of a general continuous uplift during the felsic volcanic phase. The volcanic edifice subsided in Middle Ordovician time, and was partly covered by pillow basalts and argillaceous sediment. The stratigraphic position of many of the massive sulphide deposits indicates formation near or at the close of the felsic volcanic phase. Others appear to be overlain by substantial thicknesses of felsic material.

Structural Geology

The structural history of the Tetagouche Group is complex. Many outcrops show three or more penetrative, intersecting cleavages. As a result of this repeated deformation and lack of outcrop in many areas, the distribution of stratigraphic units is difficult to define. There is also a good deal of uncertainty in the correlation of structural features and events from one part of the area to another. However, results of studies by several workers (Helmstaedt 1971; Fyffe, 1971, 1982; Luff 1975, Irrinki 1974; McBride 1976, van Staal and Williams (in press), show elements of agreement.

In the west and southwest early folds (F_1) are recumbent (Helmstaedt 1971) and plunges are consequently generally shallow. In the Heath Steele area, McBride (1976) recognized an early cleavage which he interpreted to be the result of early recumbent folding. Similarily van Staal interprets micro structures and fold geometry in the area of Brunswick #12, and Brunswick #6 mines in terms of an early period of recumbent folding and thrust faulting in which the folds verge northward similar to folds in the west and southwest part of the camp.

The second period of deformation produced tight isoclinal folding (F_2) and resulted in the development of a penetrative cleavage (S_2) formed of aligned chorite, muscovite, and, at higher grades, biotite.

The last major period of deformation (F_3) folded the rocks and the earlier formed cleavages. In the east these folds exhibit steep, northeast trending axial planar cleavage and steep plunges. The folds between Brunswick No. 6 and Brunswick No. 12 mines are of this type, as is the large fold south of the Orvan Brook deposit (Fig. 3). Farther west between Murray Brook and Restigouche deposits the late folds possess a steep, northerly trending axial planar cleavage and gentle plunges to the north.

The early deformation in the Tetagouche can be attributed to the Taconian Orogeny, since the Silurian rocks overlying the Tetagouche are unaffected by it. The late folding (F_3) is probably a result of the Devonian Acadian Orogeny.

Numerous faults have been mapped in the northern part of the Miramichi Massif, but the complex folding has undoubtedly masked the existence of many others. Most of the major faults fall into two sets (1) a northeasterly trending set that includes the Rocky Brook Millstream and the Catamaran faults and (2) a northwesterly trending set which includes the Upsalquitch-Sevogle fault.

The Rocky Brook Millstream fault in the Bathurst area forms a northern boundary to the Tetagouche Group. The Catamaran fault is roughly parallel and lies to the south of the area shown in Fig. 3. The Rocky Brook Millstream and Catamaran faults show evidence of right-handed strike-slip movements, though MacKenzie (1951) suggested that the former is a modified thrust. Right lateral offsets on the Rocky Brook Millstream fault and the Catamaran fault are approximately 22km and 6km respectively.

The Upsalquitch-Sevogle fault cuts northwestward across Fig. 3 and can be followed for at least 125km across rocks of the Tetagouche Group and those of the flanking Matapedia Basin. The nature of the movement is not known but near the Murray Brook deposit (No 10 Fig. 3) the faults appear to be a left-hand wrench.

The existence of thrust faults which might be expected to accompany a period of early recumbent folding has not been well documented, but may simply not be recognized because of younger complex folding. The existence of one such fault has been suggested by van Staal and Williams (in press).

Massive Sulphide Deposits

Although many massive sulphide deposits have been discovered in the Miramichi Massif since modern exploration began in 1952, some were found much earlier. The Austin Brook deposit (no. 2, Figure 3) was found in 1898; the Brunswick No. 6 deposit (no. 1, Figure 3) in 1907, and the Orvan Brook deposit (no. 13, Figure 3) in 1938 (MacKenzie, 1958). At present, ore is produced from only three deposits; Brunswick No. 6 and No. 12 and Heath Steele (nos. 1,3 and 4, Figure 3). The Wedge deposit (no. 6, Figure 3) produced copper ore from 1962-68, and secondary enriched copper ore was mined at the Caribou deposit (no. 3, Figure 3) in the early 1970's. Gold is currently being produced from gossan material at Heath Steele and Anaconda Caribou.

Approximately 80 percent of the sulphide deposits discovered to date occur in the northeastern structural domain northeast of the Upsalquitch-Sevogle fault. The explanation for this may be that the steep plunge of the late folds in the northeastern domain has resulted in a thicker exposed section of the volcanic complex. It is remarkable that all the massive sulphide deposits discovered to date intersect the bedrock surface.

In general the deposits consist of concordant masses of pyrite, sphalerite, galena, chalcopyrite and in places pyrrhotite. They range in size from small showings to huge masses such as that found at Brunswick No. 12 where reserves are well over 100 million tonnes.

Both shapes and orientations of the orebodies are largely dependent on the degree and style of deformation. In the northeastern structural domain many deposits are long, relatively thin lenses, occurring singly or in en echelon groups. Apparent exceptions, for example Brunswick No. 6, originated as long thin lenses (12 to 15m thick), have been considerably foreshortened into much thicker lenses (Pertold, 1970; Luff, 1975; Saif, 1978). The steep plunge of most sulphide deposits in this domain is governed by the orientation of late (post-D_1) folds.

In the southwest domain the carrot or turnip shapes of most deposits, e.g., Chester, Restigouche, Murray Brook, Half Mile Lake and Chester (nos. 9, 10 and 11, respectively, Figure 3), are the result of F_2 folds and the S_2 crenulation cleavage (Helmstaedt, 1971; Rankin and Davies, 1979). F_2 folds in this domain have shallow plunges to the north, northwest, and west, and consequently sulphide deposits have similar attitudes.

A typical deposit comprises fine-grained, massive pyrite containing parts rich in sphalerite-galena and/or chalcopyrite-pyrite (and/or pyrrhotite). The Zn-Pb-rich zones are commonly layered and may be separated from the Cu-rich parts. Slump folds and other soft sediment deformation structures are relatively common. Texture is dominated by a fine-grained granoblasstic intergrowth of sulphide minerals, mainly pyrite. Porphyroblastic, colloform and cockade-like structures are also present, though the latter two appear to be supergene features. Metal zoning is well displayed in a number of deposits, including Brunswick No. 12 and No. 6, Heath Steele and Caribou, (Rutledge, 1972; Lusk, 1969; and Cavalero, 1970). In these deposits the Zn-Pb-rich part commonly occurs stratigraphically above the Cu-rich zone, which may be locally discordant.

In most cases the immediate host rock is chloritic and/or siliceous, and, in some deposits, the chlorite-rich rock is intercalated with banded magnetite-hematite-quartz (Algoman type) iron formation (Gross, 1965; Davies 1972b).

The relationship between iron formation and massive sulphides is observed in several deposits, including those at Brunswick and Heath Steele. In these deposits iron formation either grades laterally into pyritic Zn-Pb sulphides (Boyle and Davies, 1964; MacMillan, 1969; and Rutledge, 1972), or forms small lenses and extensive blankets overlying and extending well beyond the sulphides (McBride 1976). The sulphides and oxides in places occur independently of each other.

In other deposits, e.g. the Half Mile Lake and Murray Brook deposits, the host rock is a sequence of chloritic siltstone and greywacke, with intercalated rhyolitic tuff capped by mafic metavolcanic rocks (Rankin and Davies, 1979; Harley, 1979).

The relative stratigraphic positions of the sulphide deposits in the volcanic pile remains a problem. In the Heath Steele area, MacMillan (1969) recognizes two stratigraphic zones. He concludes that the so-called Boundary deposit and the Stratmat deposits (no. 12, Figure 3) occur at the same stratigraphic level, and that both lie stratigraphically above the Heath Steele deposits (no. 4, Figure 3).

The Canoe Landing Lake deposit, together with the Orvan Brook, (no. 13, Figure 3) Rocky Turn and Armstrong Brook (no. 14, Figure 3) appear to represent the highest stratigraphic level in which sulphide deposits are found. These deposits occur in intercalated sedimentary rocks and felsic volcanic rocks near the contact with the younger basaltic flows and tuffs. The Caribou deposit (no. 5, Figure 3), however, appears to lie at a lower stratigraphic level (Cavalero, 1970).

Alternatively, one stratigraphic zone repeated several times by folding, is a reasonable hypothesis for some areas, considering the polyphase deformation, and the complicated lithological interference pattern (Figure 3). Rutledge (1972) has shown that in the Brunswick No. 12 mine, the "West Zone" is a repetition of the "Main Zone". Similarly detailed mapping at the Brunswick No. 6 mine, has outlined isoclinal folds with half wavelengths of about 120m or more, superimposed on larger isoclines with half wavelengths ranging up to 3km. On the eastern margin of the volcanic complex, work by Saif (1978) indicates that the Key Anacon deposit (no. 7, Figure 3) may be stratigraphically equivalent to Brunswick No. 6 (no. 1, Figure 3) and is not an older occurrence as inferred on previous regional maps (cf. Davies, 1968). Rankin (1981) working in the northwestern part of the camp, has shown that a number of deposits (Restigouche, Murray Brook, and others) occur over a stratigraphic range of several hundred metres. It is not difficult to assign all sulphide deposits in the area to one relatively wide stratigraphic zone.

Most of the evidence gathered over the last 20 years or so supports the theory that the sulphide deposits are exhalites precipitated on the Ordovician sea floor during, or near the end of, the felsic volcanic phase (McAllister, 1960). The deposits have since been deformed and metamorphosed along with their host rocks.

BRUNSWICK MINING AND SMELTING CORP.
NO. 12 AND NO. 6 MINES

(after C. van Staal, Wm Luff, and P.F. Williams)

Introduction

The Brunswick #12 and #6 mines are 10km apart and 27km southwest of the city of Bathurst, N.B. They occur at or near the same stratigraphic horizon and form part of the complexly deformed rocks of the Tetagouche Group.

The #12 mine has lead-zinc ore reserves of 101,742,000 tonnes grading 9.10% zinc, 3.73% lead, 0.32% copper and 96.8 g/t silver. Separate copper reserves are 12,786,000 tonnes grading 1.27% zinc, 0.45% lead, 1.11% copper and 35.3 g/t silver.

The #6 mine from which 12,150,000 tonnes, grading 5.44 Zn, 2.14 Pb, 0.40 Cu, 66.5 gm/t silver has been extracted is essentially an open pit operation and ore reserves are nearing exhaustion.

Lithology

The rocks occurring in the Brunswick #12 and #6 mine areas have been subdivided by mine geologists (Pertold 1970, Rutledge 1972, Luff 1977) as shown in Figs. 4 and 5. Their division and terminology have been retained in this paper but some units have been grouped for description brevity. The units described refer specifically to the diagrams for the No. 12 mine, but the strata and their sequence is essentially the same at No.6.

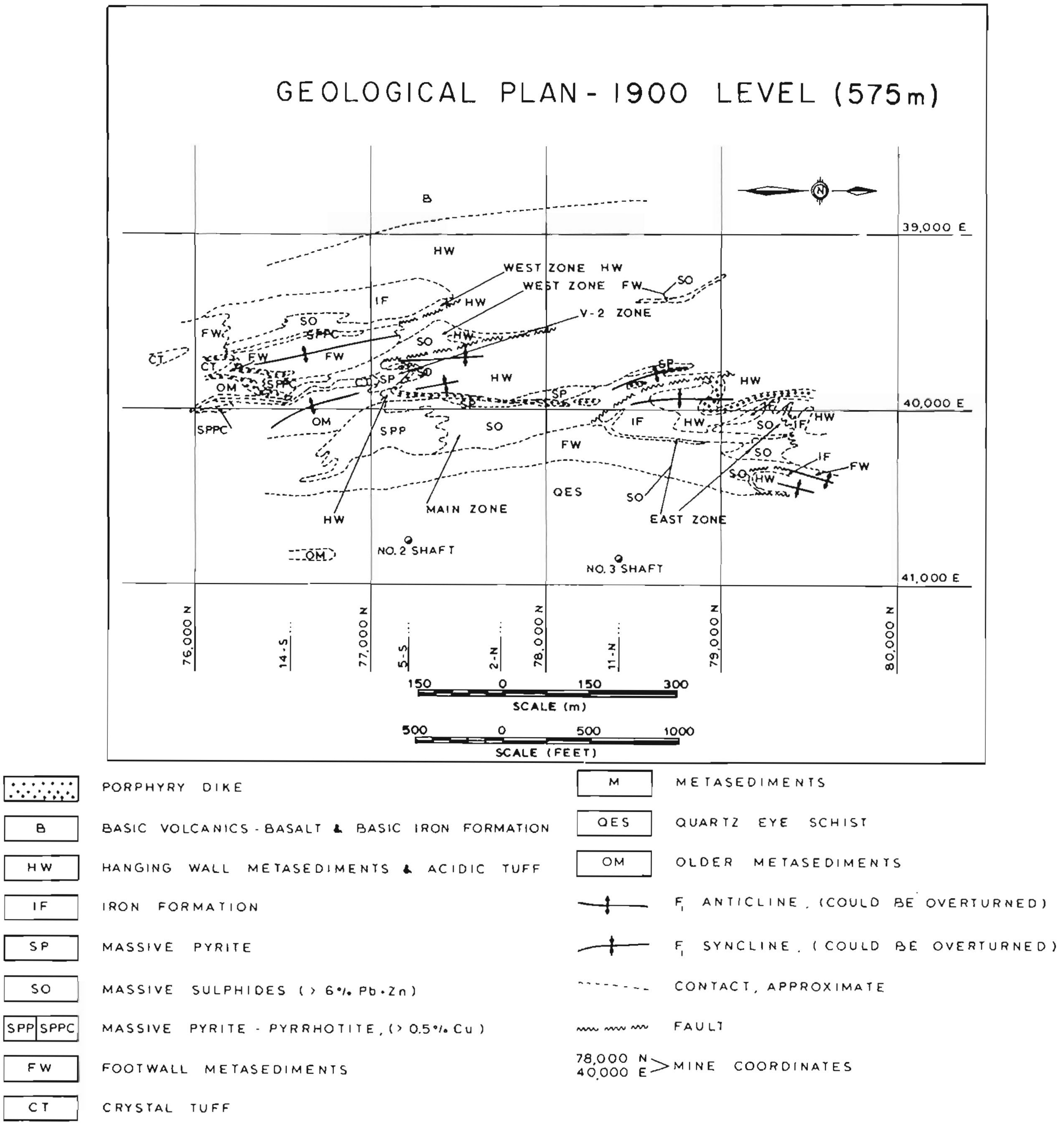


Fig. 4a. Geological plan, Brunswick No. 12 orebody.

Older metasediments. This unit consists mainly of grey quartz phyllites and quartzites which are regarded as part of the basal unit of the Tetagouche Group (Helmstaedt 1973). Dark chloritic and carbonaceous phyllites also occur, especially near the contact with the overlying augen schists. They commonly contain small amounts of disseminated pyrite and pyrrhotite, although locally small massive sulphide bodies occur.

Augen schist and crystal tuff. This unit consists mainly of felsic metavolcanic rocks. The lowest part of the unit is generally an augen schist which, because of its wide aerial extent, is believed to represent felsic ash flows (Davies 1972, Juras 1981). They are made up of large (0.5 - 2cm) relict quartz phenocrysts and megacrysts of feldspar in a fine-grained matrix of sericite, biotite, chlorite and quartz.

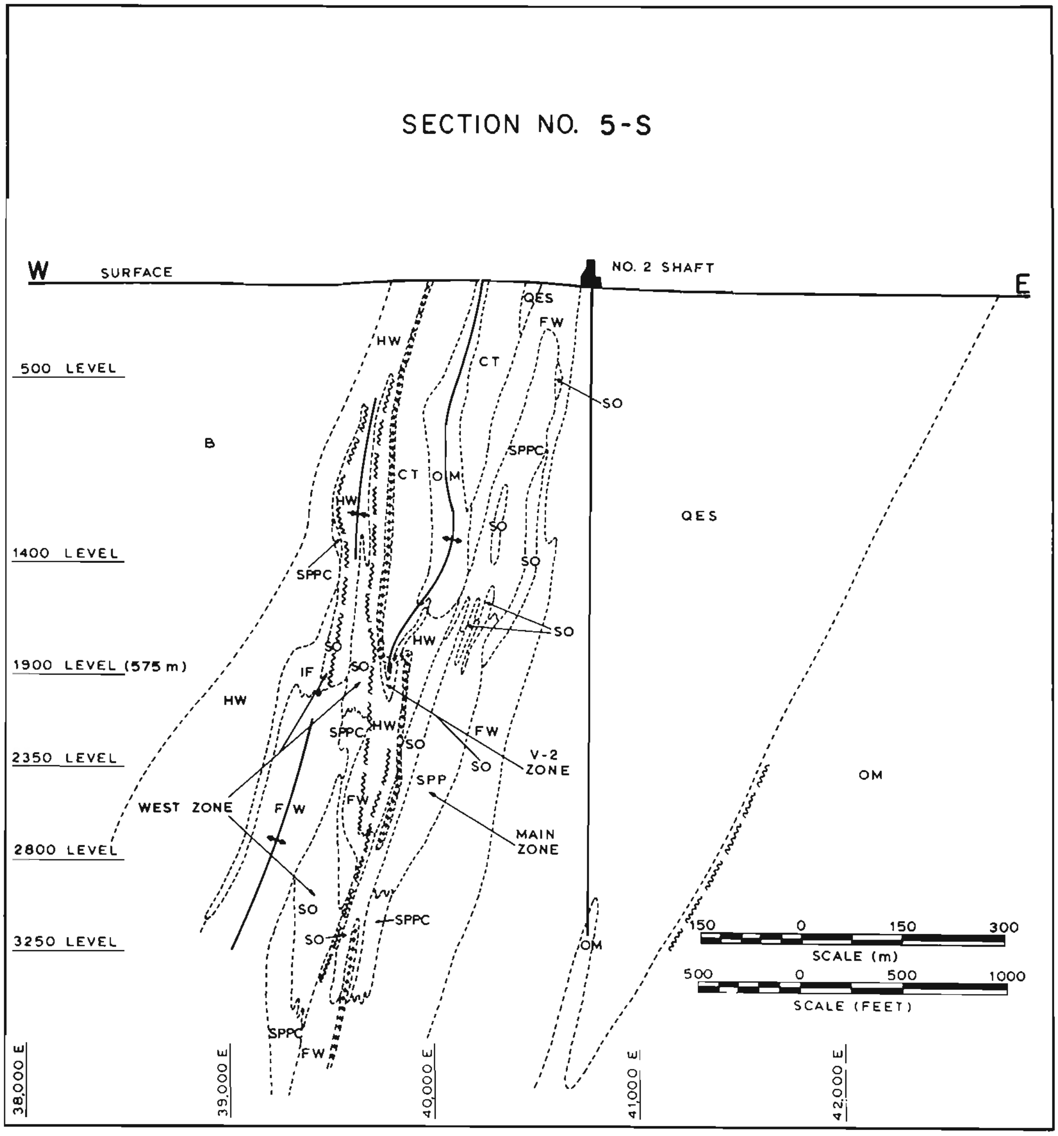


Fig. 4b. Geological cross section Brunswick No. 12 Mine.

Quartz phyllites, commonly containing relict, quartz phenocrysts, occur towards the top of the unit. These rocks are generally regarded as the metamorphic equivalents of ash-fall crystal tuffs.

Footwall metasediments. This unit consists mainly of green, chloritic phyllites with thin interlayered bands of chert and sulphides. It is mainly found close to or underneath the massive sulphides and has been assumed by some to represent an alteration zone and to contain part of a primary stockwork zone (Goodfellow, 1975; Juras, 1981).

Chlorites in the footwall zone typically are iron-rich and closely resemble the chlorites of the silicate facies of the iron formation, which also includes clastic beds and sulphide stringers. These chloritic phyllites could be interpreted as primarily a footwall iron formation and their origin through feeder pipe related alteration remains in doubt.

Massive Sulphides. The massive sulphide bodies are divisible into three units: (1) chalcopyrite zone, which carries minor amounts of sphalerite and galena and minor to large amounts of chalcopyrite and pyrrhotite; (2) massive sulphide-lead-zinc orebody - consisting of layered sphalerite-galena-pyrite with minor chalcopyrite and pyrrhotite; and (3) pyrite zone, consisting of mainly massive, fine-grained pyrite, with minor sphalerite, galena and chalcopyrite. The massive sulphide bodies are 80-90 percent fine-grained sulphides, consisting mainly of pyrite, sphalerite,

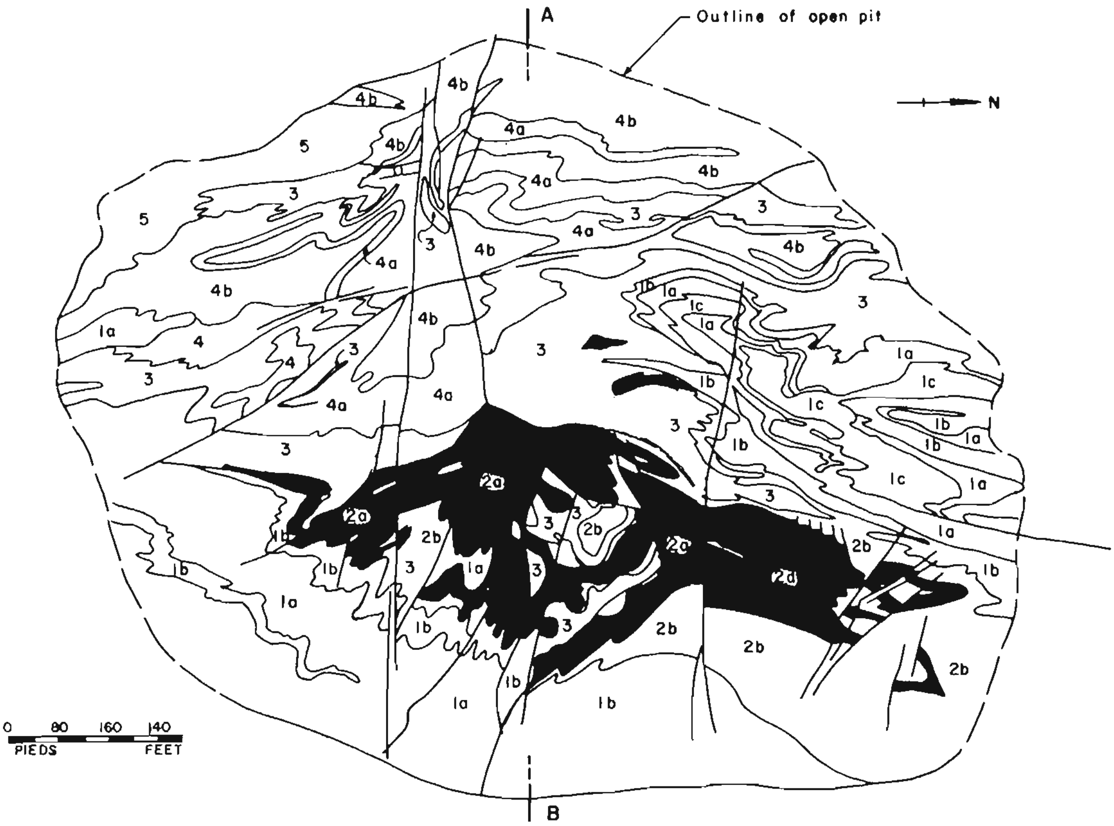


Fig. 5a Geological plan of Brunswick No. 6 orebody (after Pertold, 1970)

1 Augen Schist
  1a quartz augen schist
  1b quartz-chlorite-sericite, and chlorite-sericite schist
  1c quartz-feldspar augen schist

2 Sulphide Deposit
  2a massive pyrite with sphalerite and galena (> 4% Zn + Pb)
  2b includes, low grade (<4% Pb + Zn) massive pyrite, disseminated pyrite, and pyrrhotite-chalcopyrite mineralization.

3 Iron formation; oxide; chlorite and carbonate facies

4 Upper volcanic rocks
  4a quartz-sericite-chlorite and chlorite sericite schist
  4b metarhyolite, metarhyolitic tuff, meta-agglomerate.

5 Metadiabase

galena, chalcopyrite, pyrrhotite, tetrahedrite and bornite, with minor amounts of numerous other sulphides and secondary minerals. The 10 to 20 percent of gangue minerals consist mainly of quartz, carbonate and chlorite, with minor amounts of sericite, graphite and other minerals. Some magnetite occurs in the No. 6 orebody and the east ore zone at No. 12 mine.

Iron formation. This is a group of iron-rich rocks, including the massive sulphides, found at both No. 12 and No. 6 mines. The iron formation is generally divided into four facies, namely the carbonate, oxide and silicate facies, which are generally mapped as iron formation, and the sulphide facies. They occur as lenses and contacts are commonly gradational.

Hanging wall metasediments and felsic metavolcanics. This unit consists of gray, chlorite-sericite phyllites which grade upwards into felsic metavolcanics. The latter rocks include probable basic flows and pyroclastics. A reddish hematitic phyllite occurs near the top of the unit.

Mafic volcanic rocks. Metabasalts, agglomerates and tuffaceous material are abundant near the top of the sequence. Thin bands of magnetite bearing iron formation occur commonly within this unit and are known as basic iron formation.

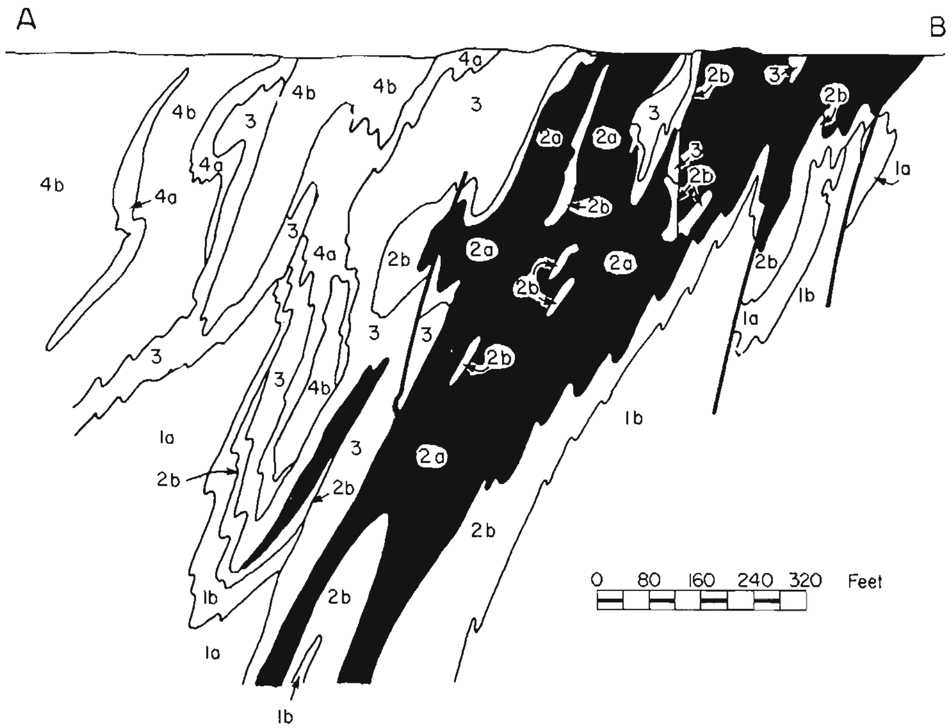


Fig. 5b Geological cross section of Brunswick No. 6 orebody to accompany Fig. 5a (after Pertold, 1970)

Metadiabase-metagabbro - This plug occurs as an irregularly shaped southwesterly plunging intrusion in the hanging wall rocks near the No. 6 mine. Mesostructures and greenschist facies mineral assemblages indicate that the intrusion predates or is coeval with an earlier deformation.

Porphyry Dyke - This dyke is the only intrusion in the No. 12 mine area. It trends north-south and cuts the other formations. It is light to dark grey and weakly schistose. Clear quartz crystals are present as phenocrysts and in most cases, white, albite feldspar, set in a finer-grained matrix of quartz, sericite, and chlorite is also present.

Mesostructure

Five generations of folds have been recognised in the mine areas. The first generation of folds (F_1) are assymmetrical interfolial and isoclinal with an axial plane foliation (S_1) in some places.

Meso- and macroscopic geometrical analysis reveals that F_1 folds had generally shallow or moderate southward dipping axial planes, ie. overturned to the north, prior to F_2 folding. F_1 folds are present up to kilometre scale in the mine areas. A strong bedding parallel foliation, locally phyllonitic and accompanied by shear band cleavage is probably a result of bedding parallel shear, which considered with all other data, indicates that F_1 folding was coeval with thrusting

F_2 folds are characterised by tight to isoclinal, easterly overturned folds that are generally accompanied by a penetrative axial plane cleavage (S_2).

F_3 folds are open to tight folds ranging from millimetre to kilometre scale. An axial plane crenulation cleavage, which has a fairly constant NE-SW trend, is generally present. A well developed L_3 intersection lineation, parallel to the F_3 folds plunges moderately to steeply to the west and may obscure the older L_2 intersection lineation completely. F_4 and F_5 folds comprise two groups of kinked bands. They have only been observed on millimetre and centimetre scale and are never seen to overprint one another. Both form separate conjugate pairs and are therefore interpreted as different generations.

Structure and Distribution of the Massive Sulphides.

Structural analysis of the Brunswick #12 and #6 mines and surroundings show that the structural history and the geometries of the two orebodies are essentially the same as shown in the simplified interpretation diagrams in Figs. 6, 7, 8, and 9. They both occur in large asymmetrical folds, which at Brunswick #12 deposit have Z-asymmetries, and are steeply plunging to the south on surface. Younging directions based on the metal zoning and the position of the sulphide facies below the rest of

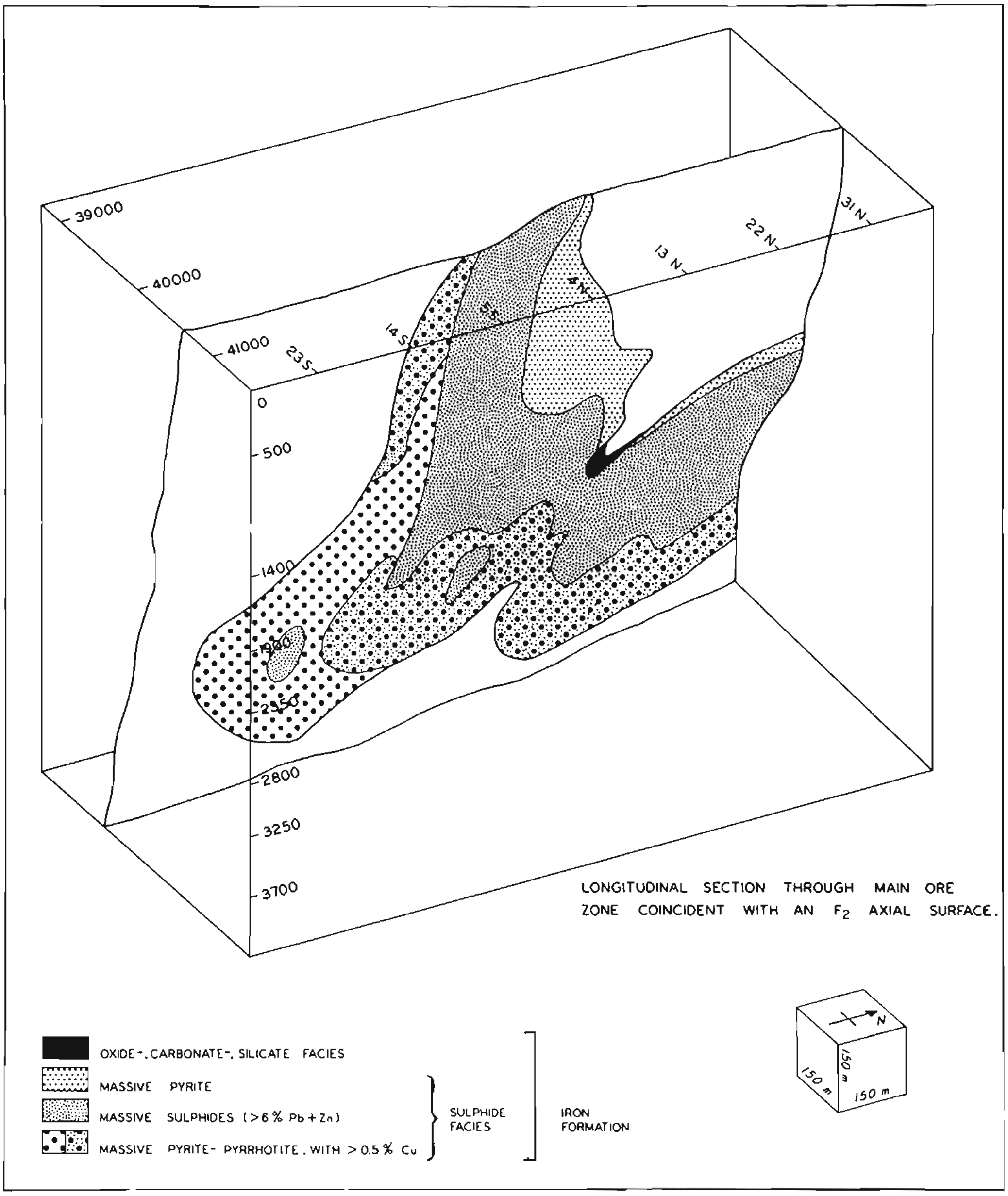


Fig. 6 Longitudinal section through the Main Ore Zone, Brunswick No. 12 orebody coincident with an F_2 axial surface. (coordinate system as in Fig. 7).

the iron formation suggests that the folds are downward facing on surface and therefore later than F_1 folds. The folds are interpreted as F_2 structures on the basis of the following evidence: 1) they refold S_1 and F_1, 2) S_2 is parallel to the axial surfaces of the folds, 3) mesoscale F_2 folds have the same plunge as the large folds, and 4) these folds are refolded by F_3.

A longitudinal section of the main ore zone at #12 and a block diagram of the whole orebody (Fig. 6, Fig. 7) show that plunges of the large F_2 folds on surface change continuously by more than 90° at depth. The southerly plunge at the surface passes through the vertical deeper down reversing plunge to the north. The amount of northward plunge gradually decreases eventually passing through the horizontal so that plunges become shallow to the south. The F_2 folds thus become upward facing with an S-asymmetry looking down plunge. The trace of the F_2 folds therefore define a large northerly overturned F_1 fold with a shallow southward dipping axial plane.

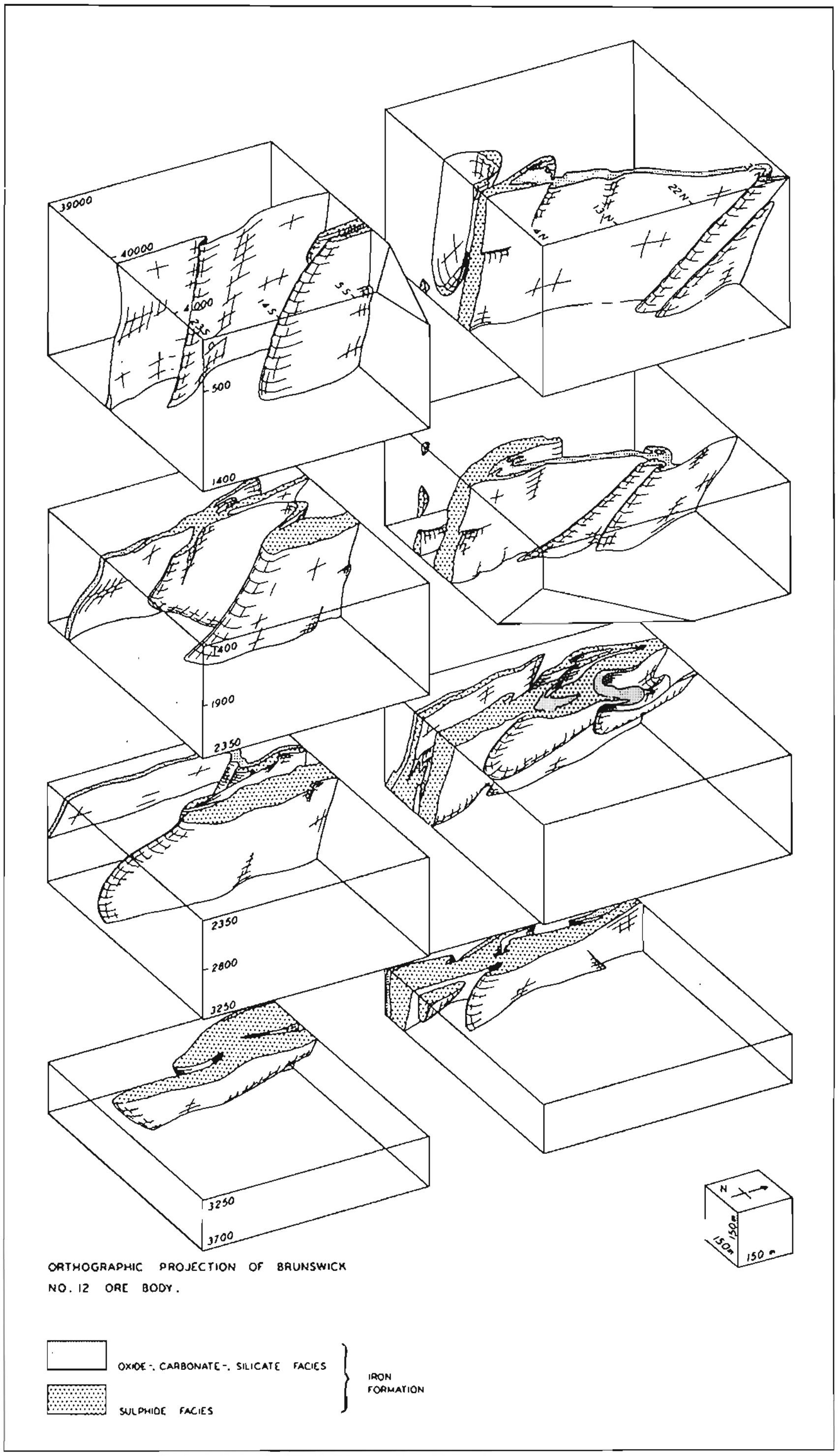


Fig. 7 Block diagrams of Brunswick #12 orebody. Vertical coordinates represent the different levels and horizontal coordinates refers to mine coordinates (in feet).

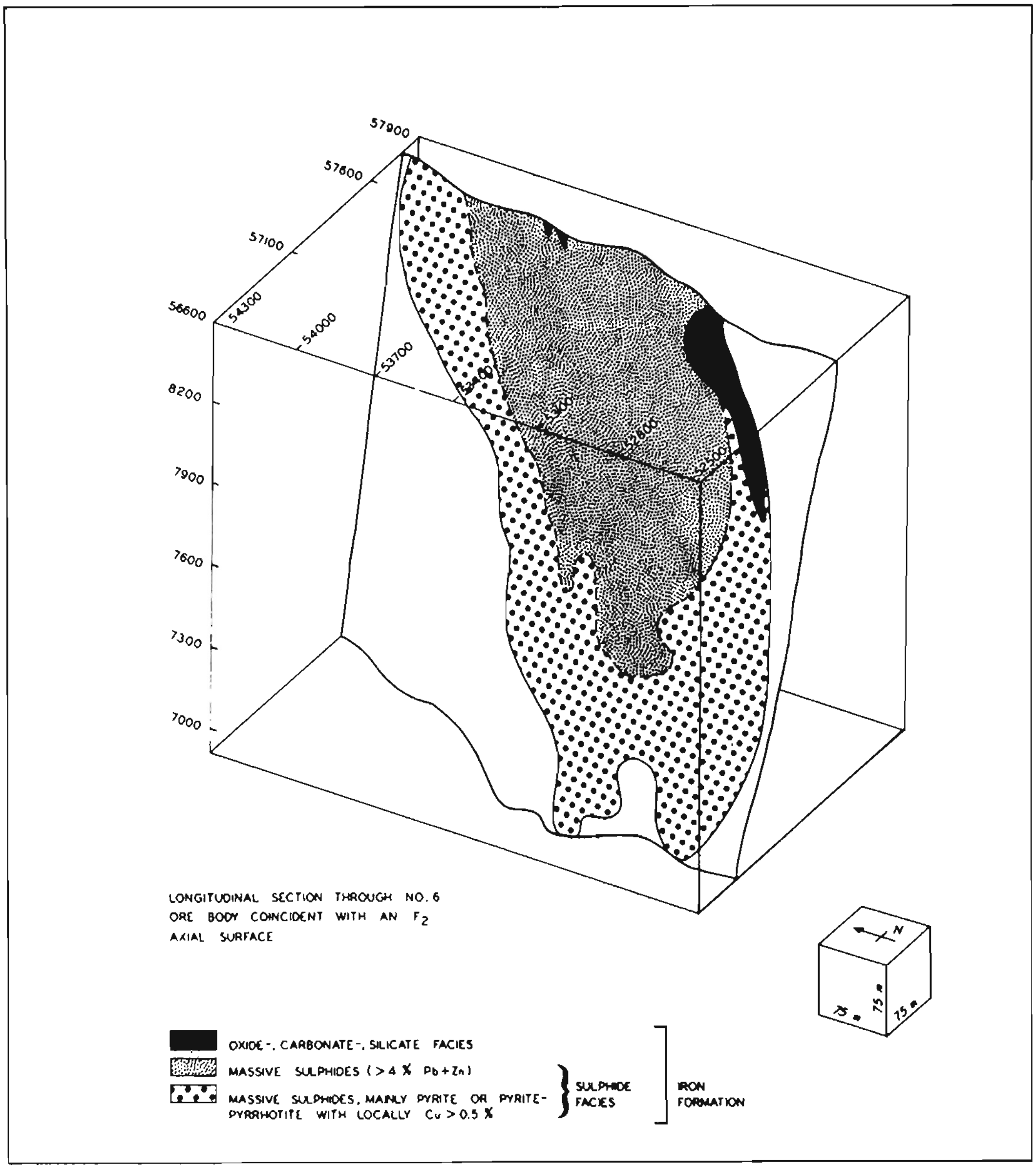


Fig. 8 Longitudinal section through No. 6 orebody coincident with F_2 axial surface. (mine coordinates in feet).

Massive sulphides in the Brunswick No. 12 mine occur in four major zones, the Main Zone, the East Zone, the West Zone and the V-2 Zone. These zones all occur at the same stratigraphic horizon (see stratigraphic sequence), but have been separated by isoclinal (F_2) folding and faulting. Mining currently is being carried out mainly in the Main Ore Zone and West Ore Zone as these are by far the largest. The sulphide bodies generally strike north-south, dip steeply west and plunge steeply to moderately north or south (see Figures 4 & 5).

All zones join up, however, below the 850m level, where the F_2 folds are formed close to the F_1 fold hinge, where the iron formation including sulphides can be expected to be thick. The separation of the sulphides on the shallower levels is probably the result of faulting and attenuation along the short limb of the large F_2 folds superimposed on F_1 attenuation, since at this spot the F_2 folds formed close to the F_1 limb, where the iron formation and sulphides were probably thin prior to F_2 deformation.

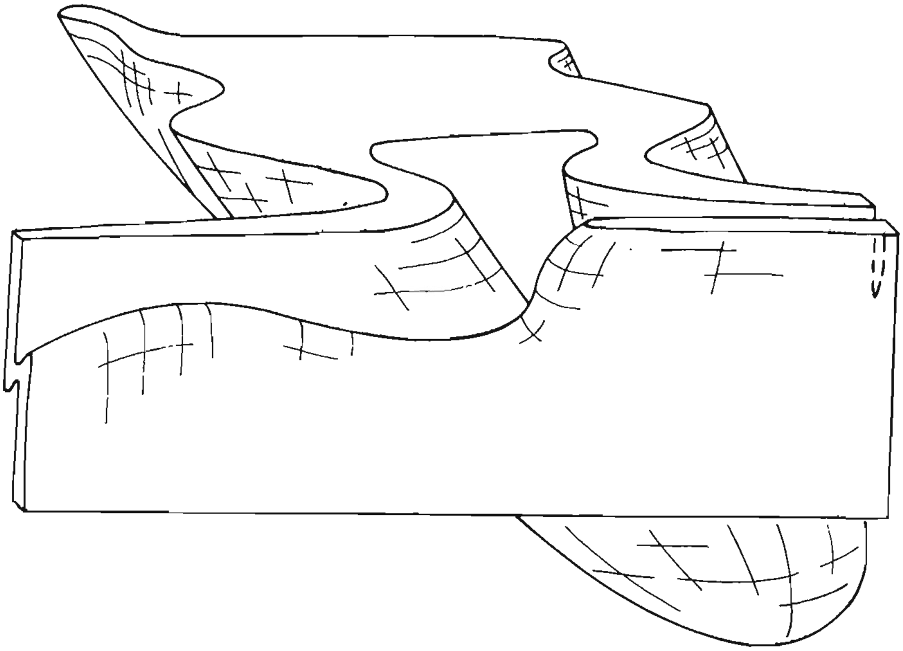


Fig. 9 Schematic three dimensional diagram showing the geometry of the No. 6 Orebody.

The attenuation of alternate limbs of almost isoclinal folds resulted in an almost en échelon pattern of tabular bodies that correspond to the hinges and long limbs of the F_2 folds. Transposition is also evident within the sulphide bodies where intrafolial isoclinal F_2 folds and boudinage occur commonly.

The essentials of the geometry of the #6 orebody are shown in Fig. 8. and 9. Structural analysis reveals also that the large upright folds are F_2 structures, which have been superimposed on a large F_1 fold with a steeper southwards dipping axial plane than that at #12. The orebodies occur thus in the noses of tight asymmetrical basins suggesting that thickening and economic concentration of sulphides is due to deformation.

Zonation of the Sulphide Bodies.

The #12 and #6 orebodies are divided into three zones (Pertold 1970, Rutledge 1972, Luff 1977). Cu is mainly concentrated in the massive or crudely layered pyrite of zone 1 at the footwall, whereas Zn and Pb are mainly concentrated in the well layered sulphides of zone 2, which lies immediately above zone 1. Zone 3 at the hanging wall comprises fine-grained massive pyrite with thin irregular layers or lenses of sphalerite and galena.

The present distribution of these zones, however, is complicated. Zones may be discontinuous and zoning is more lateral than perpendicular to primary layering in the #12 Main and West ore zones. These complications can be adequately explained by the intense folding, boudinage and attenuation of the zones during the F_2 deformation which is illustrated by sections parallel to F_2 axial surfaces (Figs. 6 & 8) where complications arising from the F_2 deformation are largely eliminated and zonation is seen to be fairly complete and simply folded by F_1. Thus the evidence suggests a simple, vertical zonation, ranging from zone 1 to zone 3 prior to deformation. All other structural data indicate also that the mineralization, with the exception of some remobilized material, has been affected by the earliest deformation recorded in the country rocks. This is compatable with the proposed volcanogenic - exhalative origin of the ores. However, proximal features such as a feeder pipe-stringer zone and syngenetic alteration are either missing or obscured by deformation and later alteration. Structural analysis of the stringer rocks by van Staal showed that it comprises two types of stringers. One set is parallel to the compositional layering of the surrounding clastic material and chert and therefore is interpreted as primary layers, whereas the other set, which is crosscutting, is parallel to the axial surfaces of F_1 or F_2 folds and therefore may represent a late remobilization feature rather than feeder pipes for the overlying massive sulphide unit.

Conclusive evidence for syngenetic feeder pipe type alteration is lacking and at least some of the alteration that is spatially related to the #12 orebody post-dates the intrusion of the felsic dyke and the deposition of the basalts.

HEATH STEELE MINES

(after D. McDonald)

Introduction

The Heath Steele property is 50 kilometres southwest of Bathurst in northern New Brunswick (Fig. 3). Sulphide deposits at Heath Steele lie within a polydeformed sequence of felsic metavolcanic and metasedimentary rocks of the Tetagouche Group (Skinner, 1974).

Although nine sulphide deposits have been delineated on the mine property, only five major zones will be discussed. Recent mining operations have been confined to the B zone, which has reserves of 24.4 million tonnes grading 4.25% zinc, 1.41% lead, 1.24% copper and 68.9 gms/tonne silver.

General Geology

A series of ore zones termed the "B", "A-C-D" and "E" zones (Fig. 10) exhibit a conformable relationship with the enclosing rocks of the mine sequence (Units 1 to 3). Most deposits form steeply dipping bodies that trend in an east-west direction across the property. Within this sequence, the sulphide deposits overlie alternating bands of metasediment (meta-argillite, metasiltstone and metasandstone) and crystal metatuffs. A broad horizon consisting of interbedded quartz and quartz-feldspar crystal metatuff lies with sharp contact over the sulphide deposit or associated banded iron formation.

The mine sequence of rocks is bounded to the south by a series of east-west striking faults which separates them from extensive units of siliceous volcanic rocks including massive rhyolite and coarse pyroclastics (lappili tuff, breccia and agglomerate) with isolated concentrations of pillowed and massive mafic volcanic flows (Owsiacki, 1980). To the north of the mine sequence, dominant rock types include felsic crystal tuffs and siliceous pyroclastic breccia and agglomerates. The fact both north and south acid volcanic sequences are quite similar, suggests that they may be stratigraphically equivalent.

Most production has come from the B zone. Detailed structural analysis in this area by McBride (1976) defined five deformational episodes. The relationship of cleavage (S_1) to bedding as observed in the B zone, and the present configuration of the A-C-D orebodies, led McBride to conclude that the oldest deformation developed north-northwest facing recumbent folds (D_1). In the A-C-D zone, only the four later deformations were observed during subsequent studies (Owsiacki and McAllister, 1979). The lack of internal features similar to those attributed to D_1 may be a result of masking effects by later deformations or the limited intensity of D_1.

In the B zone, the second deformation (D_2) is manifest by steep, westerly plunging isoclinal folds, while A-C zone rocks form major upright or steeply inclined folds that plunge gently west. Folding was accompanied by an axial planar cleavage (S_2) developed by parallel orientations of micas with quartz-feldspar crystals. Due to later deformations, S_2 trends are variable, ranging in orientation from 50° to 120°.

The third deformation is defined by open folds with steep southerly or northerly plunges. Fracture cleavage developed during D_3, forming at inflection points of F_3 crenulations and folds. Open folds with shallow, easterly plunges were generated during the fourth episode (D_4), whereas the fifth (D_5) produced steep, northeast trending cleavage in the B zone. Evidence for the final two periods of deformation was scarce in the A-C-D zone, suggesting intensities were weak.

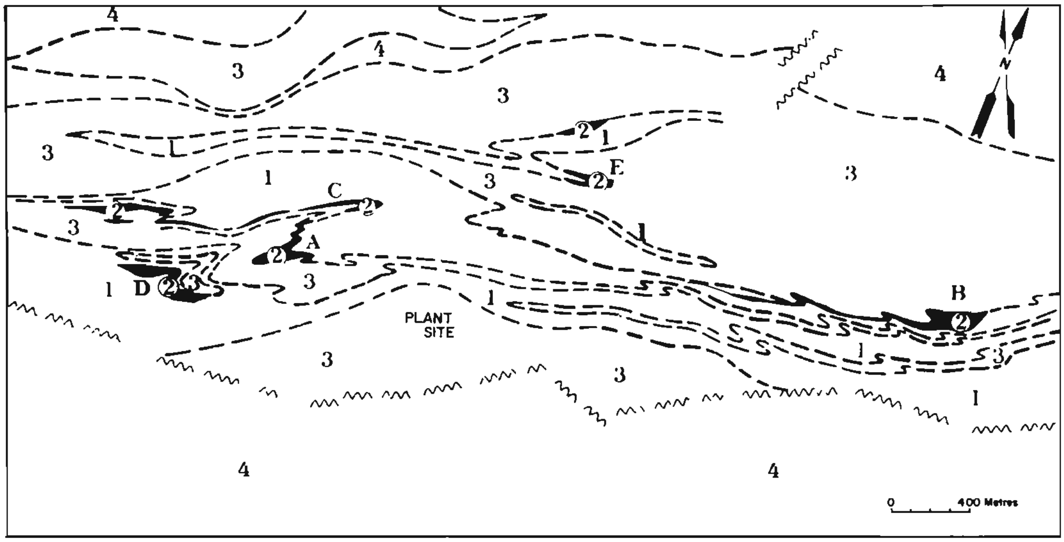
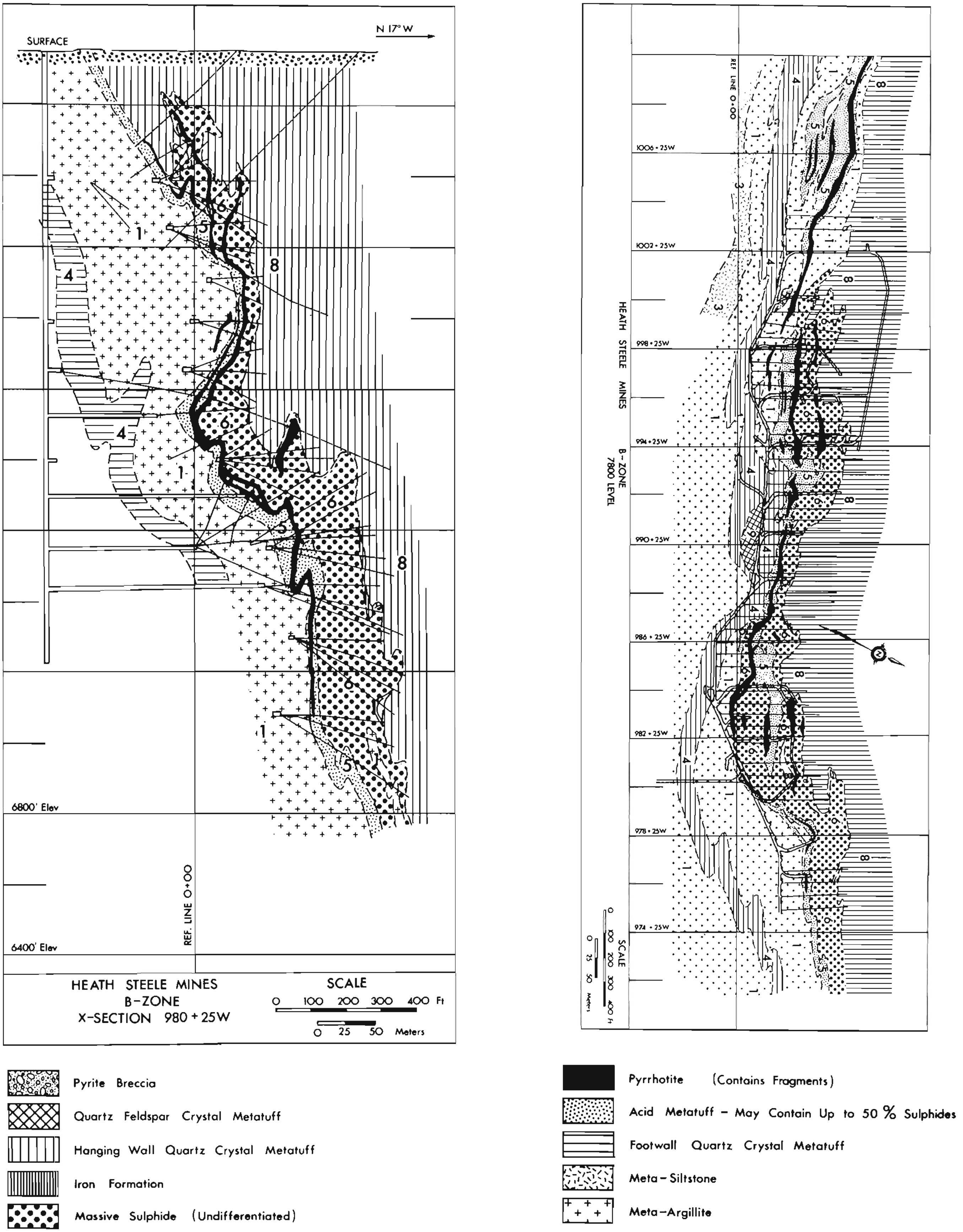


Fig. 10 Simplified geological map of Heath Steele area, showing the location of orebodies relative to other stratigraphic units.
Legend: 1 - metasediments; 2 - massive sulphides; 3 - quartz and quartz-feldspar crystal metatuff; 4 - acidic volcanic rocks. (after Owsiacki, 1980)



Figs. 11 & 12 Geological plan and cross section of the Heath Steele B-zone orebodies.

B zone. The B zone forms a continuous, tabular body that has been traced over a strike length of 1500 metres and a depth of 600 metres (Fig. 11 and 12). This conformable body strikes east-west, dips steeply to the north and is deformed into major D_2 parasitic folds, which plunge steeply to the west (Fig. 13). A third deformation episode produced only minor folding within the sulphides.

The enclosing volcanic-sedimentary sequence has been interpreted as water-lain crystal and ash flow tuffs with associated clastic sedimentary rocks. Stratigraphically, the banded quartz-feldspar crystal metatuff grades northward into quartz crystal metatuffs. Within the overlying metasedimentary unit, originally coarse-grained sandstones and siltstones were concentrated to the west of the deposit, while fine-grained mudstones (argillites) accumulated below it. These facies changes suggest a transition from higher energy conditions in the west to a relatively calm environment proximal to the deposit. Acid metatuffs form diffuse footwall contacts with the sulphide deposit.

Sulphide textures and distribution suggest that each orebody was formed syngenetically, accumulating from exhalative solutions in subaqueous basins (Lusk, 1969; Wahl, 1978). Along the margins of these basins, oxidizing conditions resulted in precipitation of banded magnetite iron formation.

The ore minerals occur in three definite mineralogical associations or facies: massive pyrite, banded pyrite-sphalerite-galena and a pyrrhotite-chalcopyrite fragmental ore. Some units of massive pyrite are monomineralic, but most commonly contain bands of chlorite,quartz and magnetite. Banded pyrite-sphalerite-galena facies consist of alternating pyrite-rich and sphalerite-galena rich bands. A fragmental ore containing rounded to subangular sulphide and lithic fragments is confined to a pyrrhotite matrix. This copper rich fragmental ore lies mainly along one wall of the B zone (Figs. 11 and 12). It also forms a major part of the A-C zone to the west (Fig. 14). In some areas the breccia appears to both overlie and underlie the lead-zinc

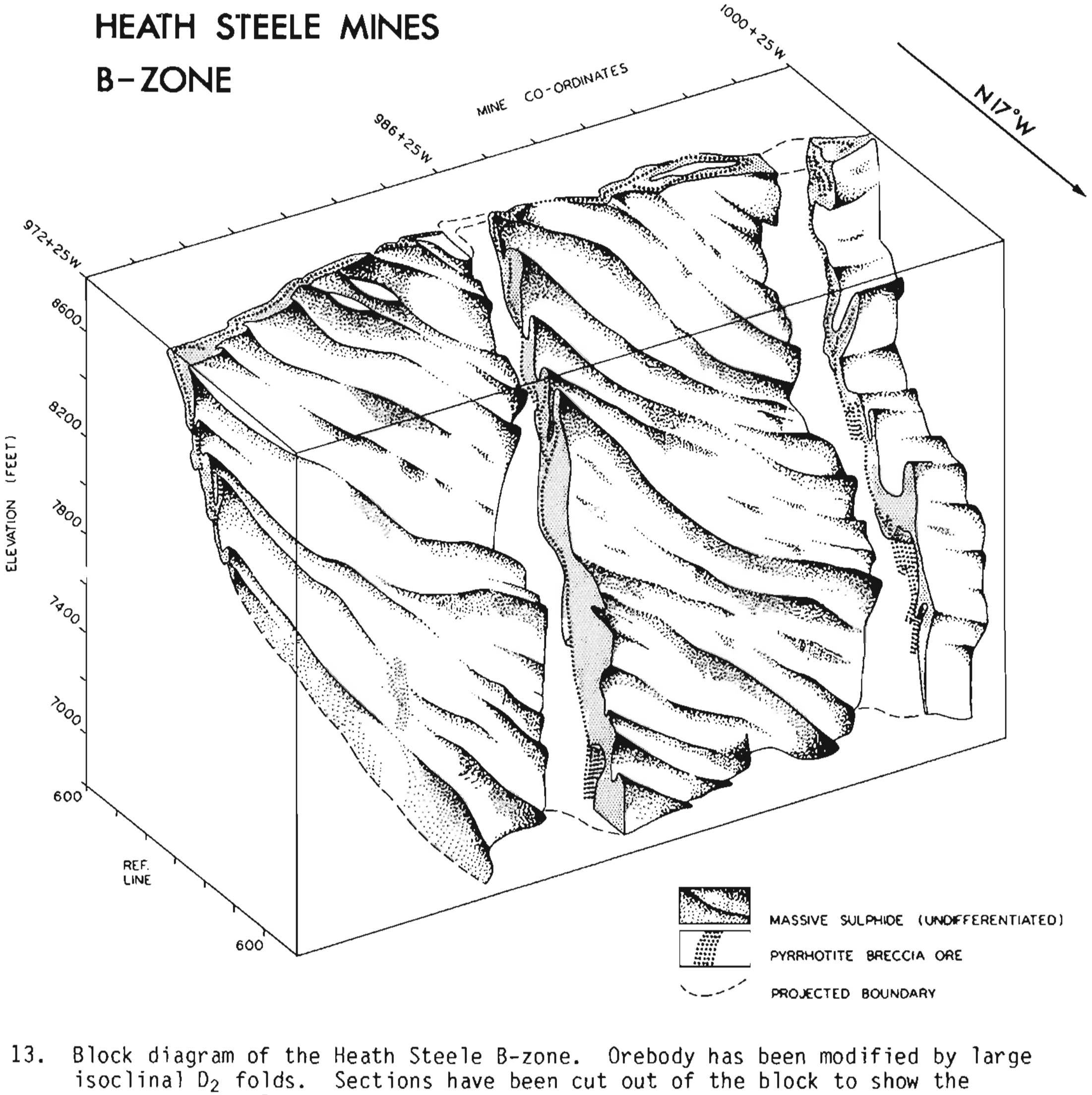


Fig. 13. Block diagram of the Heath Steele B-zone. Orebody has been modified by large isoclinal D_2 folds. Sections have been cut out of the block to show the crosscutting relationship between the orebody and pyrrhotite fragmental ore.

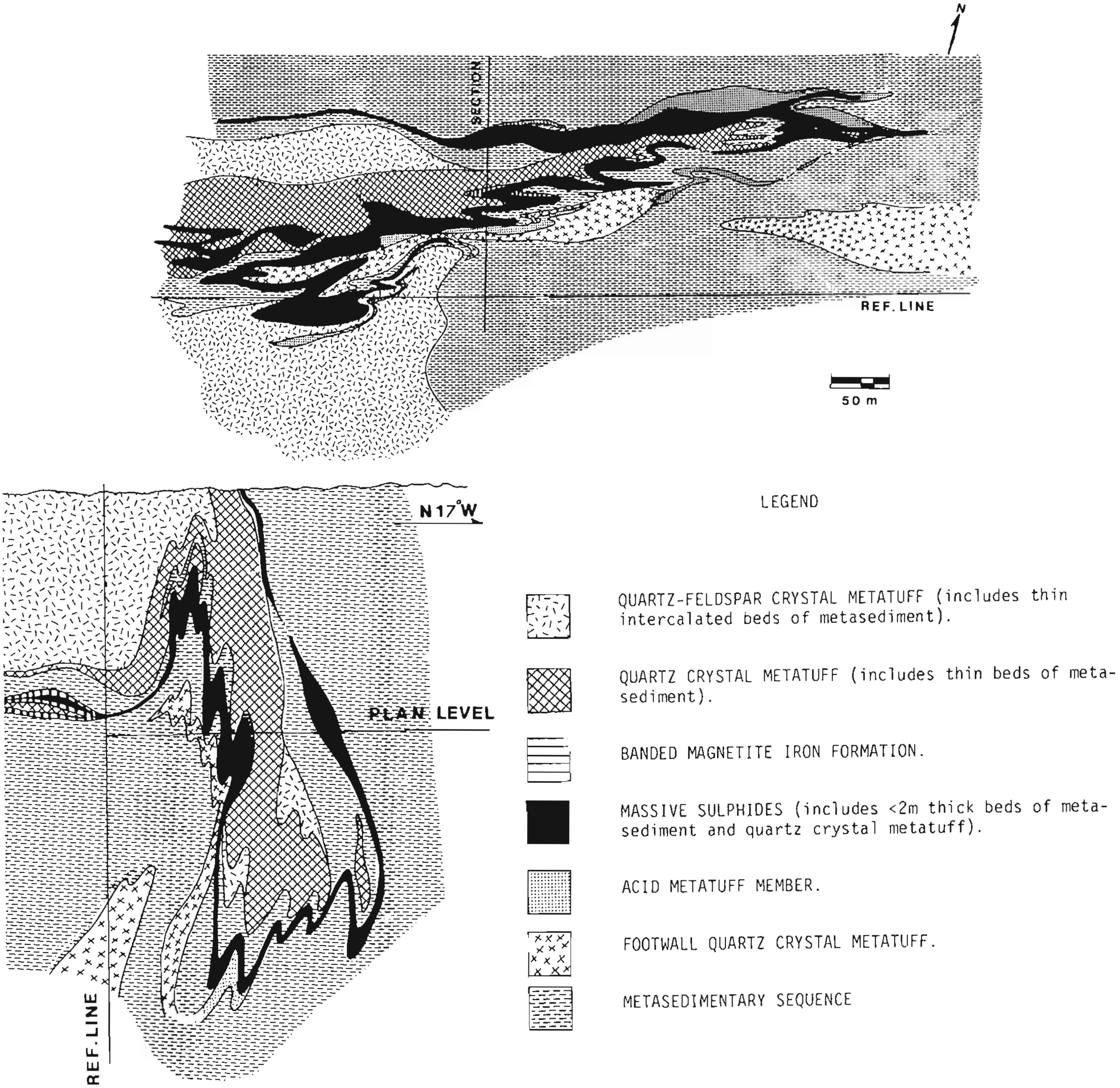


Fig. 14 Geological plan and section of AC orebodies Heath Steele Mines (after Owsiacki, 1980)

ore, in other places it appears cross cutting.

A preliminary investigation by Owsiacki and McAllister (1979) attribute the fragmentation to volcanic disturbances which initiated soft sediment slumpage and transport of materials. The present writer suggests subsequent tectonic processes were a major contributor to fragmentation.

Thin layers of iron formation (oxide, carbonate and silicate facies) lie above, within and marginal to the orebody. In the east, oxide facies form peripheral to the massive sulphide body. Quartz and quartz-feldspar crystal metatuffs overlie the iron formation.

A-C-D Zone (after Owsiacki, 1980). The A-C zones form a semi-continuous ore body, that is approximately two kilometres in length and has been followed for at least four hundred metres down dip. Due to the lack of outcrop and the structural complexity of the area, the relationship between the A-C and D zones is still unknown.

Both sulphides and host rocks have been deformed into major D_2 folds, plunging shallowly west with limbs dipping steeply south. Subsequent deformation (D_3) has produced a gentle warping of the F_2 fold structures.

The C zone (Fig. 14) occurs as a synform which overlies a thick metasedimentary sequence of banded meta-argillite and metasiltstones. Dividing this sequence are discontinuous lenses of footwall quartz and quartz-feldspar crystal metatuff. Immediately below the sulphide body is a thin, intermittent layer of acid metatuff, containing bands of pyrite and pyrrhotite. A thick succession of quartz and quartz-feldspar crystal metatuff overlies the sulphide deposits.

The C zone exhibits a lateral zoning. The north limb of the synform is a copper rich fragmental ore. Massive pyrite and banded pyrite-sphalerite-galena ores are restricted to hinge areas of parasitic D_2 folds. Iron formation (magnetite and chloritic types) is confined to the south limb of the main synformal structure.

Accumulated ore reserves for the A,C, and D zones are 4.7 x 10^6 tonnes grading 1.00% Cu, 1.31% Pb, 5.34% Zn and 48.4 gms/tonne Ag (W. Gates, unpublished report, 1979).

E zone. The E zone (Figure 15), located midway between the B and A-C-D zones, appears from geophysical surveys, to belong to a common stratigraphic horizon, and, enclosing metasediments and metavolcanics in the E zone closely resemble those associated with the B Zone.

In general, the main body strikes east-west and dips steeply south. Both sulphides and accompanying rocks are folded and plunge steeply west. Although internal base metal zoning is highly disrupted, the distribution of banded iron formation would suggest the stratigraphic sequence is overturned.

Within the sulphide deposit, a fragmental pyrrhotite ore lies conformably within the enclosing rocks. A pyrite breccia, consisting of blocks of solid sulphide embedded in a sandy, porous pyrite matrix, forms a planar crosscutting feature. This planar configuration would suggest the breccia formed during late-stage faulting. Reserves for the E zone are 1.2 x 10^6 tonnes grading 1.56% Cu, 1.98% Pb, 4.33% Zn, and 73.1 gms/tonne Ag (W. Gates, unpublished report, 1979).

North Boundary Zones. A number of potentially

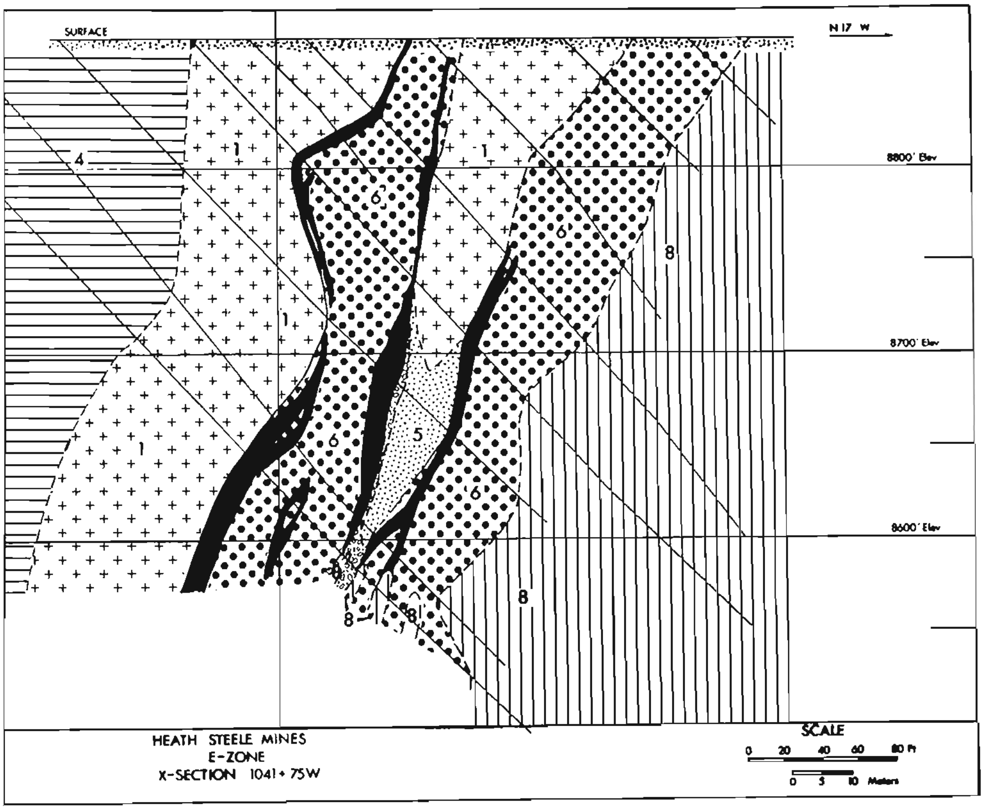


Fig. 15 Geological cross section through the Heath Steele E orebody. (same legend as figs. 11 & 12)

economic concentrations of disseminated sulphides are present in the northwest corner of the Heath Steele Mining Lease. They occur as an extension of similar zones to the north which have been defined by Cominco-Stratmat drill programs. The sulphides occur in fine-grained metasediments and acid pyroclastic rocks which represent an environment distinctly different from that of the previously described Heath Steele sulphide zones.

GEOLOGY OF THE CARIBOU DEPOSIT
(after R.A. Cavalero, 1970)

Introduction

The Caribou massive sulphide deposit (Fig. 3), lies in the north central part of the large, oval-shaped volcano-sedimentary folded belt underlain by the Tetagouche Group of rocks. Positioned on the northwest flank of a major northeast trending anticline, the deposit occurs as four stratiform tabular lenses arranged en echelon and dipping steeply around the limbs and nose of a local northerly plunging synclinal fold. The sulphide lenses occur within a thin sequence of locally pyritic metasedimentary phyllite and chlorite schist (footwall) at their contact with acid metavolcanic schists (hanging wall).

Stratigraphy and Petrology

Enveloping the footwall phyllite is a wide band of graphitic metasedimentary rocks that delineate the fold structure. These carbonaceous rocks are crenulated to highly contorted; they contain thinly interbedded black, slaty phyllite and metagreywacke. Intermediate(?) volcanic rocks, intercalated with minor acid volcanic schist and meta-sedimentary phyllite, are predominant in the footwall of the graphitic member on the west limb. The east limb footwall (Fig. 16) consists of meta-andesite, acid volcanic schist, and minor phyllite cut by a large porphyritic microgranite dyke and small rhyolite, andesite(?) and diorite dykes, all of which post-date the well developed regional schistosity.

The hanging wall rock adjacent to the sulphide lenses consists of strongly sheared, barren, quartz-sericite orthoclase schist; the unit is mineralogically simple, but is highly variable in colour and texture. Minor thin beds of phyllite occur throughout. Eight members of the hanging wall sequence have been differentiated on the west limb. They are considered to be predominantly water-lain pyroclastics, and vary from light-coloured, bedded tuff to dark-grey, dense, porphyritic tuff (possibly of flow origin). Only two of the members extend to the east limb, where a new sequence of schist units occurs on the hanging wall at a higher (?) stratigraphic position in relation to the west limb schists, but in the same position in relation to the footwall phyllite and sulphide lenses.

The core of the syncline consists of a thick sequence of competent potash rhyolite porphyry, alternating with bands and lenses of schist similar to those of the hanging wall. The sequence is considered to be a series of recurring ash flows of similar composition and water-lain tuffs.

Mineralogically, the entire hanging wall acid volcanic series consists of quartz, green

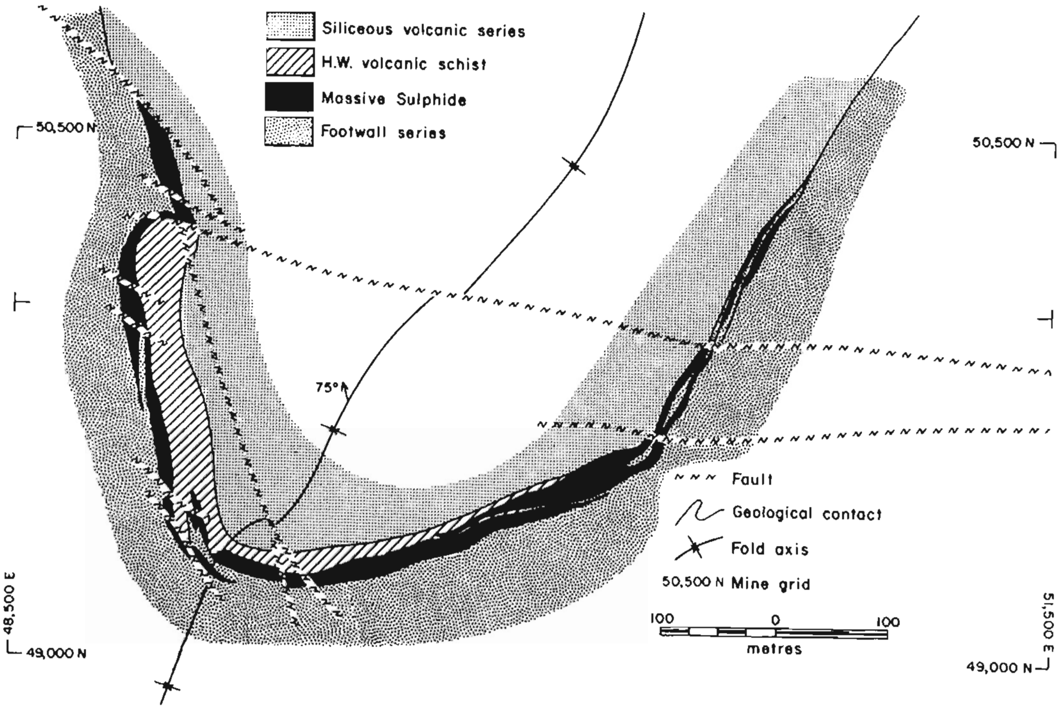


Fig. 16 Geological plan, Anaconda-Caribou deposits (after Cavalero, 1970).

muscovite, pale yellow sericite, pink orthoclase, and locally albitic feldspar. Chlorite is minor to absent throughout.

Massive Sulphides

Three of the sulphide lenses occur along the west limb (northwest, north, and south sulphide bodies). The fourth occurs along the east limb (east sulphide body) and is essentially made up of a number of smaller lenses. The occurrence of hanging wall-type schist fingering in towards the footwall from the north between the distal ends of adjacent lenses is characteristic, whereas the footwall rocks remain at a relatively constant position with respect to the sulphide mass.

The west limb lenses have similar characteristics. The massive sulphide is very fine-grained, consisting of pyrite (greatly predominant), magnetite, and base metal sulphides carrying values in Zn, Pb, Cu, Ag, and Au. Chlorite is the chief gangue mineral, and quartz-carbonate seams are common. Mineralogical and textural layering parallel to the bounding surfaces and sharp wall rock contacts are prevalent. Across-layer and lateral base metal zoning is a prominent feature, with concentrations of Pb and Zn along the hanging wall, Cu locally along the footwall, and a pyritic core zone. Ratios of Zn:Pb average 3:1 on the west limb; Ag values vary proportionately to the Pb-Zn content. Gold is less dependent on the Pb-Zn content and may locally occur with arsenopyrite in the low-grade areas. Pyrrhotite, common in many of the local deposits, is absent throughout.

While most of the characteristics are similar, marked differences identify the east sulphide body. Across-layer zoning is absent for the most part; high Pb-Zn content occurs from footwall to hanging wall over the west half of the lens and grades laterally to pyritic sulphide to the east. Magnetite is weak to absent; Zn:Pb ratios approach 2:1. Quartz, locally as thin parallel quartz phyllite lenses, is the chief gangue mineral.

The length of the individual lenses ranges up to 305m. The total length of the mineralized zone is nearly 1,524m around the fold structure. The depth of mineralization is unknown.

Capping the primary sulphides is a zone of secondary enrichment which extends to a depth of 45m. In this zone, the primary sulphides are enriched in copper minerals, the most abundant of which is chalcocite, with lesser amounts of covellite, bornite, azurite and tenorite. The copper grade of the secondary zone ranges from a high of over 7% near surface, gradionally decreasing to the average copper grade of 0.4% at the primary-secondary interface. Lead and zinc depletion is quite variable within the secondary zone while silver and gold values are similar to those in the primary ore.

Above the supergene ore, covered by a thin layer of glacial till, is a gossan zone varying from 1 to 12m thickness. The zone, enriched in Au and Ag, consists predominantly of limonite and silica with goethite, minor jarosite, and, locally, plumbojarosite.

To extract the relatively small but high grade secondary copper reserves, a small, short term mining and milling operation was established in 1970 and operated intermittently through 1974. During this period approximately 363,000 tonnes of copper ore were extracted by open pit mining and treated in the concentrator.

Structure

Three major phases of deformation are present in the mine area. The first, occurring in Ordovician time, is the most pervasive but the least documented. During the Taconic orogeny, isoclinal folding is considered to have taken place, accompanied by low-grade regional metamorphism. The prominant schistosity (S_1), was developed axial planar to local interfolial folds at this time. Emplacement of the massive sulphide either accompanied or preceded this episode, with deformational evidence of the sulphide minerals and general concensus of a volcanic exhalative source suggesting the latter.

A shallow dipping S_2 crenulation cleavage can be observed to change orientation around the limbs of the Caribou fold indicating that the fold post-dates S_1 and S_2.

F_3 deformation, assumed to be related to the development of the major regional anticline to the east, occurs as well developed kink-folds in all rocks throughout the mine area; it is locally seen within the sulphide lenses toward their distal ends. These minor folds, developed during the Acadian orogeny (Devonian), warp S_1 and are everywhere oriented subperpendicular to S_1 with essentially vertical dips (Davis, 1972).

The Caribou fold is a local F_4 fold developed later during the Acadian orogeny and uniformly folds S_1, S_2 the sulphide lenses, and the local lithologic units. Similar orientation of the F_3 kink-folds with respect to the Caribou fold limbs suggests the latter event was instrumental in reorienting the pre-existing kinks.

Following emplacement of the dyke rocks in the mill site footwall zone, late-stage faulting, first in a NW direction and then EW, ocurred as the last deformational stage cutting all of the pre-existing structures.

Tops have yet to be determined in the mine area; however, the base metal zoning compared to zoning in other volcanic-associated sulphide deposits throughout the world, disseminated sulphide in the footwall phyllite and schist adjacent to the massive sulphide with a barren hanging wall, and a single andesite fragment found in the schist suggest tops lie toward the hanging wall in the true synclinal sense. Contacts between schist units offer dual interpretation or are adverse to the syncline theory.

Evidence of an alteration haloe has yet to be fully tested. However, a decrease in potash content toward the hanging wall contact is evident from the bleaching of feldspars and a sharp decrease of orthoclase in quartz-orthoclase veins.

FOURNIER GROUP

Stratigraphy

The Ordovician ophiolitic suite exposed in the Elmtree Inlier has been termed the Fournier Group by Young (1911). According to Pajari et al. (1977), the Fournier Group exposed along the coast near Pointe Verte (Figure 17) can be divided into two main units: (1) deformed gabbro, peridotite, basic dykes and amphibolite injected with trondhjemitic veins and overlain by a melange of highly disturbed greywacke containing olistoliths of pillow basalt; (2) a thin unit of pillow basalt overlain by greywacke and referred to as the Pointe Verte Formation. Inland, on the recently constructed Bathurst to Belledune highway, greywacke and slate of the Elmtree Group (Young 1911; Fyffe 1975) conformably overlies pillow basalt of the Fournier Group. The lower part of the Elmtree Group must then be considered equivalent to the upper part of the Pointe Verte Formation.

Inland, exposures of plutonic rocks along the Canadian National Railway tracks near Green Point Station are medium- to coarse-grained troctolitic gabbro transected by narrow zones of strongly foliated, fine-grained amphibolite that truncates the igneous banding in the gabbro. The gabbro is intruded by dykes and veins of light pink trondhjemite and diabase that also truncate the banding.

Diabase dykes are particularly abundant in gabbro exposed within a small inlier north of the main outcrop belt of the Fournier Group (Figure 19). The east-trending, subvertical dykes of the inlier become more plentiful northwards where they form a composite swarm interpreted as an oceanic sheeted dyke complex (Rast and Stringer 1980).

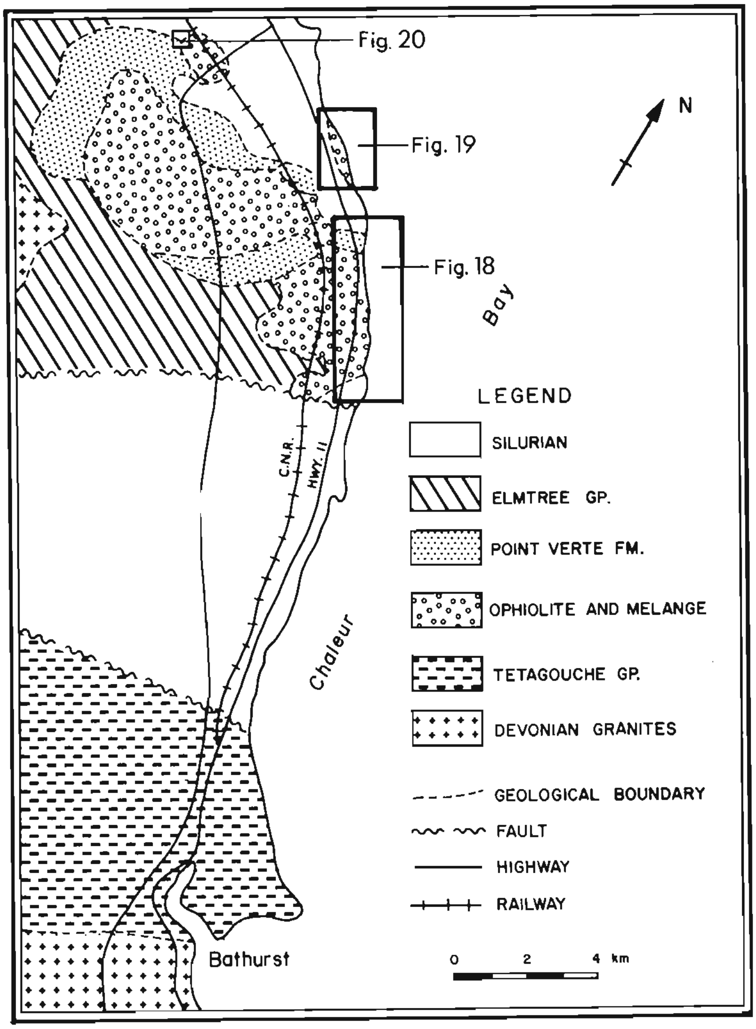


Fig. 17 Geology of the Elmtree Inlier.

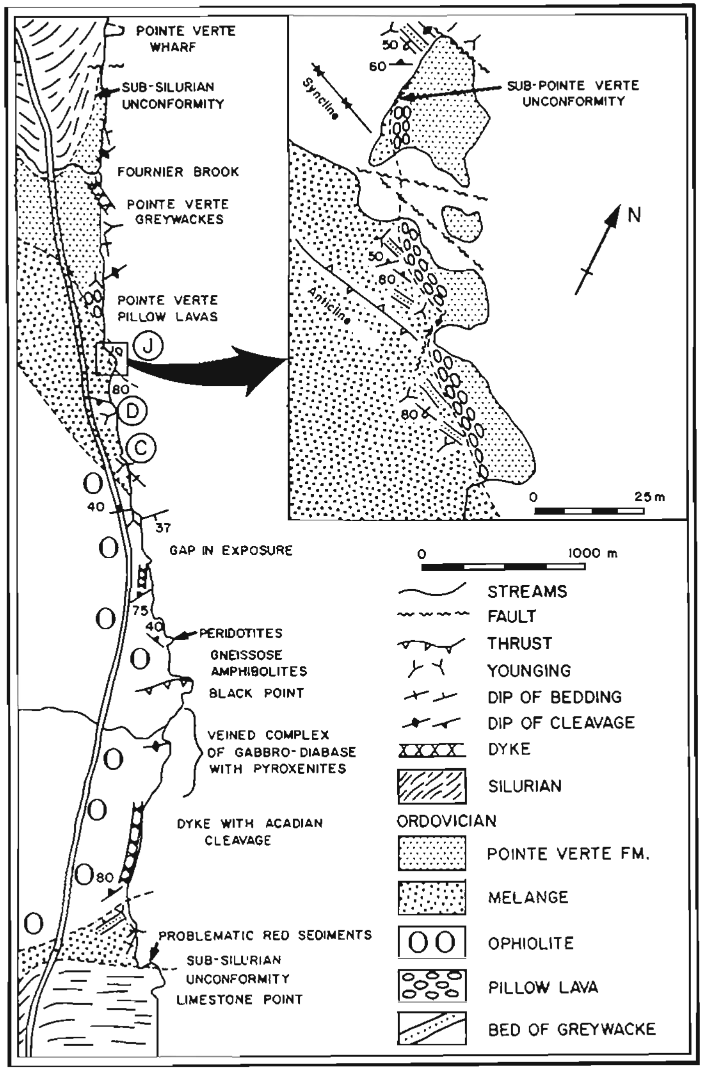


Fig. 18 Geology of the coastal section of the Elmtree Inlier (after Rast and Stringer, 1980).

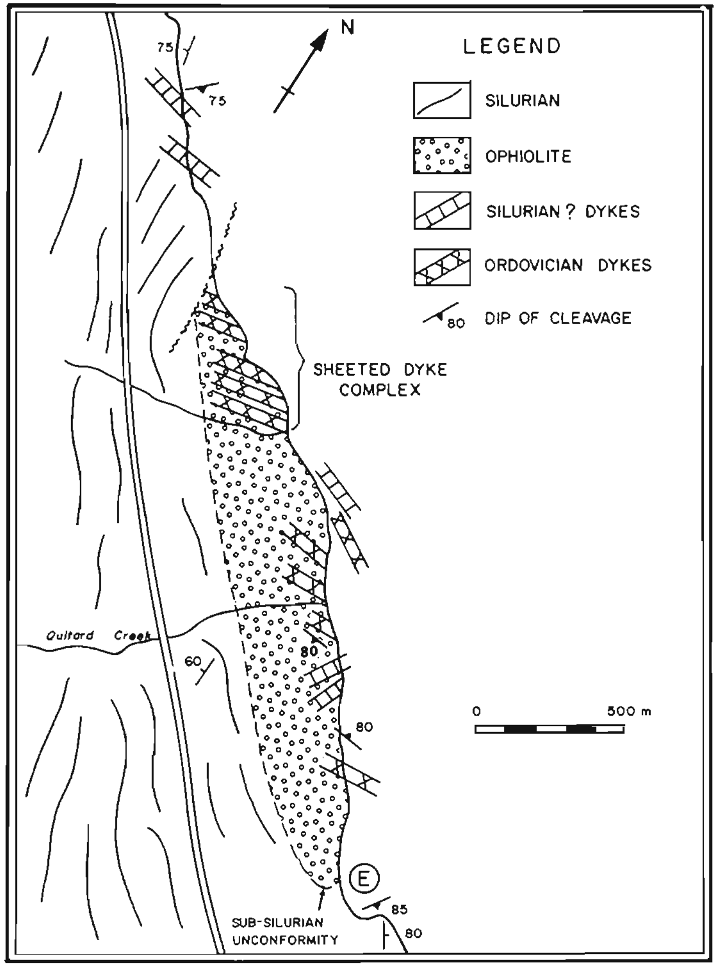


Fig. 19 Geology of the sheeted dyke complex (after Rast and Stringer, 1980).

Sedimentary rocks overlie the plutonic complex south of the mouth of Fournier Brook (Figure 18). The lowermost sediments form a melange of steeply dipping, highly deformed slate, greywacke and chert containing olistoliths of pillow basalt. Pillow lava and thick-bedded greywacke of the Point Verte Formation may rest unconformably on the melange. The unconformity may represent a contact between a large olistolith and the main body of the melange in which case both the melange and Pointe Verte Formation should be regarded as one and the same unit. However, Rast and Stringer (1980) argue that the unconformity is regional. Whichever interpretation is correct, the important point is that the sedimentary rocks along the coast are much more disrupted than those inland and may reasonably represent the site of a former subduction zone as suggested by Pajari et al. (1977).

Structure

The sedimentary melange possesses a west-northwest-trending cleavage subparallel to bedding (Figure 18). A second northeast-trending cleavage is axial planar to steeply plunging folds. The facing direction on the second cleavage under the Point Verte Formation unconformity is downward indicating earlier folds are present in the melange (Rast and Stringer 1980). Northwest-trending kinks fold the second cleavage.

The greywacke above the unconformity contains a single, poorly developed northeast-trending cleavage. Rast and Stringer (1980) contend that this structural difference supports the concept of a regional unconformity but admit that the more massive nature of the greywacke above the unconformity may have prevented the development of the first cleavage observed in the slate below the unconformity.

Inland, a steep, northeast-trending cleavage in the slate of the Elmtree Group exposed along the Belledune River transects a gently dipping cleavage with a east-northeast trend.

A tectonic foliation parallel to the igneous banding in the gabbroic rocks of the ophiolitic complex is most likely equivalent to the first cleavage in the sedimentary rocks. Zones of amphibolite within the gabbro possess a strong, subvertical, northeast-trending schistosity that truncates the foliation in the gabbro. This schistosity is equivalent to the second cleavage in the low grade sedimentary rocks. A static growth of hornblende occurred after development of the schistosity. A potassium-argon age of 462 ±23 million years confirms the pre-Silurian age of the deformation.

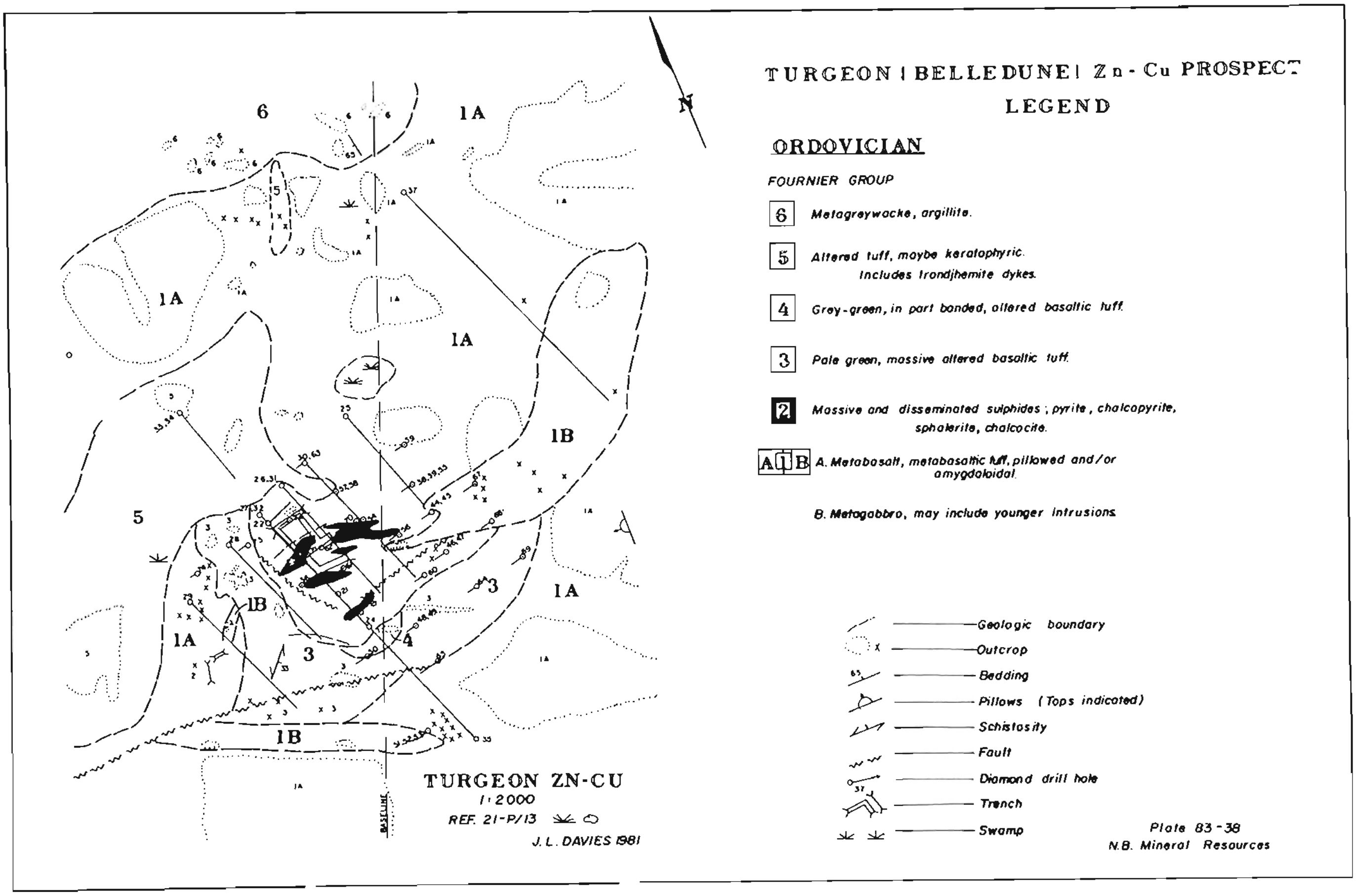
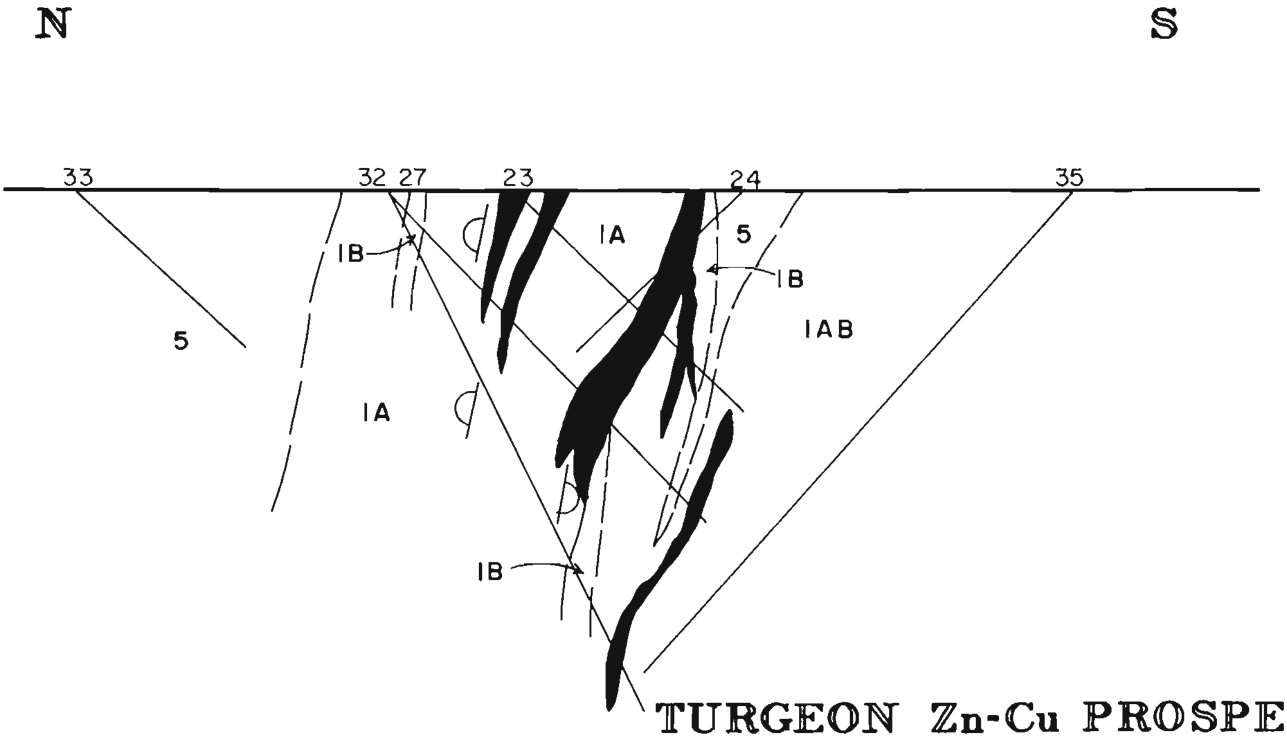


Fig. 20 Geology of the Turgeon-Belledune Zn-Cu Prospect.



TURGEON Zn-Cu PROSPECT

cross-section to accompany figure 20

Scale 1:2000

Note: Section draw from early drilling. Later drilling was along east-west sections.

Fig. 21a Geological cross section of the Turgeon-Belledune Zn-Cu Prospect.

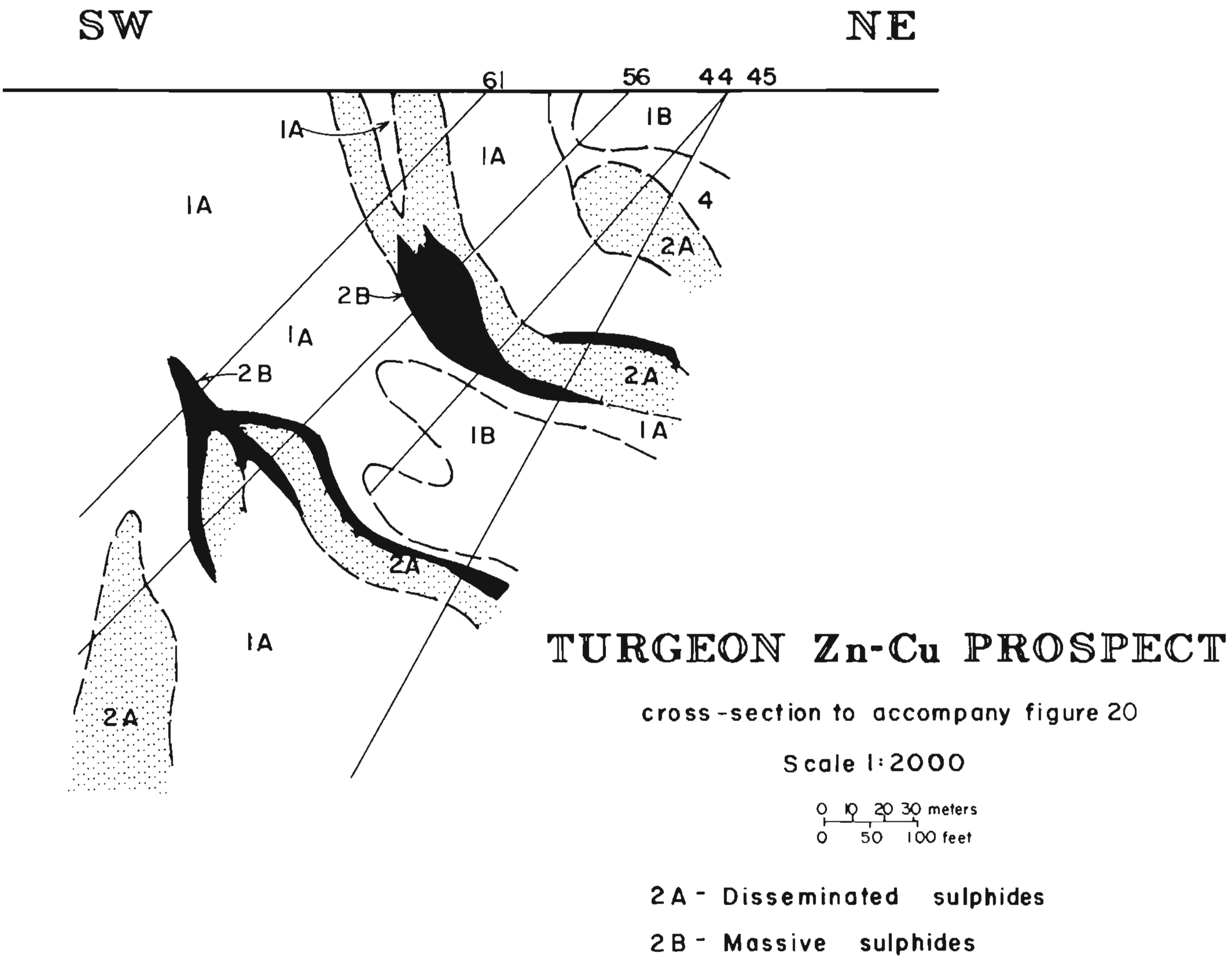


Fig. 21b Geological cross section of the Turgeon-Belledune Zn-Cu Prospect.

Massive Sulphides

A small pyritic zinc-copper deposit has recently been outlined in the northwestern part of the Elmtree Inlier by Esso Minerals Limited. Interest in the area began in the 1950's when disseminated sulphides were found in silicified basaltic rocks. Drilling and trenching during this period however, was not successful. In the early 1960's prospectors C. Willett and J.W. McCarthy discovered an additional chalcocite showing and optioned the property to Industrial Mineral Exploration Limited. The property was converted to Mining License 1155 in 1967 and a new company, Heron Mines Limited, was formed. Self-Potential, Induced Polarization, VLF-EM, resistivity, magnetic, gravity and soil geochemical surveys provided targets for ten diamond drill holes put down by Heron Mines Limited. Only the last three holes (drilled 1977) however, intersected what appears to be the main massive sulphide deposit. The property was optioned to Esso Minerals Limited in 1978, who carried out an intensive drilling program comprising approximately 70 holes. Esso Minerals terminated their option in 1982.

According to the most recent work, the geology of the Fournier Group in the vicinity of the showings comprises a sequence of altered and metamorphosed pillowed and/or amygdaloidal basaltic lavas, and fine- to medium-grained tuffs, that interfinger with and are overlain by metagreywacke and argillite. The Fournier Group rocks are overlain by Silurian sedimentary rocks of the Chaleur Group.

The two main sulphide deposits, the "Powerline" and "Beaver Pond", consist of massive lenses, pods, veins and disseminations of pyrite, sphalerite and chalcopyrite. They occur in chloritized and epidotized basaltic lavas and pyroclastic rocks with minor jasper and chert near intensely altered and bleached rocks that were initially interpreted as metarhyolites or metadacites. It appears, however, these latter rocks are hydrothermally altered basaltic rocks.

The "Powerline" deposit (Figs. 20 and 21) comprises 1 to 2 million tonnes, grading 4.0% zinc and 1.5% copper, whereas the "Beaver Pond" occurrence is considerably smaller.

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ROADLOG FOR FIELD TRIP TO STRATABOUND SULPHIDE DEPOSITS OF WEST-CENTRAL NEW ENGLAND

John F. Slack and Paul J. Atelsek*

U.S. Geological Survey
954 National Center
Reston, Virginia 22092

This field trip is designed as a guide to the principal stratabound mineral deposits of west-central New England (Fig. 1). The trip includes visits to both sediment-hosted and volcanic-hosted massive sulphide deposits, and also to an unusual stratabound manganese deposit. The first day, in eastern Vermont, covers the Elizabeth mine and related geology of the Orange County copper district, in which the sulphide deposits are hosted chiefly by metasedimentary rocks of Early Devonian (?) age. The second day provides a reconnaissance of the geology of the Green Mountain anticlinorium in Vermont, and includes stops in Proterozoic and lower Paleozoic terranes with potential for a variety of stratabound mineral deposits. The third day, in northwestern Massachusetts, examines the massive sulphide ores at the Davis mine and the surrounding geology of a volcanic belt of Middle Ordovician age. The last day visits the stratabound manganese deposits and associated geology of the Betts mine, also in Massachusetts, which has associated iron formation and massive sulphide (all Middle Ordovician).

The diverse geology and mineral deposits examined on this trip provide a basis for discussing the origins of different types of stratabound mineral deposits. Most previous workers in New England have interpreted these deposits as hydrothermal replacements related to regional metamorphism or granitic intrusion. Their stratabound and largely stratiform nature, however, suggests formation by syngenetic or diagenetic processes. Some of the deposits, such as Davis, are clearly related to submarine volcanism and are believed to be syngenetic chemical precipitates. Others, such as Elizabeth, are more enigmatic, and may have formed by an entirely different mechanism. It is hoped that this trip will stimulate interest in these various deposits, and encourage speculation about possible ore-forming processes.

Some of the stops and geologic descriptions for this trip have been taken from previous field guides. Most of the field trip stops in the Proterozoic basement rocks and eastern cover sequence of the Green Mountain anticlinorium (second day) are condensed from Thompson (1972). On the third day of the trip, the guidebook chapter by Ratcliffe (1979) has been used for the identification of formations in several roadcuts in Massachusetts. One of the stops on the third day, along the Chickley River, is reproduced in part from Hatch et al. (1967).

DAY 1. ELIZABETH MINE AND RELATED GEOLOGY

Daily Mileage	Comments and Descriptions
0.0	Leave Quechee Inn, Quechee, Vt. Turn left onto main road (Clubhouse Rd.).
0.5	Junction with Deweys Mill Road. Bear right.
1.4	Intersection with Route 4. Turn left (east).
4.7	Junction with Interstate I-89 (north). Turn right onto I-89.
6.6	Outcrops of Gile Mountain Formation on left.
7.8	Cross White River.
8.2	Roadcuts of Gile Mountain Formation.
9.6	Outcrops of Gile Mountain Formation.
10.0	Roadcuts of Waits River Formation (Sharon Rest Area).
11.5	Outcrops of Waits River Formation on right.
12.3	Begin roadcuts of Gile Mountain Formation.
15.7	Cross White River.
16.6	Begin outcrops of Waits River Formation.
19.7	Outcrops of Gile Mountain Formation on left.
19.9	View of town of Royalton, Vt., in valley to right.
20.5	Begin outcrops of Gile Mountain Formation.
23.6	Cross White River.
23.8	Exit 3 at Royalton, Vt. Turn right.
24.1	Junction with Route 107. Turn left (east).
24.7	Intersection with Route 14. Turn right (south).

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* With contributions by M. P. Annis, J. A. Docka, M. M. Godchaux, D. D. Hickmott, and P. Karabinos.

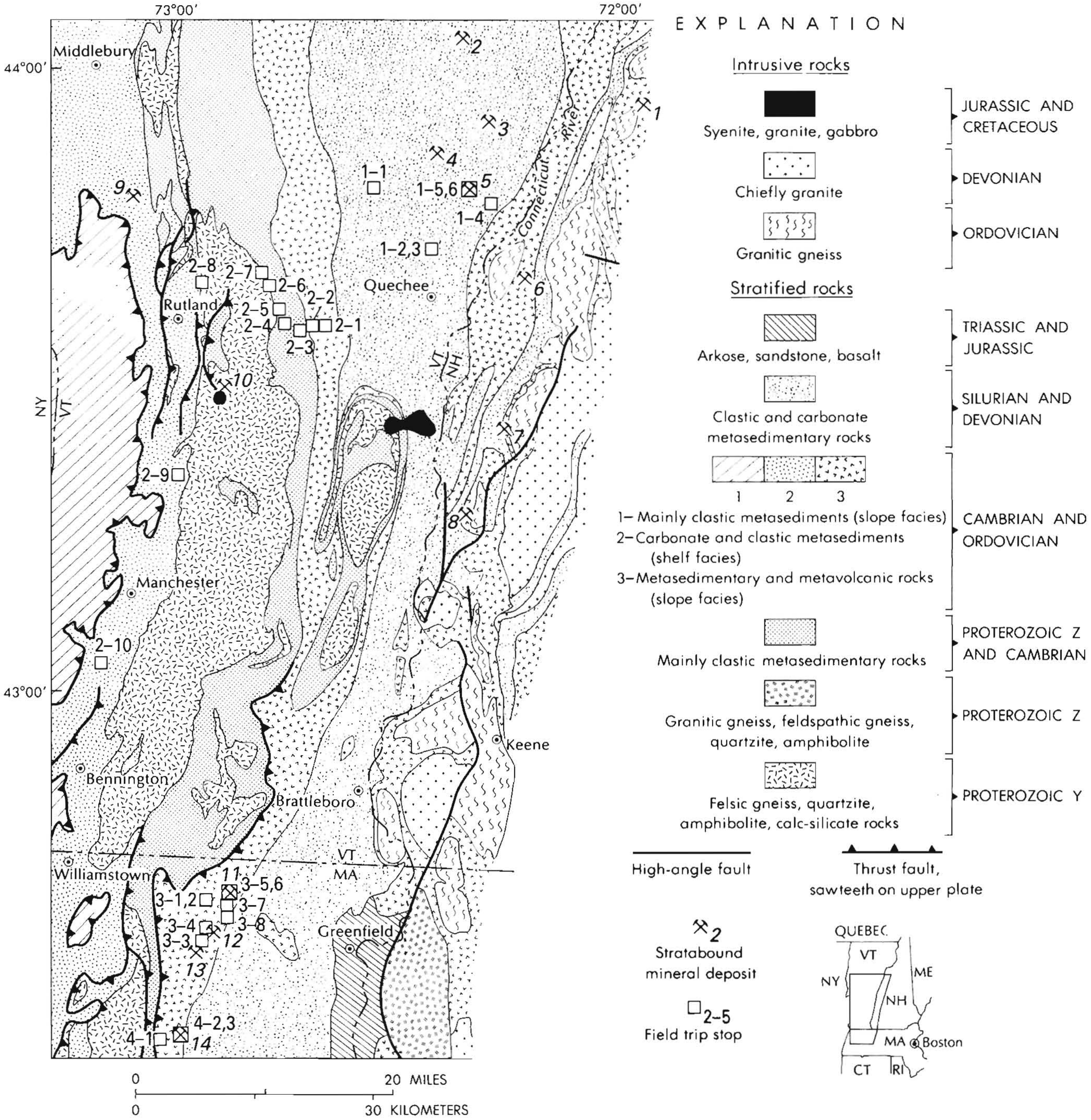

Figure 1. Simplified geologic map of west-central New England showing the location of stratabound mineral deposits and field trip stops. Geology compiled mainly from Doll et al. (1961), Thompson et al. (1968), and Zen et al. (1983). Stratabound mineral deposits after Gair and Slack (1979). Key to deposits: 1) Ore Hill lead and zinc, 2) Pike Hill copper and zinc, 3) Ely copper and zinc, 4) Orange and Gove copper and zinc, 5) Elizabeth copper and zinc, 6) Unnamed copper, 7) Croydon copper and zinc, 8) Neal copper, 9) Brandon lead and zinc, 10) Cuttingsville pyrrhotite, 11) Davis copper and zinc, 12) Hawks copper and zinc, 13) Hawley iron, and 14) Betts manganese.

26.3 Town of Royalton, Vt.

27.5 STOP 1-1. Walk down steep bank to rock peninsula on north side of White River. Outcrops here are clastic metasedimentary rocks of the western belt of the Lower Devonian(?) Gile Mountain Formation. Note excellent lithologic layering, relict graded beds, and possible cross beds. Also note prominent folds and a young oblique foliation.

28.3 Intersection with Route 110 at South Royalton, Vt. Continue straight ahead on Route 14.

30.3 Outcrops on left of Waits River Formation.

31.4 Large sand and gravel pit on left.

33.4 Junction with Route 132 in town of Sharon, Vt. Turn left.

33.5 Access ramp to I-89 south. Turn right.

38.1 Sharon Rest Area. Exit right and walk back to roadcut on south side of highway. (Special Note: Geologic or other non-emergency stops are prohibited on interstate highways in Vermont. Permission must first be obtained from the Vermont Traffic Committee, 133 State Street, Montpelier, Vt. 05602).

--- STOP 1-2A. Typical lithologies of the Lower Devonian (?) Waits River Formation, consisting of metamorphosed quartzose limestone (and dolostone), calcareous mica schist, and minor interlayered quartzite. Natural outcrop near fence shows characteristic punky brown weathering, abundant quartz pods and lenses, and locally developed tight folds.

--- STOP 1-2B. Walk across highway and proceed south along median strip for approximately 1000 ft. Roadcut exposes contact between Waits River Formation and overlying Standing Pond Volcanics, the latter consisting of fine-grained amphibolite (with thin lenses and laminae of quartz) and minor hornblende-bearing schist. Also note here abundant epidote-rich pods and layers, disseminated sulphides, and fine-grained spessartine-quartz rocks (coticules).

--- STOP 1-2C. Cross highway and walk to roadcut on east side of northbound lanes. Outcrop shows interlayered micaceous quartzite and quartz-mica schist in lowermost part of the Gile Mountain Formation. Note here minor pods and lenses of hornblende-rich schist. At north end of roadcut, near the projected contact with the underlying Standing Pond Volcanics, are exposures of sulphidic black chert and coticule rocks.

40.0 Leave (eastern) Sharon Rest Area and proceed north on I-89 (mileage resumes after returning from western rest area).

40.4 Outcrops of Waits River Formation on right.

44.5 Exit 2 at Sharon, Vt. Turn right at exit.

44.7 Junction with Route 132. Turn left.

44.9 Intersection with Route 14. Turn left.

48.9 Outcrops of Waits River Formation on left.

51.1 Junction with West Hartford-Quechee Road. Turn right onto bridge crossing White River.

51.2 Intersection with Pomfret Road. Turn right.

51.5 STOP 1-3 (Optional). Park near pull-off on right. Walk down trail to outcrops along river edge. Rock promontory exposes abundant metamorphosed chemical sediments associated with the Standing Pond Volcanics. Note layered sulphidic cherts, thin contorted coticule beds, and stratabound lenses of white granular quartz.

51.8 Return to bridge crossing White River.

51.9 Junction with Route 14. Turn left.

58.0 Intersection with Route 132. Turn right and continue past (underneath) I-89 exits.

62.6 Roadcut exposures of Waits River Formation.

64.7 Junction at South Strafford, Vt. Turn right and continue on Route 132.

69.3 STOP 1-4. Park near guardrail. Exposures along creek are typical clastic metasedimentary rocks of the Gile Mountain Formation. Principal lithology here is foliated quartz-mica schist; also present are minor lenses of calcareous mica schist. Note especially the lack of lithologic layering and graded bedding, as observed at Stop 1.

--- Turn around and proceed back to South Strafford.

73.8 Intersection with South Strafford-New Boston Road (unmarked) in South Strafford. Turn left at sharp bend in road.

75.6 Elizabeth mine tailings visible in valley to the left.

75.8 Access road to Elizabeth mine on right. Continue straight ahead.

76.5 Junction with Gove Hill Road on left. Proceed straight ahead.

76.9 STOP 1-5 (Optional). Park at bottom of hill. Walk west on trail, upstream along creek, for about 600 feet. Outcrop in creek exposes interlayered quartz-mica and mica-quartz schist showing local graded

	beds (not typical of the Gile Mountain Formation in this region). Note here also minor lenses of knobby hornblende-rich schist, and irregular quartz veins.
---	Return along trail to road and proceed back towards South Strafford.
78.0	Junction with Elizabeth mine road. Turn left.
78.7	Parking area for access to south pit. Walk west up small road to western edge of open pit.
---	STOP 1-6A. Overlook of main south (No. 2) pit, appx. at coordinate 8600N. The sulphide ore zone here forms a nearly isoclinal synform, striking N5°E and plunging gently (<10°) to the north. The sulphide layer and overlying (hangingwall) rocks in the core of the synform have been largely mined out.
---	STOP 1-6B. Walk north along east side of pit appx. to coordinate 9200N, to examine lithologies in the stratigraphic footwall of the ore zone (lower part of the mine sequence). Exposures here show (from west to east): 1) calcareous hornblende schist, 2) minor disseminated to partly massive sulphide of the No. 3 orebody, 3) cordierite-biotite schist, and 4) beds of resistent impure quartzite. In this area, the quartzites directly underlie the main (No. 1) orebody. To the north and south along strike, the footwall of the main massive sulphide zone is underlain by a calcareous feldspar rock (Stop 6F below).
---	STOP 1-6C. Walk north to area immediately north of the northern end of the south pit, appx. at coordinate 9500N. This area exposes the lower part of the stratigraphic hangingwall of the main (No. 1) orebody. From west to east, the sequence (in ascending order) consists of: 1) massive pyrrhotite with minor chalcopyrite, 2) sulphidic tourmalinite, 3) tremolite-phlogopite schist (very thin here), 4) laminated hornblende-plagioclase rock, and 5) coarse garnet-mica schist (with minor hornblende). Note that in this area the tourmalinite appears to be a facies equivalent of the massive sulphide ore.
---	STOP 1-6D. Walk north along strike across access road to small prospect pit, appx. at coordinate 9600 N. Outcrop here is well-layered vuggy tourmalinite containing locally abundant albite and minor green (Cr-bearing) muscovite. Vuggy nature of the tourmalinite is due to the weathering out of sulphides (disseminated pyrrhotite and chalcopyrite).
---	STOP 1-6E. Walk north to area of small square shaft, appx. at coordinate 9700N. Ledge next to shaft is composed of sulphidic tremolite-phlogopite schist, in places showing fine-grained thin laminae of albitic plagioclase. Also note here another exposure of laminated hornblende-plagioclase rock.
---	STOP 1-6F. Walk north to southern end of north (No. 1) pit, appx. at coordinate 10,000N. Exposed on east side of pit is a slightly layered calcareous feldspar rock, forming the immediate stratigraphic footwall of the sulphide orebody. Note orange weathering pits (after carbonate), minor lenses of grey clinozoisite, and plagioclase-rich felsic matrix.
---	STOP 1-6G. Walk west across south end of north pit, then north along west wall (east of old road), to appx. coordinate 10,600N. Small outcrops here show calcareous coticule rock in stratigraphic hangingwall of the mine sequence, consisting of fine-grained quartz, calcite, biotite, and abundant spessartine (Mn-rich) garnet.
---	STOP 1-6H. Walk west about 200 feet to view outcrops of typical Gile Mountain Formation surrounding the mine sequence, here consisting of foliated quartz-mica-garnet schist and rare interbeds (<10 cm thick) of graphitic kyanite-mica schist.
100.7	Arrive Quechee Inn. End of Day 1 roadlog.

DAY 2. REGIONAL GEOLOGY OF THE GREEN MOUNTAIN ANTICLINORIUM

Daily Mileage	Comments and Descriptions
0.0	Leave Quechee Inn. Turn left onto Clubhouse Road.
0.5	Junction with Deweys Mill Road. Bear right.
1.4	Intersection with Route 4. Turn right (west).
1.5	Cross Quechee Gorge.
5.1	Junction with Route 12 South. Continue straight ahead on Route 4.
9.1	Junction with Route 12 North in Woodstock, Vt. Continue straight on Route 4.
9.9	Outcrops on right of Waits River Formation.
16.4	Outcrops on right of Missisquoi Formation.
17.4	Junction with Route 100A at Bridgewater Corners. Proceed straight ahead on Route 4.
18.0	STOP 2-1. Roadcut on left of Whetstone Hill Member of the Ordovician Missisquoi Formation. Examine a range of lithologies here including carbonaceous and sulphidic schist, quartz-feldspar granofels, and minor garnet-bearing metapelite.

18.7	Outcrops on right of Stowe Formation.
18.9	STOP 2-2. Roadcut on right of Lower Ordovician Stowe Formation. Principal lithology here is a distinctive green quartz-chlorite schist containing abundant large garnets and pods and lenses of quartz. To the north, this formation includes significant amounts of greenstone and amphibolite (see Doll et al., 1961).
19.3	Outcrops on right of Stowe Formation.
19.9	Outcrops on right of Stowe Formation.
20.4	Begin outcrops of Ottauquechee Formation.
21.5	STOP 2-3. Roadcuts of Cambrian Ottauquechee Formation. Exposures on the right include carbonaceous and non-carbonaceous schist and quartz-feldspar granofels. Note here pods and lenses of quartz and complex isoclinal folds. Also present is a nearly vertical mafic dyke, probably of Mesozoic age.
22.6	STOP 2-4. Outcrop on right of the Pinney Hollow Formation of Late Proterozoic (Z) or Early Cambrian age. Chief lithology here is a green chloritoid-bearing phyllite containing both muscovite and paragonite. Note also pods and lenses of quartz, and the development of a distinctive crenulation cleavage.
23.1	Junction with Route 100 at West Bridgewater. Continue straight ahead (west) on Route 4.
23.2	Gravel pit on left.
24.1	Outcrops of Hoosac Formation on left.
24.2	Intersection with Mission Farm Road. Turn right.
24.4	STOP 2-5. Outcrops on right expose contact between Hoosac and Tyson Formations, both of Late Proterozoic (Z) or Early Cambrian age. Overlying Hoosac Formation consists mainly of coarse albitic schist. Underneath the overhanging ledge is dolomite within the upper part of the Tyson Formation. Thompson (1972) reports local lenses of iron oxides along this contact and interprets them as metamorphosed terra rosa.
24.6	Stone church on right.
25.0	Junction with Route 4. Turn right.
25.4	Roadcuts of Tyson Formation on left.
26.7	STOP 2-6. Small outcrop left (west) of the highway exposes exact contact between basement rocks of the Middle Proterozoic (Y) Mount Holly Complex and cover rocks of the overlying Tyson Formation. (NO HAMMERS, PLEASE!) Viewed from above (top of outcrop), the unconformity is marked by contrasts in metamorphic fabrics between the Mount Holly and the Tyson, and by truncated graded beds at the base of the Tyson.
27.6	STOP 2-7A. Roadcut opposite Sherburne Valley Inn (on left) exposes distinctive polymictic conglomerate in the lower part of the Tyson Formation. Note blue (rutilated) quartz pebbles (DO NOT HAMMER!) and deformed cobbles of quartzite and felsic gneiss.
27.8	STOP 2-7B. Walk along left side of highway, adjacent to outcrops of the Tyson Formation and the Mount Holly Complex. Basement rocks here (far end of outcrops) consist of felsic schist and gneiss and local bodies of granitic pegmatite. The precise basement-cover contact is obscure in this area.
29.7	Intersection with Killington ski area access road (Killington Road) on left. Continue straight ahead (west) on Route 4.
29.8	Junction with Route 100 North. Proceed straight on Route 4.
36.0	Roadcut on left of Mount Holly Complex.
37.1	Village of Mendon, Vt.
37.3	STOP 2-8 (Optional). Roadcut on left of Mount Holly Complex. Lithologies exposed here include massive thick-bedded quartzite, feldspathic quartzite, granitic pegmatite, and chlorite-rich schist (possibly retrograded amphibolite).
41.0	Intersection with Route 7 in Rutland, Vt. Turn left and proceed south on Route 7.
46.0	Junction with Route 103 on left. Continue straight ahead on Route 7.
48.4	Outcrops on right are dolomites of the Monkton Quartzite.
48.7	Outcrops on left of Winooski Dolomite.
49.7	Outcrops on left of Winooski Dolomite.
51.2	Junction with Route 140 in Wallingford, Vt. Continue straight ahead (south) on Route 7.
52.9	View across valley to left of massive cliff-forming outcrops of the Cheshire Quartzite.
53.4	Roadcut on right of dolomites of the Monkton Quartzite.
55.7	Village of South Wallingford.
55.9	Quarry to right of road in marbles of the Shelburne Formation.
59.4	Roadcuts of Dunham Dolomite.
59.9	View of Dorset Peak (3804 ft.) ahead on right.

60.5	Intersection with Mt. Tabor Road in Danby, Vt. Turn left (east).
61.5	STOP 2-9. Park near bridge and walk upstream on north side of creek. Outcrops along trail are Cheshire Quartzite of Early Cambrian age. Principal lithology here is massive vitreous orthoquartzite, in places showing well-developed cross-bedding.
62.5	Return to Route 7. Turn left (south).
63.9	Roadcuts on right of Winooski Dolomite.
67.7	Outcrops on left of Dunham Dolomite.
70.2	Village of East Dorset.
70.7	Roadcuts on right of Dunham Dolomite.
75.7	Intersection with Route 30 (South) in Manchester Center, Vt. Continue straight ahead on Historic Route 7A.
77.9	Little Equinox Mountain (3315 ft.) on right.
80.5	Outcrops on right of Clarendon Springs Dolomite.
82.6	Gravel pit on right.
85.1	Junction with Route 313 in Arlington, Vt. Proceed straight (south) on Route 7.
86.6	Intersection with Route 313 (East) and exit for new Route 7. Turn left.
86.9	Roadcuts of Clarendon Springs Dolomite.
87.8	STOP 2-10. Roadcut of Monkton Quartzite of Early Cambrian age. Outcrops here consist of thin-bedded dolomite and minor quartzite and pyritic phyllite. To the north, dolomites within this formation host a small Mississippi-Valley type Pb-Zn deposit at Lion Hill, near Brandon, Vt.
88.4	Junction with new Route 7. Turn right at exit towards Bennington.
95.2	Outcrops on right of Clarendon Springs Dolomite.
97.7	Outcrops on right of Cheshire Quartzite.
99.3	Roadcuts of Cheshire Quartzite.
100.4	View of Bennington Battle Monument on the right. The monument commemorates a victorious battle in 1777 in which local volunteers from Vermont and nearby Massachusetts soundly defeated an entire regiment of British troops.
100.8	Junction with Historic Route 7A (Kocher Drive). Proceed straight on Route 7.
102.0	Intersection with Route 9 in Bennington, Vt. Continue straight ahead (south) on Route 7.
107.0	Roadcut on right of carbonates of the Bascom Formation (or correlatives).
108.7	Roadcut on left of Mount Anthony Formation.
109.7	Begin outcrops of Walloomsac Formation.
111.3	Junction with Route 346 (on right). Continue straight on Route 7.
113.0	Outcrops on left of carbonates of the Bascom Formation (or correlatives).
113.3	Massachusetts State line.
115.7	Intersection with Route 2 in Williamstown, Mass. Turn right.
115.8	Arrive Williams Inn. End of Day 2 roadlog (cumulative mileage = 216.5).

DAY 3. DAVIS MINE AND RELATED GEOLOGY

Daily Mileage	Comments and Descriptions
0.0	Leave Williams Inn. Turn left onto Route 2 East.
0.5	Williams College.
0.7	Junction with Route 43. Continue straight ahead (east) on Route 2.
5.5	North Adams, Mass.
5.8	Intersection with Route 8A. Proceed straight on Route 2 (also Route 8).
6.5	Junction with Route 8. Bear right (east) on Route 2.
9.4	Roadcuts at hairpin turn of Hoosac Formation.
10.1	Outcrops on left of Hoosac Formation.
10.3	Western summit of Hoosac Range.
13.0	Whitcomb (eastern) summit.
13.8	Outcrops on right of Rowe Schist.
17.0	Begin outcrops of Moretown Formation.
19.7	Roadside park on left.
21.8	Cross railroad tracks.
22.6	Cross Deerfield River. Turn left onto Zoar Road.
23.0	STOP 3.1. Roadcut exposure on right of upper part of Ordovician Moretown Formation. Lithologies here include chloritic quartz-feldspar granofels, greenstone, and minor garnetiferous metapelite. Outcrop contains complex structures involving

	isoclinal folds and local crenulation cleavage. Note especially here distinctive thin layers of orange to pink coticule rock, composed of fine-grained quartz and spessartine (Mn-rich) garnet. Some of the coticule beds are associated with abundant tourmaline and magnetite.
---	Turn around and proceed back towards Route 2.
23.2	STOP 3-2. Roadcut on left of lowermost part of Hawley Formation, of Middle Ordovician age. Rock types here are dominantly mafic metavolcanic greenstone and amphibolite. Note great variations in deformation, in which zones of intense folding and shearing alternate with zones where none is apparent. In these latter areas are preserved primary amygdules, elliptical volcanic bombs, and rare plagioclase phenocrysts.
23.4	Intersection with Route 2. Turn right (west) and cross Deerfield River.
23.6	Intersection with Tower Road. Turn left at Mohawk Park.
24.1	Cross railroad tracks.
24.6	Cross Chickley River.
24.7	Intersection with West Hawley Road (Route 8A). Turn right (south).
25.6	Cross Chickley River.
26.7	Junction with Pudding Hollow Road. Turn left across bridge and walk north across second bridge to rail fence on left.
26.8	STOP 3-3. Outcrops in this area are within lower mafic part of the Hawley Formation and contain well-preserved volcanic structures. Along stream bank are pillowed greenstones, in which pillows are as large as 1 m in diameter. Outcrops in field above show irregular epidote-rich forms, possibly altered volcanic bombs or detached pillows.
26.9	Return to intersection with Route 8A. Turn right (north).
28.9	Intersection with Tower Road. Bear right on Route 8A (North).
29.4	STOP 3-4. Outcrops on right are in middle part of the Hawley Formation, here consisting of greenstone, fine-grained amphibolite, and garnet-bearing metarhyolite. Note abundance of felsic rocks, in contrast to mafic lithologies within lower Hawley Formation (previous stops).
29.8	Intersection at bridge. Turn left across railroad tracks on Route 8A North and cross Deerfield River.
30.0	Junction with Route 2. Turn right (east) on Route 2 (also Route 8A North here). Enter town of Charlemont, Mass.
30.6	Turn left at country store onto Route 8A North.
30.9	Cross Bissell covered bridge.
32.0	Intersection with Maxwell Road. Bear right across small bridge.
34.1	Junction with Dell Road. Turn left across Mill Brook and proceed on Route 8A (North).
35.4	Intersection with Rowe Road. Bear left and continue on Route 8A.
36.8	Junction. Bear left on Number Nine Road.
38.4	Intersection with Cyrus Stage (Groll) Road (unmarked). Turn left.
39.2	Intersection with Dell Road on left. Proceed straight on Cyrus Stage Road.
40.0	Junction with Davis mine road. Turn left.
41.4	STOP 3-5 (Optional). Outcrop on right of road is within middle part of Hawley Formation. Principal lithology here is garnet- and hornblende-bearing felsic gneiss and minor biotite-rich quartzose schist. These rocks are interpreted as metamorphosed rhyolites and volcaniclastic sediments.
42.1	STOP 3-6. Davis mine. Turnout on left for access to mine area. Follow trail down to small open pit (WARNING: THIS IS A COLLAPSE PIT, NOT AN EXCAVATION PIT. IT IS EXTREMELY DANGEROUS!). Exposed in pit are a variety of lithologies including rhyolitic metatuff, massive sulphide, and chlorite- and biotite-rich volcaniclastic metasediments. Metamorphosed chemical sediments are represented by gahnite quartzite (metachert) and a thin chlorite-rich schist. Note complete lack of greenstone and amphibolite. Distribution of massive sulphides and wall rocks here suggests repetition by folding, rather than stratigraphically separate sulphide layers.
44.2	Turn around and rejoin Cyrus Stage Road. Turn right.
45.8	Junction with Number Nine Road. Turn right.
50.1	Cross Mill Brook and intersect Dell Road. Bear right on Route 8A towards Charlemont.
52.2	Intersection with Maxwell Road. Turn right.
52.3	STOP 3-7. Outcrops in creek to right are in upper part of Hawley Formation. Exposures are of massive, layered andesitic tuffs. Note well-preserved euhedral plagioclase crystals (relict phenocrysts) and local lithic fragments. This unit stratigraphically overlies the massive sulphide

	deposits at both the Davis and Hawks (Mt. Peak) mines.
53.4	Cross covered bridge.
53.5	STOP 3-8. Roadcut on left exposes transition from volcanic-rich part of upper Hawley Formation to uppermost (overlying) carbonaceous schist unit. Metavolcanic rocks here are mainly greenstone and amphibolite. Pelitic schist unit is carbonaceous and locally garnetiferous, and resembles parts of the overlying Goshen Formation.
53.7	Junction with Route 2. Turn right (west).
72.8	North Adams, Mass.
78.5	Arrive Williams Inn. End of Day 3 roadlog (cumulative mileage = 295.0).

DAY 4. BETTS MINE AND RELATED GEOLOGY

Daily Mileage	Comments and Descriptions
0.0	Leave Williams Inn. Turn right onto Route 2 West (also Route 7 South here).
2.3	Intersection with Route 2 West. Continue straight ahead on Route 7 South.
4.2	Junction with Route 43. Continue south on Route 7.
7.5	Outcrops on right of Greylock Schist.
8.3	Outcrops on right of Walloomsac Formation.
9.1	Outcrops on left of Stockbridge Formation.
9.5	Outcrops of Stockbridge Formation.
9.8	Begin outcrops of Walloomsac Formation.
15.1	Town of Lanesborough, Mass.
17.3	Pontoosuc Lake on right.
20.0	Intersection with Route 9 in Pittsfield, Mass. Turn left (east) onto Route 9.
22.5	Junction with Route 8 North. Continue straight ahead (east) on Route 9.
24.9	Intersection with Route 8 South in Dalton, Mass. Turn left to continue east on Route 9 (also Route 8A here).
31.3	Intersection with Route 8A (North). Proceed straight (east) on Route 9.
32.2	Roadcut on left of Stamford Granite Gneiss.
33.9	Outcrops of Hoosac Formation.
36.3	Outcrops on left of Moretown Formation.
36.8	Outcrops on right of Moretown Formation.
37.4	Cross Westfield River. Intersection with West Bush Road. Turn left.
---	STOP 4-1. Roadcuts at intersection are in lower part of Ordovician Moretown Formation. Lithologies include quartz-feldspar granofels and minor amphibolite and pelitic schist. Note locally developed "pin-stripe" fabric, folds, and crenulation cleavage. Coticule rocks are apparently absent here.
37.9	Intersection with Packard Road. Turn left.
---	STOP 4-2. Outcrops here are within upper part of Moretown Formation. Western end of outcrop shows amphibolite and minor greenstone (locally folded). Eastern part of outcrop consists of chloritic quartz-feldspar granofels, felsic schist, and metapelite. Note well-developed chevron folds, quartz veins, and thin layers and lenses of magnetite-rich rocks and coticules.
38.6	Entrance to Betts mine on left. Walk in along trail to north, parallel to Packard Street.
---	STOP 4-3A. Small outcrop to right of trail is slightly carbonaceous schist of the Hawley Formation. This lithologic unit forms part of the stratigraphic hangingwall overlying the manganese ore zone at the mine (to west). Note small garnets here and well-developed crenulation cleavage.
---	STOP 4-3B. Walk west to area north of north pit. Small outcrop along west side of prospect is garnetiferous felsic schist. This is a characteristic lithology of the area surrounding the Betts deposit.
---	STOP 4-3C. Walk south to rock peninsula on north side of pit. A small outcrop of coticule is exposed just north of pit. Peninsula outcrop is magnetite-bearing quartzite of the mine sequence. The major manganese ore zone is exposed in the north wall of the pit, just west of peninsula. On peninsula, note lenses of fine-grained magnetite (-jacobsite) iron formation and large quartz vein with associated coarse pyrite.
---	STOP 4-3D. Walk south to outcrops of massive layered amphibolite. This lithology is in stratigraphic hangingwall of the ore zone. The amphibolite, composed mainly of hornblende and plagioclase, is interpreted as a metamorphosed basalt.
---	STOP 4-3E. Main (south) pit of the Betts manganese mine. Principal rock types here are felsic schist, quartz-feldspar granofels, quartzite, and magnetite(-jacobsite) iron formation. The manganese ores form a stratabound zone composed of Mn-silicates, Mn-carbonates, and Mn-oxides, in places associated with massive sulphide

(chiefly pyrrhotite). Principal manganese minerals are rhodochrosite, kutnahorite, rhodonite, tephroite, and sonolite. Note that in contrast to the coticules, spessartine is minor here.

39.3 Return to Prospect Street to intersection with Route 9. Turn right (west) and proceed to Albany, N.Y., airport (cumulative mileage to Route 9 intersection = 334.3). End of trip.

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STRATABOUND MASSIVE SULPHIDE DEPOSITS OF THE ELIZABETH MINE, ORANGE COUNTY, VERMONT

Malcolm P. Annis
Department of Geology
University of Cincinnati
Cincinnati, Ohio 45221

John F. Slack
U.S. Geological Survey
954 National Center
Reston, Virginia 22092

Alan L. Rolph*
Department of Geology
University of Cincinnati
Cincinnati, Ohio 45221

INTRODUCTION

The Orange County copper district, in east-central Vermont, contains stratabound and commonly stratiform massive sulphide deposits with significant amounts of copper and zinc. The Elizabeth mine developed the largest known deposit and is distinguished by being the greatest past metal producer in the New England States. The district also contains important sulphide deposits to the north of Elizabeth at Orange and Gove, at Ely, and at Pike Hill.

Elizabeth is the best known and most studied of the deposits, and is the focus of a current re-examination of the district. Most previous workers have proposed that the ores formed by hydrothermal replacement during metamorphism or granitic intrusion. Our work, however, demonstrates that the massive sulphide deposits occupy specific stratigraphic positions, and that the ores have been subjected to the same deformation and metamorphism as the surrounding country rocks. This chapter summarizes data from our current investigations that document these features, and that provide a basis for evaluating the origin of the deposit.

PREVIOUS STUDIES

Many studies of the Elizabeth deposit and its environs have been made since the initial descriptions by Hitchcock et al. (1861). Various accounts of the ores and the early operations of the mine are given in Wheeler (1883), Howe (1886), Wendt (1886), Peters (1891), Smyth and Smith (1904), Fay (1909), Judson (1909), and Weed (1904; 1911). Later reports on the mine are presented by Anderson (1931), Jacobs (1944a), Benson et al. (1950), and Lutjen and Kearney (1953).

Regional geologic investigations have been made throughout east-central Vermont. The earliest publications are by Richardson (1902) and Hitchcock (1912). Studies in the Strafford quadrangle were made by Jacobs (1944b) and Doll (1944), the latter first mapping and recognizing the Strafford dome. The structure of the region was studied extensively by White (1949) and White and Jahns (1950). Lyons (1955) mapped the Hanover quadrangle to the south. Rolph (1982), in the most recent work, examined the detailed stratigraphy and structure surrounding the deposit.

Modern geologic work on the mine began with studies by the U.S. Geological Survey and Harvard University. White (1943) briefly described the results of mapping at the mine, as a part of a larger study of the entire district (White and Eric, 1944). In a more detailed study, McKinstry and Mikkola (1954) examined the ores and wall rocks and concluded that the deposit formed by replacement during regional metamorphism. Howard (1959a; 1959b; 1969) studied the structure and alteration at the mine, and reached a similar conclusion. Jenks (1968; 1971), recognizing the importance of the conformable nature of the ores, first proposed a premetamorphic, syngenetic origin for the deposit. Other, more recent, studies have concentrated on the tourmaline-rich rocks at and near the mine (Slack and Annis, 1981; Plaus, 1983), and on the geochemistry of the wall rocks (Slack, 1983). Additional geologic and geochemical investigations are also underway.

MINING HISTORY

The mining history of the Elizabeth deposit has been reviewed by McKinstry and Mikkola (1954) and Howard (1969). In 1793, an outcrop of the orebody was discovered, but initial attempts to produce iron failed. Beginning in 1809, the deposit was mined for copperas (iron sulphate), which was used in treating timber, as a dye, and in the manufacture of ink. Copper production started in 1830 by open-pit methods; underground mining began in 1886. Copper was produced intermittently from 1830 until 1930, when the mine closed. In 1943, the mine was reopened by the Vermont Copper Company and production continued through early 1958, when the mine closed permanently.

Total production from the Elizabeth mine is estimated at about 3.2 million tons of ore averaging 1.8% Cu and 0.5% Zn (Gair and Slack, 1979; 1980). White and Eric (1944) stated that the early production (1830-1930) yielded 10.5 million pounds of copper from 250,000 tons of ore at an average grade of 2.2% Cu. These figures were considerably surpassed by the production from the later years 1943-1958, amounting to nearly 3 million tons of ore (101 million lbs Cu) averaging 1.7% Cu (Howard, 1969). Some of the pyrrhotite was shipped for the manufacture of sulphuric acid. Zinc and silver were recovered from the copper concentrates, the latter amounting to 0.16 oz/ton in the ore; gold averaged 0.01 oz/ton and was also recovered (McKinstry and Mikkola, 1954). No other metals were produced from the mine.

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*Present address: Shell Oil Company, Houston, Texas.

REGIONAL GEOLOGIC SETTING [1]

One of the most important features of the district is the regional geologic distribution of the deposits (Fig. 1). The two largest orebodies, Elizabeth and Ely, occur in the clastic metasedimentary rocks of the Gile Mountain Formation. In contrast, the Pike Hill (Eureka-Union) deposits to the north are located entirely within the calcareous Waits River Formation. Similar massive sulphide ores at Orange and Gove and at Cookville occur in or near the amphibolites of the Standing Pond Volcanics (White and Eric, 1944). When all of these deposits are considered together, the copper district is seen to transgress major lithostratigraphic boundaries. When considered individually, however, the Elizabeth deposit is seen to be stratiform (although intensely deformed); Ely, and probably others, also are stratiform. The distribution of these stratabound and apparently stratiform deposits within a belt that includes three diverse lithologic units focusses special interest on the regional stratigraphy and structure of the district.

Stratigraphy

The geology of eastern Vermont is dominated by intensely folded and metamorphosed sedimentary and very minor mafic volcanic rocks apparently of Early Devonian age (Fig. 1). These rocks make up part of the regionally extensive Connecticut Valley-Gaspe Synclinorium that is traceable from southern Massachusetts northward into Quebec. In Vermont, this synclinorium contains three distinct lithologic units: 1) the Waits River Formation, 2) the Standing Pond Volcanics, and 3) the Gile Mountain Formation. The Waits River Formation is a thick sequence of quartzose metalimestone and metadolostone, calcareous mica schist, and minor marble. The Standing Pond Volcanics is a thin unit composed mainly of fine-grained amphibolite, although locally it contains minor amounts of hornblende schist, sulphidic metachert, and fine-grained spessartine-quartz rock (coticule). The Gile Mountain Formation, in contrast, is a dominantly clastic metasedimentary sequence of quartz-mica schist, mica schist, micaceous quartzite, and minor calcareous mica schist, hornblende schist, and amphibolite.

The most controversial aspect of the regional geology involves the stratigraphic succession of these three formations. One interpretation, proposed by Murthy (1957), Ern (1963), and Goodwin (1963), places the Waits River stratigraphically above the Gile Mountain Formation. The opposite model, in which the Gile Mountain overlies the Waits River, has been more widely accepted (Doll, 1944; White and Jahns, 1950; Lyons, 1955; Dennis, 1956; Hall, 1959; Chang et al., 1965; Fisher and Karabinos, 1980; Rolph, 1982). A third possibility is that the two formations are broadly contemporaneous and represent lateral facies of deposition.

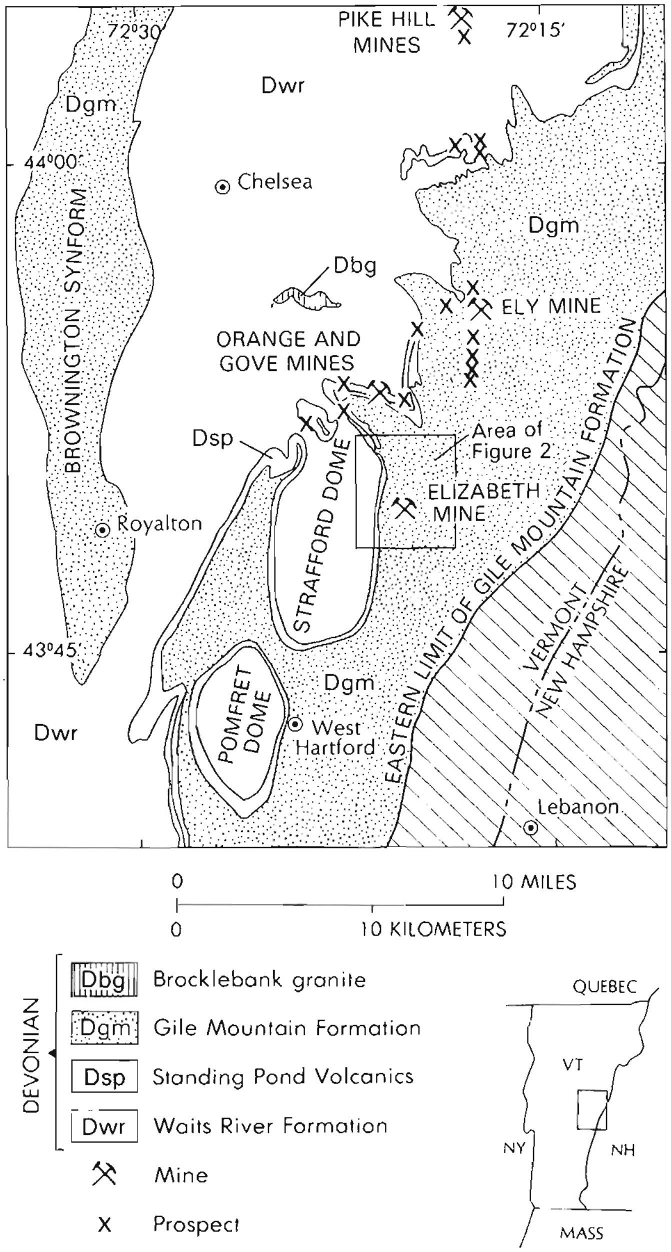

Figure 1. Geologic map of the Orange County copper district, Vermont. Geology after Doll et al. (1961). Distribution of sulphide deposits compiled from White and Eric (1944).

Recent studies of relict graded bedding in the Gile Mountain Formation have partially constrained the stratigraphic models. Fisher and Karabinos (1980) determined younging directions from numerous well-exposed graded beds along the White River near Royalton, Vermont (Fig. 1). On both flanks of the Brownington synform they found that the graded beds consistently face towards the Gile Mountain Formation. Rolph (1982) recognized similar relationships in the Gile Mountain Formation in the vicinity of the Elizabeth mine. These collective observations provide strong evidence that the Gile Mountain Formation stratigraphically overlies the Waits River Formation in the area.

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[1] Note: Mineral modifiers are used in order of increasing abundance.

Regionally, however, the two formations may be time transgressive. Clastic sedimentation at one locality in the Gile Mountain Formation could have taken place contemporaneously with dominantly carbonate deposition of the Waits River Formation at another locality. This model is supported by the gradational nature of the transition zone between the two formations, which shows progressively more abundant clastic material in the Waits River Formation near the contact.

The key to an understanding of the Gile Mountain - Waits River contact may involve the Standing Pond Volcanics. This formation, commonly interpreted as a mafic (basaltic) tuff, has an extraordinary strike length (Fig. 1). In the area of the Strafford dome, the Standing Pond marks the boundary between the carbonate and clastic metasedimentary formations. However, to the north, the Standing Pond progressively diverges from the contact and occurs within the Waits River Formation (Doll, 1944); Lyons (1955) mapped a similar distribution to the south. In places, the Standing Pond occurs entirely in the Gile Mountain Formation (Fig. 2). This departure from the lithostratigraphic boundary, when considered together with its probable volcanic origin, suggests that the Standing Pond Volcanics is a time-stratigraphic marker. This in turn implies that the lithostratigraphic contact of the Waits River and Gile Mountain Formations is time-transgressive in the district (White and Jahns, 1950; Rolph, 1982).

Structure

The structure of the region is a composite of two principal stages of deformation and a later, more local arching that formed the Strafford and Pomfret domes (White and Jahns, 1950). During the first stage of deformation, the rocks were folded and a schistosity (S-1) developed approximately parallel to bedding (S-0). The second stage produced large, tight to isoclinal folds (F-2) that dominate the structure outside the Strafford and Pomfret domes; an additional cleavage and schistosity (S-2) also formed during this stage. The structures of these two stages of deformation display similar orientations (away from F-2 fold hinges), and their respective schistosities typically intersect at very acute angles.

The Elizabeth synform (Fig. 2) is one of several large, second-stage F-2 folds in the area that trend approximately north and plunge gently (12°-15°) to the north. The axial surfaces of these folds dip moderately steeply (about 65°) to the east. In the vicinity of the Gile Mountain - Waits River contact northwest of the mine, these folds are more open and trend northwest. Here, the axes are steeper and plunge down the dip of the axial surfaces (White and Jahns, 1950, Fig. 10).

The Strafford and Pomfret domes are outlined by the distribution of the Standing Pond Volcanics (Fig. 1). These domes are not simple anticlines, however, but cleavage arches in which an axial planar schistosity dips radially away from the center of the domes (White, 1949; Lyons, 1955). In the area west of the Elizabeth mine, the structural limit of the Strafford dome lies outward from (and east of) the Standing Pond Volcanics. Folds in this outer area are more compressed than corresponding folds farther to the east (Rolph, 1982). To the north, the compressed folds trend northwest and parallel the configuration of the dome.

Metamorphism

Metamorphic zones in eastern Vermont strike generally north and approximately parallel to the regional structural and stratigraphic trends (Thompson and Norton, 1968). The zones are delineated by the common isograds mapped in pelitic schists. Within the study area (Fig. 2), the metamorphic grade increases progressively from biotite on the west to garnet ± kyanite and to staurolite ± kyanite on the east (Rolph, 1982). Kyanite is especially prominent, forming coarse-bladed crystals in many of the highly micaceous (aluminous) schists. Although sillimanite is apparently absent in the pelitic (quartz-mica) schists of the area, Plaus (1983) tentatively identified fibrolitic sillimanite in tourmalinite zones 0.7 km east of the mine site (Fig. 2). Cordierite also occurs locally in biotite-rich schists within the kyanite-staurolite zone near the Whitcomb Hill antiform (Fig. 2, UTM 13.9/ 58.0), approximately 2.7 km north of the mine; Jacobs (1944b) also reports sillimanite from near Whitcomb Hill. Because the cordierite and sillimanite both occur in rocks of unusual bulk composition, their presence probably reflects their non-pelitic chemistry, and not local variations in temperature or pressure during metamorphism.

Intrusive Rocks

Granitic intrusive rocks are common in eastern Vermont, particularly north of the district (Doll et al., 1961). All of the granitic bodies in this part of Vermont are unfoliated to weakly foliated, post-tectonic intrusions of Acadian (Devonian) age. The small Brocklebank granite, 11 km northwest of the mine (Fig. 1), belongs to this series of intrusives. The sulphide deposits of the district occur well to the east of this granite, however, and their distribution shows no spatial association to it. There is, therefore, no compelling reason to relate the formation of the ores to this (or other) intrusive granites.

Minor bodies of mafic intrusive rock are also present in the area. Doll (1944) describes fine-grained black dykes and sills as much as 10 m thick cutting the Gile Mountain Formation, including one dyke trending east about 2 km south of the Elizabeth mine. Mafic dykes are also known underground in the mine, where they form unfoliated, crosscutting bodies as much as 2 m thick containing phenocrysts of titaniferous augite and amygdules composed of calcite, prehnite, and laumontite (Howard, 1969). The discordant, post-tectonic nature of these intrusions and their mafic compositions suggest that they are related to the alkaline rocks of the White Mountain magma series of Mesozoic age (Foland and Faul, 1977).

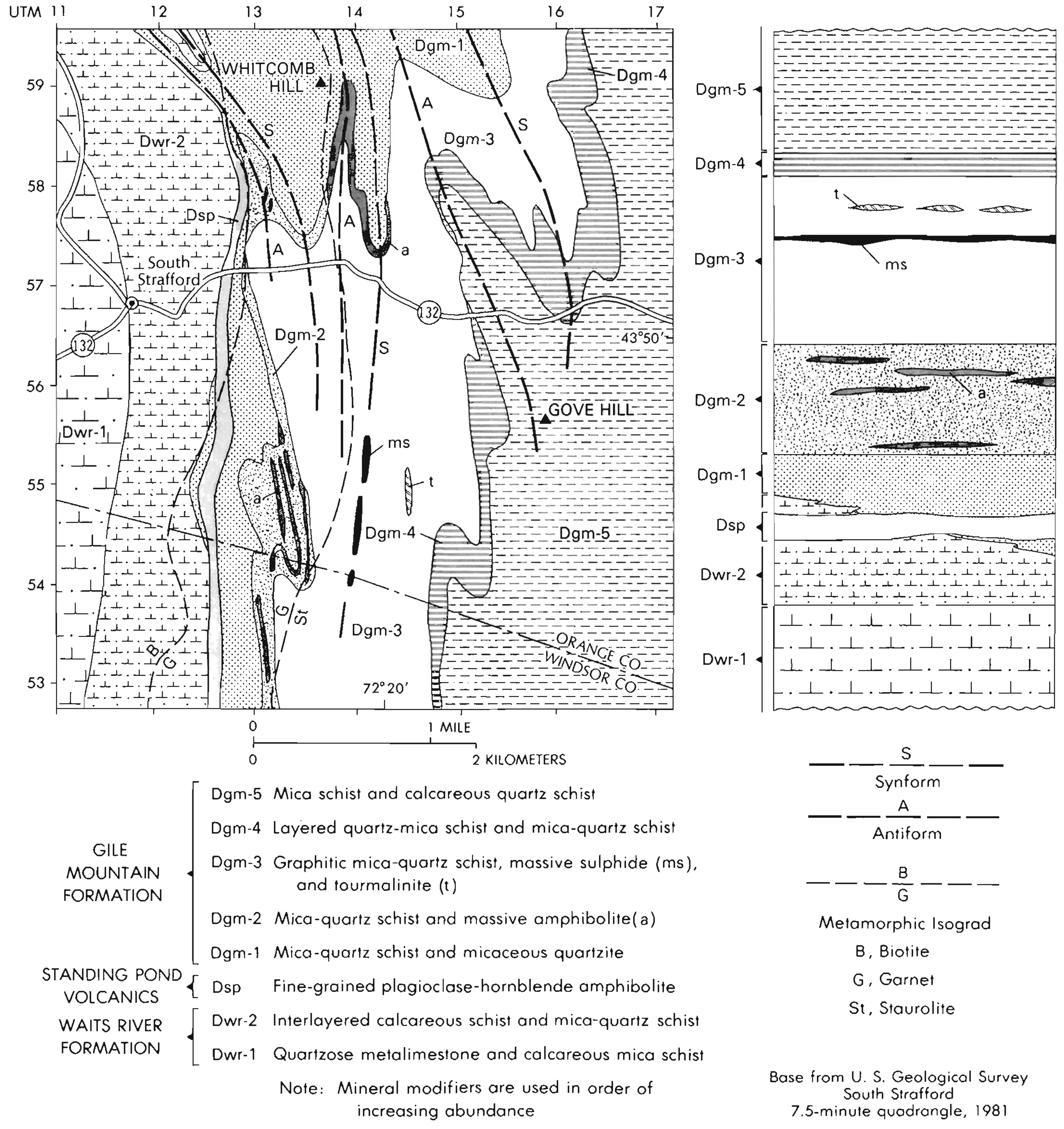

Figure 2. Geologic map and stratigraphic column for the Elizabeth mine area (modified from Rolph, 1982).

GEOLOGY OF THE MINE AREA

Stratigraphy and Structure

The massive sulphide deposits of the Elizabeth mine occur east of the Strafford dome and entirely within the Gile Mountain Formation (Figs. 1, 2). The sulphide ores are one of several unusual lithologies present at a particular stratigraphic horizon of the formation. As outlined by Rolph and Annis (1980) and Rolph (1982), this horizon occurs well above the base of the Gile Mountain Formation and forms part of an overall fining-upward clastic sequence (Fig. 2). The lowermost unit recognized in this sequence (unit 1) consists of interlayered mica-quartz schist and micaceous quartzite. The next overlying unit (2) includes similar mica-quartz schist, but is distinguished by the presence of conformable lenses of amphibolite. The third stratigraphic unit (3) is the most varied, and contains all of the sulphide deposits in the mine area. It consists dominantly of graphitic and non-graphitic mica-quartz schist and quartz-mica schist. Locally, thin layers (<5 cm) contain as much as 16 percent graphite. The massive sulphides and associated rocks of the mine sequence (described below) occur in the upper part of this unit. Stratigraphically above the mine sequence in this unit are additional unusual lithologies including coticule and quartz-tourmaline schist or tourmalinite (Plaus, 1983). Unit 4 is distinguished by its characteristically layered rocks, and consists of interlayered quartz-mica schist and mica-quartz schist with locally preserved graded beds. Unit 5, the uppermost unit, consists of mica schist and minor calcareous quartz schist.

Structurally, the massive sulphide ores and related rocks of the mine sequence occur within the Elizabeth synform. In the mine area, this synform commonly is isoclinal and its axial surface dips approximately 65° east; the east limb generally is overturned. In the central part of the mine (underground) the synform plunges gently (12° - 15°) to the north. In the southern and very northern parts of the mine, however, the plunge is much shallower, and the synformal axis is in places nearly horizontal (Howard 1959a). A longitudinal section and plan of the mine (Fig. 3) show that the ores and associated wall rocks conform to the plunge of this synform. Geologic cross sections (Fig. 4) further show that the massive sulphides are stratiform within the core of the synform. Other minor folds of diverse orientation and plunge intersect the Elizabeth synform and complicate the structure. The only significant fault, in the northern part of the mine, offsets the orebody about 15 m (McKinstry and Mikkola, 1954).

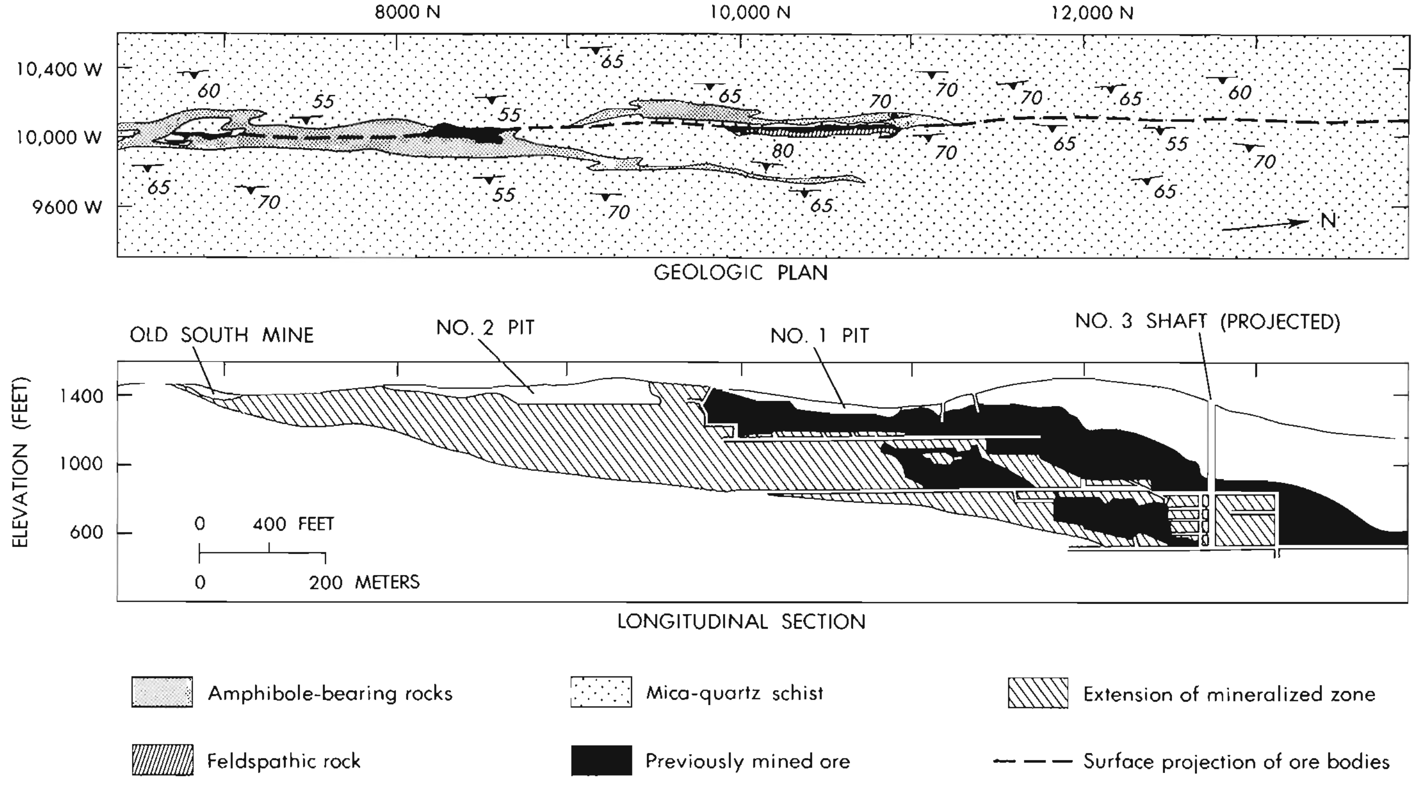

Figure 3. Geologic plan and longitudinal section of the Elizabeth mine (modified from White, 1943).

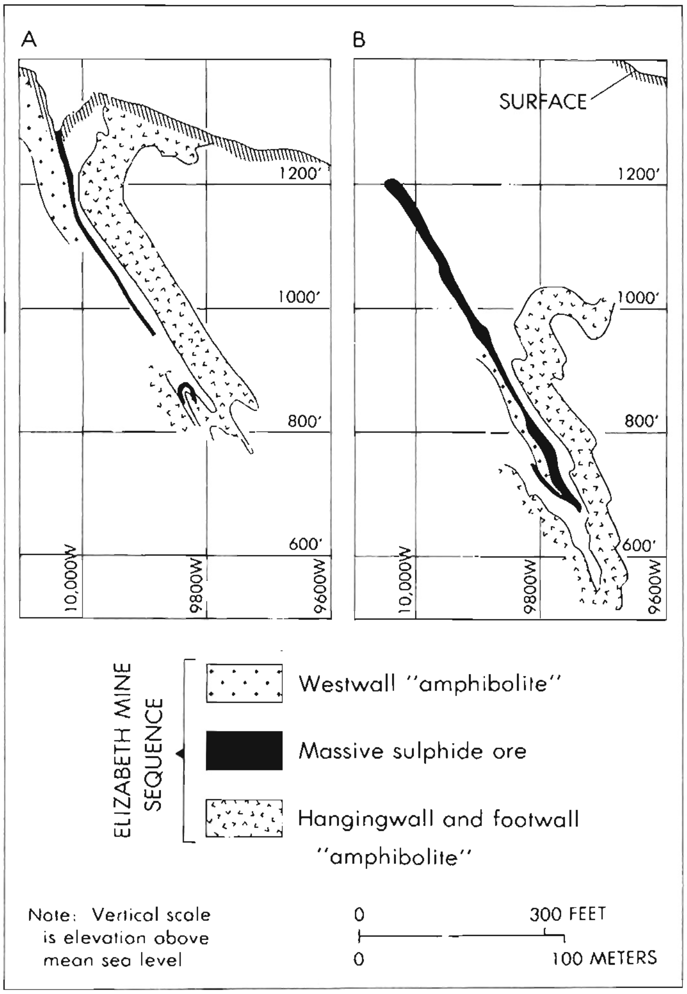

Figure 4. Geologic cross sections of the Elizabeth mine. Section A located at mine coordinate 10,500 N; section B at 12,000 N. Modified after McKinstry and Mikkola (1954) and published with permission from Economic Geology.

Sulphide Orebodies [1]

The sulphide orebodies have been described in detail by McKinstry and Mikkola (1954) and Howard (1969). Production has come from four apparently stratiform orebodies covering a total strike length of nearly 3.4 km. Three of these were developed in the Foster-Cleveland section between coordinates 7900 N and 17,700 N; the fourth was mined at the Old South mine near 6900 N (Fig. 3). The main or No. 1 orebody was mined from the two open pits and from underground to the north; the No. 2 orebody represents a faulted segment of this same zone. The No. 3 orebody was developed only at the very northern end of the mine (14,200 N - 16,700 N), and forms a separate stratigraphic unit (see below). The production from the Old South mine apparently came from an extension of the main (No. 1) orebody.

The sulphide orebodies vary a great deal in thickness. The average thickness of the ore is reported to have been about 7 m, with a maximum of nearly 20 m (McKinstry and Mikkola, 1954). Howard (1969) correlates the thickest sections of the ore with major drag folds, particularly in the No. 1 pit, in the No. 2 pit, and at the Old South mine. In these areas, as well as in thinner ore zones, the massive sulphides typically contain fragments or inclusions of schistose wall rock (McKinstry and Mikkola, 1954, Figs. 25-27) that produce a characteristic "durchbewegung" texture (Vokes, 1969). Pods and boudins of quartz are also common in the ore, and in places outline the patterns of folds.

The most complete mineralogic description of the orebodies is found in McKinstry and Mikkola (1954). Pyrrhotite is by far the most abundant mineral, occuring both in massive sulphide and as disseminations in many of the wall rocks. The chief ore mineral is chalcopyrite, which typically shows mutual intergrowths with pyrrhotite; it reportedly occurred in greater amounts in the northern part of the mine. Pyrite is less common and forms distinctive cubes as much as 5 cm in diameter in massive pyrrhotite. Sphalerite is a minor constituent characteristically disseminated throughout the ore. More unusual are lenses of nearly solid sphalerite as much as 0.3 m thick (McKinstry and Mikkola, 1954, p. 27), and a sphalerite-rich marble containing anomalous (9000 ppm) Mn (J. F. Slack, unpub. data). Other sulphides known in trace amounts are galena, molybdenite, cubanite, tetrahedrite-tennantite, and valleriite. The most important gangue minerals are quartz, plagioclase, tourmaline, calcite, and rutile.

The Mine Sequence

Our recent studies show that the massive sulphide deposits at the Elizabeth mine form part of a complex sequence of unusual lithologies at a specific stratigraphic horizon in the Gile Mountain Formation. This sequence of lithologies, here termed the "mine sequence," is contained within slightly graphitic mica-quartz schist of unit 3, well above the basal contact with the Waits River Formation (Fig. 2). The mine sequence includes rocks mapped by White (1943), McKinstry and Mikkola (1954), and Howard (1969), and additional, previously undescribed, lithologies. It is defined as including all rocks stratigraphically above the base of the hangingwall and footwall amphibolite of McKinstry and Mikkola (1954), and stratigraphically below the top of their westwall amphibolite (Figs. 4, 5). The overall thickness of the mine sequence varies -- especially in the noses of folds -- but averages approximately 30 m along the length of the ore zone. The lithologies and respective stratigraphic relations are presented here on the basis of surface mapping alone. Detailed studies of drill core from the mine, currently underway, should in the future provide a more complete description of the mine sequence.

One major difficulty in describing the mine sequence involves the use of the word amphibolite. Previously, McKinstry and Mikkola (1954) used this term to designate specific stratigraphic units -- the hangingwall and footwall amphibolite, and the westwall amphibolite (Fig. 4). Howard (1959a, 1959b, 1969) continued to use these terms, and many workers have since inferred (erroneously) that the deposit is

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[1] Note: The mine coordinate (grid) system was established in English units of measurement (feet), and is retained throughout this report.

hosted mainly by mafic metavolcanic rocks. It is important to note, however, that many of these so-called "amphibolites" contain quartz and as little as 8 percent hornblende (Howard, 1969, p. 12) and are thus not true amphibolites. We adopt a more rigorous terminology here, and restrict the use of the term amphibolite to rocks containing little or no quartz, abundant plagioclase, and a minimum of 50 percent hornblende.

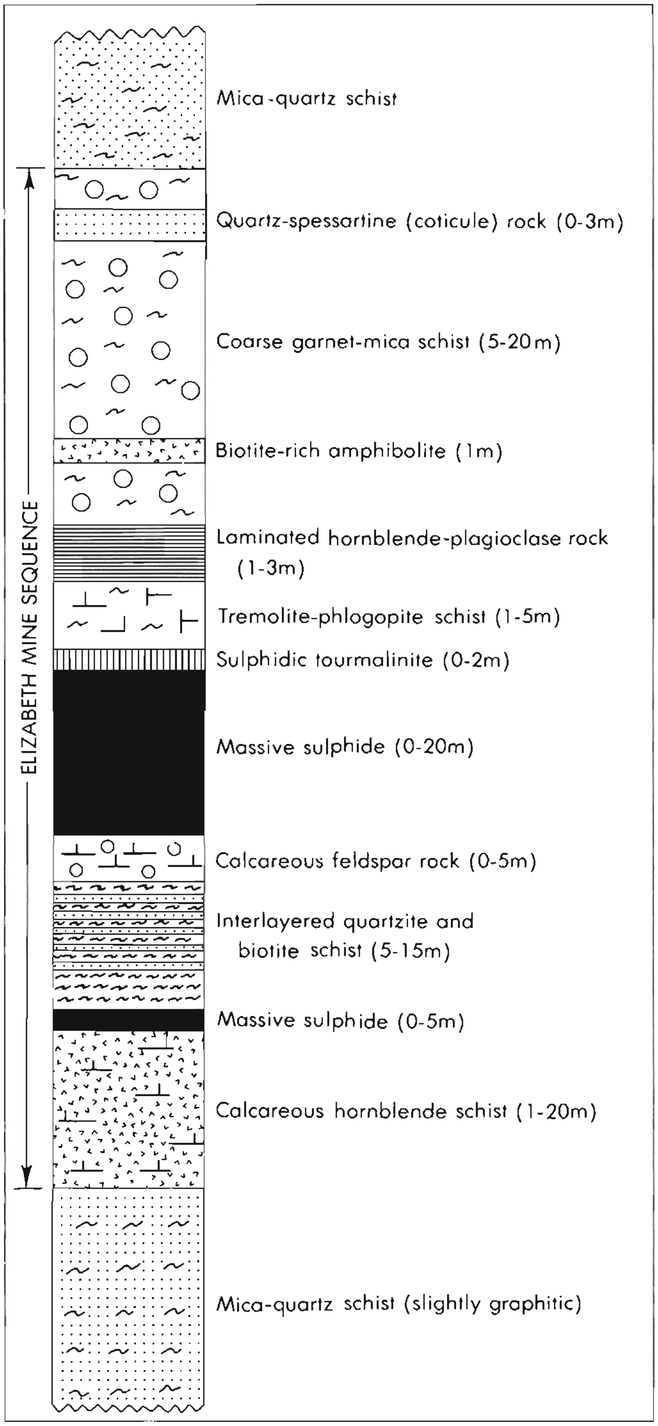

Figure 5. Generalized lithostratigraphy of the Elizabeth mine sequence.

The lowermost unit of the mine sequence (Fig. 5) is a medium to coarse-grained calcareous hornblende schist equivalent to the hangingwall and footwall amphibolite of McKinstry and Mikkola (1954). Within the limits of the mine, this unit varies greatly in thickness, from as little as 1 m to as much as 20 m (Howard, 1969, Plates 8-24). The hornblende schist is a distinctly layered rock containing large crystals of hornblende up to 10 cm in length. The matrix consists mainly of plagioclase and calcite, accompanied by minor quartz and clinozoisite; biotite, pyrrhotite, and oxide minerals (magnetite, rutile) are accessories. The hornblende schist is noteworthy in having large amounts (10-30%) of porphyroblastic calcite, and only trace to minor (<5%) biotite. In places, this unit contains more abundant (40-50%) hornblende, but these mafic layers appear to be volumetrically minor.

The next overlying unit is a discontinuous layer or lens of disseminated to massive sulphide (Fig. 5). This sulphide unit corresponds to the No. 3 orebody as described by Howard (1969). It was mined only at the northern end (underground), from coordinates 14,200 N to 16,700 N. To the north of these coordinates, this ore zone apparently is missing. In the southern part of the mine, including the area of the open pits, the No. 3 ore zone is exposed locally as a concentration of heavily disseminated to massive pyrrhotite-rich sulphide as much as 1 m thick (Fig. 5).

The stratigraphically overlying unit is a mixed sequence of biotite-rich schist and interlayered impure quartzite. This unit varies in thickness from approximately 5 to 15 m in the southern area of the mine, and appears to thicken to the north (Howard, 1969, Plates 8-21). The biotite schist, more abundant in the lower part of the unit (Fig. 5), contains many stratabound lenses composed of quartz and minor carbonate. The main part of the rock consists of abundant brownish-black biotite, porphyroblastic (1-3 mm) plagioclase, and minor garnet, quartz, and muscovite. Layers of impure quartzite less than 1 m thick are common near the stratigraphic top of the unit and form resistant outcrops along the east walls of the open pits. The quartzites consist of granoblastic to slightly aligned quartz, minor garnet and actinolite, and traces of biotite, plagioclase, and carbonate.

A distinctive calcareous feldspar rock locally underlies the main (No. 1) orebody (Fig. 5). This unit is tentatively correlated with a feldspathic rock mapped by White (1943) and White and Eric (1944), and later briefly described by Howard (1959a). It was previously known only from the east side of the north pit (Fig. 3), but recent mapping has extended its distribution to the south pit. The calcareous feldspar rock varies greatly in texture and mineralogy, but is dominantly an unfoliated to slightly layered unit consisting of plagioclase and coarse carbonate accompanied by minor quartz, pyrrhotite and biotite. Reconnaissance microprobe studies by P. J. Atelsek (U.S. Geological Survey) indicate that some of the carbonate is an Fe-bearing dolomite. In places, this rock also contains small (<1 cm thick) grey seams and lenses composed almost entirely of clinozoisite oriented parallel to foliation.

Overlying the main ore zone is a sulphidic layered tourmalinite (Fig. 5). This unusual rock forms a stratigraphic unit less than 2 m thick composed of quartz, tourmaline, albite, sulphides, and minor tremolite and green (Cr-bearing) muscovite. The rock commonly displays a coarse fabric in which layers of brown Mg-tourmaline (dravite) alternate with layers rich in albite and quartz. The dravite, which constitutes 10 to 30 percent of the rock, appears to have been misidentified previously as idocrase (cf. McKinstry and Mikkola, 1954, p. 21). In the area between the open pits (ca 9500 N), the tourmalinite is highly sulphidic and represents a facies of the ore zone. Most of the surface exposures of this rock have a vuggy texture, however, in which the sulphide minerals (pyrrhotite, chalcopyrite) have been leached away.

The tremolite-phlogopite schist of McKinstry and Mikkola (1954) is a distinctive stratigraphic unit known both from underground and surface exposures. It varies in thickness from slightly less than 1 m to perhaps as much as 5 m, and displays textures that range from schistose to decussate. Essential minerals are tremolite and pale-brown biotite (phlogopite). Other, generally minor minerals, include plagioclase, quartz, calcite, brown to black tourmaline, and diopside (?); pyrrhotite and rutile are common accessories. In some outcrops, the mineral proportions are somewhat different and plagioclase is abundant. The plagioclase forms fine-grained granoblastic grains in thin (<1 cm) laminae between lenses of tremolite and phlogopite; it also forms abundant euhedral porphyroblasts, particularly at the south end of the mine (McKinstry and Mikkola, 1954).

Stratigraphically above the tremolite-phlogopite schist is a laminated felsic unit 1 to 3 m thick consisting mainly of fine-grained granoblastic plagioclase. This distinctive rock contains abundant albite-oligoclase in thin (1 mm) laminae bounded by seams of biotite. The biotite, together with hornblende and garnet, generally make up less than 30 percent of the rock. Other (accessory) minerals are quartz, chlorite, muscovite, tourmaline, rutile, and pyrrhotite. The garnet and hornblende form porphyroblastic crystals through which the felsic laminae may be traced. The garnets are less common, and occur as sparse, euhedral crystals 0.5-2.0 cm in diameter. The hornblendes are more abundant, forming larger (1-3 cm) crystals oriented obliquely to the laminae; some are pseudomorphically replaced by biotite. This rock is equivalent to the basal portion of the westwall amphibolite of McKinstry and Mikkola (1954), and appears to be the "altered amphibolite" described in detail by Howard (1959b; 1969). It shows a gradational contact with the overlying coarse garnet-mica schist.

The thickest unit in the stratigraphic hangingwall is a coarse-grained garnet-mica schist that contains thin layers of biotite-rich amphibolite and calcareous coticule (Fig. 5). This unit, in total, corresponds to the major part of the westwall amphibolite of McKinstry and Mikkola (1954). It ranges in thickness from only a few metres to as much as 20 m, the thicker portions being confined to the southern end of the mine (Howard, 1969, Plates 8-24). The coarse garnet-mica schist is similar in many respects to the underlying laminated hornblende-plagioclase rock, but it displays a more schistose texture and contains greater amounts of garnet and mica. The garnets are particularly distinctive and form large euhedral crystals as much as 7 cm in diameter. The micas consist of both biotite and muscovite, the latter apple-green and Cr-bearing (Howard, 1959b, p. 1431) especially where in contact with garnet. Hornblende is present in subordinate amounts (<20 %) in this unit, forming coarse (10-15 cm) sprays and rosettes typically retrograded to biotite. The matrix is mainly fine-grained granoblastic sodic plagioclase and biotite, accompanied by accessory quartz, muscovite, clinozoisite-epidote, and carbonate.

The amphibolite and coticule in the coarse garnet-mica schist each make up only a minor part of the unit (Fig. 5). Unfortunately, a complete section of this upper unit is not exposed at the surface, so the exact stratigraphic positions of these rocks are unknown. The amphibolite appears to occur in the lower part of the unit, forming a thin layer about 1 m thick and consisting of hornblende, plagioclase, and minor (5-10%) biotite, with only traces of quartz and carbonate. The coticule rock occurs as a local lens as much as 3 m thick near the top of the sequence and is composed of quartz, calcite, biotite, and abundant, fine-grained spessartine (Mn-rich) garnet.

GEOCHEMISTRY

Geochemical studies currently in progress (Slack, 1983) confirm that the rocks of the Elizabeth mine sequence are substantially different from the common lithologies of the Gile Mountain Formation. Table 1 presents chemical analyses of representative samples from the mine sequence (nos. 1-9), for comparison with samples from the surrounding Gile Mountain Formation (nos. 10-12). Relative to the surrounding country rocks, the mine sequence lithologies clearly contain more Fe, Mg, Na, Ca, Mn, B, S, and CO_2.

The wall rocks of the mine sequence have particularly interesting chemical compositions that are considered to reflect a variety of protoliths. The calcareous hornblende schist in the stratigraphic footwall (Table 1, no. 1) appears to be an impure mafic tuff, deposited in calcareous sediments. The overlying biotite-rich schist (no. 2) contains abundant Fe and Mg and may represent a metamorphosed alteration zone or chemical precipitate. The analysis of the impure quartzite (no. 3) shows a very high silica content that probably reflects an origin as a quartz-rich detrital sediment. The calcareous feldspar rock (no. 4) contains substantial Fe and Mg in addition to carbonate; its protolith is as yet unknown.

Rocks in the stratigraphic hangingwall of the deposits have significant Fe, Mg, Na, and, locally, Mn and B. The albite-rich tourmalinite (Table 1, no. 5) contains major amounts of B and Na, and is interpreted as a boron-rich chemical sediment (Slack, 1982). The overlying tremolite-phlogopite schist (no. 6) is extremely enriched in Fe, Mg, Ca, and CO_2, and is believed to be a metamorphosed dolomitic marl. The laminated hornblende-plagioclase rock (no. 7) has large amounts of Na but a chemistry inappropriate for a keratophyre or spilite; it may be a metamorphosed chemical sediment or an impure metatuff. The overlying coarse garnet-mica schist (no. 8) has a

TABLE 1.--CHEMICAL ANALYSES OF ROCKS FROM THE ELIZABETH MINE AREA, VERMONT (FROM SLACK, 1983)

[Analyses obtained by X-ray fluorescence and rapid rock (Shapiro, 1975) methods. Major-element analyses by Z. A. Hamlin and J. R. Lindsay, U.S. Geological Survey. Determination of volatiles and S and C by Z. A. Hamlin and J. R. Gillison, U.S. Geological Survey].

	1	2	3	4	5	6	7	8	9	10	11	12
	81-24	82-61	82-35	82-44	80-58A	82-31B	82-32	82-33	82-52	82-64	82-79	82-68
SiO_2	41.20	55.00	78.00	37.70	77.10	42.50	52.50	49.60	48.50	76.70	64.90	46.50
TiO_2	0.79	1.00	0.58	0.75	0.88	0.81	1.10	1.30	0.53	0.63	1.10	2.10
Al_2O_3	16.20	19.70	8.60	14.70	13.70	15.60	21.20	22.70	12.20	10.80	17.80	29.20
Fe_2O_3	1.74	0.99	0.40	0.03	0.34	0.28	1.55	1.17	0.34	1.05	0.92	0.65
FeO	7.20	6.20	3.50	5.90	0.24	7.20	6.60	9.90	13.70	3.10	4.20	6.60
MnO	0.12	0.17	0.14	0.13	0.02	0.28	0.16	0.37	2.50	0.05	0.10	0.09
MgO	5.20	4.70	1.90	5.90	0.90	11.70	2.30	1.40	2.00	2.10	2.30	3.40
CaO	18.10	4.80	5.80	15.70	1.15	7.60	3.10	5.00	11.30	0.93	1.40	0.96
Na_2O	1.80	0.53	0.29	1.60	2.10	3.00	6.10	4.50	0.15	1.70	1.30	2.10
K_2O	0.29	4.40	0.13	0.63	0.32	1.80	2.20	2.30	0.50	2.10	3.10	4.40
P_2O_5	0.10	0.13	0.07	0.06	<0.05	0.05	0.11	0.09	0.30	0.09	0.08	0.09
CO_2	6.70	0.50	1.50	14.70	0.01	3.80	0.11	0.37	6.00	0.01	0.08	0.01
H_2O^+	0.77	1.80	0.69	0.72	0.37	2.40	1.30	1.10	0.61	1.30	2.00	3.40
H_2O^-	0.05	0.15	0.08	0.03	0.45	0.22	0.13	0.08	0.18	0.13	0.21	0.16
S	0.16	0.25	<0.01	1.80	0.21	1.80	0.38	0.04	<0.01	0.04	<0.01	<0.01
C (org)	ND*	0.22	0.02	0.21	ND	0.03	0.01	0.01	0.07	0.19	0.03	0.70
Total	100.42	100.54	101.70	100.56	97.84†	99.07	98.85	99.93	98.89	100.92	99.53	100.37

* ND = not determined.

† Total does not include 1.4 weight percent B_2O_3.

1 -- Calcareous hornblende schist (Mine Sequence), from haulageway of south (No. 2) pit, appx. coord. 8600 N.
2 -- Biotite-rich schist (Mine Sequence), from east wall of south (No. 2) pit, appx. coord. 9200 N.
3 -- Impure quartzite (Mine Sequence), from east wall of south (No. 2) pit, appx. coord. 9200 N.
4 -- Calcareous feldspar rock (Mine Sequence), from east wall of north (No. 1) pit, appx. coord. 10000 N.
5 -- Albite-rich tourmalinite (Mine Sequence), from small outcrop between two pits, appx. coord. 9600 N.
6 -- Tremolite-phlogopite schist (Mine Sequence), from small outcrop between two pits, appx. coord. 9700 N.
7 -- Laminated hornblende-plagioclase rock (Mine Sequence), from outcrop between two pits, appx. coord. 9700 N.
8 -- Coarse garnet-mica schist (Mine Sequence), from west wall of south (No. 2) pit, appx. coord. 9000 N.
9 -- Calcareous coticule rock (Mine Sequence), from west wall of north (No. 1) pit, appx. coord. 10600 N.
10 -- Micaceous (biotite ± muscovite) quartzite (from surrounding Gile Mountain Formation).
11 -- Staurolite-garnet-kyanite-muscovite-biotite-quartz schist (from surrounding Gile Mountain Formation).
12 -- Graphitic garnet-kyanite-quartz-biotite-muscovite schist (from surrounding Gile Mountain Formation).

surprisingly similar bulk composition and could have had a similar origin. The calcareous coticule rock (no. 9) is distinguished by anomalous Mn, as well as by abundant Ca, Fe, and CO_2. The presence of large amounts of calcite in this rock is particularly significant, because it suggests a protolith of impure manganese carbonate, rather than Mn-rich chert (cf. Hickmott et al., 1983).

SUMMARY AND CONCLUSIONS

Our work to date has yielded significant new information about the Elizabeth deposit and provided a foundation for a better understanding of its genesis. New geologic mapping has demonstrated that the massive sulphide deposits are associated with a variety of unusual lithologies at a particular stratigraphic horizon. The deposits are located within a slightly graphitic mica-quartz schist unit of the Gile Mountain Formation, and form part of an overall fining-upward clastic sequence (Fig. 2). The presence of minor amounts of graphite in the lower part of this unit is interpreted to reflect deposition under reducing (euxinic) conditions.

The massive sulphides are enclosed by a sequence of lithologically unusual wall rocks. These wall rocks locally contain significant amounts of hornblende, plagioclase, calcite, dolomite, muscovite, biotite, tremolite, phlogopite, spessartine garnet, and tourmaline, and are unlike the dominantly clastic metasediments typical of the Gile Mountain Formation. The mineral assemblages in the mine sequence rocks, like the assemblages in the country rocks, reflect both their bulk chemical composition and the intensity of the metamorphism. The mine sequence rocks contain comparatively large amounts of

Fe, Mg, Ca, Na, Mn, B, and CO_2. These constituents are not believed to result from metamorphic differentiation, however, but rather from an essentially isochemical metamorphism of a sequence of unusual sedimentary and (or) volcanic rocks. These rocks are interpreted as mixtures of chemical, clastic, and tuffaceous sediments.

The stratabound and generally stratiform nature of the massive sulphides suggests a predeformational and premetamorphic origin by syngenetic or diagenetic processes. Most previous workers have proposed a hydrothermal replacement origin for the ores in which mineralization was accompanied by alteration of amphibolite (McKinstry and Mikkola 1954; Howard, 1959b, 1969). Our model, in contrast, views the "altered amphibolites" and other lithologies of the mine sequence as primary stratigraphic units that largely preserve original bulk compositions. Future studies of the unusual lithologies at the mine should provide a basis for ultimately interpreting the depositional environment of the ores, and for guiding exploration programs in the district.

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VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS OF THE DAVIS MINE, HAMPSHIRE COUNTY, MASSACHUSETTS

John F. Slack
U.S. Geological Survey
954 National Center
Reston, Virginia 22092

Martha M. Godchaux
Department of Geology
Mount Holyoke College
South Hadley, Massachusetts 01075

Rosemarie L. Graves*
U.S. Geological Survey
954 National Center
Reston, Virginia 22092

INTRODUCTION

The Davis mine, in Hampshire County, northwestern Massachusetts, produced pyrite and minor copper from massive sulphide deposits in metamorphosed volcanic and volcaniclastic rocks of Ordovician age. The Davis deposit is the largest of a group of stratabound and apparently stratiform mineral deposits known in the Hawley mineral belt. Many of these deposits are spatially related to mafic and(or) felsic metavolcanic rocks at specific stratigraphic levels. Recent work, described here, has confirmed the existence of a variety of primary (igneous) structures and textures in some of the metavolcanic rocks. These features and the volcanic stratigraphy together provide a framework for understanding the genesis of the deposit, and for the identification of favourable exploration targets in the area.

MINING HISTORY

The Davis mine is significant in having the largest recorded metal production in Massachusetts. Details of the mining history are given in Rutledge (1906), Quinn (1943), and McCarthy (1967). The deposit was first acquired by Mr. Herbert J. Davis (after whom the mine is named), following reports of boulders of pyrite on a nearby farm. The mine opened in 1882 and operated almost continuously until 1910, when mining ceased. At that time the pillars were robbed and the underground workings collapsed, forming the small open pit still visible today. The deposit was mined chiefly for pyrite, although minor amounts of copper were also produced. The pyrite was used in the manufacture of sulphuric acid.

The records from the mine are incomplete and the exact size of the deposit is unknown. Through 1892, production is stated to have been 334,552 tons (Emerson, 1898); this figure presumably is only for pyrite. Production of blister copper is recorded separately for the years 1905, 1906, and 1908, totaling nearly 20,000 pounds (Quinn, 1943). Slack (in Gair and Slack, 1980) previously estimated the size of the deposit at about 0.5 million tons. This figure is now considered too conservative, and a revised estimate is here placed at 1 million tons of massive sulphide. No complete records are available on the grades of the ore.

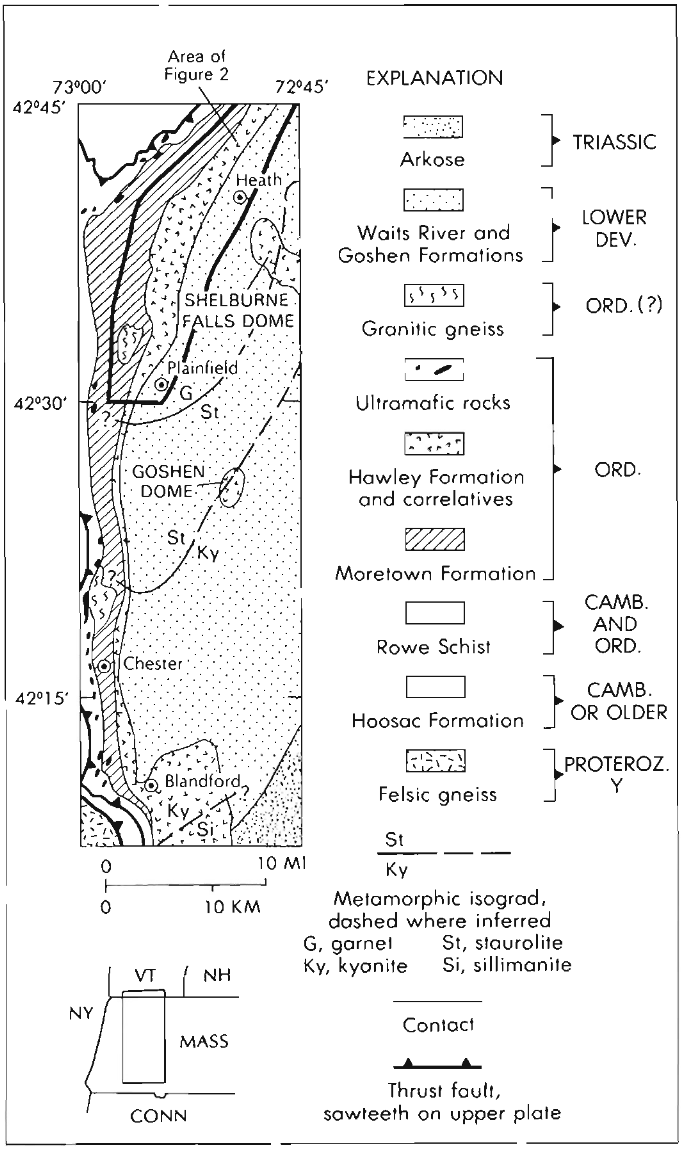

Figure 1. Generalized geologic map of the east flank of the Berkshire massif (modified from Hatch, 1975; and Zen et al., 1983).

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*Present address: 12708 Connecticut Ave., Wheaton, Md.

PREVIOUS STUDIES

The sulphide deposits and geology surrounding the Davis mine have been studied since the end of the 19th century. The geology of the region was first examined during the pioneering early investigations of Emerson (1898). Detailed geologic work began with a cooperative mapping program between the Commonwealth of Massachusetts and the U.S. Geological Survey, resulting in quadrangle maps by Chidester et al. (1967) and Hatch and Hartshorn (1968), the latter presenting the geology of the Hawley Formation in the Davis mine area. In a related publication, Hatch (1967) redefined the Hawley Formation and described lithologic and stratigraphic details of the metavolcanic and metasedimentary rocks.

Reports on the Hawley mineral belt and its sulphide deposits are numerous. General descriptions of the mineral belt are given by Perry (1934) and Quinn (1967). Emerson (1898) described many of the deposits; Ross (1914) investigated the Hawks (Mt. Peak) mine near Charlemont. The most comprehensive paper, by Quinn (1943), presents both the geology and mining history of the major deposits. Specific reports on the Davis mine have been made by Rutledge (1906), Weed (1911), McCarthy (1967), Bwerinofa (1972), Green (1977), and Helm (1982). An account of the history of the mine is given in McCarthy (1967). Bwerinofa (1972) described the mineralogy of the ores and wall rocks, and analyzed soil samples for copper and zinc. A more detailed soil geochemical survey of the mine area was made by Green (1977). The recent work of Helm (1982) mainly is a study of the major-element chemistry of the Hawley Formation surrounding the deposit. Mineralogical reports on the gahnite at Davis include older studies by Dana (1885), Crosby and Brown (1887), and Flint (1908), and recent electron microprobe analyses presented by Spry and Scott (1983).

REGIONAL GEOLOGIC SETTING

The Davis deposit is hosted by the Ordovician Hawley Formation, one of a sequence of lower Paleozoic units comprising the east flank of the Berkshire massif (Fig. 1). West of the Hawley belt is a dominantly clastic metasedimentary package that includes (from oldest to youngest) the Hoosac Formation, the Rowe Schist, and the Moretown Formation. A major thrust fault separates the aluminous metapelites of the Hoosac Formation from the overlying units to the east (Stanley, 1978). The Rowe Schist, composed of phyllite, pelitic schist, and minor quartzite and amphibolite, is noteworthy in containing local lenses of ultramafic rock (Fig. 1) which may represent remnants of obducted oceanic crust. The overlying Moretown Formation is a mixture of quartz-feldspar granofels, pelitic schist, and minor amphibolite, and is characterized in many places by a distinctive "pinstripe" appearance.

The largest proportion of volcanic rocks is found in the Hawley Formation (Hatch, 1967). Along strike to the south into Connecticut, and to the north into Vermont, the Hawley Formation and its correlatives apparently undergo facies changes and are dominated by clastic metasediments. In the area of this report, the principal rock types are greenstone, amphibolite, carbonaceous and non-carbonaceous metapelite, and a variety of felsic to intermediate-composition (metavolcanic) gneisses and schists. Protoliths of the mafic rocks are mainly basaltic flows and agglomerates, which in places have well-preserved pillow structures (Hatch, 1967). The felsic rocks include rhyolitic tuffs and coarse pyroclastic breccias interlayered with volcaniclastic sediments. Rocks of intermediate composition are represented chiefly by andesitic crystal tuffs.

The Hawley Formation is unconformably overlain to the east by the Goshen and Waits River Formations of Early Devonian age. These rocks form an integral part of the regionally extensive Connecticut Valley-Gaspe synclinorium that extends northward into eastern Vermont and southern Quebec. In Massachusetts, the Goshen and Waits River Formations consist of phyllite and pelitic schist, minor calcareous schist and quartzite, and rare beds of calcite marble. Unmetamorphosed arkose and basalt of Mesozoic age are found farther to the east and southeast (Fig. 1).

The pre-Silurian rocks of the region have been affected by both the Taconic (Ordovician) and Acadian (Devonian) orogenies. Hatch (1975) has recognized four stages of deformation accompanied by metamorphism and local granitic intrusion. Most of the deformation, and the peak of metamorphism, are interpreted as having taken place during the Acadian orogeny. Differences in tectonic style between the pre-Silurian rocks and the younger Devonian sequence suggest some displacement along the upper contact of the Hawley Formation (Hatch, 1975). In the younger Devonian rocks, the distribution of metamorphic isograds (Fig. 1) shows that the highest grades of metamorphism were attained to the south, near Blandford. The distribution of isograds in the pre-Silurian rocks is more complex (Cheney et al., 1980), and is not shown.

THE HAWLEY MINERAL BELT

The Hawley mineral belt (Perry, 1934; Quinn, 1967) is noteworthy in containing a variety of stratabound (and commonly stratiform) mineral deposits. The deposits occur within Ordovician metavolcanic and metasedimentary rocks, both in the Hawley Formation and in the underlying Moretown Formation (Fig. 2). In terms of past production, the most important deposits are massive pyritic sulphides in the northern part of the belt. The largest sulphide deposit was developed at the Davis mine; smaller deposits occur to the west at the Mary Louise mine and to the south at the Hawks (Mt. Peak) mine (Quinn, 1943). Iron deposits are present at the Hawley mine and at nearby prospects southwest and northwest of Charlemont. Manganese deposits occur mainly in the southern part of the mineral belt near Plainfield, the largest having been developed at the Betts mine.

The ores of the Betts mine consist of stratabound lenses of Mn-carbonates and Mn-silicates associated with quartz, magnetite (-jacobsite) iron formation, and massive sulphide (Quinn, 1945; Hickmott et al., 1983). This deposit thus differs from the fine-grained spessartine-quartz rocks or coticules (Emerson, 1898; Renard, 1878) that comprise the other manganese occurrences in the belt. The coticules occur not only to the south near Plainfield (Hatch, 1969), but also in the northern part of the belt near Charlemont, both within the quartz-feldspar granofels of the upper Moretown Formation, and in the carbonaceous schists

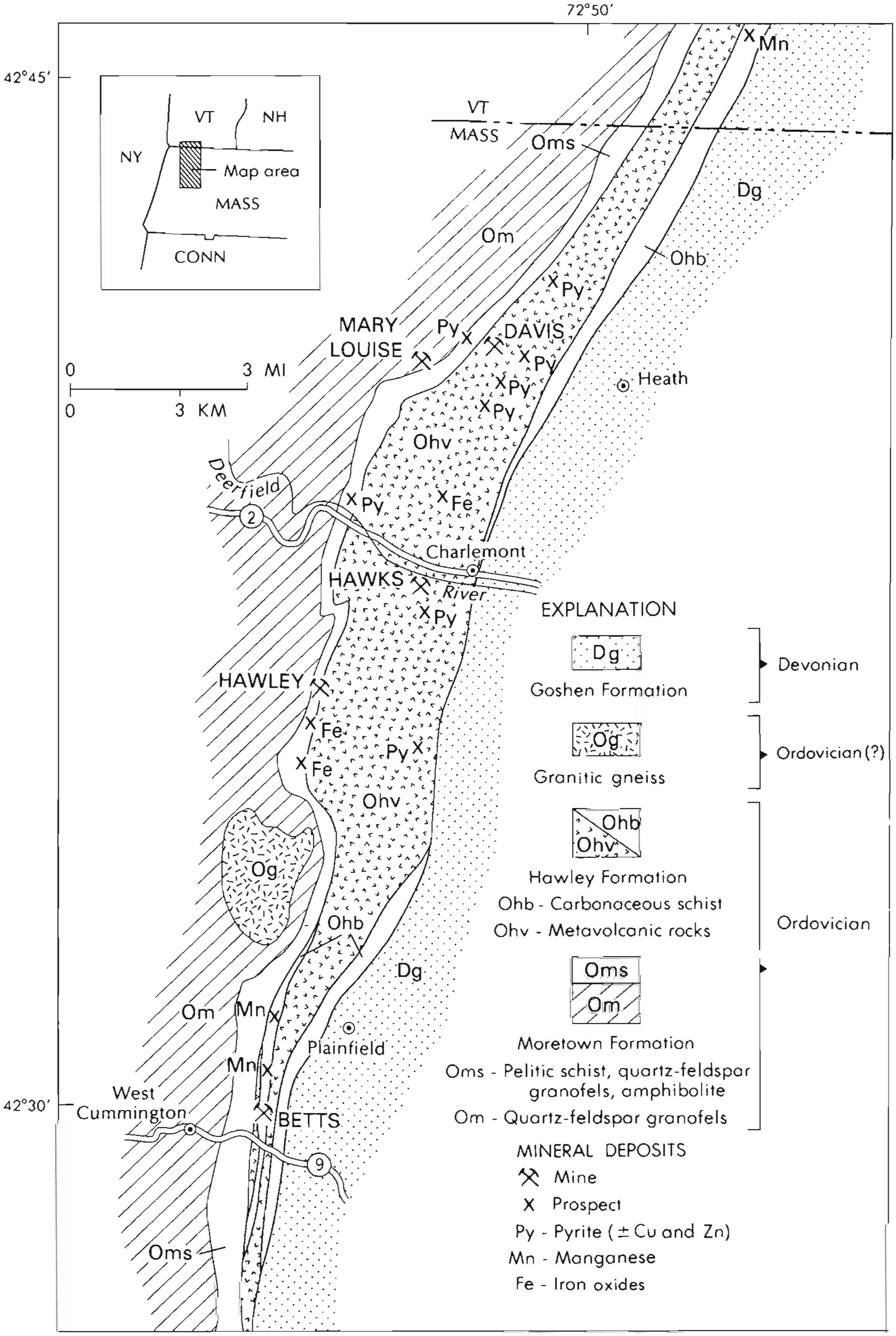


Figure 2. Geologic map showing stratabound mineral deposits of the Hawley mineral belt. Compiled from Emerson (1898), Quinn (1943, 1967), Hatch (1969), Hatch and Hartshorn (1968), Osberg et al. (1971), Chidester et al. (1967), and Zen et al. (1983).

of the Hawley Formation.

The iron deposits consist of concordant, stratiform lenses of magnetite or hematite iron formation. The largest deposit, at the Hawley mine near Forge Hill, has been described by Emerson (1898) and Perry (1934). The Hawley deposit forms a 1-m-thick lens of massive specular hematite, magnetite, barite, quartz, and coticule; no sulphides are present. The hematite occurs in a foliated, micaceous layer as much as 0.3 m thick. At depth, the deposit is apparently dominated by magnetite intercalated with quartz and coticule. Fragments of coarsely crystalline layered barite 5 cm thick found on the mine dumps (by JFS) presumably form part of the deposit as well. Fluorite has also been reported from an iron prospect about 1 km south of the Hawley mine by Emerson (1898).

The conformable nature of the deposits of the mineral belt and their relationship to stratigraphy (Fig. 2) imply that they formed contemporaneously with their enclosing host rocks, and prior to deformation and regional metamorphism. Previously, Emerson (1898) and Quinn (1967) interpreted the deposits as fissure veins of hydrothermal origin. However, the deposits are not true veins, and are, for the most part, concordant with bedding. The processes that formed the surrounding country rocks must be broadly related to the processes that formed the contained mineral deposits. The detailed geology of individual deposits, described below for the Davis mine area, must therefore be considered in any assessment of the genesis of the ores.

VOLCANIC STRATIGRAPHY

The Hawley Formation has been subdivided during previous geologic mapping by Hatch and Hartshorn (1968) and Osberg et al. (1971). The subdivisions are summarized by Hatch (1967) and consist of three principal volcanic units. The most widespread of these units forms the lower and middle part of the formation and was designated as undivided greenstone, amphibolite, quartz-mica schist, and feldspathic schist and granulite. A second unit of plagioclase granulite was recognized as a distinctive stratigraphic marker contained within the former, undivided sequence. The third volcanic unit, previously mapped only south of Charlemont (Osberg et al., 1971), has been described as chlorite schist with plagioclase "insets." A separate, dominantly metasedimentary unit of carbonaceous pelitic schist and minor amphibolite forms the uppermost part of the Hawley Formation in the area (Hatch, 1967; Hatch and Hartshorn, 1968).

Our subdivision of the Hawley Formation (Fig. 3) relies not only on lithology but also on primary volcanic structures and textures. Many of the rocks in the region are severely folded and sheared and show only metamorphic fabrics. However, in weakly deformed areas, primary volcanic features are well preserved and serve as the basis for distinguishing mineralogically similar rocks. Previously, Hatch (1967) and Hatch et al. (1967) described pillow structures and fragmental textures from parts of the Hawley Formation. We have recognized many additional volcanic features we consider critical to an accurate interpretation of the depositional environment of the Davis deposit. These are described below for each respective stratigraphic unit.

The lowermost unit of the Hawley (Ohp, Fig. 3) is a mafic sequence of massive to schistose, nonbanded, dark greenish-black to black amphibolite showing local pillow structures. The pillows are typically 1 m in diameter, with epidotized cores and chlorite-rich rims. The pillow zone, where present, commonly constitutes the very base of the formation; it is apparently absent in the northern part of the area near the Davis mine. The pillows probably reflect submarine deposition of mafic lava flows. Above this pillow zone is a thick sequence of fine-grained greenstone and black amphibole-rich schist in which hornblende and chlorite are much more abundant than plagioclase. None of these rocks have plagioclase megacrysts or coarse lithic fragments and are interpreted as basaltic tuffs. Overlying this sequence to the east is a series of discontinuous lenses of massive amphibolite containing pale-green epidote-rich nodules. These nodules may represent either altered, detached pillows or relict volcanic bombs.

The middle unit of the Hawley (Ohv, Fig. 3) is the most diverse and interesting of the major units and contains all of the significant sulphide deposits. It consists of pyroclastic mafic and felsic metavolcanic rocks and local accumulations of volcaniclastic metasediments. The basal portion is composed of alternating pale-green, fine-grained felsic granofels and dark-green to black, chlorite-hornblende schist. Some of the felsic rocks contain small (3-5 mm) red garnets with distinctive feldspathic coronas; others contain garnet and hornblende, or biotite or chlorite in a random or aligned orientation. In places, the felsic rocks are marked by extremely long (to 30 cm) crystals of hornblende forming the "fasciculite" of Emerson (1898). Although uncommon, this unit also contains spectacular volcanic meta-agglomerates. In undeformed areas, felsic (rhyolitic) breccias have been recognized with subrounded to angular fragments as large as 0.5 m; associated mafic meta-agglomerates contain fragments of amygdaloidal greenstone (lava) in a fine-grained (tuffaceous) matrix. These pyroclastic rocks, with minor intercalated volcaniclastic metasediments, are overlain by a dominantly mafic sequence of coarse-grained banded amphibolite characterized by orange spots or pits after ankerite (?). Interlayered carbonate-free amphibolites and more felsic metavolcanic rocks also contain "fascicules" of coarse hornblende. This latter sequence of dominantly mafic rocks is believed to have originated as basaltic and andesitic tuffs.

Near the top of the mixed mafic-felsic sequence described above is a distinctive plagioclase-rich stratigraphic unit. This unit (Ohg, Fig. 3) is a white to pale green gneiss consisting essentially of granoblastic oligoclase and quartz, with only minor amounts of mica, chlorite, hornblende, and garnet. It was previously mapped by Hatch and Hartshorn (1968) in the northern part of the area (Heath quadrangle) and is here correlated with a lithologically similar rock mapped by Osberg et al. (1971) to the south. Hatch (1967) described angular feldspar crystals and faint compositional layering in this rock, and interpreted it as a metamorphosed crystal tuff. The abundance of plagioclase and quartz in the rock suggests that it is of rhyolitic composition.

Another marker unit of the Hawley Formation is a crystal- and lithic-rich metatuff (Oht, Fig. 3). This rock was previously mapped only in the Plainfield Quadrangle south of Charlemont (Osberg et al., 1971),

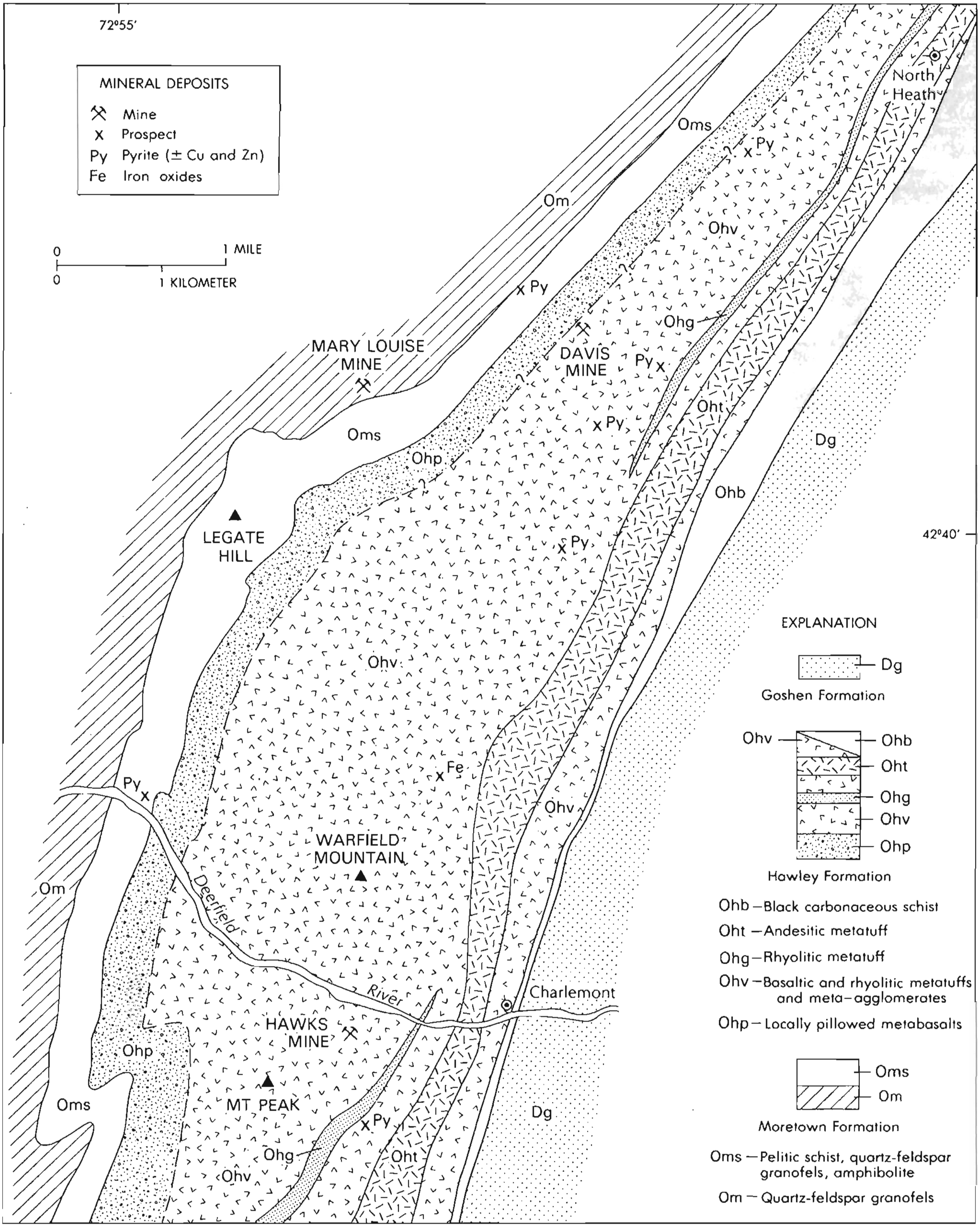


Figure 3. Geologic map of the Charlemont-Heath area. Modified from Chidester et al. (1967), Hatch and Hartshorn (1968), and Osberg et al. (1971).

and has been briefly described by Hatch (1967) and Hatch et al. (1967). It consists of fine-grained green or dark-gray chlorite schist containing subhedral to euhedral plagioclase crystals as much as 1 cm long. In some outcrops, this rock is interlayered with a fragmental metavolcanic rock showing angular to ovoid felsic clasts of uncertain origin; they may represent rock fragments or pumice lumps. Preliminary chemical analyses (M. M. Godchaux, unpub. data) suggest that these crystal and lithic tuffs are dominantly of intermediate (andesitic) composition.

In summary, the metavolcanic rocks of the Hawley Formation are interpreted as a sequence of mafic to felsic lavas, tuffs, and breccias of submarine origin. The lithologies and textures of the rocks form the basis for a stratigraphic division in which a lower sequence of locally pillowed basaltic lavas and fine-grained basaltic tuffs (Ohp, Fig. 3) is overlain successively by coarse rhyolitic and basaltic agglomerates and tuffs (Ohv), by rhyolitic (plagioclase-rich) crystal tuffs (Ohg), and by andesitic crystal and lithic tuffs (Oht). An uppermost unit composed dominantly of carbonaceous pelitic schist (Ohb) forms a euxinic clastic sedimentary cover over the volcanic sequence. The relatively wide map distribution of metavolcanic rocks in the Charlemont-Heath area (Fig. 2) is believed to be volcanic, rather than tectonic in origin, and is considered to represent a major volcanic edifice. This edifice appears to be built chiefly by a pyroclastic cycle of rhyolitic and basaltic agglomerates and tuffs (Ohv, Fig. 3) that contain all of the important sulphide deposits of the area. The locations of the sulphide mines and prospects, and one iron prospect (Fig. 3), suggest that the stratabound deposits occur at two main stratigraphic levels. The Davis deposit is situated near the base of the pyroclastic rhyolitic and basaltic sequence, whereas the Hawks (Mt. Peak) deposit (and sulphide prospects along strike to the north) occur near the top of the sequence. The geologic setting of the Davis deposit in this sequence is presented below.

GEOLOGY OF THE DAVIS MINE

The ores of the Davis mine consist of stratiform lenses of granular pyritic sulphide that vary greatly in thickness. The lenses trend northeast and parallel the schistosity of the surrounding country rocks. Quinn (1943) stated that the sulphides were mined for 275 m along their length and more than 400 m downdip. In underground workings, the orebody reportedly thickened and thinned along strike and contained large inclusions ("horses") of wall rock (Rutledge, 1906). According to Emerson (1898), the sulphides commonly attained a thickness of 7 m, and reached a maximum thickness of 18.5 m. The massive sulphide exposures in the open pit (Fig. 4) are only 0.5 to 1.5 m thick, however. These variations in the thickness of the massive sulphide are interpreted to be principally due to folding. Repetition by folding explains the distribution of sulphide layers and rock types in the pit[1/], as well as in drill core (cf. Bwerinofa, 1972).

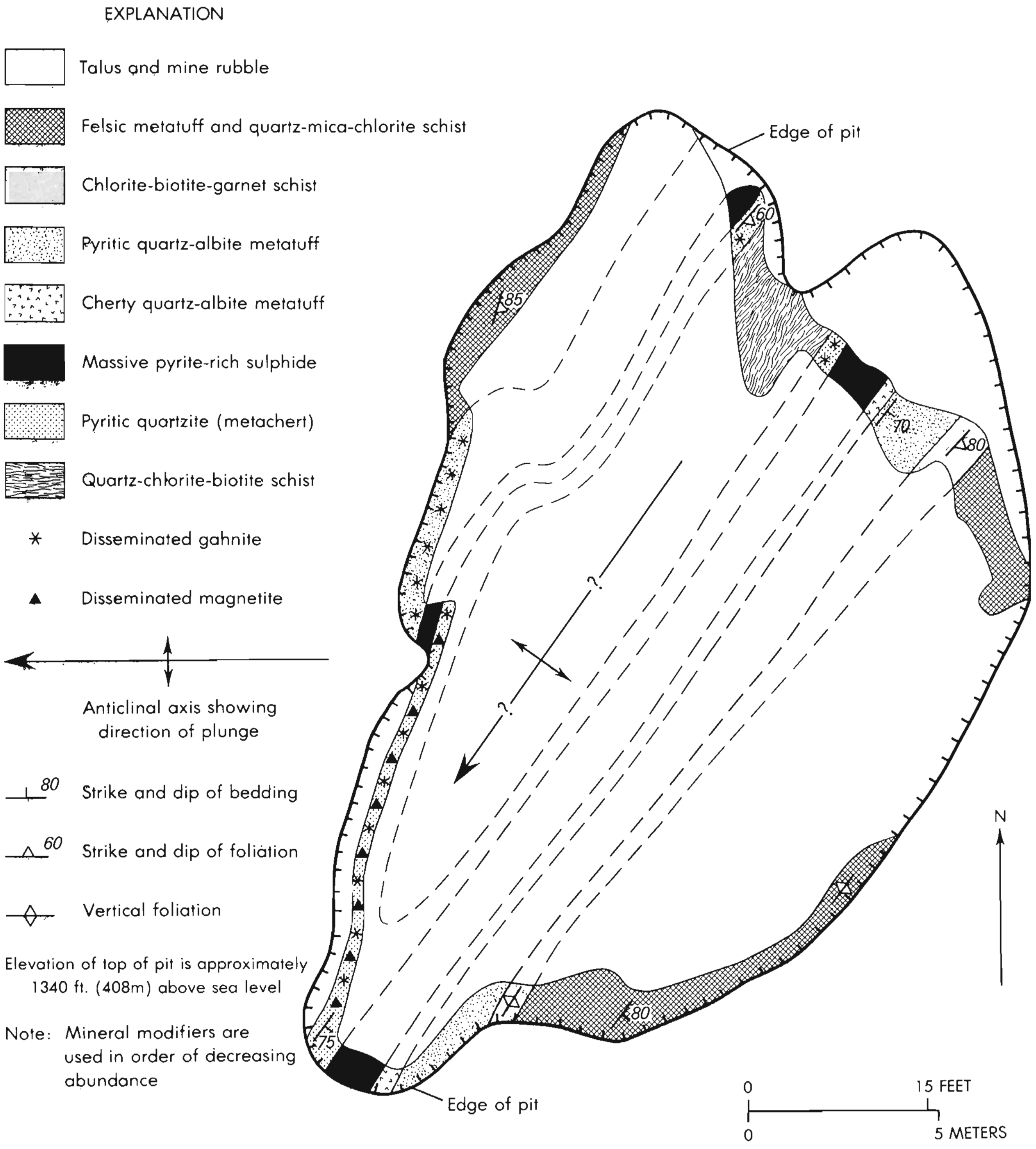
The wall rocks hosting the deposit are mainly silicic in composition. In the open pit and in drill core, mafic rocks (greenstone, amphibolite) are rare. Felsic rocks predominate and consist of rhyolitic metatuff, metamorphosed quartz-rich chemical sediments, and micaceous volcaniclastic metasediments. Rocks exposed in the eastern part of the pit contain local concentrations of Ba, Mn, and Pb (J. F. Slack and R. L. Graves, unpub. data) and are interpreted as the stratigraphic hangingwall of the deposit. The stratigraphically lowest unit of the hangingwall sequence is a distinctive white to pale-gray cherty rock forming thin (1-3 cm) layers intercalated with seams of granular pyrite. This rock consists of subhedral to euhedral crystals of plagioclase set in a fine-grained groundmass of granoblastic quartz and albite. It contains large amounts of silica (72 wt % SiO_2) and sodium (7.1 wt % Na_2O) and is believed to be a keratophyric metatuff. Overlying this unit is an assemblage of muscovite-rich felsic rocks containing small (<1 cm) lithic fragments and abundant disseminated pyrite; these also appear to be metatuffs. A distinctive dark-green mafic unit less than 1 m thick overlying these tuffaceous rocks is composed of abundant coarse chlorite and only minor biotite and garnet, and is believed to have originated as a chemical sediment. Rocks exposed along the extreme eastern edge of the pit are interlayered felsic metatuffs and micaceous (biotite-rich) volcaniclastic metasediments.

The footwall rocks are exposed in places along the western and northern parts of the pit and are dominantly metamorphosed chemical and volcaniclastic sediments. Immediately underlying the massive sulphides is a gahnite-rich quartzite containing sparse muscovite, plagioclase, and local concentrations of magnetite (Fig. 4). In places, this unit contains 10 to 30 percent coarse disseminated magnetite and gahnite; possibly related are thin (<5 cm) intervals of fine-grained magnetite iron formation observed in drill core and in Davis Mine Creek to the north. These gahnite- and magnetite-rich rocks are interpreted as metamorphosed exhalative chemical sediments (metacherts). An underlying unit, exposed in the core of a fold along the north wall, is a quartz-chlorite-biotite schist containing local spots of ankerite(?). The mineralogy of this rock suggests that it is probably a volcaniclastic sediment.

ORE MINERALOGY AND GEOCHEMISTRY

The mineralogy of the Davis mine has been described briefly by Quinn (1943) and in detail by Bwerinofa (1972). The principal sulphides are pyrite, chalcopyrite, and sphalerite. Pyrite is by far the most abundant, characteristically forming granular masses of discrete euhedral crystals or crystal aggregates. Chalcopyrite and sphalerite occur most commonly as interstitial fillings between grains of pyrite. Pyrrhotite is volumetrically minor, intergrown with chalcopyrite and rimming pyrite; in places it is altered to marcasite. Galena is rare and generally is only visible under the microscope. Sections of massive sulphide from the open pit, from drill core, and from underground (Harvard collection) have been studied microscopically and additionally show thin lamellae of cubanite in some coarse chalcopyrite ore, and traces of Ag and Bi tellurides as inclusions in galena. Molybdenite, reported from the mine by Perry (1934) and Quinn (1943), has not been observed.

[1/] A large rock from the north wall containing a prominent anticlinal fold nose has recently (1982-1983) collapsed onto the floor of the pit.



Tape and compass map by
J. F. Slack and R. L. Graves, 1980

Figure 4. Geologic map of the Davis mine pit.

TABLE 1.--TRACE ELEMENT CONTENTS (IN PPM) OF SULPHIDE-RICH ROCKS FROM THE DAVIS MINE, MASSACHUSETTS

[Semiquantitative spectrographic analyses* by J. L. Harris, U.S. Geological Survey. Quantitative atomic absorption analyses for Au, Hg, Se, and Te by Roosevelt Moore, U.S. Geological Survey]

	1 JS-79-12	2 RG-80-6	3 RG-80-26	4 RG-80-48	5 Mass-81	6 Mass-81a	7 Mass-88	8 Mass-96
†Ag (0.1)	68	9.6	4.2	25	350	35	35	5.6
As (150)	---	180	---	260	---	---	---	---
Au (.05)	---	---	---	---	0.8	---	---	---
Ba (2.2)	670	790	59	10	1200	780	20	26
Bi (10)	53	19	---	70	---	19	---	---
Cd (32)	180	---	---	37	240	---	240	---
Ce (43)	---	---	---	74	43	---	---	---
Co (1.0)	95	8.7	1.0	160	---	34	29	130
Cr (1.0)	4.5	1.8	1.8	2.7	2.2	3.4	3.2	3.9
Ga (1.5)	13	16	8.9	10	13	15	14	13
Hg (.05)	0.15	¶ ND	ND	ND	1.8	1.7	1.5	1.4
La (10)	---	---	---	22	17	---	---	---
Mn (1.0)	250	52	650	760	1300	46	1300	140
Mo (1.0)	18	---	7.4	---	---	---	34	8.8
Nb (6.8)	6.0	---	6.9	5.3	---	---	4.1	9.0
Ni (1.5)	20	3.0	3.4	---	6.5	2.8	4.3	4.7
Pb (6.8)	810	220	37	120	81	150	42	85
Sc (1.0)	---	10	4.7	2.6	3.9	5.2	---	3.2
Se (.01)	17	ND	ND	ND	19	5.3	3.3	25
Sn (1.5)	§ H	---	---	---	100	H	H	H
Sr (1.0)	9.8	12	---	---	17	---	11	---
Te (.01)	7.9	ND	ND	ND	52	14	5.0	11
V (1.5)	6.9	20	8.9	2.5	14	4.1	9.3	14
Y (1.5)	---	3.9	4.4	---	4.6	---	---	8.4
Yb (.15)	H	---	---	---	---	---	---	0.65
Zr (3.2)	50	69	24	100	14	130	---	---

* Reported values are determined by automated semiquantitative spectrographic methods (Dorrzapf, 1973) and have relative standard deviations for each reported concentration at +50% and -33%. Elements looked for but not found, and their lower limits of determination (in parentheses): B (6.8), Be (1.0), Dy (22), Er (4.6), Eu (2.2), Gd (15), Ge (4.6), Hf (15), Ho (6.8), In (6.8), Ir (15), Li (32), Lu (15), Nd (32), Os (22), Pd (1.0), Pr (68), Pt (4.6), Re (10), Rh (2.2), Ru (2.2), Sb (32), Sm (10), Ta (460), Tb (32), Th (22), Tl (4.6), Tm (4.6), U (320), W (10), Yb (0.15).

† Numbers in parentheses are detection limits (in ppm) for each respective element. Undetected elements are indicated by a dash (---).

§ H indicates an unresolved analytical interference.

¶ ND = not determined.

1 -- Channel sample across 1-m face of massive sulphide, north end of open pit (0.4% Cu, 3.8% Zn).
2 -- Gahnite-bearing pyritic quartzite (metachert) from footwall of massive sulphide, north end of open pit (0.1% Cu, 1.1% Zn).
3 -- Gahnite- and magnetite-rich pyritic quartzite (metachert) adjacent to massive sulphide, west side of open pit (<0.1% Cu, 2.6% Zn).
4 -- Chlorite-rich pyritic sulphide from drill core DDH-1, 62-m (203-ft) depth (0.9% Cu, 0.4% Zn).
5 -- Massive sphalerite and chalcopyrite in mica-chlorite schist from 16 level underground (3.0% Cu, 10.0% Zn).
6 -- Muscovite-rich granular pyritic sulphide from 16 level underground (1.0% Cu, 0.2% Zn).
7 -- Coarse granular pyritic massive sulphide from 16 level underground (1.5% Cu, 10.0% Zn).
8 -- Coarse granular pyritic massive sulphide from unknown underground location (0.7% Cu, <0.1% Zn).

The Davis mine is perhaps best known for its abundance of the zinc spinel, gahnite. Specialized studies of the Davis gahnite are reported by Dana (1885), Crosby and Brown (1887), Flint (1908), and recently by Spry and Scott (1983). The gahnite occurs both in massive sulphide and in the silicate wall rocks of the deposit. In hand specimen, it forms dark-green to bluish-green euhedral crystals as much as 1 cm in diameter. One underground sample from the Harvard University collection shows perfectly formed greenish-black octahedra of gahnite set in a matrix of quartz and minor sulphide. It is not ubiquitous, however, as many sections of the massive sulphide lack gahnite. It appears to be most common in sphalerite-rich ore and in a distinctive quartz-rich stratigraphic unit exposed in the open pit (Fig. 4). This unit also contains abundant pyrite and local concentrations of disseminated magnetite, the latter constituting 10 percent of the rock in places. The magnetite and gahnite are intergrown both in this rock, and, with sphalerite, in some of the massive sulphide. Chemical analyses of the gahnite from the mine show about 37 weight percent ZnO (Dana, 1885).

Sulphide-rich rock samples from the Davis mine were analyzed for 58 minor and trace elements by a combination of semiquantitative spectrographic and quantitative atomic-absorption methods (Table 1). The analyses indicate that the amounts of Cu and Zn vary significantly, even among samples of typical granular pyritic ore (nos. 1, 6, 7, 8). Zinc is also high in gahnite-rich rocks lacking sphalerite (nos. 2, 3); Pb is low (<0.1 %) in all samples. The geochemical data also show anomalous amounts of Ag, As, Bi, Cd, Co, and Te. The high levels of Ag in the samples of massive sulphide are generally in amounts equivalent to 1 or 2 oz/ton. Some of the Ag, and probably all of the Bi and Te, are contained in inclusions of tellurobismuthite, tetradymite, and volynskite (?) identified in the galena (microprobe analyses by P. J. Atelsek, U.S. Geological Survey). However, the amount of such Ag-bearing minerals in some samples seems insufficient to account for the high Ag values, suggesting that Ag may also be held in galena or other minerals. The As and Co concentrations are more difficult to explain because neither arsenopyrite nor cobaltite has been observed; these elements may be in solid solution in the pyrite. The Cd values correlate well with Zn grades, and probably are contained in the sphalerite.

GENESIS OF THE DEPOSIT

The massive sulphide deposits of the Davis mine are believed to have formed contemporaneously with their enclosing host rocks and prior to deformation and regional metamorphism. The ores, although folded and metamorphosed, maintain a true stratiform character. The deposits are thus not veins, but rather layers or beds of sulphide. An understanding of the genesis of the ores is therefore dependent on an understanding of the genesis of the country rocks.

The sulphide deposits are intimately related to explosive volcanic activity. The deposits are contained in the lower part of the Ordovician Hawley Formation, in a sequence of rhyolitic and basaltic agglomerates and tuffs mixed with minor volcaniclastic sediments. This sequence of rocks contrasts with an underlying mafic volcanic unit composed of basaltic lavas (locally pillowed) and tuffs. In detail, the Davis sulphides are closely associated with felsic (keratophyric) tuffs and with minor chemical sediments, and appear to mark the transition from dominantly mafic to dominantly felsic volcanism in the Hawley Formation. The Hawks (Mt. Peak) deposit to the south (Figs. 2, 3) occurs at a higher stratigraphic level, and may be related to a younger cycle of pyroclastic volcanism.

The conformable nature of the deposits and their intimate association with fragmental volcanic rocks suggest a syngenetic origin involving submarine fumaroles or hot springs. This is in essence a volcanogenic model, in which the ores and volcanic rocks are viewed as related products of the same geologic processes. In the Charlemont-Heath area, massive sulphides may be interpreted as one end member in a spectrum of chemical sediments that include gahnite-rich quartzite, iron formation, and coticule. These unusual rocks are believed to have originated as Zn-, Fe-, and Mn-rich hydrothermal cherts, respectively. The association of gahnite-rich quartzite and iron formation with the Davis ores suggests that the occurrence of such lithologies elsewhere in the Hawley mineral belt (Fig. 2) is of exploration significance. The massive sulphide and iron formation recognized at the Betts manganese mine (Hickmott et al., 1983) is equally important and suggests the possibility that the Betts ores are a distal time-stratigraphic facies of the Hawks or Davis deposits. A more thorough study of the Hawley Formation is needed to answer such questions, as well as to provide the framework for further mineral investigations.

ACKNOWLEDGMENTS

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MINERALOGY, PETROLOGY, AND GENESIS OF THE MANGANESE ORES OF THE BETTS MINE, HAMPSHIRE COUNTY, MASSACHUSETTS

Donald D. Hickmott
Department of Earth and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

John F. Slack
U.S. Geological Survey
954 National Center
Reston, Virginia 22092

Janet A. Docka
Department of Geological Sciences
Harvard University
Cambridge, Massachusetts 02138

INTRODUCTION

The Betts mine near Plainfield, Massachusetts, developed the southernmost ore deposit in the Hawley mineral belt. The Betts deposit forms a stratabound manganese-rich zone within metasedimentary and metavolcanic rocks of Ordovician age. Deformation and metamorphism have concentrated and recrystallized the ores into an amphibolite-grade assemblage of Mn-carbonates and Mn-silicates. The principal manganese minerals are rhodochrosite, kutnahorite, rhodonite, tephroite, and sonolite. The chief gangue mineral is quartz. Associated with the ores are lenses and layers of pyrrhotite-rich massive sulphide and magnetite(-jacobsite) iron formation. The Betts deposit shares geologic and geochemical features with many stratiform sulphide ores of the world, and thus suggests a potential for nearby base-metal sulphide deposits.

MINING HISTORY

Mining at the Betts deposit began in 1848 and continued sporadically throughout the 19th century, both for low-grade manganese carbonate ore and as a source of gem rhodonite. Kunz (1890, p. 153) claimed that the Plainfield rhodonite was "equal in quality and beauty to the Russian rhodonite." After being dormant for many years, the mine reopened in 1925, with production peaking between 1939 and 1941 (Quinn, 1945). The mine was worked in two small open pits which had a maximum depth of 11 m (Mosier and Thomas, 1949). Total production is estimated at 10,000 to 12,000 tons of ore which averaged 20-25 percent manganese (Quinn, 1945). Production ceased in 1943, as open-pit mining became difficult and demand for manganese decreased.

PREVIOUS STUDIES

Manganese was first described in western Massachusetts by Hitchcock (1825), who reported an occurrence of manganese minerals in glacial boulders from the area. The Betts deposit was briefly noted by several other workers in the 19th century (Nash, 1827; Kunz, 1890). The most thorough early description and geologic interpretation was presented by Emerson (1898). Emerson examined the Betts ore zone, two smaller deposits to the north in Plainfield, and the boulders reported by Hitchcock. He observed (p. 171) that a line between the boulders and the Betts mine "has the direction of the glacial striae of the region," and concluded that all of the rhodonite occurrences had originated in Plainfield. Emerson (1898) believed that both the Betts deposit and the iron deposits at the Hawley mine to the north formed hydrothermally in association with a large fault. Brashears (1933) and Perry (1934) each briefly described the mineralogy of the Betts mine, but offered no alternative to Emerson's theory of hydrothermal ore genesis.

Quinn (1945) studied the geology of the Betts mine in conjunction with a strategic minerals exploration project during World War II. He found no evidence for the existence of Emerson's fault, but continued to favour a high-temperature hydrothermal origin for the deposit. Quinn (1945) hypothesized that the manganese minerals had precipitated hydrothermally, replacing quartzite in the noses of drag folds. In conjunction with the work of Quinn (1945), Mosier and Thomas (1949) and Scharon et al. (1945) described, respectively, the results of diamond drilling and magnetic surveys at the mine. Franks (1953) studied the mineralogy and mapped mineral distributions, and also concluded that the deposit formed by hydrothermal replacement of quartzite. Hatch (1969) briefly examined the Betts deposit during bedrock mapping of the area, and on the basis of comparisons with the surrounding coticule rocks, first suggested that it was not a hydrothermal deposit but rather a metamorphosed sedimentary manganese bed.

Specialized mineralogical studies of the Betts mine have focussed on both the secondary oxide minerals and on the primary silicates and carbonates. The oxide minerals have been examined by Frondel et al. (1960) and by Kim (1980). Dunn (1976) analyzed a suite of rhodonites from the ore zone. Most recently, Hickmott (1982, 1983) investigated the mineralogy and metamorphic petrology of the deposit and demonstrated that the manganese ores are sedimentary accumulations metamorphosed to the amphibolite facies.

REGIONAL GEOLOGIC SETTING

The Betts mine is located within the Ordovician Hawley Formation, one of a sequence of metamorphosed lower Paleozoic units on the east flank of the Berkshire massif in western Massachusetts (Fig. 1). This sequence consists of multiply deformed and polymetamorphosed eugeosynclinal shale, greywecke, and volcanic rocks. The oldest unit in this sequence is the Hoosac Formation, an aluminous metapelite deposited

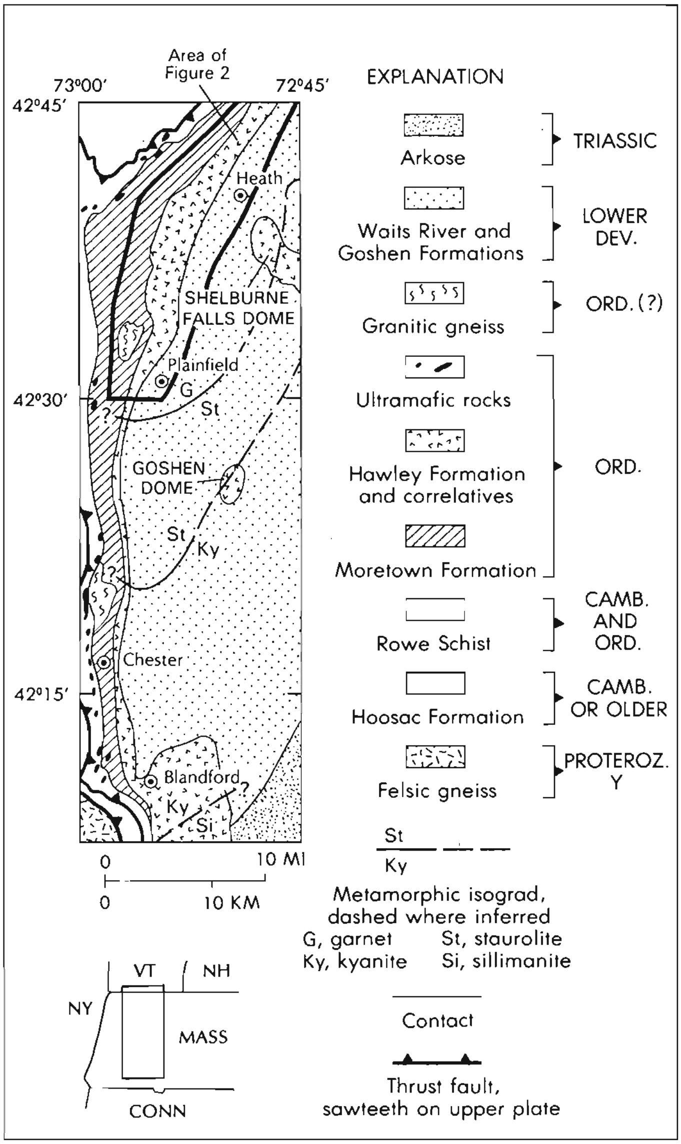

Figure 1. Generalized geologic map of the east flank of the Berkshire massif (modified from Hatch, 1975; and Zen et al., 1983).

on Grenvillian basement during late Proterozoic or Early Cambrian time. The overlying units, the Rowe Schist, the Moretown Formation, and the Hawley Formation, are accumulations of metasedimentary and metavolcanic rocks deposited on oceanic crust during the Cambrian and Ordovician (Hatch, 1967). These three units consist of beds and lenses of quartz-feldspar granofels, felsic schist and gneiss, amphibolite, and carbonaceous and noncarbonaceous metapelite. Serpentinites and talc schists contained locally in the Rowe Schist (Fig. 1) are believed to be metamorphosed ultramafic rocks derived from remnants of obducted oceanic crust.

The largest proportion of volcanic rocks is found within the Hawley Formation. The volcanic rocks include greenstone, amphibolite, and various felsic schists and gneisses. Hatch (1967) and Hatch et al. (1967) describe outcrops of metamorphosed pillow lava and fragmental textures within the Hawley Formation to the north of the Betts mine. Recent studies in the Charlemont-Heath area by Slack et al. (1983) have identified additional primary volcanic features such as rhyolitic and basaltic agglomerates and andesitic crystal tuffs. The Moretown and Hawley Formations also contain many thin layers and lenses of coticule rocks (Renard, 1878; Emerson, 1898) composed of fine-grained spessartine garnet, quartz, and minor magnetite and cummingtonite-grunerite. Most of these coticule rocks occur in dominantly metasedimentary portions of the upper Moretown Formation and in carbonaceous metapelites within the Hawley Formation (Hatch, 1969).

Hatch (1975) has established a detailed geologic history for the region that includes at least four separate deformational events and three episodes of metamorphism, with a maximum of garnet-grade metamorphism developed near the Betts mine (Fig. 1). Hatch (1975) suggested a single deformational and metamorphic event in the Ordovician Taconic orogeny, and three deformations accompanied by two metamorphic events during the Devonian Acadian orogeny. The area around the Betts mine has not been seriously affected by post-Acadian tectonism.

THE HAWLEY MINERAL BELT

The Hawley mineral belt (Perry, 1934; Quinn, 1967) is noteworthy in containing a variety of stratabound (and commonly stratiform) mineral deposits. The deposits occur within Ordovician metavolcanic and metasedimentary rocks, both in the Hawley Formation and in the underlying Moretown Formation (Fig. 2). In terms of past production, the most important deposits are the massive pyritic sulphides in the northern part of the belt. The largest sulphide deposit was developed at the Davis mine (Slack et al., 1983); smaller deposits occur to the west at the Mary Louise mine and to the south at the Hawks (Mt. Peak) mine (Quinn, 1943). Iron deposits are present at the Hawley mine and associated prospects southwest of Charlemont, and also at a small prospect northwest of Charlemont. Manganese deposits occur mainly in the southern part of the mineral belt near Plainfield, the largest having been developed at the Betts mine.

The iron deposits consist of concordant, stratiform lenses of magnetite or hematite iron formation. The largest deposit, at the Hawley mine near Forge Hill, has been described by Emerson (1898) and Perry (1934). The Hawley deposit forms a 1-m-thick lens of massive specular hematite, magnetite, barite, quartz, and coticule; no sulphides are present. The hematite occurs in a foliated, micaceous layer as much as 0.3 m thick. At depth, the deposit is apparently dominated by magnetite intercalated with quartz and coticule. Fragments of coarsely crystalline layered barite 5 cm thick found on the mine dumps (by JFS) presumably form part of the deposit as well. Fluorite has also been reported from an iron prospect about 1 km south of the Hawley mine by Emerson (1898).

The conformable nature of the deposits of the mineral belt and their relationship to stratigraphy (Fig. 2) imply that they formed contemporaneously with their enclosing host rocks, and prior to deformation and regional metamorphism. Previously, Emerson (1898) and Quinn (1967) interpreted the deposits as fissure veins of hydrothermal origin. However, the

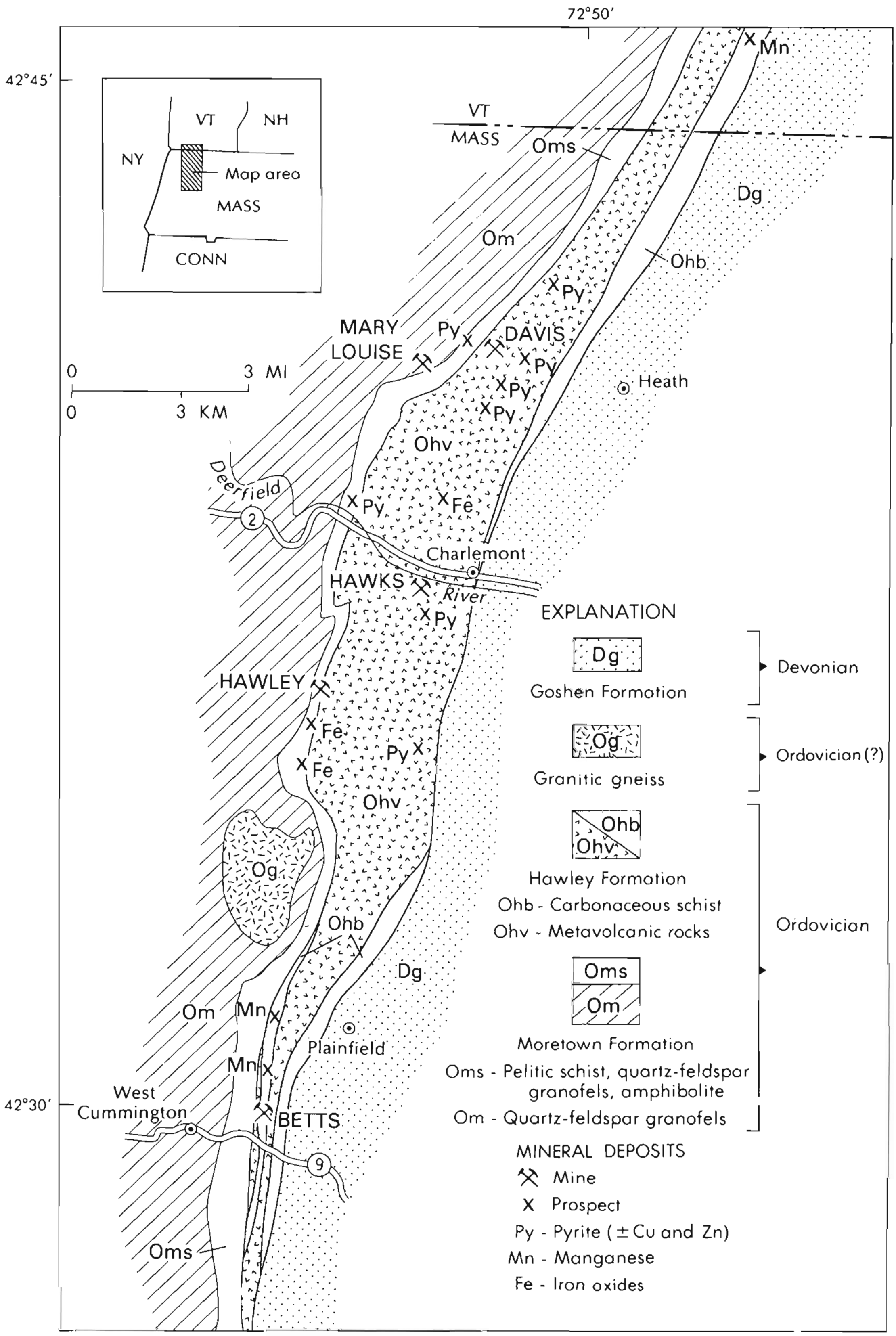

Figure 2. Geologic map showing stratabound mineral deposits of the Hawley mineral belt. Compiled from Emerson (1898), Quinn (1943, 1967), Hatch (1969), Hatch and Hartshorn (1968), Osberg et al. (1971), Chidester et al. (1967), and Zen et al. (1983).

deposits are not true veins, and are, for the most part, concordant with bedding. The processes that formed the surrounding country rocks must be broadly related to the processes that formed the contained mineral deposits. The detailed geology of individual deposits, described below for the Betts mine, must therefore be considered in any assessment of the genesis of the ores.

GEOLOGY OF THE MINE AREA [1]

The Betts mine occurs within a dominantly carbonaceous metasedimentary unit of the Hawley Formation (Fig. 2). Regionally, this unit consists of carbonaceous quartz-muscovite-biotite-garnet-chlorite phyllite and fine-grained carbonaceous quartzite interbedded with minor amounts of feldspathic schist and thin bands of amphibolite (Hatch, 1969; Osberg et al., 1971). In the vicinity of the ore zone, the rocks have been divided into four subunits (Fig. 3), each of which has a characteristic bedding style, grain size, and mineralogy. From west to east, these subunits are:1) a medium-grained plagioclase-biotite-muscovite-quartz-garnet-(chlorite) felsic schist containing thin layers of interbedded quartzite and amphibolite, as well as significant amounts of accessory pyrite; 2) the ore-bearing quartzite, a highly fractured unit containing lenses, pods, and stringers of quartz, Mn-carbonates, Mn-silicates, magnetic oxides, and massive sulphide; 3) a thick-bedded, medium-grained plagioclase-hornblende-biotite amphibolite; and 4) a medium-grained, fissile, carbonaceous plagioclase - muscovite-biotite - garnet schist. Assuming a general younging direction to the east (Hatch, 1969), the felsic schist would occupy the stratigraphic footwall of the ore zone, and the amphibolite and carbonaceous schist successive portions of the hangingwall.

Scharon et al. (1945) conducted a ground magnetic survey around the Betts mine and identified large magnetic anomalies. The anomalies are produced by the magnetic spinels (magnetite-jacobsite) associated with the manganese ores, occurring both as disseminations and as layers and lenses of granular iron formation. The magnetic map (Fig. 4) reveals two areas of intense magnetic response. One of these corresponds to the south pit, whereas the second (to the southwest) may represent a concentration of manganese minerals presently covered by glacial debris. This map also reveals a strong correlation between elongate magnetic highs and the northeast-trending regional schistosity, suggesting conformity of the ores to the surrounding metamorphosed strata.

All of the rocks of the mine area have undergone at least two phases of deformation and two periods of metamorphism. The predominant foliation trends N10E-N20E, parallel to the regional schistosity (Hatch, 1969). This foliation is locally overprinted by a later deformation manifested as small-scale crenulation folds and as large-scale drag folds. The manganese ores appear to be concentrated by this secondary deformation, as a distinct change in the attitude of the primary schistosity is visible around the south pit (Fig. 3). The precise structure of the ore zone is unknown because most of the surface of the deposit is now coated with ubiquitous manganese oxides. Some insight into the structure is provided by the early work of Franks (1953), who mapped the ore and wall rocks in the south pit. His map pattern shows a series of tight, isoclinal structures in which the ore occurs in the cores of folds; the limbs are composed of successive layers of quartz-garnet, sulphide, and a schist-quartzite transition zone (Franks, 1953, Fig. 2). Although the iron formation was not separately shown, the map of Franks does clearly illustrate the stratabound nature of both the manganese ores and the massive sulphides.

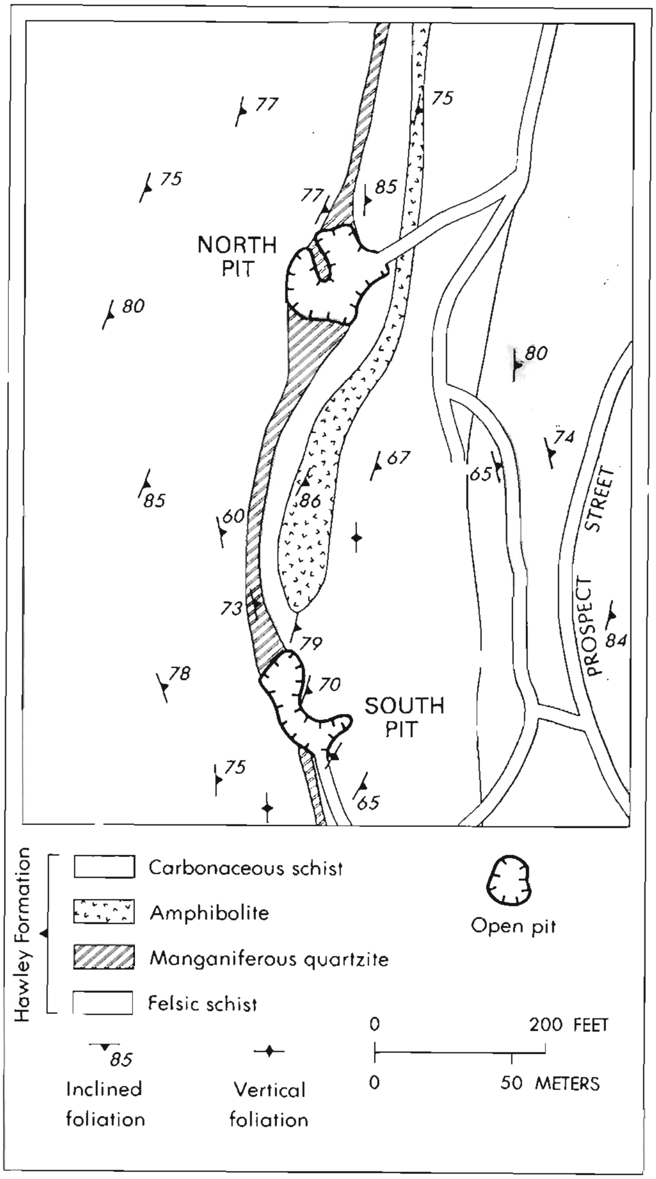

Figure 3. Geology of the Betts mine area (after Hickmott, 1982).

MINERALOGY

The principal manganese minerals in the ore zone are rhodochrosite, kutnahorite, rhodonite, tephroite, sonolite, and spessartine (Table 1). The chief gangue

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[1] Note: Mineral modifiers are used in order of decreasing abundance.

TABLE 1.--MINERALOGY OF THE BETTS MANGANESE MINE, MASSACHUSETTS

Mineral	Ideal Formula	Relative Abundance*	First Recognition	Identification Method†	Comments
Quartz	SiO_2	M	Emerson	M, O	Principal gangue mineral.
Rhodochrosite	$MnCO_3$	M	Emerson	M, X, O	Most abundant ore mineral.
Rhodonite	$MnSiO_3$	C	Emerson	M, X, O	With carbonate and tephroite.
Tephroite	Mn_2SiO_4	C	Brashears	M, O	With carbonates, sonolite, rhodonite.
Spessartine	$Mn_3Al_2(SiO_4)_3$	C	Emerson	O, M	Common in veinlets cutting ore.
Sonolite	$Mn_9(SiO_4)_4(OH)_2$	C	Hickmott	M, X, O	Typically fluorine-rich.
Kutnahorite	$Ca(Mn,Mg,Fe)(CO_3)_2$	C	Dunn	M, X, O	Ordering may be retrograde.
Magnetite	Fe_3O_4	C	Emerson	O, M	Abundant in layers of iron formation.
Pyrrhotite	$Fe_{1-x}S$	C	Quinn	O, M	Chiefly in lenses of massive sulphide.
Chalcopyrite	$CuFeS_2$	m	Quinn	O	A minor phase in massive sulphide.
Neotocite	$(Mn,Fe)SiO_3.nH_2O$	m	Quinn	M, O	Possibly altered from rhodonite.
Pyrite	FeS_2	m	Quinn	O, M	Chiefly in massive sulphide zones.
Caryopilite	$(Mn,Mg)_3Si_2O_5(OH)_4$	m	Hickmott	M, O	In veinlets altering tephroite.
Barite	$BaSO_4$	m	Quinn	M, O	Strontium-rich (to 2 wt% SrO).
Apatite	$Ca_5(PO_4)_3(OH,F,Cl)$	m	Hickmott	M, O	Disseminated in carbonate (F-rich).
Muscovite	$KAl_2Si_3O_{10}(OH)_2$	m	Quinn	O	With quartz & spessartine in veinlets
Chlorite	$(Mg,Fe)_{12}(Si,Al)_8O_{20}(OH)_6$	m	Quinn	O	With quartz & spessartine in veinlets
Cobaltite	$CoAsS$	tr	Slack	M, O	In massive sulphide (Ni-rich).
Sphalerite	$(Zn,Fe)S$	tr	Slack	M, O	Traces in massive sulphide.
Marcasite	FeS_2	tr	Slack	O	An alteration product of pyrrhotite.
Jacobsite	$MnFe_2O_4$	tr	Docka	M	Occurs in iron formation.
Molybdenite	MoS_2	tr	Quinn	O, M	Found with quartz & spessartine.
Galena	PbS	tr	Dunn	O	Unconfirmed species.
Arsenopyrite	$FeAsS$	tr	Quinn	O, M	Occurs in carbonate-rich ore.
Ilmenite	$FeTiO_3$	tr	Quinn	O, M	Contains significant Mn.
Rutile	TiO_2	tr	Quinn	O	Unconfirmed species.
Calcite	$CaCO_3$	tr	Quinn	O	Possibly misidentified kutnahorite.
Cummingtonite	$(Mg,Fe)_7Si_8O_{22}(OH)_2$	tr	Quinn	O, M	Occurs with quartz & spessartine.
Fluorite	CaF_2	tr	Docka	M, O	Occurs in rhodochrosite-rich rocks.
Alabandite	MnS	tr	Docka	M, O	Implies low fO_2, high fS_2.
Pyrophanite	$MnTiO_3$	tr	Docka	M, O	Possibly misidentified ilmenite.
Schallerite	$(Mn,Fe)_8Si_6As(O,OH)_{26}$	tr	Docka	M, O	Primary texture implies high fO_2.
Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	tr	Quinn	O	In nearby amphibolites.
Biotite	$K(Mg,Fe)_3(Al,Fe)Si_3O_{10}(OH)_2$	tr	Quinn	O	In associated pelitic rocks (Ba-rich).
Chloritoid	$(Fe,Mg)_2Al_4Si_2O_{10}(OH)_4$	tr	Quinn	O	Possibly misidentified tourmaline.
Tourmaline	$NaFe_3Al_6Si_6O_{18}(BO_3)_3(OH,F)_4$	tr	Docka	O	Occurs in associated pelitic rocks.
Epidote	$Ca_2(Al,Fe)_3(SiO_4)_3OH$	tr	Quinn	O	In nearby amphibolites.
Alleghanyite	$Mn_5(SiO_4)_2(OH)_2$	tr	Quinn	O	Possibly misidentified sonolite.
Bementite	$Mn_8Si_6O_{15}(OH)_{10}$	tr	Quinn	O	Possibly misidentified caryopilite.
Pyrolusite	MnO_2	tr	Brashears	O	Probably misidentified species.
Psilomelane	$BaMn_9O_{16}(OH)_4$	tr	Brashears	O	Probably misidentified species.
Loellingite	$FeAs_2$	tr	Docka	M, O	Found with arsenopyrite & schallerite.
Huebnerite	$MnWO_4$	tr	Docka	M, O	Occurs in rhodochrosite-rich rocks.
Scheelite	$CaWO_4$	tr	Docka	M, O	Occurs in rhodochrosite-rich rocks.
Bafertisite	$Ba(Fe,Mn)_2TiSi_2O_7(OH,F)_2$	tr	Docka	M, O	Occurs in rhodochrosite-rich rocks.
Sarkinite	$Mn_2(AsO_4)(OH)$	tr	Docka	M, O	Tentative identification.
Cryptomelane	KMn_8O_{16}	tr	Frondel et al.	X	In black oxides coating the deposit.
Birnessite	$Na_4Mn_{14}O_{27}\cdot 9H_2O$	tr	Frondel et al.	X	In black oxides coating the deposit.
γMnO_2	MnO_2	tr	Frondel et al.	X	In black oxides coating the deposit.
Rancieite	$(Ca,Mn)Mn_4O_9\cdot 3H_2O$	tr	Kim	X	In black oxides coating the deposit.
Hematite	Fe_2O_3	tr	Quinn	O, M	In black oxides coating the deposit.
Limonite	$FeO(OH).nH_2O$	tr	Quinn	O	In black oxides coating the deposit.

* M = major; C = common; m = minor; tr = trace or rare.

† M = electron microprobe; O = optical; X = x-ray diffraction.

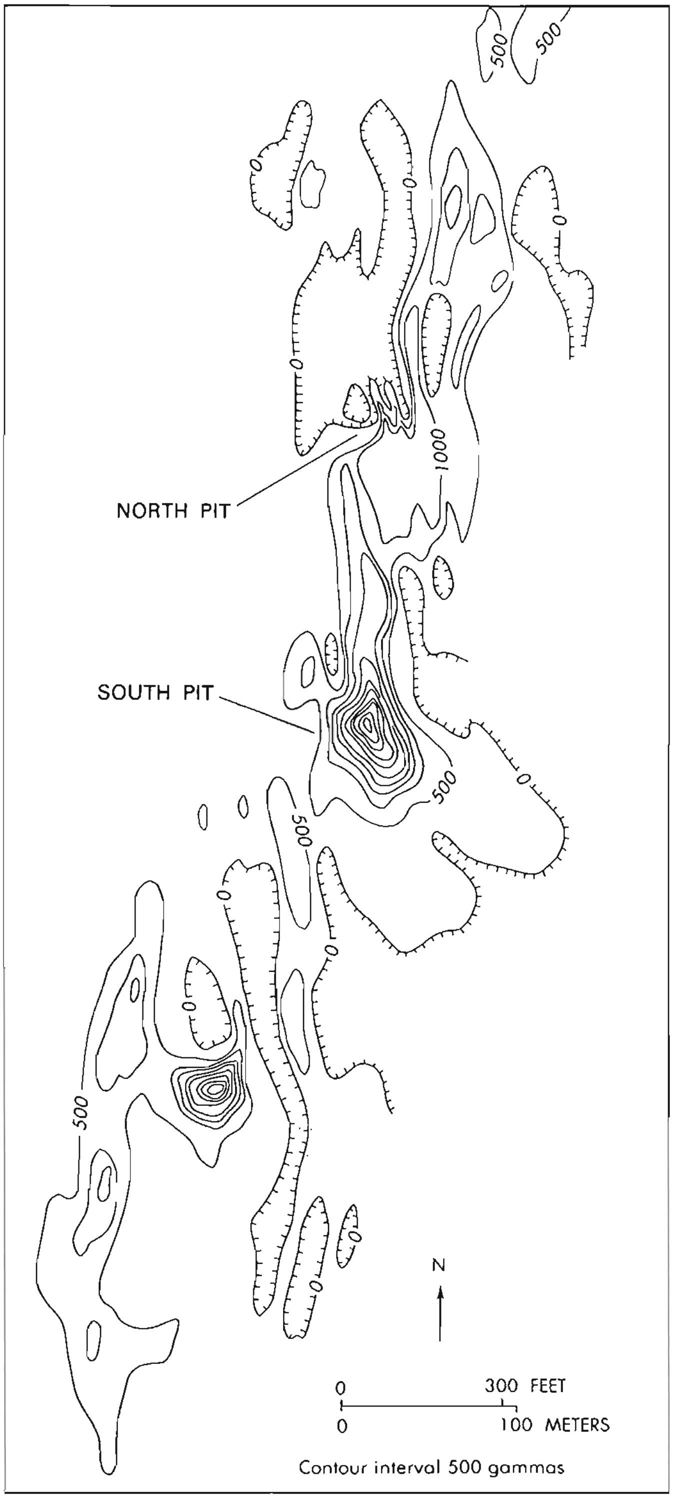

Figure 4. Ground magnetic map of the Betts mine area (modified from Scharon et al., 1945).

mineral is quartz. Several minor mineral species have also been discovered during recent petrographic, X-ray and electron microprobe investigations (Hickmott, 1982; J. A. Docka, unpub. data). Species reported for the deposit are summarized in Table 1. Brief descriptions of the more important minerals are presented below.

Quartz, the most common mineral in the ore zone, occurs both as medium-grained (1 mm) euhedral crystals and as fine-grained (<0.5 mm) anhedral grains. Macroscopically, these occurrences correspond, respectively, to vein quartz and to primary (premetamorphic) quartz. Quartz occurs with all of the major manganese minerals in the deposit except tephroite and sonolite.

Mn-carbonates constitute most of the primary ore and more than 75 percent of the manganese-bearing material in most thin sections. The carbonates display three distinct habits: 1) white to pink, coarse-grained (0.05-2.0 mm) irregular porphyroblasts; 2) round, equigranular, fine-grained (<0.1 mm) crystals, and 3) pink, fine-grained irregular grains. X-ray diffraction study gives evidence for two carbonate species, kutnahorite, which has an ordered (dolomite) structure, and rhodochrosite, which has a disordered (calcite) structure. The mineral habits do not individually distinguish the two carbonate species. Kutnahorite occurs only with quartz, rhodonite, and rhodochrosite, and is Ca-rich. In contrast, rhodochrosite is ubiquitous, occurring with virtually all of the reported minerals. The composition of the rhodochrosite varies across the $Ca(Mn)(CO_3)_2$-$MnCO_3$ solvus, and is dependent on the type and composition of coexisting minerals.

The other important manganese minerals in the deposit are tephroite, rhodonite, sonolite, jacobsite, and spessartine. Tephroite probably is the most common manganese silicate, forming very fine-grained (<0.05 mm) rounded equigranular porphyroblasts disseminated in carbonate, or anhedral crystals associated with rhodonite, sonolite, or carbonate. Rhodonite occurs as medium-grained (0.05-1.5 mm) tabular, blocky crystals with tephroite and carbonate, as fine-grained (<0.1 mm) monomineralic aggregates, and as elongate, bladed, comb-textured crystals surrounding fine-grained rhodonite. The fine-grained rhodonite appears to have formed during an early, low-grade metamorphic event, and then to have recrystallized into comb-textured rhodonite during a peak metamorphic episode (Hickmott, 1982). Sonolite, the manganese analog of clinohumite (Table 1), occurs as fine-grained (0.02-0.05 mm) rounded crystals in association with tephroite and rhodochrosite; optically, it can only be distinguished from tephroite by its twinning. Sonolite from the Betts mine is noteworthy in containing significant substitution of fluorine into the hydroxyl sites of the crystal structure. Spessartine garnet is typically associated with vein quartz and carbonate, and less frequently with the other Mn-silicates. It generally is coarse grained (to 0.5 cm), particularly in recrystallized (?) quartz veins, although where associated with primary minerals it tends to be very fine grained (<0.02 mm). Jacobsite-magnetite solid-solution is the most common oxide mineral, coexisting with all the principal ore and gangue minerals in the deposit, and contains as much as 17 weight percent MnO by microprobe analysis (J. A. Docka, unpub. data).

Sulphide minerals occur in veinlets and as stratabound lenses in the ore zone. Much of the sulphide appears to have been remobilized during regional metamorphism. Pyrrhotite is the chief sulphide, typically coarse grained (to 3 mm) and altered along fractures to marcasite. Pyrite occurs both as very coarse cubes (0.5-1.0 cm) in quartzite (north pit), and as medium-grained subrounded inclusions (0.5-3 mm) in pyrrhotite-rich massive sulphide. Some massive sulphide also contains minor chalcopyrite and microscopic traces of sphalerite and cobaltite (Table 1).

GEOCHEMISTRY

Representative rock samples from the Betts mine were analyzed for 58 minor and trace elements by a combination of semiquantitative spectrographic and quantitative atomic absorption methods (Table 2). The geochemical data were obtained on 23 samples from drill core, outcrop, and mine dumps, and show anomalous amounts of Ag, As, Au, Ba, Co, Cu, Mo, Ni, P, Pb, Se, Sr, W, and Zn. The concentrations of these elements are considerably higher than those of normal sedimentary and volcanic rocks, and are believed to reflect the original concentrations in the manganese deposit.

Many of the high trace-element values are related to specific mineral species in the ores. Concentrations of base metals (Cu, Pb, Zn) are generally greater in samples of massive sulphide containing minor chalcopyrite and sphalerite (Table 1); trace amounts of cobaltite yield anomalous Co (ca 100 ppm). The sulphide-rich samples also contain high concentrations of Ag, Ni, and Se (Table 2). The Ni values are explained by Ni-rich cobaltite, which contains as much as 5 weight percent NiO by microprobe analysis. No discrete Ag or Se minerals have been identified, however.

Other enriched metals in the deposit include As, Au, Ba, P, Sr, and W. Although arsenopyrite has been reported by Quinn (1945), the high As values determined spectrographically (Table 2) are on sulphide-free samples consisting mainly of Mn-carbonates and Mn-silicates. The As in these samples resides chiefly in the mineral schallerite, a rare As-silicate, and possibly in sarkinite, a hydrous As-oxide (Table 1). Atomic-absorption data show trace amounts of Au in several samples, but no Au phases have been identified. Anomalous amounts of Ba and Sr are due mainly to fine-grained strontian barite intergrown with some of the carbonate- and silicate-rich ores; a newly recognized occurrence of bafertisite in Betts samples (Table 1) may also account for some of the Ba (Docka, 1983). The very high content of P (2500 ppm) in the quartz-spessartine vein (?) sample (no. 4) reflects the mineral apatite. The presence of unusual amounts of W in one of the samples is explained by occurrences of huebnerite and scheelite recently identified during microprobe studies. Anomalous concentrations of fluorine have also been discovered in the hydrous minerals from the deposit (Table 1), which appear to be a characteristic feature of many coticule rocks (J. F. Slack and J. A. Docka, unpub. data).

METAMORPHIC PETROLOGY

The mineral assemblages and mineral compositions in the ore zone and in the surrounding metapelites allow limits to be placed on temperature, pressure, and fluid compositions during metamorphism. The rhodochrosite-kutnahorite solvus has been used as a geothermometer in several studies of metamorphosed manganese deposits (Winter et al.,1981; Peters et al., 1978). The existence in the deposit of Mn-carbonates with compositions that span the experimental solvus of Capitani and Peters (1981) suggests peak temperatures of greater than 550° C (Hickmott, 1982). Application of the garnet-plagioclase-biotite-muscovite geobarometer of Ghent and Stout (1981) and the garnet-biotite geothermometer of Ferry and Spear (1978) to the surrounding pelites (D. D. Hickmott, unpub. data) yields pressure and temperature estimates, respectively, of approximately 8-9 kbars and 510° C. The lower temperature recorded by the pelitic assemblage, and the presence of the minerals kutnahorite, neotocite, and caryopilite (Table 1), may be due to retrograde metamorphism (Hickmott, 1982).

The sequence of prograde reactions in a given bed is dependent on the local fluid composition during metamorphism. The compositions of several analyzed assemblages from the Betts mine are plotted in the system $CaO-MnO-SiO_2$ in Figure 5. This topology is not consistent with isothermal and isobaric metamorphism at constant fluid composition because of the presence of crossed tie lines. The addition of CO_2 as a plotting component (Fig. 6) suggests that some of the crossed tie lines could be due to variation in $X(CO_2)$ within the deposit. The variation in fluid composition reflects either: 1) variations in the bulk composition of the sedimentary layers of the original protolith, or 2) differing permeabilities of sedimentary layers, allowing variable amounts of fluid infiltration in individual layers.

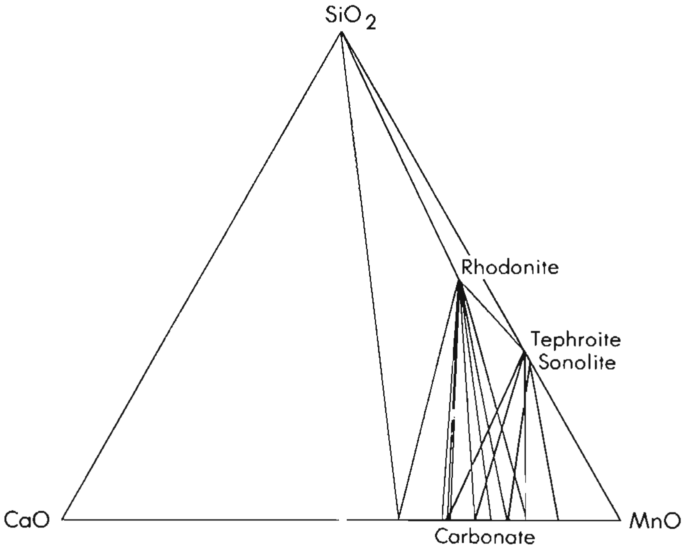

Figure 5. Ternary $MnO-CaO-SiO_2$ plot of electron microprobe analyses of manganese minerals from the Betts mine. Tie lines connect coexisting phases. From Hickmott (1982).

The mineral assemblages and mineral compositions in the deposit yield information about the fluid phase during metamorphism. The existence of the primary hydrous phase, sonolite, and the assemblage quartz-rhodonite-(Mn-carbonate) at >550°C and 9 kbar, and the occurrence of rhodonite as the primary pyroxenoid, together require the predominance of a water-rich fluid during the metamorphism of the deposit. The experimental work of Peters et al. (1973) and Maresch and Mottana (1976) and the extrapolation of these experiments to high pressure (e.g., Winter et al., 1981) implies that $X(CO_2)$ was <0.5 in the quartz-rhodonite-carbonate ore zones.

TABLE 2.--TRACE ELEMENT CONTENTS (IN PPM) OF ROCK SAMPLES FROM THE BETTS MANGANESE MINE, MASSACHUSETTS

[Semiquantitative spectrographic analyses[*] by J. L. Harris, C. J. Skeen, and B. A. Spillare, U.S. Geological Survey. Quantitative atomic absorption analyses for Au and Hg by Roosevelt Moore, and for Se and Te by Roosevelt Moore and William d'Angelo, U.S. Geological Survey]

	1 JS-81-50-1	2 JS-81-50-3	3 JS-81-50-4	4 JS-81-50-5	5 DDH-37A	6 DDH-46	7 HU-117905	8 HU-117906
[†]Ag (0.1)	3.8	---	6.5	0.36	---	---	---	---
As (150)	---	170	---	---	---	---	---	610
Au (.05)	---	0.13	---	0.28	0.14	---	0.38	0.09
B (6.8)	---	37	---	13	---	---	---	53
Ba (2.2)	23	1700	15	240	5100	140	91	81
Be (1.0)	---	---	---	---	1.2	---	---	---
Cd (32)	---	---	---	91	---	---	---	---
Co (1.0)	12	39	100	---	11	120	84	28
Cr (1.0)	3.0	---	5.4	2.3	60	77	10	1.6
Cu (1.0)	32	100	380	53	9.5	910	680	3.7
Ga (1.5)	17	---	11	---	---	15	29	---
Hg (.05)	0.05	0.09	0.06	0.08	0.14	0.10	0.08	0.32
Mo (1.0)	---	63	---	9.8	---	14	[§] H	---
Nb (6.8)	---	50	7	9.8	---	---	14	41
Ni (1.5)	20	---	58	---	46	110	140	130
P (700)	---	---	---	2500	---	---	---	---
Pb (6.8)	83	---	47	---	---	---	---	---
Sc (1.0)	---	1.9	16	2.4	1.5	5.9	6.3	4.0
Se (.01)	0.09	1.7	22.0	0.03	0.58	6.5	3.6	8.6
Sr (1.0)	240	290	200	160	2200	520	65	340
Te (.01)	0.02	1.1	0.02	0.48	---	0.8	3.8	0.41
V (1.5)	160	110	60	80	41	25	24	130
W (10)	H	300	H	H	H	H	H	H
Y (1.5)	---	1.8	36	---	---	3.9	19	9.7
Zn (10)	260	69	150	110	43	200	240	62
Zr (3.2)	290	---	320	580	12	33	4.9	22

[*] Reported values are determined by automated semiquantitative spectrographic methods (Dorrzapf, 1973) and have relative standard deviations for each reported concentration at +50% and -33%. Elements looked for but not found, and their lower limits of determination (in parentheses): Bi (10), Ce (43), Dy (22), Er (4.6), Eu (2.2), Gd (15), Ge (4.6), Hf (15), Ho (6.8), In (6.8), Ir (15), La (10), Li (32), Lu (15), Nd (32), Os (15), Pd (1.0), Pr (68), Pt (2.2), Re (10), Rh (2.2), Ru (2.2), Sb (68), Sm (10), Sn (4.6), Ta (320), Tb (32), Th (46), Tl (10), Tm (4.6), U (320), Yb (0.15).

[†] Numbers in parentheses are detection limits (in ppm) for each respective element. Undetected elements are indicated by a dash (---).

[§] H indicates an unresolved analytical interference.

1 -- Fine-grained magnetite(-jacobsite) iron formation (appx. 6% Mn), from dump of south pit.
2 -- Fine-grained granular carbonate-rich ore (appx. 38% Mn), from dump of south pit.
3 -- Coarse-grained pyrrhotite-rich coticule rock (appx. 6% Mn), from dump of south pit.
4 -- Coarse-grained (recrystallized) quartz-spessartine vein (?) ore (appx. 17% Mn), from dump of south pit.
5 -- Fine-grained mixed carbonate-silicate ore (appx. 18% Mn), from dump of south pit.
6 -- Massive fine-grained pyrrhotite with minor pyrite and chalcopyrite (appx. 5% Mn), from dump of south pit.
7 -- Massive fine-grained pyrrhotite with minor pyrite and chalcopyrite (appx. 3% Mn), from Harvard collection.
8 -- Fine-grained granular carbonate-rich ore (appx. 55% Mn), from Harvard collection.

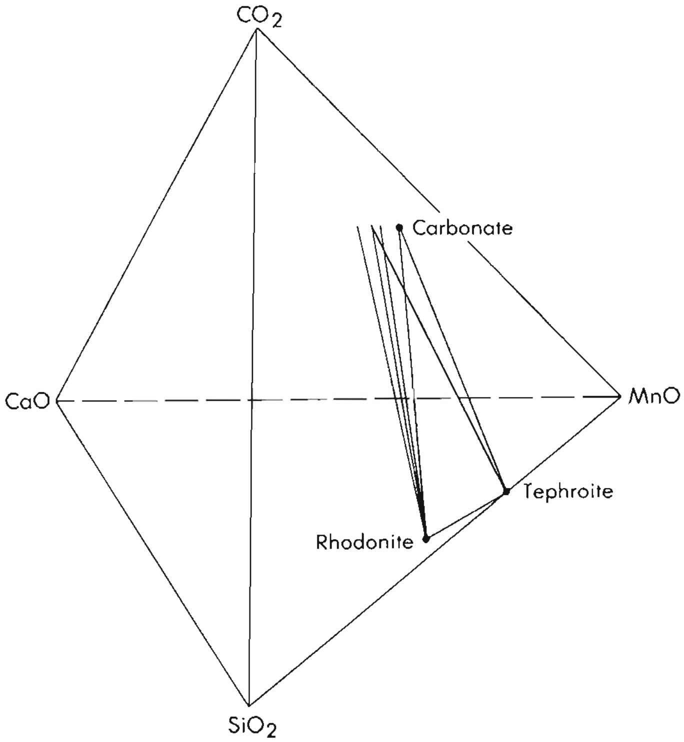

Figure 6. Quaternary MnO-CaO-SiO_2-CO_2 plot of electron microprobe analyses of the three-phase assemblage rhodonite-tephroite-carbonate, and the two-phase assemblage rhodonite-carbonate. Tie lines connect coexisting phases.

The most likely sequence of reactions up grade, based on recrystallization textures in rhodonite, estimates of fluid composition, and the experimental work of Peters (1973), is: 1) $MnCO_3 + SiO_2 = MnSiO_3 + CO_2$; 2) $MnSiO_3 + MnCO_3 = Mn_2SiO_4 + CO_2$; and, 3) $4Mn_2SiO_4 + (H_2O + F)$ [fluid] $+ MnCO_3 = Mn_9(SiO_4)_4(OH,F)_2 + CO_2$. These are all decarbonization reactions. Because the deposit was characterized by a water-rich fluid during metamorphism, we suggest that most of the CO_2 produced must have been diluted by infiltration of H_2O-rich fluids from the surrounding pelites.

GENESIS OF THE DEPOSIT

The Betts manganese deposit is comparable in some respects to the more widespread coticule rocks found throughout much of the Appalachian-Caledonian orogen. Any unified genetic model for the Betts ores and the coticules must consider both the similarities and differences between them. The similarities include: 1) a geologic setting in clastic marine sedimentary rocks and minor mafic volcanics (amphibolites); 2) a stratabound and generally stratiform character; 3) unusually high concentrations of manganese and silica; and 4) occurrence of anomalous amounts of Ba, Sr, P, and F. The principal differences include: 1) a wide lateral extent for many of the coticules, in contrast to the localized manganese concentrations at Betts, 2) the predominance of Mn-carbonates and rhodonite and tephroite at the mine, as opposed to spessartine in the coticules; 3) the lenses and layers of massive sulphide and iron formation at Betts; 4) the anomalous amounts of Ag, As, Au, Co, Cu, Mo, Ni, Pb, Se, W, and Zn at the mine; and 5) the significant variations in fluid compositions that existed in the deposit during metamorphism.

The stratabound nature of the coticules and the Betts ores suggests a volcanic origin as syngenetic Mn-rich chemical sediments. A relationship to volcanic processes is implied by the abundance of metavolcanic rocks throughout the area, especially in the Hawley Formation. Coticules are also present in the upper part of the Moretown Formation where amphibolites are common. The occurrence of coticules in the black carbonaceous schists of the Hawley Formation is not inconsistent with this model, however, because volcanism could have taken place concurrently at some distance from the depositional site of these coticules. A similar conclusion may be reached for Betts, which contains only minor metavolcanic rocks (amphibolites) in the stratigraphic hangingwall of the ores (Fig. 3).

The mineral assemblages and phase relations in the Betts ores and in the coticules do not appear to indicate the nature of the protoliths. Many authors have studied coticule-type rocks and have speculated that the original sediments were Mn-rich cherts (e.g., Schiller and Taylor, 1965). Other workers, noting the abundance of rhodochrosite in weakly metamorphosed coticules, have suggested protoliths of impure Mn-carbonates (de Dycker, 1939; Schreyer, 1975). Additional possible precursors include Mn-rich montmorillonites (Kramm, 1976), or manganiferous chamosites (Stanton, 1976; Stanton and Williams, 1978). Clearly, the abundance of carbonate minerals in the Betts ores requires that the primary sediment contain large amounts of carbonate. The phase relations, however, indicate that much of the CO_2 produced during metamorphism was lost to the surrounding country rocks. This has implications for the precursor sediments of some coticules, which could also have lost CO_2 by a series of metamorphic decarbonization reactions. One answer is probably not applicable to all metamorphosed manganiferous sediments, though, and it is possible that each of the above models is correct for different areas.

The coticule rocks and the Betts ores share some similar trace-element characteristics. Rocks from the Betts deposit contain anomalous concentrations of Ba, Sr, P, and F, caused by minor Sr-rich barite, apatite, and F-rich minerals in the ores (Table 1). These elements are also known to be present in high concentrations in coticules, such as those in New Hampshire (Clifford, 1960), Virginia (Gair and Slack, 1983), and in Massachusetts and Vermont (J. A. Docka, unpub. data). Mohr (1964) has in addition described anomalous Ba and Sr in rhodochrosite-rich coticule rocks from Wales. Concentrations of these elements appear to be typical of many manganiferous sediments and thus do not identify specific origins or sources.

Of more interest are the levels of transition elements and associated massive sulphide at Betts. Some samples from Betts (Table 2) show anomalous amounts of Ag, Au, Co, Cu, Mo, Ni, and W, as well as other metals such as Pb and Zn. A detailed comparison of these values with data for coticules is unfortunately not yet possible. However, the abundance levels of the elements in the Betts ores are clearly much higher than are found in normal sedimentary and volcanic rocks. Many of the elements, particularly Co, Cu, Ni, and Zn, are directly related to the occurrence of massive sulphide at the mine (Table 2). The massive sulphide is one of the most interesting features of all, because it is not known to occur with the other coticule beds of the area. By contrast, many major massive sulphide deposits of the world contain closely associated manganiferous sediments. Examples include coticules in the wall rocks of the Cu-Zn deposits of the Elizabeth mine, Vermont (Annis et al., 1983) and the pyrrhotite ores of the Gossan Lead district, Virginia (Gair and Slack, 1983); quartz-spessartine rocks at the Gamsberg and Aggeneys Zn-Pb-Ag-Cu deposits, South Africa (Moore, 1983); and garnet sandstones and garnet quartzites (coticules) in the Pb-Zn-Ag lodes at Broken Hill, Australia (Jones, 1968; Johnson and Klingner, 1975); Broken Hill is especially noted for its abundance of rhodonite, bustamite, and Mn-rich hedenbergite (Mason, 1973). Wagener (1980) has also described lenses of rhodonite-magnetite in the Cu-Zn ores at Prieska, South Africa.

The geologic and geochemical data presented above suggest that the coticules and the Betts ores formed from different primary fluids. Both are interpreted as syngenetic Mn-rich chemical sediments that accumulated at the sediment-sea water interface. The continuity and uniformity of the coticule beds is consistent with a model of precipitation distal from a volcanic and (or) hydrothermal source. The Betts ores in contrast contain other chemical sediments (massive sulphide, iron formation) believed to be more proximal to a source. The regional setting of the Betts mine in the Hawley mineral belt (Fig. 2) allows that the deposit may have formed contemporaneously with explosive volcanic activity to the north, in the Charlemont-Heath area (Slack et al., 1983). An intriguing possibility is that, unlike the coticules, the Betts ores may represent time-stratigraphic facies of one of the Cu-Zn sulphide deposits (Davis, Hawks) in that area. On this basis, it seems likely that the southern part of the Hawley mineral belt has a previously unrecognized potential for massive (base-metal) sulphide deposits.

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