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Tourmaline - A Prospecting Guide for Massive Base-Metal Sulfide Deposits in the Penobscot Bay Area, Maine

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TABLE OF CONTENTS

Illustrations

Table

ABSTRACT

In the Penobscot Bay area of coastal Maine, tourmaline is a common accessory mineral in granite plutons, in pegmatite and aplite dikes, and in Paleozoic metasedimentary rocks. Tourmaline is also found in some areas with stratabound base-metal sulfides. Anomalous concentrations of tourmaline in metasedimentary rocks and ores of the Penobscot Bay area are compared with similar occurrences in and around the large Sullivan Pb-Zn mine, British Columbia. Current theories on the origin of the Sullivan deposit are used as the basis for a formational model to explain the association of tourmaline-rich rocks with stratabound sulfides. The tourmalinized rocks at Sullivan are considered analogous to other types of alteration products characteristic of submarine hydrothermal systems, and thus may be effective guides to ore.

At the Black Hawk Cu-Zn mine, on the east side of Penobscot Bay, tourmaline occurs in close association with stratabound massive sulfides and in postore pegmatite and aplite dikes. The ore deposits at Black Hawk, hosted by quartzitic units of the lower Paleozoic(?) Ellsworth Schist, are interpreted as having formed mainly by syngenetic processes in a marine sedimentary environment. Tourmalines there form complex intergrowths with sulfide minerals, especially chalcopyrite and pyrrhotite, and also occur as disseminations and fracture fillings in altered wall rocks adjacent to ore. In contrast to the black Fe-rich schorls typical of the intrusive rocks, the non-granitic tourmalines are brown, red-brown, olive-green, or golden-yellow Mg-rich dravites. The distinctive textural and compositional features of the dravites at the Black Hawk deposit suggest that they represent an integral part of the Mg-rich alteration assemblage related to initial ore formation.

Occurrences of tourmaline throughout the Penobscot Bay area are evaluated for their exploration significance. Important parameters include the color and composition of the tourmaline, its coexisting mineral assemblage, and the presence or absence of accessory sulfides. An abundance of brown tourmaline (dravite) with Mg-rich silicates in a metasedimentary terrane is considered an especially favorable prospecting guide because this assemblage occurs in close association with the Cu-Zn ores at the Black Hawk mine. Similar tourmaline-bearing assemblages and a tourmaline-rich sulfide prospect identified within the Penobscot Formation suggest that the metasedimentary and metavolcanic rocks on the west side of Penobscot Bay may have as much potential for massive base-metal sulfide deposits as the productive terranes (Ellsworth Schist, Castine Volcanics) on the east side of the bay.

INTRODUCTION

Massive base-metal sulfide deposits are currently of economic interest because of their characteristic high grade and general ease of metallurgical treatment. They are mined principally for their contents of copper, zinc, and/or lead; silver and gold are recoverable from some deposits. Recent theories bearing on the origin of sratabound sulfides have stimulated new exploration in many parts of the United States, including the Appalachian Mountains, where a variety of such deposits is known (Kinkel, 1967; Gair and Slack, in press). The New England region is presently the focus of intense exploration activity following the discovery in 1977 of the very large (33 million metric ton) Bald Mountain copper-zinc deposit in northern Maine (Eng. & Mining Jour., 1979). Along the coast of Maine, the Penobscot Bay area contains two base-metal sulfide deposits 1/ of moderate size (1-2 million tons), as well as dozens of prospects and occurrences. At one of these deposits, developed by the Black Hawk mine, tourmaline is an accessory gangue mineral. This report describes tourmaline occurrences in the Penobscot Bay area, and proposes the use of tourmaline as a prospecting guide for massive base-metal sulfide deposits.

GEOLOGIC SETTING

The Penobscot Bay area, on the central Maine coast, is underlain by marine sedimentary and volcanic rocks and by a variety of igneous plutons, most of which are early to middle Paleozoic in age (fig. 1). The general geology of the coastal belt has been described by Smith and others (1907), Bastin (1908), McGregor (1964), Osberg and Guidotti (1974), Chapman (1974), Stewart (1974), Stewart and Wones (1974), and Bickel (1976). Recent geologic work has demonstrated that this coastal sequence can be distinguished from very different rocks in the Merrimack synclinorium of central Maine to the north (Ludman, 1976; Osberg, 1979). A major tectonic break separates these two geologic terranes along the northeast-striking Norumbega fault zone (Wones and Thompson, 1979). Other faults of regional significance, such as the Turtle Head fault, are roughly parallel to (and southeast of) the Norumbega fault within the coastal belt (Wones and Stewart, 1976). The rocks in the vicinity of Penobscot Bay locally contain Acado-Baltic or European fauna (Boucot and others, 1972) and are correlated by some workers with the Avalonian platform of eastern Newfoundland (Rast and others, 1976; Williams, 1978; Osberg and Skehan, 1979).

1/ Excluded from this discussion are the massive nickel-copper deposits within ultramafic rocks in Knox County, on the west side of Penobscot Bay (Houston, 1956; Rainville and Park, 1976).

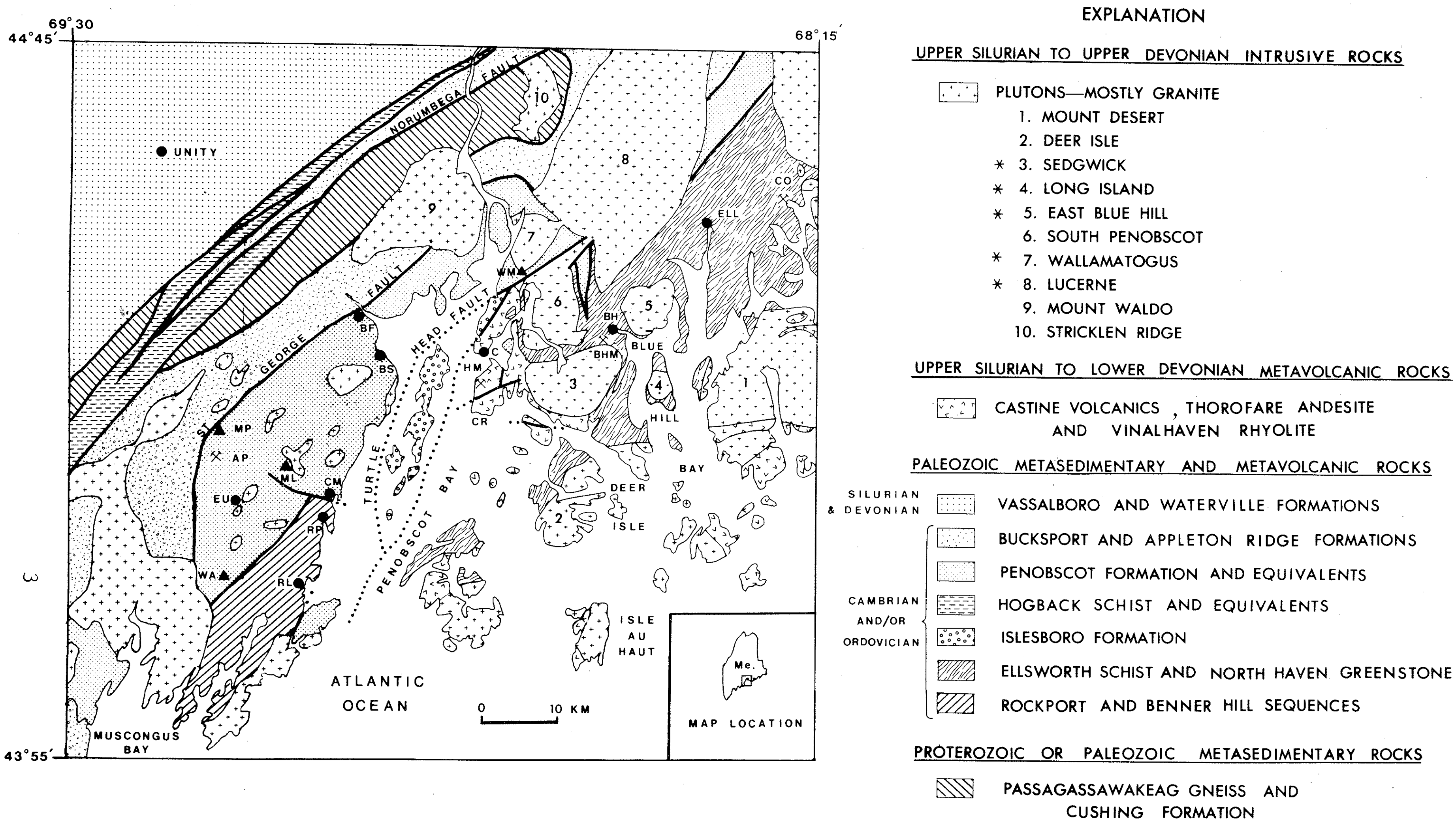

Figure 1.--Geologic map of the Penobscot Bay area, Maine, showing the location of tourmaline-bearing rocks. Granitic plutons containing tourmaline are marked by an asterisk (*) in the explanation. Non-plutonic tourmaline occurrences and other localities mentioned in the text are identified on the map by letter symbols: AP = Appleton prospect, BF = city of Belfast, BH = village of Blue Hill, BHM = Black Hawk (Blue Hill) mine (includes nearby Douglas mine and Stober prospect), BS = Bayside village, C = Castine village, CM = city of Camden, CO = Copperopolis (Custer) mine, CR = Cape Rosier, ELL = city of Ellsworth, EU = village of East Union, HM = Harborside (Penobscot) mine, ML = Megunticook Lake locality, MP = Mill Pond locality, RL = city of Rockland, RP = village of Rockport, WA = Warren locality, WM = Wallamatogus Mountain locality. Geology compiled from Bastin (1908), Bickel (1976), Chapman (1974), Hussey and others (1967), Osberg and Guidotti (1974), Smith and others (1907), and Stewart and Wones (1974). Areas containing Precambrian rocks on small islands within the Islesboro fault block (Stewart, 1974) are not shown. All faults shown are of high-angle type.

On the east side of Penobscot Bay, where the largest sulfide deposits occur, regionally metamorphosed sedimentary and volcanic rocks have been intruded by several granitic and gabbroic plutons (fig. 1). The ages of the igneous rocks are reasonably well established by isotope studies, but considerable controversy surrounds the age of the metasedimentary sequence (see Gates, 1969). Base-metal sulfide deposits are found in two principal stratigraphic units, the Ellsworth Schist and the Castine Volcanics. The age relationship between these two formations is critical, because it has a direct bearing on the genesis of the sulfide ores. The Ellsworth Schist, consisting of highly deformed ribbony quartz-chlorite-mica phyllite and minor quartzite and greenstone, has traditionally been assigned a Precambrian or early Paleozoic age (Smith and others, 1907; Wingard, 1961; Stewart, 1956); Brookins (1976) reported a Rb-Sr whole-rock isochron of 510 $\pm$ 15 m.y. (Late Cambrian) for samples of volcanic rock from the Ellsworth. The Castine Volcanics, composed mainly of basaltic and rhyolitic flows, tuffs, and agglomerates, is known to be Late Silurian to Early Devonian in age on the basis of concordant radiometric and paleontologic data (Brookins and others, 1973; Brookins, 1976).

Wingard (1958) and Stewart (1956) mapped a conglomerate at some contacts between the Ellsworth Schist and Castine Volcanics and interpreted this as an unconformity indicating a pre-Middle Silurian age for the Ellsworth, in agreement with the radiometric determination (see Brookins, 1976, for details). However, in a more recent study, Bouley (1978) argued that this conglomerate is actually a volcanic breccia, and that the multiple deformations characteristic of the Ellsworth Schist (and absent within the Castine Volcanics) were produced during sedimentary slumping, and not by pre-Castine tectonism. Bouley (1978) proposed that the dominantly metasedimentary Ellsworth Schist is a contemporaneous and distal eastern facies of a central volcanic edifice represented by the Castine Volcanics. The precise age of the Ellsworth Schist is unknown, but the weight of the evidence (Brookins, 1976) suggests that it is substantially older than, and therefore unrelated to, the Castine Volcanics.

The sequence of rocks on the west side of Penobscot Bay is more lithologically diverse and more strongly metamorphosed than that on the east side of the bay and contains a larger proportion of carbonate rocks and mature clastic sedimentary rocks. For the purposes of this report, the chief units of interest are the Penobscot Formation (and equivalents) and the Rockport and Benner Hill sequences southeast of the St. George fault (fig. 1). The Penobscot Formation is made up of micaceous phyllite, quartzite, andalusite or sillimanite schist and gneiss, and minor marble; many of these rocks are sulfidic and graphitic. The distinctive Gushee Member of the Penobscot Formation (of local usage) is composed largely of mafic rocks and contains relict structures (pillows, scoria) suggestive of a volcanic protolith (Bickel, 1976). The Megunticook sequence mapped in the Camden area by Osberg and Guidotti (1974) contains rusty quartz-mica schist, quartzite, and minor amphibolite and is lithologically similar to much of the Penobscot Formation with which it is here correlated. The Rockport and Benner Hill sequences are composed of a very different group of rocks consisting mainly of marble, quartzite, and quartzite conglomerate; these sequences were mapped by Osberg and Guidotti (1974) south of Camden and west of Rockland and are shown as a separate map unit (fig. 1).

Plutonic rocks of the region can be divided into the older Bays-of-Maine Complex, as defined by Chapman (1962), and a variety of younger granitic intrusions (Chapman, 1968; Wones, 1974, 1976). The Bays-of-Maine Complex, of Late Silurian to Middle Devonian age (Mose and Metzger, 1980; R.W. Luce, oral commun., 1979), comprises a bimodal mixture of layered mafic rocks (gabbro, minor norite and anorthosite) and associated granophyric differentiates. Granitic to granodioritic plutons, of Late Silurian to Late Devonian age (Brookins, 1976) intrude the Bays-of-Maine Complex, as well as the older Paleozoic metasedimentary and metavolcanic rocks.

Country rocks surrounding the igneous plutons have been thermally metamorphosed to varying degrees. The most extensive contact aureoles appear to be developed within sedimentary rocks around the younger granites, although local contact metamorphism is evident also near a few of the plutons of the older Bays-of-Maine Complex (Hussey and others, 1967). Adjacent to some granites, mineral assemblages consist of cordierite, andalusite, and local sillimanite, and suggest very high temperatures of metamorphism (Stewart and Wones, 1974; Wones, 1976). Away from these thermal aureoles, the regional metamorphic grade ranges from greenschist facies on the east side of Penobscot Bay to amphibolite facies on the west side of the bay (Thompson and Norton, 1968; Bickel, 1974).

MASSIVE SULFIDE DEPOSITS

Massive sulfide deposits containing base and minor associated precious metals are known in the Penobscot Bay area, as well as throughout most of New England (Gair and Slack, 1979). Early studies on the ore deposits of coastal Maine proposed an epigenetic-magmatic origin in which hydrothermal fluids were derived from nearby granitic plutons (Lindgren, 1925; Li, 1942). More recent geologic work in the area (LaPierre, 1977; Bouley, 1978) has shown that many of the base-metal deposits are stratabound and conformable with the layering of their enclosing host rocks. Current models for the genesis of stratabound massive sulfides (Solomon, 1976; Large, 1977) involve dominantly syngenetic processes of ore formation at the rock-seawater interface essentially contemporaneous with local marine sedimentation and/or volcanism. The stratabound base-metal deposits of the Penobscot Bay area are now considered by most workers to have originated by this type of process.

Young (1962) has compiled a list of the many sulfide mines, prospects, and occurrences in Hancock County, on the east side of Penobscot Bay. Most of the deposits occur in a small area bounded by the towns of Blue Hill and Castine, and by Deer Isle (Emmons, 1910, pl. II). The sulfide deposits can be divided into three principal groups: (1) those hosted by the Castine Volcanics, (2) those enclosed by the Ellsworth Schist, and (3) those within intrusive bodies of granite.

The following discussion is an attempt to synthesize the literature on massive sulfides in the region and is presented because much of the available information is dispersed in unpublished university theses. The Black Hawk deposit is emphasized because it is the only local tourmaline-bearing massive sulfide body to have been studied in detail. The Harborside deposit is discussed because of its importance in the controversy surrounding the genesis of stratabound base-metal sulfides in the Penobscot Bay area. Sulfide deposits in granitic rocks are not further considered.

Harborside Mine

The Harborside or Penobscot mine is located on Cape Rosier 4 km south of the town of Castine (fig. 1). Bouley (1978) presented a thorough description of the local geology and ore deposits. The main period of production was from 1968 to 1972, when Callahan Mining Corporation produced about 800,000 metric tons of ore averaging 5.5% zinc, 1.3% copper, 0.5% lead, and 0.5 oz/ton silver. Massive sulfides occur as pods and lenses irregularly distributed within magnesian-rich rocks and intercalated with rhyolite and andesite flows, tuffs, and breccias of the Castine Volcanics. Ore minerals include pyrite, sphalerite, chalcopyrite, and minor galena (Park and Bastille, 1973) in a gangue composed of chlorite, talc, quartz, and carbonate; no tourmaline is known from the mine area. The sulfides show the effects of weak (chlorite-grade) regional metamorphism and are only slightly recrystallized. The massive sulfides are adjacent to a brecciated rhyolite dome and are underlain in some places by a stockwork of pyrite-chalcopyrite veinlets. These features suggest that the Harborside deposit formed in a proximal [2/] Kuroko-type of environment (Bouley, 1976; 1978).

Black Hawk Mine

The Black Hawk or Blue Hill mine is just southwest of the town of Blue Hill and about 16 km east-northeast of the Harborside mine (fig. 1). The ore deposits at the Black Hawk mine differ from those at the Harborside mine mainly in that they (1) are enclosed within quartzitic units of the Ellsworth Schist, (2) contain a more complex suite of Mg-rich silicate gangue minerals (including tourmaline), and (3) are more highly recrystallized and remobilized by the contact metamorphism surrounding a nearby granite pluton. The Black Hawk deposit beneath Second Pond was developed by Kerramerican, Inc., and from 1972 to 1977 yielded nearly 1 million metric tons of sulfide ore averaging 6.9% zinc and 0.9% copper; lead and silver also were recovered. The mine is currently inactive but contains reserves of about 1.4 million tons of 8.1% zinc (Kerr-Addison Mines Annual Report, 1972-1977).

The ore deposits comprise stratabound and broadly stratiform massive sulfides within metasedimentary rocks of the Ellsworth Schist (fig. 2). The principal host is the Pond Quartzite Member (of local usage), one of several arenaceous units described from the mine area (Jones, 1969; Howd and Drake, 1974). Past production has come mainly from the A Zinc and Mammoth zones, which occur near the stratigraphic top of the Pond Quartzite. The other principal mineralized horizon, the L.S.P. (Lower Second Pond) zone, is stratiform and stratabound along the base of the Pond Quartzite. Large sills and dikes of granite and small bodies of pegmatite-aplite occur throughout the mine area and crosscut the sulfide deposits (LaPierre, 1977; Badawy, 1978). These granitic rocks, which caused a high-temperature contact-metamorphic assemblage of cordierite + andalusite $\pm$ sillimanite $\pm$ K-feldspar to form in adjacent Ellsworth Schist (Lutes, 1976; Badawy, 1978), are believed to be related to the Lower Devonian [3/] Sedgwick pluton exposed 1 km south of the mine area (fig. 1).

[2/] Throughout this report, the term "proximal" is used in the sense of Large (1979), to refer to a stratabound sulfide deposit that overlies an alteration pipe or feeder zone (fumarolic center) through which ore solutions discharged onto the sea floor. Such a fumarolic or exhalative center need not coincide with a volcanic center, as proposed by Plimer (1978), but may be localized in *either* volcanic or sedimentary rocks.

[3/] Brookins (1968) reported a Rb-Sr age of 395 $\pm$ 15 m.y. for the Sedgwick pluton.

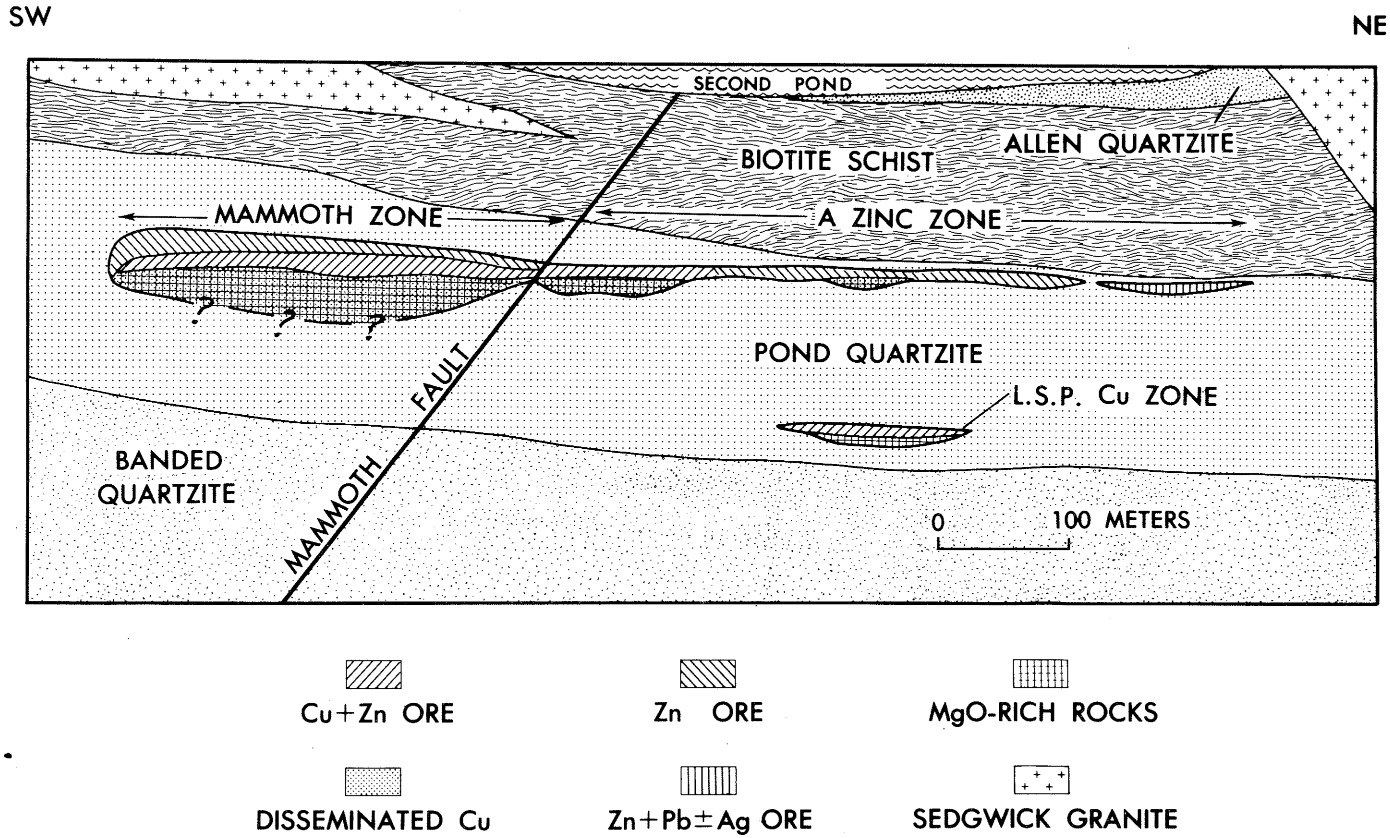

Figure 2.--Geologic cross-section of the Black Hawk mine area, Maine, showing principal sulfide deposits and ore types (modified after LaPierre, 1977 and Bouley, 1978). The Allen, Pond, and Banded Quartzite Members and the Biotite Schist (Gneiss) Member of the Ellsworth Schist are names of local usage (Greenwood and Hogan, 1965; Howd and Drake, 1974). L.S.P. = Lower Second Pond. Horizontal scale = vertical scale (no vertical exaggeration).

Mafic igneous rocks in the vicinity of Second Pond are volumetrically very minor and include coarse-grained diorite-gabbro, amphibolite, and diabase (Howd and Drake, 1974; LaPierre, 1977). Most of the amphibolites are premetamorphic and probably represent former basaltic flows and/or sills within the Ellsworth Schist (Forsyth, 1953; Jones, 1969). Intrusive bodies of gabbro-diorite and some postore mafic dikes are thought to be related to the Bays-of-Maine Complex; the youngest dikes are lamprophyres that have been isotopically dated as Middle Jurassic (Wingard and Brookins, 1964; Brookins and Wingard, 1973).

The sulfide deposits at the Black Hawk mine comprise massive tabular lenses and disseminations and are in many places associated with an Mg-rich silicate gangue. Individual ore bodies typically pinch and swell, especially within the stratiform deposits of the A Zinc zone. Disseminated ore is more common in the Mammoth zone, where scattered sulfides and alteration patches locally extend 10 m or more below the upper massive deposits (Bouley, 1978; Slack, 1979, unpub. data). Major sulfides are sphalerite, chalcopyrite, pyrrhotite, pyrite, and galena. Rocks containing abundant silicate gangue minerals, termed "RAD" at the mine (LaPierre, 1977), form coarse intergrowths with the sulfides, particularly in the western A Zinc and Mammoth zones. Extensive petrographic and microprobe studies by Badawy (1978) show this gangue to be an Mg-rich assemblage composed of cordierite, talc, muscovite-phlogopite, Mg-chlorite, tremolite-anthophyllite, calcite-dolomite, and dravite (Mg-tourmaline). The distinctive mineral compositions within this assemblage may reflect a combination of effects, but are believed to result mainly from Mg-metasomatism associated with initial ore formation (e.g., Sangster, 1972; Large, 1977). Later modifications of these compositions probably were imposed by sulfide-silicate reactions produced during contact metamorphism by the postore Sedgwick granite pluton (Badawy, 1978).

Patterns of altered rock and metal zoning provide a basis for evaluating the origin of the Black Hawk deposit. Lateral zoning is especially distinct, as shown by a change from the Cu + Zn ores of the Mammoth and western A Zinc zones, to the Zn ± Cu characteristic of the central A Zinc zone, to the Zn ± Pb ± Ag of the eastern part of the A Zinc zone (LaPierre, 1977). Vertical zoning is best documented by comparing different ore horizons, such as the Cu-rich L.S.P. zone and the A Zinc zone stratigraphically above (fig. 2). The zoning patterns and the distribution of disseminated sulfides and Mg-alteration products suggest that a major fumarolic vent, through which the ore solutions discharged, was located near the present site of the Mammoth zone. According to this model, the Black Hawk deposit, considered to be of exhalative synsedimentary origin, would thus represent a proximal (e.g., Large, 1979) rather than a distal environment as proposed by Bouley (1978). This interpretation further suggests that no genetic relationship exists between the Harborside and Black Hawk deposits, and that massive sulfides of the Black Hawk type--proximal and hosted by metasedimentary rocks--need not be peripheral to a volcanic center such as that near the Harborside mine on Cape Rosier (fig. 1).

TOURMALINE OCCURRENCES

Unusual concentrations of tourmaline are generally found in close association with pegmatites or granitic plutons and are considered to be normal products of late magmatic differentiation processes. Sedimentary rocks also contain tourmaline as an accessory detrital mineral, but rarely in excess of a few volume percent. In several types of mineral deposits that have a magmatic parentage, such as copper breccia pipes and tin-bearing veins, tourmaline may be an important gangue mineral. Less well known is the association of tourmaline with stratabound massive sulfides. Tourmaline has been reported as a minor phase in many stratabound base-metal deposits; in a few ore bodies it may compose a significant part of the gangue.

The most notable occurrence of tourmaline with massive sulfides is at the large Sullivan Pb-Zn mine in southeastern British Columbia (Freeze, 1966). At Sullivan, tourmaline forms a felted mass of fine-grained crystals intergrown with quartz, principally in the footwall of the ore body (fig. 3). Microprobe studies indicate that this tourmaline is characteristically Mg-rich and is compositionally distinct from the Fe-rich schorls found in granite stocks of the region (Ethier and Campbell, 1977). The local geological setting of the ore body and the distribution of alteration zones, including the tourmalinized rock, suggest that the massive sulfides at Sullivan overlie a former collapse area through which a metal-bearing boron-rich brine was discharged onto the sea floor (Campbell and Ethier, 1977; Campbell and others, 1978).

Other stratabound sulfide deposits that contain tourmaline are representative of widely varying ages and geographic locations. Many seem to be preferentially hosted by metasedimentary rocks or by a mixture of metasediments and mafic metavolcanic rocks. Notable examples within this category include several mines in the Zambian Copper Belt (Mendelsohn, 1961); the Black Bird mine, Idaho (Anderson, 1947); the Ore Knob deposit, North Carolina (Kinkel, 1967); the Bleikvassli mine, Norway (Vokes, 1963); and the Elizabeth mine in the Vermont Copper Belt (McKinstry and Mikkola, 1954). Tourmaline also occurs with massive sulfides hosted in part by felsic metavolcanic rocks, such as at the Big Stubby deposit, western Australia (Reynolds and others, 1975); the Vihanti and Pyhasalmi mines, Finland (Rouhunkoski, 1968; Helovuori, 1979); the Rosebery deposit, Tasmania (Braithwaite, 1974); the Pecos mine, New Mexico (Krieger, 1932); and in the Mineral district, Virginia (Katz, 1961; Slack, 1979, unpub. data). In all these deposits, little or no evidence exists for a primary plutonic or secondary metasomatic origin for the tourmaline, thus suggesting that boron-rich fluids were associated with the initial formation of the sulfide ores.

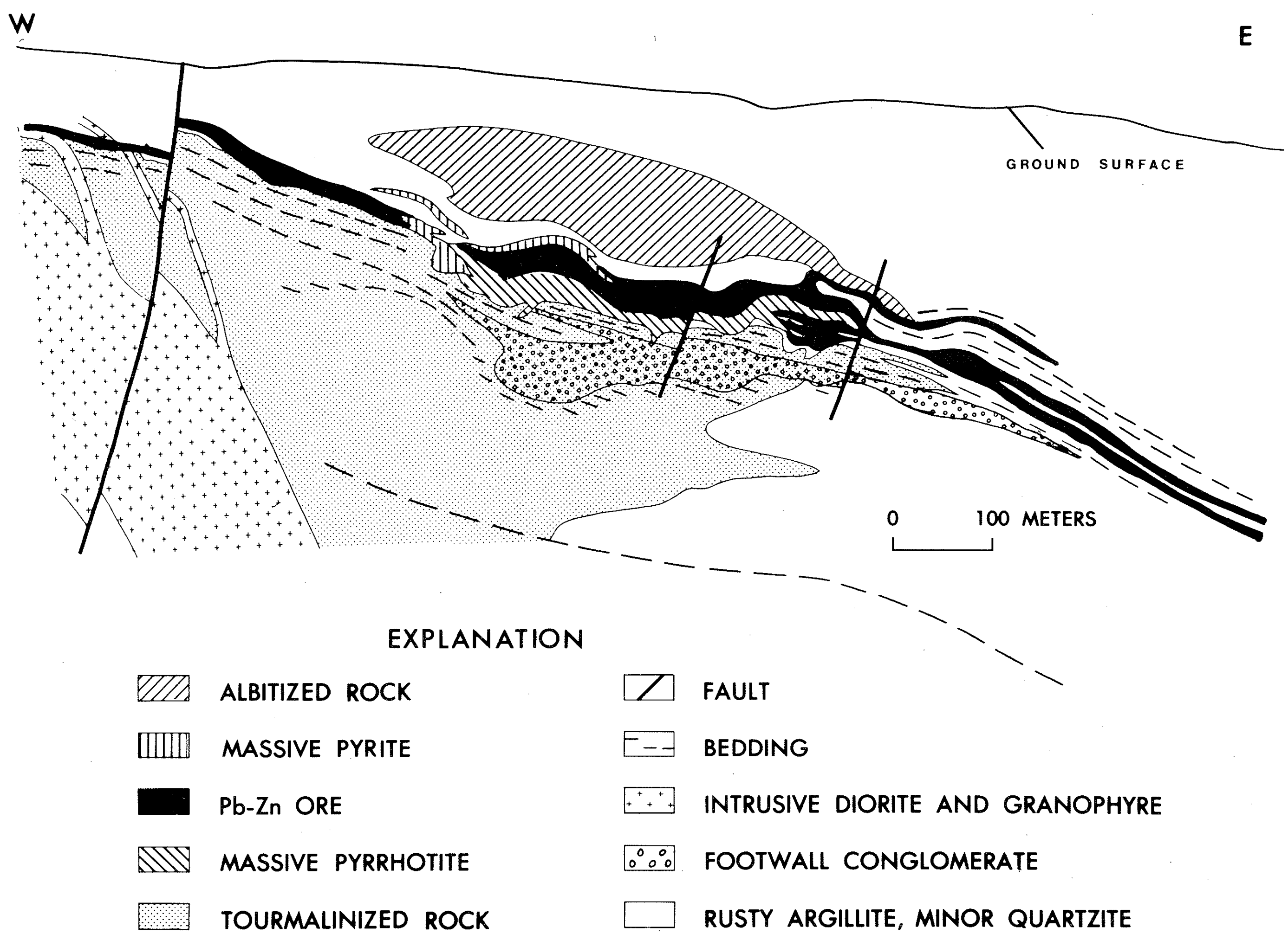

Figure 3.--Geologic cross section of the Sullivan mine area, British Columbia, showing sulfide deposits and altered zones (modified from Freeze, 1966). Country rock (rusty argillite, minor quartzite) comprises part of the Aldridge Formation of late Precambrian age. Vertical scale = horizontal scale (no vertical exaggeration).

Black Hawk Mine

Tourmaline has been reported from the Black Hawk mine by several workers, but its occurrence has never been described in detail. Howd and Drake (1974) first mentioned it; a later study by LaPierre (1977) found tourmaline to be concentrated especially in the southwestern part of the mine, in the western A Zinc zone. Badawy (1978), in a more detailed petrographic and microprobe study, discovered abundant tourmaline also in the Mammoth zone and identified it as dravite, an Mg-rich tourmaline. On the basis of reconnaissance X-ray analysis, Bouley (1978) suggested that the tourmaline may be the manganiferous variety, tsilaisite. A more thorough investigation of the textural and compositional variations of the tourmaline is currently underway and was reported on in preliminary form by Slack and others (1980).

Tourmaline at the Black Hawk mine is most abundant in the copper-rich Mammoth and western A Zinc zones, where it occurs in close association with sulfides, in altered wall rocks, and in some postore pegmatite-aplite dikes. Tourmaline is present in a variety of colors and compositions. Brown or golden yellow dravite (Mg-tourmaline) forms intergrowths commonly with pyrrhotite and chalcopyrite but rarely with sphalerite, galena, or pyrite. Adjacent to ore, altered Pond Quartzite may contain isolated patches of columnar needles or blocky crystals of red-brown dravite. Other localities show sunbursts of radiating golden dravite as much as 1 m in diameter and and veins composed of dravite, Mg-chlorite, and quartz. In contrast, black crystals of Fe-rich tourmaline (schorl) are found as late magmatic segregations in granitic pegmatite and aplite dikes. The non-granitic tourmaline (dravite) occurrences could have originated by one of several processes, including (1) tourmalinization related to the late pegmatites and aplites, (2) boron metasomatism associated with initial sulfide mineralization, or (3) tourmaline alteration along major postore faults. The distinctive composition of the dravite and its preferential localization near copper-bearing parts of the mine suggest that it is an integral part of the Mg-rich alteration assemblage associated with initial sulfide deposition, and that it has been subsequently recrystallized and remobilized during contact metamorphism imposed by the Sedgwick pluton and related dikes and sills (Slack and others, 1980).

Other Sulfide-Related Occurrences

Tourmaline has also been recognized as an accessory gangue mineral in several small sulfide deposits of the region (table 1). At the Stober (Stover Hill) prospect, tourmaline is associated with stratabound sulfides in the Ellsworth Schist. The Stober prospect may be considered part of the Blue Hill mining district, as it is only 1.5 km northeast of the Black Hawk Cu-Zn mine at Second Pond (Emmons, 1910, pl. II). Geologic mapping by Jones (1969) and Cheney (1967) suggest that the mineralized rock at the Stober prospect, which contains coarse crystals of tourmaline (Gilson and Williams, 1929), may occur along the same stratigraphic horizon (Pond Quartzite) as the ores at the Black Hawk mine. The Douglas mine (Earl, 1950), 0.5 km northwest of the Black Hawk mine, produced a small amount of copper from a sulfide body localized apparently at a lower stratigraphic horizon within the Douglas Quartzite Member. A "pegmatitic vein" there composed of quartz, tourmaline, and muscovite along the footwall of the ore body (Forsyth, 1953) is interpreted to be non-plutonic in origin because of a lack of reported K-feldspar. An occurrence of tourmaline with sulfides at the Copperopolis (Custer) mine 30 km northeast of Blue Hill (fig. 1) is similarly problematic in origin--the sulfides are found in fractures within the Ellsworth Schist (Li, 1942), but a stratabound nature has not been confirmed for the deposit.

On the west side of Penobscot Bay, base-metal sulfide occurrences are limited to a few sulfide-bearing quartz veins and to a copper prospect near Appleton (Hussey and Austin, 1958; Cheney, 1967). The host rocks for these occurrences are the Penobscot Formation and equivalent rocks southeast of the St. George fault (fig. 1). The Appleton prospect is of particular interest because it contains tourmaline as a major gangue mineral associated with chalcopyrite and pyrrhotite in regionally metamorphosed rocks (amphibolite, feldspathic schist) of the Penobscot Formation (Bickel, 1971).

Metasedimentary and Metavolcanic Rocks

In the Penobscot Bay area, several workers have reported tourmaline-rich metasedimentary and metavolcanic rocks (table 1). On the east side of Penobscot Bay, occurrences of non-plutonic tourmaline (with or without sulfides) are confined mainly to the Ellsworth Schist, as an accessory detrital mineral (Cavalero, 1965) and locally as acicular porphyroblasts as much as 2.5 cm long (McGregor, 1964). In the Belfast quadrangle, on the west side of the bay, Bickel (1971) described abundant tourmaline locally in high-grade metamorphic rocks of the Penobscot Formation. At one locality, near Mill Pond, a massive quartz-tourmaline rock containing traces of pyrrhotite is found with rusty-weathering amphibolite and albite quartz-granulite, and is in many places associated with Mg-rich chlorite and talc; a second locality on the east shore of Megunticook Lake has abundant tourmaline in a sillimanite-mica schist. Amphibolite probably of volcanic origin contains tourmaline in a marble quarry near Warren (Cheney, 1967). In the adjacent Rockland quadrangle, Bastin (1908) described a tourmaline-rich garnet schist. To the east of the Belfast quadrangle, in the Bayside area, tourmaline locally forms 1-cm-wide veinlets cutting an andalusite schist (D. B. Stewart, oral commun., 1979).

TABLE 1.--TOURMALINE OCCURRENCES IN THE PENOBSCOT BAY AREA

Type	Location	Description	References
Plutonic			
	Sedgwick pluton	Black tourmaline (schorl) in late pegmatite and aplite, and in quartz veins near intrusive contacts (surface exposures and underground at Black Hawk mine)	Wingard (1961, p. 68-70) Wones (1974, p. 109) Wones (1976, p. 62) Slack et al. (1980, p. 83)
	East Blue Hill pluton	Tourmaline crusts and rosettes along contact; also accessory tourmaline in granite and aplite	Wingard (1961, p. 51, 65) Jones (1969, p. 37)
	Long Island pluton	Green tourmaline with scheelite, fluorite, and molybdenite in pockets along northeast contact	Wingard (1961, p. 63)
	Lucerne pluton	Tourmaline present in small amounts throughout the pluton, and in related leucocratic dikes	Cavalero (1965, p. 40) Wones (1974, p. 111)
	Wallamatogus pluton	Accessory dravite in two-mica Wallamatogus granite northwest of Pierce Pond	Wingard (1961, p. 71)
	Isle Au Haut pluton	Large black tourmaline crystals in pegmatite at Birch Point, north end of Isle Au Haut	Luce (1962; oral commun., 1980)
	Rockland-East Union granitic dikes	Large black crystals and radiating dark green tourmaline in pegmatite and aplite dikes south of Rockland and near East Union	Bastin (1908, p. 6) Cheney (1967, p. 13)
Non-Plutonic			
	Black Hawk mine	Golden yellow, dark olive-green, brown, and red-brown tourmaline (dravite) intergrown with chalcopyrite and pyrrhotite, and associated with quartz, Mg-chlorite, talc, cordierite, and Mg-amphiboles; also as fracture-fillings and replacements (with quartz ± dolomite ± sulfides) of Pond Quartzite adjacent to ore	Howd and Drake (1974, p. 183) LaPierre (1977, p. 49-50) Badawy (1978, p. 32-35, 81, 113) Bouley (1978, p. 108, 109, 114, 115) Slack et al. (1980, p. 83)
	Douglas mine	Black tourmaline with muscovite + quartz in "pegmatitic veins" along footwall of ore zone	Forsyth (1953, p. 15)
	Stober prospect	Large (>1cm) tourmaline crystals associated with sulfide minerals	Gilson and Williams (1929, p. 191)
	Copperopolis prospect	Minor tourmaline in chlorite schist associated with sulfide minerals	Li (1942, p. 37)
	Appleton prospect	Tourmaline associated with chalcopyrite, pyrrhotite, and pyrite in mineralized amphibolite and feldspathic schist	Hussey and Austin (1958, p.7) Bickel (1971, p. 323) Cheney (1967, p. 13, 19)
	Ellsworth quadrangle	Trace accessory tourmaline in Ellsworth Schist locally as acicular porphyroblasts (to 2.5 cm)	Cavalero (1965, p. 20) McGregor (1964, p. 38-39)
	Wallamatogus Mountain	Small prisms of brown tourmaline with quartz, muscovite, and magnetite in schist	Smith et al. (1907, p. 4, 9) Wingard (1961, p. 33)
	Belfast quadrangle	Tourmaline-rich zones within Gushee Member of Penobscot Formation, locally with Mg-chlorite and talc. Muscovite schist (9% tourmaline) on east shore of Megunticook Lake; massive quartz-tourmaline rock (55% tourmaline) with pyrrhotite, near Mill Pond	Bickel (1971, p. 55, 66)
	Bayside area	Tourmaline in recrystallized zone near granite plutons, and in thin (1 cm) veinlets cutting andalusite schist	Smith et al. (1907, p. 10) Stewart (oral commun., 1979)
	Rockland area	Abundant brown tourmaline and garnet in mica schist of Penobscot Formation, 1 km southwest of Rockport	Bastin (1908, p. 3)
	Warren area	Tourmaline associated with amphibolite in marble quarry near Warren	Cheney (1967, p. 13)

Plutonic-Pegmatitic

Tourmaline is known as an accessory mineral in many of the granitic rocks of the Penobscot Bay area (table 1). It is found in the form of black schorl in pegmatite and aplite, and locally in veins crosscutting the margins of some plutonic bodies. Segregations of black schorl, like those in postore dikes from the Black Hawk mine, typically are intergrown with coarse-grained quartz, K-feldspar, and muscovite and clearly are products of late-stage magmatic activity. Similarly, the association of tourmaline with fluorite, scheelite, and molybdenite within pockets in the Long Island pluton (Wingard, 1961) suggests an origin related to the host granite. These plutonic occurrences of tourmaline thus differ from the concentrations found in metasedimentary rocks, including those associated with stratabound sulfides.

The origin of the tourmalines that fill fractures in the margins of the granitic rocks is unclear. These tourmalines may be brown, green, or black, and contrast in their textural and mineralogical associations with the tourmalines found as late magmatic segregations. At the Black Hawk mine, some postore dikes and sills of Sedgwick granite are crosscut by veins composed of dravite + quartz $\pm$ sulfide $\pm$ carbonate. Preliminary analysis suggests that these late veins are not related to the granitic rocks, but may represent remobilized material from the tourmaline-rich alteration assemblage associated with formation of the massive sulfide deposits (Slack and others, 1980).

TOURMALINE: A GUIDE TO ORE

Sullivan--A Formational Model

Data from a variety of geologic and geochemical studies indicate that the boron in tourmaline associated with massive sulfides must have originated from the same hydrothermal sources that formed the ore deposits. Recent work by Ethier and Campbell (1977) has demonstrated that the boron content of the tourmalinized footwall of the Sullivan ore body is much too high (by at least two orders of magnitude) to have been derived through normal sedimentary processes, either as a detrital phase or as a chemical precipitate from seawater. The likelihood of a postore plutonic-magmatic origin for this tourmaline is ruled out by the presence of stratabound tourmaline-rich laminae within adjacent sediments and by the absence of nearby granitic intrusions; the lack of volcanic rocks in the stratigraphic column precludes a marine volcanic source. Ethier and Campbell (1977) proposed that the tourmaline was precipitated either from a boron-rich brine or from a silica-boron colloid, and that the boron-bearing fluids reached the sea floor through the same channelways used by the metal-bearing solutions. This interpretation is critical, because it suggests that the tourmalinized rock at Sullivan is a direct product of the hydrothermal activity associated with formation of the massive Pb-Zn ores. Anomalous concentrations of tourmaline within or near stratabound base-metal sulfide deposits may therefore be viewed as analogous to other types of alteration characteristic of submarine hydrothermal systems, including silicification, chloritization, and albitization.

Effects of Metamorphism

Preliminary observations at the Black Hawk mine and at the Elizabeth mine, Vermont, suggest that tourmaline may be considerably recrystallized and remobilized during high-grade metamorphism. The ore deposits at the Elizabeth mine are stratabound massive sulfides within lower (?) Paleozoic schist, quartzite, and amphibolite in the Connecticut Valley Synclinorium (McKinstry and Mikkola, 1954; Howard, 1969). There, the copper-bearing massive sulfides and their enclosing host rocks have been subjected to a postore amphibolite-facies regional metamorphism. Tourmaline at the Elizabeth mine occurs in a variety of rock types, and many crystals are very coarse grained--as much as 5 cm or more in length (Slack, 1979, unpub. data). By contrast, the bulk of the tourmalinized rock at the Sullivan mine, British Columbia, preserved under greenschist-facies conditions (Ethier and others, 1976), comprises a felted mass of extremely fine-grained (< 0.5 mm) needles of dravite intergrown with quartz, chlorite, muscovite, or pyrrhotite (Ethier and Campbell, 1977). These distinct differences in grain size between Elizabeth and Sullivan are interpreted to be a function of the recrystallization of tourmaline under higher temperature and higher pressure conditions of regional metamorphism at the Elizabeth mine.

Contact metamorphism developed near large bodies of intrusive rock may also result in the recrystallization and increased grain size of pre-plutonic tourmaline. At the Black Hawk mine, coarse needles and blocky crystals of dravite are common within the sulfide deposits and adjacent wall rocks, where postore dikes and sills of granite, diorite or gabbro, and pegmatite-aplite are found (Slack and others, 1980). Freeze (1966) reported an analogous increase in the grain size of tourmaline close to a postore intrusion of diorite-granophyre in the lower workings of the Sullivan mine. The effects of contact metamorphism on tourmaline thus appear to be generally similar to those inferred for regional metamorphism.

In addition to undergoing recrystallization, tourmaline may be remobilized after initial deposition and transported large distances during metamorphism. Near the southern end of the open pit at the Elizabeth mine, late-metamorphic fractures are filled with irregular patches and crusts composed of quartz + tourmaline + calcite ± sulfide (Slack, 1979, unpub. data). Some of these crusts extend for as much as 10 m laterally away from the main part of the ore body and suggest such remobilization and transport of tourmaline. Similarly, tourmaline-rich pods and veins found in the wall rocks several meters or more from the main ore zones at the Black Hawk mine may reflect remobilization and transport of tourmaline during contact metamorphism. Currently ongoing projects at these two mines will examine in more detail the nature of the metamorphic recrystallization and remobilization of tourmaline associated with massive sulfide deposits.

Prospecting Guides

Anomalous concentrations of tourmaline in metamorphic rocks and near the borders of granitic plutons may be used as prospecting guides for massive base-metal sulfide deposits. In metasedimentary rocks, tourmaline-rich laminae or accumulations of tourmaline in excess of several percent may reflect the former existence of submarine hydrothermal activity. In some places, this hydrothermal activity could have been associated with the production of stratabound sulfides, as suggested by tourmaline concentrations in the vicinity of the Sullivan mine, British Columbia (Ethier and Campbell, 1977). In the Penobscot Bay area of coastal Maine (fig. 1), similar occurrences of tourmaline-rich metasedimentary rocks are known on the east side of the bay in the Ellsworth Schist, and on the west side of the bay at several localities within the Penobscot Formation (table 1).

In a high-grade metamorphic terrane, rocks containing both tourmaline and sulfides, especially chalcopyrite or pyrrhotite, may be more direct guides to hidden base-metal deposits. Such an association might represent either part of the feeder zone of a stratabound sulfide deposit, or, alternatively, ore-related material remobilized along faults or fractures during metamorphism. The best example of this type of tourmaline is found at the Black Hawk mine near Blue Hill. Similar occurrences identified at the Stober, Copperopolis, and Appleton prospects (fig. 1) therefore warrant further investigation.

Tourmaline concentrations near the margins of granitic plutons are more difficult to evaluate in terms of their prospecting potential. If the strata of a region are known to contain large amounts of tourmaline, such as the Aldridge Formation in Canada hosting the Sullivan Pb-Zn deposit (Ethier and Campbell, 1977), then postore granites with late magmatic tourmaline-bearing phases (i.e., aplites, pegmatites) may reflect simple assimilation of boron-rich sedimentary material into the magma prior to crystallization. Examples in this category in the Penobscot Bay area might include the tourmalines identified in the Lucerne, Sedgwick, East Blue Hill, and Isle Au Haut plutons, and the pegmatites of the Rockland and East Union areas (table 1). This type of tourmaline occurrence probably has limited exploration significance because the contamination of magma by boron-rich country rocks (if it took place at all) may have been at great depths. However, if the granites themselves are crosscut by tourmaline-rich veins, then another explanation must be sought. At the Black Hawk mine, quartz-tourmaline-sulfide veins that crosscut postore intrusions of the Sedgwick granite are interpreted as altered rock initially formed during deposition of the massive sulfide ores and subsequently remobilized during or after intrusion of the Sedgwick pluton. This type of tourmaline occurrence could therefore serve as a valuable prospecting guide to nearby base-metal sulfide deposits, in the Penobscot Bay area and elsewhere.

Additional prospecting guides to consider are the color of the tourmaline and its coexisting mineral assemblage. Although tourmaline may exhibit a wide range of colors and compositions, a general rule is that the Fe-rich variety, schorl, is commonly black, whereas dravite, the Mg-end member, typically is brown (Deer and others, 1966). Brown magnesian tourmaline is believed to be significant because of its association with some stratabound sulfide deposits, either as isolated grains in ore or as intergrowths with quartz and Mg-rich silicate gangue minerals. Such Mg-dominant assemblages are interpreted to be a product of magnesium metasomatism produced during initial submarine hydrothermal activity, and not a result of later regional or contact metamorphism. However, post-depositional metamorphism may also cause compositional changes in ferromagnesian minerals. For assemblages in which tourmaline coexists with Fe-Mg silicates, increasing metamorphic grades produce larger Fe/(Fe + Mg) ratios in tourmaline relative to other phases (O'Connor, 1980). Where sulfides are present, sulfide-silicate reactions commonly yield smaller Fe/(Fe + Mg) ratios for ferromagnesian minerals (Bachinski, 1976; Badawy, 1978). The presence of Mg-tourmaline (dravite) might therefore reflect either sulfide-silicate reactions during metamorphism or an overall bulk compositional control. An abundance of brown dravite associated with other Mg-rich silicates in a metasedimentary terrane could thus be used as a prospecting guide for massive sulfide deposits. In the Penobscot Bay area, such assemblages are common at the Black Hawk Cu-Zn mine near Blue Hill (Slack and others, 1980). Similar assemblages have been described by Bickel (1971) in the Belfast quadrangle, on the west side of the bay, where tourmaline-rich rocks of the Gushee Member of the Penobscot Formation locally contain Mg-chlorite and talc; some outcrops also have abundant cordierite and anthophyllite (Bickel, 1976). This type of mineral assemblage is believed to have great exploration significance because of its close association with the Cu-Zn ores at the Black Hawk mine (Lindgren, 1925; Badawy, 1978). Because the environment of formation of the Black Hawk deposit is considered to have been independent of a volcanic center, the potential for similar sediment-hosted massive sulfides may be equally favorable within units such as the Penobscot Formation and equivalent rocks southeast of the St. George fault (fig. 1). The rocks on the west side of Penobscot Bay should therefore have as much potential for massive base-metal sulfide deposits as the productive terranes (Ellsworth Schist, Castine Volcanics) on the east side of the bay.

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DATE DUE

GORHAM CAMPUS

FEB 2 5 1992 [redacted]

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JAN 1 4 199[illegible]

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