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MISCELLANEOUS
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MOLYBDENITE IN WISCONSIN
Occurrence and Potential

by Jeffrey K. Greenberg

available from
Geological and Natural History Survey
University of Wisconsin-Extension
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INTRODUCTION

Wisconsin is known for its history of lead-zinc and iron mining, and most recently for the discovery of major zinc-copper massive sulfide deposits. In addition, there has been continuing interest in exploration for other mineral resources, including molybdenite, the primary ore of molybdenum. Although molybdenite is relatively scarce in Wisconsin, it is a critical industrial mineral and is therefore worthy of attention.

This report is intended to briefly document Wisconsin molybdenite occurrences with a general assessment of the potential for molybdenum resources in the state. A summary of the geological classification of molybdenum deposits and some basic economic considerations have been included as background information. It is not the purpose of this report to serve as a comprehensive analysis of the subject, but to provide a base to encourage further research on molybdenite mineralization.

In order to characterize Wisconsin's molybdenite occurrences, descriptions from previously unpublished studies have been incorporated with new observations and analyses. It is important to see how the geology of Wisconsin and its known occurrences fit into the context of world-wide molybdenite deposits. From a comparison of the situation in Wisconsin with commercial ore deposits in North America it is possible to estimate the economic mineral potential of existing prospects and to speculate on other areas of exploration interest. At present (1982), the world market for molybdenum is depressed, and there is too little known about the real extent of molybdenum mineralization in Wisconsin. However, both of these conditions should change in the future.

MOLYBDENUM AS A MINERAL RESOURCE

Molybdenum, a whitish metal, occurs in nature primarily associated with sulfur in the mineral form of molybdenite, MoS_2. Other mineral compounds--wulfenite ($PbMoO_4$), powellite ($Ca(Mo,W)O_4$), molybdite (MoO_3), ferrimolybdite ($Fe_2Mo_3O_{12}$-$8H_2O$) are known, but are commercially unimportant relative to molybdenite, the molybdenum disulfide.

In the United States, molybdenum is produced by both underground and open-pit operations. Molybdenum is the primary mineral product at only three mines, but these account for over half of the U.S. production. The remaining molybdenum production is as a by-product, principally of large copper porphyry ore bodies in Arizona and Utah. By-product production occurs at 16 mine properties in the U.S.

Molybdenum ore, whether primary or by-product, must be beneficiated (broken-down and purified), because even primary ore is generally less than 0.5% Mo and by-product ores are usually less than one-tenth as rich. The molybdenite concentrate produced from beneficiation processes is about 90% MoS_2. This is either used directly, roasted to produce technical-grade molybdic oxide (MoO_3), or further refined into high purity MoS_2. MoO_3 may undergo further treatment producing a variety of intermediate substances or be used directly. Molybdenum is used principally in metal production (largely steel manufacturing) which accounts for 75% of the Mo consumed (O'Donnell, 1982). The remaining consumption is taken-up in chemical applications, as lubricants, catalysts, and in pigments. As an alloying ingredient in steel, molybdenum imparts qualities of increased strength, resistance to physical deterioration, and increased resistance to chemical attack.

The molybdenum market in the U.S. is dominated by a few, large producers, for example, the principal U.S. producer is the subsidiary of AMAX Inc., Climax Molybdenum Company, which operates the Climax and Henderson mines. The price of molybdenum on the market is tied closely to a producer price set by contracts between the producer and consumer companies. This producer price generates a steady flow of cash to the molybdenum mining industry and provides encouragement for continued market growth (Thomson, 1982). "By-product only" producers create a second price for molybdenum in a shorter-term spot market trade environment. Spot-market trade is subject to the vagaries of the world molybdenum market and is more sensitive to short-term supply/demand situations.

The United States is a net exporter of molybdenum, having a reserve base of nearly 12 million pounds. Mine production in 1981 was 145,000 pounds with apparent domestic consumption for the year at 54,000 pounds (O'Donnell, 1982). Exports of molybdenum concentrates and molybdic oxide were estimated at 50,000 pounds for 1981.

MOLYBDENUM ORE DEPOSITS

Although there are several classes of molybdenum ore deposits in the world, the vast majority involve one primary ore mineral, molybdenite, and one major source, felsic plutonic rocks (Vokes, 1963; Baxter, 1978; Kummer, 1979). These felsic plutons may include true granites, granodiorites, quartz monzonites (adamellites), and quartz and feldspar porphyries. The different classes of deposits vary according to their particular relation to these host plutons. Available publications arrive at no concensus as to the exact categories of molybdenite deposits. However, all classification schemes can be generalized by the following major deposit types: I) Vein type, usually quartz veins or quartz-rich veins; II) Disseminated type, mineralization dispersed throughout a portion of a pluton; III) Pegmatite-aplite type; IV) Porphyry type, also known as Cu-Mo-porphyry type which can include types 1 through 3; V) Contact-metasomatic type, developed in country rocks near the margin of felsic plutons. These five types or classes of molybdenite deposits are shown in figure 1 and have characteristics that often occur together in a single area (mine, mining district, and so forth) and are at times difficult to separate; for example, a very quartz-rich pegmatite may grade into a quartz-vein type deposit.

It is important to note that all the proposed types of deposits are the result of hydrothermal or metasomatic fluid transport near the end of or just following an intrusive episode. The temperature of ore formation is considered to be high relative to many other types of sulfide mineralization (Barton and Skinner, 1967). These fluids are solutions characterized by high sulfur activities (hence the formation of molybdenum sulfide), and often by the evidence of fluoride activity in the form of minor fluorite. Some molybdenite deposits contain almost no economic or gangue minerals other than quartz and molybdenite; whereas others are rich in copper (porphyry type) or rich in Be, W, Bi, Sn, Nb, Zr, Ti, and U in various combinations (particularly pegmatite or contact-metasomatic types). Next to quartz, pyrite and chalcopyrite are the minerals most commonly associated with molybdenite in all deposit types. Many, if not most deposits also exhibit some oxidation of ore in the conversion of molybdenite to molybdite or more commonly, ferrimolybdite. In some mines where oxidation is extensive ferrimolybdite as well as the sulfide is produced in concentrates (Mitchell, 1945).

The ore grade or richness of particular molybdenite deposits is not the prime factor determining economic importance. It is more necessary that a deposit contain a very large volume of moderate-grade ore than a small volume of very high-grade ore. According to this criterion, porphyry-type deposits are the greatest sources of molybdenum, with mineralization involving large volumes of the host pluton and surrounding rocks. In contrast, the more restricted deposit types such as pegmatite, quartz-vein and contact-metasomatic, may be very high-grade but contain only minor volumes of ore.

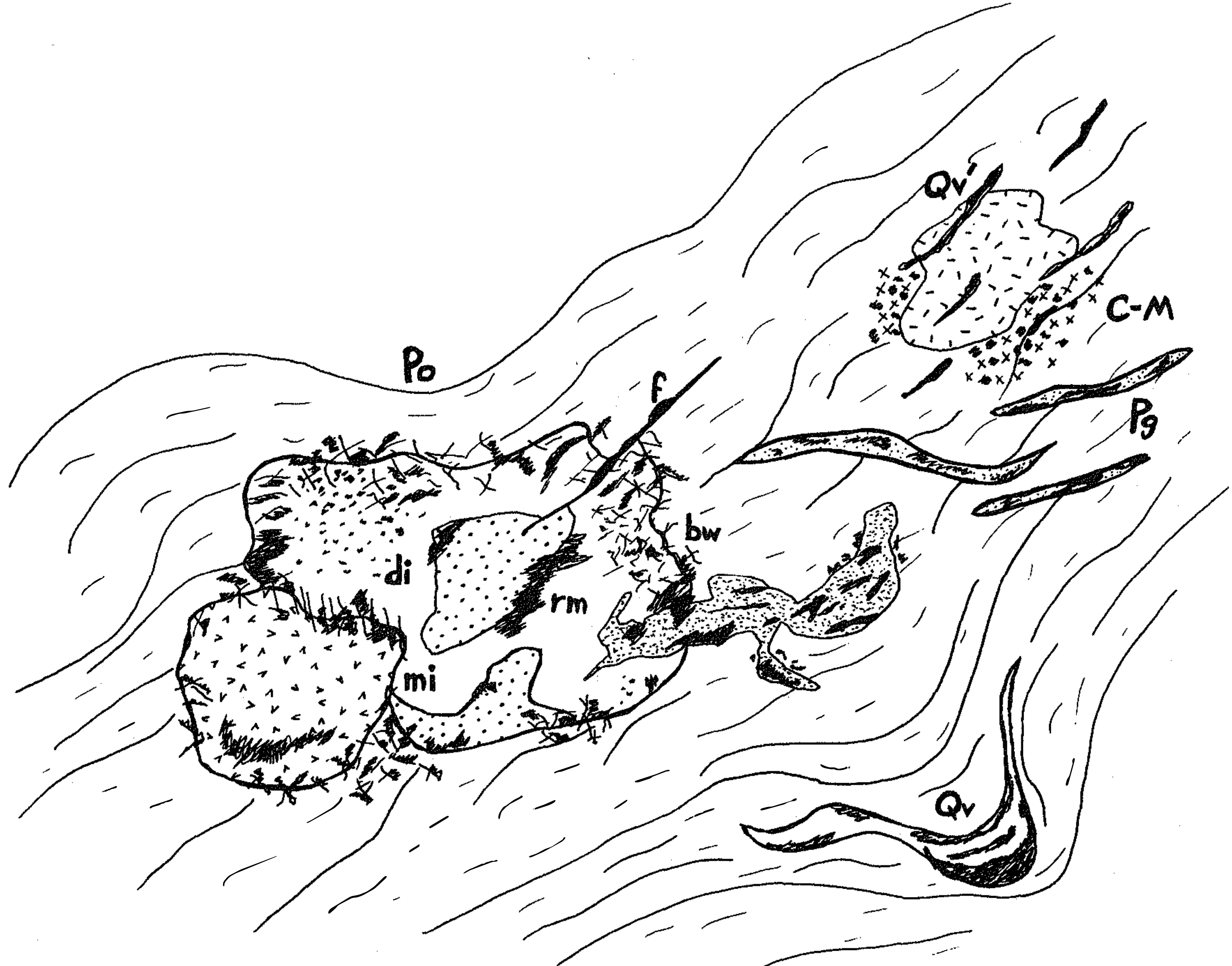

Figure 1.
Summary sketch of molybdenum mineralization-deposit types. No scale intended. Blackened areas and cross-hatching indicate mineralization. Po-porphyry Cu-Mo type, di-disseminated, mi-multiple intrusion, rm-replacement mass, bw-boxwork f-fault; Qv-isolated quartz-vein type; Qv'-quartz-vein type associated with intrusion; Pg-pegmatite type; C-M-contact metasomatic type.

Description of Deposit Types

I. Vein Type

Most economically important molybdenum deposits are characterized by mineralized quartz veins or vein networks. However, mineralization is not restricted to quartz veins in these major producer deposits which are associated with porphyry-type mineralized plutons (see IV below). Deposits where ore is restricted only to quartz veins (the true vein-type) are common, but are seldom economic. True vein-type deposits are most often found in or near granitic plutons, but other non-economic occurrences are known in gold-producing districts throughout the world's older, Precambrian volcanic terranes (fig. 1). These veins are usually without any direct relationship to plutonic bodies. In all veins, molybdenite occurs in plate-like masses, typically concentrated around the vein walls and along fractures in the quartz (Baxter, 1978).

In Canada, some veins contain valuable quantities of bismuth (Vokes, 1963), although overall, Canadian vein-type molybdenum deposits are only of marginal economic importance. Quartz-vein molybdenite in western Australia is known to occur with pyrite ± fluorite, sheelite, and wolframite (Mulgine deposit; Baxter, 1978). In the U.S., perhaps only the Questa, New Mexico district (Carpenter, 1968) has some deposits which could be considered as quartz-vein molybdenite producers.

II. Disseminated Type

In some rare instances, plutonic rocks have been mineralized only with broadly disseminated molybdenite concentrations. By themselves, these occurrences are devoid of any real economic potential. Not only are the ore grades too low (typically much less than .05% Mo), but the disseminations are usually limited to replacement masses which occur in hydrothermally altered areas of a pluton. These disseminations may become exploitable when combined with other types of mineralization in porphyry deposits (fig. 1).

III. Pegmatite-Aplite Type

Depending on magmatic parameters such as the depth of crystallization, water content, and temperature, felsic plutons may be characterized by: (1) few if any quartz veins or pegmatite dikes; (2) abundant quartz veins, or (3) abundant pegmatites and aplite dikes. Unlike the majority of quartz veins, pegmatite masses can be quite large, and when mineralized, include significant quantities of molybdenum ore. However, molybdenite is not often concentrated in large volumes in host pegmatites.

Molybdenite occurs in pegmatites as disseminated interstitial plates (much as do micas in some igneous rocks) as well as in concentrations near contacts and within areas of hydrothermal alteration. This mineralization may be associated with the genesis of various other ore and gangue mineral phases (base-metal sulfides, beryl, uraninite, apatite, topaz, columbite, cassiterite, monzite, and so forth).

Vokes (1963) notes that molybdenite-bearing pegmatites are common in the Precambrian terranes of Canada, but that major occurrences are too few to be important economically. The same relationship appears to be true for other parts of the world.

IV. Porphyry Type

Prophyry-type molybdenite deposits typically have very complex mineralization patterns involving large volumes of rock. Molybdenite is usually most abundant in stockwork fracture and vein networks on the periphery of host plutons. In porphyry deposits, other ore locations may include disseminations and replacement masses within the pluton, large quartz veins, dikes, faults and other structures, and invaded country rocks (fig. 1).

In all but a few cases, porphyry mineralized intrusives are of calc-alkaline chemical affinity (Westra and Keith, 1981). This is to say that these rocks in their original unaltered state are not overly alkaline nor silica deficient, but are chemically typical of most continental orogenic areas, such as the western U.S. (Guild, 1978) or southwest Asia. Molybdenite deposits in association with alkalic plutons are rare, and are usually better known as sources of other economic commodities.

Pervasive hydrothermal alteration is a key feature marking mineralized portions of porphyry intrusives. More specifically, the alteration is not just the addition of water to break-down feldspars and other minerals, but also the real addition of components such as Si, K, Al, and base metals. The hydrothermal processes are concentrated in the upper levels of intrusions and near contacts, and hence, mineralization is localized near the pluton's periphery.

Three major varieties of alteration have been identified in the ideal case of a volatile-rich molybdenum (actually Cu-Mo)-porphyry intrusive (Lowell and Guilbert, 1970). This general case was developed from observations of deposits in the western U.S. where sedimentary wall rocks are common. Alteration occurs on both sides of contacts. As shown in cross-section (fig 2), alteration ranges from "prophylitic" at distance from the pluton, to "argillic" (or "phyllic") nearer the pluton to "potassic" nearest the contacts. The first two alteration types involve the replacement of original mineral assemblages by hydrous phases. Potassic alteration is often synonymous with potassium metasomatism, in which rock is replaced by orthoclase and K-rich micas. This phenomenon frequently accompanies molybdenite mineralization (Barnes, 1967; Stanton, 1972).

Multiple intrusion and multistage hydrothermal activity are complicating factors which increase the efficiency of mineralization in porphyry-type deposits. Successive magmas and fluids have the effect of saturating the host rocks in ore components and refining ore deposition (Eidel and others, 1968; Wallace and others, 1968; Wallace and others, 1978). Wallace and others (1968) carefully detailed the amazing complexities associated with mineralization in the Climax molybdenite deposit. The Climax deposit has typically produced over 50 million pounds of molybdenum (MoS_2 + MoO_3) concentrate per year. No other type of deposit could possibly contain this quantity of ore.

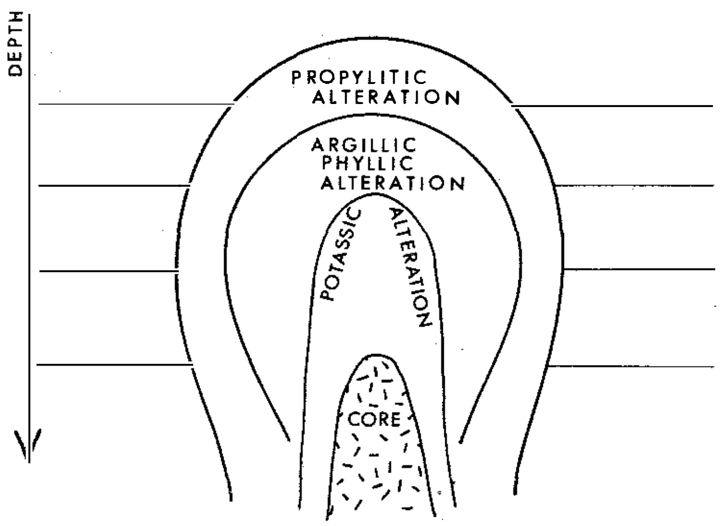

Figure 2.
Alteration zones around a pluton shown in vertical section. Modified after Lowell and Guilbert (1970).

V. Contact-Metasomatic Type

Although Kummer (1979) and others have mentioned contact-metasomatic settings for molybdenite mineralization, this class of deposits is unusual and by itself, accounts for only a small fraction of the world's production of molybdenum. The economic limitation is that mineralized skarns or tactites do not possess large volumes of rock with sufficiently high metal content.

From the category name, contact-metasomatic deposits imply those located near pluton contacts where country rocks have been baked and invaded by mineralizing fluids (fig. 1). Peculiar mineral assemblages often accompany ore deposition. Some early interpretations proposed that the country rocks were the source of ore fluids. However, most evidence now indicates that magmatic fluids are likely sources for mineralization. Many of the better known examples of these deposits are in metamorphosed limestones and dolomites in Ontario.

Precambrian Geologic Setting in Northern Wisconsin

The Precambrian bedrock-geology of northern Wisconsin is characterized by different terranes, each consisting of a somewhat distinct age-group of rock units. These areas are outlined on figure 3 which is generalized from the Bedrock Geology Map of Wisconsin (Wisconsin Geological and Natural History Survey, 1981).

In the extreme northwestern part of the state, rock units are grouped as Keweenawan in age, about one billion years old. The units are mainly volcanic and sedimentary rocks deposited within and along the huge fault-bounded trough which includes Lake Superior. A few Keweenawan intrusions (gabbroic to granitic) also occur in this terrane. Granites dated as Archean in age (2.8 billion years old), as well as gneisses and metavolcanic rocks inferred to be Archean, are located southeast of the Keweenawan units. Archean-age gneisses and metavolcanic rocks are also found in the southernmost extreme of the major Precambrian shield area in Wisconsin. By far the largest area of Precambrian bedrock is made up of two Early Proterozoic (about 1.9 billion years old) Penokean-age terranes which trend southwest to northeast over most of the central and eastern parts of northern Wisconsin. The Penokean terranes can be summarized as a northern belt of mostly metasedimentary rocks and Archean gneiss domes and a southern belt of predominantly metavolcanic rocks intruded by various types of plutons. The two terranes are separated by the Niagara Fault (fig. 3). Some of the Penokean-age plutons are granites which host the known and potential molybdenite occurrences in Wisconsin.

Igneous rocks comprising approximately 9000 km^2 in the southeast of Wisconsin's Precambrian shield form the 1.5 billion year old Wolf River batholith. These rocks are different phases of alkali granite with associated syenite and anorthosite. There are also several small inliers of post-Penokean-age granites and rhyolites (about 1.75 billion years old; similar to the Mo-bearing rocks in the northeast) and quartzites in south-central Wisconsin. These inliers are exposed within Paleozoic sedimentary bedrock south of the major exposure of the Precambrian.

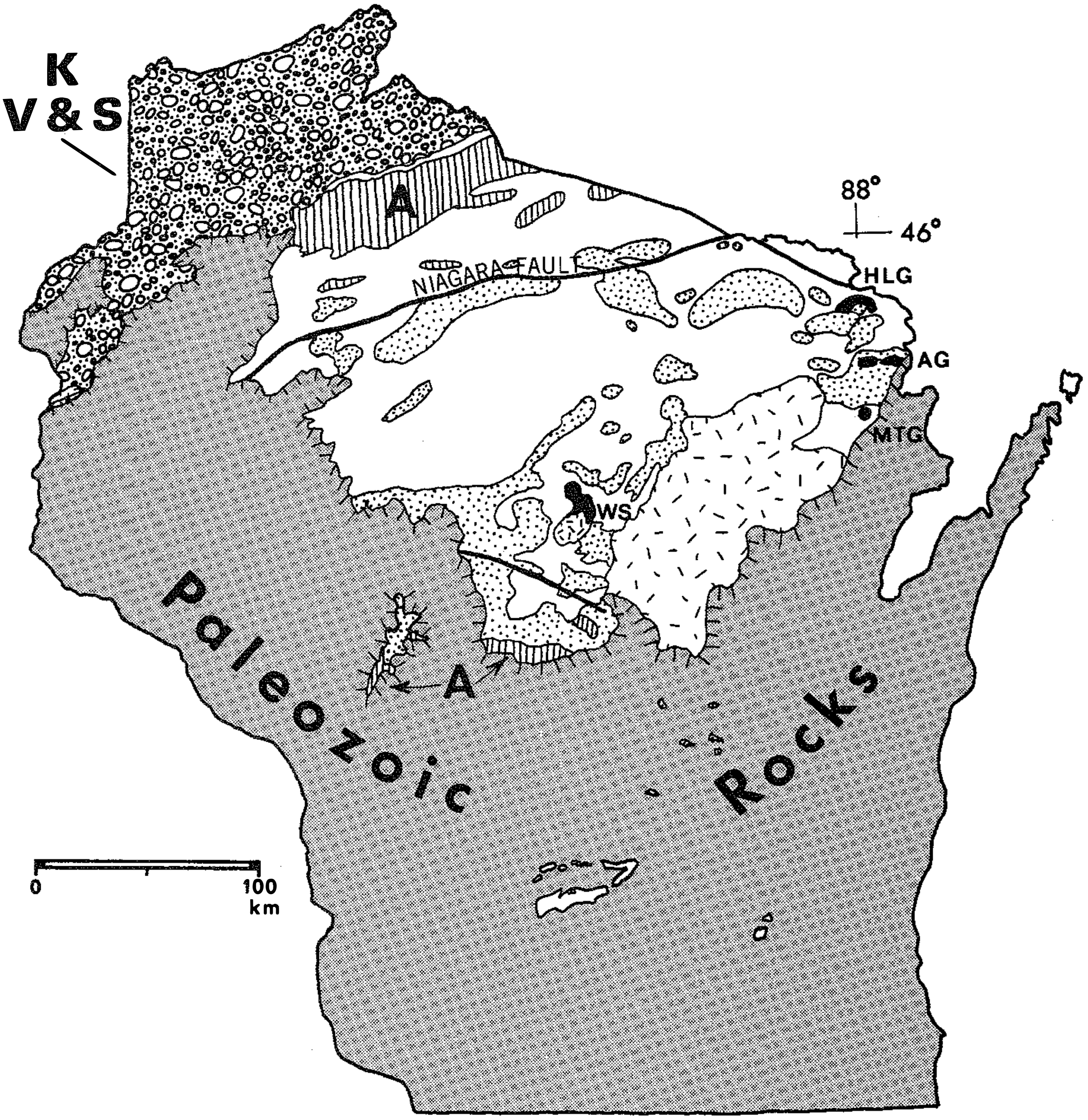

Figure 3. Simplified geologic map of Wisconsin showing the four molybdenite occurrences: HLG-Hoskins Lake Granite, AG-Amberg Granite, MTG-Mount Tom Granite, WS-Wausau Syenite. Keweenawan-age volcanic and Sedimentary rocks (K V & S) are shown in pebble-pattern; Archean-age rocks are in vertically-ruled pattern; Penokean-age volcanic and sedimentary rocks are within the northern Wisconsin Precambrian region and are shaded; Penokean-age granitic and gneissic rocks are in stippled patterns; the 1.5 billion year old plutons are in a random-dash pattern. Scattered inliers of Precambrian granite, rhyolite, and quartzite are exposed within the southern exposure of Paleozoic rocks. Map modified after the geology map of Wisconsin (Wisconsin Geological and Natural History Survey, 1981).

MOLYBDENUM IN NORTHERN WISCONSIN

Molybdenite occurrences in Wisconsin have only been recognized since the 1930s and 1940s (Fisher, 1957). Since that time no economic production has taken place, but nearly 1400 kilograms of molybdenite were removed from the Middle Inlet property (see below) from 1939 to 1940. In addition, several prospect pits were excavated on what is now the Frank Wolsker property in Florence County (also below). In each case, fairly high-grade ore exists in sub-economic quantities. Ore removed from the Middle Inlet property averaged near .15% Mo. This was hand-picked from much leaner material, however.

Middle Inlet (Camp Five) Prospect

Location and History

The best known molybdenite prospect in Wisconsin is the Camp Five operation near Middle Inlet in Marinette County (figs. 3 and 4). This property is in the SW¼NW¼ of sec. 18, T. 33 N., R. 20 E. and occupies but a few acres. Prospecting began in 1937 with increased activity from 1939 to 1940. The major prospecting operation was conducted by the Wisconsin Molybdenite Corporation, founded for this purpose alone. Processing equipment (crushers, and so forth) were utilized in the extraction of just over 2800 kg. of 47.82% molybdenum concentrate. Sporadic interest in this property continued into the late 1970s, even though the prospecting operations were abandoned in the 1940s (fig. 5).

Geologic Setting

The molybdenite occurrence at Middle Inlet is contained within the northern margin of a granite pluton (Greenberg and Brown, 1980). This circular body (as defined by its geophysical signature) is informally referred to as the Mount Tom granite, and is exposed in an inactive quarry on the flank of Mount Tom (figs. 4 and 6). Mount Tom granite is predominantly red to red-gray and contains mineral phases in the proportions given in Table 1. This is a two-feldspar biotite-granite that contains signs of late-magmatic (subsolidus) reactions between phases. Some of these features include albite mantling perthite grains, altered cores of zoned plagioclase, and quartz grains embayed against plagioclase. No pegmatites were observed at the quarry nor at any of the other granite exposures. However, aplite dikes (fig. 6) and quartz veins are abundant. Chemically (Table 2a), the granite is calc-alkaline and meta- to peraluminous. Samples are characteristically very siliceous (74% SiO_2), potassic (5.2% K_2O) and typical with regard to most trace elements in calc-alkaline granites. (The major exception is high levels of Ba 1000 parts per million [ppm] or greater.)

Although outcrops are not sufficient to be certain, available data (including geophysical) indicate that metavolcanic rocks almost completely surround the Mount Tom pluton. A very extensive terrane of reddish granite is

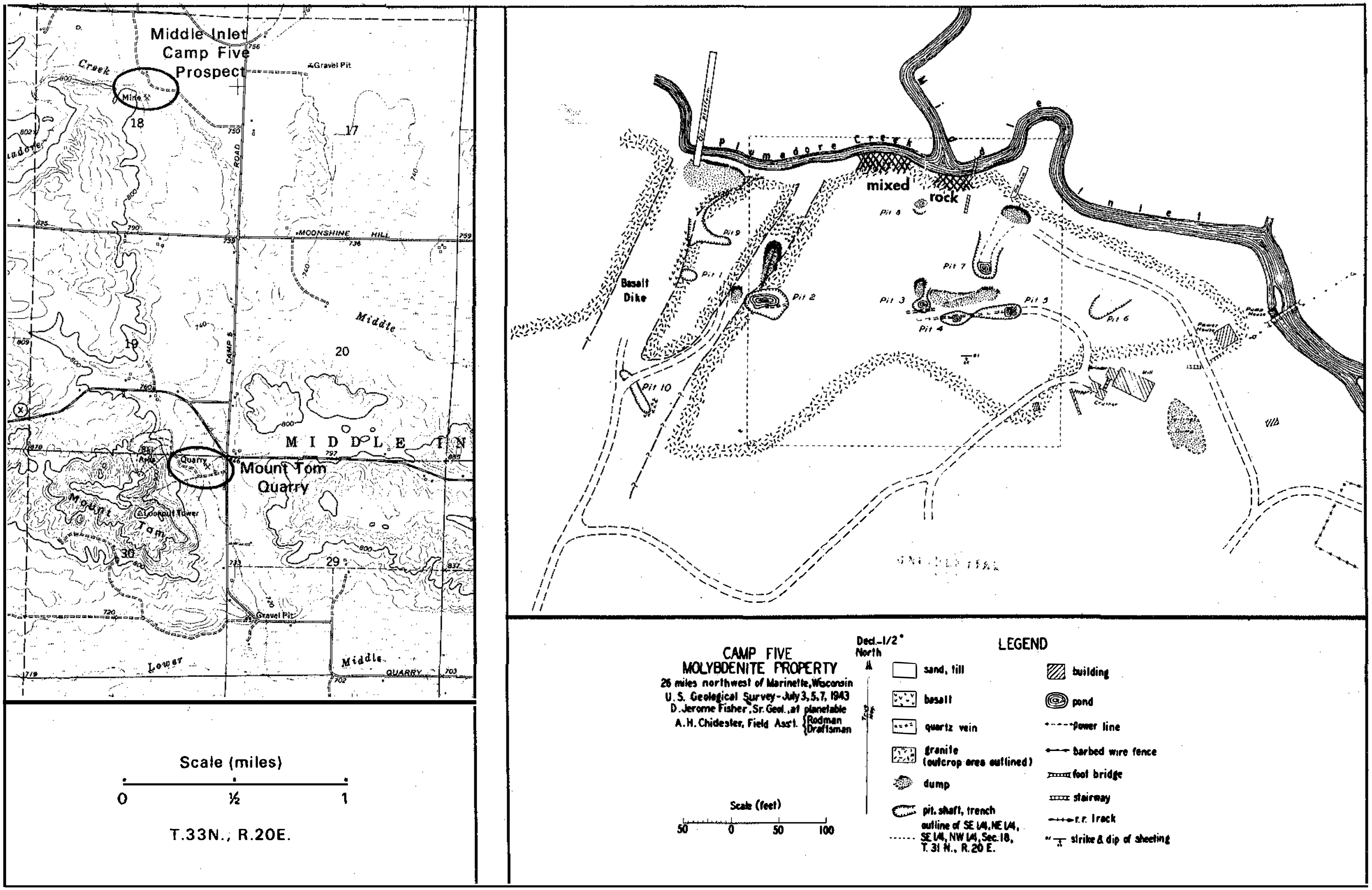

Figure 4. Location and prospect maps of the Middle Inlet molybdenite occurrence. Maps taken from the Mount Tom 7½ minute topographic quadrangle and Fisher (1957).

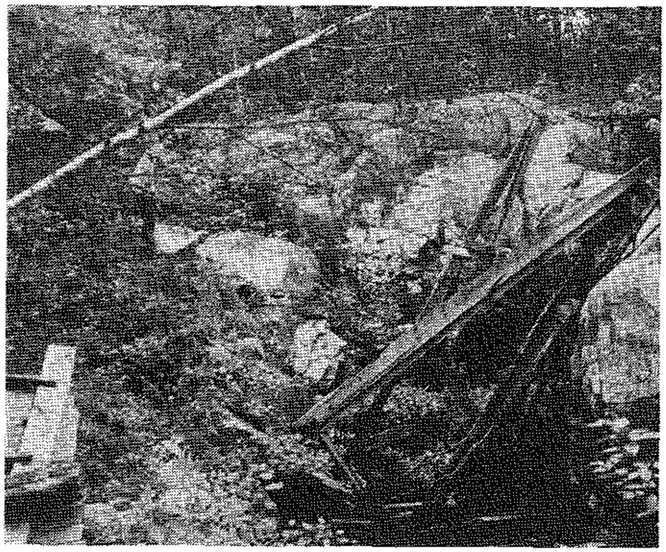

Figure 5.

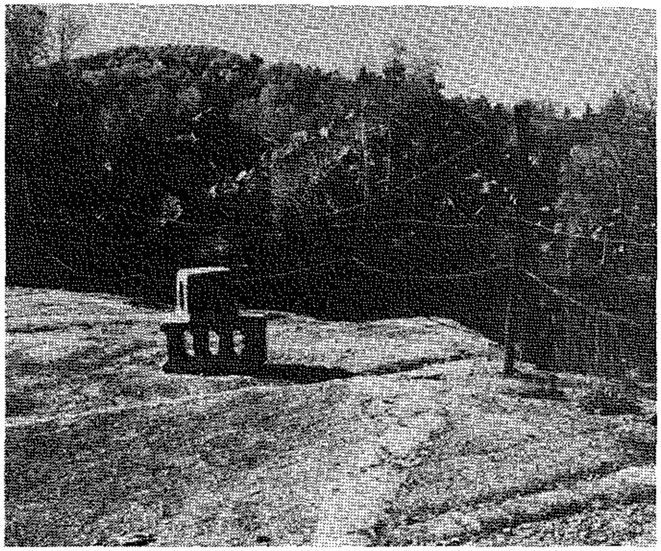

Figure 6.

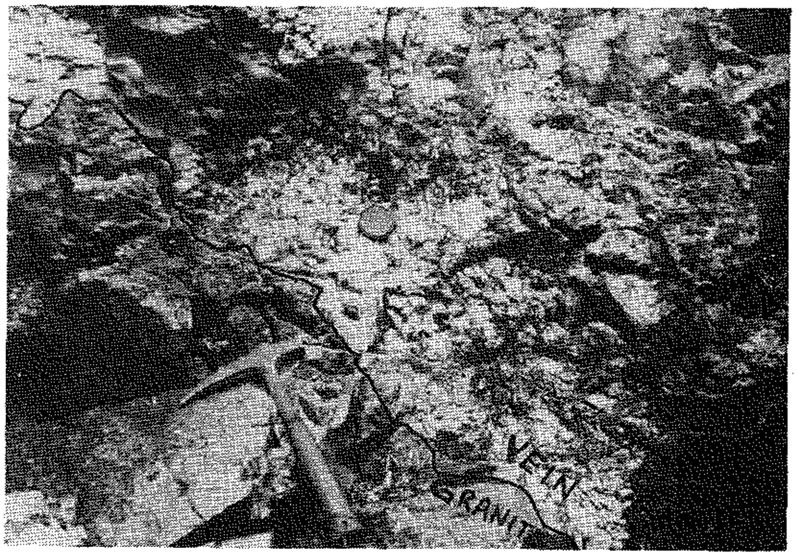

Figure 7.

Figure 5.
Broken-down workings at the main excavation of the Middle Inlet prospect.

Figure 6.
Mount Tom granite exposed in the quarry with Mount Tom in the background. Note the aplite dike in the bottom center of the picture. Located in NE¼NE¼ sec. 30, T. 33 N., R. 20 E.

Figure 7.
Molybdenite (gray) filling fractures in quartz (white) at Middle Inlet. The quartz vein is in contact with altered granite on the left side of the picture.

located north of the Middle Inlet area (about seven kilometers). This is the Athelstane granite mass which is very similar petrologically to the Mount Tom rocks and could be comagmatic. All of these granitic plutons appear to be post-tectonic, that is, they are predominantly unfoliated and otherwise deformed only in certain discrete zones. The age of the Athelstane rocks is about 1.85 billion years (Van Schmus and others, 1975).

Due to the lack of exposure, the metavolcanic rocks in the Middle Inlet area are poorly known, but they are assumed to be part of the Penokean volcanic belt which trends structurally from southwest to east across the entire region. These rocks are intruded by the granites, but, their exact age is unknown. In many places, the mafic volcanic rocks have been incorporated as inclusions in plutons. Furbish (1953) described a mixed-zoned of magma contamination at the Middle Inlet molybdenum property where granite has assimilated mafic country-rocks.

Although Krewedl (1967) postulated east-west faulting north of the mineralized veins at Middle Inlet, there is no evidence of major faulting in the area. There is no obvious correlation between molybdenite mineralization and post-magmatic structural features in this particular case.

Local Geology, Nature and Extent of Mineralization

Morris (1940), Furbish (1953), Fisher (1957), and Krewedl (1967) briefly describe the geology and mineralization at the Middle Inlet prospect. A rough map of the area is shown in figure 5. Molybdenite occurs in irregular quartz veins (to 4 meters thick) cutting granite. Most of the exploited veins and other major ones observed strike E-NE and are nearly vertical. Small concentrations of quartz, which Fisher (1957) considers as the latest generation, are almost completely barren with respect to mineralization. The prospect's workings intersect quartz veins in ten pits (fig. 4). Molybdenite is concentrated near the center of veins, along fractures (fig. 7). In very sporadic instances, the molybdenite occupies as much as 20% of the vein material. Ore grades in the veins appear to vary randomly, as do the pinch-and-swell thicknesses of different veins. Other minerals, including fluorite and pyrite, are only rarely encountered in the larger veins. Ferrimolybdite and hematite occur with or without fluorite in some of the smaller quartz segregations in the granite and along some of the vein-fracture walls.

The origin of the quartz veins and molybdenite appears to be intimately related to easterly and northeasterly-trending fractures and minor faults localized near the margin of the host granite. Hydrothermal fluids utilized the available fractures as conduits for mineral deposition and replacement. In many places, vein-introduced quartz is concentrated within altered granite beyond defined vein walls. Fisher (1957) observed a gradual transition from a quartz vein, to a feldspar-quartz boundary zone, to altered granite and eventually, unaltered granite. The change from vein to altered granite is usually more abrupt, however.

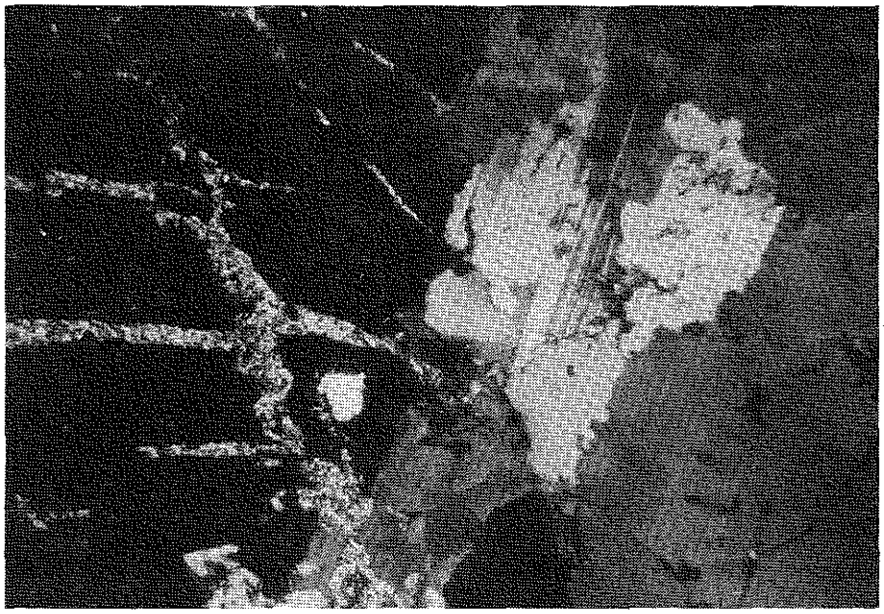

Figure 8. Photomicrograph of microveinlet of mostly calcite, sericite and quartz transecting altered granite at Middle Inlet. Horizontal dimension, about 8 mm.

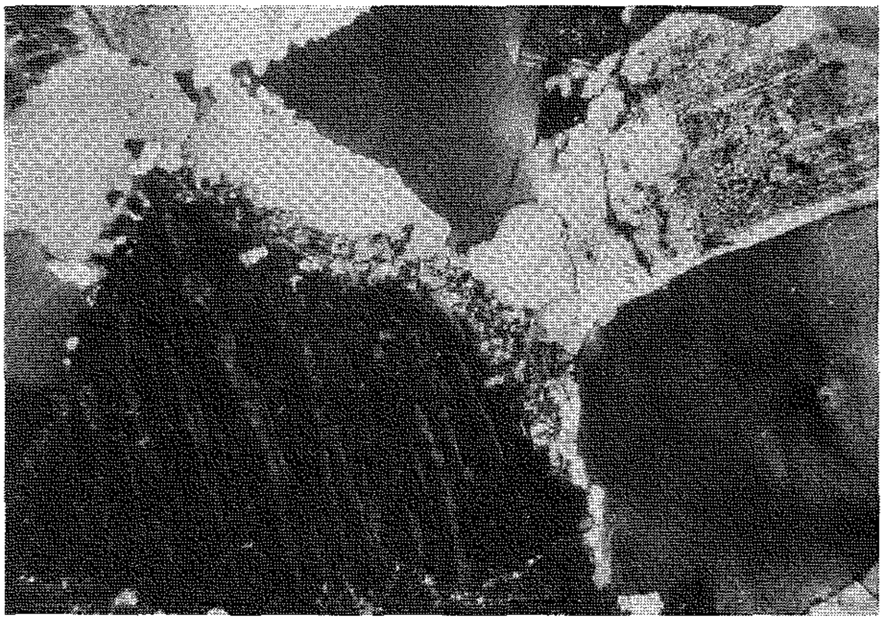

Figure 9. Photomicrograph of mortar texture in Middle Inlet granite, displaying strained quartz and feldspar with finely granulated quartz concentrated at large-grain boundaries. Horizontal dimension, about 8 mm.

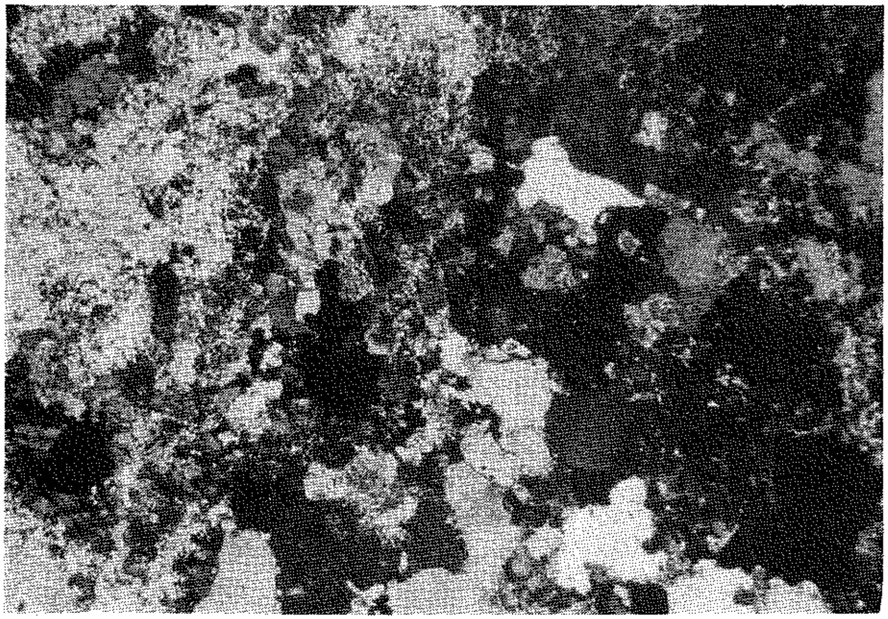

Figure 10. Photomicrograph of hybrid "mix-rock" consisting of large sericite clots and many small grains of secondary microcline, from the northern margin of the Middle Inlet prospect area (see fig. 4). Horizontal dimension, about 8 mm.

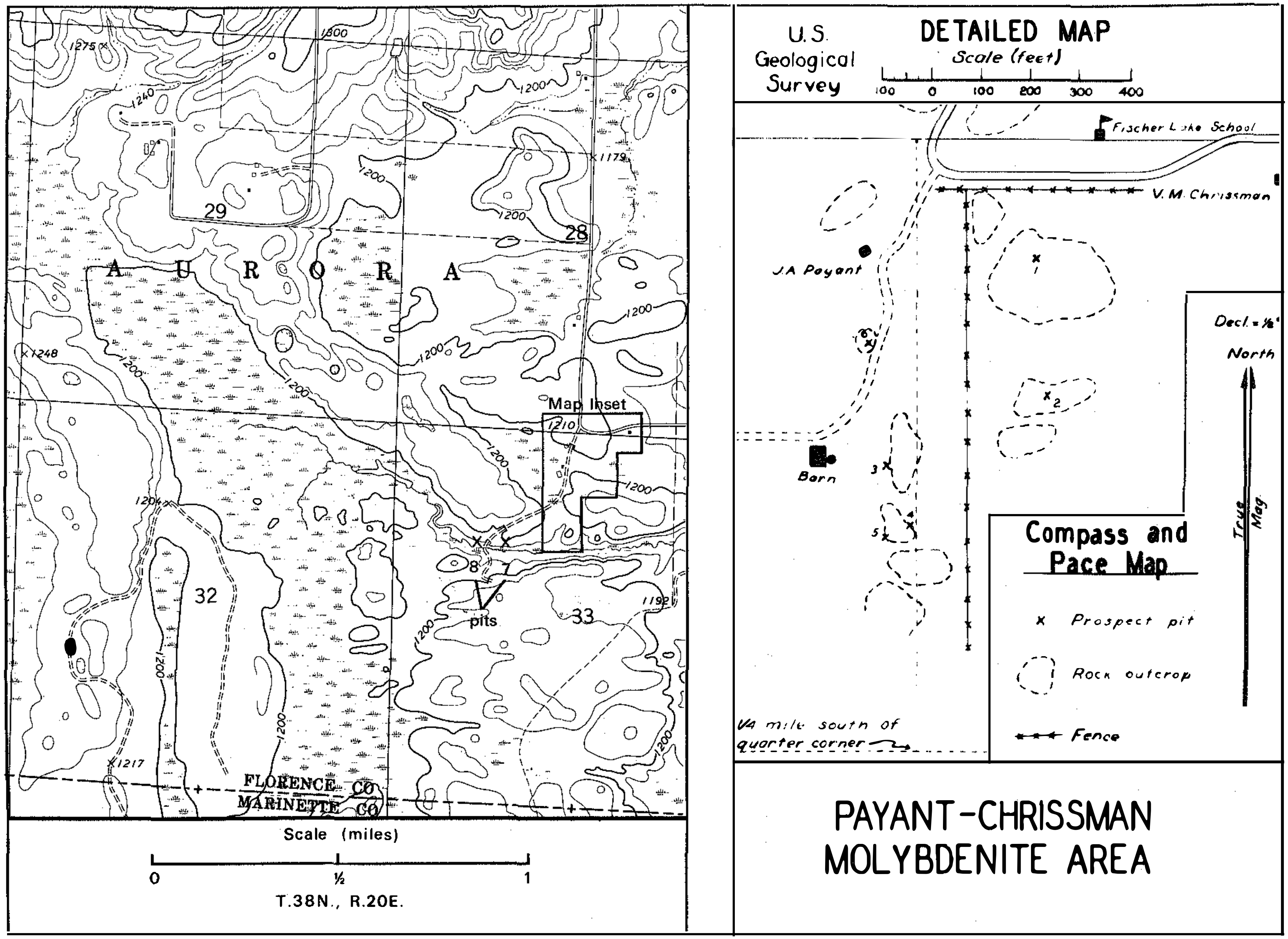

Figure 11. Location and prospect maps of the Florence County molybdenite occurrence. Maps taken from the Dunbar 7½ minute topographic quadrangle and Fisher (1957).

The rare, unaltered granite at the prospect is very similar to the rock at the Mount Tom quarry (about 2.5 km to the southeast). Almost all the Middle Inlet host-granite shows the effects of hydrothermal alteration in the abundance of sericite, epidote, chlorite, and secondary quartz ± calcite in micro-veinlets (fig. 8). Near the quartz veins, much of the observed granite is altered, with white micas, chlorite, quartz, and rarely albite replacing original mineral assemblages. In addition, thin sections of granite from samples near quartz veins display moderate to severe amounts of unresolved strain. Plagioclase grains are often bent, and primary quartz has been polygonized with tiny mortar-texture quartz grains developed along the boundaries of larger grains (fig. 9). Molybdenite is sparsely disseminated in altered granite, but always within about a meter of molybdenite-mineralized quartz veins.

At the north end of the prospect area, a thin zone of granite-mafic mixed rock is exposed (fig. 4). Aside from containing pyrite, samples of this hybrid display potassium metasomatism, with plagioclase altered to and replaced by sericite and large quantities of small, secondary microcline grains (fig. 10). One collected sample of mixed rock contains discrete patches of pyrite and vugs lined with euhedral microcline. It could not be determined whether this alteration is related to or contemporaneous with other alteration and molybdenite crystallization.

As depicted on the map (fig. 4), one or more mafic dikes, with the same orientation as some quartz veins, have intruded the granite. Fisher (1957) described the dike rock as basalt, and Furbish (1953) used the term lamprophyre. There are some very minor contact effects where the dike has baked the granite, and it might also be concluded that the dike is later than quartz vein development (Krewedl, 1967). No quartz can be found in the dike. It is conceivable, however, that the veins and dike might be contemporaneous.

The total exposed area of molybdenite-bearing veins or rock at Camp Five is about 20 m wide and extends the length of the outcrop along strike (of the veins). Only a fraction of the rock in this area displays mineralization and much of that at about .15% Mo on the average has been removed by prospectors. Any estimates of remaining ore must be extremely small if only exposed rock is considered. Exploratory drilling was completed on an unexplored part of the Camp Five property by Exxon in 1973 (P. Schmidt, oral comm.). Apparently, nothing too encouraging was found. Drilling away from the exposure could possibly increase the potential amounts of molybdenite, but the estimated ratio of ore to waste rock would probably not increase.

Florence County Prospect

Location and History

The Florence County prospect pits (formerly called the Payant-Chrissman property by Fisher, 1957) are located on figure 11 and occur in the north-central part of sec. 33, T. 38 N., R. 19 E. (fig. 3). The pits where molybdenite has been found are scattered across the property in several outcrops. One pit has been built over and is now inaccessible.

Molybdenite was first discovered on the Payant property during the excavation of a well. Pits were later dug and blasted to exposure mineralization. Academic interest remains in these pits, but at present, only sample and minor test material has been removed.

Geologic Setting

For two reasons, the geologic environment of the molybdenite prospect in Florence County is perhaps better understood than that around Middle Inlet. Primarily, bedrock outcrops are more abundant in Florence County than in southern Marinette County. Also, several reports and graduate theses are published information sources for rocks in Florence County; foremost among these are Cain (1962), which provides helpful descriptions of the area and its surroundings, and Dutton (1971), which has contributed data on the geology north and west of the prospect.

The prospect is situated in the western lobe of the arcuate Hoskins Lake granite body (Cain, 1962). The pluton is approximately the same age (1.85 billion years old; Banks and Cain, 1969; Van Schmus and others, 1975) as Athelstane granite and most of the other dated plutonic and volcanic rocks in northeastern Wisconsin, thus making all these units likely products of the Penokean orogeny (Van Schmus, 1980). Compositionally, Hoskins Lake rocks are compositionally true granite with gradations to granodiorite as plagioclase and mafic content increase (table 1). Textures are generally porphyritic with large (to 5 cm) potassium feldspar phenocrysts in a medium- to fine-grained groundmass of quartz, plagioclase, microcline, and mafic minerals (mostly biotite). The rock is typically foliated, with alignment of phenocrysts, groundmass biotite, or both. Cain (1962) notes that rocks in the west lobe of the pluton exhibit a strong N. 40° E. to N. 80° E. directional preference in biotite and phenocryst orientation, while only the micas and groundmass have this orientation in the east lobe. It is not unusual, as Cain mentions, for the phenocrysts to be aligned N-S, that is, nearly perpendicular to the groundmass and regional foliation, in the east. The difference between the two lobes can be explained in terms of regional tectonics.

The Hoskins Lake and other units in the area lie at the eastern end of a very major E-W trending structural boundary (Greenberg and Brown, 1980). The boundary is expressed in geophysical lineaments, some lithologic changes, and strong deformational fabrics in the various rock types. Recent field observation and the structural map of Cain (1962) suggest that the western lobe of the Hoskins Lake pluton was more strongly affected by deformational stress than the eastern lobe. Phenocrysts in the west were reoriented or more probably recrystallized under the influence of the prevailing regional stress field, whereas the stress was probably not great enough in the east to alter the original crystallization or igneous-flow orientation of phenocrysts. However, this structural concept alone does not explain all the unusual characteristics of the Hoskins Lake granite that may relate to molybdenite mineralization.

The geological complexity of this area in Florence County is enhanced by the proximity of certain other tectonic features. A unit known as the Dunbar gneiss is located just southwest of the Hoskins Lake granite and is in contact with the pluton's western lobe. The gneiss is truly a tectonic complex of intrusions (mostly pegmatites) cutting various types of gneissic and migmatitic units. All the rocks have been deformed, the oldest ones preserving several generations of folding. E-W oriented structures appear to be the most dominant. At many places, the proposed contact of the Dunbar gneiss with other units (including the Hoskins Lake granite) is gradational and complicated, due to structural and chemical interaction. About eleven kilometers north of the Hoskins Lake granite and fourteen kilometers north of its contact with the Dunbar gneiss, the prominent Niagara fault (Dutton, 1971) separates the tectonic belt containing all previously mentioned units, as well as amphibolite-facies metavolcanic rocks and metagabbros from lower-grade metasedimentary units to the north. Molybdenite is only associated with granitic units (Hoskins Lake granite, Athelstane granite) of the metavolcanic belt in northern Wisconsin (fig. 3).

Local Geology, Nature and Extent of Mineralization

In Fisher's 1957 report on molybdenum in Wisconsin, little mention was made of the granitic host rocks for mineralization at the Payant-Chrissman, Florence County prospect. The molybdenite-bearing pegmatites were simply said to occur in "schist and gneiss." Upon inspection of the geologic maps for this area, the rock-type description appears to be in conflict with the exposed Hoskins Lake granite. However, especially along the western and southwestern margin of the pluton, a great deal of country rock-granite interaction is evident. The typical porphyritic appearance of the granite is also obvious in rocks that are not strictly magmatic. The best interpretation is probably that the granite and country rocks (metasedimentary?) at the prospect have intermingled through metasomatism and metamorphism to form a pegmatite-rich hybrid with igneous-appearing K-feldspar phenocrysts (to 50%) in a dark, foliated groundmass of biotite, plagioclase (oligoclase to andesine), quartz, and minor microcline. This rock is nearly a schist or gneiss that looks like a granite. Except for the phenocrysts, it approximates a diorite in composition. Perhaps some of the associated pegmatites have been sweat-out of a more felsic precursor. The metasomatism and complex crystallization history are mentioned by Cain (1962) and alluded to by Fisher (1957) through the process of introducing potassium feldspar into the country rock at the prospect. The present study indicates that this same phenomena was a crucial factor for molybdenite concentration; that is, the potassium metasomatism in this area was contemporaneous with mineralization.

In contrast to the quartz-vein molybdenite association at Middle Inlet, the Florence County prospect is most correctly classified as a pegmatite type of occurrence. Virtually all the molybdenite is incorporated in the pegmatites with none found in the country rocks. Pegmatites occur in different forms: (1) distinct dikes (fig. 12) up to a few meters wide, usually conformable to the foliation (N. 30° E. to N. 70° E.); (2) concordant lenses or pods; (3) discordant patches; and (4) thin concordant to discordant stringers and veinlets. The dikes and stringers in particular are frequently zoned with quartz cores and feldspars (mostly potassium-rich) ± muscovite growing perpendicular to contacts. As Fisher (1957) observed, quartz originating in pegmatites may form secondary veinlets intruding across the dikes and into country rocks. Fisher also believed that some quartz segregations may constitute a development younger than all other features. Mineral composition of the pegmatites varies according to the relative abundance of the four major phases-quartz, K-feldspar, plagioclase, and muscovite. Biotite was rarely observed. Quartz-rich and K-feldspar-rich variants are the most common. Interesting minor phases include: garnet, tourmaline, pyrite, chalcopyrite, and fuchsite (a Cr-muscovite). Chemical analyses of four pegmatite samples (Table 2a) show a range of silica values from 70% to over 79% depending upon the amount of free quartz. K_2O averages near 5%, except in altered samples, such as F8-Mo, which contain high K_2O (9.67%). Rb is uniformly high in the pegmatites (greater than 300 ppm), probably reflecting the very late hydrothermal activity. The pegmatites are best categorized as peraluminous calc-alkaline granites.

The 8 pits at the Florence County prospect (fig. 11) show that there are different modes of molybdenite occurrences within the pegmatites. Most commonly, discrete flakes of molybdenite cluster in quartz segregations, large perthite crystals, and veinlets. Some pyrite and red hematite-staining also occur in the clusters. Only rarely are the molybdenite flakes disseminated through large portions of dikes or pods. In at least one case, molybdenite was observed to exist in layers and conform to the zoning in a dike. Perhaps the most interesting environment of mineralization is in a hydrothermally altered pegmatite, located near the south end of the Wolsker property (fig. 11, pits 4 and 5). Granitic country-rock in contact with the altered pegmatite contains pyrite and sericitized phenocrysts (fig. 13). At this site, relatively recent prospecting has blasted surface rock without the formation of a pit (fig. 14). Much of the broken pegmatite is highly altered, with red K-feldspar and red-yellow staining (hematite, ferrimolybdite). Pyrite and muscovite are abundant, and molybdenite grains are scattered throughout the greisen. Other features are quartz-lined vugs and secondary, euhedral orthoclase crystals replacing original phases (fig. 15). Orthoclase and muscovite are clear indications of potassium metasomatism (potassic alteration) associated with molybdenite. The transfer of potassium from the Hoskins Lake granite into its surroundings apparently included molybdenum and possibly other resources as well. In fact, uranium exploration has taken place in a similar geologic environment only a few kilometers to the northwest of the molybdenite prospect.

If Fisher's (1957) estimations (with the concurrence of the present author) are considered even partially accurate, the Florence County prospect contains molybdenite as less than .05% of the exposed outcrop, which by itself, does not constitute a large volume of rock. Therefore, like the workings at Middle Inlet, this prospect has dubious resource potential.

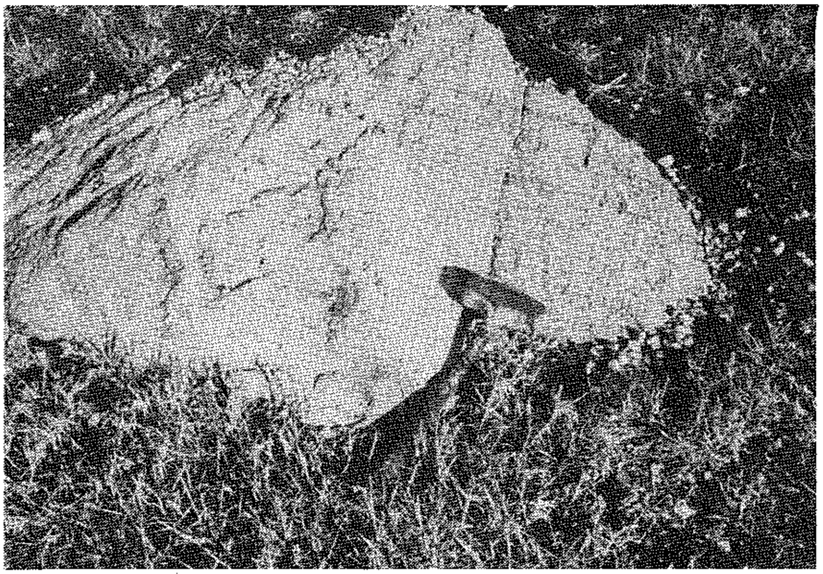

Figure 12. Pegmatite dike (light-colored) cutting Hoskins Lake Granite in Florence County.

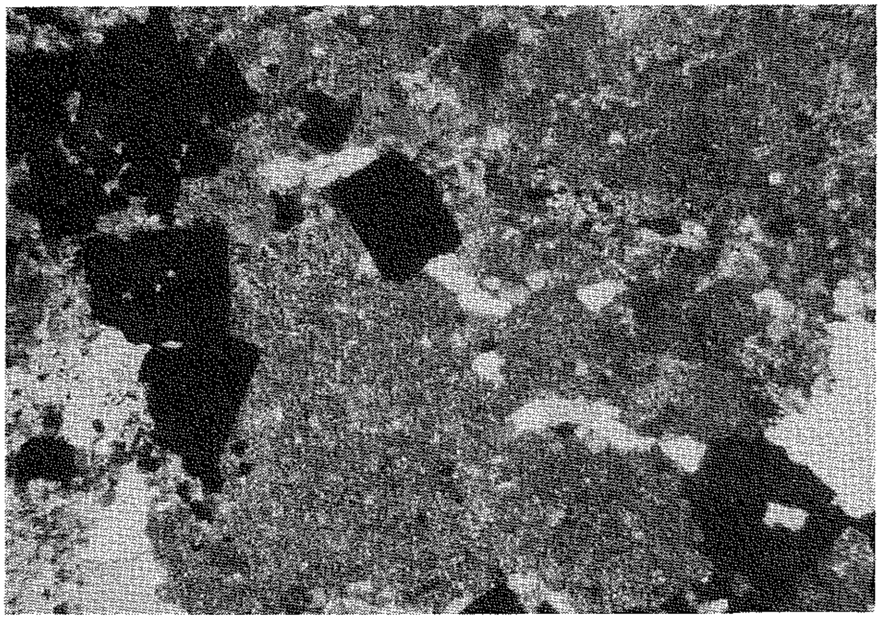

Figure 13. Photomicrograph of altered country-rock granite from the Florence County molybdenite occurrence, containing large sericitized phenocrysts and abundant pyrite. Horizontal dimension, about 8 mm.

Figure 14. Blasted exposure of altered pegmatite (pit number 4, fig. 11) on the Frank Wolsker property, Florence County.

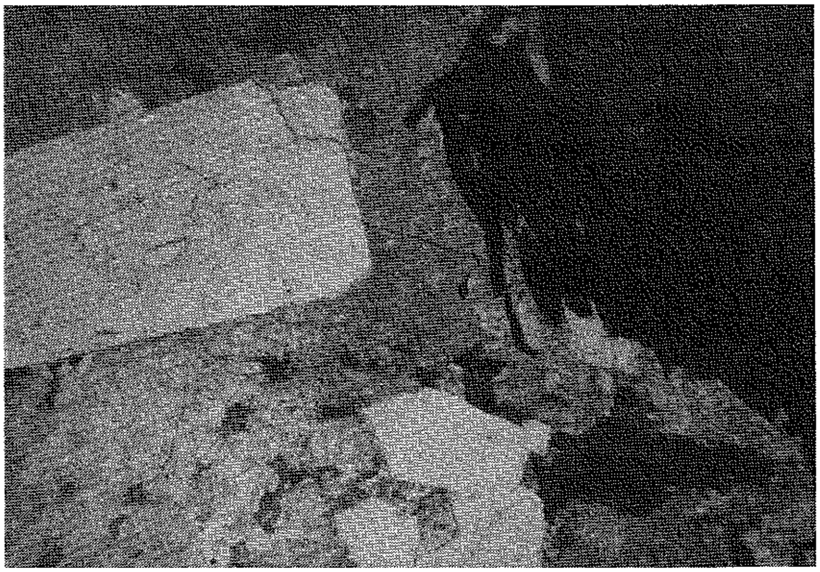

Figure 15. Photomicrograph of mineralized pegmatite displaying molybdenite (black) and secondary euhedral orthoclase (light gray), from pit number 4 on the Frank Wolsker property, Florence County. Horizontal dimension, about 8 mm.

EVALUATION OF MOLYBDENUM POTENTIAL IN WISCONSIN

Summary of Known Occurrences

The Middle Inlet and Florence County molybdenite prospects are not the only occurrences known in the state. Morris (1940) and a letter in the files of the Wisconsin Geological and Natural History Survey, from Mr. Lyle Daniels to the State Geologist in 1941 discuss the occurrence of molybdenite grains in a pegmatite cutting granite at Amberg, Wisconsin (fig. 3, NW¼SE¼ sec. 10, T. 35 N., R. 21 E.). This is a minor occurrence in a flooded granite quarry, but it also illustrates the association of granitic intrusions with molybdenite in northeast Wisconsin. Pegmatite dikes similar to those throughout northeast Wisconsin are common in the granite at Amberg (fig. 16). As described (Morris, 1940), the molybdenite-bearing pegmatite is also similar to those mineralized at the Florence County Prospect.

The addition of the Amberg occurrence illuminates a potentially important relationship. All the known molybdenite occurrences in granites (3) are restricted along a north-south line in the eastern tenth of the exposed Precambrian terrane in Wisconsin (fig. 3). This relationship may be a coincidence, or it may suggest that a specific environment conducive to mineralization exists in the northeast.

In addition to the above granitic associations, there is one other known molybdenite occurrence in Wisconsin and one reported but unconfirmed. Scattered grains of molybdenite can rarely be found in pegmatitic phases of the Wausau syenite (Morris, 1940). This isolated occurrence (fig. 3) from Wausau is likely the result of rare-metal enrichment typical in peralkaline pegmatites. However, seldom is molybdenite economically concentrated in peralkaline intrusions (Mutschler and others, 1981). The Wausau syenite is therefore not considered as particularly significant. Morris (1940) also mentioned the existence of molybdenite in "limestone" (p. 58) near Mellen in northwest Wisconsin. This is not a proven occurrence, but its location and description imply a skarn environment of mineralization.

Even though there are only four verified cases, it is important to examine the major similarities and differences among the molybdenite occurrences in order to identify possible guides to mineralization. The two main prospects are compared and contrasted below with additional notation where appropriate for the Amberg granite quarry. The syenite occurrence is considered a unique and exceptional case. The possible occurrence at Mellen is too conjectural for evaluation. Abbreviations are: MI, Middle Inlet; FC, Florence County; AQ, Amberg Quarry.

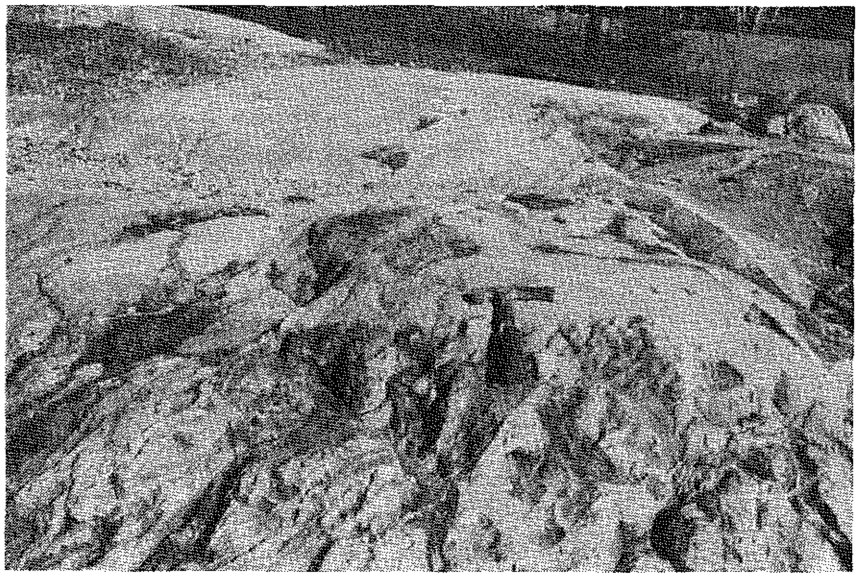

Figure 16. Exposure of Amberg gray granite cut by thin pegmatites in an abandoned granite quarry, Marinette County.

Table 1. Modal Mineralogy of Molybdenite Host Granites.

Sample Number	D-36	D-165	D-168
Potassium feldspar	40%	35%	45%
Oligoclase	15%	25%	20%
Quartz	20%	20%	15%
Biotite	20%	15%	15%
Other	5%	5%	5%

Hoskins Lake Granite (from Cain, 1962)

	Ranges for Six Samples
Perthite and microcline	30-37%
Primary plagioclase (An_{30})	23-27%
Secondary plagioclase (An_{12})	1- 3%
Quartz	28-33%
Biotite-chlorite	2-5%
Other	Trace-1%

Mount Tom Quarry Granite (Athelstane - type)

A) Prospects Compare:

1. alkaline-rich granite association (+AQ)
2. similar age (+AQ)
3. important role of silica mobility
4. potassium metasomatism
5. dikes or veins at least partly controlled by regional foliation (AQ?)
6. key minerals--quartz, muscovite (sericite), pyrite
7. geographic location in same region (+AQ)
8. lack of country rock mineralization (+AQ)
9. some chemical interaction with country rocks

B) Prospects Contrast:

1. quartz-vein mineralization (MI)
2. pegmatite mineralization (FC-AQ ?)
3. albitization (MI)
4. post-tectonic host pluton (MI-AQ)
5. syn-tectonic (?) host pluton or proximity to a complex structural zone (FC)

This listing perhaps indicates a higher degree of similarity than dissimilarity. Obvious correlations include the host-rock type, general location, age, and limit of mineralization to dikes or veins. Also implied is the dependance on hydrothermal processes (K-metasomatism) and some structural control of mineralization. The Amberg granite occurrence bears characteristics of both the others, and it could be said that all three vary significantly only in some geochemical details.

Geochemical Data

Chemical analyses of five Middle Inlet samples and five samples from the Florence County molybdenum prospect (table 2a) indicate that there is more difference between the two occurrences than just contrasting mineralization types (quartz vein versus pegmatite). The host-rocks at both localities are calc-alkaline, K_2O - and Al_2O_3 - rich granites, but they are not the same. Even where visably altered and mineralized, the Middle Inlet granite varies little in major element chemistry (except for SiO_2) from the unaltered rock. This uniformity suggests that the Mount Tom pluton may represent an unzoned, homogeneous intrusion. The same data is also evidence that there was little actual net transfer (gain or loss) of chemical constituents during quartz-vein development and mineralization. It has been commonly observed that there is little correlation between the composition of unaltered host granitoids and the presence of molybdenum mineralization (Govett and Nichol, 1979; Barr and O'Beirne, 1981). Such appears generally to be true for the Middle Inlet occurrence, where Krewedl (1967) found higher than background levels of Mo only in silicified granite at the prospect.

Even among only four samples, the granite and pegmatites of the Hoskins Lake granite in Florence County display great chemical variability. This is

Table 2a. Chemical Analyses of Rock Samples from Wisconsin Molybdenite Prospects.

	1	2	3	4	5	6	7	8	9	10
SiO_2	75.90	74.92	76.17	76.04	74.27	70.72	75.84	79.47	70.15	68.17
TiO_2	.11	.09	.10	.11	.17	.14	.01	.02	.01	.37
Al_2O_3	13.14	14.20	13.46	13.74	13.31	16.64	14.42	12.13	15.35	16.76
$Fe_2O^{*}_3$	1.06	.64	.83	.77	1.82	1.33	.38	1.53	.42	2.75
MgO	.25	.14	.18	.14	.22	.30	.06	.13	.09	.49
CaO	.39	.10	.21	.11	.33	1.39	.18	.06	2.08	.77
Na_2O	2.30	2.11	2.46	3.23	3.38	4.59	3.63	.22	2.27	2.73
K_2O	5.53	6.75	5.80	5.46	5.24	4.72	5.62	4.37	9.67	6.73
Rb	131	166	133	121	132	339	396	422	649	428
Sr	53	45	47	70	68	279	26	16	59	182
Y	35	21	29	18	46	7	7	5	28	26
Zr	126	162	134	148	220	89	33	49	69	149
Ba	1074	1516	1057	1087	1168	1393	78	264	246	1112

*Total Fe as Fe_2O_3

Major elements are weight %

Trace elements are parts per million

1. Middle Inlet sample M1-Mo; altered molybdenite-bearing granite
2. Middle Inlet sample M2-Mo; slightly altered red granite
3. Middle Inlet sample M3-Mo; similar to M1-Mo
4. Middle Inlet sample M4-Mo; "fresh" red granite
5. Mount Tom quarry sample 1; quartz. biotite-chlorite-rich granite
6. Florence County sample F1B-Mo; gneissic phase of large "country rock" pegmatite
7. Florence County sample F6H-Mo; tourmaline, garnet, pyrite-bearing pegmatite
8. Florence County sample F7D-Mo; quartz-perthite pegmatite
9. Florence County sample F8-Mo; Molybdenite-bearing altered pegmatite
10. Florence County sample F6C-Mo; "Hoskins Lake granite," porphyritic, pyrite-rich

Table 2b. Chemical Analyses of Rock Samples from Various North American Molybdenite Occurrences.

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	73.89	77.20	81.30	60.14	67.40	76.16	70.3	70.3	68.87	58.84	76.9	76.7
TiO_2	.26	.11	.09	1.39	.62	.01	.22	.22	.50	.71	.13	.05
Al_2O_3	12.98	11.96	9.61	16.29	15.07	12.56	13.9	15.4	14.33	17.84		
Fe_2O_3	.89	.13		1.30	1.06	.58	2.3	1.7	4.19	3.17	13.4	13.0
FeO	.67	.16	.94	5.82	2.66	.29	1.2	.52	1.49	2.86	1.2	.6
M_gO	.21	0	.01	2.60	1.39	.06	.50	.42	1.01	1.98		
CaO	.92	.18	.30	4.81	2.70	.27	.90	.73	.15	6.15	-	.6
Na_2O	3.34	3.65	2.44	3.64	3.69	3.82	3.2	3.7	.15	3.18	.2	.06
K_2O	5.26	5.03	3.59	2.28	3.53	4.41	5.8	5.8	4.74	4.22		
P_2O_5	.06	-	-	.36	.15	.02	.10	.07	.15	.35	.87	.42
Rb	222	364	241	101	170	326	-	-	-	-	3.9	4.2
Sr	80	15	15	465	302	68	-	-	-	-		
Y	-	-	-	-	-	-	-	-	-	-	4.3	4.7
Zr	191	105	95	-	-	-	-	-	-	-		
Ba	305	35	50	797	882	162	-	-	-	-		
Zn	23	57	33	84	153	38	-	-	-	-		
Pb	20	39	108	18	99	82	-	-	-	-	130	30
Cu	3	7	.5	168	202	47	500	480	7,300	tr	4	15
S	100	500	11,300	2110	1230	50	9,500	1,300	47,900	1,300	34	20
F	-	-	-	630	510	275	-	-	3,500	1,000		
Mo	-	-	Min.	4	4	3	300	45	Min.	-	420	100

Major elements are weight %
Trace elements are parts per million
Min.-specifies molybdenite mineralized samples, without analyses

1 "K-feldspar Megacrystic granite", Newfoundland (from Whalen, 1980, p. 1253)
2 Aplite, Newfoundland, (from Whalen, 1980, p. 1253)
3 Mineralized aplite, Newfoundland, (from Whalen, 1980, p. 1253)
4 Quartz monzodiorite, Nova Scotia, (From Barr and O'Beirne, 1981, p. 400)
5 Porphyritic granite, Nova Scotia, (from Barr and O'Beirne, 1981, p. 400)
6 Aplite, Nova Scotia, (from Barr and O'Beirne, 1981, p. 400)
7 Alaskite, North Carolina, (from Schmidt, 1978, p. E28)
8 Quartz monzonite, North Carolina (from Schmidt, 1978, p. E28)
9 Altered monzonite, Nevada, (from Stanton, P. 395)
10 Unaltered monzonite, Nevada, (from Stanton, p. 395)
11 Unaltered granite, Alaska, (from Hudson et al, 1979, p. 1813)
12 Altered granite, Alaska, (from Hudson et al, 1979, p. 1813)

no doubt due to large grain-size and the resulting inability to pick samples large enough to accurately represent the overall composition. In contrast to the Mount Tom-Middle Inlet samples, the pegmatites are much higher in Rb, and their very low K/Rb ratios indicate extreme magmatic fractionation. The abnormally high K_2O content (9.67%) of sample F8-Mo reflects the predominance of secondary orthoclase and white mica introduced during potassium metasomatism. Both factors, the extreme fractionation and metasomatism, are conducive to the concentration of molybdenum in the pegmatites. The somewhat analogous late-to-post-magmatic feature at Middle Inlet was quartz vein development. It could be speculated that the Hoskins Lake area is just what would be found at Middle Inlet if a few kilometers of crust were eroded away, exposing pegmatites as higher temperature and pressure equivalents of quartz veins. The reported occurrence of molybdenite in pegmatites of the Amberg granite is probably but not certainly analogous to the mineralization in Florence County pegmatites.

The granitic host-rocks for molybdenite occurrences in Wisconsin are quite silicic and felsic, and this should be accepted as a prospecting guide. However, throughout the world there is a wide variability in molybdenite host-pluton types, the great majority of which can be described as calc-alkaline and aluminous. Mutschler and others (1981) characterized the chemistry of host-plutons and alteration associated with many western U.S. molybdenum deposits and prospects. Two classes of mineralized intrusions were identified, a granite "system" and a more mafic granodiorite "system". This classification is mostly concerned with porphyry-type deposits, but it is also generally applicable to magmas that host molybdenite occurrences.

Table 2b lists the rock chemistry of host-plutons for various North American molybdenite deposits and prospects. A few general similarities are noteable among the different plutons. K_2O is generally high, over 4%, but is only 2.3% in one sample from Nova Scotia (Barr and O'Beirne, 1981). Na_2O shows no enrichment or albitization tendency. This contrasts with the sodium metasomatism commonly attendant with igneous uranium mineralization. Other element abundances emphasize the whole continuum of possible host-rock types within the general calc-alkaline category. SiO_2 varies from 58.5% to 77.2% in unaltered samples and from 68.9% to 81.3% in altered (silicified) rocks. Al_2O_3 and the alkali and alkali-earth trace elements, Rb, Sr, and Ba are also quite variable, indicating that a wide range of feldspar compositions and relative abundances can occur in mineralized plutons. Therefore, the stark differences between Middle Inlet host-rocks and those at the Florence County prospect are not surprising. Unfortunately (for exploration purposes), the only good concentrations of pathfinder elements occur in the alteration or mineralized zones of host rocks. Cu, S, and often F accompany Mo in most cases. Krewedl (1967) found anomalously high Mo (26 ppm) with high Cu (505 ppm) in some of the metasomatized (assimilated?) pyrite-rich hybrid rock at Middle Inlet. He concluded that some molybdenite mineralization may be unexposed along the northern edge of the prospect area.

Guidelines for Molybdenum Exploration in Wisconsin

As a result of examining the various characteristics of Wisconsin's molybdenite occurrences, a broad scheme of guidelines (or criteria) for molybdenite exploration is proposed. Normally, these criteria would also apply to related mineralizations such as copper, tungsten, tin, bismuth, and uranium in granitic rocks. To a limited extent, this is true here. However, due to the absence or paucity of other metal concentrations with molybdenite in northeastern Wisconsin, the criteria should be extended only with reservation. In order to reduce the amount of subjectivity in this proposition, criteria have been chosen and given priority on the basis of known worldwide deposits of molybdenite, and also roughly according to the format utilized in Greenberg and others (1977).

Several occurrences of molybdenite, with and without copper mineralization, are known in the southern complex crystalline terrane of Michigan's Upper Peninsula (Bodwell, 1972). This area is about 80 kilometers due north of the Florence County prospect in Wisconsin. Like Wisconsin, the Michigan occurrences may constitute a restricted province with its own unique characteristics. The major apparent relationship between the two regions is in their longitudinal situation on 88° W. The significance of longitude is unknown.

The mineralization in Michigan is associated with quartz veins and pegmatites that intrude Archean-age (pre-2.5 billion year old) gneisses and granite and also Proterozoic iron formation, quartzites, and metagraywackes. Associated minerals include, chalcopyrite, bornite, beryl, tourmaline, tetrahedrite and muscovite (Henrich, 1976). Two of the reported occurrences are in gold mines and two are in iron mines.

A very intriguing relationship can be observed on the map of Bodwell (1972). In the vicinity of the marked molybdenite prospects in northern Michigan there is a major belt of Proterozoic metasedimentary rocks, the Marquette Trough, compressed between two Archean massifs. Molybdenite is known only on the northern edge of the Trough and in the Archean Southern Complex to the south. This contrasts greatly with the known gold prospects which occur only on the north edge of the Trough and in the Archean Northern Complex to the north. The demarcation between gold and molybdenum provinces is probably a function of the early crustal distribution of these two elements. Therefore, prospecting for gold out of a gold province may be futile. Likewise, in Wisconsin, where gold is virtually unknown the crust may never have been enriched in this element. This comparison leads to the seemingly trite conclusion that areas of known occurrence have significant resource potential. In practical terms this suggests seeking new deposits in proven areas, perhaps before extending prospecting elsewhere. The <u>prime</u> exploration criterion of a known metallogenic province may supercede all others mentioned below.

When examined worldwide, the criteria necessary for molybdenum deposits are few.

A. The only essential prerequisites for molybdenite mineralization are:

   1. felsic plutons (usually calc-alkaline) for source rocks;

   2. some type of hydrothermal activity (usually water, silica, and alkali-rich alteration).

B. The most common tectonic environments for deposits are:

   1. Precambrian shield areas (as in Ontario and western Australia)

   2. Phanerozoic continental-orogenic areas (as in the western United States, British Columbia, and the Andes).

   Deposits within these areas are typically near the same age and may constitute a molybdenum province of several deposit types.

C. The important geological entities known as hosts for molybdenite mineralization are:

   1. veins (mostly quartz-rich);

   2. pegmatites and aplites;

   3. plutons themselves (either complex porphyry-types or simple disseminations);

   4. wall rocks (skarns, tactites).

   These are roughly the same categories as presented in the introduction. Geologic hosts other than the above should normally not be considered as prime exploration targets.

D. Other complicating factors which are particularly important in the economic quality of deposits are:

   1. structural features, such as faults and cataclastic zones;

   2. multiple intrusions;

   3. multiple alteration (hydrothermal, metasomatic) episodes.

   These are all secondary processes which may enrich primary mineral concentrations.

In Wisconsin, the essential criteria (A-1 and A-2) for molybdenite mineralization have obviously been fulfilled. Any future exploration should be focused on felsic plutonic areas where there is evidence of hydrothermal activity. A strong inducement to exploration may be the fact that all the significant molybdenite occurrences in Wisconsin are in rocks of approximately the same age and in a tightly restricted region of a Precambrian shield area (criterion B-1). The three occurrences in the state may constitute a minor example of a molybdenum province. In reference to criterion C, it is not considered likely that the conditions necessary for porphyry deposits exist in Wisconsin. Porphyry deposits are almost entirely restricted to criterion B-2, Phanerozoic continental-orogenic areas (Sillitoe 1972; Torske, 1976). Veins, pegmatites, and contact metasomatic occurrences are all common in Precambrian terranes (Voke, 1963) and may exist in Wisconsin in addition to occurrences already known. The last category of exploration criteria (D) should narrow economic searches for molybdenum to those targets or parts of targets where maximum enrichment is predicted.

Suggesting actual targets for molybdenum exploration in Wisconsin is not easy. Beyond the most obvious target area, that of the northeast--in and around the known molybdenite occurrences--I must register the disclaimer that suggestions are speculative and should constitute only a first order evaluation. The general indication is that Wisconsin does not have the geology or prospecting history which would indicate a high potential for molybdenum resources. Neither of the two known prospects contain any realized resource potential.

Granitic terranes in Wisconsin's extreme northeast include the sites of three molybdenite occurrences. The total area intruded by potential host-plutons is about 1000 km^2 (fig. 3). Pegmatites, quartz veins, and potassium metasomatism are widespread and abundantly evident. Structural complications and multiple intrusions are also known at various locations in this region. This 1000 km^2 (area I on fig. 17) is given the highest exploration potential. Two others (II and III) are designated as general targets. Both areas contain relatively abundant exposures of alkaline-rich granitic rocks in the age range of about 1.75-1.85 billion years old. Area II covers a large part of Marathon County, and is structurally very complex. This area also includes the traces of molybdenite in 1.5 billion year old alkalic syenite. Area III is located south of II and is similar. Some of the granites in this area are distinctly altered and variably deformed. Also included in Area III are some of the granitic rocks exposed as inliers in Paleozoic bedrock south of the main exposure of Precambrian rocks.

The prime difficulty in examining these exploration targets is their limited exposure and the resulting lack of observable contacts between plutons and country rock. No exploration tool can adequately remove the obscuring effect of thick glacial overburden characteristic of much of Wisconsin.

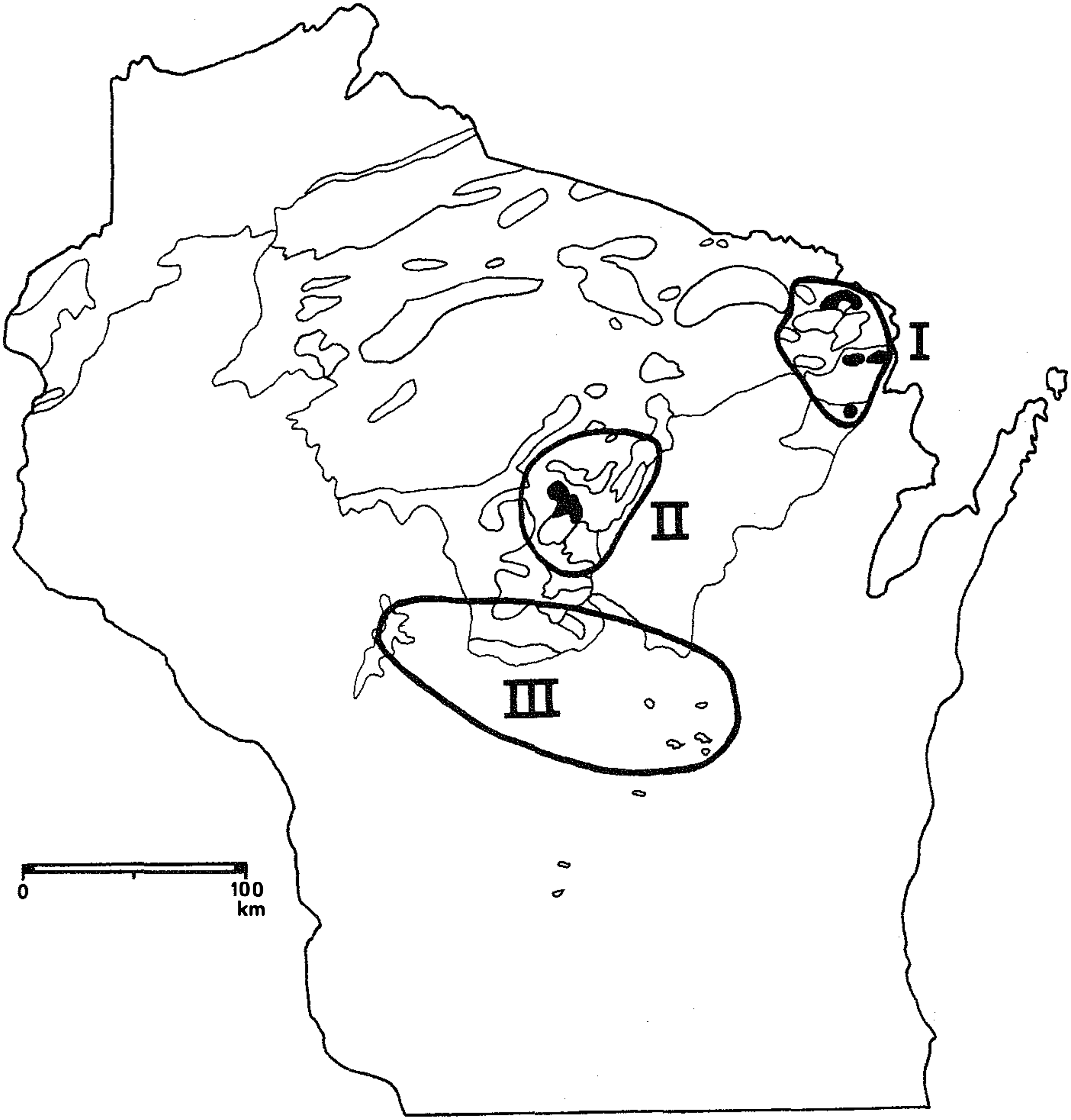

Figure 17. Outline geology map of Wisconsin showing three areas considered to have the most likely potential for molybdenite mineralization. Modified after the page-size geology map of Wisconsin (Wisconsin Geological and Natural History Survey, 1981).

Pluton bodies can be roughly delineated (beneath overburden) through the combination of gravity and magnetic surveys. Detailed surveys are often precise enough to locate contacts and thus the vicinity of highest mineralization potential. Electromagnetic methods of various kinds may have application in locating areas of faulting, strong hydrous-alteration, and metallic-mineral (including sulfide) accumulation. Once rock which fulfills several exploration criteria is sampled at the surface or by drilling, the material can be analyzed for major and key trace-elements. Evidence of alteration may at times be present in unusually high alkali contents or other major element anomalies. However, trace elements such as Cu, Pb, Zn, F, Bi, W, Sn, in addition to Mo itself may be enriched to the point of becoming true pathfinder guides to molybdenite mineralization. Unfortunately, fresh, unaltered plutonic host-rocks are usually devoid of these anomolies (Govett and Nichol, 1979). Only the rocks altered during mineralization are dependable as consistent exploration guides.

Indirect exploration methods can also be good indicators of molybdenite concentration. The geochemical analysis of soil and glacial materials (Bolviken and Gleeson, 1979) in combination with analyses of ground water, surface water, and stream sediments is a technology capable of revealing the dispersion of pathfinders from an orebody. In addition, organic sediments (lake bottoms, bogs, and so forth) and especially plants are known to act as accumulators of molybdenum (Carlisle and Cleveland, 1958). These methods might prove to be particularly helpful in Wisconsin, where the National Uranium Resource Evaluation (NURE program of the U.S. Department of Energy) has already resulted in the identification of areas with anamolous concentrations of various metals.

The above discussion leads to the conclusion that a highly integrated exploration approach, incorporating many if not all the possible methods would be best suited to the search for molybdenum and most other metallic resources in Wisconsin. The geologic criteria mentioned and direct exploration techniques should be utilized to first narrow-down the target possibilities. Next, indirect techniques would affect more accurate targeting.

As already stated or implied, the nature of molybdenum resources in Wisconsin does not constitute any economic concern at present, nor perhaps in the foreseeable future. In order for molybdenite exploitation to be a possibility, both the readily accessible supply of molybdenum elsewhere and the lack of supply in Wisconsin must change status. There is little doubt among market analysts that molybdenum will have continued if not enhanced importance in worldwide industrial utilization. This factor may keep exploration for new ore deposits as a viable proposition among mineral companies.

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