FLAMBEAU - A PRECAMBRIAN SUPERGENE ENRICHED MASSIVE SULFIDE DEPOSIT

by

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ABSTRACT

The Flambeau volcanogenic massive sulfide deposit located in northwestern Wisconsin occurs within the southern lobe of the Canadian Precambrian Shield. The steeply dipping tabular body is enclosed within a complex pile of cyclic schistose intermediate to felsic fragmental volcanics. No chloritic alteration pipe is recognized but adjacent rocks have undergone magnesia metasomatism and subsequently were metamorphosed to the upper greenschist or lower amphibolite facies.

Although modest in size the deposit is of special interest in that it has an extensive and well preserved supergene enrichment blanket. Economic minerals found within a pyritized quartz-sericite schist are chalcocite and bornite overlying primary chalcopyrite.

INTRODUCTION

The discovery on November 6, 1968 of massive sulfide mineralization south of Ladysmith marked the first significant copper discovery in Wisconsin. Announcement of the find in 1970 by Kennecott Copper Corporation triggered extensive base metal exploration activity throughout northern Wisconsin (Erdosh, 1975) which continues to date. As a result, three additional massive sulfide deposits have been found. These are the Thornapple (Kennecott), the Pelican River (Noranda), and the Crandon (Exxon) deposits (see Figure 1). Although the Flambeau deposit is copper-rich, the other deposits are zinc dominant with insubordinate amounts of copper and lead. Thus the discovery of the Flambeau far exceeds in importance the size of the deposit since its discovery has resulted in what could be the development of a new domestic mining district.

Wisconsin has a long tradition of lead and zinc mining from the Upper Mississippi Valley District (Friz, 1975). However, copper production from the District has been insignificant, with approximately 10,000 short tons of ore produced (Heyl, 1973). Hope for additional copper sources was revived when native copper and later chalcocite ores were discovered on the Michigan Upper Peninsula, to diminish when subsequent exploration west along strike into Wisconsin was unsuccessful. Consequently little interest was shown by most copper companies to further explore the state.

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1 Flambeau Mining Corporation, Ladysmith, Wisconsin

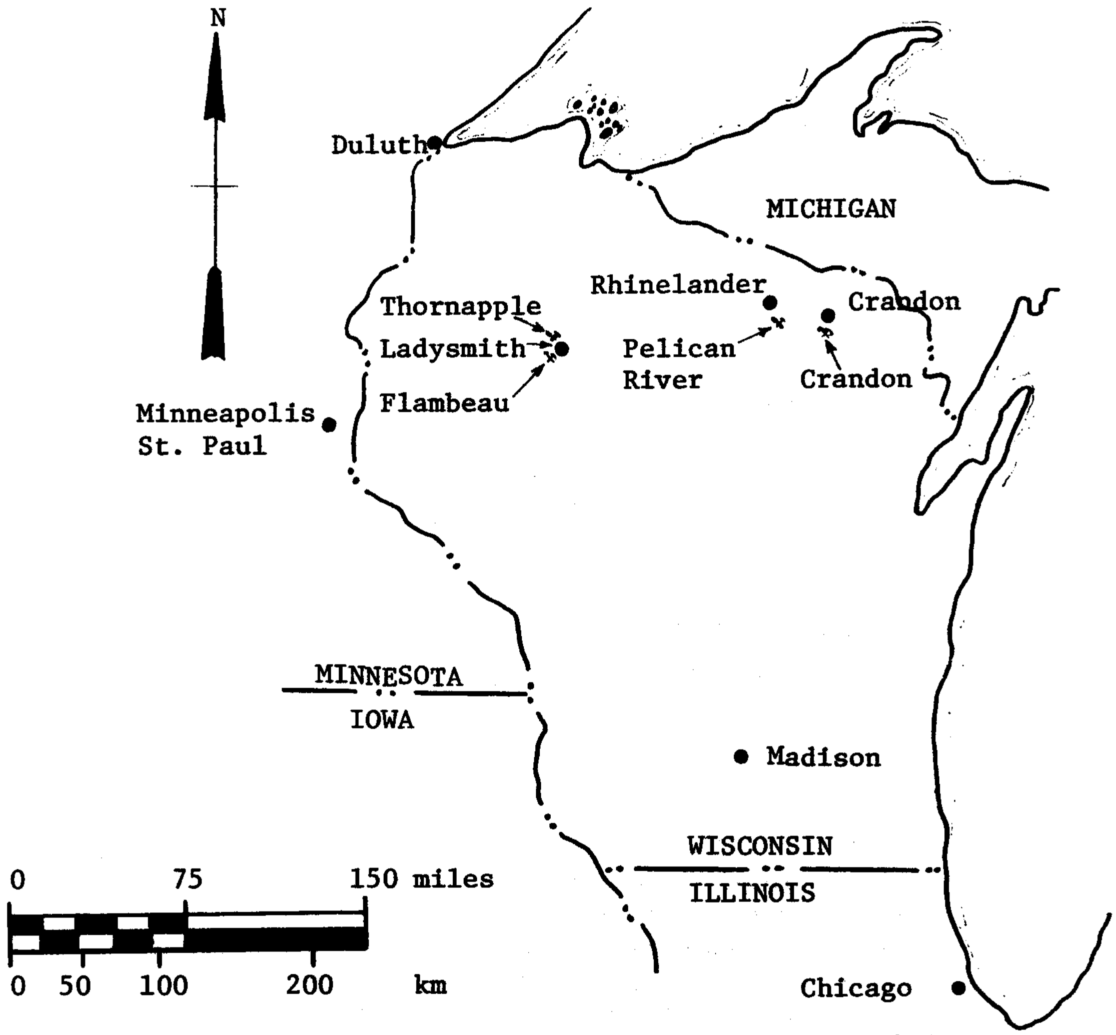

Figure 1. Location of Known Wisconsin Massive Sulfide Deposits

Kennecott resumed exploration in northwestern Wisconsin in the mid-1960's after the recognition by Jack Phillips, company geologist, that three rock exposures in Rusk County closely resembled Precambrian terranes common to Ontario known to contain massive sulfide mineralization. Phillips' interest in this area derived in part from a Wisconsin Geological Survey report of the recovery in 1914 from a hand-dug well in the southern part of the county of a specimen described as, "...a mashed porphyry at a depth of about 30 feet. The rock is very schistose, light colored, and in many places stained bluish-green by copper minerals." (Hotchkiss, 1915). Excellent work by Carl Dutton (Dutton, 1970, 1971) was also instrumental in further attracting Kennecott to northern Wisconsin. However it was not until the development and application of improved airborne geophysical techniques that the extensive Pleistocene cover could be pentetrated and an assessment made of the Precambrian suboutcrop (Schwenk, 1976).

LOCATION AND CULTURAL SETTING

The Flambeau deposit is located in northwestern Wisconsin approximately 200 kilometers northeast of Minneapolis-St. Paul and 350 kilometers northwest of the state capitol at Madison (Figure 2). Immediately north of the 1,100-hectare project site is the town of Ladysmith, a picturesque rural-retail community of 3,700 and county seat of Rusk.

Transportation facilities are excellent. Ladysmith lies at the junction of north-south and east-west highway and railroad systems. The deposit may be conveniently reached by traveling south 2.5 kilometers on State Highway 27 from its junction with U. S. Highway 8, thence west 0.5 kilometers on a private gravel road to the geographic center of the deposit.

Topographically the county and project site are characterized by gently rolling sub-parallel ridges striking generally in an east-to-northeast direction. Greatest relief is normally found along the outside bends of the major rivers, although banks greater than 15 meters are uncommon. The Flambeau River cuts diagonally across the county from the northeast corner to meander through Ladysmith, across the project site and over the west end of the deposit before turning south to its confluence with the Chippewa River.

Weather conditions are typically continental (cool summer phase) with temperature extremes for the county ranging from a recorded high of 42°C to a low of -40°C. Precipitation averages 85 cms per year. Annual snowfall averages 109 cms to cover the ground from mid-December through to the beginning of April.

REGIONAL GEOLOGY

The general geology of Wisconsin (Figure 2) has been known for many years. The bedrock in northern Wisconsin is a part of the southern edge of the Superior Province of the Canadian Precambrian Shield.

Keweenawan intrusives, extrusives and sediments of Late Precambrian age are restricted in Wisconsin to the south shore of Lake Superior. To the south of the Keweenawan rocks are alternating east-west-trending bands of gneissic Archean rocks of Early Precambrian age (Sims, 1976) and Middle Precambrian rocks of the Penokean complex (Van Schmus, 1976). Of considerable economic interest is the Flambeau volcanic belt (Myers, 1974) which consists predominantly of Middle Precambrian metavolcanics (Figure 2). The Flambeau volcanic belt with the Flambeau deposit located at its west end stretches across the state for a total of 300 kilometers to the Michigan border. This belt of intermediate to felsic metavolcanics contains all the presently known economic Wisconsin massive sulfide deposits.

Paleozoic sediments dip gently away from the Precambrian basement in ever-increasing thicknesses to the east, south and west. Except for the driftless area in southwestern Wisconsin, Pleistocene glaciation covered the state with unconsolidated heterogeneous deposits of various thicknesses. A general geochronology of Wisconsin Precambrian rocks is shown in Table 1.

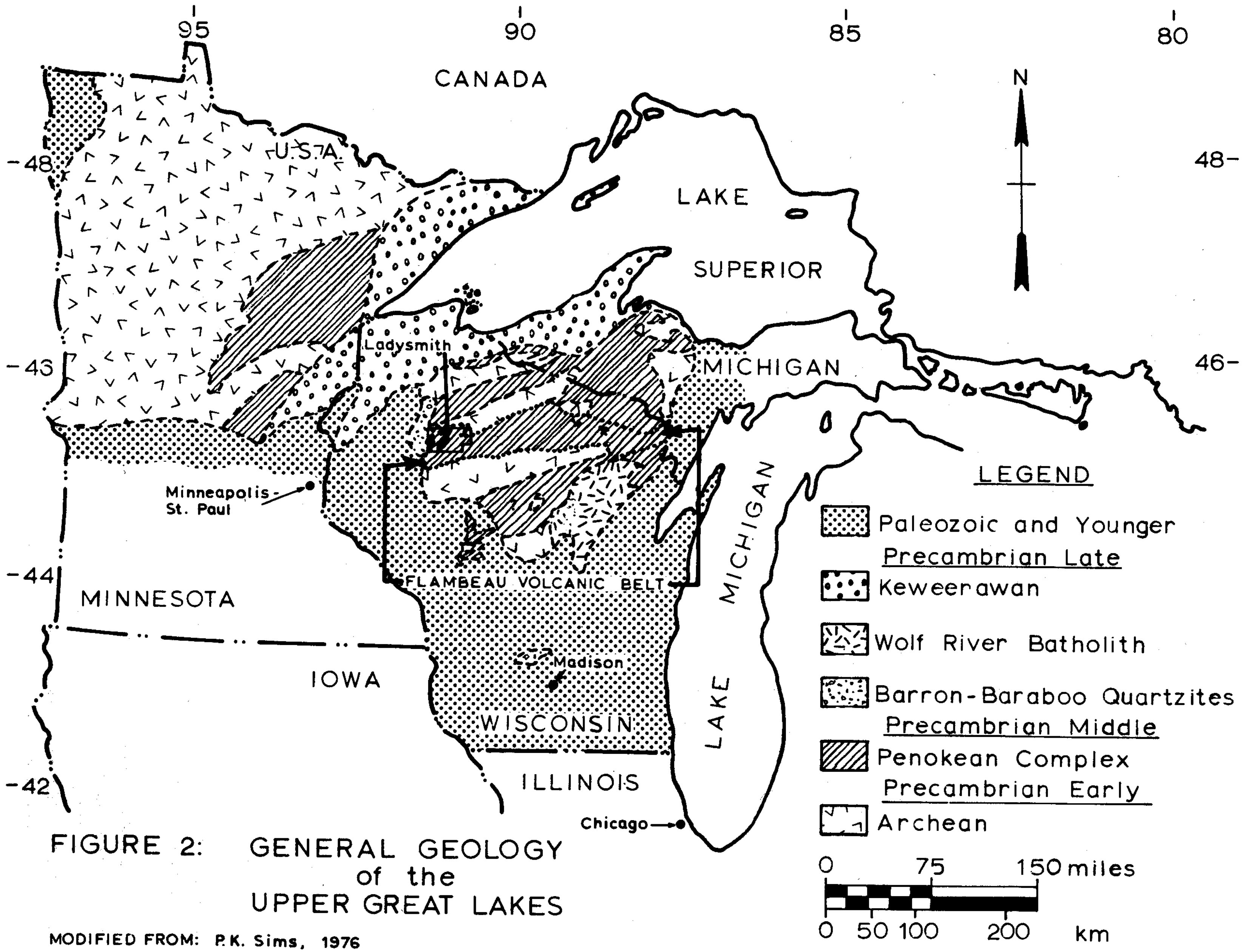

FIGURE 2: GENERAL GEOLOGY of the UPPER GREAT LAKES

MODIFIED FROM: P.K. Sims, 1976
Van Schmus, 1977 in press

Table 1. General Geochronology of Wisconsin

Paleozoic and younger

		Age	Unit	Lithology
			——Unconformity——	
PRECAMBRIAN	Late	1.1 b.y.	Keweenawan	Sediments Mafic intrusives Mafic lava flows
			——Unconformity——	
	Middle	1.5 b.y.	Wolf River Batholith	Anorogenic plutonic complex
		1.8 b.y.	Barron-Baraboo Quarzites	Sediments
			——Unconformity——	
		2.4 b.y.	Penokean Complex	Granites Iron formation Metasediments Metavolcanics (mineralized)
			——Unconformity——	
	Early	Older than 2.4 b.y.	Archean	Granites Metasediments and volcanics Gneisses

GEOLOGIC SETTING - RUSK COUNTY

An interpretation of the geologic history of Rusk County is hindered by extensive deposits of glacial material. Precambrian exposures are scarce and are generally found along river bottoms. Most of our geologic knowledge of the county comes from interpretation of aerial geophysics and diamond-drill cores (Figure 3).

The Precambrian basement consists of deformed and slightly to intensely metamorphosed volcanics and sediments of Middle Precambrian age. These rocks are found in east-northeasterly trending, steeply dipping, moderately to highly schistose belts. Regional metamorphism has produced upper greenschist to lower amphibolite mineral suites. Surrounding the "greenstone" belts are large intrusives ranging in composition from granite to gabbro, although granodiorite and tonalite are more common. Unconformably overlying the Middle Precambrian rocks are scattered outcrops of gently dipping Barron quartzites. Outliers of Cambrian sandstone which form a continuous unit to the southwest occur throughout central Rusk County.

The Flambeau deposit lies near the northern flank of a complex belt of highly schistose, alternating intermediate to felsic fragmental metavolcanics of unknown thickness. These rocks were dated by the U.S.G.S. using the lead isotope method on galena and found to be 1,820 million years old (Stacey, 1976).

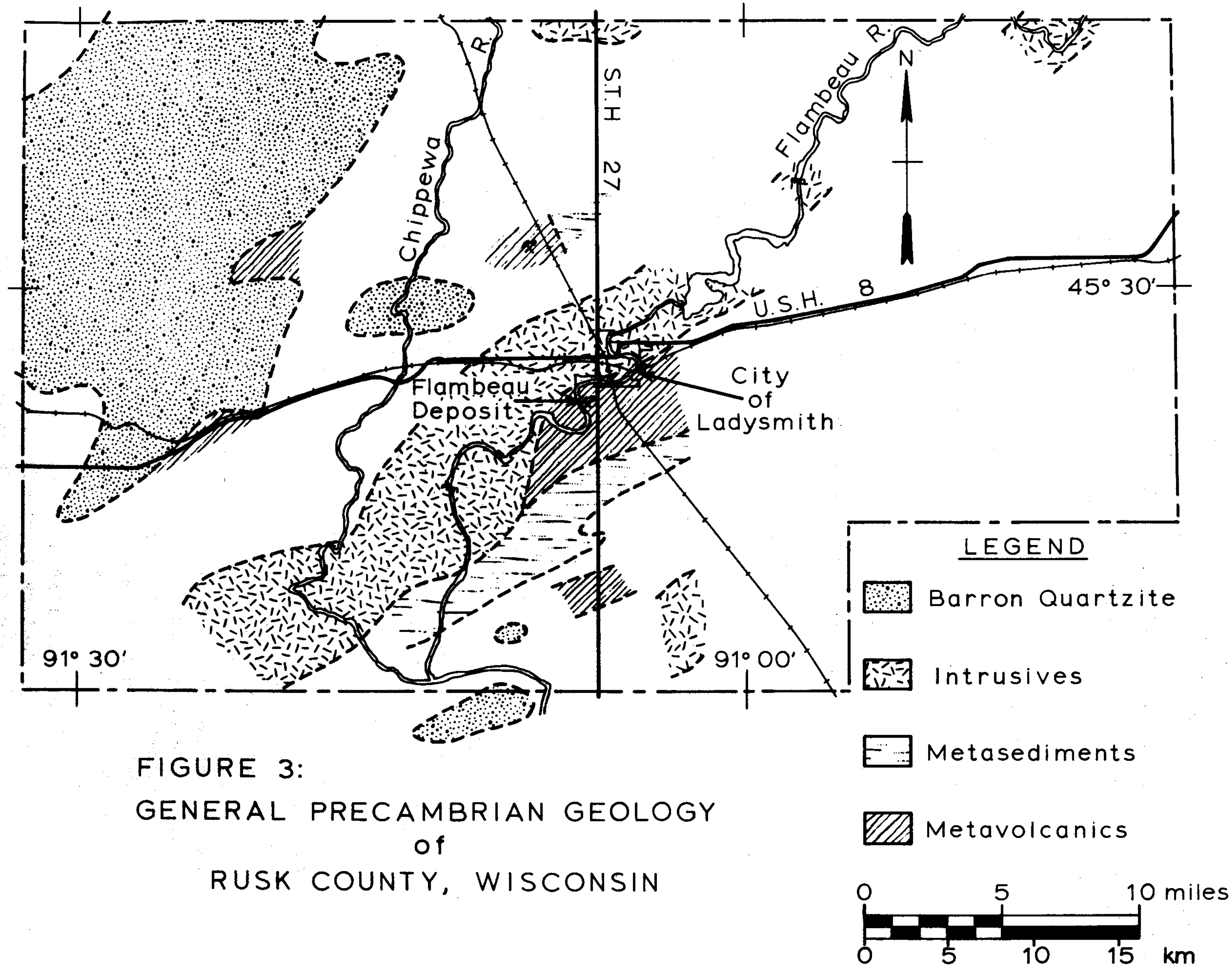

FIGURE 3:
GENERAL PRECAMBRIAN GEOLOGY
of
RUSK COUNTY, WISCONSIN

A large tonalite intrusive or series of intrusives underlies much of the Flambeau River valley north of Ladysmith, at Ladysmith, and southwest of town where it truncates the known mineralized metavolcanics. To the east along strike, the mineralized felsic metavolcanics interfinger with and grade into more intermediate metavolcanic rocks.

In a southerly direction across strike from the deposit, the metavolcanics become progressively more sedimentary in character to grade into graphitic schists interbedded with intermediate flows.

GEOLOGY OF THE DEPOSIT

Geologic data for the remainder of this paper comes almost exclusively from megascopic and microscopic examination of diamond-drill cores. Only one rock exposure of a highly foliated, intermediate metavolcanic rock overlain unconformably by Cambrian sandstone has been found on the project site 750 meters south of the deposit.

Classification of the mineralized Flambeau metavolcanics poses a variety of problems. The original volcanic pile was a complex interfingering of variably textured, multicompositional volcanics with abrupt vertical and horizontal facies changes. The combined effects of metasomatic alteration, regional metamorphism and subsequent superimposed intense supergene alteration render rock identification difficult. Despite these problems, sufficient relict textural evidence remains to interpret the Flambeau rocks as originally part of a cyclic fragmental volcanic pile.

Rocks are classified on their characteristic metamorphic mineral assemblages. Whole-rock chemical analyses and thin-section studies have aided interpretation of parent-rock types. Table 2 lists the metamorphic rock names and assumed genetic equivalents.

Table 2. Classification of the Flambeau Volcanics

	Rock Name	Genetic Name
Hanging-wall	Quartz-eye schist	Dacitic quartz crystal tuff Rhyolitic quartz crystal lapilli tuff
	Actinolite schist	Dacitic and andesitic flows
	Chlorite, spessartite and andalusite-biotite schists	Dacitic and andesitic tuff and lapilli tuff
Ore Horizon	Quartz-sericite schist Metachert	Rhyolitic lapilli tuff Chert
Footwall	Actinolite and chlorite phyllite	Andesitic tuff
	Actinolite and andalusite-biotite schist	Dacitic-andesitic lapilli tuff
	Quartz-eye schist	Rhyolitic-dacitic quartz crystal tuff

Distribution of sulfide minerals suggests that the Flambeau metavolcanics have been overturned. Usage hereafter of hangingwall and footwall are spatial, and not stratigraphic.

Hangingwall Rocks

Quartz-Eye Schist

A major and easily recognizable unit is a quartz-eye schist of unknown thickness (Figures 4 and 5) believed to have originally been a quartz crystal tuff. Two types of fragments occur. First, aggregates of quartz grains form the distinctive bluish "eyes" that vary from 1 mm to 10 mm, averaging 5 mm, in size. Some quartz aggregates show relict euhedral outlines, but more commonly they are polygonal-shaped grains. Microscopically the "eyes" consist of two, three or more quartz grains with partially developed triple-point junctions suggesting metamorphic recrystallization (Figure 6). Secondly, lithic fragments are recognized as elongated thin bands generally conformable with rock foliation. These pyroclastic fragments consist predominantly of quartz with highly variable amounts of sericite, plagioclase and chlorite (Figure 7). They are less distinctive than the quartz fragments because of more gradational contacts and a composition closely resembling that of the rock matrix.

The matrix is fine grained (0.05 mm to 0.1 mm) and well foliated. Both chlorite and sericite, either of which can constitute up to 50% of the rock volume, occur in thin layers with quartz. Pyrite is disseminated throughout the matrix in amounts generally less than 1%. Variable amounts of plagioclase and cordierite up to 20% are present in the matrix.

Actinolite Schist

At or near the base of the quartz-eye schist is a series of narrow actinolite, chlorite and spessartite garnet-rich rock units. These units are fine grained and gray-green in color. The thickest of these units, the actinolite schist, is partially to completely enclosed by an andalusite-biotite schist. Because of its relatively massive texture, plano-convex shape and mineral assemblage, the actinolite schist is interpreted to have originally been a lava flow of intermediate composition. Approximately 8% of this rock consists of actinolite that occurs as long, somewhat randomly oriented needles or rosettes up to 2 mm in size.

Chlorite-Spessartite Schist

The chlorite-spessartite units on the other hand are well foliated and contain felsic volcanic fragments in a greenish-gray, finely crystalline matrix of quartz, biotite, chlorite (20% to 25%) and garnet (2%). The evenly distributed, light-orange to pink, dodecahedral spessartite porphyroblasts are only found in the unit closest to the deposit. In drilling, the presence of garnet is used to signify approach to the andalusite-biotite schist containing first significant amounts of sulfide mineralization.

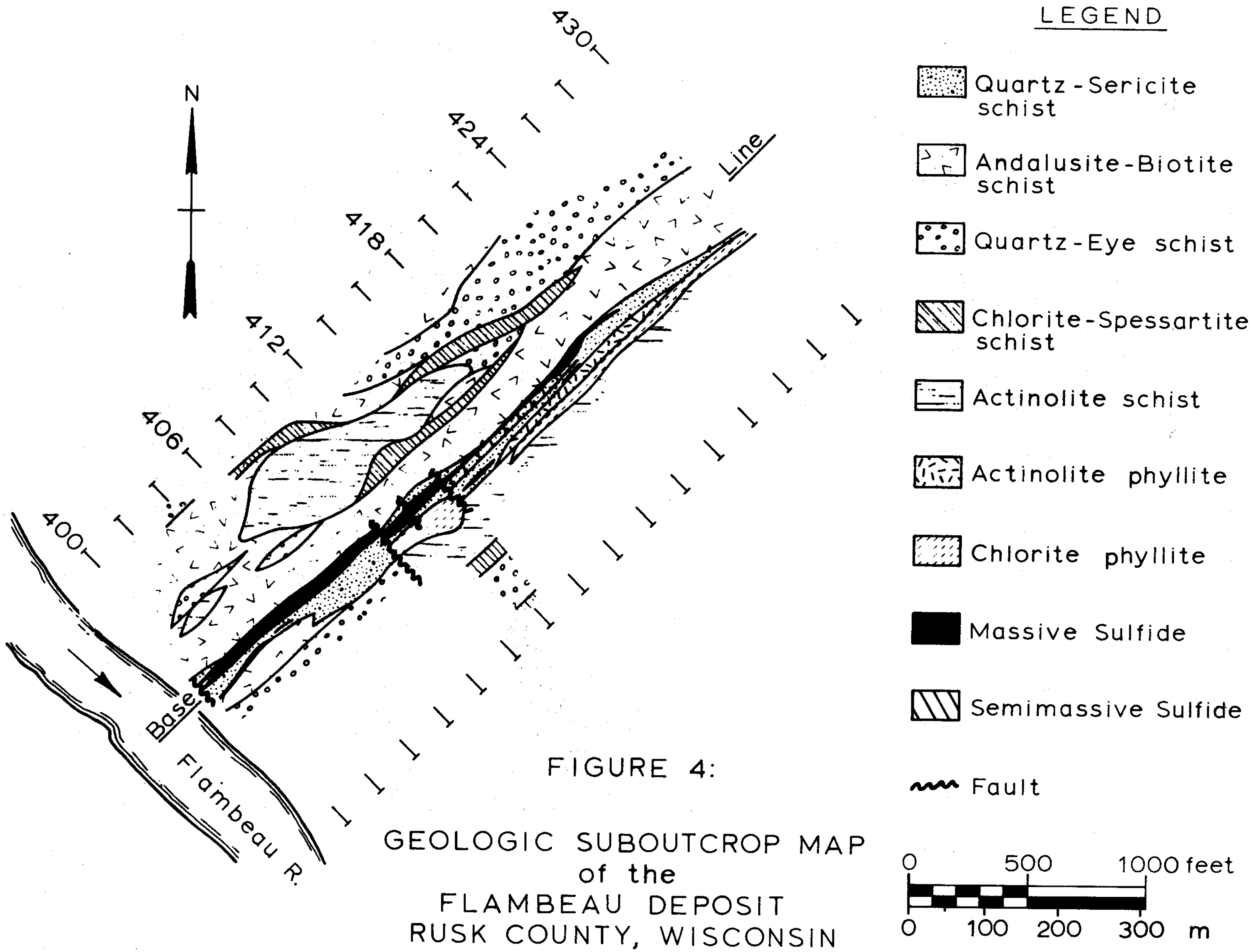

FIGURE 4:

GEOLOGIC SUBOUTCROP MAP
of the
FLAMBEAU DEPOSIT
RUSK COUNTY, WISCONSIN

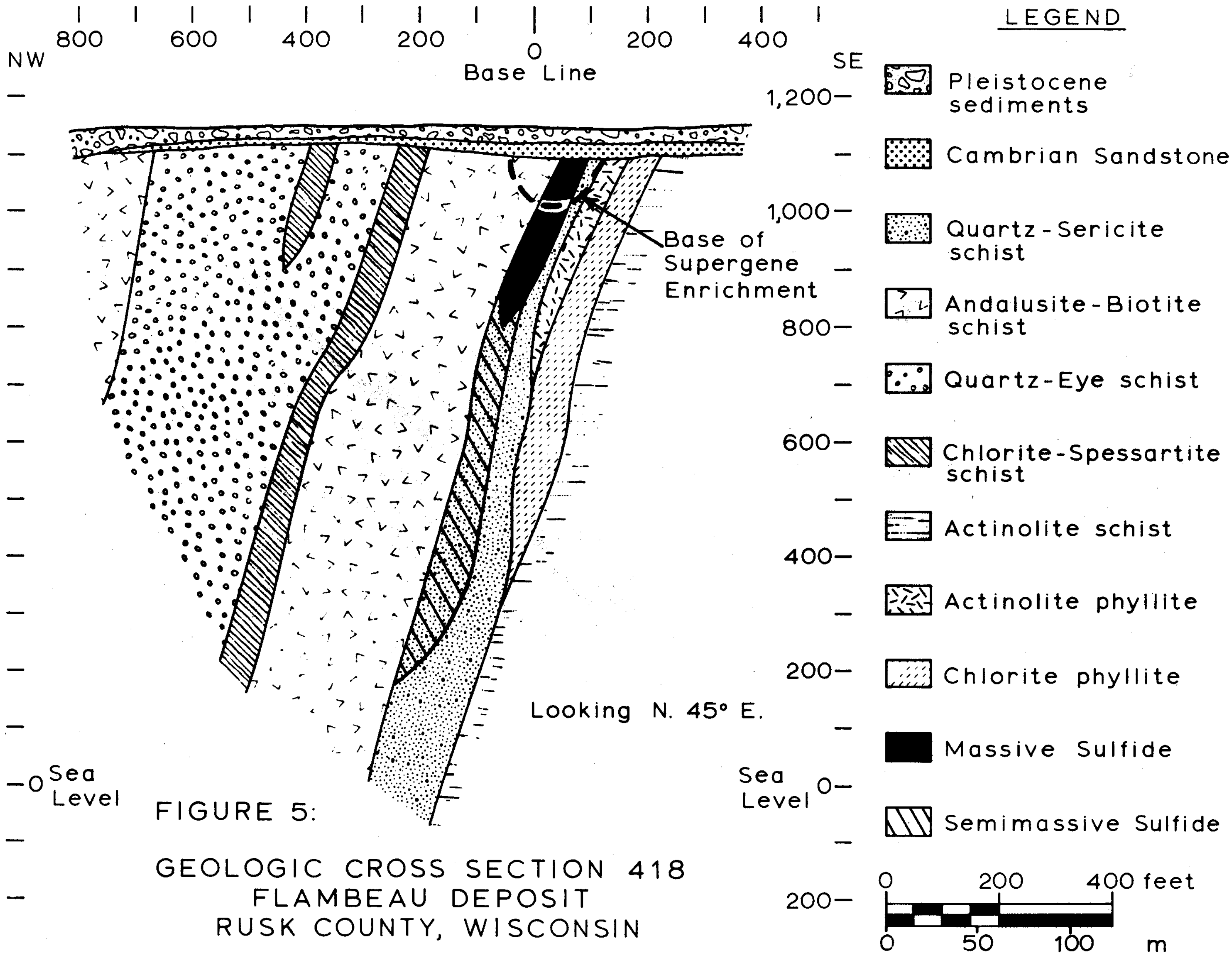

FIGURE 5:

GEOLOGIC CROSS SECTION 418
FLAMBEAU DEPOSIT
RUSK COUNTY, WISCONSIN

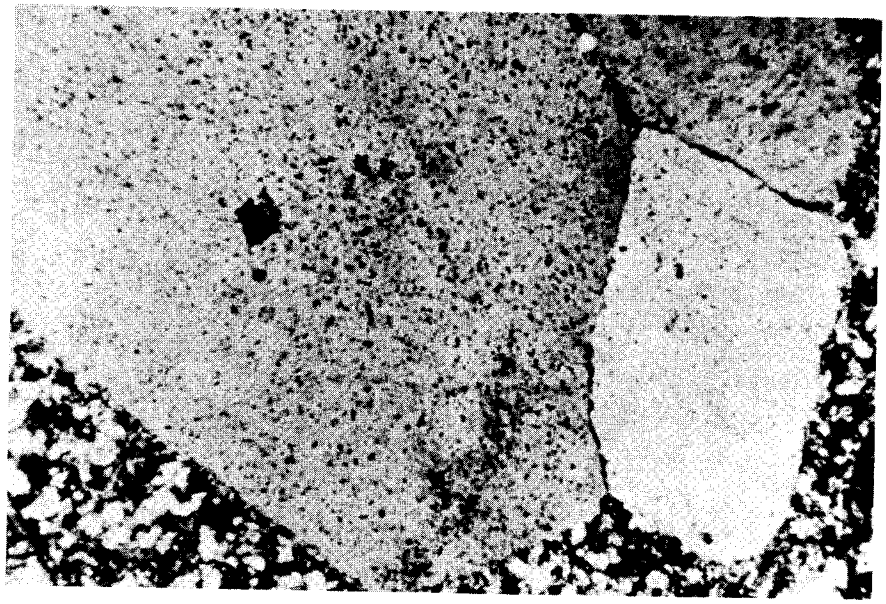

Figure 6. Photomicrograph of quartz-eye schist. A larger quartz fragment made up of three grains in a quartz-sericite matrix. These fragments appear as quartz "eyes" in the hand specimen. The largest grain is 1 mm across. Cross-polarized light.

Figure 7. Photomicrograph of fragmental metavolcanic. Plagioclase fragment elongated along biotite-rich shears in an accumulation of squashed lapilli. Width of field approximately 3.5 mm.

Andalusite-Biotite Schist

In contact with the hangingwall of the ore horizon is a fine-grained, well foliated and fragmental andalusite-biotite schist. Without exception, all holes drilled into the hangingwall volcanics have penetrated this schist before entering the deposit. The thickness of the andalusite-biotite schist is fairly constant along the strike of the deposit, averaging 45 meters (Figures 4 and 5). This schist is unique among Flambeau rock units in that it displays a mixture of andalusite and biotite porphyroblasts. Andalusite porphyroblasts make up 10% to 15% of the rock and occur in a variety of sizes and degrees of crystallinity. Large irregular patches often exceeding 5 mm of unidentified, waxy-appearing, light-bluish-gray, sieved-textured porphyroblasts are interpreted to have been originally andalusite, now altered to clay-like minerals. However, most andalusite is light gray in color, and occurs as subhedral to euhedral, nearly square prisms averaging 4 mm long. Biotite porphyroblasts (0.3 mm to 3 mm) are more common throughout the unit than andalusite porphyroblasts but amounts vary widely from 5 to 25 volume percent. Porphyroblasts of andalusite and biotite and matrix chlorite noticeably decrease along strike to the east, with a corresponding increase in quartz and sericite. Two fragment types conformable with the rock folia have been recognized. The more common granular quartz-sericite fragment is narrow, flattened and elongated, containing 5% to 7% pyrite with minor chalcopyrite. Sulfide mineralization increases toward the ore horizon and is found chiefly in the quartz-sericite fragments or as conformable thin lenses within the rock matrix. The other common fragment type consisting of transluscent quartz, probably metachert, tends to be more poorly mineralized.

Ore Horizon

Quartz-Sericite Schist

The mineralized quartz-sericite schist is believed to have been a rhyolitic lapilli tuff. This siliceous fragmental unit, hereafter referred to as the ore horizon, is traceable for approximately 4,500 meters and ranges in thickness from 7.5 meters to a maximum of approximately 60 meters. The average thickness of this unit where it contains the deposit is 35 meters.

The ore horizon is a light-gray, fine-grained, well foliated rock having a matrix of quartz (up to 60%) and sericite (50%) with accessory chlorite, biotite and andalusite. Matrix minerals rarely exceed 0.1 mm in diameter. Fragments are moderately well preserved and make up 5% to 10% of the rock although, in selected core sections, up to 60% felsic fragments may occur. Ninety percent of the fragments are composed of quartz and sericite with the remaining 10% derived from brecciated metachert. Both the size and shape vary, with most fragments measuring 2 mm to 4 mm in diameter, while some fragments exceed 2 cms. The more common shape is lensoid to subrounded with an occasional subangular piece. In well foliated sections of the ore horizon rich in chlorite, biotite and sericite, the foliation curves pronouncedly around the quartz-sericite fragments.

Intimately associated with the mineralization and within or very close to the ore horizon are fragments or narrow, discontinuous beds of metachert. These are a white to gray, fine-grained, aphanitic rock consisting almost entirely of granular recrystallized quartz. Metachert is considered at Flambeau to be an excellent exploration guide for massive sulfide mineralization.

The felsic ore horizon, being more erosion resistant, forms an area of slight positive relief in the Precambrian suboutcrop, except in the east central portion of the deposit (sections 416 and 418).

Footwall Rocks

There is a distinct change in the volcanic cycle from the acidic ore horizon to the more intermediate footwall rocks. Thin units of actinolite and chlorite phyllites and schists either pinch out or are in fault contact with the ore horizon or the quartz-eye schist. Further away from the deposit the quartz-eye schist, as in the hangingwall, becomes the major rock unit.

Paleozoic Rock

Unconformably overlying the Precambrian bedrock is a thin, narrow outlier of relatively flat-lying Cambrian sandstone. This formation, consisting of a clean, well sorted, friable quartz sandstone with thick clay partings, lies directly over the deposit except at the west end. To the east the sandstone reaches a maximum thickness of 9 meters and has a maximum lateral extent of 150 meters on either side of the deposit.

Pleistocene Glacial Cover

The Flambeau project area has a silt-rich glacial cover which ranges from 3 meters over the west end of the deposit to 9 meters at the opposite end. Rapid thickening of glacial material to the northwest suggests the presence of an ancestral Flambeau valley. Various glacial deposits are present including poorly sorted and heterogeneous outwash and till material, and somewhat better sorted silty sands and silts.

ALTERATION

Metasomatic

Wallrock alteration around and stratigraphically beneath volcanogenic deposits has been well documented. The more common alteration products are chlorite pipes (Boldy, 1968); strongly schistose, chloritic, talcose and serpentine-rich rocks (Hutchinson, 1965); and dalmatianite, usually a combination of cordierite and anthophyllite spots best developed at Noranda, Quebec (DeRosen-Spence, 1969).

Intense alteration is present around the Flambeau deposit. It is difficult however to separate local metasomatic effects from those of regional metamorphism, which produced assemblages characteristic of the upper greenschist or lower amphibolite facies. Additional whole-rock chemistry on units away from mineralization will undoubtedly assist in the construction of a more comprehensive wallrock-alteration model.

A comparison of whole-rock chemistry of major Flambeau units with world averages (Nockolds, 1954) for various volcanic rocks is shown in Table 3. In general, Flambeau rocks fall near the average compositions for dacites and calc-alkaline rhyolites with significant differences in some oxides which may best be explained by metasomatic processes. Major metasomatic changes appear to be substantial increases in magnesia and ferrous iron, and relatively large losses in lime, soda and potash. The low potash values are surprising and might represent potash deficiencies in the original rock.

No chloritic or brecciated alteration pipe is recognized at Flambeau. However, the metasomatic alterations may have occurred in a pipe-like zone, the character of which has been destroyed by tectonic deformation. It is generally felt that hydrothermal solutions must have percolated through the volcanic rocks prior to and during mineralization.

The deposition of mineralization is visualized as having taken place subaqueously in an area of hot springs and fumarolic activity on the flanks of a cyclically active volcanic pile. Copious amounts of mineral-pregnant brines reacted with seawater producing gelatinous sludges that eventually entered a shallow stratigraphic trap. Felsic volcanic accumulation and mineralization continued sporadically during the waning stages of the volcanic cycle until the mineral sludges were buried by a new volcanic surge of a more intermediate composition.

During the Penokean orogeny the mineral deposit was folded and uplifted, and unknown quantities of sulfide minerals eroded and donated to the ancient environment. Later deposition of Paleozoic sediments halted further erosion of the Precambrian bedrock.

Supergene

During Late Precambrian time the folded Flambeau volcanics were completely decomposed by surface weathering to form an impermeable clay saprolite layer. The saprolite is best preserved under an unaltered outlier of Cambrian sandstone to depths of 2 to 6 meters below the unconformity.

In general the saprolite is thickest adjacent to the ore horizon and thins rapidly away from the deposit beneath the glacial cover. The color of the saprolite is commonly bluish-green, although various shades of gray, white, tan and iron oxide discoloration are noted. The saprolite consists almost entirely of micron-sized chlorite particles with minor amounts of quartz and mica.

Beneath the saprolite layer is an extensive zone of moderate supergene alteration that straddles but somewhat favors the more mineralized hangingwall

Table 3. A Comparison of Flambeau Whole-Rock Analyses with World Average Dacite and Rhyolite Compositions

Wt. %	World[1] Avg. Dacite	Flambeau Dacitic Lapilli Tuff[2]	Deviation From World Avg.	World[1] Avg. Rhyolite	Flambeau Rhyolitic Lapilli Tuff[2]	Deviation From World Avg.	Flambeau Rhyolitic Qtz. Crystal Lapilli Tuff[2]	Deviation From World Avg.
SiO_2	63.58	63.12	-0.46	73.66	73.28	-0.38	73.07	-0.59
Al_2O_3	16.67	16.78	+0.11	13.45	14.47	+1.02	13.46	+0.01
FE_2O_3	2.24	2.25	+0.01	1.25	1.86	+0.61	1.01	-0.24
FeO	3.00	6.45	+3.45	0.75	2.23	+1.48	2.80	+2.05
MgO	2.12	8.13	+6.01	0.32	3.42	+3.10	5.61	+5.29
CaO	5.53	0.73	-4.80	1.13	0.91	-0.22	0.50	-0.63
Na_2O	3.98	0.54	-3.44	2.99	0.64	-2.35	1.88	-1.11
K_2O	1.40	2.00	+0.60	5.35	3.19	-2.16	1.67	-3.68

1 Average dacite and calc-alkali rhyolite from Nockolds (1954)

2 Ron Bianchi and Ruth Hendricks, analysts, Kennecott Exploration Services, Salt Lake City, Utah

side of the deposit. Average width of alteration is 90 meters to a depth of about 45 meters. The base of alteration is highly erratic depending on rock porosity, fracturing, jointing and mineralogy of the original rock. On several cross sections, supergene effects such as rock bleaching and sericite decomposition along well defined structures are recognized to depths exceeding 120 meters. Rock identification is impossible in the saprolite and difficult in the deeper, less decomposed and altered metavolcanics.

STRUCTURE

Precambrian structure in northern Wisconsin is predominantly controlled by the effects of the Penokean orogeny, although structural work by Myers (1974) indicates the presence of at least two additional but lesser deformation periods. The Flambeau volcanics are therefore interpreted to lie within a northeast-trending, steeply northwest-dipping limb of a Penokean-age isoclinal fold. Other than this major structure, only crenulations and minor drag folds are recognized in the drill core.

Schistosity is the predominant rock fabric and appears to be parallel or nearly parallel to primary bedding. Whereas the schistosity dips to the northwest, observed lineations plunge 80^{o} to the northeast. The orientation of volcanic fragments and the plunge of the massive sulfide deposit are parallel to this lineation trend.

Fault breccia and clay gouge have been noted. The direction and dip of these structures is imprecisely known but they appear to be high-angle faults trending north-northwest. Several faults have offset the deposit by as much as 9 meters.

FORM OF THE DEPOSIT

The crudely tabular-shaped Flambeau deposit is stratiform and lies along the upper contact of the ore horizon (Figure 5). Contact relations between the deposit and the overlying andalusite-biotite schist are sharp to gradational over a distance of 2 to 6 meters and is rarely sharp. Diamond-drill testing has outlined a body averaging 15 meters in width over a strike length of 720 meters, and bottoming approximately 240 meters below the surface. Reserves are indicated to be 5.5 million tonnes.

Several short, narrow, satellitic massive sulfide lenses, parallel with the main body, are present in the footwall rocks. The largest satellitic lens which is 4 meters wide with a strike length of 150 meters is located 25 meters beneath the west end of the main deposit. This steeply plunging lens also bottoms at approximately 240 meters below the surface.

Along strike to the west, the deposit fingers out and is probably faulted against the weakly mineralized ore horizon. Less is known about the east end other than that the deposit rapidly grades into disseminated pyrite.

MINERALOGY

Although modest in size, the Flambeau deposit is of special interest among Canadian Shield-type massive sulfide deposits in that it exhibits extensive supergene enrichment. This is not to imply that supergene enrichment has not occurred over Canadian equivalents, for it has, but none to the recollection of this author have been enriched to the extent found at Flambeau. Many Canadian deposits contain thin, generally covellite-rich caps, but such enrichment was not a significant amount of the total ore-reserve picture. Three of the better known massive sulfide enriched deposits in North America are at Ducktown, Tennessee (Gilbert, 1924), at the United Verde Extension, Jerome, Arizona (Anderson, 1958), and at the Detour deposit, Quebec (verbal communications, R. C. Schmidt, Pickands Mather and Company, November 1976).

Primary Mineralization

Pyrite (60%) is the chief mineral with lesser amounts of chalcopyrite (12%) and sphalerite (2.5%). Gold, silver, galena and pyrrhotite occur in minor quantities. The above minerals occur in various proportions and combinations as massive, semimassive and disseminated-type sulfide mineralization. The author has, based on drill-core observations, defined massive sulfide to contain greater than 50 weight percent sulfides, semimassive to contain between 20 and 50 weight percent, and disseminated to contain less than 20 weight percent. Although the above definitions may conflict with previous work on other deposits, they best suit conditions at the Flambeau deposit.

Massive sulfide predominates in the upper part of the steeply dipping and overturned deposit to 180 meters beneath the suboutcrop. However, the east central portion of the sulfide deposit contains semimassive mineralization (Figure 4). The semimassive mineralization increases with depth from a strike length of 150 meters in the suboutcrop to 720 meters at 180 meters beneath the surface. A disseminated sulfide halo which averages 65 meters in width and contains 7% pyrite encloses the massive-semimassive mineralization. The halo extends along strike for at least 1,500 meters in either direction and downdip for an unknown distance. Therefore, massive-semimassive sulfide mineralization gradually decreases with depth and rapidly decreases horizontally away from the deposit.

The massive sulfide mineralization displays well developed horizontal mineral zoning. The hangingwall tends to be chalcopyrite-rich with sphalerite noticeably increasing toward the footwall. All the footwall satellitic lenses are sphalerite-rich. Based on stratigraphic-mineral zoning work conducted at the Noranda District (Gilmour, 1965) where copper favors the stratigraphic footwall, it is believed that the Flambeau deposit is overturned.

The chalcopyrite zone is heterogeneous to poorly banded. Banding present is crude and reflects the alignment of chalcopyrite-rich bands with gangue inclusions and sphalerite (Figure 8). In places this zone has a granular appearance due to an abundance of polygonal-shaped grains up to 3 mm in diameter (Figure 9). Chalcopyrite occurs as interstitial fillings

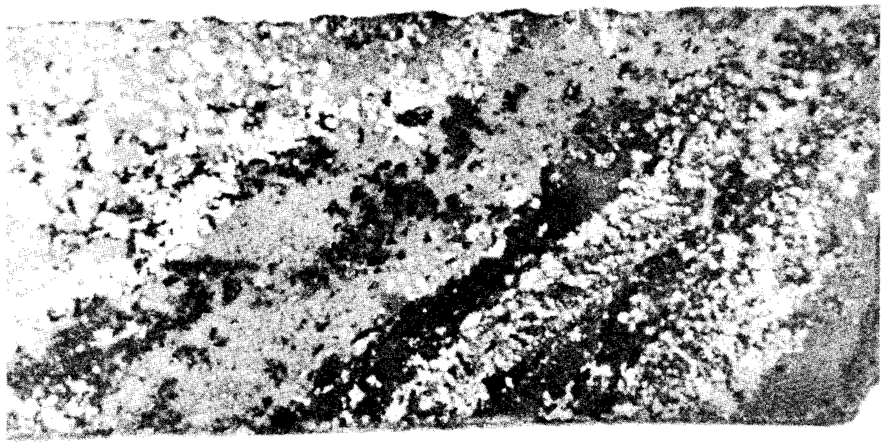

Figure 8. Banding of pyrite-chalcopyrite-sphalerite mineralization, Flambeau deposit, Wisconsin. Massive sulfide mineralization showing banding of pyrite (white), chalcopyrite (light gray), and sphalerite (dark gray). Length of drill core approximately 10 cms.

Figure 9. Photomicrograph of massive sulfide mineralization. Typical section of massive sulfide mineralization showing polygonal-shaped pyrite grains and interstitial chalcopyrite (light gray); pyrite grain shapes are probably the result of recrystallization. Pyrite grains about 0.5 mm. Reflected light.

(1 mm to 3 mm) around pyrite grains, as large irregular masses up to 50 mm, and as inclusions in sphalerite. Remobilized veinlets of chalcopyrite and sphalerite have been noted crosscutting the crude banding.

Mineral banding on a scale of 1 mm to 40 mm is better developed near the footwall. This fabric is a result of alternating layers (fragments?) of pyrite and honey-brown to dark-brown, generally iron-rich sphalerite. The banding is approximately parallel with the enclosing rock folia. Intimately associated with the sphalerite are irregular to elongate grains, films and wisps of galena.

Electron microprobe examinations indicate that gold occurs in its native state or as electrum scattered throughout the deposit, whereas silver is concentrated toward the zinc-rich footwall.

Gangue minerals are quartz (metachert), sericite and lesser amounts of chlorite and andalusite. The grain size and distribution of the gangue minerals are highly variable; they may occur as small, irregular particles 2 mm to 5 mm; as patchy inclusions 40 mm to 50 mm; or as narrow, concordant, ellipsoidal lenses or fragments.

The semimassive sulfide mineralization is weakly zoned due to small amounts of widely scattered sphalerite. Pyrite is again the predominant sulfide and forms narrow, sub-concordant, massive to semimassive layers interbedded with weakly mineralized and chloritized quartz-sericite schist and metachert. Chalcopyrite is coarser grained than that found in the massive sulfide mineralization, occurring as large irregular masses up to 50 mm in diameter. It also occurs as interstitial fillings around the 1 mm to 3 mm pyrite grains. Small amounts of sphalerite (less than 1%) are scattered throughout the zone as grains, as narrow bands up to 6 mm in width, and as occasional irregular clots less than 7 mm in diameter.

Across strike from the massive sulfides, the disseminated pyrite halo favors the hangingwall volcanics for a distance of 45 meters into the andalusite-biotite schist. The footwall is mineralized for only half that distance. No economic mineralization is present in the disseminated zone since the chalcopyrite content averages less than 1%.

Secondary Mineralization

Well developed vertical mineral zoning is displayed in the supergene enriched portion of the deposit as shown in Figure 10. Indeed, a classic gossan-oxide-supergene enriched-primary zoned model has been developed and preserved along most of its strike length.

The extent and degree of enrichment depend on various field conditions; deferential rock permeability, structure, sulfide content and of course a fluctuating water table are but a few of the more important parameters. At Flambeau the medium-grained, subhedral, granular, pyrite-rich massive sulfides are more permeable than the enclosing volcanics. The well developed schistosity planes directed the mineral-pregnant acidic surface waters down and along but not across primary bedding planes.

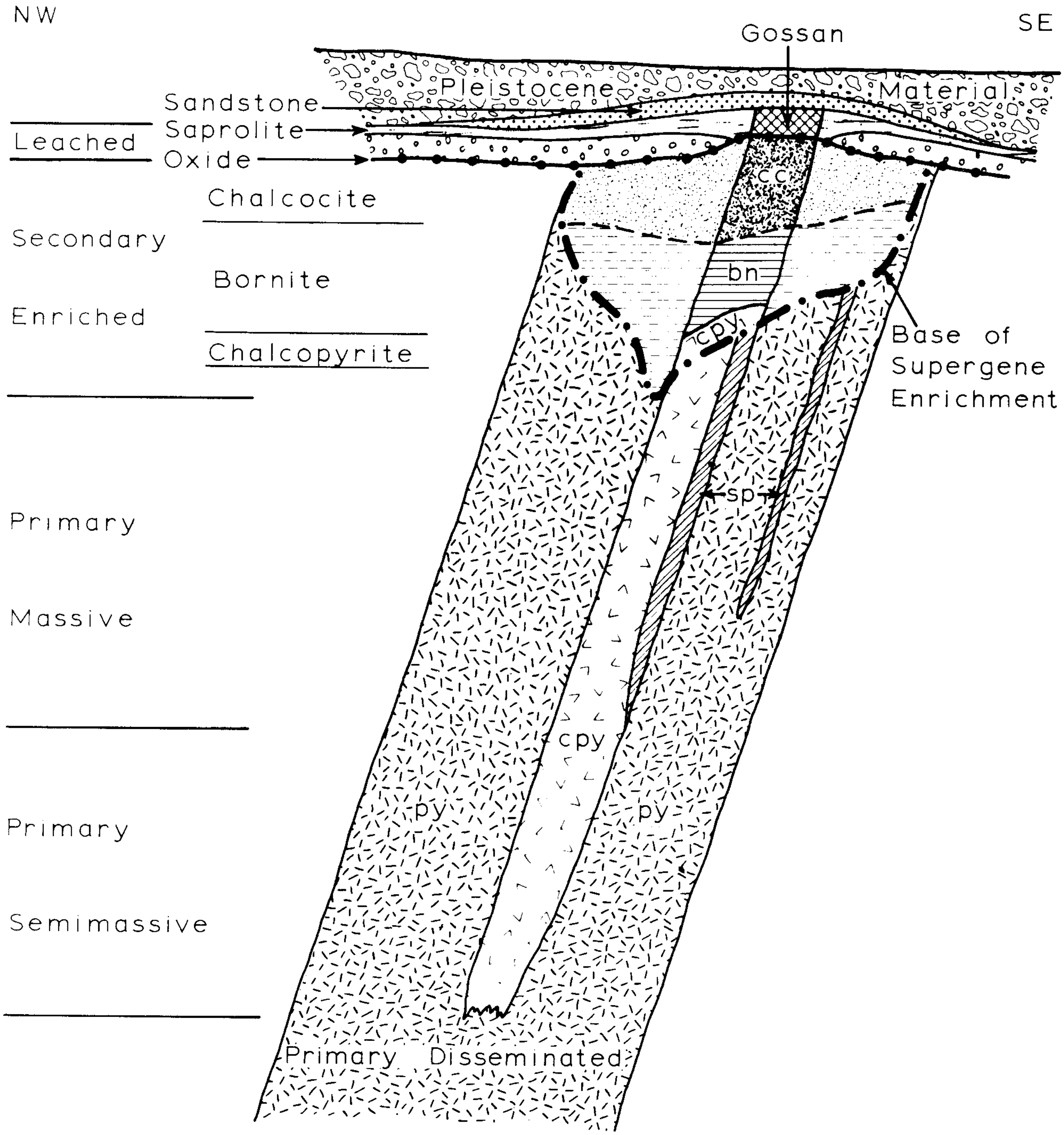

FIGURE 10: IDEALIZED CROSS SECTION SHOWING MINERAL ZONING of FLAMBEAU DEPOSIT RUSK COUNTY, WISCONSIN

Secondary mineralization is confined to the deposit and the immediate enclosing pyritic halo where a combination of excess pyrite and sufficient copper sulfides produced conditions favorable for enrichment. The deepest enrichment is found within the massive sulfide portions of the deposit to depths of 55 meters below the suboutcrop surface. In the east central portion of the deposit, secondary enrichment is restricted to within 25 to 30 meters of the suboutcrop due to lower sulfide content and more impermeable conditions.

A 5-meter thick "gossan" or siliceous "cap" is in sharp contact with massive to semimassive mineralization. The gossan is a multicolored, siliceous, iron oxide-rich cap of highly variable texture, hardness and porosity. The chief mineral, quartz (90%), occurs as massive to vuggy blocks, as angular to subrounded, randomly oriented fragments (0.5 cm to 2 cm), and as irregular to sugary clasts (4 mm to 5 mm). A mixture of hematite and goethite acts as a cementing agent and is also found in sandy pockets or in illite-rich zones.

Overlapping the gossan-secondary sulfide contact is a one-meter zone of oxidation. This zone is recognized by earthy coatings, specks and botryoidal tenorite-melaconite, malachite and azurite. In addition, small amounts of cuprite and chalcotrichite occur. Native copper is present as foil or flake coatings on joint surfaces; however, it is more commonly found in thicker sheets (1 mm to 3 mm) away from the deposit near or at the base of the leached cap. Copper oxides occupy well developed vertical joints and faults to 20 meters below the suboutcrop surface.

The supergene sulfide mineralization exhibits two distinct zones of approximately equal dimensions. The upper chalcocite zone and lower bornite zone have been developed at the expense of all primary sulfides. The contact between the two zones is gradational. Chalcocite occurs as irregular steely masses, as thin coatings on bornite or pyrite, and as sooty films and fracture fillings. In the lower zone, numerous reticulating veinlets of bornite replace fractured chalcopyrite. As this replacement became more complete, the veinlets coalesced forming irregular masses of bornite. The enrichment sequence continued, with bornite, in a similar manner, replaced by massive chalcocite (Figure 11). At each successive enrichment step, additional pyrite was consumed so that at the end of the process, appreciable amounts of iron sulfides were replaced by bornite and chalcocite.

Sphalerite is preferentially replaced relative to chalcopyrite and pyrite, with pyrite being the least reactive. Consequently, zinc values are generally less than 0.05% in the supergene mineralization.

At the base of the bornite zone, secondary chalcopyrite occurs as botryoidal-like coatings less than a millimeter thick on primary chalcopyrite or as micro tetragonal crystals on bornite. The base of the secondary enrichment zone is highly irregular depending on joint control, faulting, primary sulfide permeability and mineral content.

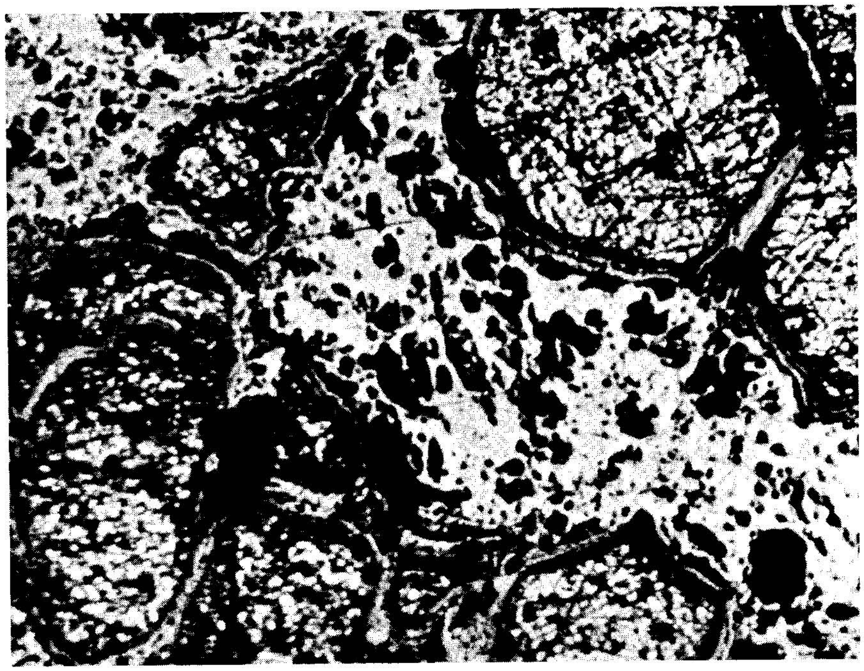

Figure 11. Photomicrograph of supergene sulfide mineralization showing remnant pyrite rimmed by chalcocite within a bornite matrix.

Enrichment is not restricted to the massive-semimassive sulfide deposit but has also occurred within the disseminated pyrite halo. As expected, the extensively pyritized, more felsic and permeable hangingwall volcanics are preferentially enriched relative to the chlorite-rich footwall rocks. Grains of pyrite and chalcopyrite are either totally or partially replaced by chalcocite and bornite. These secondary minerals occur as grains, micro-rimmings or sooty coatings within a quartz-clay-sericite matrix.

ENVIRONMENTAL SETTING - A DISCUSSION

The Flambeau deposit has afforded a rare opportunity to study the relationships of an undisturbed mineral body with its recent environment. In part these studies were a spinoff from the state-required environmental impact report necessary to obtain mining permits. It is concluded that the deposit is in continual reaction with the environment, and contributing significant quantities of acid and heavy metal ions to the surface via capillary action from the oxidizing deposit into the groundwater.

Figure 12 illustrates present conditions measured from monitor wells, soil, and geobotanical surveys. Without question the Flambeau deposit is contributing significantly to the high levels of heavy metal ions in the groundwater, soils and vegetation over the deposit and down the hydraulic gradient to the northwest.

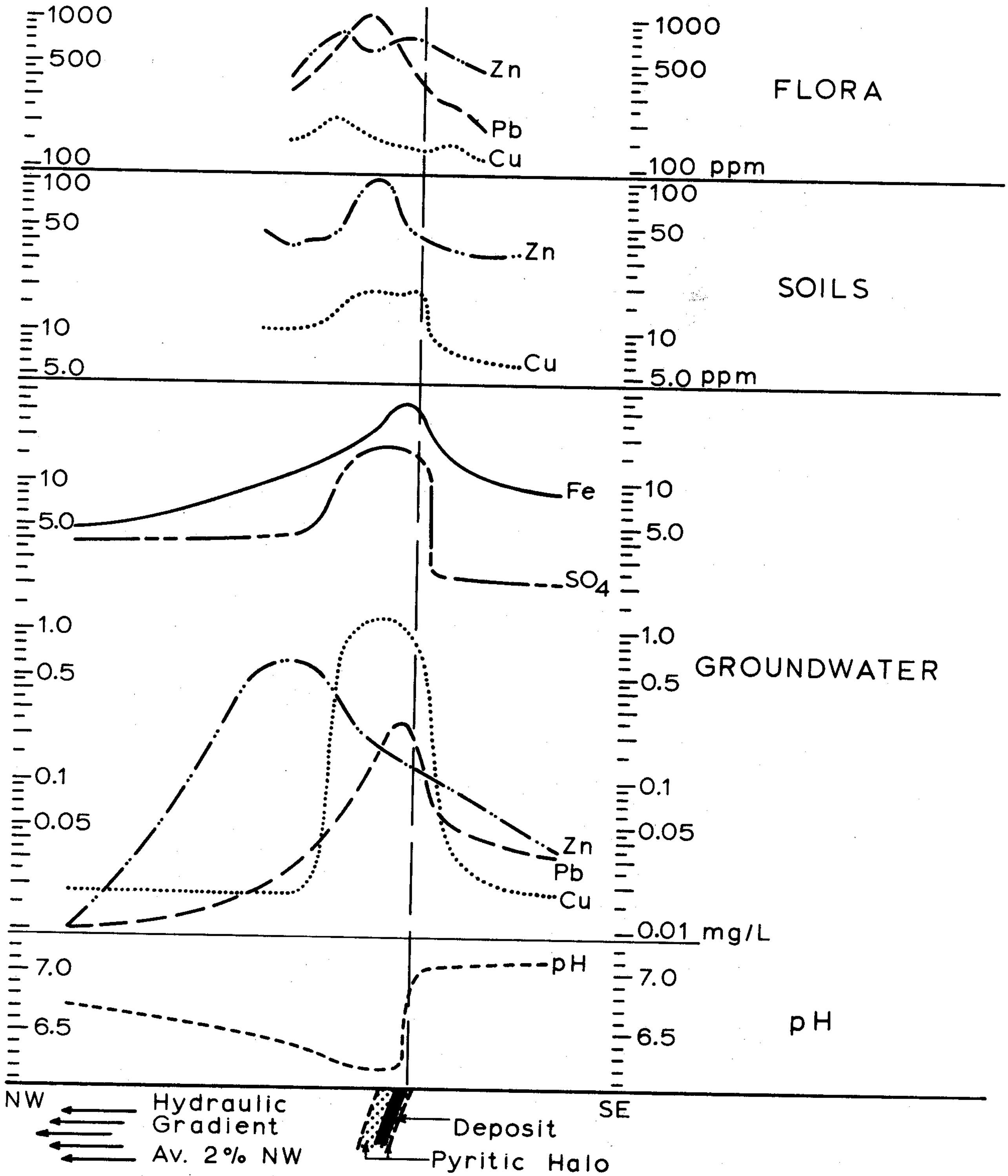

FIGURE 12: IDEALIZED CROSS SECTION RELATIONSHIPS BETWEEN FLAMBEAU DEPOSIT and its ENVIRONMENT

Groundwater samples are collected from six wells located across the strike of the deposit. Two of these wells are located on cross section 402 over the deposit and hangingwall pyritic halo. The six wells sample the aquifer contained within the Pleistocene glacial cover to depths of 5 to 30 meters below the surface. Cross section 409 was selected for soil analyses, with samples taken 60 cms below the surface every 15 to 30 meters along the section line. Although copper and zinc values are appreciably higher in the soils over and northwest of the deposit, mercury values for unexplainable reasons are not anomalous. Lead analyses were not conducted. Trees located on cross section 402 were sampled, taking "two-year twigs" from hemlock, oak, maple and elm. Results, using the ash-weight method, were averaged and plotted on Figure 12 to prevent bias caused by bioconcentration of metal ions by certain tree species. For example, onsite hemlock northwest of the deposit have bioconcentrated lead up to 3,990 ppm. However, surface water and benthos monitoring of the Flambeau River opposite and downstream of the deposit indicate that the contaminated groundwater is rapidly dispersed by river flow which averages 515 hectoliters per second (1,840 cfs).

Geochemical data shown on Figure 12 could be of future significance in exploring for buried massive sulfide mineralization. However, this data was collected after the fact and therefore played no role in the exploration for and discovery of the Flambeau deposit.

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