

# Volcanogenic Massive Sulfide Deposits of Northern Wisconsin: A Commemorative Volume

*Edited by Gene L. LaBerge*



**Institute on Lake Superior Geology**  
*Proceedings*

**Volume 42, Part 2**

### Front Cover

Aerial photo of the Flambeau mine and vicinity looking north. Flambeau Mining Company photo. © T-BO Studios

### Back Cover

Photo of a 4.0 cm tall twinned orthorhombic chalcocite crystal recovered from a cavity in the supergene ore. The purple patina is produced by a thin coating of bornite on the chalcocite. From the collection of F. John Barlow. Photo by Malcolm Hjerstedd, Munroe Studios, Neenah, WI.

**Proceedings**  
**Volume 42, Part 2**  
FIRST PRINTING—MAY 1996

**Publisher**

Institute on Lake Superior Geology

**Distributor**

Theodore J. Bornhorst  
c/o Department of Geological Engineering, Geology, and Geophysics  
Michigan Technological University  
1400 Townsend Drive  
Houghton, Michigan 49931-1295

ISSN 1042-9964

**Reference to Volume 42, Part 2 should follow the example below:**

LaBerge, G. L., Ed., 1996, Volcanogenic massive sulfide deposits of northern Wisconsin: A commemorative volume: Institute on Lake Superior Geology Proceedings, 42nd Annual Meeting, Cable, WI, v. 42, part 2, 179 p.

***Proceedings***

**Volume 42, Part 2**

**Institute on Lake Superior Geology**

**Volcanogenic massive sulfide deposits  
of northern Wisconsin: A commemorative volume**

**Edited by: Gene L. LaBerge  
Department of Geology  
University of Wisconsin Oshkosh, Oshkosh, WI 54901**

**Published for  
42nd Annual Meeting  
Institute on Lake Superior Geology  
Cable, Wisconsin  
May 15-19, 1996**

**ISSN 1042-9964**

## PREFACE

The mineral industry has played an important role in deciphering the local and regional geology of the Lake Superior region by gathering basic geologic information to assist in the exploration for and development of mineral resources. More than a century ago the discovery of the great iron ore resources in the Lake Superior region led to numerous studies by mining companies, government surveys, and academic institutions, providing a wealth of information on the geology of the iron-bearing districts, as well as the sedimentary sequences and the contained ore deposits. The copper deposits of northern Michigan provided the impetus for similar detailed and regional studies yielding a basis for understanding these important resources. Although research on the genesis of the mineral deposits and the regional geology is on-going, we continue to utilize much of the basic data provided by mining companies. However, relatively little information was compiled on the area of northern Wisconsin now known as the Wisconsin magmatic terranes.

In the 1960s, a new concept of sulfide ore deposition related to volcanic activity — volcanogenic massive sulfide deposits — led to widespread exploration activity by numerous companies for this type of deposit in the Lake Superior region. Along with new concepts of ore deposition came new technology to aid in the search for mineral deposits. Aeromagnetic and airborne electromagnetic (EM) surveys became standard procedures, and, along with ground magnetics, EM and gravity surveys, these geophysical techniques have greatly modified both detailed and regional exploration. Drill core data provided by exploration companies has provided the "ground truth" to permit broad-scale correlation of rock units within the region. Much of these data have been made available to government surveys to permit at least a "first pass" at deciphering the bedrock geology of the "Wisconsin magmatic terranes," which are very poorly exposed because of the thick cover of glacial deposits.

Although our present understanding of the geology of northern Wisconsin is an outgrowth of the efforts of many scientists, I believe it is important that we recognize the central role that the mineral industry has played. Therefore, I feel it is appropriate that all of the chapters in this volume except one were written by geologists in the mineral industry, for some of these authors represent some of the corporations and individuals who have been at the forefront of generating some of the basic data. I am confident that the data and interpretations contained in these papers will be helpful in promoting an understanding of massive sulfide deposits as well as further refining the regional geology of the Wisconsin magmatic terranes.

## ACKNOWLEDGEMENTS

This volume was conceived by Edward May, who thought a volume on volcanogenic massive sulfide deposits in Wisconsin would be appropriate in conjunction with the field trip to the Flambeau Mine. We all owe Ed a vote of thanks for initiating the project. Each of the authors took time from their schedule to prepare descriptions of the various deposits. I would like to acknowledge, with thanks, their efforts. I extend my thanks to Suzanne Nicholson of the U.S.G.S. who reviewed all of the manuscripts. A very special thanks to Mary Fahley, in the Geology Department at UW-Oshkosh, who undertook the task of getting all the manuscripts on one computer and formatting the volume. I really couldn't have done it without her.

Proceeds from the sale of this volume will be used by the Institute on Lake Superior Geology to help fund student travel to future Institute meetings. The following organizations and individuals have made financial contributions to help defray the cost of publication of the volume, and in so doing, have contributed to future generations of student participants at Institute meetings. Thanks to each contributor.

List of Contributors

Flambeau Mining Company  
 Kennecott Exploration Company  
 Ames Construction, Inc.  
 BHP Minerals International, Inc.  
 Crandon Mining Company  
 Boart-Longyear  
 Cooper Engineering  
 DeWitt, Ross & Stevens, S.C.  
 Foth and Van Dyke  
 David Hoffman  
 Peter J. Hoffman  
 Midwest Drilling  
 Minnesota Exploration Association

North Central Mineral Ventures, Inc.  
 (in memory of E. H. Eisenbrey)  
 T. D. Drilling, Inc.  
 Wood Communications Group  
 Ayres Associates  
 F. John Barlow  
 Edward R. May  
 Casey Jones, Burminco  
 Glen W. Adams  
 Russell C. Babcock  
 Jack V. Everett  
 Gene L. LaBerge  
 Paul G. Schmidt

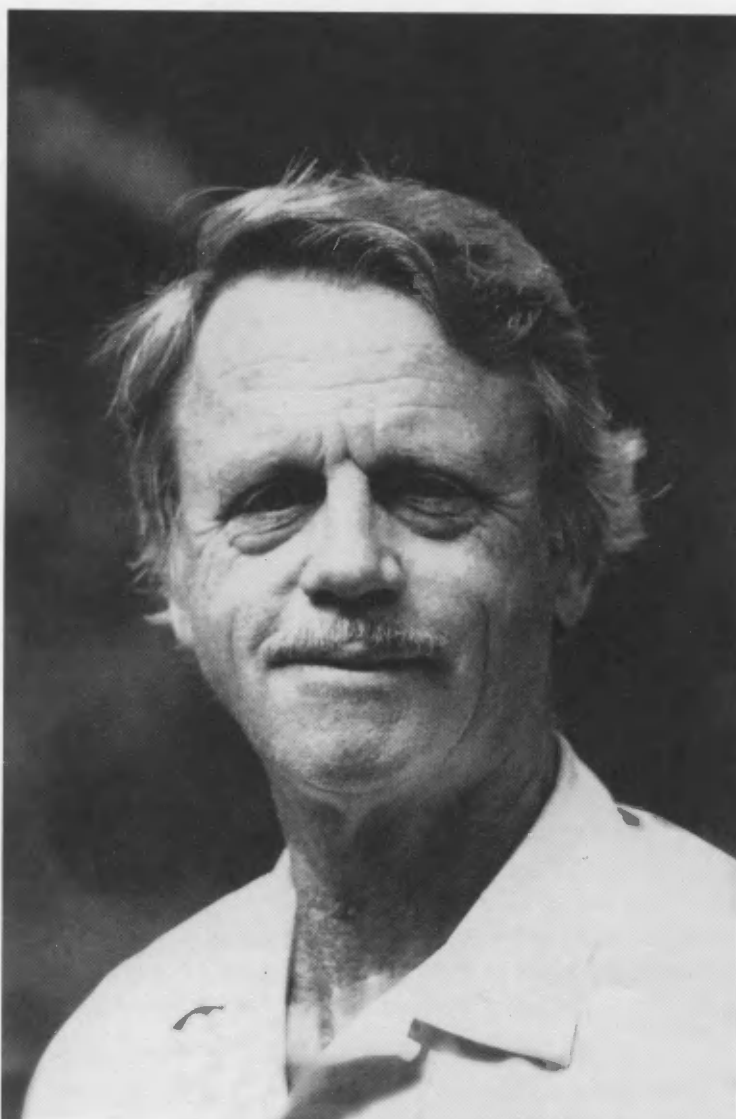
## DEDICATION

**Edward H. Eisenbrey**  
1926 - 1985

"Ned" Eisenbrey, to whom, along with his co-worker Jack Phillips, this volume and meeting are dedicated, can truly be said to be one of the "fathers" of the study and exploration for volcanogenic massive sulfide mineral deposits in Wisconsin.

Those of us who had the good fortune to work with Ned in the Precambrian shield of the Upper Midwest and elsewhere, recognize that he had a unique talent as an ore finder, a geologist, and a teacher. In the last ten years of his life, during my close association with him as a co-worker and friend, I marveled at his uncanny, often apparently intuitive knack for sizing up a mass of geophysical data, mix it with an apparent minimum of hard geologic ground truth and to come up with targets that, in a remarkable number of cases, were not graphite, not "formational," not just pyrite, but were mineralized prospects and potential base and precious metal deposits.

During his tenure in Wisconsin and Bear Creek (Kennecott) he was responsible for the initiation of drilling at the site of the current Flambeau Mine. He also recognized and proposed



drilling at the Thornapple site (now fittingly named the Eisenbrey prospect). Subsequently, in his year with the North Central Mineral Venture and in his capacity as a senior geologist with Earnest K. Lehmann & Associates, he recognized the mineralization of the Reef deposit and was instrumental in, among others, the discovery of the Ritchie Creek prospect and the Horseshoe deposit which was discovered on the day of his untimely death. His insight was also important in our later discovery of the Bend deposit in Taylor County.

Ned was born in 1926 and grew up in Cleveland, Ohio. He attended the Staunton Military Academy in Virginia. During World War II, he enlisted in the U.S. Navy at age 17 and served in the South Pacific. He graduated in geology from Case Western in 1950 and obtained a MS from the University of Toronto in 1952. During his college summers, he worked as a surveyor on the Quebec, Nova Scotia and Labrador Railroad then being built to develop the Labrador iron mines.

On graduation, he joined the American Metal Company and worked on massive sulfide deposits in New Brunswick. Later, he transferred to various other locals including Virginia, Colorado, Wyoming, and Arizona. Following the merger of American Metals and Climax to form AMAX in 1958, he was a consultant and mine operator in Arizona.

In 1959, he joined Bear Creek, working first on the exploration of the porphyry copper deposit at Safford, Arizona, and later as an assistant to Paul Bailey, the President of Bear Creek. In 1963 he joined the Rocky Mountain regional office of Bear Creek and in 1967 moved to the upper midwest. Leaving Bear Creek in 1971, he first managed the North Central Mineral Venture for Superior Oil, and then joined Ernest K. Lehmann & Associates in 1975. He worked with ELA until his death in 1985.

He and Elizabeth (Liz) Eisenbrey were married in 1955. They have two children, Mary and Fred. With Liz's help and the support of his family, he was able to maintain an active and full life in spite of a severe diabetic condition, which hampered him during almost all of his adult life.

His interests outside of geology were strongly focused on his desire to share his knowledge and his abilities as a teacher. In this capacity, he was active in the Boy Scouts and in his church. In the later years of his life, he had a keen interest in introducing earth science teachers to geology and ore deposits. He participated in a program for this purpose at the University of Wisconsin-Platteville. Teaching came naturally to him. This skill, coupled with his acute knowledge of economic geology generally and volcanogenic massive sulfides in particular, was a gift from which all his associates benefitted. We are still indebted to him for his knowledge, his skill in applying that knowledge and his sharing it with us.

Ernest K. Lehmann  
August, 1995

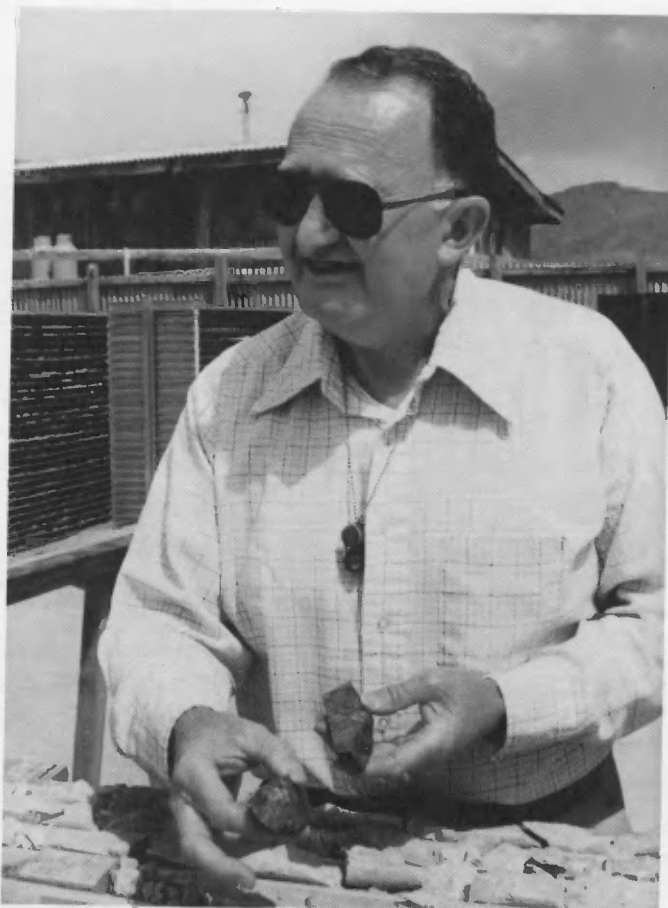
**Memorial to John S. Phillips**  
1928 - 1987

On March 20, 1987, Jack Phillips was killed in a plane crash as he was returning from work at Andacollo, Chile, to his home in Santiago, ending an outstanding career in minerals exploration.

Jack grew up on a ranch 30 miles south of Cripple Creek, Colorado, and his interest in geology may have been stirred by visits to this old mining camp. He graduated from the Colorado School of Mines in 1949, and began his professional career at the New Jersey Zinc Company mine in



Gilman, Colorado. This was interrupted by a two-year hitch with the U.S. Army in Germany, where he met his caring and supportive wife, Danielle, a French interpreter with the Army. On returning to the U.S., he earned his M.S. degree at Syracuse, and his Ph.D. at Harvard, studying under Hugh McKinstry.



Jack joined Cominco in 1960, exploring the Jerome District in Arizona, applying the volcanogenic model recently developed at Bathurst, New Brunswick. In 1965, he was hired by Kennecott to manage a drilling project near Marquette, Michigan, testing the Kona Dolomite for rhodesian-type copper deposits. At the same time, Jack was characteristically looking for other exploration possibilities, and, influenced by his Jerome experience, recognized the area west of Ladysmith, Wisconsin, as having potential for hosting volcanogenic massive sulfide deposits. Before his transfer to another assignment, Jack's enthusiasm and persistence led to Kennecott's approval of an INPUT survey, which resulted in the discovery of the Flambeau deposit in 1968.

Jack continued to work for Kennecott for a number of years, mostly in the Western U.S., but including foreign assignments as well. He joined Chevron in 1978, was instrumental in bringing it into the Stillwater platinum operation, and later headed its copper exploration in Chile.

Jack is remembered by those of us privileged to have known him, for his keen interest in all types of ore deposits, his enthusiastic approach to exploration, and his enjoyment in exchanging thoughts with fellow geologists.

Ray E. Gilbert  
Englewood, Colorado

## TABLE OF CONTENTS

	<u>Page</u>
PREFACE	
ACKNOWLEDGEMENTS	
DEDICATION	
INTRODUCTION	
HISTORY OF EXPLORATION FOR VOLCANOGENIC MASSIVE SULFIDES IN WISCONSIN	by Russell C. Babcock . . . . . 1
GENERAL CHARACTERISTICS AND GEOLOGIC SETTING OF THE WISCONSIN MAGMATIC TERRANES	by Gene L. LaBerge . . . . . 17
A GEOLOGIC FRAMEWORK FOR EARLY PROTEROZOIC VOLCANOGENIC MASSIVE SULFIDE DEPOSITS IN WISCONSIN: AN EXPLORATION MODEL	by Theodore A. DeMatties . . . . . 31
AN OVERVIEW OF THE FLAMBEAU SUPERGENE ENRICHED MASSIVE SULFIDE DEPOSIT GEOLOGY AND MINERALOGY, RUSK COUNTY, WISCONSIN	by Edward R. May and Stephen R. Dinkowitz . . . . . 67
CASE STUDY OF ENVIRONMENTAL REQUIREMENTS FOR THE PERMITTING, OPERATION, AND RECLAMATION OF A METALLIC MINERAL MINE IN WISCONSIN-FLAMBEAU MINE	by Jana E. Murphy and Richard T. Dachel . . . . . 95
EISENBREY: A STRUCTURALLY COMPLEX PROTEROZOIC COPPER-ZINC MASSIVE SULFIDE DEPOSIT, RUSK COUNTY, WISCONSIN	by Edward R. May . . . . . 107
GEOLOGICAL SUMMARY - CRANDON DEPOSIT	by A. J. Erickson and R. Côté . . . . . 129
THE BEND DEPOSIT: AN EARLY PROTEROZOIC COPPER-GOLD VMS DEPOSIT.	by Theodore A. DeMatties and William F. Rowell . . . . . 143
GEOLOGY OF THE LYNNE BASE-METAL DEPOSIT, NORTH-CENTRAL WISCONSIN, U.S.A.	by Glen W. Adams . . . . . 161

## HISTORY OF EXPLORATION FOR VOLCANOGENIC MASSIVE SULFIDES IN WISCONSIN

Russell C. Babcock  
Chief Geologist (Retired)  
Kennecott Exploration Company  
Salt Lake City, Utah

### INTRODUCTION

Exploration for massive sulfide deposits in Wisconsin was driven by the observation that whereas numerous base metal deposits and mines were present in the Superior Craton north of Lake Superior, none were known in rocks suspected to be of the same age south of the lake. It was assumed that the reason for this was not a lack of deposits but rather the presence of extensive glacial cover south of the lake. Therefore, exploration in Wisconsin focused on techniques that would lead to the discovery of blind deposits beneath this glacial cover. Such was the reasoning of Kennecott geologists who began the first phase of the modern era of base metal exploration and mining in Wisconsin in the early 1950's.

Kennecott pursued its exploration program in Wisconsin without competition intermittently for almost two decades before announcing the discovery of the Flambeau Deposit in 1970. With this announcement dozens of competitors joined Kennecott in Wisconsin, opening a second phase of this exploration history, one of competitive and relatively unencumbered activity. This phase ended and the third phase began when Exxon announced the discovery of the huge Crandon Deposit in 1976. Within a year after this announcement the political climate changed dramatically in Wisconsin. The third phase of exploration in Wisconsin became one of difficult regulation, permitting, and taxation, made even less palatable by a sustained period of very low base metal prices. In 1993 Kennecott finally brought the Flambeau Deposit into production, and in 1995 Exxon and Rio Algom joined in an attempt to bring the Crandon Deposit on stream. Perhaps a fourth, productive phase will soon be added to this history.

### PHASE ONE: THE KENNECOTT YEARS

#### Early Kennecott Exploration

Kennecott established an exploration program on the Duluth Gabbro in 1951 following the discovery of copper-nickel mineralization along the Kawishiwi River in Minnesota. A few years later an office was set up in Mellen, Wisconsin, to test some copper-nickel occurrences in the Mellen Gabbro. The geologist in charge of this office, George Moerlein, began looking for massive sulfide deposits in Wisconsin in 1954, and although he found a number of iron sulfide occurrences, none contained more than trace amounts of base metal sulfides. Moerlein compiled the references to sulfides in the literature and visited the offices of the government geologists who were involved in mapping in Wisconsin and Upper Michigan.

Carl Dutton, a U.S.G.S. geologist working with the Wisconsin Geological and Natural History Survey, showed Moerlein a copper-stained rock reported to have come from a hand-dug well at a schoolhouse south of Ladysmith. Moerlein could find little at the schoolhouse site other than a

small amount of felsic schist with some weak copper staining but with little evidence of having contained much sulfides.

Kennecott flew extensive airborne electromagnetic surveys over their copper-nickel properties in Minnesota and the Mellen, Wisconsin, area in 1954. Several surveys of several lines each were also flown over sulfide occurrences in Wisconsin that were felt to have some potential for base metals. One of these surveys was flown over the schoolhouse south of Ladysmith. None gave Kennecott much encouragement and no anomalous response was seen at the schoolhouse. On the basis of this survey Kennecott assumed that the glacial overburden in western Wisconsin was probably too thick for effective use of airborne electromagnetics.

In spite of this lack of encouragement, Kennecott continued to feel strongly that base metal massive sulfide deposits could be hidden under the glacial overburden in Wisconsin. Through the last half of the 1950's Dr. W. F. Read, Professor of Geology at Lawrence College in Appleton, spent a good part of his summers prospecting in northern Wisconsin for Kennecott. Using glacial till sampling (pebble counts), abundant stone fences in some areas, and mapping every outcrop he could find, Bill Read added significantly to Kennecott's understanding of the bedrock geology of Wisconsin. He found almost no base metals but mapped several areas of pyritic felsic schist. The author worked with Read for two of these summers, visiting the schoolhouse site for the first time in 1956, but like most young geologists of the time, had no understanding of what was to become the volcanogenic massive sulfide model.

Moerlein recognized the potential for Rhodesian-type copper deposits in the Kona Dolomite near Marquette, Michigan, just prior to the closure of Kennecott's Wisconsin office in 1962. In 1965 Jack Phillips was hired by Kennecott to pursue this target and establish an office in the Upper Peninsula. In 1966 Phillips visited the Wisconsin Geological and Natural History Survey and U. S. Geological Survey in Madison to see if other prospects could be generated in Michigan and Wisconsin. There he "rediscovered" the copper-stained sample of felsic schist from the well at the schoolhouse south of Ladysmith, reportedly still on Carl Dutton's desk. Dutton told Phillips of showing the rock to Moerlein and some of the work Kennecott had done in Wisconsin.

Fortunately for Kennecott, Phillips had spent his previous several years working on volcanogenic massive sulfide deposit exploration and was fully aware of the new model for these types of deposits developed in Canada in the early 1960's. He knew that the discovery of the major base metal deposits at Bathurst, New Brunswick, and Kidd Creek, Ontario, were the direct result of applying this new model to exploration in Canada. He recognized in the schoolhouse rock the slightly pyritic, felsic volcanic material common to the new volcanogenic massive sulfide model. When he visited the schoolhouse site a few weeks later he recognized and became very excited about the potential for finding another Kidd Creek deposit in Wisconsin. Schoolhouse became a pivotal prospect for Kennecott in Wisconsin.

A review of the Kennecott files led to Read's and Moerlein's work, which in turn led Phillips to quickly recognize the presence of several pyritic felsic volcanic piles elsewhere in north-central Wisconsin. The records in Madison and some mapping indicated sulfides to the west of Ladysmith near Weyerhaeuser and at Blue Hill. Magnetic surveys run with dip needles along widespaced lines in the early 1900's by the Wisconsin Geologic and Natural History Survey indicated areas of possible "greenstone" bedrock. It was clear that a major exploration effort was justified.

Phillips' experience in volcanogenic massive sulfide exploration exposed him to the newly developed INPUT system, the time-domain airborne electromagnetic system of Barringer Research.

This system had significantly greater resolution and depth of penetration than the system used by Kennecott in the 1950's. The success of the volcanogenic model and the INPUT system in Canada, and the confidence and enthusiasm of Phillips in and for the potential of the felsic volcanic terrain he saw in Rusk County, was sufficient for Kennecott to plan a significant program in 1967. With this new model and new technology they would try one more time to find a massive sulfide deposit under glacial cover south of Lake Superior.

### Flambeau Discovery

Flying began in May, 1967, on a survey located just west of Ladysmith (Figure 1). The first line indicated a strong, six-channel conductor that was to become the Flambeau Deposit; the second line to the west picked up only a weak conductor. On the strength of the first line conductor, and the strong recommendation of the Geotrex geophysicist, Don Wagg, two additional lines were flown to the east of line one, and confirmed the presence of a very strong but short responsive body at shallow depth.

Other anomalies were found, many of which were long and although strong, probably represented formational conductors. Wagg was convinced that the first line anomaly, called F-22, was the best and should be drilled first. It was not the first anomaly drilled, however, for reasons of land availability rather than priority. The apparent success of Kennecott's first airborne survey encouraged them to plan a second survey east of their initial one. At the same time crews were mobilized to conduct ground follow-up surveys on the better anomalies as land agreements were signed.

Electromagnetic, magnetic and gravity surveys were completed at anomaly F-22 and all were strongly indicative of a sizeable massive sulfide deposit. There were no nearby outcrops which would give any clue as to the geology of the anomaly, but one outcrop of andesitic volcanics one mile to the south suggested that the right environment was present. Based on the geophysical signature Kennecott geophysicist Carl Schwenk was absolutely certain he was seeing a classic volcanogenic massive sulfide deposit. On November 6, 1968, Kennecott's first hole, drilled under the direction of Helmut Sichermann, intersected tens of feet of chalcocite mineralization hosted by pyritic metavolcanic rocks. The next few holes established F-22 as the first volcanogenic massive sulfide copper-zinc deposit to be found in the Superior Craton south of Lake Superior. The presence of thick chalcocite mineralization was a complete surprise to Kennecott, and the fact that it clearly represented Precambrian enrichment prior to the deposition of the basal Cambrian sandstone was even more intriguing.

### Thornapple Discovery

Detailed geologic mapping and prospecting began in the Ladysmith area in 1966 and was accelerated as soon as it was apparent that the airborne survey had turned up a sizeable number of anomalies. This work identified several occurrences of felsic volcanic rocks in and around Rusk County, the pattern of which determined the lay-out of Kennecott's first airborne survey. One outcrop in particular, found by geologist Bill Spence under a railroad bridge over the Thornapple River, contained weakly mineralized iron formation. When Kennecott's third airborne survey was flown in 1969 it covered this Thornapple area, and a modest anomaly was found, but it was coincident with a local power line, railroad, and bridge, and was attributed to "culture".

Responsibility for the Wisconsin project was handed over to E. H. "Ned" Eisenbrey, one of Kennecott's senior geologists, in early 1967. He was as enthusiastic about the Ladysmith area as

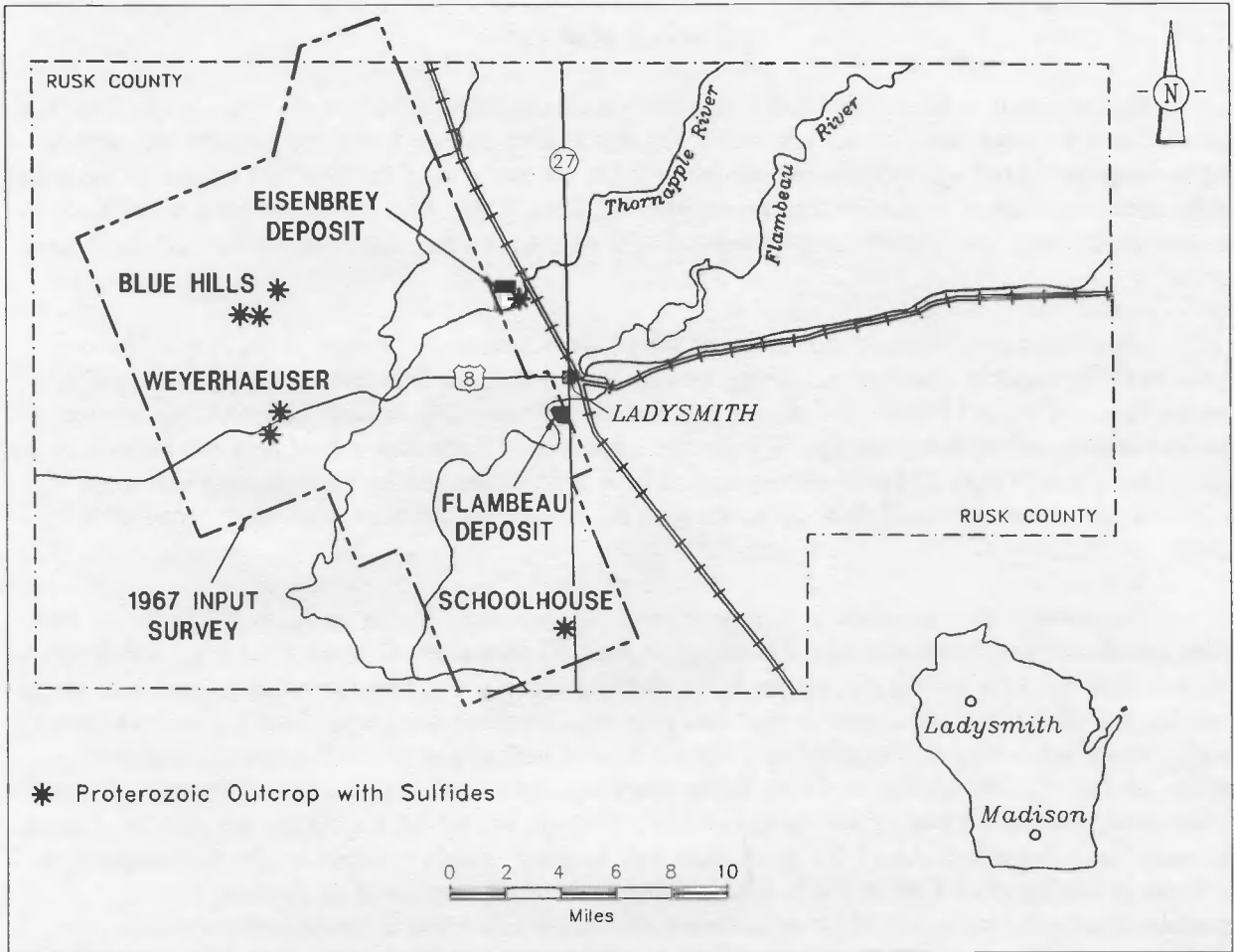


Figure 1. KENNECOTT'S FIRST AIRBORNE ELECTROMAGNETIC SURVEY WITH THE LOCATION OF MASSIVE SULFIDE DEPOSIT AND CHIEF OUTCROPS, RUSK COUNTY, WISCONSIN

Phillips had been before him. He supervised the initial flying and encouraged Wagg to fly the extra lines on the F-22 anomaly. He also managed the detailed geological and geophysical work and drilling that followed. He had made a large commitment to the success of the project. As a sign of this commitment he was not about to let the Thornapple anomaly, coincident with mineralized iron formation, go untested. He and geologist Bob Stuart completed three holes in the Thornapple area before overcoming the objections of the geophysicists and securing some ground surveys. They completed a ground magnetic survey which produced a good anomaly west of the weakly mineralized outcrop and ran one gravity line which also was anomalous. In 1970 the fourth hole at Thornapple intersected thick sulfides with intervals of copper and zinc mineralization. Kennecott had made their second volcanogenic massive sulfide discovery in Wisconsin.

Momentum built in the Kennecott program and new airborne surveys continued to produce new anomalies. Broad areas were flown with aeromagnetics to locate favorable volcanics, and smaller areas were flown with INPUT (Figure 2). Land was acquired and ground surveys completed farther to the north and east. Like the anomalies near Ladysmith, most were related to formational sulfides or graphite, while others consisted of only sulfides. Some anomalies were on land that could not be acquired at the time, and were deferred for later follow-up. Surveys in the Schoolhouse area produced only weak airborne anomalies, indicating that little conductive material was present. Perhaps the 1955 survey was testing bedrock after all, but no conductors were present. Had Kennecott covered the area to the north of Schoolhouse, Flambeau might have been found thirteen years earlier.

### **Newcomers Join the Search**

Kennecott announced the discovery of the Flambeau Deposit in 1970. Several companies already knew or learned then that Kennecott had discovered something new and exciting in Wisconsin, and recognized an environment favorable for volcanogenic massive sulfides. Duval, Exxon, Noranda, U.S. Steel and several other companies joined the search and were flying or planning surveys by 1972.

But while others were moving in, Kennecott was moving out. Late in 1971 Kennecott's exploration program suffered heavy and universal budget cuts which essentially ended the Wisconsin program. Drilling continued on the F-22 anomaly, now called the Flambeau Deposit, and at Thornapple, but all exploration in Wisconsin had ceased by the end of 1972. At this time Kennecott had flown less than half of the favorable terrane, as it was then known. In 1966 the author pointed out to an enthusiastic Jack Phillips on his first visit to the Schoolhouse prospect that the most difficult job was not to convince Kennecott that they should fly an airborne geophysical survey over part of Rusk County, but that they should continue to fly airborne surveys in Wisconsin until they found "the big one." In spite of their success, in 1972 Kennecott was leaving with the job undone.

### **PHASE TWO: EXPANDED EXPLORATION**

Kennecott continued to drill both the Flambeau and Thornapple deposits over the next few years, defining reserves at Flambeau that would be developed for production in 1993, but outlining only a small, structurally complex resource at Thornapple. Detailed descriptions of these deposits will be the subject of separate articles in this volume by May and Dinkowitz (Flambeau) and May (Thornapple, now the Eisenbrey Deposit).

In 1969 the job of drilling out the Flambeau Deposit was assigned to Ed May, who became and remains Kennecott's key geologist and project champion. Drilling under May's direction defined the precious metal gossan, chalcocite enrichment zone, and the underlying, classic copper-zinc

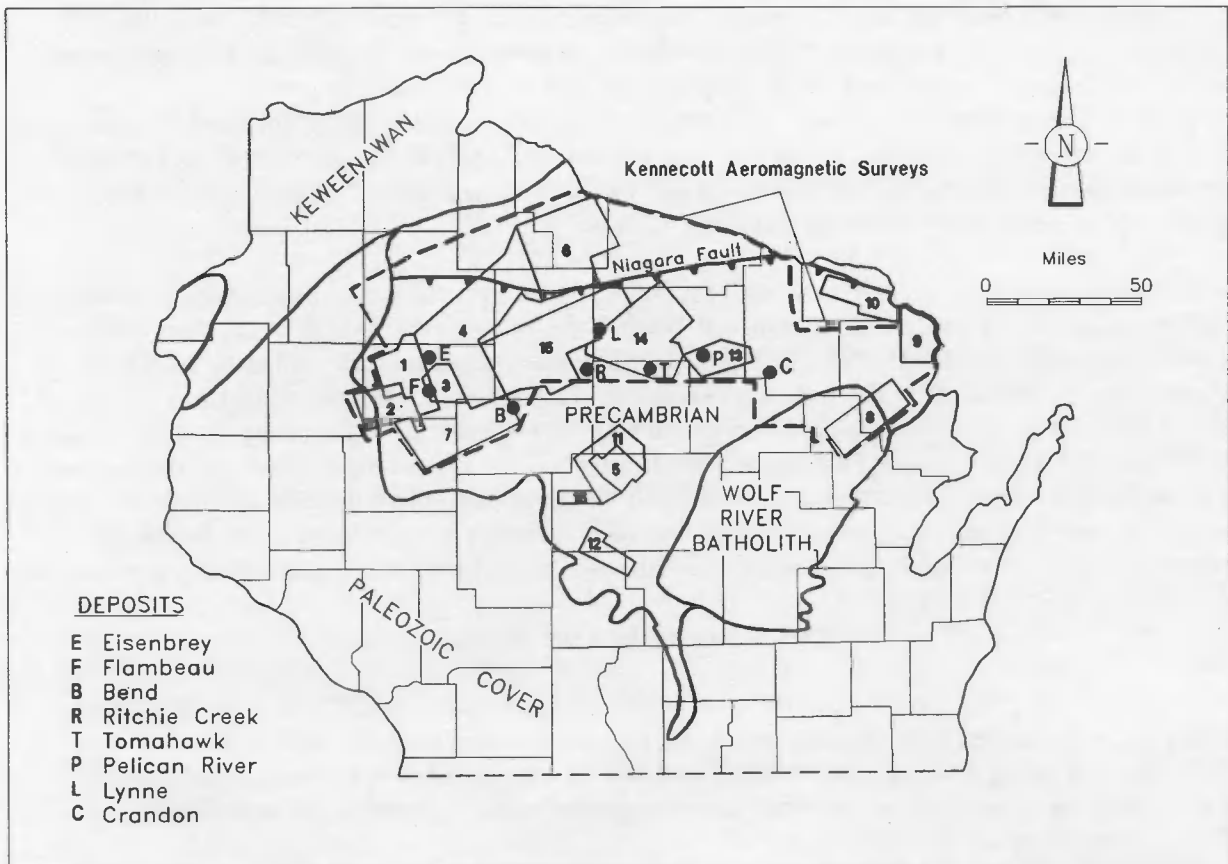


Figure 2. KENNEBECOT PRE-CRANDON AIRBORNE  
ELETROMAGNETIC AND MAGNETIC SURVEYS  
(in order flown, 1967-1971)



volcanogenic massive sulfide deposit. He persisted in producing excellent geologic records at a time when the outlook for the project was uncertain, a contribution which would pay off for Kennecott in the 1990's.

### Exxon Program

Exxon was the second major company to begin a volcanogenic massive sulfide program in Wisconsin. Jim Mancuso of Exxon's Houston office became aware of Kennecott's intense drilling activity at Ladysmith in 1969 and recognized the marks of a new discovery. In 1970 he assigned Mel Erskine the task of organizing and implementing an exploration program. Erskine completed a wide-spaced airborne magnetic survey over a large area east and northeast from Ladysmith and identified several potentially favorable terrains for airborne electromagnetic surveys. Exxon also began to map and prospect the geology of northern Wisconsin in great detail, and by this means added several other target areas to their list.

Paul Schmidt became Exxon's District Manager in early 1971 and took over responsibility for the Wisconsin program, and Jerry Dolence was transferred in as Project Geologist. Eleven airborne electromagnetic surveys were flown in 1971 and 1972, including one in the Tomahawk area (Figure 3). Results were equivocal and there was talk of pulling out of Wisconsin. After all, Flambeau had already been found and was small. However, follow-up of the Tomahawk survey in 1973 led to the discovery of the small Hawk deposit which, although not commercially viable, gave Exxon sufficient encouragement to undertake additional airborne surveys, including a huge airborne magnetic survey of most of northern Wisconsin. This was used successfully to identify volcanic bedrock areas favorable for testing with electromagnetic surveys. Field geology and prospecting was expanded. This second surge of activity included a survey eastward from the Tomahawk area where a completely covered greenstone belt was inferred based on the interpretation of magnetic survey results.

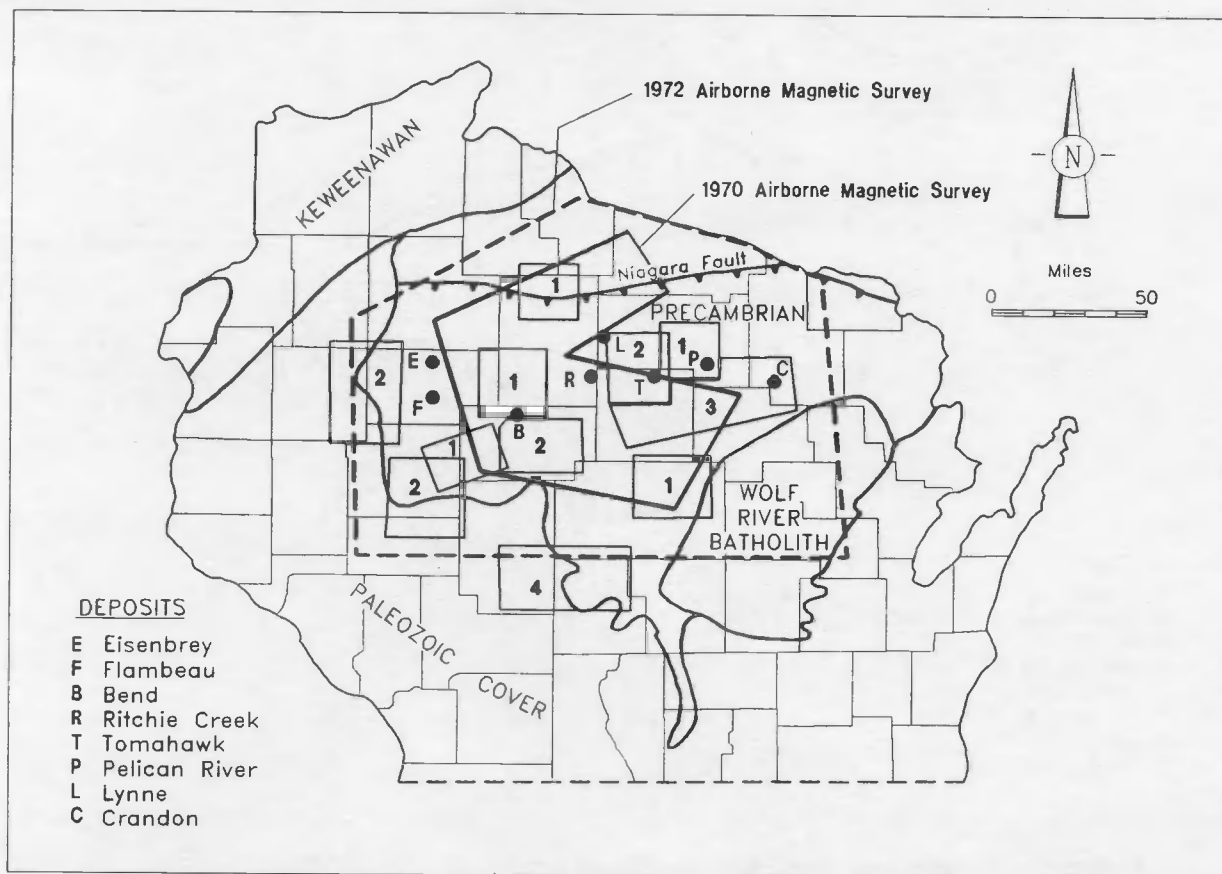


Figure 3. Exxon Pre-Crandon airborne electromagnetic and magnetic surveys (1=1970, 2=1972, 3=1973, 4=post-Crandon)

After four years and little more than a technical success to show for their efforts, Exxon decided to terminate exploration in Wisconsin in 1975. Schmidt was given sufficient funds to drill four more anomalies before wrapping up the program. One of these was a mile-long, six-channel anomaly at Skunk Lake detected in the 1974 survey east of Tomahawk. Although the anomaly was rated only as "fair" because it lacked a magnetic response, Schmidt decided it deserved a test (Schmidt, 1991). The first drill hole in this anomaly in July, 1975, discovered clearly ore-grade base metal sulfides. By July, 1976, when the details of the new Crandon Deposit were released to the public, it was apparent to the industry and the public that Exxon had found "the big one."

### Noranda Program

Noranda was the third major player in Wisconsin. Geologic reconnaissance work began in 1968 and in 1970 Bob Miller heard Gene LaBerge talk about the rhyolites at Wausau while attending a meeting of the Institute on Lake Superior Geology, visited the area, and liked what he saw. Miller started a program right away under the direction of District Geologist Lawrence Machesky (Mudrey, *et al.*, 1991). Frank Condon also came down from Canada as project geologist. Several airborne electromagnetic surveys were completed in the early 1970's, including a large survey in Forest and Oneida Counties flown in 1973 (Figure 4). A large number of good-looking anomalies turned up on this survey, many of which were on County land. An agreement was reached with Consolidated Paper Company to explore their large holdings in northern Wisconsin, which gave the Noranda program a good start. A strong anomaly on the Pelican River was acquired and drilled, and Noranda had its first discovery. The Pelican River Deposit turned out to be small and of only modest grade, but it stimulated one of the longest, most continuous exploration efforts by any company in Wisconsin. Don Cross was brought in from Canadian operations in 1975 because of his volcanogenic massive sulfide experience.

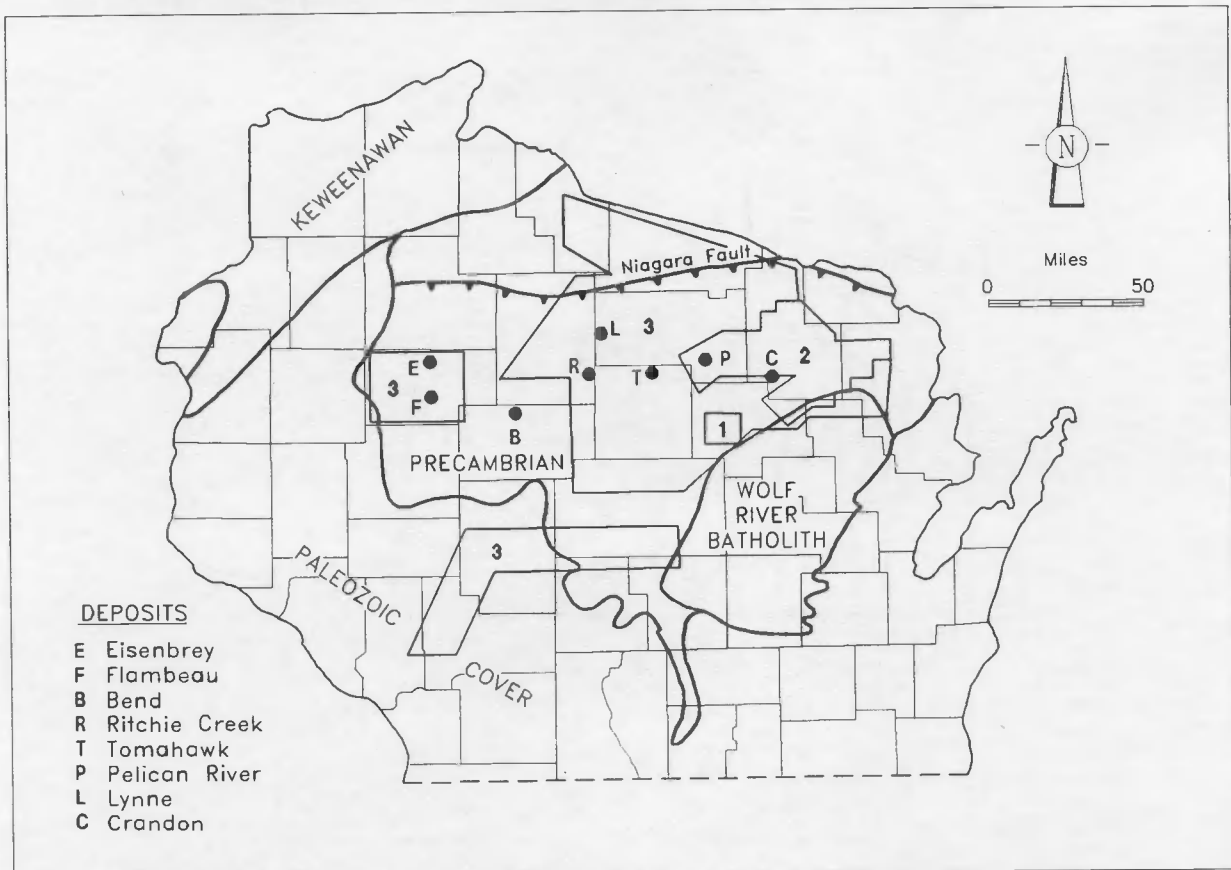


Figure 4. Noranda pre-Crandon airborne electromagnetic surveys (1=1971, 2=1973, 3-post 1974)

Like Exxon, Noranda completed considerable geological mapping and prospecting to supplement their airborne work, and compiled the available data. Noranda had the perceived advantage of their experience in the Noranda District in Quebec, a classic volcanogenic massive sulfide district. Miller recognized that the outcrops around Monico were what they were looking for in Wisconsin, and their work in the Pelican River area started from there and expanded outward.

Every company had their own idea of what constituted favorable terrane for prospecting in Wisconsin, based on their interpretation of poorly exposed bedrock and differing views of the detailed volcanogenic massive sulfide model. Noranda was attracted to the large area of pyritic felsic volcanics around Monico. Their airborne surveys were located on the basis of geology, magnetic patterns, assumptions regarding land availability, previous exploration by competitors, and the limits of budgets. There was no sure way of knowing what areas had been flown by the competition, and there was often an overlap of competing surveys. After the announcement by Exxon of the Crandon discovery, Noranda realized that one of their surveys stopped just short of Skunk Lake. In looking over the tapes of the survey it became clear that the survey plane had made its turn over Crandon and had actually picked up a strong, six channel anomaly. Such data picked up outside the survey area is often discounted or not reported, and in this case escaped Noranda's consideration. In addition, so many responses turn up in the course of an ordinary electromagnetic survey that is unlikely that all will be checked. Coming back to these old surveys with new ideas and new models is standard procedure, and eventually paid off for Noranda at Lynne.

### U. S. Steel Program

By 1974 both Noranda and Exxon realized that their chief competitor in the greater Monico area was U. S. Steel. U. S. Steel had been exploring in Wisconsin since the early 1950's, admittedly for iron. The U. S. Steel program was conceived by Ralph Marsden, who felt that perhaps they could find an iron deposit of higher than taconite grade in the older, more highly metamorphosed rocks south of the Gogebic Range. The field work was being directed by Cedric Iverson and consisted of relatively crude magnetic surveys, but also detailed geologic mapping and pebble counts on three-mile centers all across northern Wisconsin. Iverson used large numbers of student geologists, including at least one current authority on the geology of northern Wisconsin, Gene LaBerge.

When U. S. Steel learned of the discovery of the Flambeau Deposit, Iverson was asked why he had not found it, a question many exploration managers would be asked as subsequent discoveries were announced. This was enough to stimulate the conversion of Iverson's program from iron to base metals, and by 1970 U. S. Steel was flying airborne surveys in Chippewa County. They based their priorities on their knowledge of Precambrian bedrock, pebble count results, and some semiquantitative geochemical results from soil samples taken at pebble count stations. Their program moved to Taylor, Wood, and Portage Counties, and there was no shortage of anomalies (Figure 5). U. S. Steel flew some large aeromagnetic surveys, but mostly in the search for iron formation north of the Niagara Fault. Drilling results were not encouraging, however, and the U. S. Steel crew referred to themselves as the "Pyrrhotite Kings" of Wisconsin. Of course they would drill only those anomalies with a magnetic response, a consequence of their understanding of the volcanogenic model.

The U. S. Steel airborne program had moved into the area south of Monico and Crandon by 1974, again with a number of airborne anomalies but no base metals. They were gravitating to the Monico area for the same reasons that Noranda and Exxon favored the area, the abundance of sulfide-bearing felsic schist. There must have been considerable overlap of surveys, if not out and out competition for land.

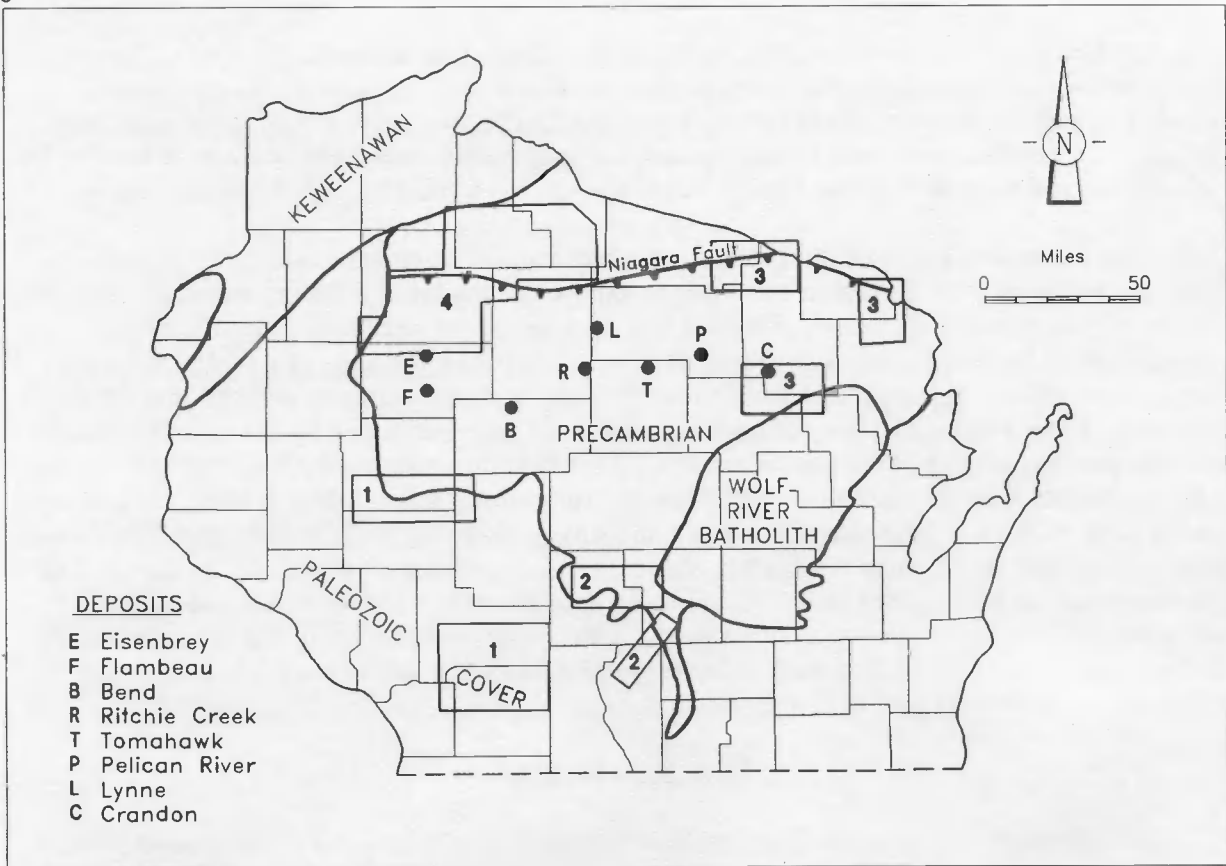


Figure 5. U.S. Steel pre-Crandon airborne electromagnetic surveys (in order flown, 1970-1975)

When it became apparent to U. S. Steel that Exxon had a discovery at Crandon they took a look at their data for the area. Like Noranda, U. S. Steel had flown two lines over the Crandon Deposit which picked up the anomaly. One they attributed to culture and the other to topography. Part of the problem was that the airborne system that U. S. Steel was using was not as sensitive as that used by Exxon. U. S. Steel looked at their pebble count and geochemical data, too, and found that a gravel pit near Crandon had more sulfide-bearing felsic volcanic pebbles than anywhere else in the state. Hindsight is wonderful; the more difficult task is converting hindsight into foresight and carrying on. Not many succeed. Kennecott, Noranda, and U. S. Steel had all missed their chance to find "the big one."

Iverson kept at it for a couple years after Crandon, but eventually U. S. Steel retired from the Wisconsin scene empty-handed. He observed that all the base metal deposits and occurrences were located along a fairly narrow east-west line from Crandon to Flambeau, with only iron sulfides on either side. It remains to be seen whether or not this "Highway Eight Lineament" has any geological merit, or whether it is merely an artifact of the exploration model of the day.

#### Other Companies

The Duval Corporation learned of Kennecott's activity at Flambeau and quickly initiated a field program in 1970, flying an area in Marinette County in 1971. This program under the direction of A. L. Barker was designed to explore an area with some favorable volcanics but little outcrop well east of Ladysmith, in an area where large blocks of County and some State land might be available

for leasing (Mudrey, *et al.*, 1991). A small, low-grade sulfide iron formation-type deposit was found in early 1972 after ground testing and drilling eight anomalies. Although no further discoveries were made by Duval, their technical success tended to expand the efforts of other companies into eastern Wisconsin.

As many as a dozen other companies came into Wisconsin in the early 1970's; some of these are listed on Table 1. More surveys were flown, offices opened and closed, and anomalies drilled, but only small deposits or shows were found. In later years much of the data generated by these companies became available to others through joint ventures and farm-out agreements, and provided a foundation for intermittent exploration and the discovery of a few additional small deposits in the 1980's. But no more large deposits were found.

TABLE 1

Companies Exploring in Wisconsin 1969 to 1976

Exxon	ACNC (INCO)	Cerro de Pasco
Kennecott	Cleveland Cliffs	Calumet & Hecla
AMAX	Noranda	National Lead
Superior Oil	U. S. Steel	Kimberly Clark
Cominco	Anaconda	Midwest Oil
Universal Oil Products	Homestake	General Crude Oil
New Jersey Zinc	ASARCO	
Texasgulf	Phelps Dodge	

The political climate in Wisconsin prior to 1976 was beginning to show signs of the problems which would erupt within a year. The State recognized at the time of the Flambeau announcement that it did not have sufficient regulatory and statutory control to handle a developing base metal industry. Kennecott worked with the State to develop a set of permitting rules and reclamation regulations which, although modified, form the basis for the current legal framework. Kennecott also began to work with the legislature to develop a reasonable tax regime. Unfortunately by 1976 many of the issues surrounding mine development and taxation were moving toward discord, rather than agreement.

**PHASE THREE: THE PROBLEM YEARS**

The discovery of the Crandon Deposit was the beginning of the third phase of base metal massive sulfide exploration in Wisconsin. Exxon accelerated its program and others came into the state, or rebuilt their earlier programs. Unfortunately, the excitement of the exploration community was soon severely dampened by political events in Madison. Efforts to regulate and tax, or even stop, base metal mining were accelerated. What was perhaps a local issue involving Kennecott and the residents of Rusk County suddenly took on a new perspective. Acrimonious debate began on a new level over both economic and environmental issues. In 1976 Kennecott was denied a local zoning permit to develop its Flambeau deposit. The following year the Wisconsin Legislature enacted an untenably high tax on base metal mining. The years between 1976 and 1991, when Kennecott finally received approval for the Flambeau mine, became a roller coaster ride of off-again, on-again exploration involving intermittent political negotiations at local and state levels, compounded by historically low metal prices.

### **Kennecott Returns**

Kennecott attempted to resurrect the Flambeau project several times, but concern for the political climate in Wisconsin, severe financial problems brought on by depressed copper prices, opportunities in gold elsewhere, and new ownership, all impacted the project and kept it on the shelf. In 1986, Larry Mercado was assigned to the project and moved to Ladysmith, and by the late 1980's had developed a strong commitment from Kennecott management to obtain permits for an open pit, direct shipping operation. This coincided with an upturn in copper prices, the purchase of Kennecott by RTZ, and a new government attitude in Madison which was more supportive of mining. Although some of the negative concerns of the earlier years remained to be overcome, Mercado's five-year effort brought reason to the front and in January, 1991, Kennecott received the necessary state and local permits and started construction. In May, 1993, after a brief delay for a final environmental review, based on the discovery of an unusual, wayward clam in the nearby Flambeau River, the mine was in production.

### **Exxon Leaves**

Geological and engineering work progressed smoothly at Crandon following the initial drilling. Ed May was hired to manage the development drilling and produce resource and reserve estimates, and his experience at Flambeau was put to good use. By 1980 most of the technical work was in hand and it remained for the engineers and managers to develop a mine plan and get it permitted.

Exxon began to encounter the same kind of political problems at Crandon that Kennecott ran into at Flambeau. Development of a reasonable mine plan was frustrated by the passage of the punitive tax law in 1977 and a series of unresolved revenue and environmental issues. These uncertainties complicated the permitting process. Although a revised tax law took effect in 1981, other issues such as local zoning were still obstacles to obtaining a permit. The political climate in Wisconsin was decidedly unfriendly. On top of this, metal prices were as low as they had been in decades. It was not a good time to try to promote a base metal mine in Wisconsin to management.

Before permitting efforts could be carried forward, a decision was made by Exxon in 1986 to get out of the minerals exploration business and to divest itself of its mineral properties. Over the next several years several companies entertained the possibility of developing Crandon in joint venture with Exxon, but again a combination of poor metal prices and concern over the political risks in Wisconsin prevailed. In 1994 Exxon and Rio Algom announced a joint effort to permit and operate a scaled-down underground zinc mine at Crandon, subject to a positive feasibility report and acquisition of the necessary permits. This effort is currently in full swing and appears to be headed toward success. Governor Thompson has repeatedly supported responsible mining, and it appears that the overall political climate has changed for the better.

### **Noranda Persists**

The years following the Crandon announcement were difficult ones for Noranda, as well. Carl Schwenk took over management of the program and continued to explore the greater Monico area with encouragement but no real success. Glen Adams joined the program from Exxon. In 1978 Wisconsin passed into law the Geologic Information Act which required all subsurface exploration data, whether from government or private land, to be made a part of the public record. You can imagine the concern this caused in the exploration community, given the number of companies involved and the intensity of competition. Noranda took up the cause of the industry and filed suit

against the state in 1979 to overturn this law. To demonstrate the seriousness of their concern for this law and the punitive tax burden, Noranda closed their Wisconsin office in 1978, although they maintained their land holdings and continued on a reduced basis to test their better targets. In anticipation of success in overturning the Geologic Information Act, Noranda reopened their Rhinelander office in 1981, and renewed their exploration efforts. They still liked, but could not acquire, the Oneida County land. Several more good grade but small size discoveries would come along, but nothing approaching economic scale.

Although Noranda was frustrated by the fact that good anomalies on Oneida County land could not be acquired, they maintained their interest in them and worked with the County to develop a leasing policy. When it was announced in 1989 that there would be a lease sale, Noranda had a good idea of what land was favorable. They won the bid for land in Lynne Township and drilled their second significant discovery in January of 1990. The Lynne Deposit is a tribute to the persistence of Noranda, their faith in the volcanogenic massive sulfide model, and the importance of appreciating and using old data.

### New Companies Join The Search

Competition continued at a high level after 1976, in spite of the adverse political environment and low metal prices. In addition to the standard base metal companies with their "go-it-alone" approach, a proliferation of joint ventures were formed. Leading the way was Ernie Lehmann who established several ventures with oil companies such as Chevron, Getty, Superior and General Crude. Ernie had been a consultant for several of these companies prior to Crandon, but became an equity partner in these new ventures. Ned Eisenbrey joined Ernie after Kennecott pulled out in the early 1970's, and Ernie attributes much of the success of these joint ventures to Ned's ability to sort out which anomalies were sulfides and which were graphite. From 1980 to 1984 these ventures added Ritchie Creek, Bend, Horseshoe, and Jump River to the list of discoveries in Wisconsin. These are small deposits, at this point, but continue to be of interest and may some day, like any of the other numerous small deposits, lead to bigger things. Opportunities still exist for those who persist.

A list of some of the companies who entered the fray following the Crandon announcement are shown in Table 2. This list is probably not complete, but will illustrate the scale of interest and competition that existed, and essentially continues today.

**TABLE 2**

#### Companies entering Wisconsin After Crandon

AMOCO	Getty
Chevron	Dennison
Kerr McGee	B.I.A. (Mole Lake)
Falconbridge	BHP
Inspiration	Cyprus
Newmont	Sharp Resources
St. Joe	
Rayrock	

## PHASE FOUR: THE PRODUCTIVE YEARS

Entry into the next phase of the history of massive sulfide exploration in Wisconsin is almost upon us, or may have already started. Two operating base metal mines in northern Wisconsin confirm Kennecott's original thesis of the 1950's: there is no reason why major deposits should not occur under glacial cover on the Superior Craton south of Lake Superior. Exploration now has been conducted for forty years based on this premise, by a large number of companies. North of Lake Superior new discoveries are still being made after a much longer period of exploration, using more sophisticated technology and models. There is no reason why the same persistence and approach will not be brought into Wisconsin. Many of the anomalies found in earlier electromagnetic surveys remain untested, for reasons of land inaccessibility, weaker response, or unavailability of the proprietary data. Some areas with potential may have been missed, deep targets under small, nearsurface occurrences may be developed, and clearer understanding of the bedrock geology may generate a more favorable interpretation of potential for parts of northern Wisconsin. Whatever the case, the fact that two major deposits have been found and were brought into, or are headed for, production will certainly stimulate a resurgence in exploration. Let us all hope that this fourth phase of massive sulfide exploration in Wisconsin is the smoothest, longest, and most successful.

### Acknowledgements

A history is never complete because all the people who form it are generally not always represented in the telling of it, nor are the memories of those polled always reliable. In the case of the early volcanogenic massive sulfide exploration in Wisconsin a few of the players are still around and have given advice on this presentation of some of the history involved. Much of the Kennecott story was compiled as part of a paper authored by Michael Mudrey of the Wisconsin Geological and Natural History Survey in 1991 in which this author participated. Other comments on Kennecott's experience were solicited from Larry Mercado and Ed May. Events in Exxon's history were discussed with Paul Schmidt and Ed May. Noranda's experiences were reviewed with Bob Miller, Michael Donnelly, Carl Schwenk, and Glenn Adams. The activities of U. S. Steel were recounted by Cedric Iverson and Thon Ginn. Ted DeMatties and Ernie Lehman offered comments on the more recent exploration history in Wisconsin. All contributed to the list of players on Tables 1 and 2. Ed May and Jay Hammitt reviewed this paper and provided very constructive comment and encouragement.

Exploration history is complicated by the fact that programs and discoveries are team efforts. Geologists, geophysicists, and managers at several levels all become intricately involved in the planning and implementation of any one program. All deserve a share of the credit, and the blame, as things go right and wrong. Explorationists understand that it is often external factors that force decisions that make or break a program. It is a tribute to explorationists that they persist in their optimism and enthusiasm, often for decades, in spite of the variety of obstacles they encounter. The successful but unfinished search for volcanogenic massive sulfide deposits in Wisconsin is a prime example of how talent and persistence combine to win the day, to the benefit of us all.



### References Cited

- DeMatties, T. M., 1994, "Early Proterozoic Volcanogenic Massive Sulfide Deposits in Wisconsin: An Overview," *Economic Geology*, vol. 89, p. 1122.
- Mudrey, M. G., Jr., Evans, T. J., Babcock, R. C., Jr., Cummings, M. L., Jr., Eisenbrey, E. H., LaBerge, G. L., 1991, *in* Hollister, V. F., ed., "Case Histories of Mineral Discoveries, Volume 3, Porphyry Copper, Molybdenum, and Gold Deposits, Volcanogenic Deposits (Massive Sulfides), and Deposits in Layered Rock": Society for Mining, Metallurgy, and Exploration, Inc., p. 117.
- Schmidt, P. G., "Discovery Case History of the Crandon Massive Sulfide Deposit, Forest County, Wisconsin," *in* Hollister, V. F., ed., "Case Histories of Mineral Discoveries; Volume 3, Porphyry Copper, Molybdenum, and Gold Deposits, Volcanogenic Deposits (Massive Sulfides), and Deposits in Layered Rock": Society for Mining, Metallurgy, and Exploration, Inc., p. 99.



## GENERAL CHARACTERISTICS AND GEOLOGIC SETTING OF THE WISCONSIN MAGMATIC TERRANES

by Gene L. LaBerge

Geology Department  
UW-Oshkosh  
Oshkosh, WI

### ABSTRACT

The Wisconsin magmatic terranes (referred to by workers in the mineral industry as the "Ladysmith-Rhineland volcanic belt") constitute a major addition to the Lake Superior region that formed during Early Proterozoic convergent tectonics. Radiometric dating indicates that the volcanic and plutonic rocks were generated between 1,890 and 1,830 million years ago. Continuing geological, geochemical, and geophysical studies have allowed refinements on earlier interpretations of the general character and tectonic setting of the terranes. Available information indicates that a variety of different geological environments, including an oceanic island arc, back arc basins, and a continental volcanic arc, and perhaps other environments are represented within the area commonly referred to as the Wisconsin Magmatic terranes.

Recognition of the existence of the magmatic terranes in the 1960's led to extensive exploration for volcanogenic massive sulfide deposits in Wisconsin. Geophysical surveys identified dozens of exploration targets that were subsequently drilled. These data have added greatly to the database on the volcanic belt, an area that is generally very poorly exposed because of the thick cover of glacial deposits.

Three areas within the magmatic terranes contain sufficient outcrop to permit traditional geologic mapping: the Pembine area in northeastern Wisconsin, the Monico area in the central part of the belt, and the Marathon County area on the southern margin of the belt. Studies in these areas suggest that each area represents a different environment. The Pembine area contains remnants of a dismembered ophiolite and an oceanic island arc. The Monico area contains an older sequence of gneissic rocks overlain by a bimodal suite of basalts and rhyolites that may represent a back-arc, or perhaps an intra-arc rift environment. This postulated rift may represent the "Highway-8" lineament, along which most of the major sulfide deposits formed. The Marathon County area contains several sequences of volcanic and plutonic rocks that appear to have a more complex origin. Some volcanic rocks belong to a basalt-andesite-rhyolite sequence that appears to be arc-related. A sequence of caldera-related rocks in the Wausau area unconformably overlies an older volcanic sequence, and appears to be a post-tectonic feature. These various environments may host rather different types of mineral deposits.

### INTRODUCTION

In the past several decades great strides have been made in understanding the geologic evolution of the Lake Superior region. One of the major developments has been the recognition of a major belt of Early Proterozoic volcanic and plutonic rocks, named the Wisconsin Magmatic Terranes, that extends across northern Wisconsin from near Pembine, Wisconsin, westward approximately 200 miles to near Weyerhaeuser, Wisconsin (Figure 1). However, rocks correlated with the magmatic terranes are present in eastern Minnesota and northern Iowa, and the terranes extend eastward under Lake Michigan (probably to the Grenville Front). The belt is overlain by

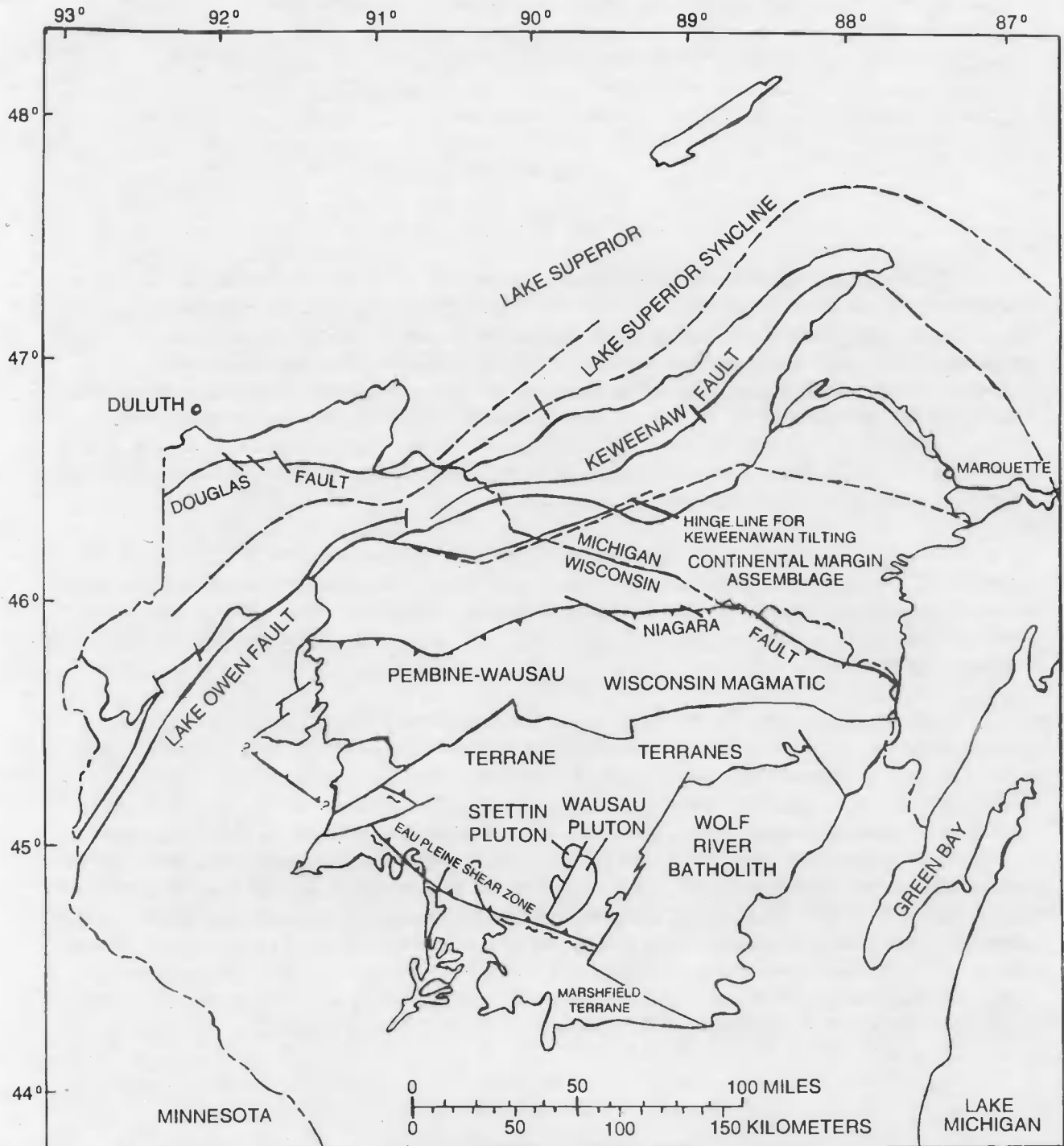


Figure 1. Generalized tectonic map of the southern part of the Lake Superior region (modified from Sims, 1992).

Paleozoic rocks to the east and west, and most of the belt is covered with a thick mantle of glacial deposits, with the result that much of the belt is not exposed.

The northern boundary of the belt is the Niagara Fault zone (Greenberg and Brown, 1983), which separates the volcanic and plutonic rocks from the dominantly Early Proterozoic sedimentary rocks of the Marquette Range Supergroup that were deposited on the margin of the Archean Superior Craton. The southern margin of the volcanic and plutonic belt is near Stevens Point, in central Wisconsin, where Archean rocks are again present (Morey and others, 1982). Thus, the belt is about 100 miles wide. The Middle Proterozoic Wolf River Batholith cuts out a major portion of the volcanic and plutonic belt in northeastern Wisconsin.

Because of the cover of glacial deposits, elucidation of the major features of the volcanic and plutonic belt has been a long-term process with major input from the mineral industry. The early compilation of geologic data by Dutton and Bradley (1970) demonstrated that outcrop density necessary for mapping was present in only a few areas: the Pembine area in the east, the Monico area about 80 miles to the west, and the Wausau area in the south. The Wausau area was mapped in 1969-1975 (LaBerge and Myers, 1983); the Pembine area was the subject of several graduate theses, and was mapped by Sims and Schulz (1993); the Monico area was also the subject of several graduate theses (Schriver, 1973; Venditti, 1973; Bowden, 1978), and was mapped by LaBerge, John Franklin, and John Klasner in 1990-1991 (LaBerge and Klasner, in review). However, it remained for the regional aeromagnetic survey by Karl (Zietz, Karl, and Ostrom, 1978) to provide a basis for extrapolation of data from one area to another. Detailed aeromagnetic and EM surveys and drill core data from various mining companies have provided much of the lithologic information currently available for unexposed portions of the Wisconsin magmatic terranes.

The general distribution of major units within the volcanic belt was shown on the regional geologic map of Morey and others (1982). Recent lithologic, geochemical, geochronologic, and structural data permitted Sims (1992) to refine the bedrock geology of the belt.

### **General Features of the Wisconsin Magmatic Terranes**

The Wisconsin magmatic terranes consist of an extensive suite of volcanic, plutonic, and associated sedimentary rocks that formed in the Early Proterozoic Penokean Orogen of the Lake Superior region. The rocks were produced during a complex convergent tectonic regime that existed from about 1,890 m.y. to 1,830 m.y. ago along the southern margin of the Archean Superior craton. A number of massive sulfides and other mineral deposits were produced during the Penokean igneous activity and tectonism. Convergent tectonics culminated with accretion of an island arc (or arcs) to the Superior Craton as well as collision of an Archean "microcontinent" of unknown dimensions with the accreted island arc.

Outcrops and drill core data indicate that the most widespread rocks are massive and pillowed basalts, with localized areas of andesitic to rhyolitic volcanic rocks and associated sedimentary rocks, mainly graywackes (Figure 2). Areas of metasedimentary rocks may represent a variety of environments. Graphite is abundant in some sedimentary sequences, but is largely lacking in others.

In the Pembine area the older rocks in the volcanic succession are tholeiitic basalt and basaltic andesite with associated gabbro sills (Sims and others, 1989) that comprise the Quinnesec Formation. The discovery of sheeted dikes, serpentinites, and plagioclase-rhyolite within the Quinnesec Formation suggests that these rocks are a dismembered ophiolite (Schulz, 1987). The tholeiites are overlain by a sequence of calc-alkaline rocks (the McAllister and Pemene volcanics, Jenkins, 1973) ranging in

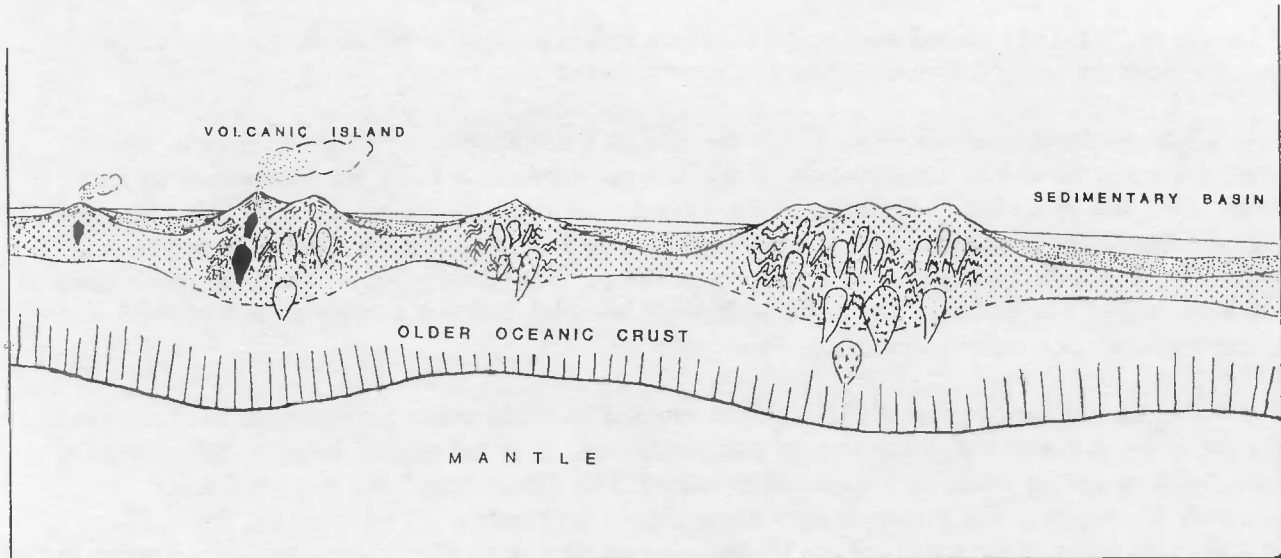


Figure 2. Idealized east-west cross-section of the Wisconsin magmatic terranes, showing felsic volcanic centers alternating with sedimentary basins.

composition from andesite to rhyolite, whose composition falls within the fields of subduction-related magmatic suites and are geochemically similar to volcanic suites from oceanic island arcs (Sims and others, 1989). Both subaerial rhyolites (volcaniclastic rocks) and subaqueous (hyaloclastite) rhyolites are present in the Pemene Formation, indicating at least periodic emergence in the area.

Volcanic rocks in the Monico area comprise a bi-modal sequence of high-Al basalts and low-SiO<sub>2</sub> andesites interbedded with felsic volcanic rocks of dacite to rhyolite composition (Sims and others, 1989). The mafic rocks are massive to pillowed with pillow breccia (Figure 3) relatively common. Pillows tend to be highly vesicular. Felsic volcanic rocks are massive porphyritic flows and lithic tuffs (subaqueous?) along with some probable subaerial welded tuffs (Figure 4) (LaBerge and Klasner, in review). The bimodal volcanic sequence has generally undergone only greenschist grade metamorphism, and presumably overlies amphibolite grade rocks exposed north of Highway 8 (Figure 5). A large quartz porphyry (the Neptune Lake porphyry) is intrusive into the amphibolite-grade rocks, and may have resulted in widespread chloritization, epidotization, and quartz-feldspar veining of the overlying volcanic succession near the Pelican River deposit (Figure 6). Several massive sulfide deposits, the Pelican River, Duckblind, and Wolf, occur within the volcanic sequence, and may have formed from the fluids that gave rise to the hydrothermal alteration. The volcanic rocks are compositionally similar to the bimodal calc-alkaline rocks that host Kuroko-type massive deposits elsewhere (Sims and others, 1989) and may represent a back-arc basin. However, according to K. J. Schulz (personal communication, 1995) the composition of the Monico volcanic suite appears to be unique within the Wisconsin magmatic terranes. He suggests that the volcanic rocks in the Monico area may be a remnant of an intra-arc rift that split the Pembine-Wausau Terrane, and may be the setting of the massive sulfide deposits. This postulated intra-arc rift may account for the so-called "Highway 8 lineament" formed by the known distribution of massive sulfide deposits within the terrane.

In central Wisconsin, the basaltic rocks in Marathon County are tholeiitic with compositions that are very similar to basalts of the Quinnesec Formation (Sims and others, 1989). Several large gabbroic bodies and several serpentinites are also associated with the basaltic rocks in Marathon County (LaBerge and Myers, 1983) (Figure 7). The tholeiitic sequence in Marathon County is overlain by calc-alkaline andesite to rhyolite rocks (LaBerge and Myers, 1984) that contains abundant, vaguely bedded, waterlaid tuffs and breccias and some welded (subaerial) tuffs and flows. Thus,



Figure 3. Photo of basaltic debris flow southwest of Monico. Wisk broom in upper right-hand portion of photo provides a scale.

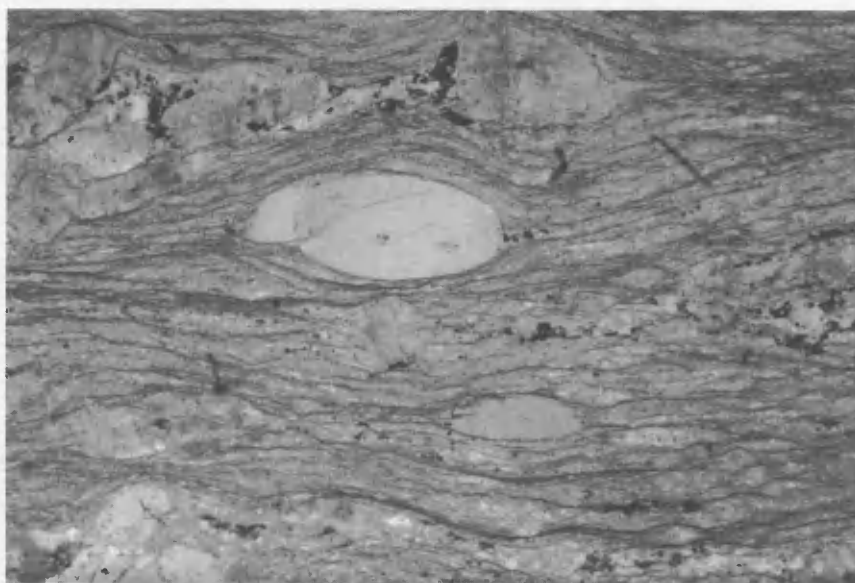


Figure 4. Photomicrograph of somewhat deformed felsic tuff southwest of Monico. Note the deformed quartz phenocryst near the center of the photo. Horizontal dimension of photo is 6 mm.

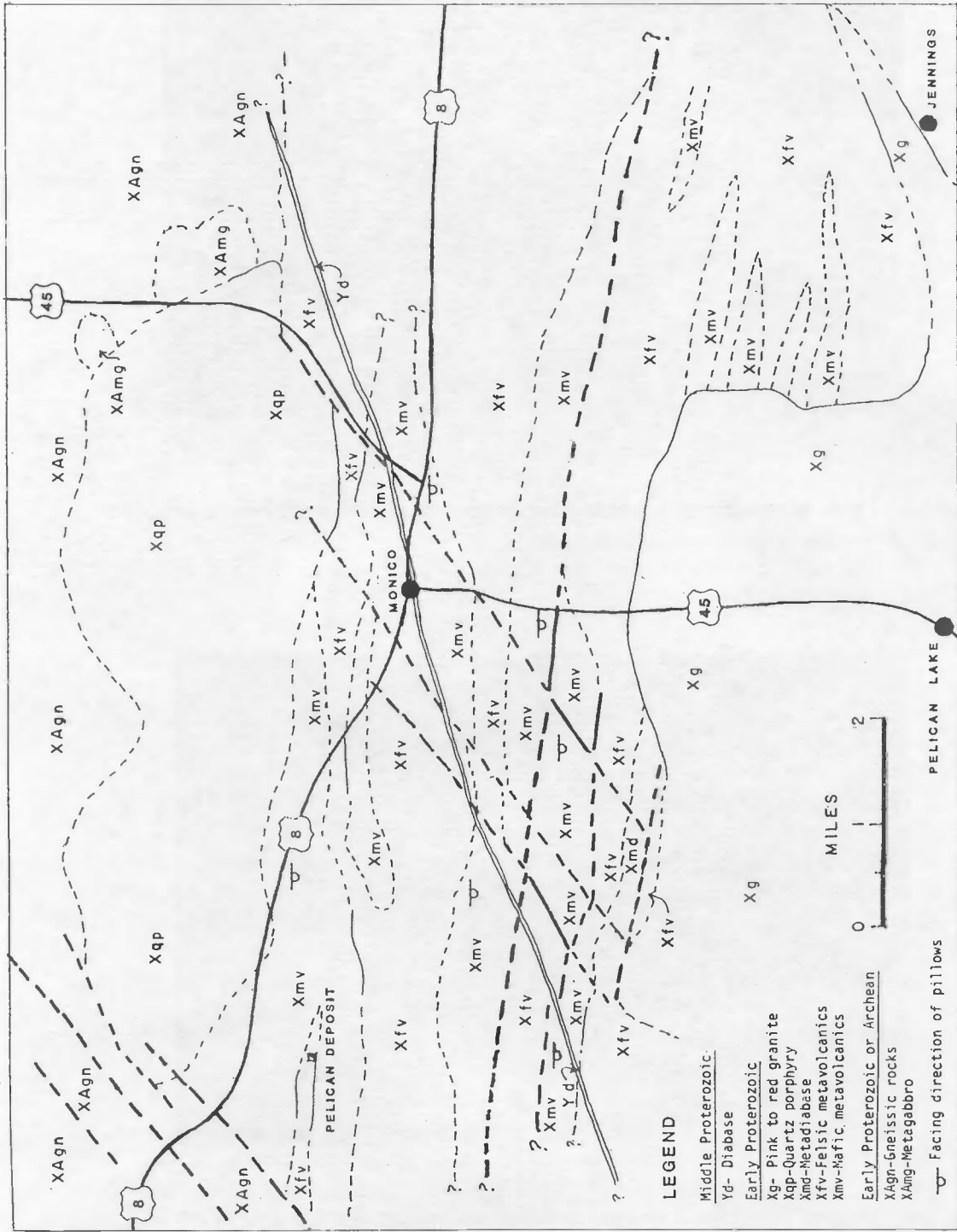


Figure 5. Geologic map of the Monico area. (From LaBerge and Klasner, in review.)





Figure 6. Photo of highly altered basalt from west of the Pelican River deposit. Knife is four inches long.

there are similarities between the rocks in central Wisconsin and the Pembine area. However, the calc-alkaline rocks in the Wausau area are chemically distinct from those in the Pembine area (Schulz, 1984; Sims and others, 1989). It is possible that the Marathon County area may have developed at least in part on an older basement, perhaps similar to the Archean rocks in central Wisconsin. This interpretation is supported by the presence of numerous Early Proterozoic intrusions into Archean basement rocks, and sillimanite-bearing quartzite xenolith in the 1,500 m.y. Wausau Pluton. The quartzite is interpreted to have been buried beneath the ~1,850 m.y. volcanic rocks and subsequently carried up to its present level in the syenite pluton (LaBerge and Myers, 1984). Sims and others (1989) also suggest that volcanics in the Marshfield terrane were deposited on Archean basement.

The Wausau area in central Wisconsin contains at least two distinctly different types of rhyolitic rocks. An older group of rhyolitic rocks is composed mainly of somewhat recrystallized and deformed subaqueous lithic tuffs and breccias, such as those exposed along County Hwy. J about five miles east of Wausau, and along County Hwy. A about five miles west of Wausau. They typically have a steeply dipping northeast trending foliation, with prominently flattened clasts. They are commonly interbedded with pillowed basalts, andesites, and graywackes, as shown in eastern and west-central Marathon County (fv and vs on Figure 7) (LaBerge and Myers, 1983). Locally the felsic volcanics show bleaching from hydrothermal alteration associated with significant pyritization.

The younger rhyolites are subaerial welded pyroclastic flows, flow breccias, and possible rheognimbrites along with associated volcanic sandstones and conglomerates. These rocks are

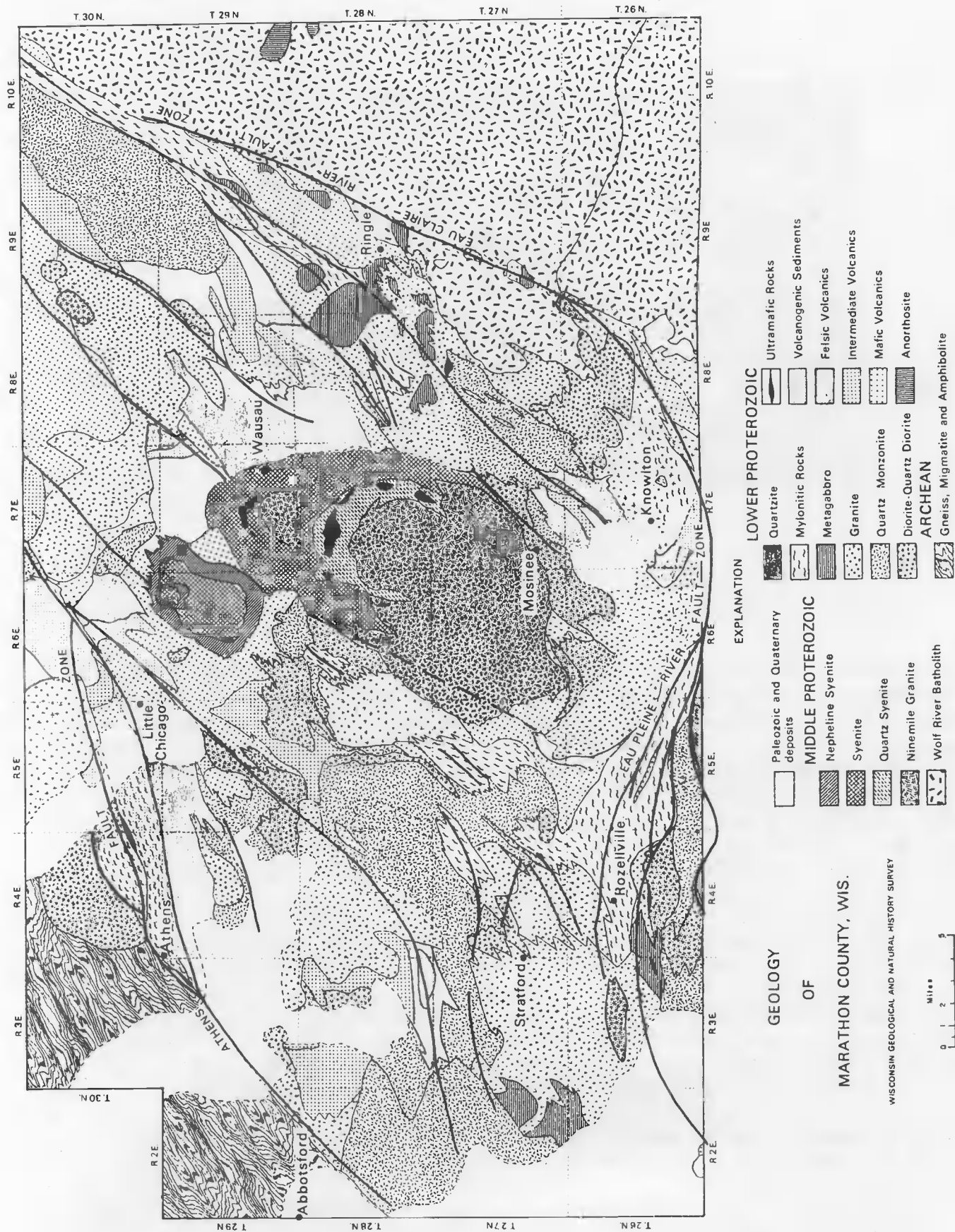


Figure 7. Geologic map of Marathon County. The "Reef deposit" is located north of Ringle in the eastern part of the map. (From LaBerge and Myers, 1983)

gently-dipping, essentially non-foliated with excellently preserved primary volcanic textures and structures. In short, they appear to be unconformable on the "older" volcanic units. Weidman (1907) named the conglomeratic units the "Marshall Hill Conglomerate", and suggested that it is unconformable on surrounding volcanic rocks. These lithologies are well exposed within the city of Wausau and in the Brokaw area south of the red granite pluton. A number of presumably normal faults offset various rhyolite lithologies within the 3M quarry at Brokaw. These offsets juxtapose lithologies unfavorable for quarrying against favorable horizons and present problems in the quarry operations. The various rhyolites consist of welded tuffs, rheognimbrites, laharic deposits, massive flows, volcanic sandstones, and massive porphyritic rhyolite. The rhyolite flows, tuffs, and lahars may be part of a caldera complex and the massive rhyolite may represent part of a resurgent dome.

In Sections 12 and 13, T.29N., R.7E and Section 8, T.29N., R.8E, just north of Wausau, a northeast-trending block of pillow basalts is in fault contact with gently-dipping rhyolite lithologies on both its north and south margins. The fault-bounded block of pillow basalts may represent an uplifted block of the older volcanic rocks on which the caldera-related rocks were deposited.

The rocks interpreted as pre-caldera phases consist of basalts, andesites, and rhyolites, and typically have a well-developed steeply dipping northeast-trending foliation. In contrast, the caldera-related rhyolites are gently dipping, and are mainly non-foliated. This suggests that the proposed caldera rhyolites are unconformable on the foliated rocks and may be post-tectonic. The red granite north of Wausau truncates the several rhyolite lithologies, and may post-date the postulated caldera.

In summary, the three areas with relatively good exposure appear to represent rather different environments within the volcanic belt: the Pembine area may be a remnant of an oceanic island arc; rocks in the Monico area may represent an intra-arc rift or back-arc basin; and the Marathon County area is a complex area formed during the general convergent tectonics that produced the Wisconsin volcanic belt.

### **Areas of Economic Interest**

The Wisconsin magmatic terranes are the host for a number of mineralized areas, mostly volcanogenic massive sulfide deposits. Although numerous areas containing some mineralization have been identified, only a handful are large enough to be of economic interest. The richer deposits include the Flambeau deposit (in production) (May, 1977, 1996), the Crandon deposit (actively working on permitting) (Schmidt and May), the Bend deposit (continued exploration) (DeMatties, 1996), the Eisenbrey (Thornapple) deposit (continued exploration) (May, 1996), and the Lynne deposit (presently inactive) (Adams, 1996). These deposits are the subject of separate chapters in this guidebook. Some smaller deposits (the Pelican River, Duckblind, and Wolf) also occur as was noted earlier in this chapter. Because these major deposits are covered in separate chapters within this volume, they will not be described here.

Deposits other than massive sulfides may also be present in the Wisconsin magmatic terranes. Examples of two other types of deposits, an epigenetic gold deposit and mineralization associated with a postulated caldera setting are discussed here.

The Reef gold deposit, in eastern Marathon County, has been examined by a number of mining companies since the mid-1970s. Mineralization in the area was first recognized during regional geologic mapping in 1970 (LaBerge and Myers, 1972). At least 80 core holes have been drilled in the area in an effort to characterize the mineralization.

The main rock types in the area of the Reef deposit are steeply dipping mafic volcanic rocks, gabbros, and serpentines with a chemistry suggesting that they have ophiolitic affinities (K. J. Schulz, personal communication, 1995). A swarm of granophyric to porphyritic felsic dikes or sills cut the mafic rocks in the mineralized area (Kennedy and Harding, 1990). The mineralized area is one of intense deformation near the Eau Claire River shear zone and lies just west of the western margin of the Wolf River Batholith. A thick sequence of metasediments and felsic volcanics, in which massive sulfides consisting mainly of pyrrhotite have been drilled, occur just west of the gold mineralized area.

Mineralization at the Reef consists of pyrrhotite, chalcopyrite and gold in silicified shear zones and quartz veins that cut the mafic volcanic rocks and gabbros. According to Kennedy and Harding (1990), the northeast-trending, northwest-dipping quartz-sulfide veins and zones of sulfide-veinlets host gold, copper, silver, and tellurium mineralization in the area of interest. They state that the mineralization is closely associated with the felsic dikes and sills and that the intrusions and vein system are hosted by a granofels unit (a distinctive, biotite-rich, foliated to mylonitic rock derived chiefly from gabbro). Visible gold in quartz-goethite blocks, widely distributed at the surface, is probably the result of weathering of gold-bearing veins (Kennedy and Harding, 1990).

Seven distinct zones of mineralization containing 454,600 tons grading 0.262 opt gold and approximately 0.28% copper have been identified, and the deposit is open at depth. The transgressive nature of the mineralization (in sheared gabbroic rocks) and the apparent relationship to felsic intrusions, indicates that the Reef deposit is epigenetic, and thus is distinctly different from the volcanogenic massive sulfide deposits elsewhere in the magmatic terrane.

Deformation resulted in the development of numerous shear zones and mylonitic rocks similar to those illustrated in Figures 8 and 9 from the Monico area. Epigenetic gold mineralization in sheared rocks of the Reef deposit suggests that other mylonitic zones may also have potential for gold mineralization.

Possible mineralization associated with the caldera-type rhyolites include the following features in the Wausau area. (1) Waste rock at an abandoned small shaft along the fault contact between pillow basalts and rhyolite along Troy Avenue in northeastern Wausau contained abundant sphalerite, some galena in a breccia zone cemented by quartz, and carbonate. (2) Numerous jasper veins and patches occur within the rhyolitic rocks in the Brokaw area. These veins appear to be jasperoid alterations of the volcanics and associated sediments and locally contain pyrite. In 1978 roadcuts for a new subdivision north of County Hwy. W on the east side of the Wisconsin River at Brokaw exposed tuffs with rounded and angular clasts to 5 cm in a finer volcanic matrix interbedded with conglomerate to the north. The conglomerate contains clasts up to 12" in diameter. Most clasts are rhyolite, but quartzite and granite boulders are also present. The matrix of the conglomerate is mainly volcanic sandstone, with local jasperoid cement in the coarser conglomerate. Extensive epidotization of units is also common. (3) Disseminated sulfide (pyrite and chalcopyrite) in the rhyolites exposed in the railroad cuts in Gilbert Park and at the former hospital in northeastern Wausau.

### Tectonic Setting

The general tectonic setting in which the Wisconsin magmatic terranes formed has been discussed in the literature since the mid-1970s. There is now a general consensus that the Penokean orogen formed in a complex convergent tectonic environment. Lack of subduction-related volcanic



Figure 8. Photo of sheared basaltic rocks with abundant quartz veins. This lithology is transitional between massive basalt and the banded mylonite shown in Figure 9. From west of the Pelican River southwest of Monico.



Figure 9. Photo of outcrop of banded mylonite that cuts basaltic rocks southwest of Monico. Hammer provides a scale.

rocks north of the Niagara Fault zone (the exposed margin of the Superior craton) clearly indicates that subduction was away from the craton margin. Ophiolitic rocks with associated calc-alkaline rocks in the Pembine area suggest the development of an oceanic island arc between 1,890 and 1,860 m.y. ago that docked against the Superior craton about 1,860 m.y. ago along the Niagara Fault zone (Sims and others, 1989). Schulz (1984) suggests that the arc was "evolved," or "mature," based on its chemistry.

The tectonic history of the southern margin of the volcanic belt is much more equivocal. Some models suggest northward subduction, away from the Archean "microcontinent" that borders the Marshfield terrane on the south (Cannon and others, 1991) whereas others suggest a southward subduction beneath the Archean microcontinent (LaBerge, 1986). The author favors a model with south-directed subduction, but recognizes that northward subduction beneath the just-accreted island arc probably also occurred. Subduction may have been both north-dipping and south-dipping before final closure of the "Penocean Sea" about 1,840 m.y. ago.

### References Cited

- Adams, G. W., 1996, Geology of the Lynne Base-Metal deposit, north-central Wisconsin, U.S.A. in *Volcanogenic Massive Sulfide Deposits of Northern Wisconsin: A Commemorative Volume*, G. L. LaBerge (ed.), Institute on Lake Superior Geology, v. 42, part 2.
- Bowden, D. R., 1978, Volcanic rocks of the Pelican River massive sulfide deposit, Rhinelander, Wisconsin: A study of wallrock alteration: Unpublished M.S. Thesis, Michigan Technological University, 62 p.
- Cannon, W. F., Lee, M. W., Hinze, W. J., Schulz, K. J., and Green, A. G., 1991, Deep crustal structure of the Precambrian basement beneath northern Lake Michigan, mid continent, North America: *Geology*, v. 19, p. 207-210.
- DeMatties, T. A., 1994, Early Proterozoic volcanogenic massive sulfide deposits in Wisconsin: An overview: *Economic Geology*, v. 89, p. 1122-1151.
- DeMatties, T. A., 1996, A geologic framework for Early Proterozoic volcanogenic massive sulfide deposits in Wisconsin: An exploration model: *in* *Volcanogenic Massive Sulfide Deposits of Northern Wisconsin: A Commemorative Volume*: G. L. LaBerge (ed.), Institute on Lake Superior Geology, v. 42, part 2.
- Dutton, C. E., and Bradley, R. E., 1970, Lithologic, geophysical, and mineral commodity maps of Precambrian rocks in Wisconsin: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-631, scale 1:500,000, with accompanying report, 15 p.
- Greenberg, J. K., and Brown, B. E., 1983, Lower Proterozoic volcanic rocks and their setting in the southern Lake Superior district: *in* *Early Proterozoic geology of the Great Lakes region*. Edited by L. G. Medaris, Jr., Geological Society of America, Memoir 160, p. 67-84.
- Jenkins, R. A., 1973, The Geology of Beecher and Pemene Townships, Marinette County, Wisconsin (Abstract), Institute on Lake Superior Geology, 19th, Madison, Wis., p. 15-16.
- Kennedy, L., Harding, T., 1990

- LaBerge, G. L., 1986, The Proterozoic geology of the Lake Superior region: in LaBerge, G. L., Attig, J. W., and Mode, W. N., Guidebook 50th Annual Tri-State Geological Field Conference, Wausau, Wisconsin, p. 1-29.
- LaBerge, G. L., and Klasner, J. S., (in review), Geology and tectonic significance of Early Proterozoic rocks in the Monico area, Wisconsin: U.S. Geological Survey Bulletin.
- LaBerge, G. L., and Myers, P. E., 1972, 1971 progress report on mapping of Precambrian geology of Marathon County: Open file report, Wisconsin Geological and Natural History Survey.
- LaBerge, G. L., and Myers, P. E., 1983, Precambrian Geology of Marathon County Wisconsin: Wisconsin Geological and Natural History Survey, Info. Circular 45.
- LaBerge, G. L., and Myers, P. E., 1984, Two Early Proterozoic successions and their tectonic significance: Geological Society of America Bulletin, v. 95, p. 246-253.
- May, E. R., 1977, Flambeau: A Precambrian Supergene Enriched Massive Sulfide Deposit: Geoscience Wisconsin, v. 1, p. 1-26.
- May, E. R., and Dinkowitz, S. R., 1996, An Overview of the Flambeau Supergene Enriched Massive Sulfide Deposit: Geology and Mineralogy, Rusk County, Wisconsin: in Volcanogenic Massive Sulfide Deposits of Northern Wisconsin: A Commemorative Volume: G. L. LaBerge (ed.), Institute on Lake Superior Geology, v. 42, part 2.
- Morey, G. B., Sims, P. K., Mudrey, M. G., and Southwick, D. L., 1982, Geologic Map of the Lake Superior region, Minnesota, Wisconsin, and northern Michigan: Minnesota Geological Survey State Map Series S-13.
- Schriver, G. H., 1973, Petrochemistry of Precambrian greenstones and granodiorites in southeastern Oneida County, Wisconsin: Unpublished M.S. Thesis, University of Wisconsin-Milwaukee, 83 p.
- Schulz, K. J., 1984, Early Proterozoic Penokean igneous rocks of the Lake Superior region: Geochemistry and tectonic implications: Abstract, 30th Annual Institute on Lake Superior Geology, Wausau, Wisconsin, p. 55-56.
- Sims, P. K., 1992, Geological Map of Precambrian rocks, Southern Lake Superior region, Wisconsin and northern Michigan: U.S. Geological Survey Miscellaneous Investigations Series Map I-2185.
- Sims, P. K., Van Schmus, W. R., Schulz, K. J., and Peterman, Z. E., 1989, Tectono-stratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean orogen: Canadian Journal of Earth Sciences, v. 25, p. 2145-2158.
- Venditti, A. R., 1973, Petrochemistry of Precambrian rocks in southeastern Oneida County, Wisconsin: unpublished M.S. Thesis, University of Wisconsin-Milwaukee, 93 p.
- Weidman, S., 1907, The Geology of North Central Wisconsin: Wisconsin Geological and Natural History Survey, Bulletin 16, 697 p.

Zietz, I., Karl, J. H., and Ostrom, M. E., 1978, Preliminary aeromagnetic map covering most of the exposed Precambrian terrane in Wisconsin: U.S. Geological Survey Miscellaneous Field Study MF-888, scale 1:250,000.



**A GEOLOGIC FRAMEWORK FOR EARLY PROTEROZOIC  
VOLCANOGENIC MASSIVE SULFIDE DEPOSITS IN WISCONSIN:  
AN EXPLORATION MODEL**

by Theodore A. DeMatties

Geological Consultant  
10-353rd Ave. NW  
Cambridge, Minnesota 55008

**ABSTRACT**

The Early Proterozoic greenstone belt of northern Wisconsin possesses some of the best volcanogenic (volcanic-hosted) massive sulfide (VMS) potential in North America. A 100-million-ton resource of base- and precious-metal-bearing mineralization, distributed in 13 or more deposits and occurrences and clustered in three districts, has been identified in the belt. Host rocks for the VMS mineralization are part of the 144 mile long, east-west trending Ladysmith-Rhinelanders metavolcanic complex, which consists of various greenschists, amphibolites, cherty iron-formations, and sericite to quartz-sericite schists. These 1880-1860 Ma old metamorphic rocks are concealed beneath Pleistocene glacial cover. Development of the Flambeau mine, initiation of mine permitting for the Lynne deposit, and reactivation of the Crandon Project indicate the belt will receive a higher level of activity than in the past.

Geologic and geophysical data compiled since the late 1960s define three depositional environments, each containing volcanogenic massive sulfide (VMS) mineralization in the 1880 to 1860 Ma Ladysmith-Rhinelanders metavolcanic complex: (1) a main volcanic-arc sequence, the structural core of the complex; (2) laterally equivalent and/or younger(?) back-arc-basin volcanic-volcaniclastic succession that includes a series of mafic volcanic piles; and (3) major felsic volcanic centers in the back-arc basin and along the flanks of the main volcanic arc.

VMS mineralization in all three depositional environments includes: (1) syngenetic and epigenetic strata-bound to stratiform massive sulfide mineralization and epigenetic strata-bound stringer sulfide mineralization within, along the flanks of, or near the top of the felsic volcanic centers; (2) syngenetic strata-bound to stratiform massive-sulfide mineralization associated with cherty magnetic iron-formation within the main volcanic-arc sequence; and (3) epigenetic stringer sulfide mineralization and syngenetic stratiform massive sulfide mineralization associated with mafic volcanic piles developed within the back-arc basin.

Identified VMS deposits and occurrences are classified by metal content into three groups (Cu, Zn-Cu, Zn-Pb-Cu). Each group exhibits various styles of mineralization which include sheets, mounds, stacked lenses, and replacements.

Potentially economic deposits are associated with felsic volcanic centers and sulfide-bearing meta-argillite formations that are favorable stratigraphic units deposited before, during, or after the ore-forming event(s).

Stratigraphic correlations supported by lead isotope data suggest most VMS deposits in the greenschist succession formed in a narrow time interval.

## INTRODUCTION

Four potentially economic volcanogenic (volcanic-hosted) massive sulfide (VMS) deposits have been discovered in northern Wisconsin since the 1960s. Only one, Kennecott's Flambeau, is currently being developed; the Crandon deposit, with an identified resource in excess of 70 million tons, is being permitted for development by the Rio Algom-Exxon joint venture.

The Lynne deposit, discovered in 1990 by Noranda, is temporarily on hold because of environmental concerns, but the Bend deposit, discovered in 1986, continues to be evaluated by Canadian junior companies Sharpe Energy and Resources and Freewest.

The Precambrian of northern Wisconsin has some of the best VMS potential in North America. About 400 prospects drill-tested since the mid-1960s has resulted in discovery of four potentially viable deposits, approximately one for each 100 prospects tested. This very high success ratio has been offset by a strict state permitting process that is believed to be responsible for the slow pace of mine development in northern Wisconsin.

A general geologic framework for volcanogenic massive sulfide mineralization was proposed for the western end of the belt (DeMatties, 1989). This paper is an expansion of that communication and summarizes important geologic features which characterize volcanogenic massive sulfide mineralization identified in the belt thus far. The proposed geologic framework can be utilized as both a genetic and empirical model for future exploration in the belt. However, as with all models, change is inevitable.

### Regional Geologic Framework of VMS Deposits in Wisconsin

Regional metamorphism that developed during intense isoclinal folding has overprinted the original volcanic and sedimentary rock units in the Precambrian terranes of northern Wisconsin. This metamorphic overprinting varied in intensity, ranging from upper amphibolite facies (relict textures are totally or partially obscured and foliation, in this case schistosity, is intense) to lower greenschist facies (relict textures are well preserved and foliation development is weak).

Knowledge of these metamorphic rock units and their distribution is derived mainly from geophysical patterns, drillhole data, and few bedrock outcrops. The present paper emphasizes the character of the rocks, their structural and stratigraphic setting, and interpretations of the original lithology and depositional environment before metamorphism and structural dislocation modified the original patterns.

### Major Geologic Terranes

The VMS deposits in northern Wisconsin lie within the Early Proterozoic Penokean fold belt of the Southern Structural Province of the Precambrian Shield (Fig. 1). In Wisconsin the fold belt is divided (Greenberg and Brown, 1983; Sims *et al.*, 1989) into two major terranes (Fig. 2). The first is the northern Penokean terrane (NPT), distinguished in part by a thick platformal turbidite sequence of clastic and chemical sedimentary rocks (Sims's continental margin assemblage) interbedded with subordinate tholeiitic metavolcanic rocks (bimodal suite of basalt-rhyolite). The NPT contains major oxide-facies iron-formations and some rare granitic intrusions. This supracrustal assemblage was deposited on an Archean basement and correlates stratigraphically with the Marquette Range Supergroup in Michigan.

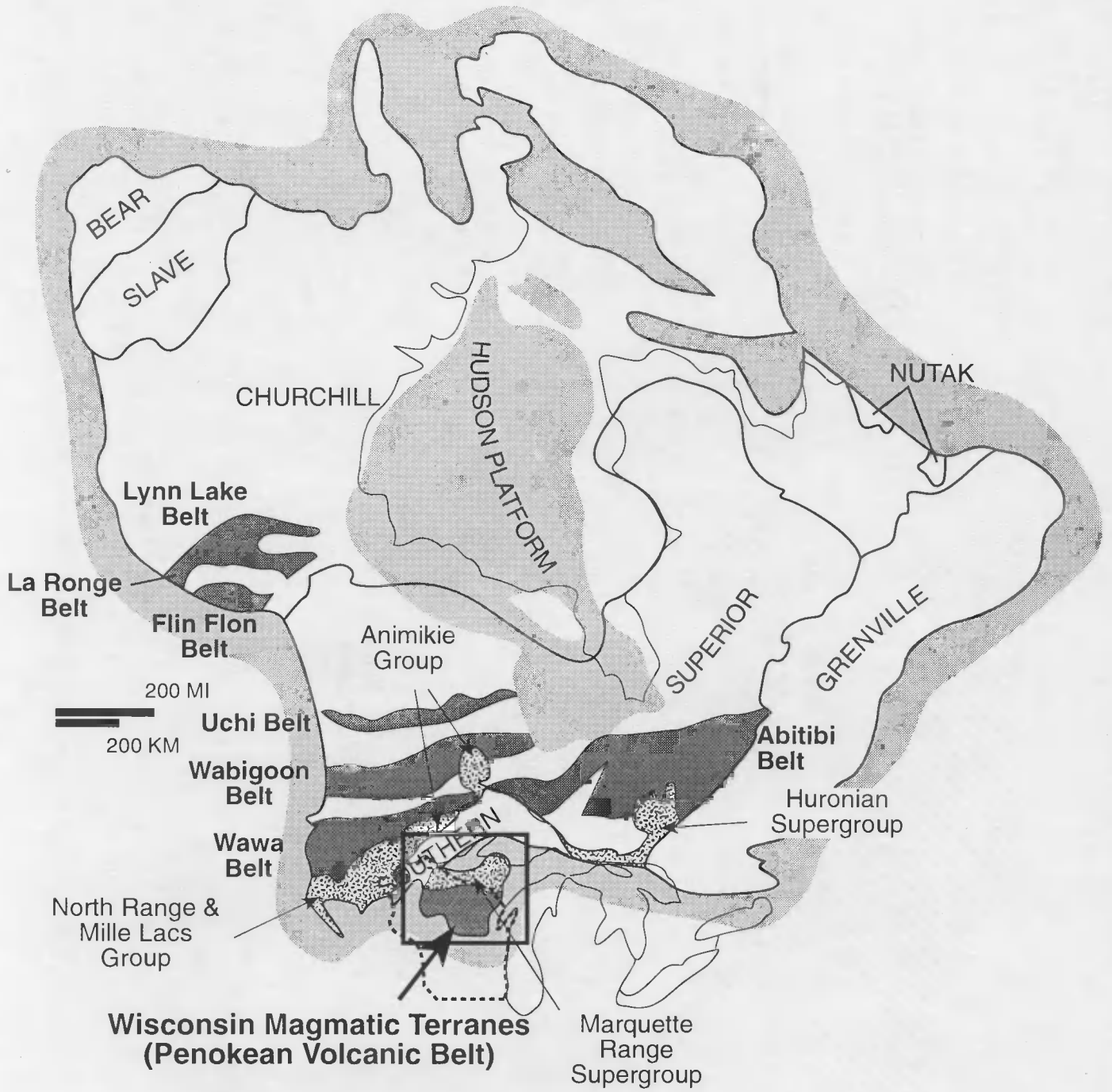


Figure 1. Geologic provinces of the Canadian Shield, including Early Proterozoic supracrustal sequences of the Penokean Fold Belt and major greenstone belts of the Canadian Shield, including the Penokean Volcanic Belt of Wisconsin (modified from Franklin and Thorpe, 1982).

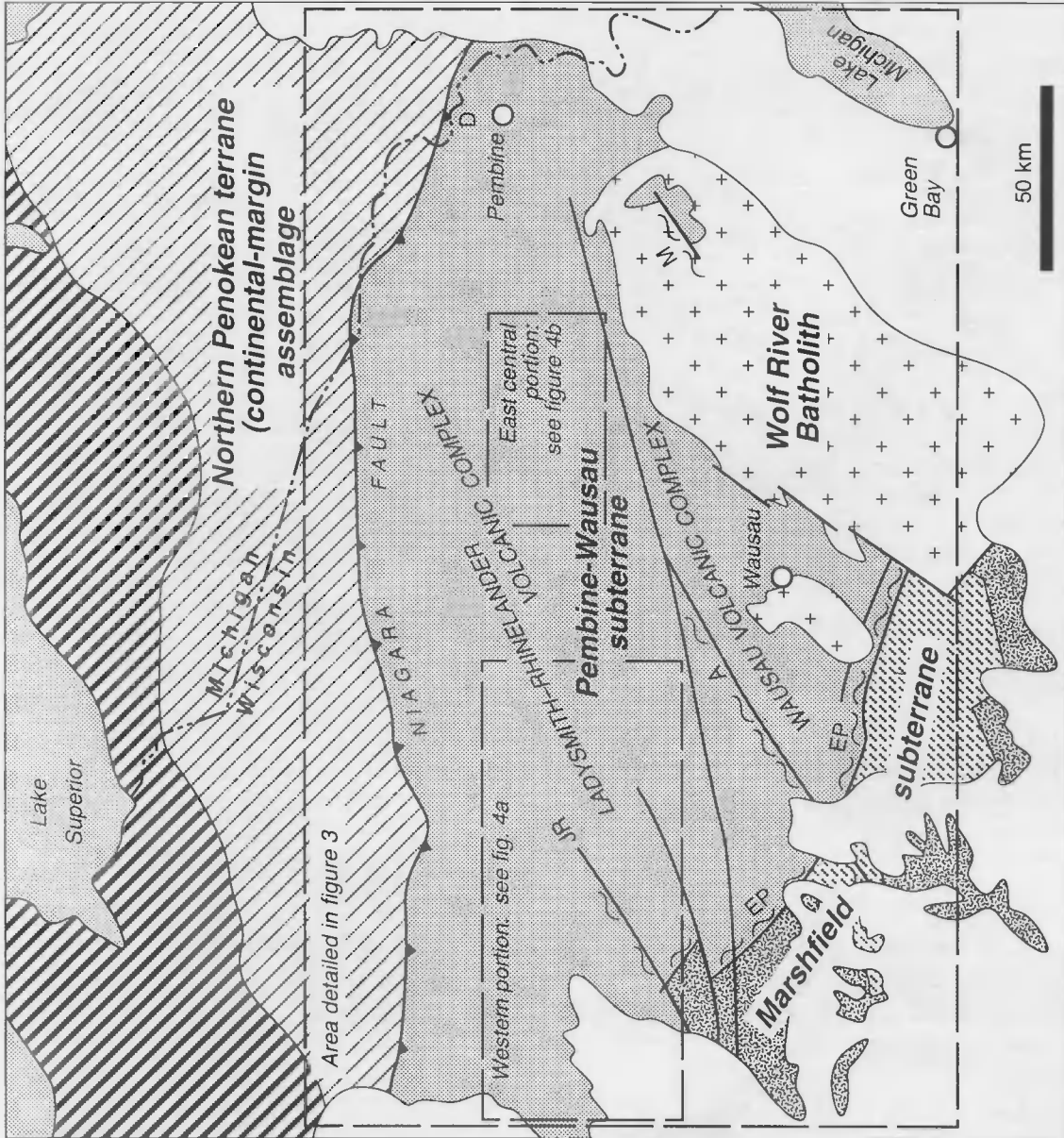





Figure 2. Geologic map of northern Wisconsin showing major terranes (modified from Sims, 1989).


**Explanation**

-  Sedimentary rocks (Paleozoic)
-  Middle Proterozoic (Keweenaw) mafic igneous and sedimentary rocks of Midcontinent rift system (1,000-1,200 Ma)
-  Anorogenic igneous rocks (1,470-1,510 Ma)



**WISCONSIN MAGMATIC TERRANES**

**Penokean Volcanic Belt (PVB)**

**PEMBINE-WAUSAU SUBTERRANE**


-  Metavolcanic and granitoid rocks (Lady Smith-Rhinelander & Wausau Volcanic Complexes; 1,760-1,880 Ma)

**MARSHFIELD SUBTERRANE**


-  Metavolcanic and granitoid rocks (1,835-1,890 Ma)
-  Gneiss (≈2,800 Ma)


**CONTINENTAL-MARGIN ASSEMBLAGE**

**Northern Penokean Terrane (NPT)**

-  Marquette Range Supergroup (1,820-2,100 Ma) and gneiss, granite, and greenstone (2,600-3,550 Ma)

 High-angle fault

 Thrust fault

 Shear zone

- A Athens shear
- EP Eau Pleine shear (suture)
- JR Jump River shear
- M Mountain shear
- D Dunbar dome

The second major terrane, south of the NPT, the Penokean volcanic belt (PVB) or Wisconsin magmatic terrane, is characterized by a volcanic island-arc-basin assemblage containing abundant calc-alkaline metavolcanic units (basalt, andesite, and rhyolite) and lesser amounts of deep- and shallow-water metasedimentary rocks. It lacks major oxide-facies iron-formation but contains abundant tonalite-granite intrusions. Radiometric dating by Sims *et al.* (1989) has established an Early Proterozoic age ranging from 1889 to 1835 Ma. They further divide this southern terrane into two volcanic-arc subterrane, the Pembine-Wausau (P-W) and the Marshfield, on the basis of lithology and structure (LaBerge and Myers, 1984).

The more northern of the two, the Pembine-Wausau subterrane, was deposited during the interval 1860 to 1889 Ma and is dominated by calc-alkaline metabasalt-andesite-rhyolite with oceanic affinities and localized bimodal high- $\text{Al}_2\text{O}_3$  metabasalt-rhyolite suites. In the vicinity of Wausau, a younger, more restricted calc-alkaline metavolcanic succession with abundant rhyolite (LaBerge and Myers's greenschist succession) was deposited at approximately 1835 to 1845 Ma on the older succession, which is considered to be 1860 to 1889 Ma in age and is part of LaBerge and Myers's amphibolite succession. Granitoid plutons dated at 1870 to 1760 Ma, ranging from gabbro and diorite through quartz monzonite and granite, intruded the volcanic succession (Sims *et al.*, 1989; LaBerge and Myers, 1983).

The southern subterrane, the Marshfield, is believed to represent remnants of an 1860 Ma volcanic succession that stratigraphically overlies Archean basement (Sims *et al.*, 1989).

The NPT, P-W, and Marshfield terranes and subterrane are separated from one another by two major paleosuture zones -- the Niagara Fault Zone and the Eau Plaine Shear Zone (Fig. 2) -- that are believed to represent Proterozoic subduction zones (Sims *et al.*, 1989). The more prominent Niagara Fault Zone is as much as six miles wide and is defined by a broadly arcuate system of ductile shears. At the exposed east end, Schulz (Sims *et al.*, 1989) has recognized dismembered subduction-zone-type ophiolites along the fault structure, which was active from 1900 to 1830 Ma, during the Penokean orogeny. This major orogenic event also resulted in intense regional-scale folding, regional metamorphism, and emplacement of major granitic plutons.

Most past and present base-and precious-metals exploration activity has been in the Pembine-Wausau arc sequence.

### Wausau volcanic complex

From regional gravity and magnetic data, and limited lithologic, geochemical, and structural data, at least two volcanic complexes can be defined in the Pembine-Wausau subterrane (Fig. 3). One in the Wausau area has been intruded by the Middle Proterozoic ( $1469 \pm 28$  Ma) Wolf River Batholith and the Wausau syenite-granite plutonic series. The unintruded portion of the Wausau volcanic complex has been intensely explored since the 1960s because of its thin glacial cover and relatively abundant outcrop.

The Wausau volcanic complex as mapped by LaBerge and Myers (1983), consists of an older (Archean? and lower Proterozoic-1880-1860 Ma?) amphibolite facies sequence (quartz-feldspar gneisses and amphibolites-metabasalts) unconformably overlain stratigraphically by younger (1845-1835 Ma) greenschist facies, cal-alkaline mafic to felsic volcanic rock suite. The volcanic rocks were syntectonically intruded by numerous calc-alkaline epizonal plutons. The complex is characterized by a number of large, nearly vertical, cataclastic fault-shear zones which form the boundaries between greenschist and amphibolite facies sequences.

Several well-developed, sulfide-bearing, felsic volcanic host sequences or centers (greenschist facies succession) mapped in the complex are interpreted by LaBerge and Myers (1983) as representing in part a subaerial depositional environment. Such an environment would not be conducive for development of VMS systems and may be one reason why no significant VMS occurrences have been discovered in this complex. Rather the complex appears to be a more favorable host to gold mineralization; a number of lode gold (quartz veins) occurrences and a small (454,600 tons @ 0.262 opt Au), structurally controlled gold deposit (Reef) are known.

### **Ladysmith-Rhineland volcanic complex**

The northern portion of the P-W subterrane is occupied by the Ladysmith-Rhineland complex, referred to informally as the Ladysmith-Rhineland Greenstone Belt (Fig. 3). Its areal extent is at least 144 miles long and 30 to 50 miles wide, striking easterly across northern Wisconsin and into the Upper Peninsula of Michigan. Sequences of metavolcanic-volcanoclastic and associated metasedimentary rocks that have been metamorphosed to varying degrees dominate the complex.

Three basic rock packages have been defined and will be discussed later in detail. The complex is covered by glacial deposits up to 200 feet thick, and bedrock outcrops are relatively rare.

Unlike the Wausau Complex, the Ladysmith-Rhineland Complex contains a number of VMS occurrences and deposits, including the potentially economic Crandon, Flambeau, Lynne, and Bend deposits.

The original contact relationship between the Wausau and the Ladysmith-Rhineland complexes is not known, but they are now in juxtaposition, their contact marked by major faults, shear zones, and granitic intrusives (Fig. 3).

## **GEOLOGIC SETTING OF VMS MINERALIZATION IN THE LADYSMITH-RHINELAND VOLCANIC COMPLEX**

An extensive geophysical database and abundant drillhole information compiled since the late 1960s by exploration companies and the state geologic survey has allowed mapping of broad, regional rock units that represent basic volcanic facies changes within the complex (Table 1, Fig. 3, 4a, and 4b). Interpretations of rock units, contact relationships, and fault structures are based on magnetic and gravity patterns. Because of the thick, widespread glacial overburden, information from outcrops is limited.

Three basic rock packages are defined. Each has distinctive rock types and structural setting. Further, each package contains VMS mineralization that is thought to be correlative based on stratigraphic and radiometric evidence.

### **Main Volcanic Arc Sequence (Pmv)**

This sequence is characterized by the presence of magnetic and nonmagnetic amphibolite or amphibolitic schist and, to a lesser degree, quartzo-feldspathic schists. Regional metamorphic grade is high, generally reaching amphibolite rank, and as a result few relict primary textures are present. Thin, interbedded oxide-facies iron-formations (Algoma type) are quite common in the sequence and can be traced in some cases for thousands of feet. Several serpentized ultramafic intrusions are present.

Table 1. General Description of Regional Volcanic Facies in the Ladysmith-Rhinelander Volcanic Complex.

Sequence	Dominant Lithology	Structure	Metamorphic Grade	Comments	VMS Mineralization
Main Volcanic Arc (Pmv)	Amphibolite or amphibolitic schist and lesser quartz-micaceous to quartz-feldspathic schists; little or no relict textures preserved; interpreted as mafic metavolcanic flows, interflow tuffs and sediments, oxide-facies iron-formation (Algoma type); sergentinized intermediate to mafic metavolcanic flows, interbedded metatuffs, tuff breccias, tuffaceous metasediments (Piv).	Steeply dipping, isoclinally folded volcanic section, NW-NE fold axes common (F.1), and tight coaxial folding (F.2) common.	Dominantly kyanite-sillimanite-staurolite-hornblende-almandine assemblages (amphibolite facies).	Amphibolite succession, forms structural core of complex; possibly an older volcanic sequence or deeper part of volcanic arc.	Depositional environment number 2. Syngenetic, stratiform, dominantly massive sulfides (pyrrhotite-byrrite) (Zn-Cu) associated with cherty magnetite iron-formation; e.g., Eisenbrey (Thornapple) deposit.
Back-Arc Basin (Pvs)	Tuffaceous metasediments (metagavwackses, reworked metatuffs, chemical metasediments) and lesser graphite and/or sulfide-bearing meta-argillite (Pms), porphyritic and/or amygdaloidal metabasalt to meta-andesite flows (calc-alkaline and tholeiitic affinity) and subvolcanic intrusives (Pmvf).	Same	Chlorite-epidote-muscovite-albite-quartz facies (lower greenschist facies) to biotite-muscovite-albite-quartz (middle greenschist facies) assemblages.	Greenschist succession, possibly a younger volcanic sequence or shallower part of volcanic arc. Partially envelops core (Pmv).	Depositional environment number 3. Epigenetic stringer sulfides (Cu-Au) and syngenetic strata-bound, stratiform massive sulfide (Zn-Pb-Cu-Au) mineralization at or near stratigraphic top of Pmvf. E.g., Kivela Zone (Ritchie Creek), Horse Shoe, Spirit prospects.
Felsic Center (Pfv)	Altered felsic volcanic sequence (dacite-rhyodacite to rhyolitic flows, metatuffs, lapilli tuffs, cherty metatuffs, and associated chemical-volcaniclastic metasediments).	Same	Chlorite-epidote-muscovite-albite-quartz (lower greenschist facies) to andalusite-cordierite-almandine-muscovite assemblages (amphibolite facies).	Mainly greenschist (amphibolite) succession. Major centers developed in the Ladysmith, Bend, Ritchie Lake areas; larger felsic sequence in Ladysmith area repeated; repetition result of volcanic cycles or folding	Depositional environment number 1. Syngenetic strata-bound and stratiform massive sulfide (Cu-Au or Zn-Pb-Cu-Ag) mineralization at or near stratigraphic top of or deeper within Pfv, or along the flanks of the center; e.g., Flambeau, Bend, Crandon, and Lynne deposits.

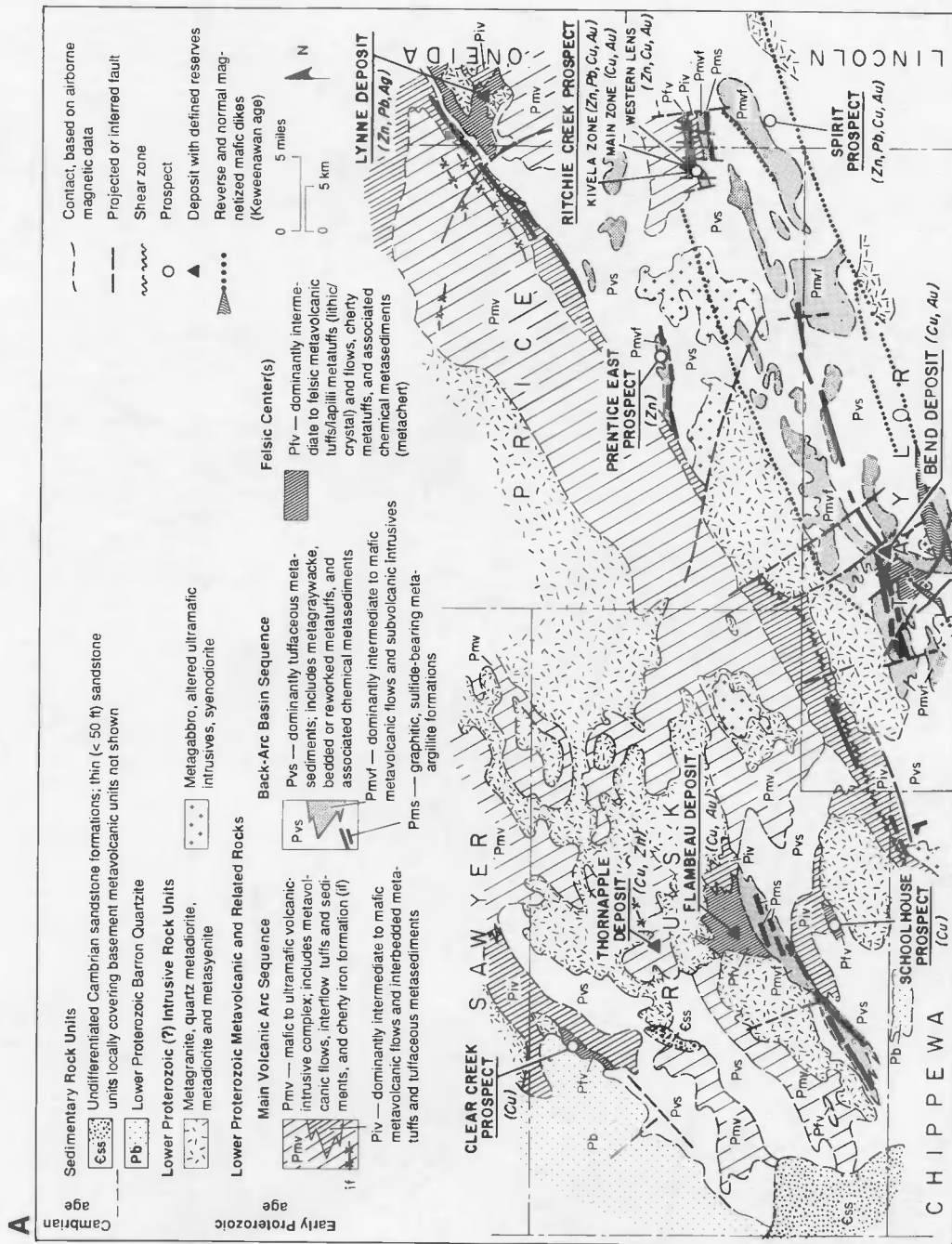


Figure 4a. General geologic map of the western portion of the Ladysmith-Rhinelander Volcanic Complex (after DeMatties, 1990).



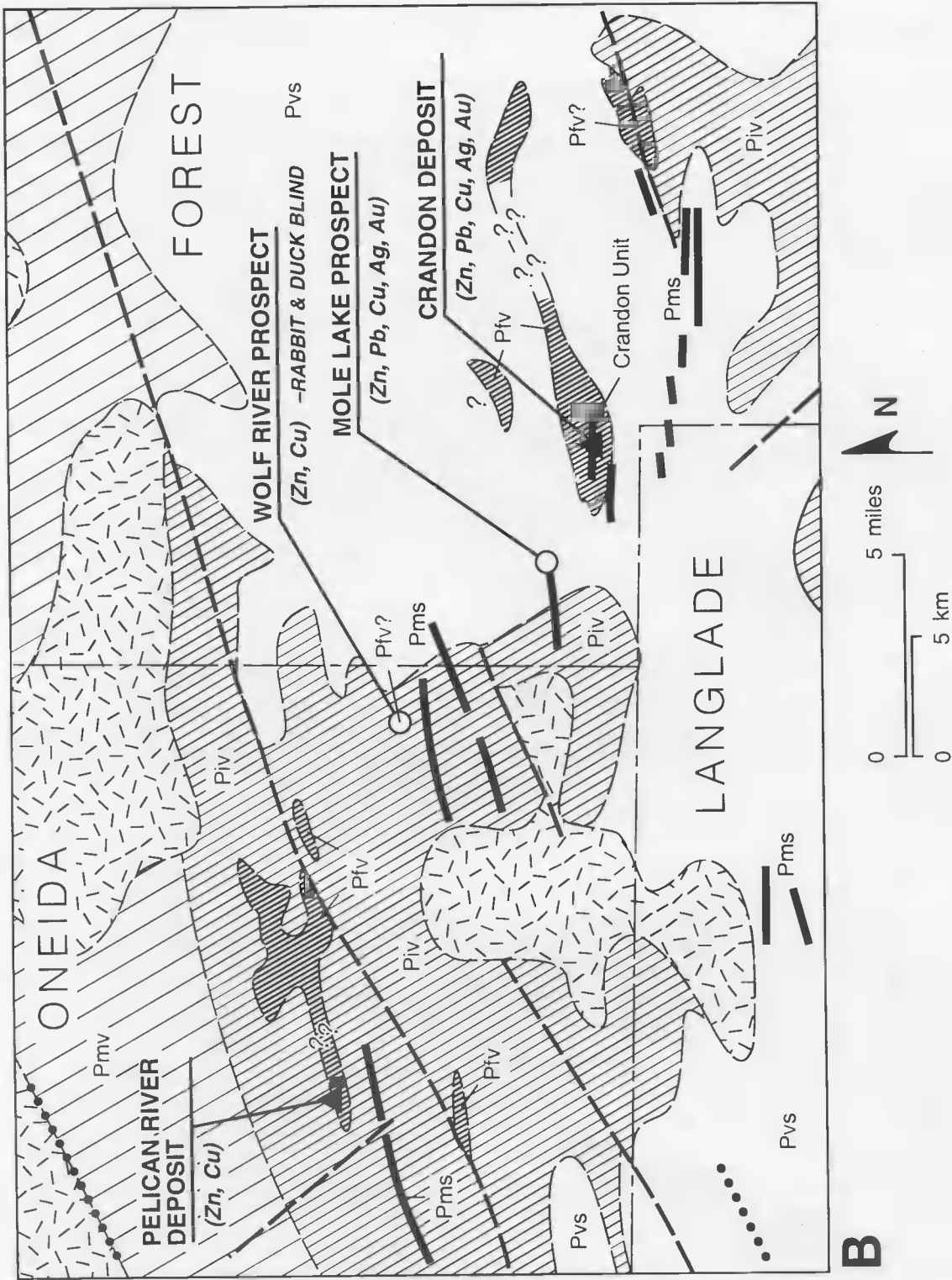


Figure 4b. General geologic map of the east-central portion of the Ladysmith-Rhinelander Volcanic Complex.

The sequence, which was deposited between 1880 and 1860 Ma (Sims *et al.*, 1989), is assigned to the amphibolite succession. Its magnetite-rich mafic composition produces a geophysical expression of strong magnetic anomalies with steep gradients and distinct gravity highs. This mappable unit forms the core of the complex and is interpreted as representing dominantly mafic flows and interflow tuffs and sediments generated in a central to proximal submarine volcanic facies and referred to in this paper as depositional environment #2.

Structurally the sequence has been complicated by steeply dipping isoclinal folding (F-1) and a pronounced second(?) refolding (F-2). This deformation has produced a fold pattern of tight, steeply plunging antiform and synform structures within the unit.

VMS mineralization is known to occur in this environment. Eisenbrey (Thornapple), the only significant deposit discovered thus far, probably represents the style of mineralization that can be expected in this sequence, i.e., tightly folded, steeply plunging, syngenetic stratiform massive sulfide mineralization (stacked lenses) associated with thin cherty magnetic iron-formation.

Partially enveloping the core sequence is a steeply dipping, isoclinally folded unit (Piv) dominated by intermediate to mafic, porphyritic and nonporphyritic metavolcanic flows and lesser chloritic schists, phyllites, and semi-schists. The unit is interpreted to be a sequence of volcanic flows with interbedded metatuffs, tuff-breccias, and tuffaceous sediments. Because regional metamorphism is lower grade and relict textures are discernible, this unit is assigned to the greenschist succession. A proximal subaqueous volcanic environment is indicated by the rock protoliths, insofar as it is known.

#### **Back-Arc Basin Sequence (Pvs)**

The back-arc basin is characterized by a steeply dipping, isoclinally folded, sequence of dominantly feldspathic, quartzo-micaceous, and chlorite schists-semischists and metachert believed to be originally tuffaceous metasediments. Rock protoliths include interbedded metagraywackes and argillites, reworked pyroclastic rocks, and chemical sediments including locally oxide-sulfide facies iron formation. Lesser intermediate to mafic metavolcanic flows are also present in the sequence. The sequence is geophysically expressed as weak to neutral magnetic anomalies and weak, broad gradient gravity anomalies.

Structurally, this unit flanks the main volcanic arc and is interpreted as representing a distal subaqueous marginal volcanic basin facies. Regional metamorphism is generally lower rank than in the main volcanic-arc sequence (Pmv) and therefore the sequence can be assigned to the greenschist succession. Locally, amphibolite grade contact metamorphism resulting from thermal effects is achieved near intrusions.

The metavolcanic flow units (Pmvf) within the basin facies tend to concentrate in distinct piles that can be mapped as moderately high magnetic anomalies. Drilling indicates that these units are usually porphyritic and/or amygdaloidal metabasalts to meta-andesites and associated tuffaceous and chemical metasediments. These volcanic piles are referred to below as depositional environment #3 and are associated with epigenetic stringer sulfide mineralization and syngenetic stratiform massive sulfide mineralization. Examples include the Kivela zone at the Ritchie Creek prospect, the Spirit occurrence and the Horse Shoe deposit.

An important series of units within the basin facies and also the Piv unit of the main volcanic arc facies are the meta-argillite formations (Pms) which are described later in detail. These units are

characterized by their distinct linear electromagnetic anomaly patterns, which allows them to be used as mappable marker horizons. These key formations are intimately associated with all the potentially economic VMS deposits.

### Felsic Centers (Pfv)

The felsic centers have been defined by drilling and identified in some outcrops, particularly toward the east end of the complex; but their magnetic expression is neutral and cannot be readily distinguished from metasediments or granitic intrusives in covered areas. Thus the exact areal extent of most of the centers is poorly known.

Extensive drilling indicates that the centers are steeply to moderately dipping sequences dominated by strongly to weakly metamorphosed and sheared quartz+feldspar-sericite-chlorite schists-semischists (commonly crystal and/or fragment-bearing) and metacherts. Protolithologies include altered dacitic to rhyolitic metavolcanic flows, pyroclastic rocks, and associated chemical-volcaniclastic metasediments. Mafic to felsic subvolcanic intrusions, feeders for the volcanic units, may be quite abundant. In several centers such as those hosting the Flambeau and Lynne deposits, large intrusions which may or may not be related to the volcanic activity have either disrupted or cut out significant portions of the felsic sequences. At Lynne, post-intrusive activity is so extensive that the host volcanic section occupies an embayment of a large tonalite pluton.

Lesser interbedded mafic metavolcanic suites are almost always present in the felsic centers, resulting in a bimodal sequence. The sequences are interpreted as proximal subaqueous felsic volcanic pile facies and designated depositional environment #1.

This environment hosts massive syngenetic stratiform and epigenetic strata-bound massive to stringer sulfide mineralization which occurs within (e.g. Flambeau, Bend, and Crandon), along the flanks of (e.g. Lynne), or near the stratigraphic top (e.g. Ritchie Creek main zone) of felsic volcanic centers. Host rock units are generally hundreds of feet thick, range in composition from quartz-sericite schist (felsic tuffs, e.g. Flambeau and Bend) to chloritic schist (argillite, e.g. Crandon), and may contain abundant chemical sediments (chert and carbonate-rich exhalites) which can overlie the syngenetic stratiform mineralization (e.g. Flambeau and Bend), or are interbedded with it (e.g. Crandon).

Although the locus of VMS mineralization within a center commonly occurs at breaks or changes in volcanic activity, there is not yet enough information to link mineralization to specific volcanic cycles within the centers.

Hydrothermal alteration associated with VMS mineralization in the centers includes sericitization, silicification, and to a lesser extent, chloritization. Limited immobile trace element studies (Lavery, 1985, and DeMatties and Rowell, 1991), indicate that widespread intense silicification (silica enrichment) may be responsible for many of the dacitic to rhyolitic compositions found in some of the centers.

At least seven major centers are known in the complex, four of which host the four potentially economic deposits. Other deposits or occurrences hosted by this environment include Pelican River, Catwillow, Wolf River, Spirit, Hawk(?), School House, and Clear Creek. The known centers are assigned to the greenschist succession and are located within the back-arc basin or along the flanks of the main volcanic arc.

## DISTRIBUTION AND CLASSIFICATION OF MASSIVE SULFIDE MINERALIZATION

To date about 100-million-short-ton resource (80 million short tons of potentially economic reserves) of base- and precious-metal massive sulfide mineralization, in 13 or more deposits or occurrences, has been discovered in the Ladysmith-Rhineland Volcanic Complex (DeMatties, 1989; DeMatties and Mudrey, 1991) (Fig. 5 and Table 2). (All tonnages herein are in short tons.) The world-class Crandon deposit accounts for approximately 72 percent of this total. The remaining tonnage is distributed among 12 or more occurrences and deposits whose average size is approximately 2.5 million short tons.

Only four deposits are believed to be potentially viable economically; the largest is Crandon, containing an identified resource<sup>(1)</sup> of 72.5 million tons. Next are Lynne, with a resource of 7.5 to 8 million tons (a mining reserve of 6.7 million tons), and Flambeau, with a resource of 6 to 7 million tons (a mining reserve of 1.9 million tons). The fourth is the Bend deposit, which contains a reserve base of 3.7 million tons. Further exploration on other deposits could expand their size and define potential mineable reserves.

The obvious gap in size between these deposits is dramatized in Figure 5. This lopsided distribution may be a function of exploration having been focused on a particular deposit or area. Table 3 compares the known Wisconsin tonnage distribution with other VMS provinces and belts. Assuming the tonnage distribution for Wisconsin VMS deposits will define a natural geometric progression similar to those in other greenstone belts, and given the large size of the complex (approximately 5700 square miles) as well as the Penokean Volcanic Belt (approximately 19,000 square miles), additional deposits with mineable reserves in the 10- to 60-million-ton range are likely to exist.

Current knowledge suggests that the known VMS deposits and occurrences are concentrated into three clusters or districts within the Ladysmith-Rhineland Volcanic Complex (Fig. 6). The spatial distribution of the three districts appears to be linear, trending in an east-west direction (the so-called Highway 8 trend), with deposits separated by 20 to 30 miles. However, a more complicated arrangement of individual deposits and occurrences is evident within each district.

Massive sulfide deposits and occurrences may be classified by ratios of principal metals into groups of copper deposits, zinc-copper deposits, and zinc-lead-copper deposits.

Because of its simplicity, Solomon's classification scheme, as modified by Huston and Large (Large, 1992), has been used in classifying Australian VMS deposits and has been adopted in this paper (Large, 1992). This classification is based upon principal metal ratios (Cu/Pb/Zn), and by use of a copper ratio ( $100 \text{ Cu}/\text{Cu} + \text{Zn}$ ) and a zinc ratio ( $100 \text{ Zn}/\text{Zn} + \text{Pb}$ ). Under this scheme, the Wisconsin deposits can be categorized (Fig. 6) into the following groups:

1. Cu deposits: Cu ratio > 60, Zn ratio > 60; e.g., Flambeau, Bend, Ritchie Creek (Main Zone).
2. Zn-Cu deposits: Cu ratio < 60, Zn ratio > 90; e.g., Crandon, Thornapple, Pelican River, Catwillow, and Hawk.

(1) The terms "resource", "reserve", "reserve base", "indicated", and "inferred" are used herein as defined in USGS Circular 831, 1980.

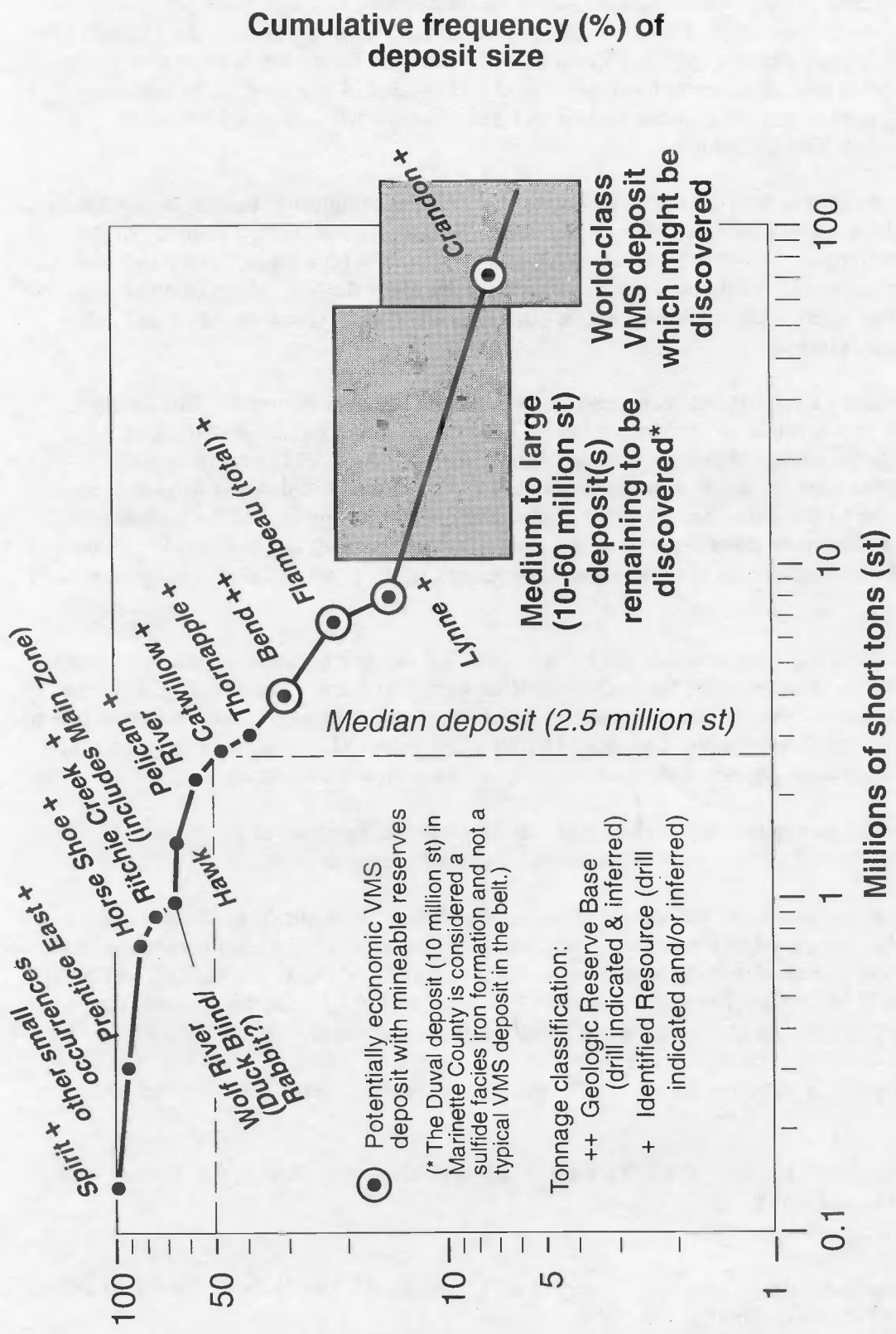


Figure 5. Current (1992) tonnage distribution of known VMS deposits and occurrences in the Wisconsin Penokean Volcanic Belt.

Table 2 - Total resource tonnages and grades reported for Wisconsin VMS Deposits 0.5 million tons or more in size.

Deposit	Status	Total Resource Identified (million st)	Drill. Reserves (million st)	Cu (%)	Pb (%)	Zn (%)	Au (opt)	Ag (opt)	Copper equivalent Grade	Cu Ratio*	Zn Ratio*
<u>Zn-Cu Type</u>											
Crandon	Mine permitting in progress	72.5	67.4 (1979)	(1.04)	0.48	5.56	0.035	1.25	4.13	15.8**	92.05**
Eisenbrey (Thornapple)	Prospect	3	--	1.5	--	3.4	trace	trace	2.8	29.4	100
Pelican	Prospect	2.2	--	1.0	present	4.50	trace	0.51	2.7	18.2	100
Catwillow	Prospect	2.9	--	1.5	--	2.60	0.02	0.45	2.96	36.6	100
Hawk	Prospect	1.5	--	0.8	--	2.7	present	present	1.77	22.9	100
<u>Zn-Pb-Cu Type</u>											
Lynne	Mine permitting on hold	7.5 to 8	6.7 (1992)	0.64	1.65	8.70	0.023	2.45	5.06	6.9	84.1
Horse Shoe	Prospect	0.74	--	2.45	0.9	5.35	0.06	1.05	6.07	31.4	85.5
<u>Cu Type</u>											
Flambeau	Under development to 7 operating mine in 1993	6 to 7	1.9 (1990)/ (1972)	10.5 (4.1)	trace	1.60	0.10	2.1 (0.88)	13.78	80.5**	100**
Bend	Application made for BLM preference right lease	?	3.7\$ (1990)	(1.49)	--	trace	0.10	0.3	3.77	100**	100**
Ritchie Creek (Main Zone)	Prospect	0.9	approx 0.5\$ (1989)	2.11	--	0.37	0.010	present	2.45	85	100

\* Average grade of deposit  
 \*\* Calculated from average grade of deposit  
 \$ Geologic reserve base  
 @ 100 Cu/Cu+Zn  
 # 100 Zn/Zn+Pb  
 + 1991 prices - 1% Cu = 2.76\$ Zn = 5.31\$ Pb = 0.045 opt Au = 5.33 opt Ag

Table 3. Comparison of Tonnage Distribution of VMS Deposits in Canadian Shield (including Wisconsin), Arizona, Australia, and Japan (as percentage of deposits in each size range).

	Millions of Metric Tonnes (Short Tons)*				Median Size	Number of Deposits
	0.1-1.0 (0.1-1.1)	1-10 (1.1-10.1)	10-100 (10.1-101.1)	100+ (101.1+)		
<u>Canadian Shield</u>						
Superior Province Abitibi, Wawa, Wabigoon Belts (Archean)	42.0%	43.0%	13.8% Leuwicourt (24 mt) Mattagami Lake (19.6 mt)	1.4% Kidd Creek (140.95 mt)	1.55 mt (1.83 st)	72
Slave Province Hackett River, Elu Inlet, Black River, Cameron River, Besulieu River Belts (Archean)	33.0%	58.7%	8.3% Izok Lake (13.4 mt)	0%	2.8 mt (3.1 st)	12
Churchill Province Flin Flon, Lynn Lake, LaRonge Belts (Proterozoic)	59.0%	34.0%	7% Fox Lake (13.2 mt) Ruttan (40.7 mt) Flin Flon (57.5 mt)	0%	1.60 mt (1.80 st)	44
Southern Province Pekoan Volcanic Belt (Proterozoic)	38.5%	54.0%	7.7% Crandon (65.8 mt)	0%	2.3 mt (2.5 st)	13
<u>Arizona</u>	92.9%	5.7%	1.4% United Verde (72.7 mt)	0%	less than 1.0 mt (1.1 st)	70
<u>Australia</u>	33.0%	57.1%	7.1% Rosebery (19.4 mt) Hellyer (16.0 mt)	2.4% Mt. Lyell (119.9 mt)**	2.7 mt (3.0 st)	42
<u>Japan</u>	80.0%	1.8%	1.6% Matsumine (30 mt) Motoyama (15 mt)	0%	less than 1.0 mt (1.1 st)	126

\*Includes reserves and/or identified resources

\*\*Includes total number of deposits

Data from Franklin and Thorpe, 1982, Large, 1990,  
and Lindberg, 1989.

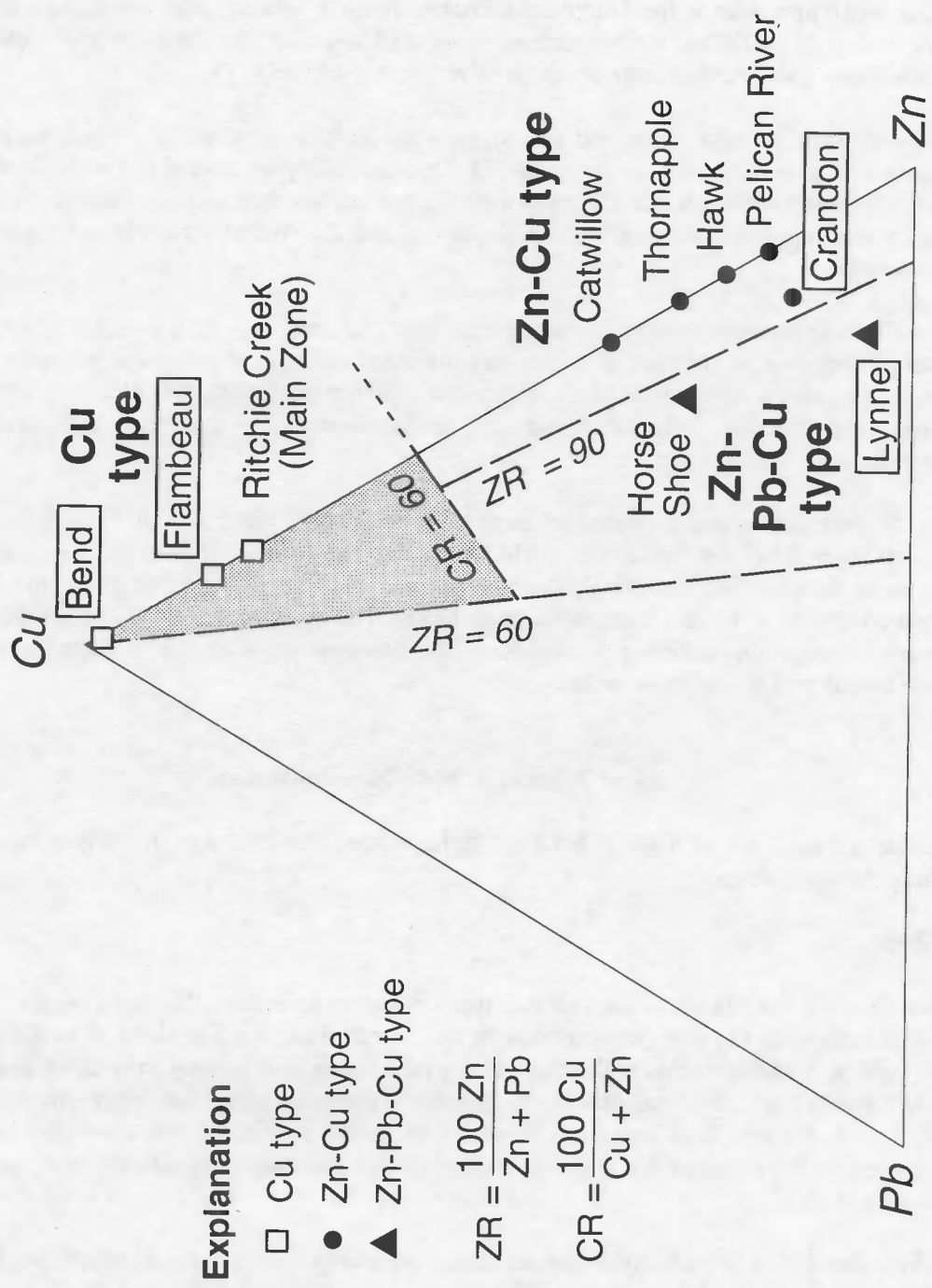


Figure 6. Weight proportions of base metals in Wisconsin VMS deposits (after LaBerge, 1992).



3. Zn-Pb-Cu deposits: Cu ratio < 60, Zn ratio = 60 to 90; e.g., Lynne, Horse Shoe.

The general mineralogy of each deposit type is given in Table 4.

An analysis of these data shows that, in general, the largest Cu deposits (Flambeau and Bend) occur in the Ladysmith district, at the west end of the complex. Zn-Cu and Zn-Pb-Cu deposits become much more prevalent in the Somo and Crandon districts. Along with this change in base-metal ratios, both gold and silver content change from the Ladysmith district (high gold, low silver) to the eastern Somo and Crandon districts (high silver, low gold) (Fig. 7).

These changes in metal ratios and content between districts give rise to a broad regional zoning pattern with generally copper- and gold-rich deposits (Cu type) toward the west, in the Ladysmith district, and zinc-rich (Zn-Cu type) deposits toward the east, in the Crandon district. Telescoping or overlapping of deposit types (Cu, Zn-Cu, and Zn-Pb-Cu) occurs in the centrally located Somo district.

These zoning patterns may be more apparent than real, and may be a function of exploration and discovery. However, if they are real, the variable metal ratios may indicate a progressive or systematic change in hydrothermal fluid chemistry (i.e., temperature,  $fO_2$ , pH, salinity), and discharge site conditions (i.e., original composition and permeability of stratigraphic footwall unit(s), and seawater depth).

The average tonnages and grades of the three deposit types are listed in Table 5 and compared with other VMS districts in the world. Although the number of Wisconsin deposits is limited, the table does suggest that the Cu deposits are above average in copper grade and gold content when compared to other Cu deposits in the table. The Wisconsin Zn-Cu and Zn-Pb-Cu deposits as a whole contain relatively average base- and precious-metal grades, but generally lower-than-average tonnages if Crandon is excluded.

### Styles of Wisconsin VMS Mineralization

At least seven styles of VMS mineralization have been recognized in the P-W subterrane. These include the following:

#### Layered Sheet

Thus far only the Flambeau deposit (Cu type) is known to exhibit this style within depositional environment #1. It is characterized by an extensive copper rich sheet of stratiform, syngenetic, layered massive sulfide with minor zinc-pyrite lenses and gold-bearing chert in the stratigraphic hanging wall. No well-developed epigenetic alteration pipe or stringer sulfide zone is present. However, a widespread laterally extensive sericite-disseminated pyrite alteration halo is developed mainly in the stratigraphic footwall rock units but also extending into the hanging wall as well (Figs. 8a and 8b).

Sulfide deposition for this style may be related to poorly focused, lower temperature (< 300 degrees C) hydrothermal fluid flow (Large, 1990).

VMS in Wisconsin

Table 4. Summary of the typical ore-related opaque minerals in Cu, Zn-Cu, and Zn-Pb-Cu VMS deposits in Wisconsin.

Type	Major Minerals	Minor Minerals	Examples	References
Cu	Pyrite, chalcopyrite, tetrahedrite - tennantite, chalcocite, bornite	gold tellurides, lead telluride, electrum, native gold, arsenopyrite, sphalerite (± galena, magnetite, pyrrhotite)	Flambeau Bend Ritchie Creek	May, 1977 DeMatties & Rowell, 1991 DeMatties, 1990
Zn-Cu	Pyrite, pyrrhotite, sphalerite, chalcopyrite (± galena, magnetite)	arsenopyrite, tetrahedrite-tennantite (± marcasite, electrum, covellite, chalcocite)	Crandon	Lambe & Rowe, 1987
Zn-Pb-Cu	Sphalerite, pyrrhotite, galena, pyrite, chalcopyrite	(± tetrahedrite, polybasite, native silver, pyrrargyrite electrum, native gold)	Lynne	Kennedy et al., 1991

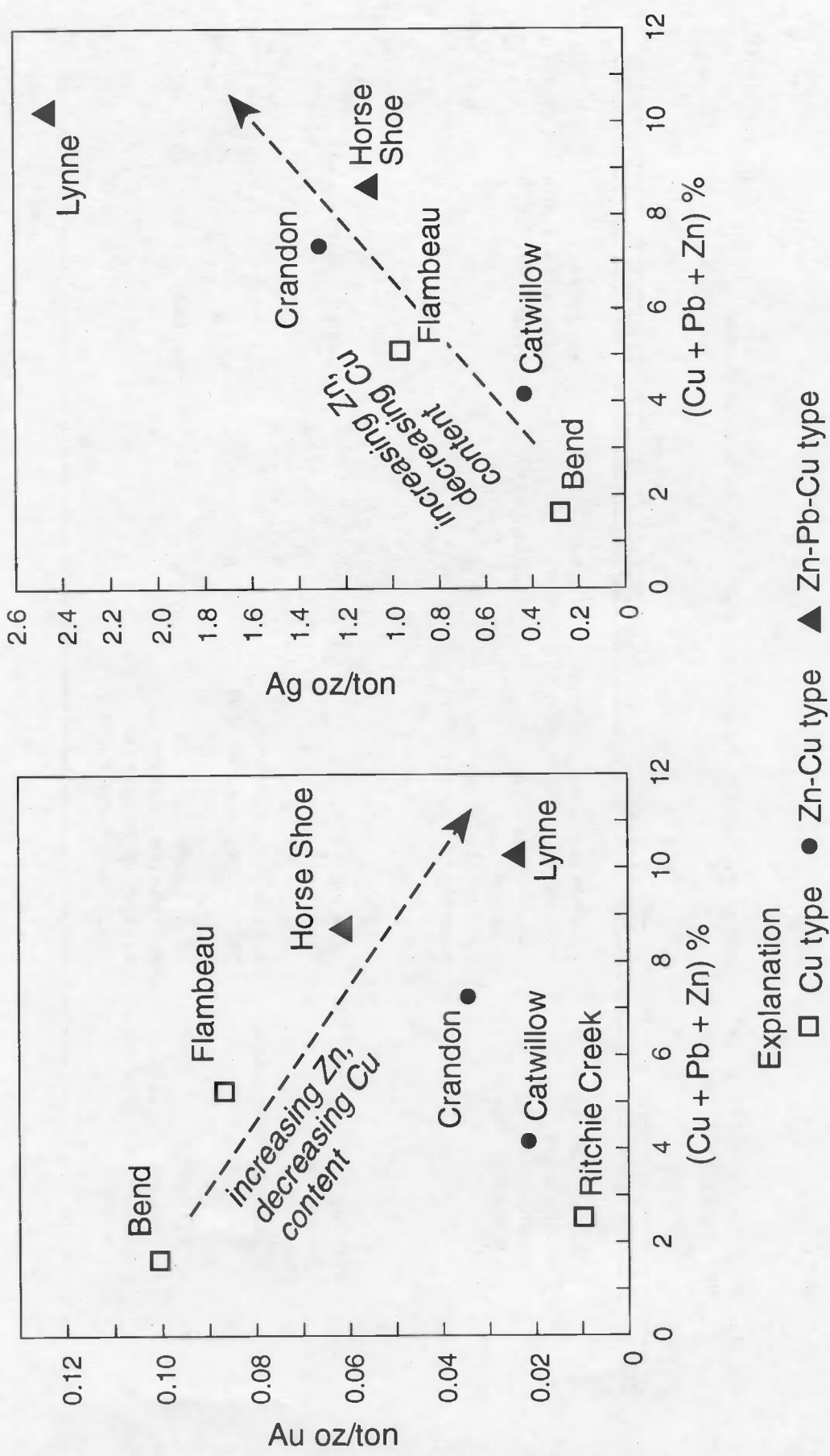


Figure 7. Variation in Au and Ag content with base-metal content for the Cu, Zn-Cu, and Zn-Pb-Cu VMS deposits in Wisconsin.

VMS in Wisconsin

Table 5 - Comparison of mean tonnage and grade data of Wisconsin and other VMS deposits.

Deposit Type	Number of Deposits	Cu (%)	Zn (%)	Pb (%)	Note <sup>1</sup>	Ag (opt)	Au (opt)	Million Short Tons	Zn <sup>2</sup> Ratio <sup>2</sup>	Cu <sup>3</sup> Ratio <sup>3</sup>
<u>Wisconsin Deposits (Proterozoic)</u>										
Cu	3	2.6	0.5	trace	2	0.43	0.09	3.5	100	88.5
Zn-Cu	5	1.2	3.8	0.5	2	0.48	0.03 (Crandon not included)	2.4	100	26.8
Zn-Pb-Cu	2	1.6	7.0	1.3	2	1.75	0.04	3.7	84.8	19.2
<u>Canadian Archean Deposits</u>										
Cu	7	1.8	0.8	0.0	6	0.26	0.01	5.9	100	69
Zn-Cu	36	1.5	3.7	0.1	34	1.1	0.02	17.3	98	28
Zn-Pb-Cu	1	2.7	10.0	1.4	1	6.2	0.02	2.2	88	21
<u>Canadian Bathurst Camp (Paleozoic)</u>										
Zn-Pb-Cu	20	0.6	5.5	2.2	19	1.8	0.01	15.7	71	9
<u>Norwegian Caledonides (Paleozoic)</u>										
Cu	7	1.9	0.5	0.0	7	0.06	0.0	3.5	100	79
Zn-Cu	17	1.6	2.0	0.0	17	0.06	0.0	5.7	98	43
Zn-Pb-Cu	1	1.0	1.2	0.2	0	--	--	20.9	86	45
<u>Australian Deposits (Archean-Paleozoic)</u>										
Cu	16	1.3	0.2	0.0	14	0.23	0.05	13.9	85	85
Zn-Cu	4	1.6	6.9	0.5	3	1.77	0.02	9.1	93	19
Zn-Pb-Cu	10	1.0	11.8	4.7	10	3.39	0.06	8.4	72	8
<u>Japanese Green Tuff Belt<sup>4</sup> (Tertiary)</u>										
Cu	4	1.1	0.2	0.0	2	0.15	0.01	3.7	87	84
Zn-Cu	2	1.3	3.8	0.0	1	1.71	0.04	3.6	100	26
Zn-Pb-Cu	11	1.7	4.7	1.1	3	2.81	0.09	13.6	82	27

1. Number of deposits for which data are available to calculate average Au and Ag grades.  
 2. [Zn/(Zn+Pb)]100  
 3. [Cu/(Cu+Zn)]100  
 4. Close clusters or unit orebodies of Kuroka deposits are grouped as single deposits. Data for all deposits other than Wisconsin are from Large, 1992.

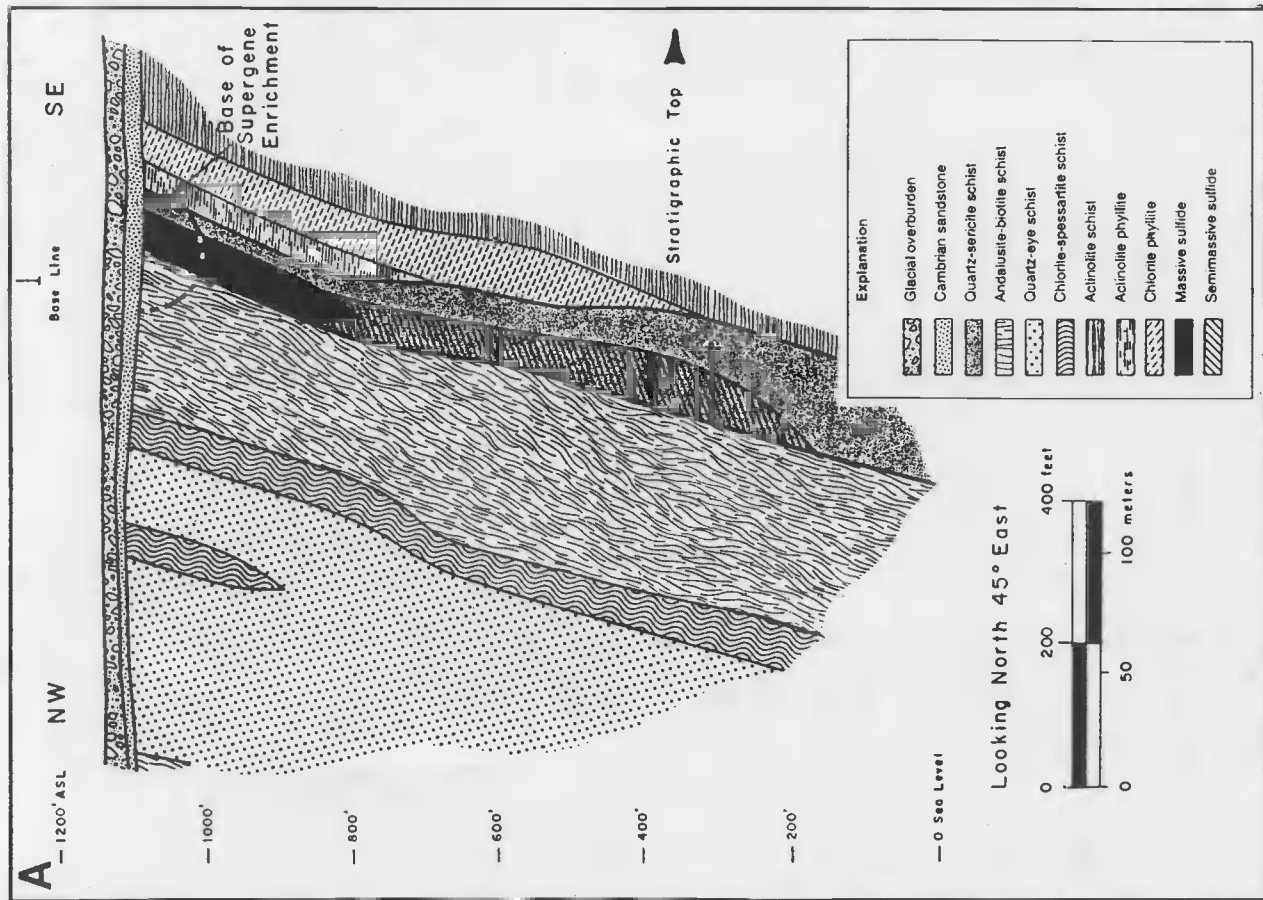


Figure 8a. Geologic cross-section 418 - Flambeau (after May, 1977).

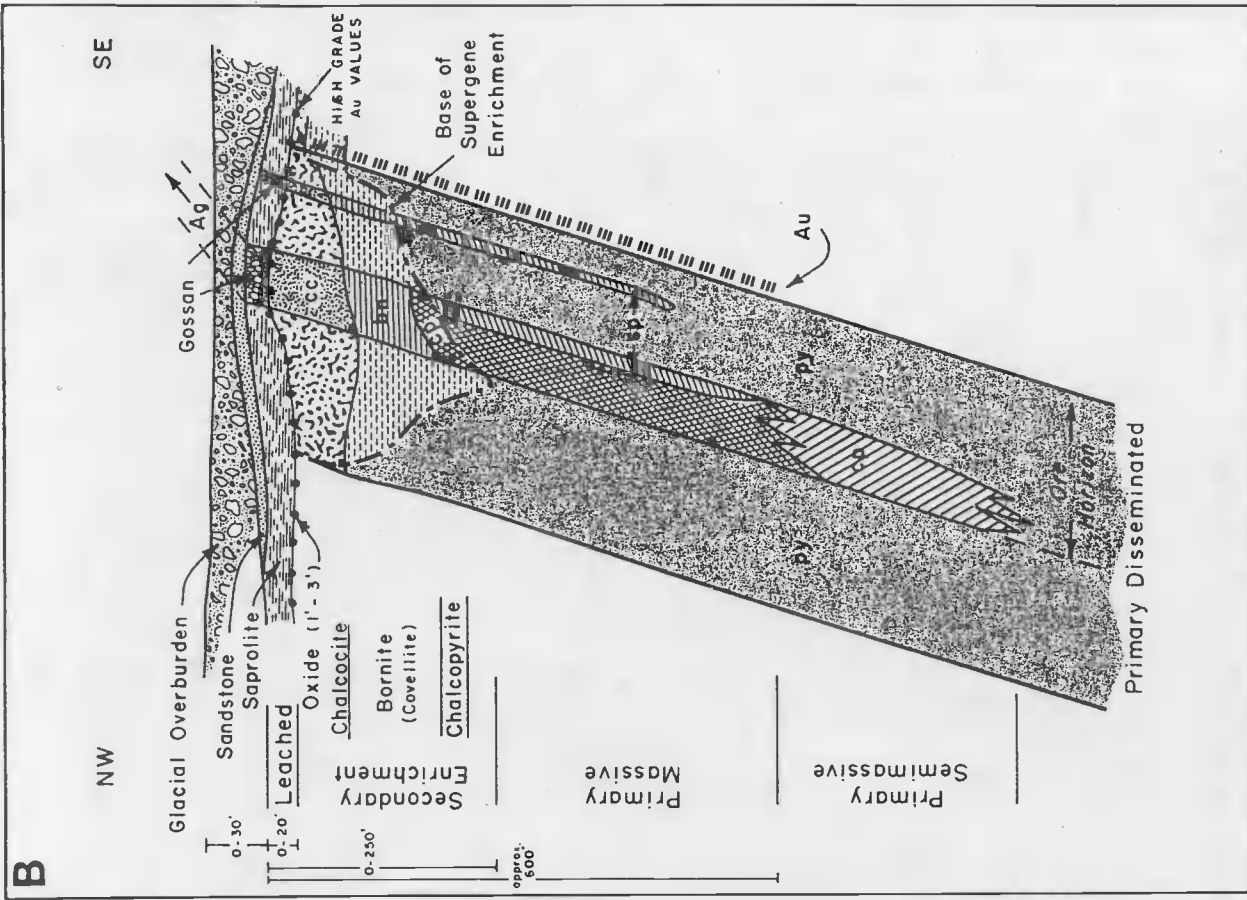


Figure 8b. Schematic cross-section showing zonation patterns - Flambeau (after May, 1977).

### **Bedded sheet plus strata-bound stringer zone**

This style of mineralization is similar to the layered sheet, except a well defined copper-rich strata-bound epigenetic stringer zone is present and extends the full length stratigraphically below a main massive zinc-lead horizon. This style of VMS mineralization commonly forms between volcanic cycles in sedimentary host units such as argillites and is characteristically developed by giant (> 55 million st) VMS deposits such as Crandon (Zn-Cu type), which is hosted in depositional environment #1. Sulfide deposition may be related to hot (> 300 degrees) poorly focused hydrothermal fluids moving through a permeable footwall rock package (Large, 1990). At Crandon the stratigraphic footwall consists of a series of breccia (debris flow) lobes (Fig. 9). This style is also represented in depositional environment #3 by the high-grade Horse Shoe (Zn-Pb-Cu type) deposit which exhibits a semiconformable stringer zone.

### **Stacked lenses**

Most identified Wisconsin VMS deposits assume this style, in which massive sulfide lenses develop at several stratigraphic levels and are connected by zones of fragment-bearing semimassive sulfides, stringer mineralization, or intense alteration with disseminated sulfides. Metal zonation and/or upward base-precious metal refining from the lowermost lens to the upper lens is common. Depositional environment #1 (greenschist succession) frequently hosts this style of mineralization as exemplified by Bend (Cu type) (Fig. 10), Pelican River (Fig. 11), Hawk, Wolf River(?) and Catwillow (all Zn-Cu types). Only the Eisenbrey (Thornapple) deposit and possibly one other occurrence (the Fence prospect) are known to exhibit this style of mineralization in depositional environment #2 (amphibolite succession).

### **Massive sulfide mound**

This style is not common in the P-W subterrane; only the Kivela zone (Zn-Cu type in depositional environment #3) at the Ritchie Creek prospect has been reported to exhibit this classic style. It is characterized by a mound-shape, syngenetic massive-semimassive sulfide accumulation which is stratigraphically underlain by a crosscutting epigenetic stringer sulfide-chlorite-sericite alteration zone. Vertical metal zonation from a copper+zinc+lead rich stringer zone to a zinc+lead+copper rich massive-semimassive zone is evident (Fig. 12). The footwall sericite-pyrite (pyrrhotite) alteration halo is generally limited in aerial extent.

This style develops when hydrothermal fluids are well focussed along a syn-volcanic structure and through a relatively impermeable footwall sequence such as the mafic flows present at the Kivela zone (Large, 1990).

### **Sulfide mound replacement**

Generally a thick mound-shaped, epigenetic sulfide accumulation which forms as a result of successive, subsurface replacements of previously deposited exhalite (commonly carbonate and/or chert rich). Vertical metal zonation pattern from a copper-rich base to a zinc-lead-silver top is strong. The Lynne deposit (Zn-Pb-Cu type) in depositional environment #1 is reported to exhibit this style of mineralization (Fig. 13).

The replacement mound style may develop from hot (> 350 degrees C) well focussed hydrothermal fluids (Large, 1990).

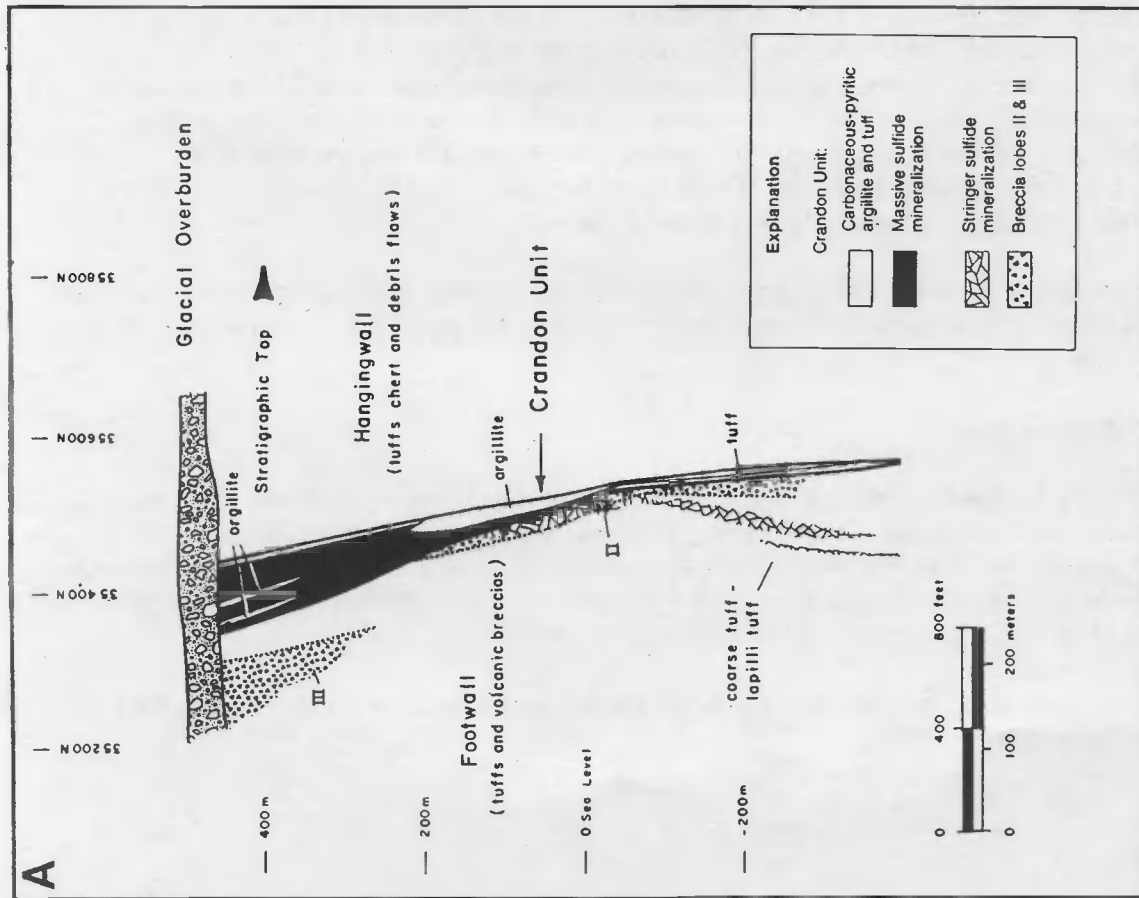


Figure 9a. Geologic cross-section 94360E - Crandon (after Lambe and Rowe, 1987).

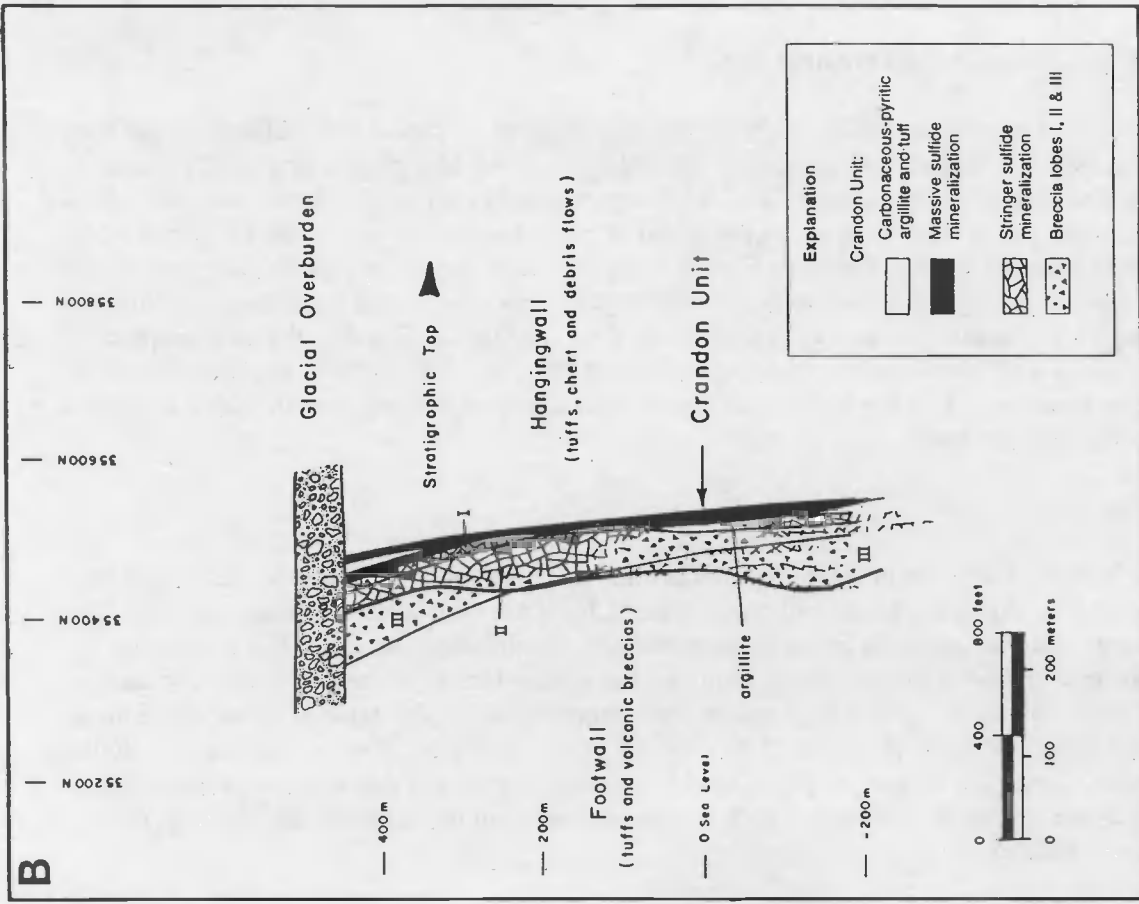


Figure 9b. Geologic cross-section 94400E - Crandon (after Lambe and Rowe, 1987).

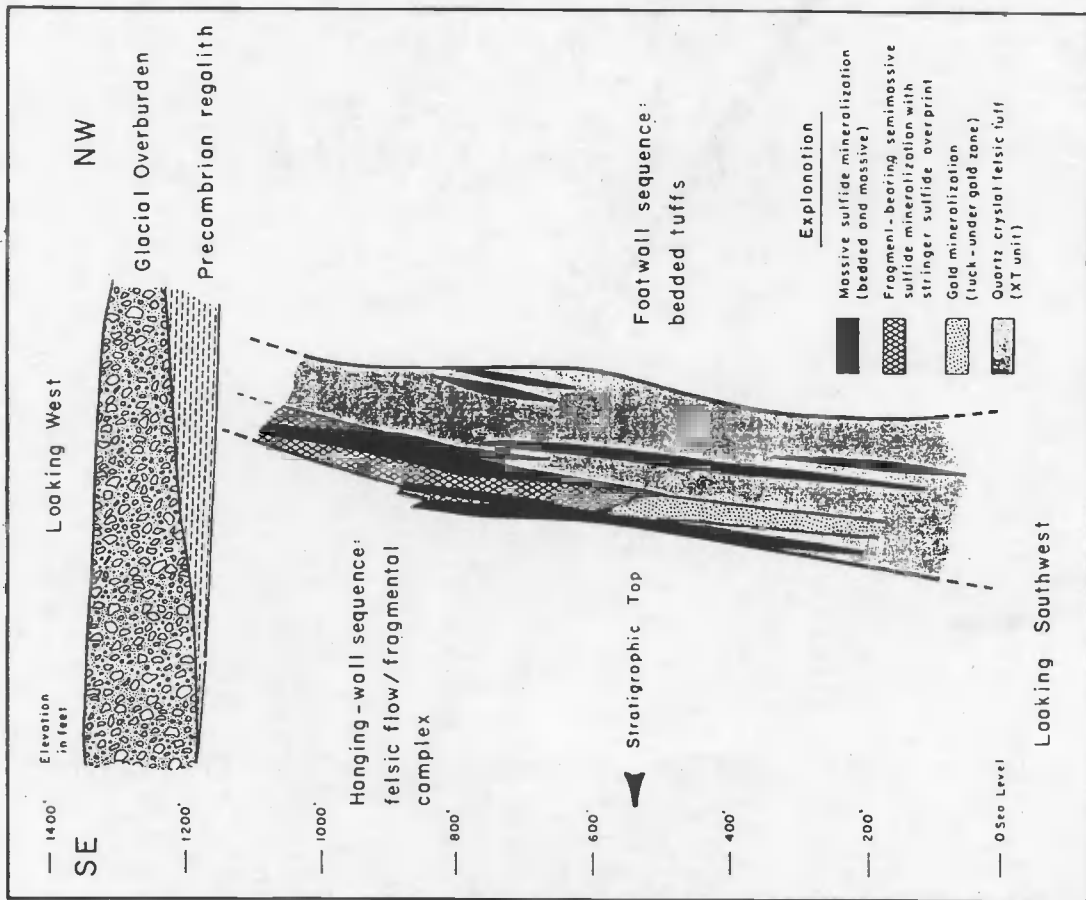


Figure 10. Geologic cross-section 49235E - Bend (after DeMaties and Rowell, 1991).

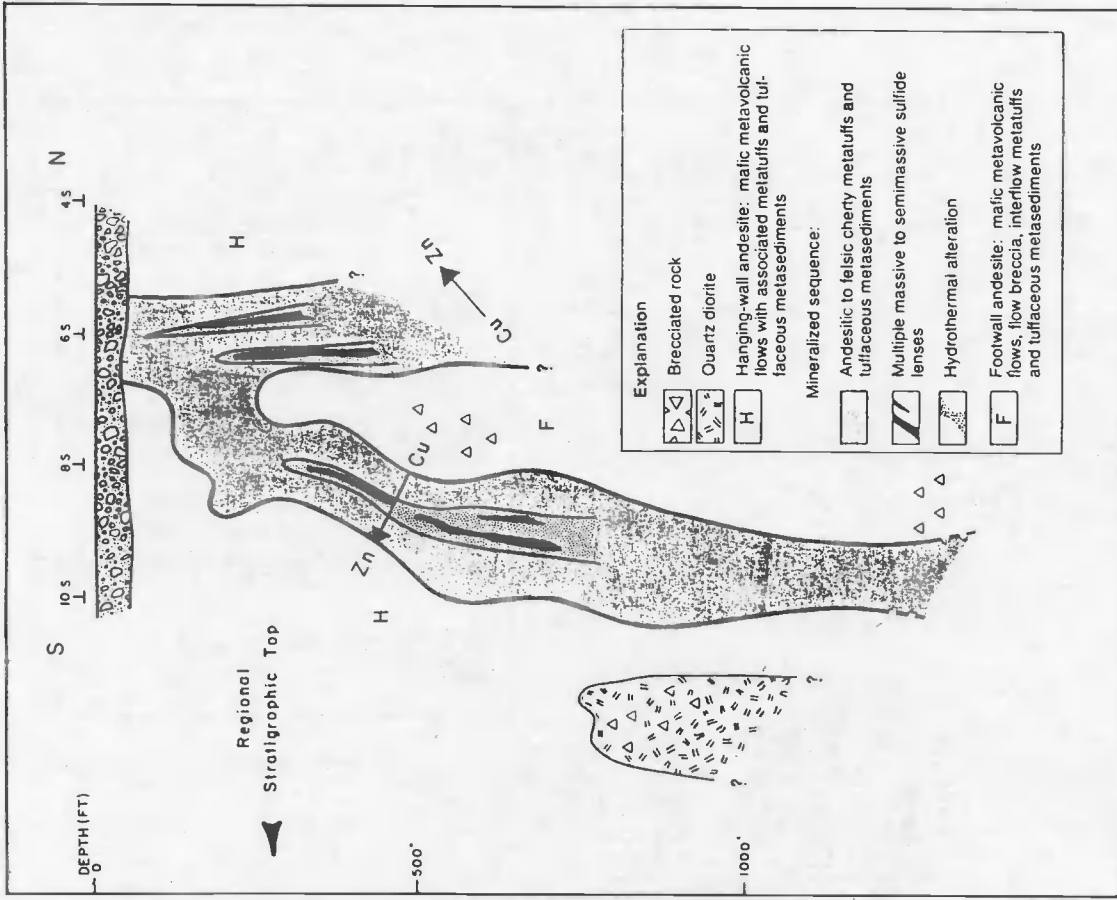


Figure 11. Geologic cross-section 110+00E - Pelican River (after Bowden, 1978).





Looking west

1600

1400

1200

1000

ELEV. IN FT

100 FT

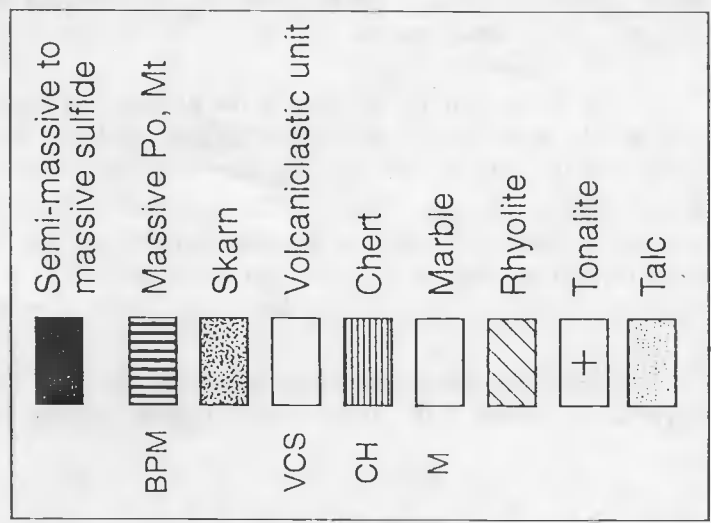
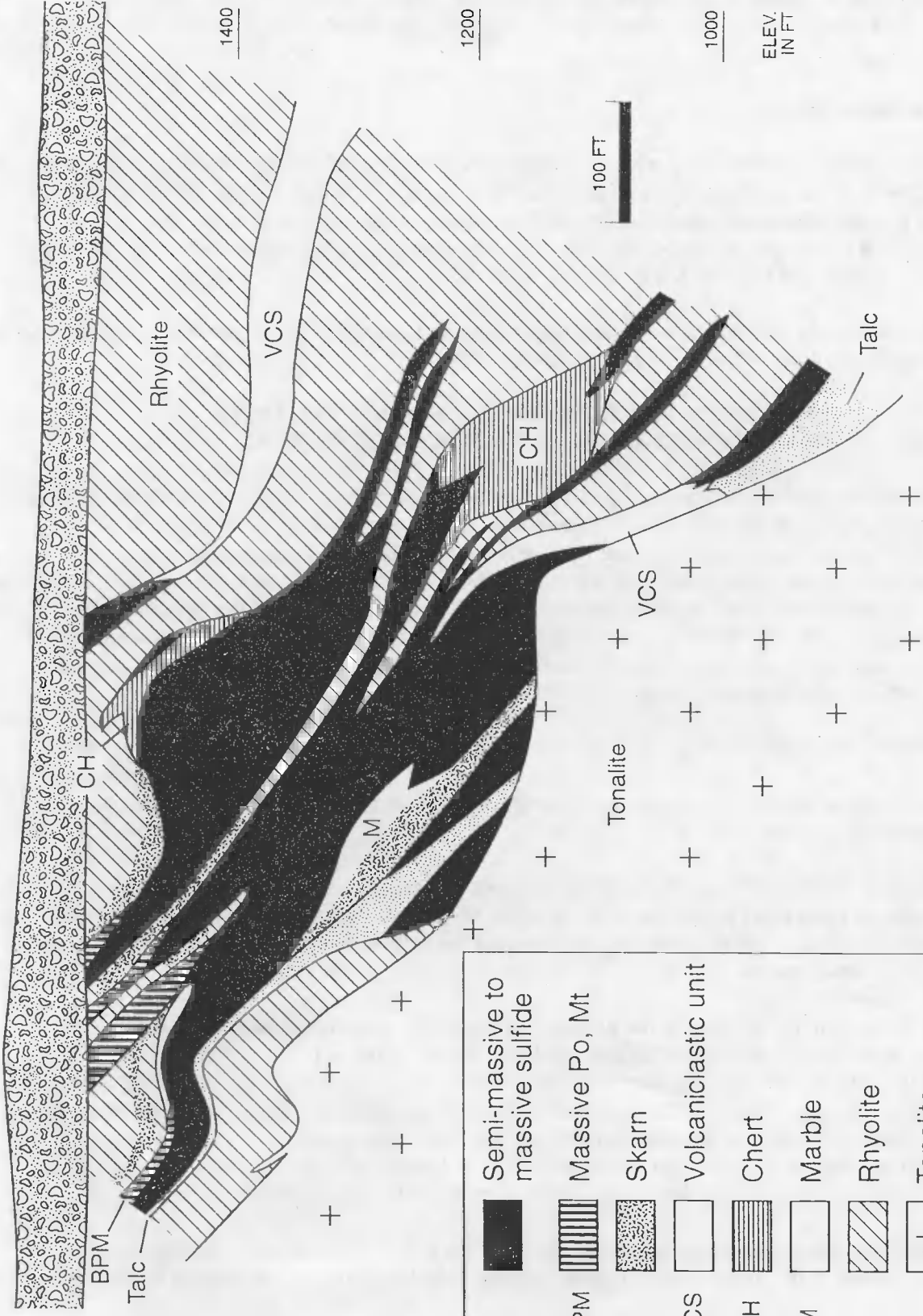


Figure 13. Geologic cross-section Line 1000E - Lynne (after Kennedy *et al.*, 1991)

## Replacement

This style is similar to the mound replacement but represents only a partial replacement of previously deposited exhalite. The Ritchie Creek main zone (Cu type) in depositional environment #1 is a good example (Fig. 14).

## Stockwork/disseminated

Broad zones of stockwork pyrite±chalcopyrite with associated sericite alteration characterize this style. These horizons could represent failed VMS systems or possibly contain central zones of massive pyrite-chalcopyrite mineralization. Minor copper±zinc lenses may be present at the stratigraphic top of the system. Good examples of this style in depositional environment #1 are found at the School House and Clear Creek (Cu type) prospects.

This style may develop from hot and dense hydrothermal fluids which move laterally through permeable volcanic units below the sea floor (Large, 1990).

## MASSIVE SULFIDE MINERALIZATION ASSOCIATED WITH META-ARGILLITE FORMATIONS (PMS)

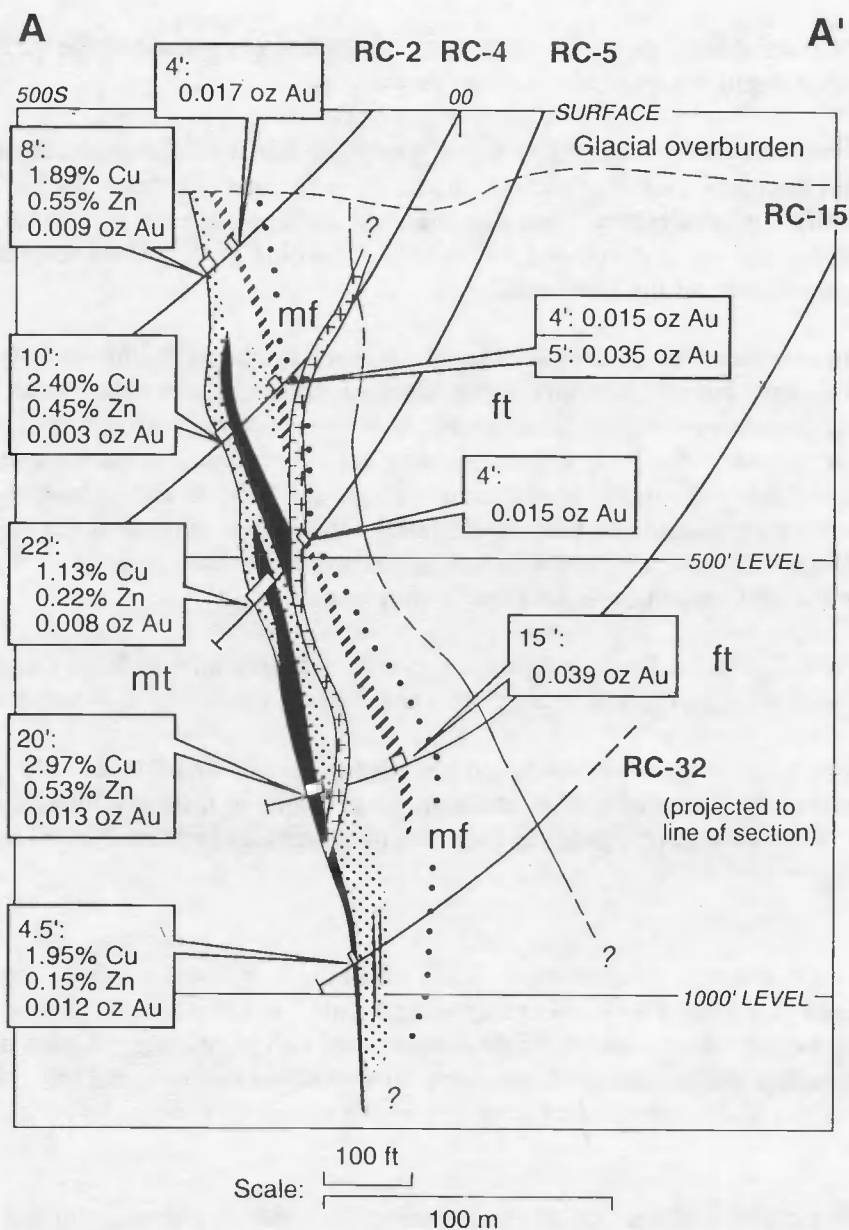
The meta-argillite formations (Fig. 4a and 4b) are important stratigraphic sub-units within the greenschist succession of the P-W subterrane and may be related in both time and space to the economic VMS deposits. These important lithologic units are expressed geophysically as long formational airborne electromagnetic (AEM) conductors, both with and without direct magnetic response. As previously mentioned, the source of the AEM conductors is usually graphite, and/or pyrrhotite-pyrite, hosted by black to greenish-gray, weakly to strongly schistose, chlorite-rich meta-argillites and associated tuffaceous metasediments (metagraywackes). Individual units are generally less than 100 feet thick and may exhibit well-developed internal lamination or bedding.

These units contain only geochemically anomalous base-metal-bearing pyrrhotite and/or pyrite mineralization with varying amounts of associated graphite or, in some cases, carbon. The sulfide-to-graphite ratio varies widely from conductor to conductor; the argillites are thought by some workers to be sulfide-facies iron-formations.

Textural evidence (Finlow-Bates, 1980) suggests that significant amounts of sulfide mineralization in these units is hydrothermal in origin rather than diagenetic. Drillhole data from many of these strataform AEM conductors indicate that the sulfide mineralization can mimic, at least in part, typical VMS systems that have both syngenetic and epigenetic components.

In some systems, graphite is not present and the massive pyrrhotite beds (with and without fine sphalerite intergrowths) may be tens of feet thick. These massive pyrrhotite beds contain fragments (usually altered meta-argillite clasts) and have a stratigraphic footwall underlying alteration zone consisting mostly of sericite, chlorite, and/or quartz (silicification), some with crosscutting pyrrhotite stringers containing fine chalcopyrite and sphalerite intergrowths. There may be more extensive stringer zones of network-textured pyrrhotite and sometimes chalcopyrite. The texture is formed by anastomosing veinlets hosted by altered meta-argillite.

Cyclic repetition of one or both components of the sulfide mineralization within a given section is common in the more well-developed systems, possibly reflecting multiple hydrothermal



#### Explanation

- |                                                                                                                                                                         |                                                                                                                                     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| <p>Mineralized horizon:</p> <p>Massive (&gt;50%) to semi-massive (30-50%) sulfide mineralization</p> <p>Sulfide-bearing hydrothermal alteration (altered exhalite?)</p> | <p>Limit of stockwork sulfide halo (&lt;30% sulfides)</p> <p>Intermediate to mafic subvolcanic intrusive</p> <p>Gold assay zone</p> |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|

Figure 14. Geologic cross-section A-A' - Ritchie Creek Main Zone (after DeMatties, 1990).

ft - felsic to mafic tuff-lapilli tuff (quartz-biotite-feldspar to biotite-feldspar-amphibole-quartz schist).

mf - altered and mineralized felsic tuff (pyritic quartz-sericite schist).

mt - mafic to intermediate tuffs and tuffaceous sediments (feldspar-biotite-amphibole-quartz schist-semischist).

pulses. Metamorphic overprinting and/or shearing may have locally remobilized the sulfides, but relict primary features are still recognizable in many formations.

Interbedded cryptocrystalline laminated chert, displaying the typical interlocking-quartz-grain texture (serrated grain boundaries) in thin section, or cherty tuffaceous sediments are almost always associated with the sulfide mineralization. Because the meta-argillite units are structurally incompetent, shear zones are easily developed within them, resulting in the brittle deformation (brecciation and fragmentation) of the chert units.

Meta-argillite is believed to be deposited as fine-grained epiclastic sediments, possibly in smaller isolated sedimentary basins, generally within the back-arc-basin sequence, under reducing conditions and during periods of volcanic quiescence. Although clusters or groups of these meta-argillite formations are found in the P-W subterrane, they are concentrated in the back-arc-basin sequence and commonly along the flanks of the main volcanic arc (Piv) of the Ladysmith-Rhinelander Volcanic Complex. No formations have been recognized in the central portion of the main volcanic-arc sequence (amphibolite succession). Argillite formations have also been mapped in the Marshfield subterrane, but their spatial distribution is not clearly understood.

All of the VMS districts defined to date are generally within a mile or less of major argillite formations. This spatial relationship was recognized early by explorationists in Wisconsin.

Although to date this sulfide mineralization has been generally found to be only geochemically anomalous or to contain low grades of copper and zinc, its presence in meta-argillite formations has metallogenic significance in terms of a possible indicator of potentially economic VMS mineralization.

## Discussion

Aside from a close spatial relationship to VMS mineralization, certain mineralized meta-argillites may be genetically related to VMS ore-forming events. In other words, the barren or weakly metal-bearing sulfide mineralization might have formed before, during, or after major ore deposition, reflecting either the beginning of the event, or deposition itself, or the last stages of the hydrothermal event in the VMS system. In terms of a modern analog, it might be considered "black smoker debris."

Current geologic data indicate that all four potentially economic and many of the subeconomic or under-explored deposits contain these units in their "local" stratigraphic section (Fig. 4a and 4b). As has been described, the Massive Sulfide Zone of the Crandon deposit is within one of these units (Crandon Unit).

Finlow-Bates (1980) discussed the possibility that the formation of graphitic argillite (carbonaceous sediments) was the result of ore deposition which set up anoxygenic conditions, a type of ground preparation in which reducing conditions allow the preservation of carbon (whose source is uncertain). The model assumes that the ore-fluid chemistry was in a reduced state, which it likely was during the Precambrian. This might explain the close spatial (genetic?) relationship of the Pms formations with the major deposits discovered thus far.

If this empirical-genetic model is valid, the stratigraphic implications are obvious: Pms formations associated with VMS deposits would represent gross time-marker horizons which mark ore-forming events and could be used in regional correlations. This concept of "favorable horizon" is a characteristic of other VMS districts, in the Canadian shield and elsewhere in the world.

Figures 3, 4a, and 4b show formations in the P-W subterrane and the western and east-central parts of the Ladysmith-Rhineland Volcanic Complex. A number of major formational groups can be seen. However, the geology is complicated and has been made even more so by isoclinal folding and faulting. Detailed correlations of individual formations are impossible at our current level of knowledge.

Using the general geologic framework which has been established for the complex, it is possible to grossly correlate the formational clusters on the basis of structural and stratigraphic position relative to the central core of the main volcanic-arc complex. At least two "sets" or groups can be defined in the western portion of the Complex: Pms I, structurally along the flanks of (probably stratigraphically above) the core, and Pms II, in the back-arc basin. A tentative interpretation of the composite stratigraphy in this area is presented in Figure 15. Under this stratigraphic arrangement, the Eisenbrey (Thornapple) deposit would occupy the lowest position within the amphibolite succession. The first major ore-related argillite formational group (Pms I) in the greenschist succession occurs stratigraphically above the Flambeau deposit, but possibly below the Lynne deposit. However, because stratigraphic interpretation has been further complicated in the Lynne area by more complex faulting, folding, and igneous intrusion, the Lynne deposit may actually be closer stratigraphically to the meta-argillite formational group than the composite section indicates, or possibly laterally equivalent to Flambeau.

The Bend deposit occupies the highest stratigraphic position and appears to be associated with the second major ore-related argillite formational group (Pms II) in the back-arc basin.

This concept can be extended to the eastern part of the belt where one prominent formational group (Pms I) can be seen linking together the Pelican River, Wolf River, and Catwillow deposits (Fig. 3 and 4b). The Crandon Unit is associated with the formational group south of the deposit, which may be the lateral equivalent of the ore horizon(?) and, using this scheme, would be considered to be associated with the Pms II formational group.

Because of complex regional isoclinal folding, the true spatial and stratigraphic separation between the two productive formational groups may be much less; they may even be the same unit in different volcanic facies. Nonetheless, gross correlations suggest that most of the ore deposits in the greenschist succession were formed in a fairly narrow stratigraphic interval and are nearly coeval in their time of deposition. The narrow stratigraphic interval and the correlation of Pms formational groups to link the VMS deposits in time are partially supported by lead isotope data.

Afifi *et al.* (1984) established a lead model age of approximately 1.8 to 1.9 Ga for Flambeau, Pelican River, Hawk, and Crandon. A strong linear trend is defined by the lead isotope data, suggesting that the deposits are nearly coeval in their formation (Fig. 16). More recent lead isotope work by Thorpe (written communication, 1992) on the Ritchie Creek, Spirit, Horse Shoe, and Lynne deposits indicates that they also plot along this trend, further supporting this contention. Thorpe's lead model age for the VMS mineralization is approximately 1.86 Ga.

As previously mentioned no meta-argillite formational groups have yet been identified in the amphibole succession of the main volcanic-arc facies. However, thin but laterally extensive oxide-facies iron-formations are known and, as described for Eisenbrey (Thornapple), may represent a similar type of favorable horizon for VMS mineralization.

There are no lead isotope data for the Eisenbrey deposit; therefore, it is not known whether it plots on the linear trend defined by Thorpe. If it does plot on the trend line and is coeval with the

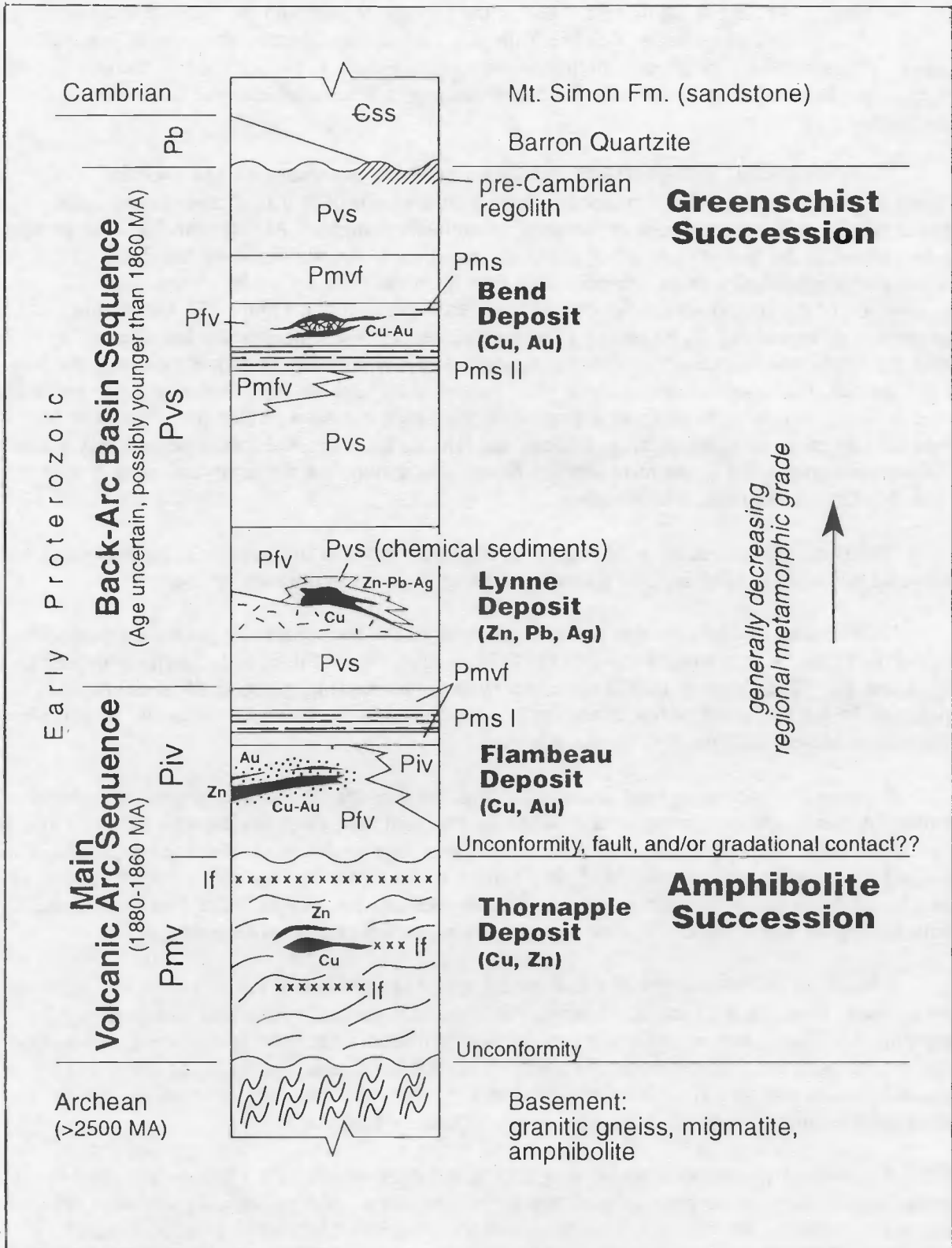


Figure 15. Schematic composite stratigraphic section, west-central portion of the Ladysmith-Rhinelander Volcanic Complex.

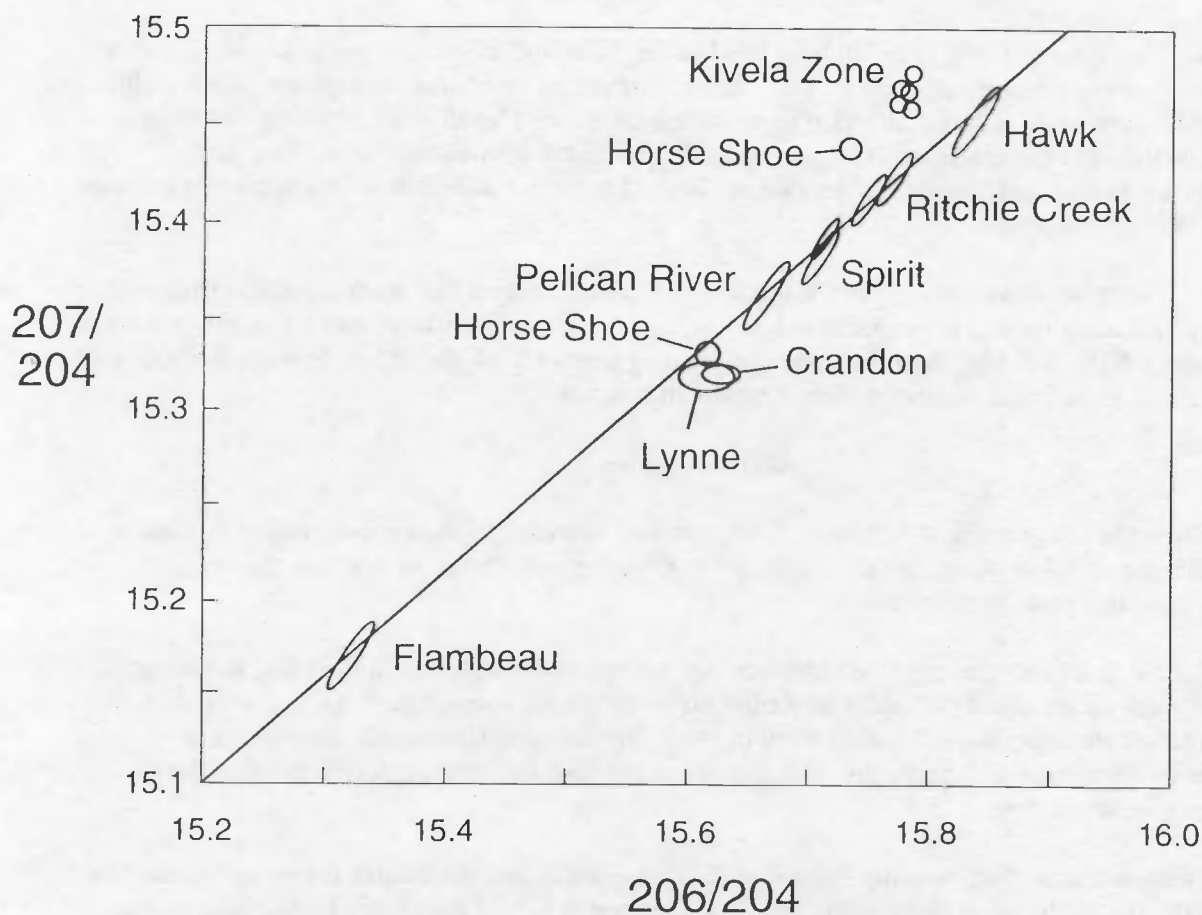


Figure 16. Lead isotope data for VMS deposits in the Wisconsin Penokean Volcanic Belt (after Thorpe, *et al.*).

greenschist succession deposits, then the oxide-facies iron-formations could possibly represent lateral equivalents of the ore-related Pms units.

### Conclusions

1. Two volcanic complexes can be recognized in the Early Proterozoic Penokean volcanic belt (Wisconsin magmatic terrane) on the basis of lithology, structure, and age relationships. These include the Wausau Complex, host to at least one structurally controlled gold deposit, and the larger Ladysmith-Rhineland metavolcanic complex, which contains at least 13 volcanogenic massive sulfide deposits and occurrences, clustered in three districts.
2. Volcanogenic massive sulfide mineralization occurs in at least three distinct geologic depositional environments. The four potentially economic deposits occur in environment #1, which is the felsic volcanic center facies.
3. The identified volcanogenic massive sulfide deposits and occurrences can be classified on the basis of metal content and divided into three groups (Cu, Zn-Cu, Zn-Pb-Cu). Each group exhibits various styles of mineralization.



4. The meta-argillite association in the Ladysmith-Rhineland metavolcanic complex may have significant exploration importance, i.e., certain formations or formational groups at the right stratigraphic level could theoretically lead to potentially economic VMS mineralization particularly in areas where they are associated with felsic centers (depositional environment #1). Two key formations are known and others may be present in the Ladysmith-Rhineland metavolcanic complex and Marshfield subterranean.

5. The Wausau volcanic complex is known to contain only a few meta-argillite formations. That lack, indicating no major breaks in volcanism, and felsic centers which may be mostly subaerial and younger (1835-1845 Ma) than the main ore-forming event (1860 Ma) might explain the poor rate of discovery of significant massive sulfide deposits in this area.

#### Acknowledgments

The author is grateful to Ernest K. Lehmann and Associates Inc. for permission to release data for this paper. Also to Economic Geology for allowing publication of portions the original manuscript for this memorial volume.

A final thanks to the late Ned Eisenbrey for his major contribution to the ideas expressed here. His exploration effort on behalf of Kennecott in the 1960s coupled with earlier work compiled by the late Jack Phillips, led to the discovery of the Flambeau and Thornapple deposits (now appropriately named the Eisenbrey deposit) and paved the way for later explorers to enter the Wisconsin greenstone belt.

On a personal note, Ned was my mentor at E. K. Lehmann and Associates for many years. He helped shape my exploration philosophy, and it is with gratitude and friendship I contribute to this commemorative volume.

#### References Cited

- Afifi, A., Doe, B. R., Sims, P. K., and Delevaux, M. H., 1984, U-Th-Pb isotope chronology of sulfide ores and rocks in the Early Proterozoic metavolcanic belt of northern Wisconsin: *Economic Geology*, v. 79, p. 338-353.
- Bowden, D. R., 1978, Volcanic rocks of the Pelican River massive sulfide deposit, Rhineland, Wisconsin: a study in wallrock alteration: Unpublished MS Thesis, Houghton, Michigan Technological University, 62 p.
- DeMatties, T. A., 1989, A proposed geologic framework for massive sulfide deposits in the Wisconsin Penokean volcanic belt: *Economic Geology*, v. 84, p. 946-952.
- \_\_\_\_\_, 1990, The Ritchie Creek Main Zone: a Lower Proterozoic copper-gold volcanogenic massive sulfide deposit in northern Wisconsin: *Economic Geology*, v. 85, p. 1908-1916.
- DeMatties, T. A., and Mudrey, M. G., Jr., 1991, Geologic setting of the Early Proterozoic base- and precious-metal-rich metavolcanic belt of Wisconsin: 37th Annual Institute on Lake Superior Geology, Eau Claire, Wisconsin, 1991, Proceedings, p. 29-33.

- DeMatties, T. A., and Rowell, W. F., 1991, Bend, a Lower Proterozoic, copper- and gold-enriched volcanogenic massive-sulfide deposit in Taylor County, Wisconsin: 37th Annual Institute on Lake Superior Geology, Eau Claire, Wisconsin, 1991, Proceedings, p. 34-40.
- Finlow-Bates, T., 1980, The chemical and physical controls on the genesis of submarine exhalative orebodies and their implications for formulating exploration concepts, a review: *Geologisches Jahrbuch*, Ser. D, no. 40, p. 131-168.
- Franklin, J. M., and Thorpe, R. I., 1982, Comparative metallogeny of the Superior, Slave and Churchill provinces in Hutchinson, R. W., Spence, C. D., and Franklin, J. M., Precambrian sulfide deposits (H. S. Robinson Memorial Volume): Geological Association of Canada Special Paper 25, p. 3-90.
- Greenberg, J. K., and Brown, B. A., 1983, Lower Proterozoic volcanic rocks and their setting in the Southern Lake Superior district: Wisconsin Geological and Natural History Survey Miscellaneous Paper 83-4, 18 p.
- Kennedy, L. P., Harding, T. A., Schaff, J. H., and Zielinski, A. M., 1991, The Lynne massive sulfide deposit, Oneida County, Wisconsin: 37th Annual Institute on Lake Superior Geology, Eau Claire, Wisconsin, 1991, Proceedings, p. 63.
- LaBerge, G. L. and Myers, P. E., 1983, Precambrian geology of Marathon County, Wisconsin: Geological and Natural History Survey Information Circular, No. 45, 88 p.
- LaBerge, G. L. and Myers, P. E., 1984, Two Early Proterozoic successions in central Wisconsin and their tectonic significance: *Geologic Society of America Bulletin*, v. 95, p. 246-253.
- Lambe, R. N., and Rowe, R. G., 1987, Volcanic history, mineralization, and alteration of the Crandon massive sulfide deposit, Wisconsin: *Economic Geology*, v. 82, p. 1204-1238.
- Large, R. R., 1990, Tonnage-grade data for VMS deposits in Ore deposit studies and exploration models: Center for Ore Deposit and Exploration Studies, University of Tasmania, Master of Economic Geology Work Manual, v. 1, section 4, parts 1, 2, and 3.
- \_\_\_\_\_, 1992, Australian volcanic-hosted massive sulfide deposits: *Economic Geology*, v. 87, p. 471-510.
- Lavery, N. G., 1985, Quantifying chemical changes in hydrothermally altered volcanic sequences - silica enrichment as a guide to the Crandon massive sulfide deposit: *Journal of Geochemical Exploration*, v. 24, p. 1-27.
- May, E. R., 1977, Flambeau - a Precambrian supergene enriched massive sulfide deposit: *Geoscience Wisconsin*, v. 1, p. 1-26.
- Sims, P. K., Van Schmus, W. R., Schulz, K. J., and Peterman, Z. E., 1989, Tectono-stratigraphic evolution of the Early Proterozoic Wisconsin magmatic terranes of the Penokean Orogen: *Canadian Journal of Earth Sciences*, v. 26, p. 2145, 2158.



**AN OVERVIEW OF THE FLAMBEAU SUPERGENE ENRICHED MASSIVE  
SULFIDE DEPOSIT:  
GEOLOGY AND MINERALOGY, RUSK COUNTY, WISCONSIN**

Edward R. May  
Consulting Mining Geologist

and

Stephen R. Dinkowitz, Geologist  
Flambeau Mining Company

**INTRODUCTION**

The discovery of the Flambeau orebody coincided with the signing of the National Environmental Policy Act (NEPA) in 1968. As a consequence, both the development of this supergene enriched massive sulfide deposit and implementation of NEPA went through intense public debate. At the same time basic industrial segments of the economy such as mining, steel, and auto manufacturing were restructuring to compete in an emerging global economy. Neither Kennecott Copper Corporation (Kennecott), the mining industry, nor governmental regulatory agencies fully appreciated the consequences of NEPA when development drilling of the Flambeau orebody was completed in 1971. Kennecott was aware, however, of the deteriorating copper market. Therefore Kennecott's Flambeau development policy was to secure the mining permits, then make a decision whether or not to develop the project. The project was discontinued in 1977 after receipt of an approved Environmental Impact Statement (EIS) but before issuance of the mining permits, due to depressed metal prices and unfavorable economics.

A lean, restructured base metal mining industry reemerged by the mid-1980's, one ready to meet mine development challenges within the context of a strong national and state environmental awareness. Kennecott reopened the Flambeau project and, shortly thereafter, entered into discussions with local city, township, and county officials and citizens. Once their concerns had been identified, a Local Agreement was drafted and signed that alleviated their concerns and allowed permit hearings to proceed under a more cooperative and constructive spirit. This bold and innovative approach has since been incorporated in Wisconsin's metallic mineral regulations.

The Flambeau Mine has been in successful production for the past three years. It has been successful economically, environmentally, socially and politically. Considerable up-front planning, public dialogue, and company commitment resulted in dire environmental predictions not coming true, for example, the water treatment plant out performs even its most enthusiastic design predictions.

Geologically, this mine has presented the industry with unusual mineral assemblages as well as an example of high grade ores which have not been mined in North America since the turn of the century. Enriched Canadian Shield massive sulfide orebodies are rare; moreover, the size and grade of the Flambeau orebody is unusual. Sampling and mining of the overlying gold-rich gossan was a technical challenge rarely experienced by North American mining geologists. The opening of the Flambeau orebody thus became a dual challenge of extracting gossan while simultaneously mining 10% Cu ore. Each of these ores required a different sampling and mining approach. This was accomplished without environmental incident during start-up of the mine through one of Wisconsin's

wettest summers. There was no offsite discharge of waters from the 182 acre site except through the approved water treatment discharge line.

The following paper is intended to give an overview of the geology and gossan/sulfide mineralogy. It is limited to observed megascopic-macroscopic data, supported only by minor microscopic and geochemical work conducted in the early 1970's.

## HISTORY

Kennecott discovered the Flambeau deposit in November 1968, following a long history of exploration in the upper Midwest, when their first diamond drill hole, drilled to test a geophysical conductor, intersected 47.7 feet averaging 9.25% Cu and 0.049 opt Au. During the 1950's George Moerlein noted that Precambrian volcanic rocks, similar to those known to host massive sulfide deposits in the Canadian Shield of Quebec, Ontario, and Manitoba occurred in Wisconsin (Babcock, 1996). Of particular note was the recording of a well dug about 9 miles south of Ladysmith in 1915 that yielded a specimen of volcanoclastic rock with copper oxide mineralization. Amazingly, this specimen is still on file in Madison eighty years later. A small airborne electromagnetic (EM) geophysical survey was flown over the nearby Schoolhouse Prospect in 1955 with negative results (Figure 1).

In 1966 Jack Philips continued the pioneering work of Moerlein with the discovery of additional "favorable looking" volcanoclastic rocks west and northwest of Ladysmith. A large airborne geophysical survey flight block including the Schoolhouse Prospect in the southeast corner, some weakly pyritized outcrops between Weyerhaeuser and Bruce, and outcrops of similar rock northwest of Bruce, was flown in May 1967. The east boundary of the aerial survey was coincident with the Flambeau River as it flows south past the future Flambeau mine site. A favorable response was noted and brought to Ned Eisenbrey's attention. He approved the addition of two short flight lines between the river and State Highway 27. These three lines delineated what was later to be the Flambeau deposit, thus initiating the rebirth of Wisconsin's base metal mining industry after an absence of nearly 25 years when the lead-zinc mines in the southwest corner of the state were closed (Schweuk 1977).

Delineation drilling at the Flambeau deposit was accomplished from 1969 to 1971. An Environmental Impact Report was compiled during 1974 and infill drilling on the west end of the deposit was completed. The EIS was approved by the Wisconsin Department of Natural Resources in early 1976; however, the mining permit application hearing was canceled after Rusk County turned down the Company's zoning request.

In 1986, the Flambeau project was reopened and another round of infill and confirmation drilling completed on the east end of the deposit. The scope of the project was changed to mine only the supergene enriched mineralization as direct shipping ore, thus eliminating on-site milling and disposal of tailings as originally proposed in the 1970's. In addition, the smaller open pit was to be backfilled and not flooded as proposed for the larger pit designed in 1976. Economic considerations precluded underground mining; consequently, the planned open pit development was restricted to a depth of 225 feet, which is the base of the deepest secondary enrichment zone.

A second EIS was submitted in 1990 to mine 1.8 million tons averaging 10.92% Cu and 0.088 opt Au. Hearings were held in 1990 and permits and approvals to commence construction were issued in January of 1991. Flambeau Mining Company, a wholly owned subsidiary of Kennecott Minerals, commenced construction in July 1991, only to be stopped by an injunction filed

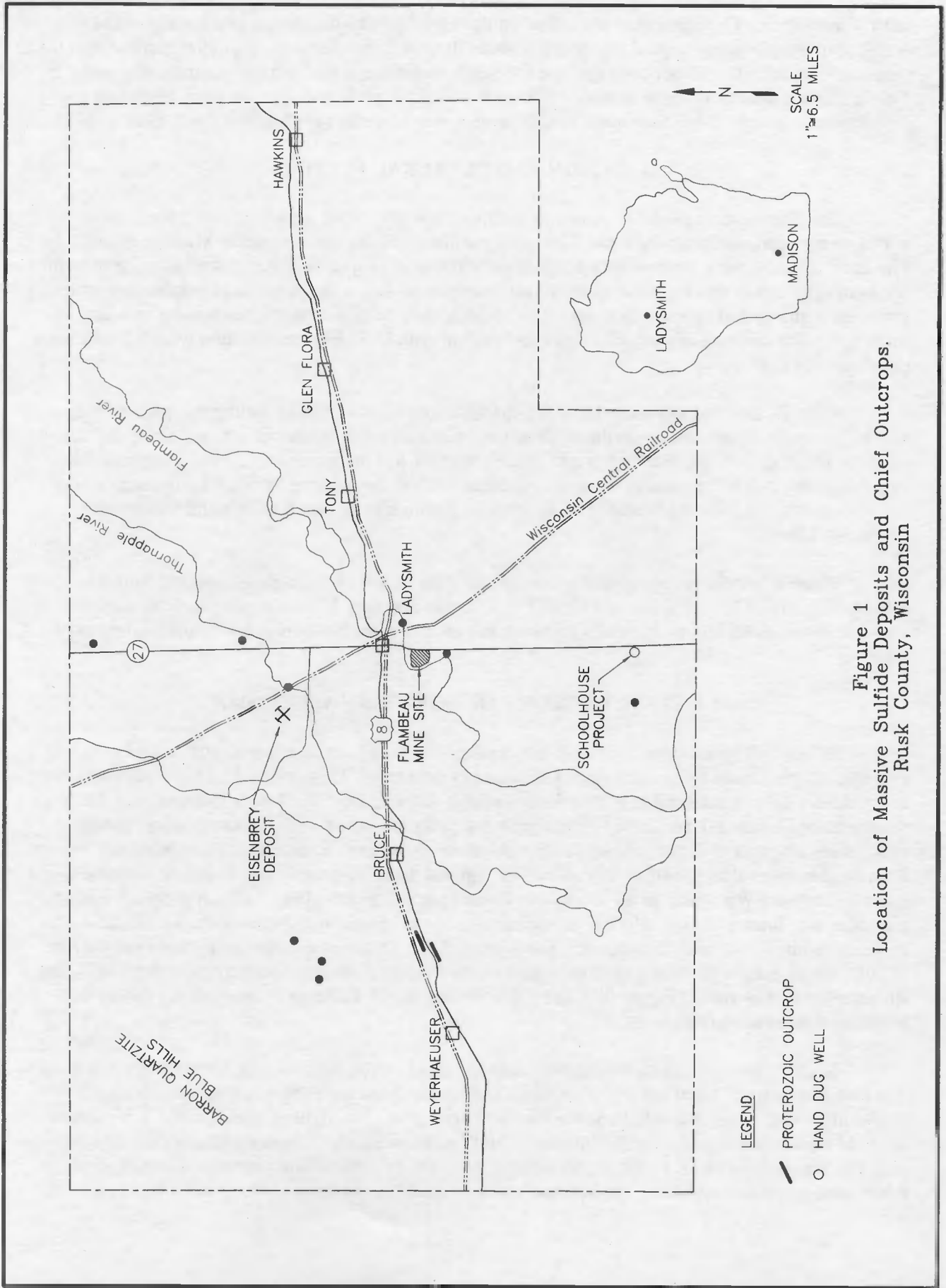


Figure 1  
 Location of Massive Sulfide Deposits and Chief Outcrops,  
 Rusk County, Wisconsin

shortly thereafter. The injunction was based on the Endangered Species Act and the suspected presence of purple warty-backed clams and unusual dragon flies. Subsequent studies showed that the proposed operation would not endanger the species in question. Construction recommenced early in 1992 and ore production began in May 1993. All told, 24.5 years had elapsed from discovery to production, although active time spent on the project was 16 years (1968 to 1977 and 1986 to 1993).

### LOCATION AND CULTURAL SETTING

The Flambeau orebody is located in northwestern Wisconsin approximately 150 miles northeast of Minneapolis-St. Paul and 220 miles northwest of the state capital at Madison (Figure 1). The town of Ladysmith, immediately north of the 2700 acre project site, is a picturesque rural-retail community of 3,900 and the Rusk County seat. Ladysmith lies at the junction of north-south and east-west highway and railroad systems. The orebody may be conveniently reached by traveling south 1.5 miles on State Highway 27 from its junction with U.S. Highway 8, then west 0.2 mile on a paved private road.

Rusk County and the project site are characterized by low, 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 45 feet are uncommon. The Flambeau River cuts diagonally across the county from the northeast corner, meandering 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 with temperature extremes ranging from a recorded high of 108°F to a low of -40°F. Precipitation averages 32 inches per year. Annual snowfall averages 43 inches, typically covering the ground from late November to the beginning of April.

### GENERAL GEOLOGY OF NORTHERN WISCONSIN

At least 13 volcanogenic massive sulfide deposits have been discovered within Early Proterozoic greenstone rocks of northern Wisconsin (DeMatties, 1994). The Ladysmith-Rhineland metamorphic belt, which strikes across the state for a distance of 150 miles, is the host rock for this mineralization. These 1.86 to 1.88 billion year old rocks consist of mafic metavolcanics, gabbroic sills, lesser amounts of felsic metavolcanics, and some cherty iron formations. The Ladysmith-Rhineland metamorphic belt clearly shows on regional airborne gravity and magnetic reconnaissance maps of northern Wisconsin as an anomalous linear feature. North of the Ladysmith-Rhineland belt are rocks that form a thick platformal turbidite sequence of clastic and chemical metasedimentary rocks including major iron formations. The Niagara Fault separates the Northern Penokean Terrane of continental margin assemblages from the Pembine-Wausau Subterrane that contains the Ladysmith-Rhineland belt of rocks (Figure 2). The paper written by G. LaBerge in this volume shows the location of these subterranea.

South of the Ladysmith-Rhineland belt are rocks of the Wausau and Marshfield Complexes. The Eau Claire shear separates the Marshfield Subterrane from the Pembine-Wausau Subterrane (LaBerge, 1996). The Marshfield Subterrane is characterized by Archean gneisses and 1.86 billion year old metavolcanic rocks and granitoids. The Wausau Volcanic Complex consists of 1.88 billion year old amphibolite facies rocks unconformably overlain by 1.84 billion year old intermediate to felsic metavolcanics. Intruding the Wausau volcanic complex are anorogenic igneous rocks, 1.47 to

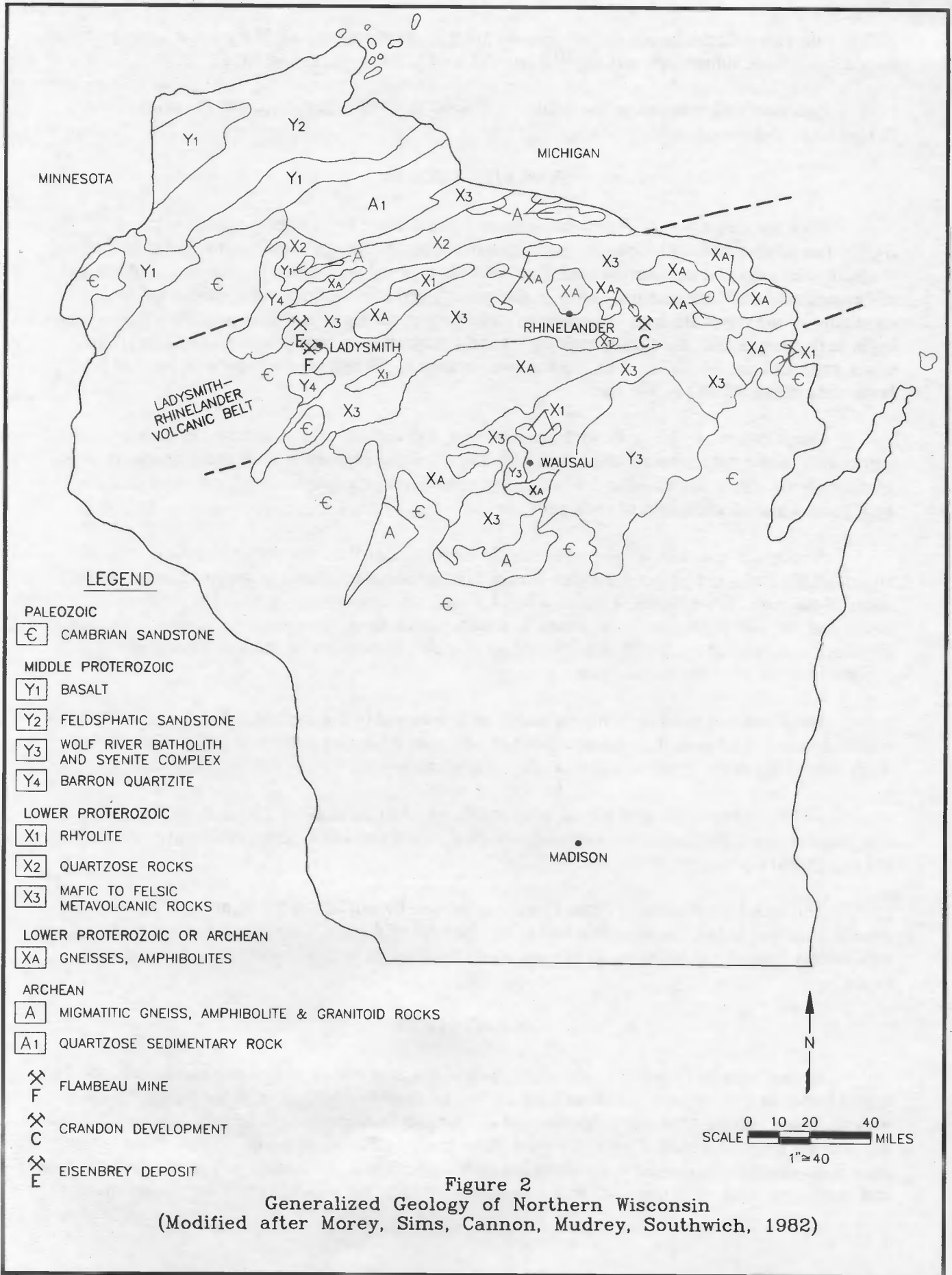


Figure 2  
 Generalized Geology of Northern Wisconsin  
 (Modified after Morey, Sims, Cannon, Mudrey, Southwich, 1982)



1.51 billion year old, the largest of which is the Wolf River Batholith. DeMatties and LaBerge more fully discuss these subterranean and the Wausau Volcanic Complex in this volume.

Paleozoic sediments overlap the southern portions of the Southern Superior Province of the Precambrian Canadian Shield.

### MINE SITE GEOLOGY

Geological data for the Flambeau orebody initially came from airborne geophysical data, 63,220 feet of diamond drill core, one outcrop and a subcrop. Interpretation of the airborne EM and magnetic data provided exploration geologists with the regional rock fabric as well as possible areas of "greenstone" rock and plutons. Most of the geology and mineralogical descriptions for the remainder of the paper are from observations made during mining of the open pit. Data from core holes in the deeper and less altered rock have been extrapolated to supplement descriptions of the upper and more altered rocks. Subcrop is approximately 1,100 feet in elevation with planned pit bottom elevations of 880 to 940 feet.

Identification of rock units while core logging was difficult due to intense alteration, particularly in the supergene enriched zone. The dominant regional metamorphic alteration suites of minerals were first identified in drill core, and subsequent petrographic work provided clues to rock genesis and identification of rock units.

An angular unconformity between steeply dipping, saprolitic altered intermediate volcanoclastic rocks and Upper Cambrian Mount Simon Sandstone crops out approximately one mile south of the mine on the banks of Meadowbrook Creek. A subcrop of Precambrian rock was discovered in 1988 during very low waters in the Flambeau River west along strike of the orebody. This rock consisted of small and large fragments of quartz-sericite schist and rusty metachert containing small amounts of malachite.

The Flambeau orebody is interpreted to be overturned to the southeast; however, stratigraphic nomenclature will be used throughout this paper. Structural hangingwall rocks in the mine on the north side of the orebody are actually the stratigraphic footwall.

Since 1993 detailed open pit mapping has occurred to the scale of 1 inch to 20 feet. This mapping has confirmed the earlier derived geological model and added some structural complications not recognized during core examination.

The rock classifications (Table 1) were developed by Jeff Hulen for Kennecott in 1970, and in general hold true today. A water-lain tuff in the footwall of the ore horizon and felsic tuff altered to sericite-clay beds in the hangingwall sequence have been added to this classification since mining began.

### PLEISTOCENE

Several ages of Pleistocene glaciation covered the area and deposited unconsolidated, poorly sorted materials that range in thickness from 12 feet to 30 feet. Most deposits are typical outwash with materials ranging from silt to boulders up to four feet in diameter. These poorly sorted outwash deposits are more interbedded with silty loess away from the Flambeau River. A two to three foot thick loess deposit covered the interbedded outwash deposits over the eastern half of the deposit. Iron and manganese staining is prevalent in the lowermost parts of the outwash and is interpreted to be of

**TABLE 1**  
**CLASSIFICATION OF FLAMBEAU MINE ROCK TYPES**  
**RUSK COUNTY, WISCONSIN**

	Rock Name	Genetic Name
<b>Hangingwall</b>	Quartz-eye schist	Dacite quartz crystal tuff and Rhyolitic quartz crystal lapilli tuff
	Actinolite Schist	Dacitic flows and tuff
	Chlorite, spessartite and andalusite-biotite schists,	Dacitic and andesite tuffs and lapilli tuffs
	Sericite-clay schist	Felsic tuff
<b>Ore horizon</b>	Quartz-sericite schist	Rhyolitic tuffs and lapilli tuff
	Metachert	Chert
	Massive sulfides	Massive Sulfides
	Feldspar-clay schist	Felsic tuff
<b>Footwall</b>	Actinolite and chlorite phyllite	Andesitic tuff
	Actinolite and andalusite-biotite schist	Dacitic-andesitic lapilli tuff
	Quartz-eye schist	Rhyolitic-dacitic quartz crystal tuff

recent origin, unrelated to the underlying sulfide orebody. A relatively well sorted, heavily iron-stained, rounded, pebble to cobble outwash overlies the sandstone and is clearly older than the overlying purplish silt-rich outwash, indicating at least two ages of Pleistocene glacial deposition at the mine site.

The last glacial period almost completely eroded the underlying Cambrian sandstone outlier. Glaciation has removed the sandstone, approximately 450 feet along strike, on the west and east ends of the orebody. In addition, several large blocks of sandstone were removed down to bedrock north of the pit perimeter (Figure 3).





A Pleistocene to Recent stream meandered across the west end of the orebody in a southwesterly direction and a waterfall was created where the stream flowed over the footwall metachert. Water-worn chert boulders were clearly evident as well as near total removal of gossan over a 200 foot strike length. The stream gravels are still visible on the south wall of the open pit.

Pleistocene glaciation has played a small structural role in the host rock geology. A small thrust fault is visible in the west pit wall. It has been interpreted that glacial forces from the north squeezed out a highly incompetent, 10 foot thick clay-sericite bed. The glacier then moved more competent footwall volcanic rock south to cover the truncated and incompetent tuffaceous unit.

### CAMBRIAN SANDSTONE

A thin, narrow, near flat-lying outlier of Upper Cambrian sandstone overlies most of the Flambeau deposit. The presence of this outlier was of enormous economic significance in that areas of poorly cemented gossan and supergene enriched sulfides were protected from erosion. The sandstone has been identified as the Mount Simon Formation. It is a light yellow to tan, very poorly cemented, medium to coarse grained sandstone with numerous light green-gray shale partings. The sandstone is characterized by rounded to subrounded, frosted, medium sized quartz grains. A thin

LEGEND

-  PLEISTOCENE STREAM CHANNEL
-  PLEISTOCENE GLACIAL TILL
-  MOUNT SIMON CAMBRIAN SANDSTONE
-  FLAMBEAU OREBODY

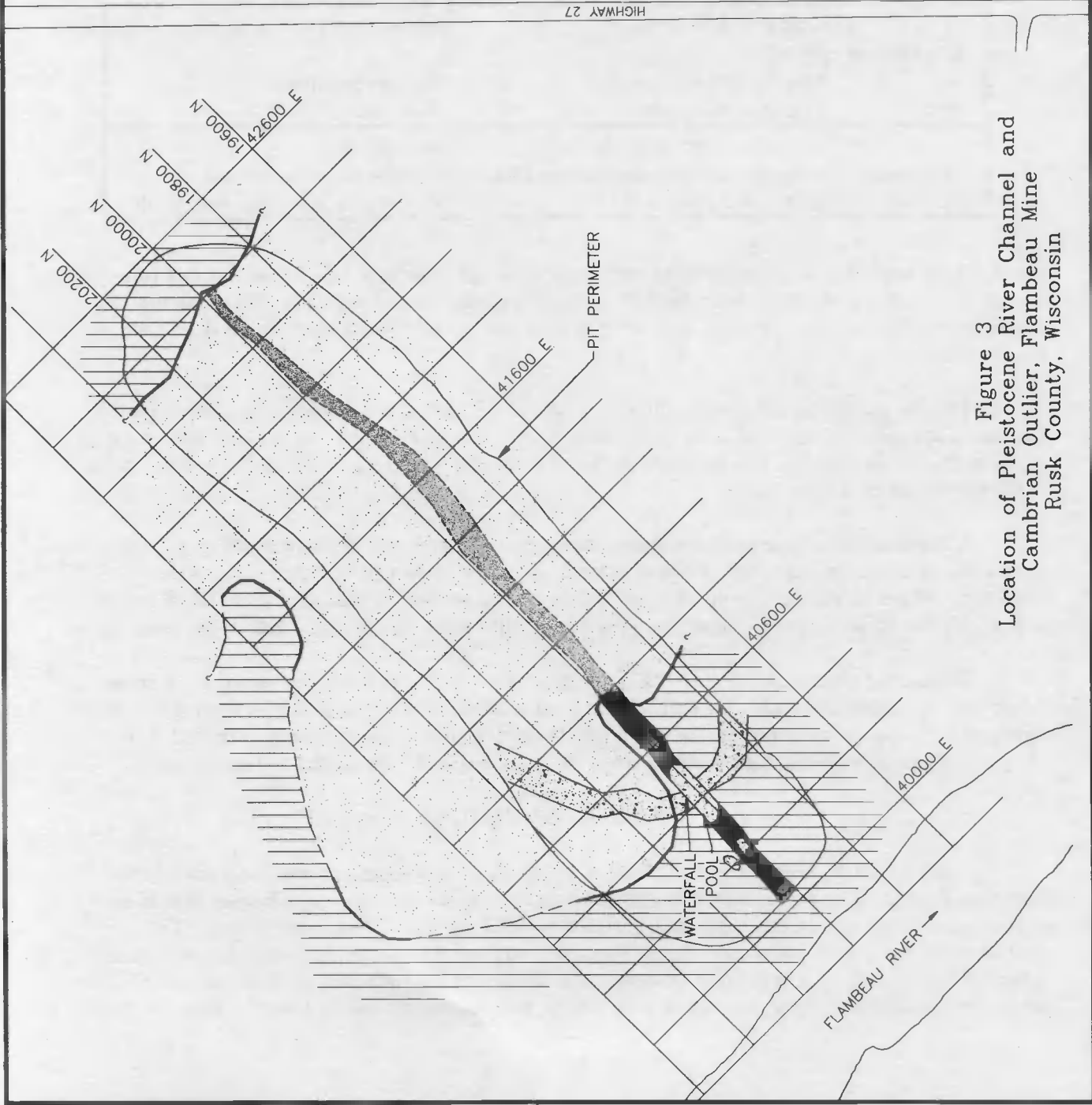
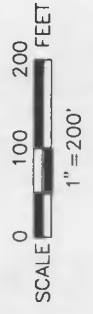
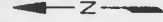


Figure 3  
Location of Pleistocene River Channel and  
Cambrian Outlier, Flambeau Mine  
Rusk County, Wisconsin

basal conglomerate is present and consists of rounded to subrounded white quartz particles up to 2.5 inches in diameter. Sandstone has been deposited in depressions and collapsed structures at the top of the gossan and in depressions between the more resistant and enclosing metachert units. No evidence was seen to suggest that these structures were post-Cambrian.

The base of the sandstone has been examined for evidence of gossan mineralization incorporated within the basal conglomerate and appears to contain no fragments of Precambrian bedrock other than quartz pebbles.

## PRECAMBRIAN GEOLOGY

### STRATIGRAPHIC FOOTWALL

The footwall rocks (stratigraphic footwall) on the north side of the deposit consist of three main units: metadacite, quartz-eye tuff, and andalusite-biotite schist (Figure 4). A more detailed description of the composition of these units has been reported previously by this author (May, 1977a). A comparison of Flambeau dacite and rhyolite tuffs with average whole-rock chemistry for such lithologies is shown on Table 2. Certain oxides such as  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$  are generally close to average. Metasomatic alteration, associated with mineralization, probably explains the large increase in FeO, and MgO and general decreases in CaO,  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$ .

TABLE 2  
A COMPARISON OF FLAMBEAU WHOLE-ROCK ANALYSES WITH WORLD  
AVERAGE DACITE AND RHYOLITE COMPOSITIONS

Wt. %	World <sup>(1)</sup>	Flambeau	Deviation	World <sup>(1)</sup>	Flambeau	Deviation	Flambeau	
	Avg. Dacite	Dacitic Lapilli Tuff <sup>(2)</sup>	from World Av.	Avg. Rhyolite	Rhyolitic Lapilli Tuff <sup>(2)</sup>	from World Av.	Rhyolitic Qtz. Crystal Lapilli Tuff <sup>(2)</sup>	Deviation From World Avg.
$\text{SiO}_2$	63.58	63.12	-0.46	73.66	73.28	-0.38	73.07	-0.59
$\text{Al}_2\text{O}_3$	16.67	16.78	0.11	13.45	14.47	1.02	13.46	0.01
$\text{Fe}_2\text{O}_3$	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
$\text{Na}_2\text{O}$	3.98	0.54	-3.44	2.99	0.64	-2.35	1.88	-1.11
$\text{K}_2\text{O}$	1.40	2.00	0.6	5.35	3.19	-2.16	1.67	-3.68

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

(2) Analyses by Kennecott Exploration Services, Salt Lake City, Utah

**Quartz Eye Schist.** The northern-most unit of the footwall stratigraphy generally consists of a very well foliated quartz eye schist that has been interpreted as a quartz crystal ignimbrite of intermediate composition. This unit is distinctive due to the presence of "bluish quartz eyes" that vary in size from 1 mm to 10 mm. Under the microscope these eyes are actually aggregates of quartz grains. Some show relict euhedral outlines, but most commonly they are polygonal-shaped grains. A triple-point junction was a commonly observed feature suggesting metamorphic recrystallization. The

**LEGEND**

PLEISTOCENE

70 GLACIAL TILL

CAMBRIAN

60 MOUNT SIMON SANDSTONE

PRECAMBRIAN PROTEROZOIC

51 QUARTZ-EYE (TUFF)

52 ANDALUSITE-BIOTITE (SEDIMENTS)

53 METADACITE (FLOWS, TUFFS)

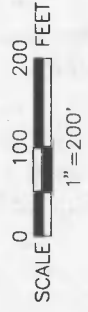
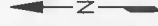
--- "B" & "C" SULLFIDE HORIZONS

40 MASSIVE SULFIDES "A" LENS

20 QUARTZ-SERICITE (RHYOLITE TUFF)

11 BIOTITE-FELDSPAR (TUFF)

SURFACE ELEVATION 1120'



HIGHWAY 27



Figure 4  
 Geological Plan Map 1050 Level, Flambeau Mine  
 Rusk County, Wisconsin

quartz eye schist also contains numerous but difficult to recognize lithic fragments of similar composition. These fragments have been greatly elongated parallel to schistosity, as have all fragments associated with the Flambeau orebody. Chief alteration minerals are chlorite, sericite, and clay, with chlorite being the dominant mineral. Whole rock chemistry taken from samples below the supergene alteration zone indicates the quartz eye schist to be dacite tuff to rhyolite lapilli tuff in composition.

Metadacite. A major lithologic change occurs at the hangingwall or south of the quartz eye schist. A complex suite of greenish-purple metadacitic rock was deposited that probably reflects intermediate flows and associated tuffbeds. Pillow structures have been sought but not found, but there is evidence of volcanic bombs. The metadacite flows produced a more massive, poorly foliated rock that has been altered from an actinolite schist below the supergene alteration zone to chlorite-clay-sericite. Surrounding and on the flanks of the metadacite are chlorite schists that are well foliated consisting of chlorite-clay-sericite. These chlorite schists are either fine-grained, chilled borders of flows, or dacite tuffs.

Contacts between rock units in the pit are generally sharp in contrast to that reported previously from examination of core samples (May, 1977b). The metadacite unit forms a major rock unit in the north wall from sections 401 to 420 in contrast to minor flows found in the south wall.

Andalusite-Biotite Schist. Partially enclosing the metadacite is another distinctive unit known as the andalusite-biotite schist. This unit extends along the entire north side of the orebody, as does the quartz eye schist. The andalusite-biotite schist contains up to 10 to 15% laths of andalusite, some of which exceed 2 inches in length. Andalusite is scattered irregularly throughout the rock and is best displayed on foliation planes. Coarse biotite occurs as distinctively cross-cutting porphyroblasts; however, it also occurs within foliation-bounded "beds" and is more common than andalusite. The andalusite-biotite porphyroblasts range in length from 0.2 mm to 3 mm and from 5 to 25% in volume. Whereas the quartz eye schist and metadacite contain 1 to 2% pyrite, the andalusite-biotite schist contains 2 to 15% pyrite. Andalusite and biotite porphyroblasts decrease in volume eastward in the open pit, with a corresponding increase in chlorite and sericite.

The andalusite-biotite schist is in contact with the northern boundary of the ore horizon and occupies the stratigraphic footwall position. In many other volcanogenic massive sulfide deposits, the stratigraphic footwall contains the stringer or feeder zone. However, no strong evidence for the presence of a discrete feeder zone or alteration pipe in these rocks has yet been identified at Flambeau. What is observed in the andalusite-biotite schist is a gradual southward increase up the footwall stratigraphic column of sericite, sulfide and chert mineralization over a stratigraphic thickness of 100 feet towards the orebody. Fragments, less than 1 inch thick, of both chert and quartz-sericite with pyrite and/or chalcopyrite increase toward the ore horizon. The quartz-sericite and chert fragments are better mineralized than the matrix, containing 5 to 7% pyrite with less than 2% chalcopyrite. The contact between the quartz-sericite and other rocks of the ore horizon is, therefore, gradational over 5 to 15 feet and difficult to identify in the pit. Geochemically, the ore horizon is readily identifiable due to the sharp increase in gold values (Table 3).

Two beds of sericite-clay and spessartite garnet occur in the footwall north of the orebody, identified as a 5 to 15-foot wide fissile sericite-clay bed that was probably a felsic tuff. One of these sericite-clay beds has been used recently as a marker horizon. Alteration has totally destroyed original mineralogy leaving a greasy mixture of highly foliated sericite-clay. This bed can be traced from the west wall to the east end of the pit where it is covered by the main haulage ramp.

**TABLE 3**  
**BUILD-UP IN GOLD VALUES IN HOLE 13, TOWARDS ORE HORIZON**  
**FLAMBEAU MINE, RUSK COUNTY, WISCONSIN**

	Geology	Footage (ft)	Copper (%Cu)	Gold (opt Au)	
Hangingwall	Andalusite --	215-220	0.189	Trace	
	Biotite Schist	220-225	0.226	0.005	
Ore Horizon	Quartz-Sericite	225-230	0.531	0.050	
	Schist	230-232	1.544	0.080	
	Massive Sulfides		232-237	11.154	0.030
			237-242	6.286	0.090
			242-247	11.762	0.210
		247-252	11.559	0.120	

A second marker bed consisting of spessartite-chlorite has been recognized in the footwall on the east end of the orebody in core samples taken beneath the pit. Metadacite flows have interrupted this bed to the west. The unit is recognized at depth by the presence of 20 to 25% chlorite and 2% light-orange to pink dodecahedral spessartite porphyroblasts. This unit has not yet been recognized in the pit.

#### ORE HORIZON

Quartz-Sericite Schist. The quartz-sericite schist of the ore horizon is interpreted to have originally been a rhyolite tuff based upon thin section studies. Interbedded within the tuff and in close association are metacherts and massive sulfide mineralization. Metacherts are interbedded with, and flank much of the enriched ore, with the thicker silica-rich beds in the stratigraphic footwall on the north side of the deposit.

The quartz-sericite schist has been explored and traced a strike length that exceeds 12,000 feet. True thickness varies from approximately 20 feet to as much as 180 feet. The average thickness is 105 feet, where it hosts the orebody. Along strike away from the orebody, the well foliated unit is recognized by an increase in sericite and pyrite but less quartz and chalcopyrite. The unit was traceable geophysically by using induced polarization (IP) which responded positively to the horizon's 5 to 15% pyrite content. Along strike, away from the massive sulfides, are also narrow zones containing cherty fragments with up to 1 or 2% chalcopyrite and/or sphalerite.

In the pit, the quartz-sericite schist is a light gray, very well foliated rock containing up to 60% quartz, up to 50% sericite, and averages 15% pyrite. There are minor amounts of chlorite, andalusite, and biotite present, particularly towards the outer edges of the unit or along strike, where a greater proportion of mafic tuff and volcanic debris appears to have been deposited.

Lapilli Tuffs. Lapilli tuffs on the stratigraphic hangingwall side of the orebody are intercalated with tuffs and exhalative deposits of the ore horizon. In general, the lensoidal-shaped felsic fragments make up from 5 to 10% of the unit although certain beds consist predominately of fragments. The ore horizon is, nevertheless, dominated by sediments and sulfides deposited under quiescent conditions with occasional outbursts of high energy as evidenced by internal lapilli units. The size of the siliceous fragments are generally less than one inch with an occasional fragment to 2 or 3 inches. Most fragments consist of sugary-textured quartz with varying amounts of sericite,

pyrite, and chalcopyrite that have been enriched to chalcocite and/or bornite. Metachert fragments up to 3 to 4 inches long and one-half inch thick have been observed in the ore horizon.

**Fine Grained Tuff.** A well-bedded, light milky tan colored siltstone or very fine grained water-lain tuff occurs at the stratigraphic top of the ore horizon. Sulfide mineralization which averages 15% in the quartz-sericite schist decreases to 2 to 4% in this horizon. An occasional fine-grained, highly elongated sulfide fragment has been noted.

Near the hangingwall of the quartz-sericite schist, and the argillized sericite schists on the east end, are erratic gold-mineralized zones. These gold-rich zones occur within fine grained massive to semimassive pyrite zones and are associated with porcelaneous-type clays. Arsenopyrite and minor galena is preferentially found in this area of the ore horizon and in the footwall or north side of the fine grained tuff. The fine grained tuff has been included within the ore horizon since this unit generally represents a water-lain sequence of materials in a quiescent depositional environment, and contains greater compositional and genetic affinities to the other units of the ore horizon than with the hangingwall rocks south of the ore horizon.

A pronounced change occurs in rock deposition stratigraphically above the fine grained tuff with the return of volcanoclastic materials similar to those in the footwall rock.

### STRATIGRAPHIC HANGINGWALL

The geology of the hangingwall is less well known since core holes and the Flambeau pit extend for only a short distance into these poorly mineralized rocks; still, a pronounced lithologic change is evident. In general, the rock units are thinner and consist of interbedded chlorite-phyllites, quartz eye schist, metadacite and biotite-feldspar schist. These lithologies represent deposition of intermediate to mafic volcanoclastic and flow rock. Further to the south, away from the deposit, the hangingwall becomes mostly quartz eye schist.

One of the deep exploration drill holes intersected a foliated mafic rock with repetitive narrow one to 2 inch zones of chlorite-epidote. These were inferred to be pillow lava structures in a mafic "dacitic" rock. Excellent pillows have, subsequently, been mapped in the hangingwall at the east end of the open pit.

### STRUCTURE

The Flambeau orebody has been interpreted to occur on the limb of a large isoclinal fold which is indicated by the fact that cleavage is parallel to the bedding. Slickensides have been noted on foliation planes indicating dynamic metamorphism during the Penokean Orogeny. The chief rock fabric is the N45°E striking foliation that dips 69° to 76° to the northwest, parallel to lithologic units.

Cross-cutting faults have been noted in the massive sulfides but cannot be traced with any degree of certainty into the host volcanoclastic rocks. Numerous, small cross-cutting displacements, with 2 to 5 foot offsets, in the footwall chert and massive sulfides on the north contact of the orebody have been disclosed by pit mapping. These displacements could represent minor graben and horst development in the original ocean floor. The presence of these fault blocks indicates to the authors that the Flambeau orebody has not been highly folded and sheared as suggested by some geologists. These structures are shown on Figure 5.



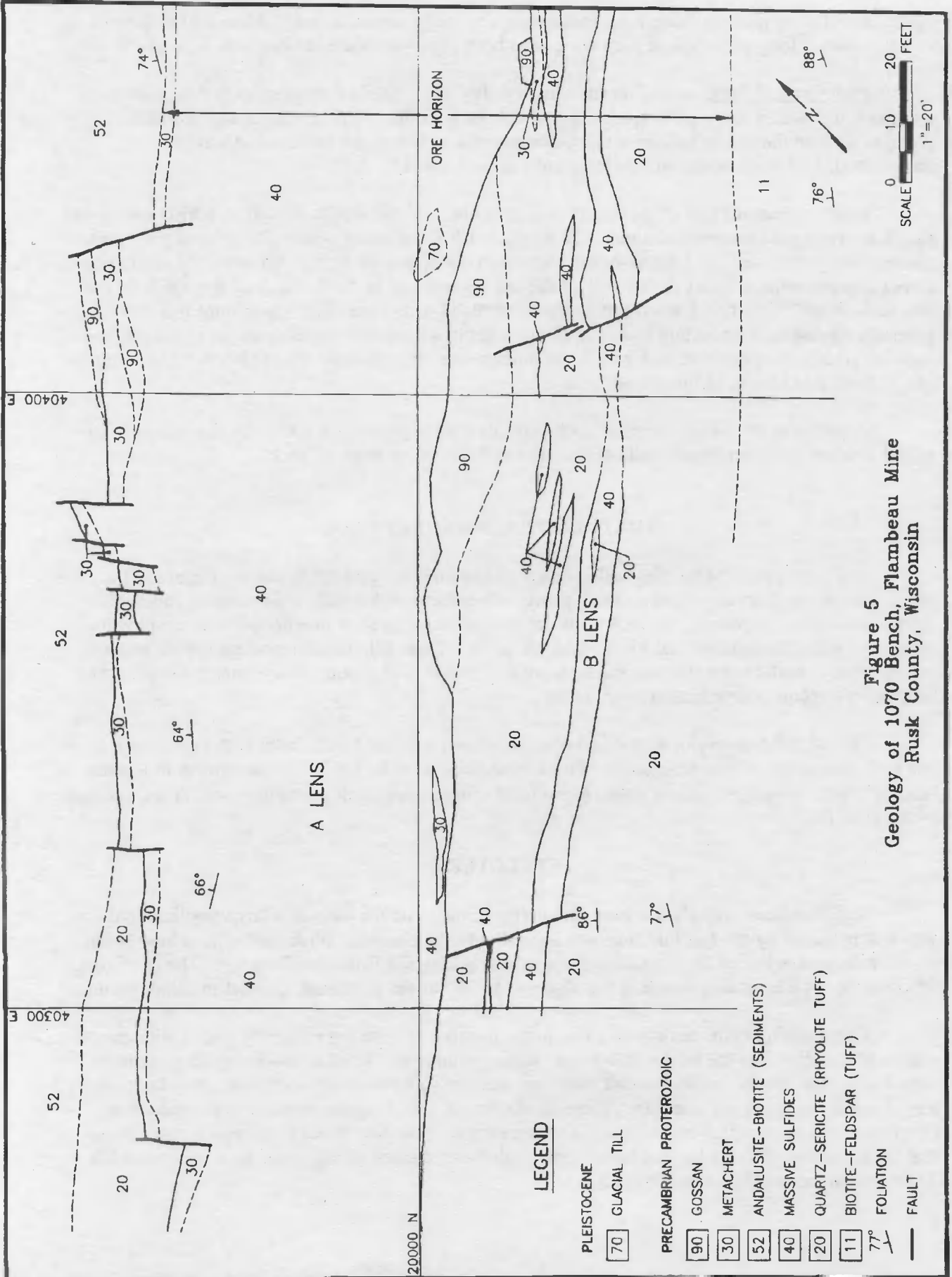


Figure 5  
Geology of 1070 Bench, Flambeau Mine  
Rusk County, Wisconsin

The largest recognized cross-cutting fault occurs near mine Section 408 where the east side of the stratigraphic footwall of the orebody has been offset 30 feet to the south. The fault strikes N85°W, and dips 65° to 85° NE. This right lateral offset relationship holds true along the strike length of the orebody where other smaller offsets have been mapped. Although these cross-cutting structures appear to be a part of the northwest fabric identified by Sims and others (1989) for the Precambrian in northern Wisconsin, none of the northwest faults at Flambeau can be traced southward into the hangingwall. Cross-cutting faults can be traced for short distances of less than 50 feet north into the footwall where they rapidly deteriorate into weak joint surfaces. It is therefore suggested that these faults are penecontemporaneous with the mineralizing events and not more deep-seated structures associated with the later Penokean Orogeny.

The east end of the orebody may have been subjected to post-ore faulting, with the end of the orebody rotated clockwise to the south. There is evidence of a fault offset at the very east end of the orebody with the east side dropped down an unknown distance. Deep drilling into the down-dropped block gave negative results.

The rock in the Flambeau open pit is intensely fractured by several series of joint sets. There are two predominant flat joint sets, one striking approximately N65°W and dipping 15° to 25°N, the second striking N75°W and dipping 30° to 40°N. There are also three principal groups of high angle joints striking: 1) N40°E dipping 65° to 85°S; 2) N85°W, dipping 65° to 85°N; and 3) N70°E dipping 65° to 85°N.

## ALTERATION

The Flambeau orebody has been subjected to intense alteration associated with primary sulfide mineralization, regional metamorphism during the Penokean Orogeny, and by significant near-surface supergene alteration of the silicate rocks leading to enrichment of the massive sulfides. The combined effect of these three processes is that original mineralogy is obscured and in some cases totally changed.

No systematic study of the alteration zones has been undertaken; therefore, the account given here is preliminary. Mineralogy of the rocks stratigraphically below the ore zone suggest a complex history of hydrothermal alteration. Abundant andalusite in the footwall rocks indicates that the primary volcanic rocks have been significantly enriched in alumina. This may have been accomplished by hydrothermal leaching by acidic fluids which removed K, Na, and Ca from the felsic and intermediate volcanic rocks (Table 2). FeO and Mg were added with iron-rich chlorite probably accounting for most of these increases. The altered rocks were presumably rich in kaolinite, which was prograded to andalusite during regional metamorphism to upper greenschist facies. The decrease in andalusite at the east end of the orebody suggests less hydrothermal alteration of the primary volcanic rocks.

This hydrothermal alteration was presumably associated with massive sulfide deposition. It must be emphasized, however, that no well-defined alteration "pipe" or stringer ore found in other massive sulfide deposits has been identified in rocks associated with the Flambeau orebody.

The two beds of spessartite-chlorite in the stratigraphic footwall indicate significant manganese enrichment in those horizons. Origin of the manganese-rich horizons is problematical. They may be the result of seawater-sediment interaction, and may not be related to hydrothermal alteration associated with the massive sulfide deposition.

Regional metamorphism produced an upper greenschist or lower amphibolite facies suite of minerals with predominately biotite, andalusite and some cordierite.

Supergene alteration, while low temperature and low pressure, profoundly altered the first two mineralogical events. The alteration effects on the sulfide mineralogy will be discussed further in the subsection entitled Supergene Enrichment. Supergene alteration produced acidic conditions that totally bleached the host rocks for a horizontal distance of 100 feet into the footwall and 50 feet horizontally south into the hangingwall volcanoclastics. The ferromagnesian minerals have been almost completely altered to clay (montmorillonite) and sericite or chlorite-sericite further away from the orebody. As described further under the subsection entitled "Gossan," large volumes of supergene activated silica were mobilized and recemented to form a hard, dense silica breccia.

On the margins of the highly bleached zone is the leached and oxidized zone where the chloritized ferromagnesian minerals plus small amount of sulfides (1 to 2%) have been oxidized.

Overlying the bleached and weathered leached zones is a thick saprolite layer. This layer varies from about 5 feet to over 30 feet of intensely clay-altered volcanoclastic rock. X-ray diffraction has identified the chief minerals to be montmorillonite, micron-sized silica and in some areas pyrite.

### OREBODY SHAPE

In general, the Flambeau orebody is a steeply dipping, near tabular massive sulfide lens. It averages 45 to 50 feet in thickness reaching a maximum thickness of about 70 feet on section 407. The strike length is 2,400 feet and is parallel to foliation. The orebody subcrops at the 1100-foot elevation and bifurcates below the 1070-foot elevation, suggesting it is actually the roots of a much larger and eroded mineral system. The main part of the orebody is referred to as the "A" lens.

The "B" lens, located south of the "A" lens, averages 10 feet in thickness. It is joined to the "A" lens at section 406 and diverges south/westward into the hangingwall, so that on section 400 it is about 100 feet south of the "A" lens.

The "C" mineralized horizon occurs 50 feet north of the "A" lens in the footwall and probably represents an early mineralizing event in an emerging mineral-rich system. The "C" horizon is less than 10 feet thick discontinuous, deficient in gold values, and poorly mineralized with chalcopyrite. Contrary to previous reports (May, 1977) the hangingwall and footwall contacts are sharp and clearly defined where seen in the open pit.

### MINERALOGY

The supergene mineralogy, paragenesis, and crystallography probably ranks Flambeau as unique among massive sulfide deposits in the Canadian Shield. Although other enriched massive sulfides have been found in the Shield, none have been as well preserved, with an extensively supergene enriched copper zone capped by a gold-enriched gossan.

### PRIMARY MINERALIZATION

Primary mineralization occurs 130 to 185 feet below the subcrop and supergene enriched 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

sulfide mineralization. Based on drill-core observations, the author has defined massive sulfide to contain greater than 50 weight percent sulfides, semimassive to contain between 20 and 50 weight percent sulfides, and disseminated to contain less than 20 weight percent sulfides. Although the above definitions may conflict with previous work on other deposits, they best suit conditions found in the Flambeau deposit.

Massive sulfide dominates the upper part of the steeply dipping and overturned deposit to 600 feet beneath the subcrop. However, the east central portion of the sulfide deposit contains semimassive mineralization. Semimassive mineralization increases with depth from a strike length of 500 feet in subcrop to 2,400 feet at 600 feet beneath the surface. A disseminated sulfide halo which averages 215 feet in width and contains 7% pyrite encloses the massive-semimassive mineralization. The halo extends along strike for at least 5000 feet 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 mineral zoning across the deposit. The stratigraphic footwall or northern part of the ore zone tends to be chalcopyrite-rich with sphalerite noticeably more abundant toward the hangingwall. Most of the hangingwall satellitic lenses are sphalerite-rich. Based on stratigraphic-mineral zoning work conducted in the Noranda District (Gilmour, 1965), where copper favors the stratigraphic footwall, it is believed that the Flambeau deposit is overturned.

The semimassive sulfide mineralization is weakly zoned with pyrite the dominant sulfide. It 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 50mm in diameter. It also occurs as interstitial fillings around the 1mm to 3mm pyrite grains. Small amounts of sphalerite (less than 1%) are scattered throughout the zone as grains, as narrow bands up to 6mm in width, and as occasional irregular clots less than 7mm in diameter.

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

## GOSSAN

A total of 115,000 tons of gossan with an average grade of 0.6 opt Au have been mined from the top of the massive sulfide orebody. Three types of gossan have been recognized during core examination and mining, which, in general, grade from chert gossan in the west end of the pit, to argillic gossan, then to ankeritic gossan in the far east end.

Chert Gossan. Chert gossan was dominant in the west half of the open pit and has been further sub-divided into the cherty breccia, the purple-red, and the sandy gossan (Figure 6).

A cherty breccia zone overlaid a purple-red gossan from Section 401 to 413. A sandy gossan occurred on the hangingwall between Sections 404 and 408. All three zones consisted of subrounded to angular cherty and possibly secondary quartz fragments. Iron oxide coated the silica-rich particles and fragments in varying amounts. Fine-grained gold was present in all three zones. Hematite was the chief iron oxide followed by goethite with lesser amounts of jarosite.

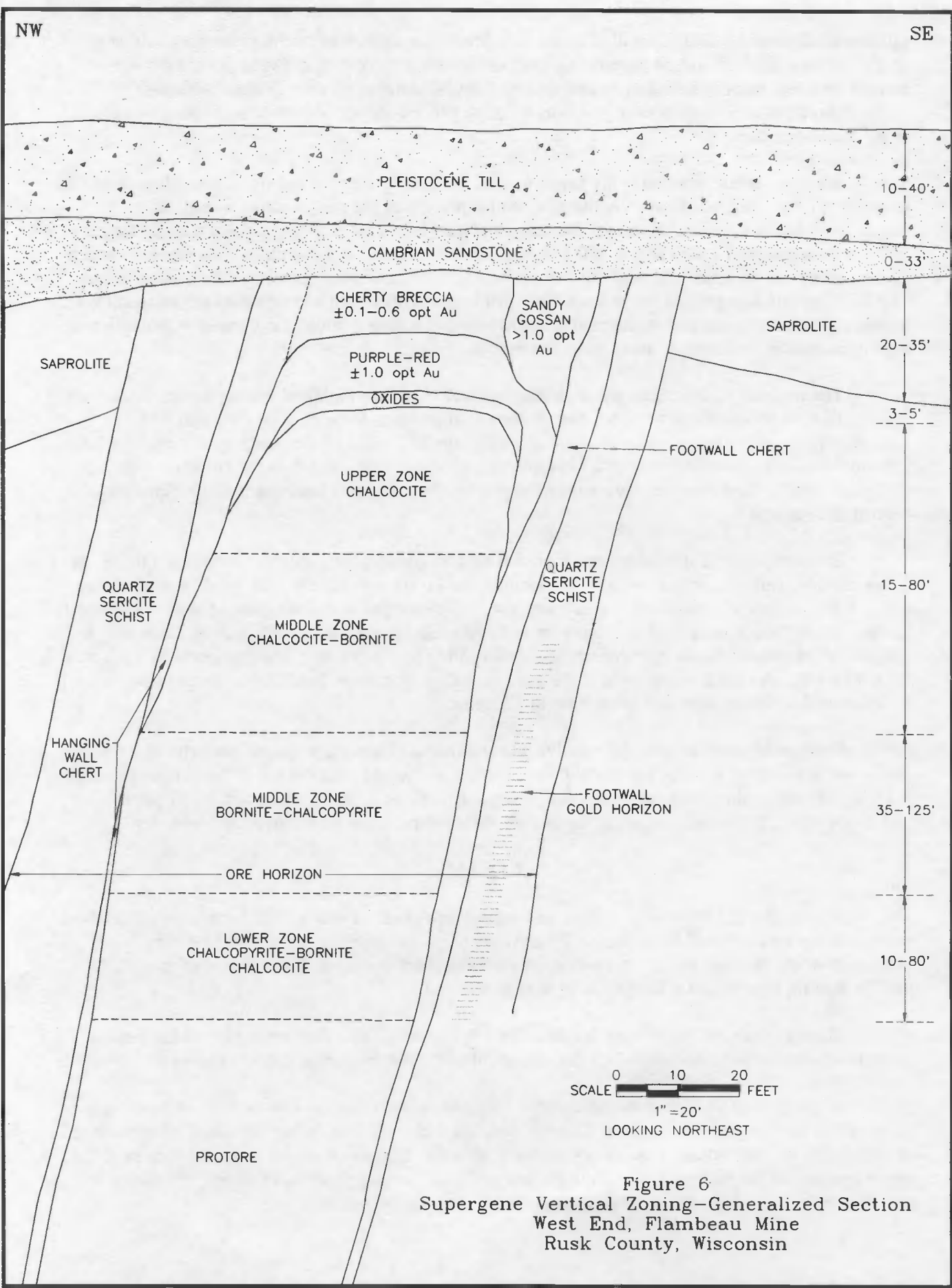


Figure 6  
Supergene Vertical Zoning—Generalized Section  
West End, Flambeau Mine  
Rusk County, Wisconsin

- i) **Cherty Breccia.** The cherty breccia or silica-rich gossan was not a true breccia, although it did contain abundant fragments of partially decomposed chert. The stratigraphic footwall chert on the north side in many places collapsed on top of this zone during volume reduction as the massive sulfides were being oxidized. These collapsed chert fragments (<2 inches) and blocks (<2 feet) capped much of the gossan. A gradual disintegration occurred from the footwall massive, hard chert towards the hangingwall where the chert became sandy in texture. A large amount of secondary silica has remained high up in the gossan, which could have been derived by solution of small amounts of cherty inclusions found around sulfide grains in the protore. Botryoidal and stalagmitic silica has been observed in the west wall gossan. The cherty breccia must have been in constant flux as the underlying massive sulfides were being leached, enriched, and then oxidized with the gossan collapsing on top. Eventually a stage of semi-equilibrium was reached where the cherty breccia was recemented into a hard, dense, light gray, poorly to nonfoliated silica-rich rock. This rock consisted of 2 mm to silt-size subrounded to angular quartz particles. Very small amounts of iron oxide, and traces of native copper, and gold make up the remainder of the rock. Quartz content ranges from 88 to 96 volume % of the rock. The cherty breccia thickness ranges from 6 to 12 feet and has a sharp contact with the underlying purple-red gossan.
- ii) **Purple-Red.** The purple-red gossan was named because of its distinct coloration resulting from a high hematite content. This zone was unconsolidated, subrounded to angular quartz grains in a matrix of hematite, goethite, and jarosite. Hematite occurs as botryoidal coatings up to 1 cm in diameter or as earthy masses. Small amounts of kaolinite have been noted. The purple-red zone ranges in thickness from 6 to 12 feet.
- iii) **Sandy-Gossan.** A sandy gossan zone formed in the stratigraphic hangingwall adjacent to the cherty breccia and purple-red zones over a thickness of 20 feet and a strike length of about 500 feet. Contacts with the adjacent two zones was gradational over a foot or two, and less gradational with the hanging wall volcanoclastics to the south. This zone had a distinct salmon pink to purple-red color, was unconsolidated and consisted of fine-grained, subrounded quartz grains with varying amounts of iron oxide and less clay particles. It was a well-sorted, iron stained quartz sand with high gold content. Fragments and blocks of sandstone several inches to a foot in size were noted as deep as 13 feet into the sandy gossan. These blocks have been tentatively identified as Late Precambrian sandstone incorporated within a water reworked section of the gossan. Gold content was in places at least two to four times higher than that in the purple-red zone.

Gold in all three zones of the chert gossan occurred as less than 20 micron-sized grains with only small amounts of silver. Silver in the gossan does not occur as electrum. In the cherty breccia zone, gold contained 2 to 4% silver, whereas gold in the purple-red contained less than 0.5% silver. The purple-red zone however, generally hosted about three to four times more gold than the overlying cherty breccia.

**Argillic Gossan.** The argillic zone formed over the orebody from Section 413 to 418. Petrographic examination of this zone has shown it to be dominated by quartz with smaller amounts of hematite, goethite, jarosite, chlorite, montmorillonite, illite, rutile, chalcopyrite, and the alunitejarosite family of minerals. This gossan was yellow-brown in color, highly foliated, broken, and contained a moderately developed zone of purple-red gossan along the base. The purple-red gossan corresponded well to underlying internal massive sulfide zones within a predominantly semimassive portion of the orebody. Free-silica values were significantly lower in both the argillic

and ankeritic gossans than in the chert gossan. The argillic gossan was about 40 feet wide and 15-20 feet thick.

**Ankeritic Gossan.** Gossan in the east end was characterized by a high ankerite and very low silica content. At least 35 vertical feet of ankerite gossan have been mined with small zones going to greater depths along contacts or strong joints. This zone was a dark purple-brown poorly to well cemented, massive textured gossan. Ankerite was well developed with cleavage planes and crystal faces up to 0.5 inch developed. It also contained quartz grains with hematite, iron oxides, native gold and lesser amounts of chalcopyrite. Silver values, in the immediate underlying enriched copper zone, are up to ten times higher than in the rest of the orebody. The reason for this phenomenon is still uncertain, but is suspected to be linked to the ankerite mineralization.

### OXIDE ZONE

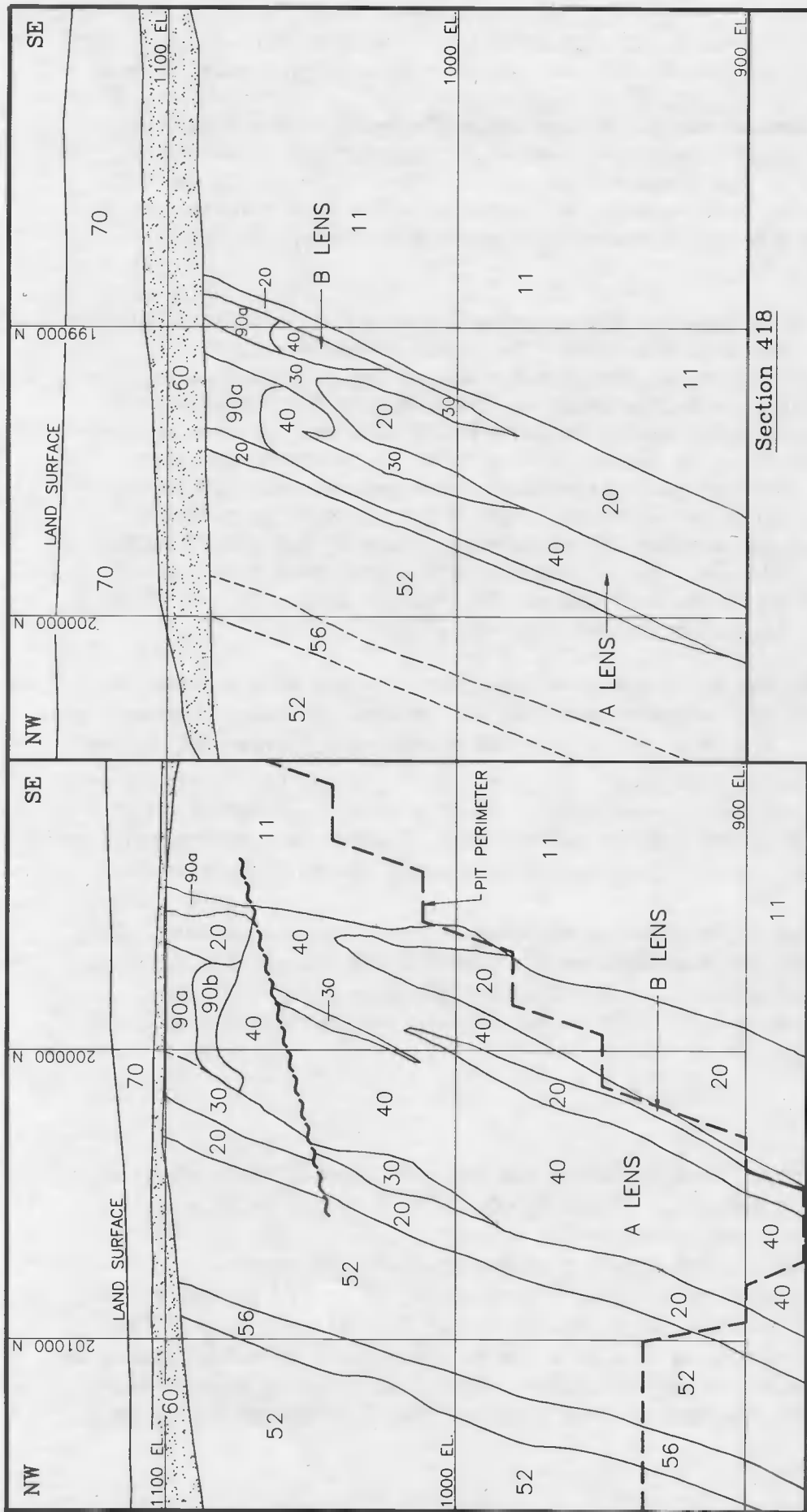
An oxide zone was present beneath much of the gossan and had a thickness of two to five feet. This zone consisted of cuprite, goethite, and malachite, with lesser amounts of azurite, chalcopyrite, and native silver. The oxide zone contained up to 20% copper oxides. Malachite occurs as earthy coatings or occasionally as botryoidal fillings. Azurite occurred as earthy fillings and occasional small crystals. Copper oxides have been found on faults and fractures 60 feet or deeper below the subcrop. At the top of the oxide zone, horizontal manganese "pipes" up to two to three inches in diameter were observed. These tubes, now filled with sand, appear to have once transported large volumes of groundwater along the top of the enriched massive sulfide orebody.

The gossan and oxide zones wrap around the sides of the sulfide orebody. The oxide zone descended about five to ten feet, whereas the gossan zone with minor azurite and malachite draped 20 to 30 feet down the flanks of the orebody in more porous areas. The top of the black supergene enriched sulfides below the gossan and oxide zones was remarkably smooth, and sloped gently at the edges towards the enclosing volcanic host rocks. Vertical relief rarely exceeded two to four feet with slope angles of one to two degrees.

### SUPERGENE ENRICHMENT

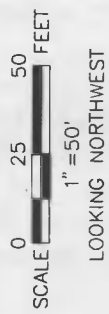
Supergene enrichment affected the primary massive, semimassive, and disseminated sulfide halo zones. The extent and degree of enrichment depended upon original base metal mineralogy, rock permeability, foliation planes, structure, and a fluctuating groundwater table. The well developed schistosity planes in the weakly mineralized volcanoclastic host rock directed mineral-rich, acidic waters to depth. Medium grained, subhedral to granular, and weakly foliated massive sulfides had a higher permeability than the clay-rich host rock permitting the supergene enrichment processes to extend to greater depths. The west end of the orebody has been enriched locally to 185 feet below the subcrop, and the east end to 140 feet, as shown on Figure 7. Enrichment has been restricted to 80 to 100 feet below the subcrop in the central part of the deposit. Enrichment in the volcanoclastic host rock was generally several tens of feet shallower and of much lower grade due to its lower permeability. The more felsic and extensively pyritized stratigraphic footwall volcanoclastic rock have been preferentially enriched relative to the more basic, less pyritic, and chlorite-rich hangingwall rocks south of the orebody.

Individual grains of primary sulfides in the disseminated sulfide halo have been partially or completely replaced with chalcocite and/or bornite. These secondary minerals form solid replacement minerals, microrimings on the protore surfaces, or as sooty coatings. Sphalerite and galena were preferentially replaced relative to chalcopyrite and even less reactive pyrite. Consequentially, zinc



Section 406

Section 418



LEGEND

- |                         |                                          |          |                         |
|-------------------------|------------------------------------------|----------|-------------------------|
| PLEISTOCENE             |                                          | CAMBRIAN |                         |
| 70                      | GLACIAL TILL                             | 60       | MOUNT SIMON SANDSTONE   |
| PRECAMBRIAN PROTEROZOIC |                                          |          |                         |
| 30                      | MEGACHERT                                | 40       | MASSIVE SULFIDES        |
| 90a                     | CHERTY GOSSAN                            | 20       | QUARTZ-SERICITE SCHIST  |
| 90b                     | PURPLE-RED GOSSAN                        | 11       | BIOTITE-FELDSPAR SCHIST |
| 52-56                   | ANDALUSITE-BIOTITE SCHIST, SERICITE-CLAY |          |                         |

Figure 7  
Geological Cross Section 406 & 418, Flambeau Mine  
Rusk County, Wisconsin



values are generally less than 0.05% and lead is rarely detectable in the enriched ore. It is suspected that some of the high grade sooty chalcocite zones were formed in areas of high primary sphalerite.

The supergene enriched mineralization is zoned vertically. The Upper zone is chalcocite dominant, the Middle zone is bornite-chalcocite dominated, and the Lower zone is a mixture of chalcopyrite-bornite-chalcocite. The formation of these zones is determined by original base metal content, fracturing, and faulting that directed supergene enriched fluids to depth within the orebody. Some of the structural features that helped determine this pattern of enrichment are shown on Figure 8.

Supergene sulfides in the Upper and Middle zones were developed at the expense of all of the primary base metal minerals and much of the pyrite. The contact between the two zones is gradational. Chalcocite occurs as irregular steely masses, microrimings, sooty films, sandy zones and fracture fillings. Some of the best copper grades were found in sandy-chalcocite areas located close to and parallel with the orebody contacts. The Upper and Middle zones of the west end of the deposit are of approximate equal vertical thickness of about 75 feet. In the Middle zone, bornite occurs as massive replacements or as numerous reticulating veinlets replacing chalcopyrite. As this replacement became more complete the veinlets coalesced to form irregular bornite masses and "veins". The replacement process continued with bornite being replaced by chalcocite. At each successive enrichment stage, additional pyrite was consumed so that at the end of the replacement process significant amounts of pyrite had been replaced. The supergene paragenesis, described in the next subsection, is based on relationships observed in the supergene enriched zone.

Botryoidal secondary chalcopyrite is common in the Lower zone as well as in the Middle zone. Chalcopyrite botryoids have been observed ranging from less than a millimeter in thickness to over five millimeters. Most of the thicker botryoids show fluctuating deposition with bornite. Micron-size tetragonal chalcopyrite crystals have been frequently noted, particularly on bornite. Bornite has not shown any crystal habits. On the other hand, chalcocite occurs in a variety of spectacular crystals both twinned and untwinned. These crystals are generally coated by blue to purple iridescent or gold colored chalcopyrite and more rarely bornite.

To form an enriched orebody the size of Flambeau would require weathering, taking mineralization into solution, and reprecipitation of a deposit on the order of 6 to 10 million tons. Therefore, the enrichment must predate deposition of the overlying Cambrian sandstone, because the volume of rock between the sandstone and the enriched zone could not have produced the enriched ore present.

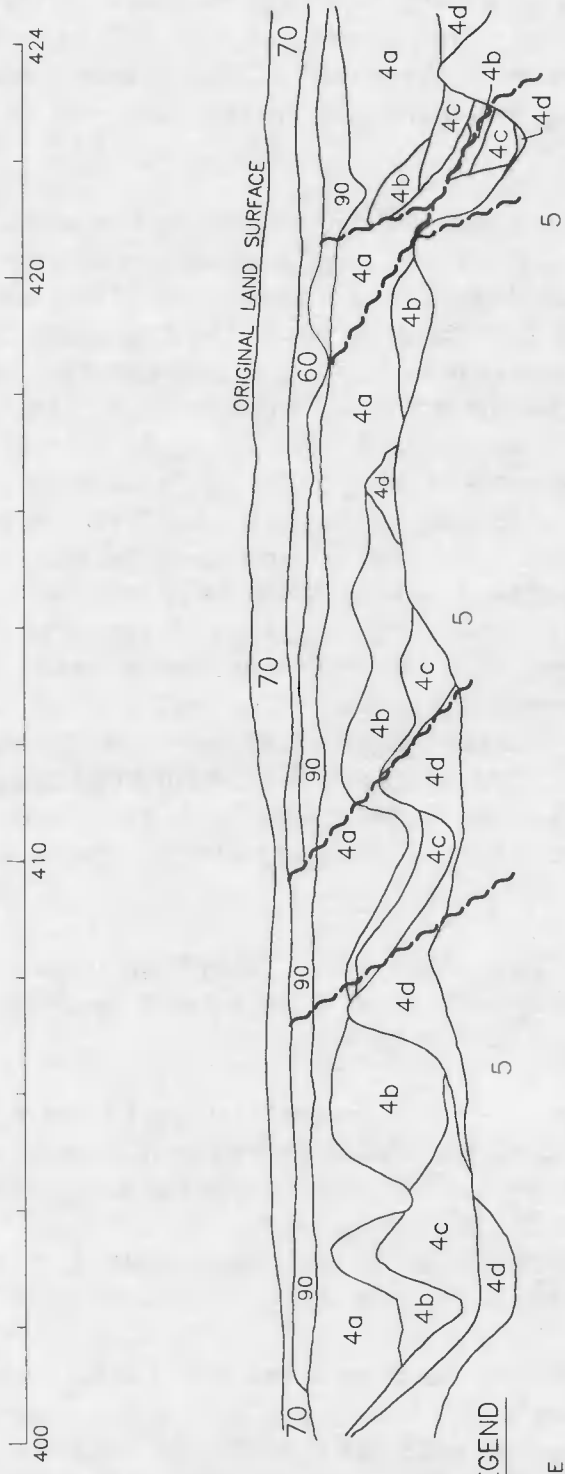
## PARAGENESIS

The paragenesis of the Flambeau orebody has been subdivided into three stages as shown on Figure 9. These stages are: 1) primary deposition of the host rocks and mineralization, 2) regional metamorphism, and 3) secondary enrichment and weathering. Stage 1 consists of three main stages of base metal and silica deposition commencing with the early "C" horizon. The second stage resulted in the formation of the "A" horizon with at three exhalative silica pulses. Pulse one formed the thicker footwall chert, pulse two was ongoing weak intermittent deposition of silica within the orebody, and pulse three formed the hangingwall chert south of the orebody. Base metal mineralization during stage two is dominated by copper with a few areas of zinc. The third stage is dominated by zinc, gold,

NE

SW

MINE SECTION



LEGEND

PLEISTOCENE

70 GLACIAL TILL

CAMBRIAN

60 MOUNT SIMON SANDSTONE

PRECAMBRIAN PROTEROZOIC

90 GOSSAN

4a CHALCOCITE-DOMINANT, UPPER ZONE

4b CHALCOCITE-BORNITE, MIDDLE ZONE

4c BORNITE-CHALCOCITE, MIDDLE ZONE

4d BORNITE-CHALCOCITE CHALCOCITE, LOWER ZONE

5 PRIMARY SULFIDES

~ INTERPRETED FAULTS

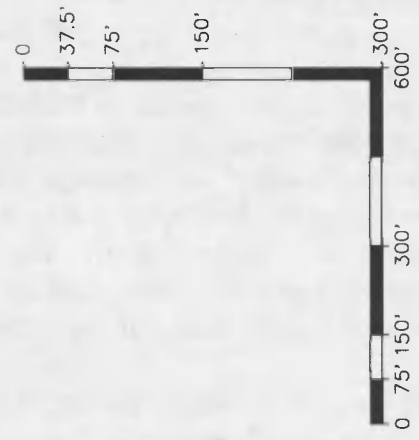


Figure 8  
 Longitudinal Section of  
 Supergene Mineralogical Zoning, Flambeau Mine  
 Rusk County, Wisconsin

LOOKING NORTHWEST

and decreasing amounts of copper extending out into the hangingwall (i.e., the "B" lens), giving a zoning profile of copper changing to zinc upward in the original stratigraphy.

Regional metamorphism is characterized by the formation of upper greenschist to lower amphibolite facies minerals. Diagnostic minerals are andalusite, spessertite garnet and biotite. Quartz "sweats" are common with many showing boudinage structures. Schistose textures and foliation developed during this stage. Chalcopyrite, and other sulfides, were remobilized to form coalescing irregular blebs, while pyrite recrystallized to form medium grained subhedral grains. These sulfides along with minor gold are associated with localized quartz "sweats" on the flanks of the orebody.

The enrichment stage resulted in the formation of a suite of secondary minerals, probably during late Precambrian time. Simplistically this stage produced significantly enriched copper values in the upper part on the deposit through the removal of iron and reprecipitation of copper from higher levels in the weathering zone. The enrichment shows the classic mineral zonation, with the conversion of primary pyrite to secondary chalcopyrite in deeper levels of the deposit, overlain by a bornite-rich zone, developed by enrichment of the chalcopyrite. Chalcopyrite is commonly found in three forms: botryoidal, rosettes of platy chalcopyrite; and shiny brassy platy open-fracture fillings. Finally, chalcocite developed by removal of iron from the bornite, probably at the paleo-water table. Native copper, cuprite, azurite and malachite developed in the oxidized zone above the paleo-water table. However, this simple pattern was complicated by local variations in porosity, permeability and mineralogy in the ore. For example, irregular masses of primary pyrite and chalcopyrite are found within the secondary chalcocite. Possible fault zones allowed oxidation and enrichment to extend much deeper in the orebody. The result is a very irregular mixture of minerals within the ore. The mineralogy is also complicated by major changes in the level of the water table that occurred subsequent to the main enrichment. The present water table is much closer to the surface than the paleo-water table during supergene enrichment, as shown by the presence of secondary oxide minerals below the present water table.

In addition to massive material, much chalcocite occurs as "sooty" and granular, or sandy-textured material that may have formed by replacement of the granular pyrite produced by metamorphism or by replacement of massive beds of sphalerite.

Enrichment also produced numerous cavities within the ore, in which late-stage minerals developed. Some cavities contain well-formed chalcocite crystals in a variety of crystal forms to nearly three inches long. These chalcocite crystals typically have a blue, purple, or brassy yellow patina produced by a thin surface coating of bornite and/or chalcopyrite. The surface coating probably formed when the rising water table placed the chalcocite crystals in the stability field of bornite and chalcopyrite.

Chalcocite crystals occur as psuedohexagonal plates up to two inches in diameter, stacked psuedohexagonal columns or barrels up to 0.75 inch long by 0.25 inch wide, twinned orthorhombic crystals, up to 2.5 inches in length by 0.75 inch in width, and curvilinear "scimitar-like" forms up to 0.5 inch long. A picture of a twinned orthorhombic chalcocite crystal appears in this memorial volume.

EARLY		LATE
<b>PRIMARY</b> @1.76 BY	<b>METAMORPHISM</b> upper greenschist to lower amphibolite	<b>SECONDARY</b> late Pre-Cambrian -? early Cambrian
Cu-Au-Ag-Zn VMS DEPOSITED IN BACK-ARC BASINAL SETTING	DURING OROGENY, SULPHIDES RECRYSTALLIZED, LOCAL PRECIOUS METAL MOBILIZATION, QUARTZ INJECTION, LOCALIZED FOLDING, POSSIBLE EXTENSIONAL SMEARING FROM REGIONAL FOLDING	SUPERGENE ENRICHMENT OF COPPER SULPHIDES, ASSOCIATED WITH GOSSAN GENESIS ON OVER-TURNED, SUB-VERTICAL DEPOSIT D/T FLUCTUATING WATER TABLE OXIDIZING AND VERY ACIDIC

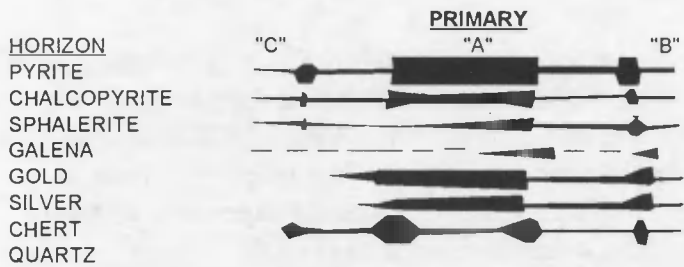
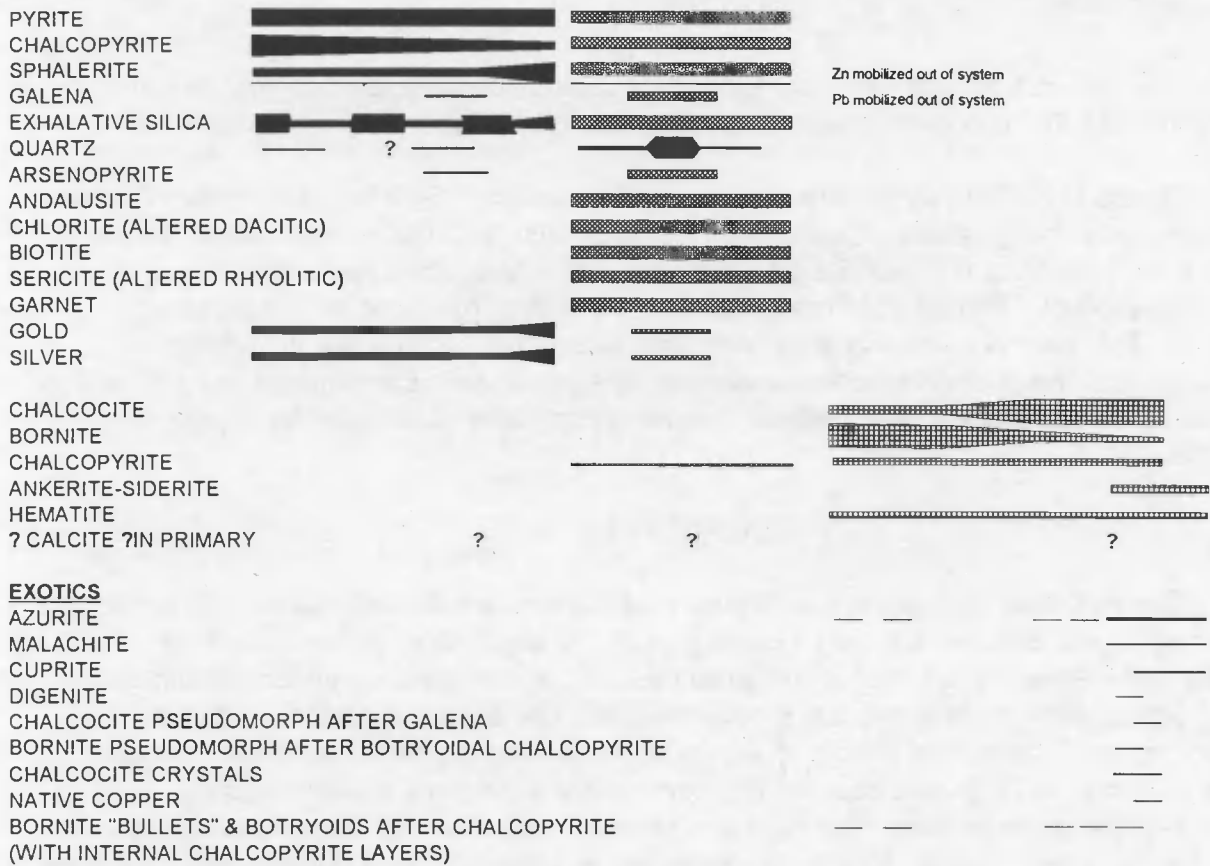


Figure 9 GENERALIZED PARAGENESIS OF THE FLAMBEAU OREBODY

Occasionally some bizarre relationships or textures occur, for example, the exquisite "scimitar-like" chalcocite crystals that occurred high up in the orebody (1070 level). In contrast, twinned orthorhombic chalcocite crystals were collected from a 3x3x10-foot vug on the 1010 level.

Other cavities contain botryoidal growths of bornite, chalcopyrite or chalcocite, or may contain encrustations of carbonate minerals (mainly ankerite, dolomite and siderite). Some carbonate crystals have tiny rosettes of chalcopyrite on which are specks of lead oxide scattered on crystal faces. Again, the chalcopyrite may have formed after the water table rose.

The gold-rich gossan evidently formed by residual concentration of gold as erosion slowly lowered the paleosurface as supergene sulfide enrichment was in progress.

Coarse crystalline pyrite with scalehedrons of arsenopyrite have been collected near the stratigraphic hangingwall. Quartz pods are associated with this mineralization, as are native gold, bornite, and chalcocite. This gold is very fine grained and is possibly a supergene product. Similar gold has been observed within, but close to, the orebody's contacts. This gold is intimately associated with quartz that contains bornite, minor chalcocite, and lesser chalcocite pseudomorphs after galena and is interpreted to be related to remobilization processes during regional metamorphism, later acted upon by supergene processes.

## CONCLUSIONS

The Flambeau orebody is a well preserved supergene enriched massive sulfide deposit capped by a gold-enriched silica-iron oxide gossan. A small, thin, poorly indurated Cambrian sandstone outlier capped the gossan and supergene enriched mineralization and helped protect them from significant glacial erosion. The dominant chalcocite-bornite enriched mineralization was formed to depths up to 185 feet below the subcrop. Copper values in excess of 20% have been mined, particularly in areas of massive steely-gray chalcocite, and zones of sooty chalcocite that probably replaced massive sphalerite. A total of 1.71 million tons grading 10.3% Cu, 0.116 opt Au, and 1.837 opt Ag will be mined from 1993 to 1997.

Three products are shipped via rail from the open pit. Gossan ore and direct smelting shipping ore greater than 14% Cu are railed to Noranda's Horne Smelter at Rouyn-Noranda, Quebec, Canada. Mill ore grading 6 to 10% Cu is railed to the Kidd Creek Mill located at Timmins, Ontario, Canada where it is concentrated then redirected to the smelter. While modest in size, the Flambeau orebody will be remembered for its classical supergene mineral zoning, high copper and gold grades, and exquisite twinned chalcocite crystals.

The importance of the pioneering environmental safeguards implemented at Flambeau match the economic contributions made by both private and public institutions (May, 1977) Successful mining of the orebody beside the Flambeau River and City of Ladysmith, while enhancing and maintaining surface and groundwater quality respectively, is in itself a milestone for the American base metal mining industry (Murphy, 1996).

### Acknowledgments

The authors wish to thank Tom Myatt, General Manager of Flambeau Mining Company, for allowing this paper to be written and for supporting and hosting the 1996 Institute on Lake Superior Geology field trip. A considerable amount of assistance was provided by Jay Hammitt, Russ Babcock, Gene LaBerge, and Ray Yost, all of whom polished the manuscripts with almost too much enthusiasm but whose insights and efforts were greatly appreciated by the authors. A special thanks to Tammy Fredrickson who repeatedly deciphered our geological scribblings and prepared the manuscript for this volume.

### References Cited

- Babcock, R., 1996, History of Exploration for Volcanogenic Massive Sulfides in Wisconsin: Institute on Lake Superior Geology, 42nd Institute, 1996 Field Trip Volume.
- DeMatties, Theodore A., 1994, Early Proterozoic Volcanogenic Massive Sulfide Deposits in Wisconsin: An Overview: *Economic Geology*, v. 89, p. 1122-1151.
- Gilmour, P., 1965, The Origin of the Massive Sulfide Mineralization in the Noranda District, Northwestern Quebec: *Geologic Association of Canada*, v. 16, p. 63-82.
- LaBerge, G. L., 1996, General Characteristics and Geologic Setting of the Wisconsin Magmatic Terranes: Institute on Lake Superior Geology, 42nd Institute, 1996 Field trip volume.
- May, E. R., 1977a, Flambeau - A Precambrian Supergene Enriched Massive Sulfide Deposit: *Geoscience Wisconsin*, v. 1, p. 1-26.
- May, E. R., 1977b, Case study of Environmental impact - Flambeau Project: *Mining Congress Journal*, v. 63, p. 39-46.
- Morey, G. B., Sims, P. K., Mudrey, M. G., and Southwick, D. L., 1982, Geologic Map of the Lake Superior region, Minnesota, Wisconsin, and northern Michigan: *Minnesota Geological Survey State Map Series S-13*.
- Murphy, J., Dachel, R., 1996, Case Study of Environmental Requirements for the Permitting Operation, and Reclamation of a Metallic Mineral Mine in Wisconsin - Flambeau Mine: Institute on Lake Superior Geology, 42nd Institute, 1996 Field Trip volume.
- Schwenk, C. G., 1977, Discovery of the Flambeau Deposit, Rusk County Wisconsin - A Geophysical Case History: *Geoscience Wisconsin*, v. 1, p. 27-42.

The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that every entry should be supported by a valid receipt or invoice. This ensures transparency and allows for easy verification of the data.

Furthermore, it is noted that the records should be kept for a minimum of seven years. This is a legal requirement in many jurisdictions and helps in the event of an audit or a dispute.

The second section focuses on the regularity of the reporting process. It suggests that reports should be generated on a monthly basis. This provides a timely overview of the company's financial health and allows for quick identification of any potential issues.

Additionally, it is recommended that the reports be presented in a clear and concise manner. Using standardized formats and consistent terminology makes it easier for stakeholders to understand the information.

The third part of the document addresses the security of the financial data. It stresses the need for robust internal controls and access restrictions. Only authorized personnel should have access to the accounting system, and all transactions should be properly authorized.

Regular backups of the data are also crucial to prevent data loss in the event of a system failure or cyber attack. Implementing these security measures helps protect the integrity and confidentiality of the financial information.

Finally, the document concludes by highlighting the role of the accounting department in providing valuable insights to management. By analyzing the financial data, the department can identify trends, forecast future performance, and recommend strategic actions to improve the company's profitability.

In summary, maintaining accurate and secure financial records is essential for the long-term success of any business. By following the guidelines outlined in this document, companies can ensure that their financial data is reliable and actionable.

**CASE STUDY OF ENVIRONMENTAL REQUIREMENTS FOR THE PERMITTING,  
OPERATION, AND RECLAMATION OF A METALLIC MINERAL MINE IN WISCONSIN -  
FLAMBEAU MINE**

by JANA E. MURPHY  
Supervisor of Environmental Affairs, Flambeau Mining Company

and

RICHARD T. DACHEL  
Environmental Chemist, Flambeau Mining Company

**INTRODUCTION**

The Flambeau Mining Company (Flambeau), a subsidiary of Kennecott Minerals Company, owns and operates an open pit copper mine located just south of Ladysmith, Wisconsin. The 181 acre mine site is bounded on the west by the Flambeau River, on the east by State Highway 27, and to the north by the City of Ladysmith. While Flambeau owns the majority of the surrounding properties as a buffer, there are private properties and homes within 100 feet of the perimeter of the mine site. The surrounding natural and anthropogenic features made the permitting of the Flambeau Mine especially unique. A representation of the unique features within and surrounding the project area are listed below:

- Flambeau River located 140 feet from west edge of pit;
- Intermittent streams requiring relocation and re-establishment;
- Wetlands requiring mitigation;
- State highway within 1000 feet of facilities;
- Private landowners within 100 feet of the perimeter of the mine site;
- The center of the City of Ladysmith is located 1.6 miles north of mine site;
- Relatively shallow groundwater table within 20 feet of surface.

**FLAMBEAU PERMITS**

Another unique aspect of Flambeau is that it is currently the only operating metallic mineral mine in the State of Wisconsin. The Flambeau Mine is also the only metallic mineral mine to receive permits under Wisconsin's current mining laws. Flambeau received its eleven permits following: 1) extensive baseline monitoring; 2) data compilation and review; 3) identification of potential environmental impacts; 4) facility design to minimize impacts; 5) submittal of permit applications and management plans; 6) Wisconsin Department of Natural Resources (WDNR) review; 7) public comment; and 8) a contested case hearing. Typically, four to five years (or longer) is required to complete the aforementioned process prior to the granting of permits allowing the operation of a mining facility.

The WDNR granted eleven permits to Flambeau during January 1991. Flambeau's permits are listed below:

- Mine Permit
- Wisconsin Pollutant Discharge Elimination System (WPDES) Permit
- Air Pollution Control Permit
- Groundwater Withdrawal Permit



- Permit for a One-Time Disposal Facility
- Water Regulatory Permits (five individual permits)
- Approval for the Wastewater Treatment Facility

In addition, numerous management plans, studies and models were submitted to the WDNR which detailed the measures to be taken to protect the environment. These management plans were incorporated by reference into Flambeau's permits.

## **STUDIES AND MODELS**

### **Waste Rock Characterization**

Several studies were performed and models developed prior to the final design of the Flambeau site facilities. One of the primary considerations was characterization of the various waste rock products. Characterization of waste rock determines: 1) the best practices for temporary stockpiling; 2) methods of water treatment prior to discharge to the Flambeau River; 3) preferred methods of backfilling the open pit; and 4) prediction of groundwater quality down gradient from the backfilled pit.

Waste rock characterization studies included both static and kinetic geochemical tests performed in a laboratory on samples which had been collected during core drilling of the orebody and surrounding waste rock. The static tests included bulk chemical analyses for all potential mine waste and acid production and neutralization tests on the waste rock composites. The kinetic tests included wet-dry leaching tests which simulated the conditions under which the waste rock would be temporarily stored. The wet-dry leaching tests were followed by saturated leaching tests which simulated conditions within the backfilled pit.

The results of the wet-dry leaching tests determined that waste rock containing less than two percent sulfur had a very low acid-producing potential. The low sulfur waste rock can be temporarily stockpiled without an underlying liner system since there is minimal potential impact to groundwater quality. Likewise, the waste rock containing high sulfur (>2%) is required to be temporarily stored on a high density polyethylene liner (HDPE) and leachate collection system since these materials have the potential to produce acidic leachate. Flambeau chose to add an additional factor of protection by restricting the waste rock placed in the unlined stockpile to that containing less than one percent sulfur. Waste rock containing less than one percent sulfur is referred to as Type I material. Type II material is that waste rock containing one percent or greater sulfur content.

### **Water Treatment Methods**

The waste characterization also determined the appropriate treatment methods for water contacting each waste rock type. Water which contacts the Type II waste rock must be treated through Flambeau's onsite Wastewater Treatment Plant (WWTP). The types of water treated are groundwater, storm water and snow melt runoff that discharge into the open pit and leachate from the Type II stockpile. The WWTP operation is discussed in detail in a following section. The Type II stockpile was anticipated to generate acidic leachate shortly after stockpiling was initiated. Following two years of stockpiling, the Type II stockpile has recently begun to generate a lower pH leachate of approximately 6 standard units (s.u.). This pH is still significantly higher than the leachate studies predicted. These studies resulted in a model predicting the leachate to have a pH of 2.95 - 4.10 s.u. Water contacting Type I wasterock requires minimal treatment. This treatment includes two settling

ponds designed to contain in excess of a 25-year storm event. Intermittent discharges from the settling ponds were anticipated during spring, summer, and fall; however, the storm water runoff has infiltrated into the open pit rather than requiring discharge.

### **Pit Backfill**

The laboratory testing of the two types of waste rock helped determine the most appropriate methods of backfilling the pit. The waste rock will be returned to the pit in the following order, bottom to top: 1) Type II waste rock; 2) Type I waste rock; 3) saprolite; 4) sandstone; 5) till; and finally 6) topsoil. Each material type is segregated as mined from the pit to allow for a sequential backfill. The saturated leaching tests indicated the potential for leachate to contain substances from the Type II waste rock. Four parameters (copper, iron, manganese and sulfate) were predicted to be found in measurable concentrations in the groundwater emanating from the Type II waste rock in the reclaimed pit. Further testing showed that the addition of lime significantly reduced the concentration of some substances within the leachate. As a result, lime will be backfilled with the Type II waste rock at the rate of 2.5 pounds lime for each ton waste rock.

The impact of these four parameters is minimal to the Flambeau River. Based upon a mean river flow of 1, 855 cubic feet per second and predicted groundwater flow into the river from the waste rock zone of 0.0045 cubic feet per second, the incremental increase in river concentrations would be:

- Copper - 0.00000034 mg/l
- Manganese - 0.0000013 mg/l
- Iron - 0.00000078 mg/l
- Sulfate - 0.0033 mg/l.

The predicted increase in river concentrations will be below analytical detection limits. It is evident that there will be minimal, actually undetectable, impact upon the Flambeau River associated with materials backfilled within the pit.

### **Groundwater Drawdown Model**

Another study performed is the model of the predicted groundwater drawdown contour and potential impacts upon private wells. Five private wells are known to be located within the maximum extent of drawdown which has been modelled to extend 2750 feet from the edge of the mine pit. Four of the wells will not be significantly impacted, while the fifth well could be impacted by a predicted eight foot drop in water elevation. The potential effects upon the five wells are considered within the Local Agreement that Flambeau signed with the local government entities. If wells are impacted by mining activities, Flambeau will provide water or replace the wells. To date, water supply to local wells has not been significantly impacted and property owners are convinced that the palatability of their water supply has improved.

### **OPERATION PHASE**

The studies and models previously mentioned provided Flambeau the knowledge to use modern technology and a pro-active environmental commitment in the construction of an environmentally safe facility. Flambeau has constructed and is operating a facility that is a model of modern mining technology, engineering and science, providing superior environmental protection. Environmental safeguards include the treatment of all contact water, suppression of dust, erosion

control, on-site spill prevention programs and an extensive monitoring program that ensures that the environmental safeguards work as they were designed and approved by the WDNR.

### Wastewater Treatment Plant

The WWTP is a key component of Flambeau's protection of groundwater and surface water in its commitment to conducting environmentally responsible mining. Sources of contact water include mine seepage, precipitation into the open pit and storm water run-off from the lined Type II stockpile and the lined crusher/loader areas. The WWTP design allows for pH neutralization and metal removal in a three-stage process consisting of lime treatment, sulfide precipitation and multi-media filtration (Figure 1). The WWTP design capacity of 800 gpm is more than adequate to handle normal conditions. The open pit acts as an ultimate sump during extreme storm events. Mine seepage and precipitation require an average pumping rate of approximately 225 gpm throughout the year. The WWTP incorporates scientific treatment processes with advanced computer technology through its control system, a General Electric LM 90-70 Series Programmable Logic Controller. Flambeau's WWTP operators, certified by the state use knowledge, experience and the control system to ensure optimum treatment and compliance with stringent effluent limitations. Flambeau began operation of the WWTP on March 15, 1993 and to date over 340 millions gallons of high quality effluent has been discharged into the Flambeau River.

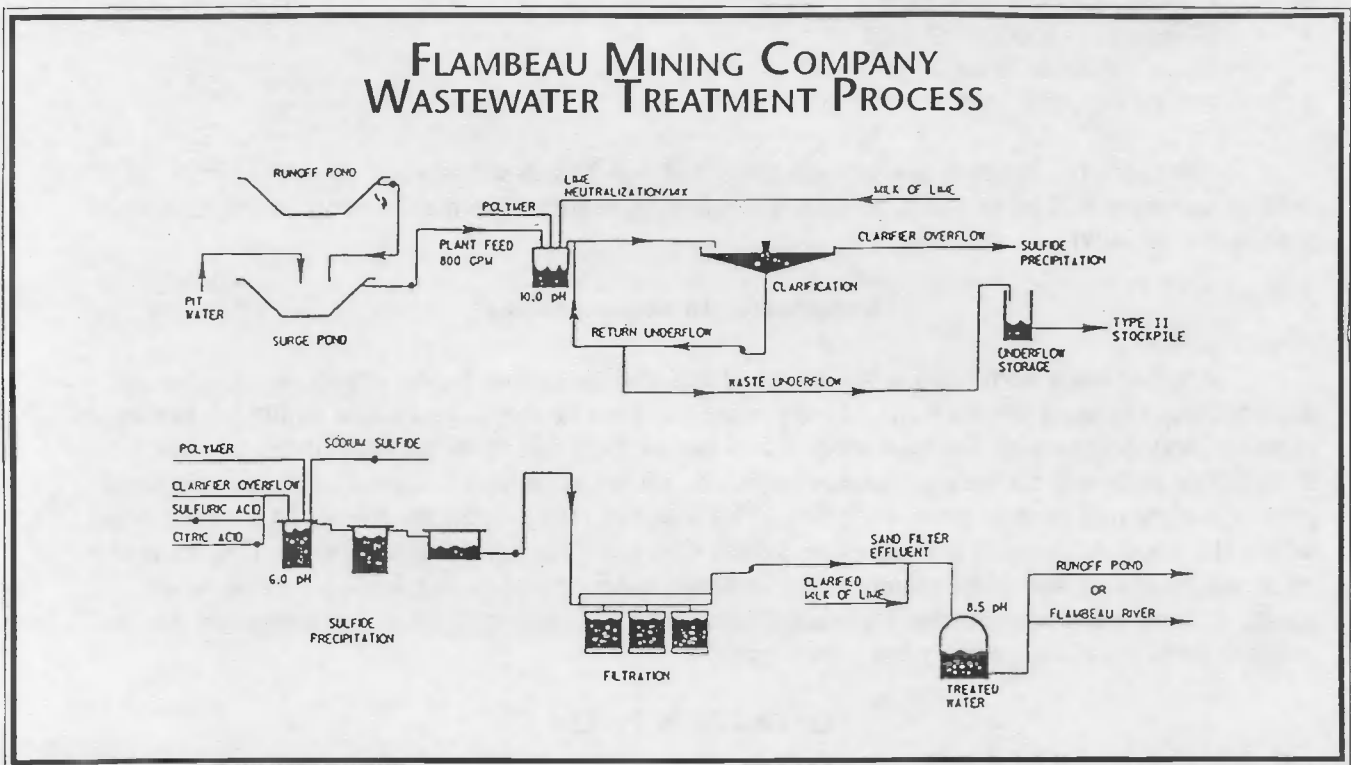


Figure 1. Flambeau's Wastewater Treatment Plant Schematic

Flambeau's WPDES permit was issued during January 1991 and defines the limitations under which the WWTP must operate. The WPDES permit contains categorical and water quality-based chemical specific limitations. The Wisconsin Administrative Code in NR809.541 places a copper action limit of 1300 ug/l as compared to Flambeau's WPDES permit limit of 50 ug/l for copper. A representation of the stringent limitations and Flambeau's effluent long-term average concentrations are listed in Table 1. WWTP effluent has fully complied with all WPDES permit categorical and water quality-based chemical specific limitations during some extreme operational periods that included a 100-year flood event on September 15, 1994.

Table 1. SUMMARY OF FLAMBEAU'S WPDES PERMIT LIMITATIONS AND EFFLUENT LONG-TERM AVERAGE CONCENTRATIONS.

	Daily Maximum Limit (ug/l)	Weekly Average Limit (ug/l)	Effluent Long-Term Average (ug/l)
Cadmium	79.8	7.1	0.02
Chromium	5400	980	<1.0
Copper	50	—	8.9
Lead	590	—	0.35
Silver	6.6	140	0.09
Zinc	300	—	11

Flambeau has an on-site laboratory with a 4100 atomic absorption graphite furnace that provides the resources to monitor the WWTP and make minor treatment adjustments to optimize its efficiency. Flambeau's on-site laboratory also allows WWTP effluent to be tested prior to discharge to the Flambeau River ensuring full compliance with chemical specific limitations. An internal limit of 25 ug/l for copper, equal to one-half the permit limitation, has been established by Flambeau to be used as a guideline for discharge criteria. If the on-site laboratory results are not less than one-half the permit limit, the WWTP effluent is discharged to the runoff pond and retreated through the WWTP until it meets this criteria. Flambeau monitors the WWTP process a minimum of every two hours to ensure that the proper adjustments are made for optimum treatment.

Whole effluent toxicity (WET) testing is also required by the WPDES permit. Flambeau's effluent is subject to chronic WET testing using *Ceriodaphnia dubia* (*C. dubia*), a water flea, and *Pimephales promelas* (*P. promelas*), fathead minnow, as test species. Flambeau's chronic WET is based upon reproduction (*C. dubia*) and weight gain (*P. promelas*). Acute WET testing is also required using *C. dubia* and *P. promelas* as test species and is based upon mortality within 100 percent effluent.

Acute toxicity tests have shown only one of the two test species, *C. dubia*, to be sensitive in undiluted effluent. Two acute toxicity tests using *C. dubia* as the test species resulted in a mortality rate greater than 50 percent which represents a positive acute toxicity. These two positive acute toxicity tests occurred within a twelve month period requiring Flambeau to complete a toxicity reduction evaluation (TRE) as prescribed by Flambeau's WPDES permit.

Flambeau conducted a TRE during the period December 1993 through January 1995. Trace-metal copper within Flambeau's WWTP effluent was determined to acutely effect the test species *C. dubia* at concentrations that were substantially below Flambeau's permit limitation of 50 ug/L copper. Research toxicity testing was performed to evaluate the relationship that hardness and organic compounds have upon acute toxicity in Flambeau's effluent. The addition of an organic chelating agent into Flambeau's effluent was found to provide effective and consistent reduction of acute toxicity. Citric acid was selected to provide the citrate ion which greatly reduced copper bioavailability within the effluent. Following approval from the WDNR, Flambeau implemented the use of citric acid within its treatment process reducing trace-metal copper toxicity to *C. dubia*. In October 1995 Flambeau presented its TRE as a case study at the 68th annual Water Environment Federation Conference held in Miami Beach, Florida.

### Stockpile Monitoring

The Type I stockpile is equipped with a collection lysimeter used to determine the characteristics of the exfiltrate. The lysimeter is sampled on a quarterly basis for a variety of parameters. Type I exfiltrate analyses to date have shown pH values in the range of 5.9-6.8 s.u. which are comparable to shallow well samples as was predicted in the waste rock characterization studies.

The Type II stockpile is lined with an HDPE liner and a collection system made up of polyvinyl chloride leachate lines. All runoff and exfiltrate is contained within the system and gravity flows into the surge pond. This contact water is then treated through the WWTP as previously discussed. The integrity of the Type II system is confirmed through annual inspections. The series of pipes between the Type II stockpile and the surge pond are camera inspected. The leachate line system below the stockpile responsible for the collection of the leachate is also assessed.

### Flambeau River Monitoring

The Flambeau River is monitored through an extensive program that further ensures the discharged effluent does not impact the quality of the river. Figure 2 shows the locations of all the Flambeau River sample points. The monitoring program began as part of the environmental studies supporting the initial permitting process. River samples were collected from sample points located upstream from the mine area as well as downstream. The collection of background water quality data was conducted once a month from October 1987 through September 1988.

As required by Flambeau's mining permit, Flambeau again commenced conducting similar surface water quality monitoring on a quarterly basis. This surface water quality monitoring consists of samples being collected at SW-1 (upstream from the mine area) and samples being collected at SW-2 (downstream from the mine site within the mixing zone of the WWTP effluent). Over 20 water quality analyses are conducted on each collected sample. The Flambeau River monitoring program to date, has shown no significant difference in the upstream samples as compared to the downstream samples.

Flambeau's environmental monitoring of the Flambeau River includes sampling river sediment. Flambeau River sediment analysis began in 1988 with the collection of sediment samples to establish a point of reference for background concentrations of selected chemical parameters. This list of chemical parameters include arsenic, beryllium, cadmium, chromium, mercury and nickel. Sediment sampling has been conducted throughout the operation phase of the mine on an annual basis.

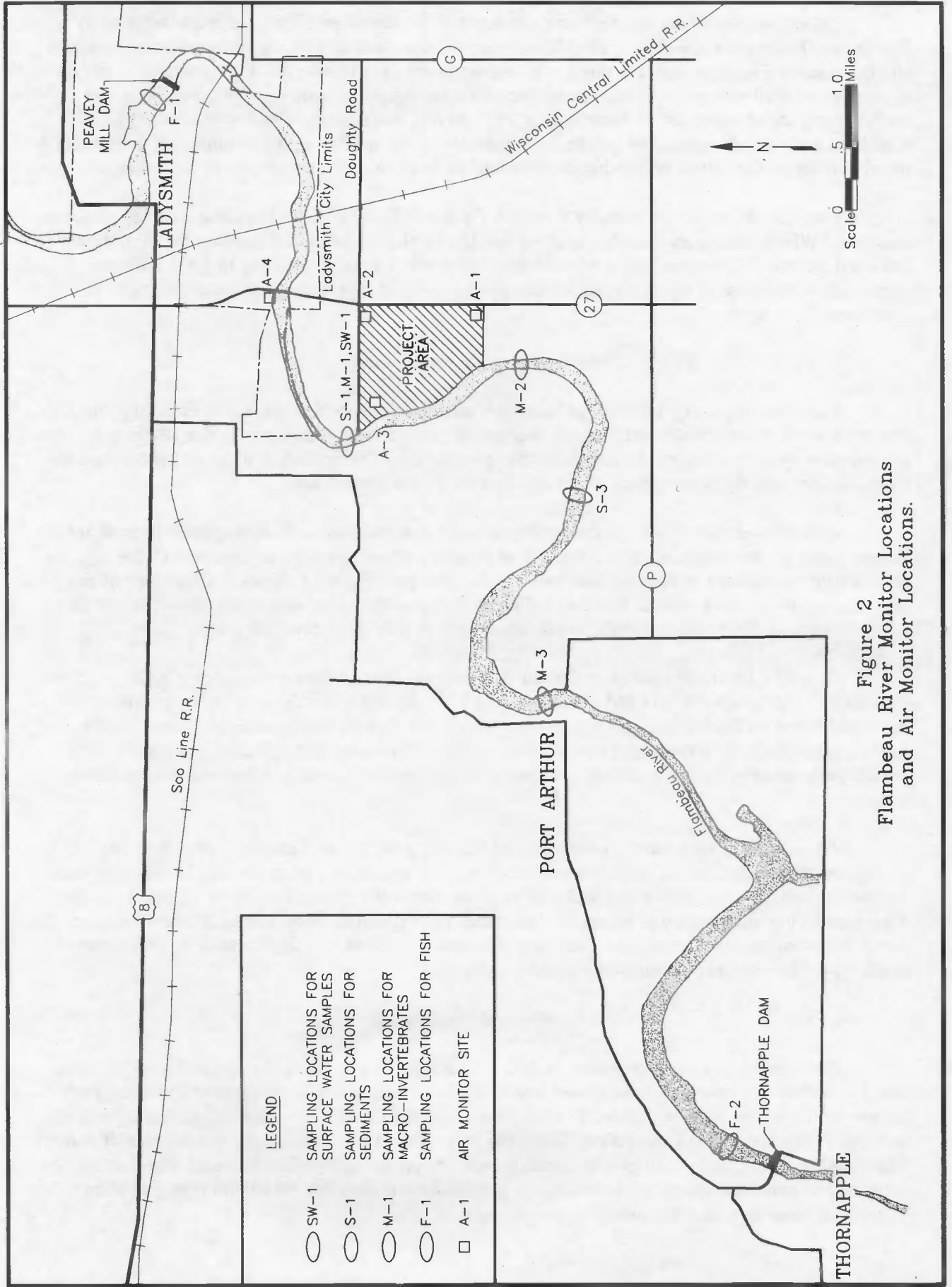


Figure 2  
 Flambeau River Monitor Locations  
 and Air Monitor Locations.

Collection of walleye on the Flambeau River is an annual monitoring event conducted by Flambeau. During the low flow period of the year various sizes of fish are collected at an upstream site (Ladysmith Flowage) and at a downstream site (Thornapple Flowage). Fillets with skin left on are tested for total mercury. The livers of fish collected at each sample site are composited and analyzed for an extensive list of parameters. Fish surveys were initiated during the Fall 1987. Flambeau has started conducting fish surveys annually again in 1991 with no significant differences in metal content of fish tissue sampled downstream of mine compared to upstream of the mine.

Crayfish are collected annually from the Flambeau River at three sampling locations for metal analyses. Whole bodies are used for analysis and the results represent a composite for all crayfish collected per site. Flambeau has conducted crayfish surveys annually starting in 1991 with no significant differences in metal content of fish tissues sampled downstream of mine compared to upstream of the mine.

### **Groundwater Monitoring**

Flambeau regularly monitors groundwater quality to ensure that the environmental protection measures work as they were designed. Collection of groundwater data began in the 1970s as baseline groundwater quality and groundwater flows were evaluated. The collection of groundwater data has continued through the construction phase and into the operational phase.

Groundwater elevations are determined weekly at numerous wells strategically located around the perimeter of the open pit. The collection of this data allows for the interpretation of the groundwater drawdown in the area surrounding the open pit. Figure 3 shows the locations of the groundwater monitoring wells. The data collected indicates the groundwater drawdown is similar to that predicted in the groundwater drawdown model previously discussed.

Groundwater quality data is collected quarterly at eleven different monitoring wells strategically placed up gradient and down gradient from the open pit. Groundwater samples are evaluated based on twelve different parameters, which are copper, manganese, pH, conductivity, hardness, sulfate iron, alkalinity, total dissolved solids, color, odor and turbidity. Quarterly groundwater monitoring has indicated no adverse impact upon the area groundwater supply during mining.

An extensive, long-term groundwater monitoring program will continue after the completion of the operational and reclamation phase of mining. The monitoring program will include a dynamic monitoring schedule for monitoring wells up gradient and down gradient of the reclaimed open pit. Two monitoring well nests will be established inside the backfilled pit following the completion of the reclamation construction activities. Each well nest will consist of two wells which will be sampled similarly to the previously established monitoring wells.

### **Wetland Monitoring**

Water level gauges were placed in five separate wetlands outside the perimeter of the mine site, but within one mile of the perimeter fence. Figure 3 shows the locations of the wetland staff gauges which are recorded monthly. If staff gauge readings as well as visual inspections of wetlands indicate a need for wetland mitigation, Flambeau will mitigate the wetlands by the addition of water. The monthly staff gauge readings will continue until the pit is backfilled. The data will then be compared to preconstruction levels and recent precipitation history for the region resulting in an established long-term and maintenance monitoring schedule.

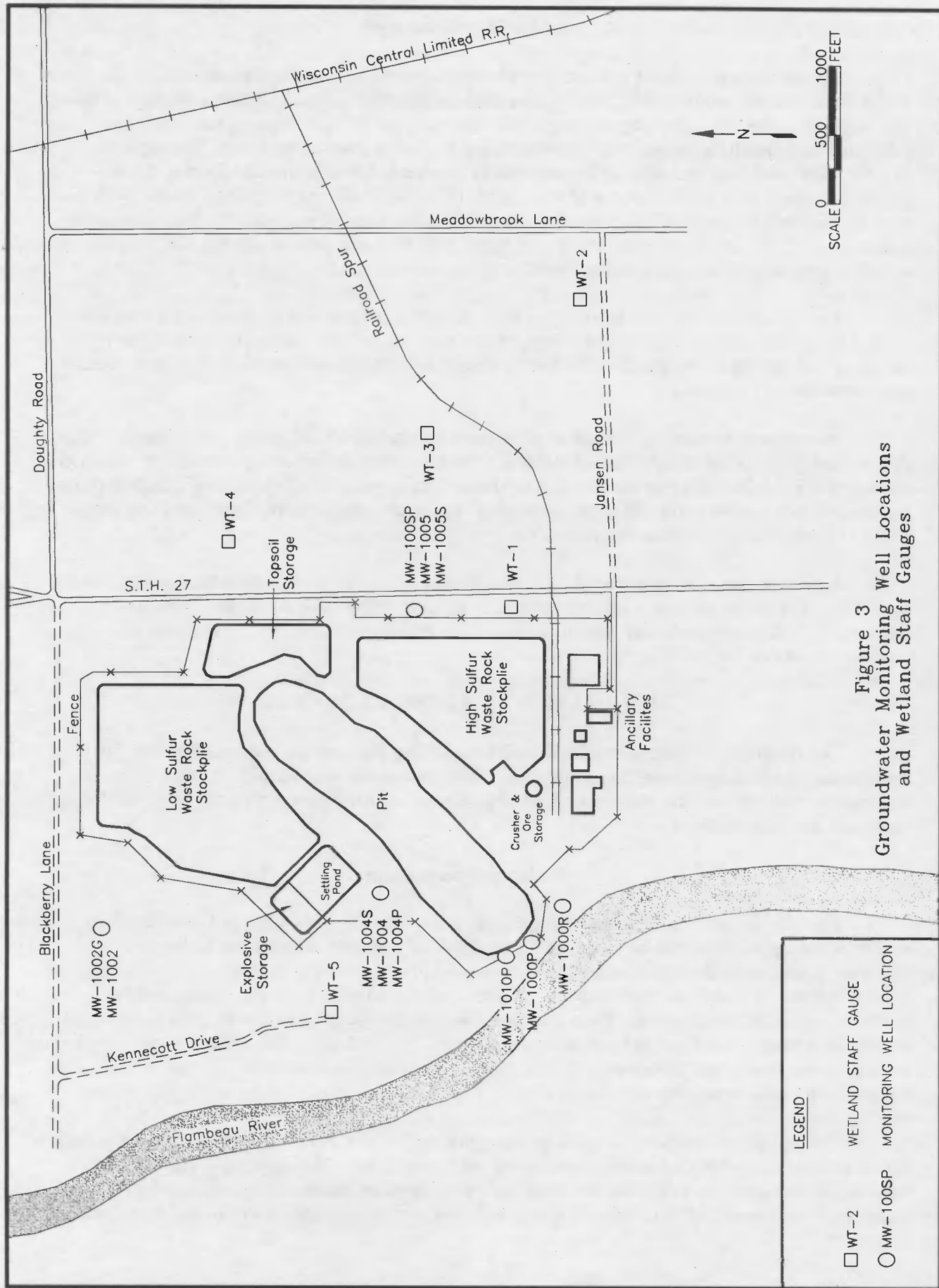


Figure 3  
Groundwater Monitoring Well Locations  
and Wetland Staff Gauges



## Ambient Air Monitoring

Particulate matter in the ambient air generated by mine operations is suppressed by the use of WWTP effluent and monitored by four high-volume air samplers. Figure 2 shows the four sampling site locations. The four sampling site locations were based on USEPA siting criteria and are calibrated on a quarterly basis. The instruments are audited at least on an annual basis by the WDNR. Each monitor operates for 24 consecutive hours starting at midnight. During the pre-production phase each monitor operated once every three days. During the mining phase, each monitor was operated once every other day. Since Flambeau had not exceeded its Total Suspended Particulates (TSP) secondary standard of 150 ug/m<sup>3</sup> following one year of mining, the sampling schedule was reduced to once every six days.

Each filter from the TSP monitors is retained with a portion of each filter being composited for a three month period. These composites are analyzed for arsenic, chromium, nickel, beryllium, cadmium and mercury. Analyses of the filter composites have resulted in very low to non-detectable concentrations of these metals.

Asbestiform monitoring is another component of Flambeau's air quality monitoring program. Asbestiform monitoring was conducted monthly from May through September during the years 1993 through 1995. Asbestiform monitoring during the first three years of active mining indicated that no asbestiform fibers were generated from the mining operations. As a result, Flambeau is no longer required to monitor for asbestiform fibers.

Meteorological data is obtained from Flambeau's Meteorological Station located south of the mine site. The meteorological station continuously collects information on the precipitation, temperature and wind speeds and wind direction. This information is submitted with the air monitoring data to the WDNR.

## RECLAMATION AND LONG-TERM CARE

The reclamation of the mine site includes backfilling the open pit and returning the site to a topography which approximates the original contours. Following establishment of final contours, reclamation includes wetland construction, topsoil, vegetative stabilization, tree planting, and long-term care and maintenance.

### Wetlands Construction

Prior to site construction, wetland delineation had identified 8.3 acres of low to medium quality wetlands which would be disturbed. The disturbed wetlands are required to be replaced. The hydric soils from the disturbed wetlands were stockpiled to be used during wetland construction. During Fall 1991, Flambeau constructed a one-acre wetland referred to as the aquascape in the northeast corner of the property. The aquascape varies from a sedge meadow to open water which allows for a range of wetland species as does the hydric soil stockpile. The aquascape not only serves to replace one acre of disturbed wetland area, but also provides information to be used for the construction of the remaining wetland area.

The aquascape has been assessed on an annual basis since 1992. The aquascape has become a stable wetland area which supports a diversity of wetland species. The aquascape was originally established with both plants and seeds. Over the past four years species diversification has dramatically increased. Several species which had been seeded remained dormant and have become

evident in only the last year. The 1995 assessment has shown an increase in diversification by seven species compared to the previous year.

### **Topsoil Stabilization**

Approximately 220,000 cubic yards of stockpiled topsoil were placed between the east end of the mine and Highway 27 and will be replaced on the mine site following backfilling and contouring. The topsoil will be stabilized with a vegetative cover consisting of native prairie grasses and wild flowers with a nurse crop of oats. Additional erosion control features including straw bales, silt fence, and mulch will be utilized. The species of wild flowers and grasses to be used during final reclamation has not been definitively determined at this time. The species of wild flowers and grasses will be selected based upon studies performed on the prairie seed test plots.

Prairie seed test plots were established on the mine site during 1993. The test plots are located on the mine site north of the Type I stockpile and south of the open pit. A total of 196 test quadrants were defined which consider the following test variables: 1) type of fertilizer; 2) type of mulch; 3) mowing; and 4) type of seed mix. The annual assessments show the progression from exotic species to desirable native species. The information gathered from the prairie seed test plot annual assessments will be utilized to select the best methods for establishment of native species for stabilization.

### **Tree Planting**

During 1991 the WDNR and Flambeau selected trees from the mine site to be transplanted to a temporary nursery located north of the Type I stockpile. The tree selection was primarily based upon the WDNR approved tree species and appropriate tree size. Trees which would grow too large before transplanting would have a low survival rate when replaced to the mine site, and were therefore not selected for placement in the temporary nursery.

Additionally, Flambeau has planted nursery stock tree seedlings into the temporary nursery during 1993 and 1995. The tree seedlings have provided information on survival rates of specific species. Also, the management of the seedlings has established procedures which will be implemented during the planting of approximately 14,000 seedlings at the time of final reclamation.

### **Long-Term Care and Maintenance**

Flambeau will be responsible for the reclaimed mine site in perpetuity with a minimum long-term care and maintenance period of 40 years. Long-term care will initiate when final site grading and revegetation have been completed.

Long-term care and maintenance will include inspections of the site, maintenance of land forms, vegetation and monitoring devices, and monitoring groundwater, surface water, vegetation and terrestrial ecology. The long-term care period monitoring plan is shown in Table 2.

Table 2. SUMMARY OF FLAMBEAU' LONG-TERM CARE  
PERIOD MONITORING PLAN.

Event	Year	Frequency
Site Inspections	1-4	Semi-annual
	5-40	Annual
Groundwater Monitoring	1-40	Quarterly
	Perimeter Wells	Quarterly
	Backfilled Pit Wells	Annually
	8-40	Every 5 years
Sediment, Crayfish & Fish	1-2	Annually
River Water Quality	1-2	Annually
Wetland Surface Flows	1-10	Spring, Summer, Fall
Vegetation Assessment	1-6	Annually
Terrestrial Ecology	1-4	Annually
	5-40	Every 5 years

### CONCLUSION

Flambeau's commitment to environmental protection goes beyond permit compliance. Respect for the environment is a personal commitment for every employee at the Flambeau Mine. This continued commitment is evident with the successful operation of this environmentally responsible mine. Flambeau's use of modern technology and personal creativity provides the environmental protection criteria which may serve as a benchmark for the mining industry.

# **EISENBREY: A STRUCTURALLY COMPLEX PROTEROZOIC COPPER-ZINC MASSIVE SULFIDE DEPOSIT, RUSK COUNTY, WISCONSIN**

by Edward R. May

Consulting Mining Geologist  
Littleton, Colorado

## **INTRODUCTION**

The discovery of the Flambeau copper-gold massive sulfide deposit in late 1968 (May and Dinkowitz, 1996) rapidly expanded Kennecott's search for satellite deposits. The search was immediately conducted along strike of the Flambeau discovery and soon expanded to cover all airborne electromagnetic (EM) anomalies within the Glen Flora airborne survey selected for review and ground follow up (Babcock, 1996). Ned Eisenbrey recalled a rusty, weakly mineralized iron formation outcrop located by Bill Spence in 1967 along the bank of the Thornapple River about 7 miles northwest of Flambeau. A weak airborne EM conductor detected in the area of the outcrop was not encouraging since a farm and railroad bridge were located on either side of the strike extension of the outcrop to which the anomaly was attributed. Eisenbrey, nevertheless decided to drill the weakly copper-zinc-silver anomalous exposure in 1970 over the doubts and objections of most of his colleagues. The first drill hole encountered a 14.6-foot interval within an iron formation that averaged 477 ppm Cu, 2400 ppm Zn, and 422 ppm Pb. The second hole was collared 350 feet to the west and resulted in the discovery of the Thornapple deposit. This hole intersected 5.9 feet true width of massive sulfides that averaged 0.44% Cu, 1.36% Zn, 0.02 opt Au, and 0.29 opt Ag. The Thornapple deposit was, therefore, a geological discovery; ground geophysics were conducted over the deposit after its discovery. Ground magnetics were run in 1970 and 1971 to trace pyrrhotite and iron formation mineralization, and one line of gravity was conducted at the same time over the thickest portion of the deposit.

A development team took over the project in 1971 after Ned and Bob Stuart had completed ten holes, six of which intersected mineralization. Unlike Flambeau, no significant supergene mineralization was encountered. The project was shelved in 1974 due to falling copper prices; however, land was purchased by Kennecott to cover the deposit and any potential strike extension.

A total of 40 holes had been drilled by 1974 to an average depth of about 500 feet below surface. A complex, isoclinally folded, eastward plunging, thin multi-lensed deposit was partially defined consisting of zoned bodies of pyrrhotite-chalcopyrite and pyrite-sphalerite mineralization. The resource was estimated to be 1.6 million tons of 1.3% Cu, 0.06% Zn, 0.007 opt Au, and 0.20 opt Ag, and 700,000 tons averaging 0.35% Cu, 4.10% Zn, 0.02 opt Au, and 0.4 opt Ag. While initial results were disappointing, the deposit was not thoroughly drilled and was open to depth.

The Thornapple deposit was renamed Eisenbrey in 1994 to honor the significant contributions made by Ned Eisenbrey to Wisconsin economic geology. In the same year, Flambeau Mining Company, a wholly owned subsidiary of Kennecott Minerals, decided to test the deposit to depth. A gravity survey was conducted to verify that the deposit was indeed plunging steeply to the east. To everyone's astonishment, a large anomaly was recognized that could not be explained by the shallow, thin sulfide intercepts cored by previous drilling campaigns. Eight holes drilled in 1994-1995 confirmed the presence of a large, near vertically dipping and plunging, complexly folded deposit. Resource estimates to depths in excess of 3000 feet indicate the presence of 50,000,000 to possibly

100,000,000 tons of low-grade copper-zinc mineralization in which copper and gold values are erratic and zinc values consistently low.

## LOCATION

The Eisenbrey deposit is easily reached via paved roads commencing at the intersection of Highways 8 and 27 in Ladysmith. Drive north on Highway 27 four miles to the junction with County Road A. Proceed west on County A for a distance of two miles then north on Bass Lake Road for 1.75 miles to the 514.5-acre project site which is east of the Flambeau township road (Figure 1). The Thornapple River bisects the west one third of the site and is entrenched 50 feet within glacial outwash. The Wisconsin Central Railroad also cuts across the site and river in a southeasterly direction. The project site is essentially flat, has an elevation of about 1160 feet, and is covered east of the river by highland mixed deciduous forest. West of the river the site is covered by old meadows and woods.

## GENERAL GEOLOGY OF NORTHERN WISCONSIN

At least 13 volcanogenic massive sulfide deposits have been discovered within Early Proterozoic greenstone rocks of northern Wisconsin (DeMatties, 1994). The Ladysmith-Rhineland metavolcanic belt within the Pembine-Wausau Subterrane, which strikes across the state for a distance of 150 miles, is the host rock for this mineralization. These 1.86 to 1.88 billion year old rocks consist of mafic metavolcanics, gabbroic sills, lesser amounts of felsic metavolcanics, and some cherty iron formations. The Ladysmith-Rhineland metavolcanic belt clearly shows on regional airborne gravity and magnetic reconnaissance maps of northern Wisconsin as an anomalous linear feature. North of the Ladysmith-Rhineland belt are rocks that form a thick platformal turbidite sequence of clastic and chemical metasedimentary rocks including major iron formations. The Niagara Fault separates the Northern Penokean Terrane of continental margin assemblages from the Pembine-Wausau Subterrane (Figure 2). The paper by G. LaBerge in this volume shows the location of these subterranees.

South of the Ladysmith-Rhineland belt are rocks of the Wausau and Marshfield Complexes. The Eau Pleine Shear separates the Marshfield Subterrane from the Pembine-Wausau Subterrane (LaBerge, 1996). The Marshfield Subterrane is characterized by Archean gneisses and 1.86 billion year old metavolcanic rocks and granitoids. The Wausau Volcanic Complex consists of 1.88 billion year old amphibolite facies rocks unconformably overlain by 1.84 billion year old intermediate to felsic metavolcanics. Intruding the Wausau volcanic complex are anorogenic igneous rocks, 1.47 to 1.51 billion year old, the largest of which is the Wolf River Batholith. DeMatties and LaBerge more fully discuss these subterranees and the Wausau Volcanic Complex in this volume.

Paleozoic sediments onlap the southern portions of the Southern Superior Province of the Precambrian Canadian Shield.

## SITE GEOLOGY

Glacial outwash covers the entire site to a vertical depth of about 50 to 60 feet into which the Thornapple River has entrenched itself to expose Precambrian bedrock. Outcroppings of Precambrian metasedimentary, metavolcaniclastic, and igneous rocks occur on either side of the Wisconsin Central Railroad bridge (Figure 3).

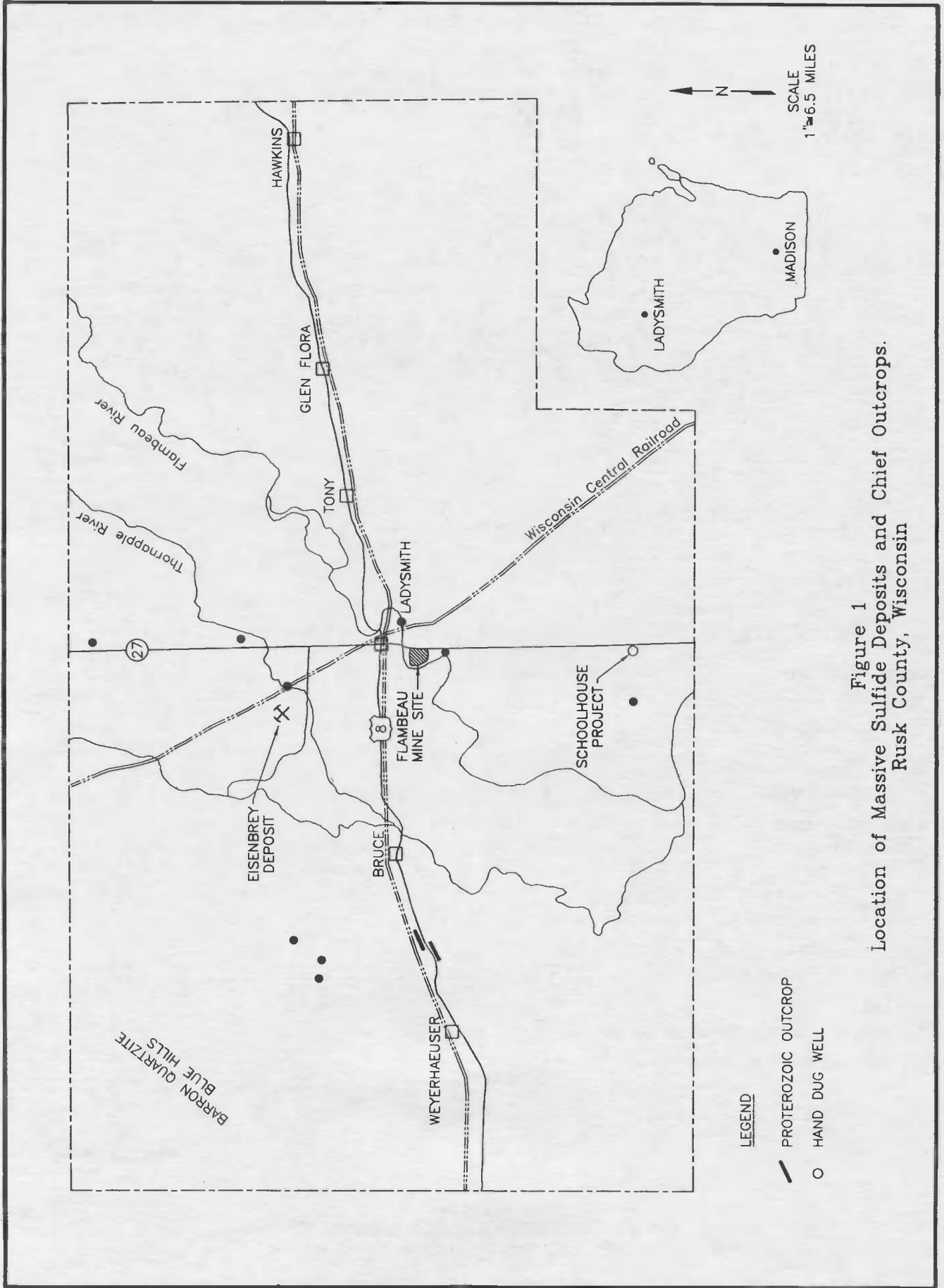
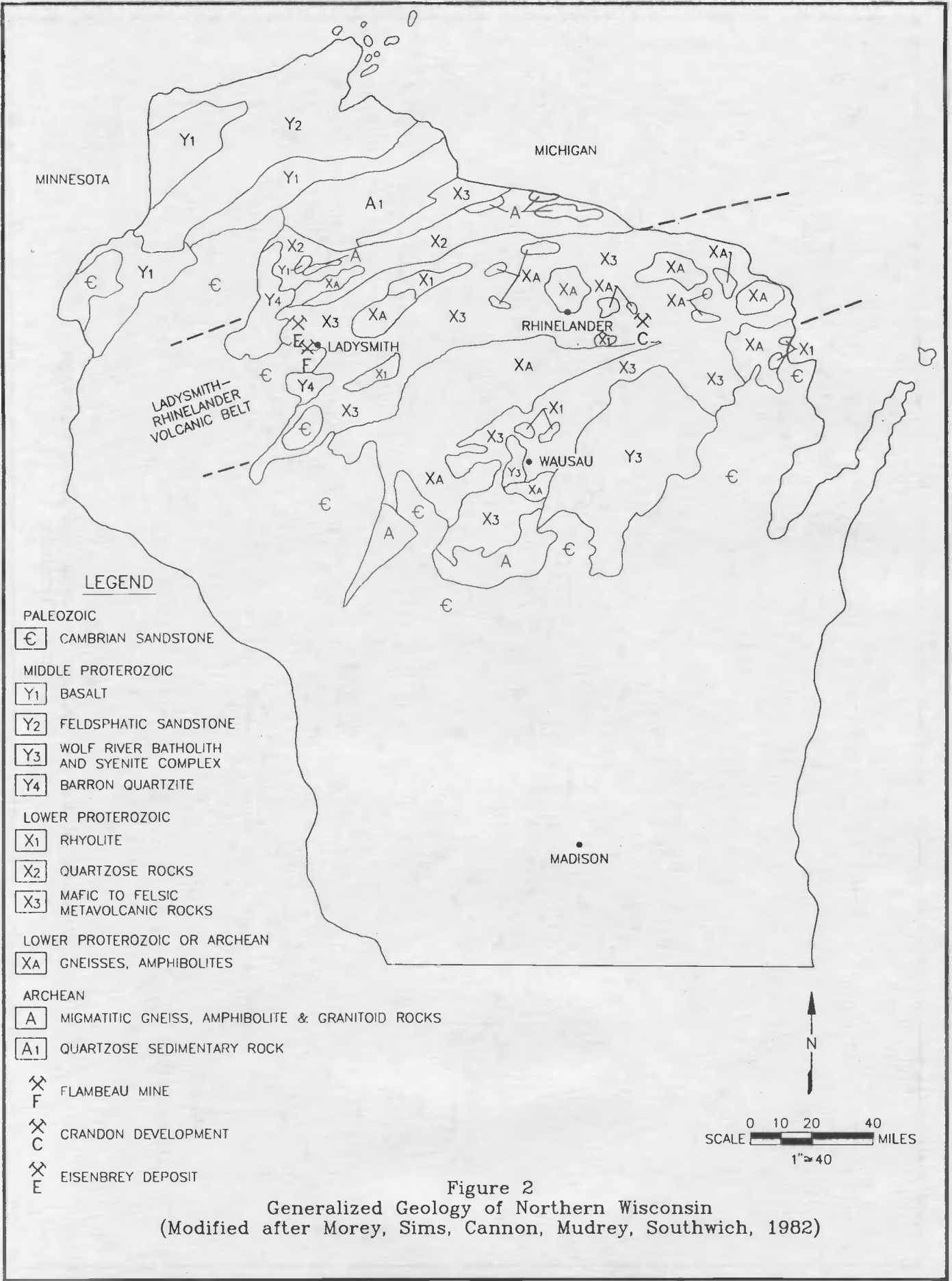


Figure 1  
 Location of Massive Sulfide Deposits and Chief Outcrops.  
 Rusk County, Wisconsin



**LEGEND**

**PALEOZOIC**

☐ € CAMBRIAN SANDSTONE

**MIDDLE PROTEROZOIC**

☐ Y1 BASALT

☐ Y2 FELDSPHATIC SANDSTONE

☐ Y3 WOLF RIVER BATHOLITH AND SYENITE COMPLEX

☐ Y4 BARRON QUARTZITE

**LOWER PROTEROZOIC**

☐ X1 RHYOLITE

☐ X2 QUARTZOSE ROCKS

☐ X3 MAFIC TO FELSIC METAVOLCANIC ROCKS

**LOWER PROTEROZOIC OR ARCHEAN**

☐ XA GNEISSES, AMPHIBOLITES

**ARCHEAN**

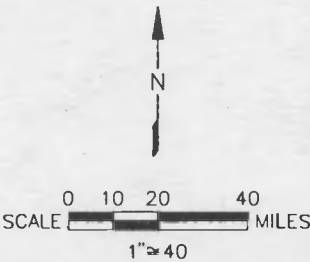
☐ A MIGMATITIC GNEISS, AMPHIBOLITE & GRANITOID ROCKS

☐ A1 QUARTZOSE SEDIMENTARY ROCK

⊗ F FLAMBEAU MINE

⊗ C CRANDON DEVELOPMENT

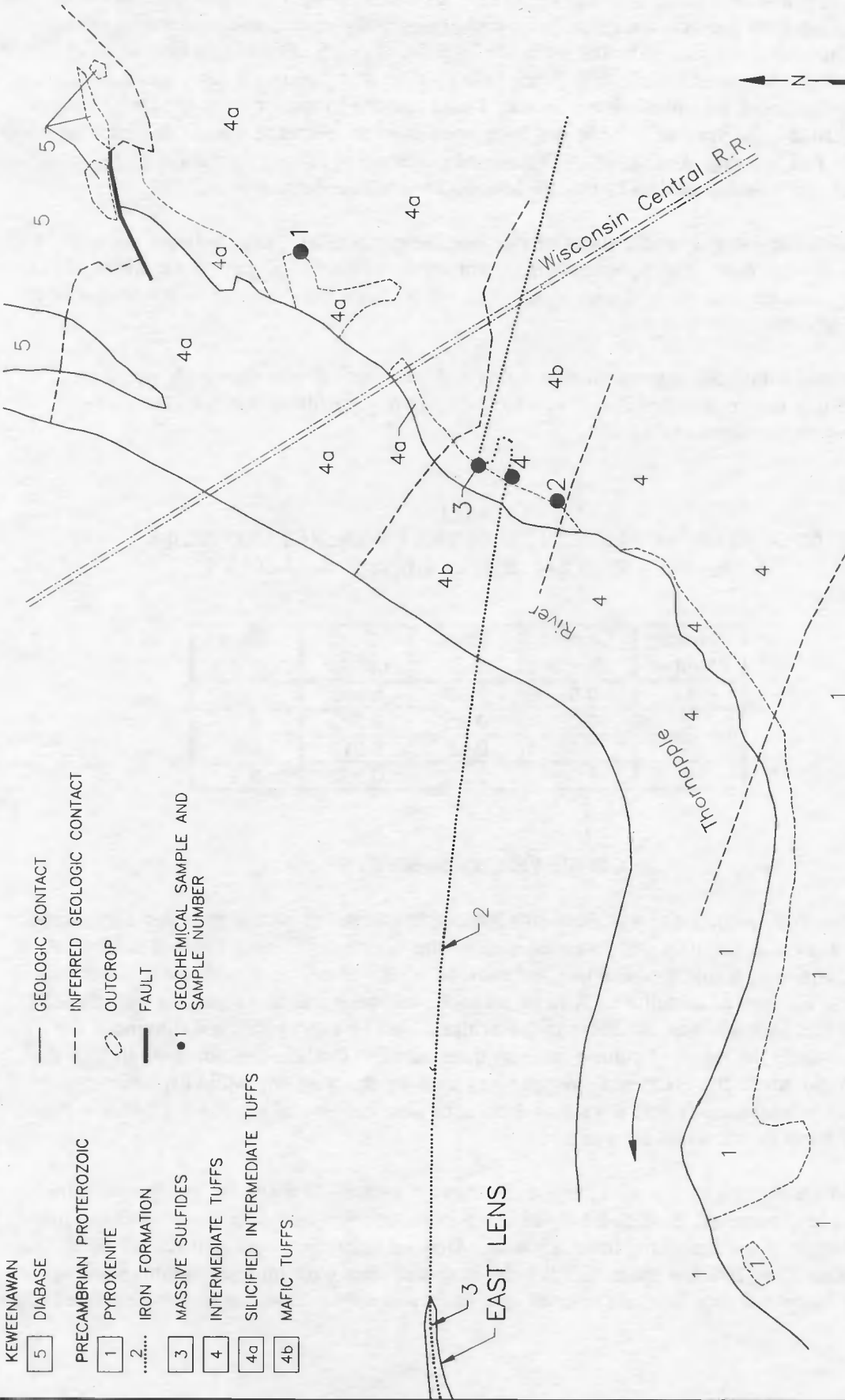
⊗ E EISENBREY DEPOSIT



**Figure 2**  
**Generalized Geology of Northern Wisconsin**  
 (Modified after Morey, Sims, Cannon, Mudrey, Southwich, 1982)

**LEGEND**

- |                                      |     |                                      |
|--------------------------------------|-----|--------------------------------------|
| <b>KEWEENAWAN</b>                    | —   | GEOLOGIC CONTACT                     |
| 5                                    | --- | INFERRED GEOLOGIC CONTACT            |
| <b>DIABASE</b>                       | ○   | OUTCROP                              |
| <b>PRECAMBRIAN PROTEROZOIC</b>       | —   | FAULT                                |
| 1                                    | ●   | GEOCHEMICAL SAMPLE AND SAMPLE NUMBER |
| 2                                    |     |                                      |
| 3                                    |     |                                      |
| 4                                    |     |                                      |
| 4a                                   |     |                                      |
| 4b                                   |     |                                      |
| <b>PYROXENITE</b>                    |     |                                      |
| <b>IRON FORMATION</b>                |     |                                      |
| <b>MASSIVE SULFIDES</b>              |     |                                      |
| <b>INTERMEDIATE TUFFS</b>            |     |                                      |
| <b>SILICIFIED INTERMEDIATE TUFFS</b> |     |                                      |
| <b>MAFIC TUFFS.</b>                  |     |                                      |



**Figure 3**  
**Thornapple River Outcrops, Eisenbrey Prospect.**  
**Rusk County, Wisconsin**



Upstream of the bridge a distance of about 0.25 mile is an outcrop of a Keweenawan diabase dike. Downstream and immediately east of the bridge are outcroppings of another dike that cuts across intermediate tuffs and graywackes. These highly regionally-metamorphosed and silicified rocks contain thin units of mafic tuffs that show very tight isoclinal folding with a near vertical plunge. West of the bridge is a mafic tuff (amphibolite schist) that contains a rusty and broken iron formation. The upstream iron formation is in a fold nose and the formation does not strike beneath the river. Instead it is interpreted to be folded back upon itself to reemerge further downstream (field observations by P. Lindberg, Aug. 1995). The second outcropping of iron formation strikes west across the river and is interpreted to be the ore horizon for the Eisenbrey deposit.

Volcaniclastic and graywacke rocks of intermediate composition occur between the mafic tuff and pyroxenite downstream. The pyroxenite is interpreted to be part of a gabbro sill with a chilled margin in sharp contact with the host sediments. The sill occupies the center of syncline that hosts the Eisenbrey deposit.

Four zones within the outcrop were sampled and geochemically analyzed. It was these geochemical results and rock exposures upon which the Eisenbrey drilling was founded. The geochemical results are shown in Table 1.

TABLE 1  
GEOCHEMICAL RESULTS FROM THE EISENBREY OUTCROPS  
EISENBREY DEPOSIT, RUSK COUNTY, WISCONSIN

Sample Number	Copper % Cu	Zinc % Zn	Gold opt Au	Silver opt Ag
1	0.03	0.03	trace	trace
2	0.03	0.05	0.003	0.1
3	0.04	0.17	0.010	0.3
4	0.06	0.20	0.002	0.1

### GEOPHYSICAL SURVEYS

The Eisenbrey project site was flown for Kennecott in 1969 as part of the Glen Flora airborne survey, and a weak EM anomaly was recorded west of the Wisconsin Central railroad bridge. A ground check, however, found a power line and railroad bridge coincidental with the EM conductor; therefore, it was discounted as culture. A large magnetic response was also recorded with the EM conductor, but this anomaly was attributed to the bridge. Ned Eisenbrey was not convinced the response was entirely the result of culture and was determined to drill the outcrop even though the iron formation did not fit the "Noranda" model being used by the company while exploring Wisconsin. No ground geophysical work was done until after base-metal anomalous massive pyrite and pyrrhotite mineralization had been drilled.

Ground geophysics conducted after the discovery consisted of magnetic and gravity surveys. The gravity survey, however, consisted only of one north-south line run over the nose of the fold that contained most of the Eisenbrey mineralization. Ground magnetics were also run on north-south lines spaced from 50 to 200 feet apart with the closer spaced lines over mineralization. Readings were taken on 50 or 100 foot intervals over an area that eventually covered approximately five square

miles and surrounded the deposit. This survey was useful in helping decipher bedrock structure and in locating suspected iron formations and one thin pyrrhotite lens.

A complex magnetic anomaly shown in (Figure 4) was observed over an east-west strike length of 1750 feet by 700 feet north-south. Drilling confirms that the large east-west elliptical response of up to 8000 gammas on the west end is coincident with the pyrrhotite-chalcopyrite fold nose of the Eisenbrey deposit. An iron formation occurs to the southeast and accounts for a northeast striking response that peaks at 12000 gammas. Near the center of the anomaly is an unexplained northwest striking response peaking at 4800 gammas.

A ground gravity survey recommended by Paul Schmidt was conducted in 1994 before commencement of deep drilling (Figure 5). The purpose of the survey was to confirm that the interpreted steeply east plunging deposit was true. This survey did indeed suggest a very steeply dipping and plunging deposit, but the size and magnitude of the anomaly was much larger than expected and could not be explained by sulfides encountered in the previous shallow drilling.

## GENERAL GEOLOGY

The Eisenbrey deposit is hosted within a thick pile of interbedded intermediated tuffs, lapilli tuffs and graywackes which have been regionally metamorphosed and folded. These Proterozoic volcanoclastic and sedimentary rocks form the platform into which younger mineralized and altered rocks were deposited. On the flanks of the massive sulfide mineralization are magnetite iron formations with weak base metal mineralization. Closer to the suspected center of "ore"/sulfide deposition the host rock is interpreted to be a dirty chert and volcanic rock altered to anthophyllite, cordierite, and magnetite with associated mafic tuffs. Minor rhyolite flows have been recognized, but do not appear to play a significant role in the formation or hosting of sulfide mineralization.

A gabbro sill was emplaced after the mineralizing events and before folding. A series of Keweenawan diabase dikes were intruded after the Penokean Orogeny to cut across the property in a northeasterly direction. Approximately 60 feet of Pleistocene glacial outwash covers the project site except where the Thornapple River has exposed Proterozoic and Keweenawan aged rocks east of the deposit.

## GEOLOGY OF THE EISENBREY DEPOSIT

Introduction. A brief geological description is presented below and is based upon core examinations, outcrop and some petrographic work conducted by Mary Jo Sweany in the 1970s. In general the rock descriptions commence with what are believed to be the oldest rock units through to Pleistocene Till.

Intermediate Dacitic Tuff and Graywacke. The most abundant rock types within the footwall, upon which massive sulfide mineralization was later deposited, consist of dacite tuffs, lapilli tuffs, and graywackes (Figure 6). Petrographic analyses of core samples repeatedly suggested the presence of graywacke. Graywacke, if present, is intercalated with thick sequences of dacitic lapilli tuffs all of which have been highly recrystallized by regional metamorphism.

In general, these tuffaceous and sedimentary rocks have been metamorphosed to a fine-grained, sugary to granular mixture of plagioclase, biotite, amphibole, and minor amounts of garnet and quartz. Relict bedding is observed under the microscope and in the Thornapple outcrop where

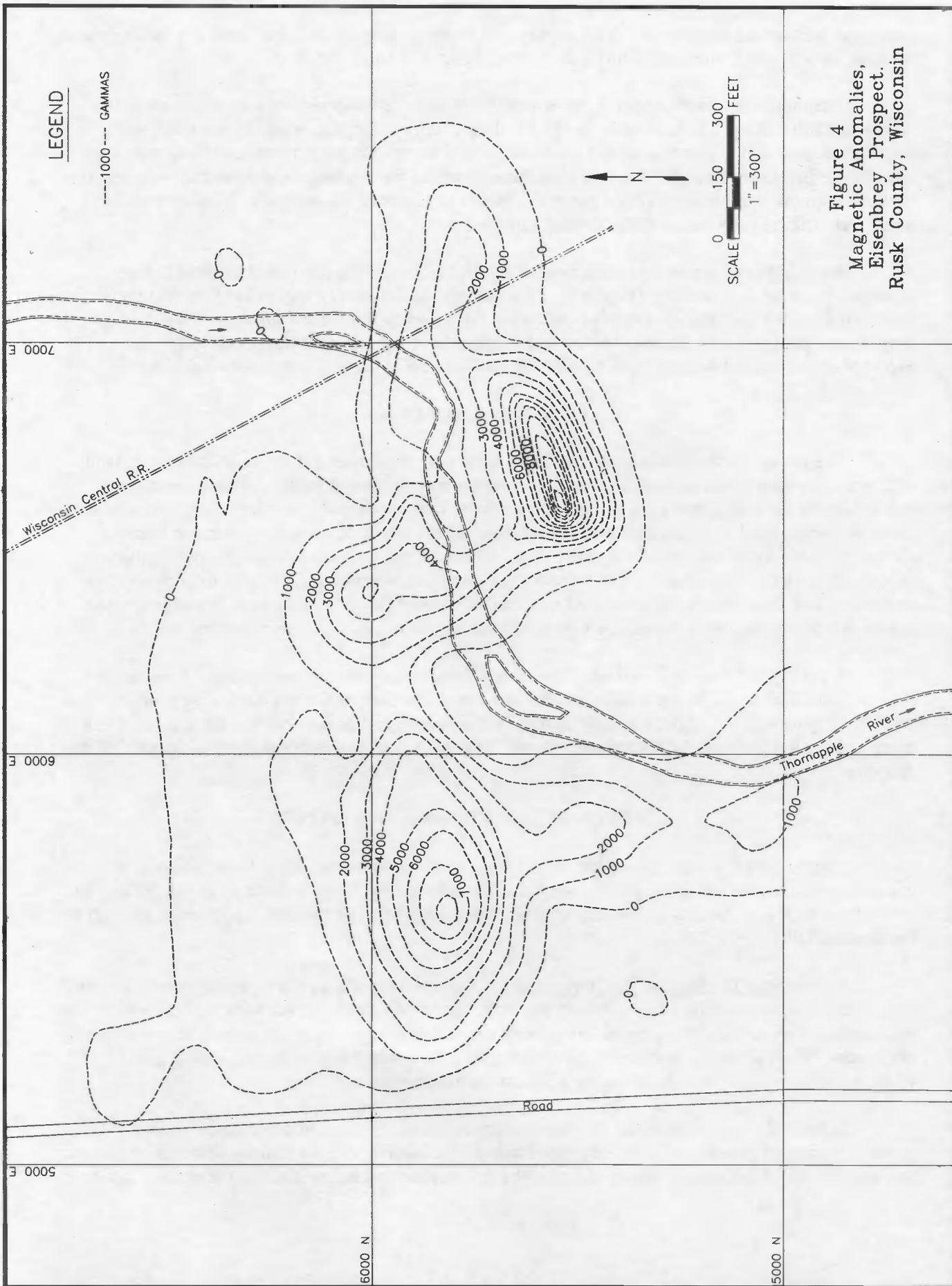


Figure 4  
 Magnetic Anomalies,  
 Eisenbrey Prospect,  
 Rusk County, Wisconsin

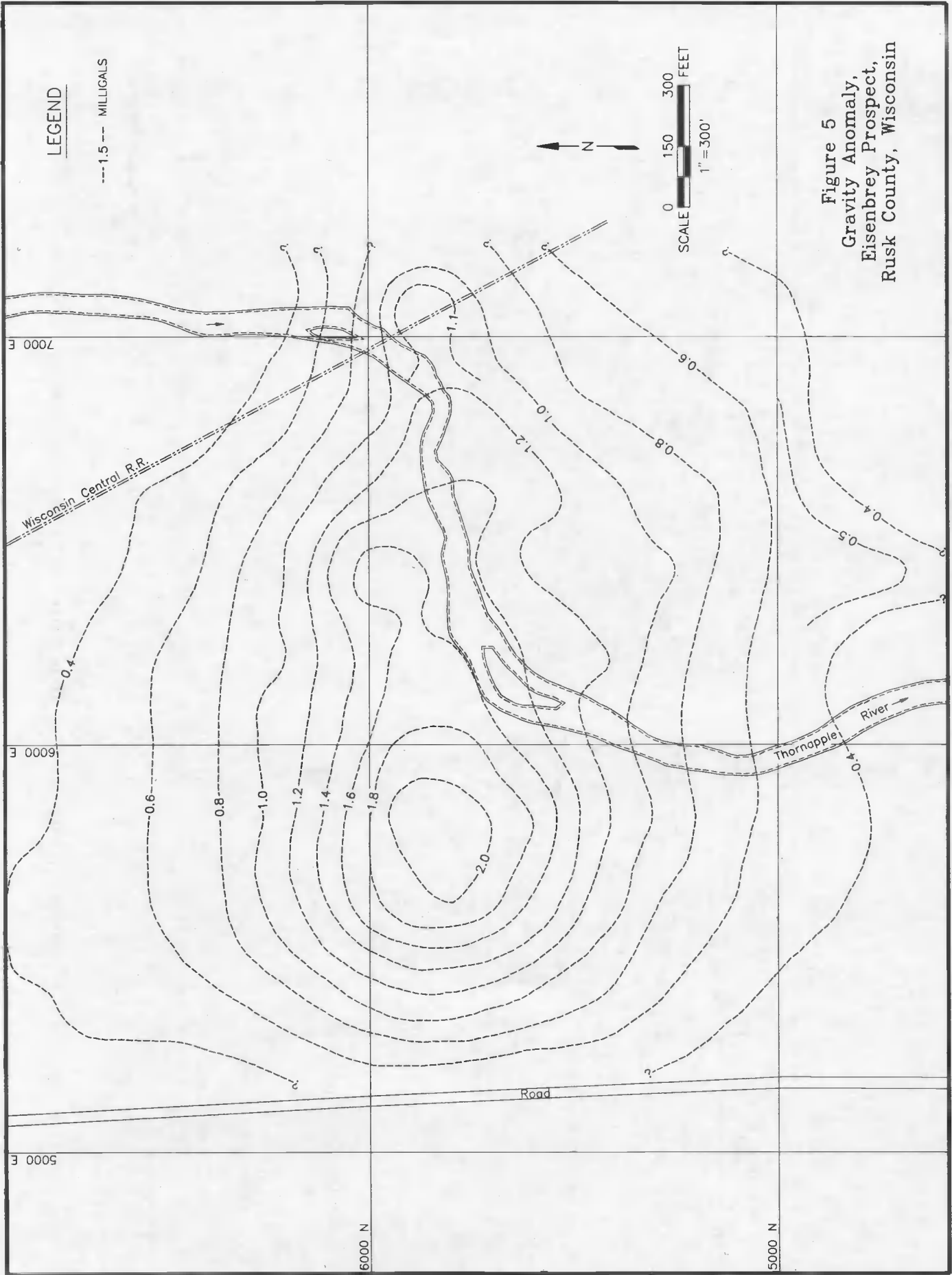


Figure 5  
 Gravity Anomaly,  
 Eisenbrey Prospect,  
 Rusk County, Wisconsin

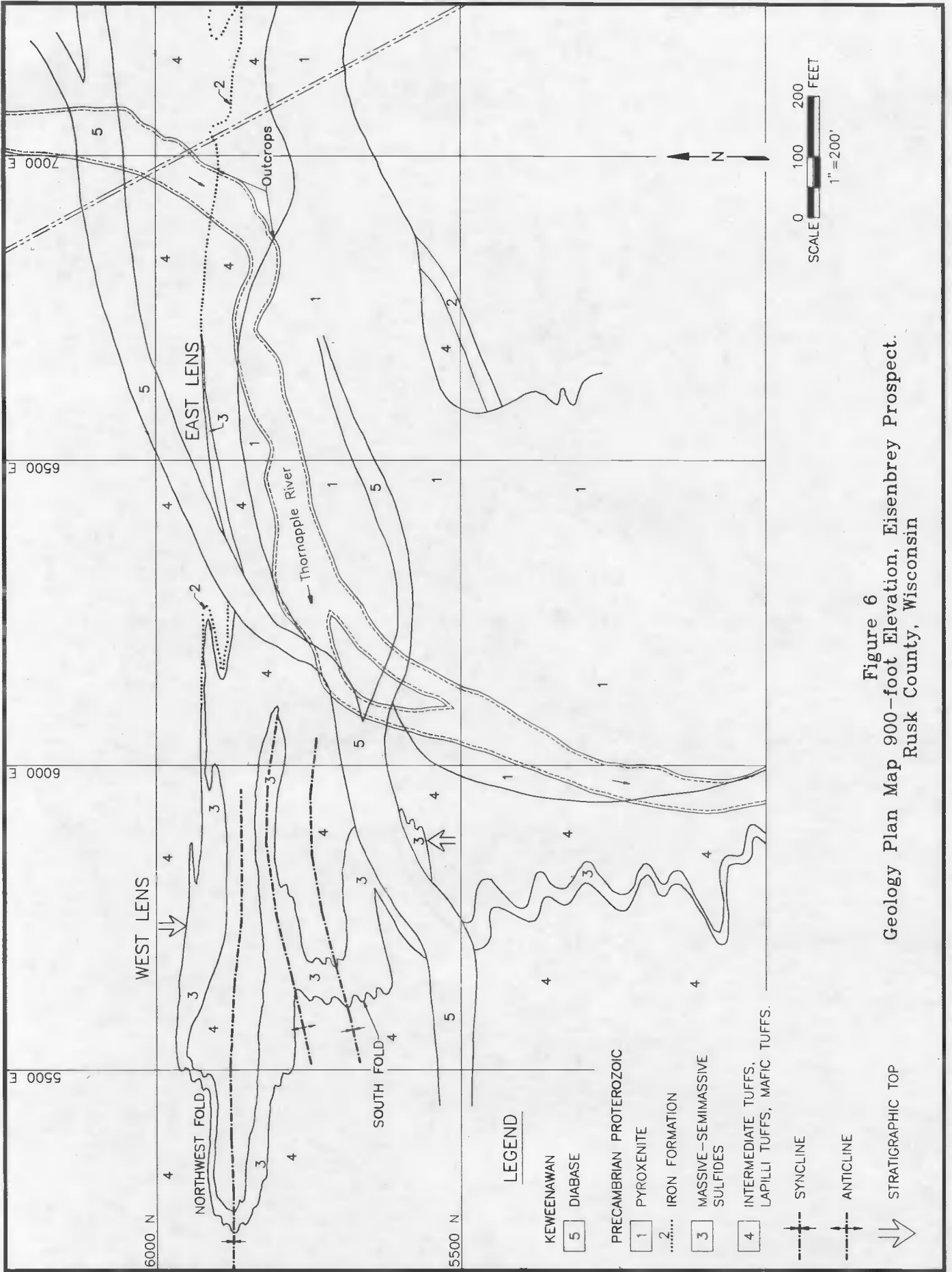


Figure 6  
 Geology Plan Map 900-foot Elevation, Eisenbrey Prospect,  
 Rusk County, Wisconsin

thin (1 to 2 inches) mafic ash beds have been isoclinally folded. Table 2 shows a strong similarity between Eisenbrey dacite tuffs and world wide average rhyolites (Nockolds, 1954).

**TABLE 2**  
A WHOLE ROCK ANALYTICAL COMPARISON BETWEEN EISENBREY  
DACITE TUFF AND RHYOLITE WITH WORLDWIDE AVERAGE  
RUSK COUNTY, WISCONSIN

Oxide Mineralization	Eisenbrey Dacite Tuff	Worldwide Dacite Average	Eisenbrey Rhyolite	Worldwide Rhyolite Average
SiO <sub>2</sub>	67.2	63.58	70.4	73.66
Al <sub>2</sub> O <sub>3</sub>	14.0	16.67	14.5	13.45
Fe <sub>2</sub> O <sub>3</sub> and FeO	6.63	5.24	4.54	2.00
MgO	2.84	2.12	1.62	0.32
CaO	2.60	5.53	2.34	1.13
Na <sub>2</sub> O	3.76	3.98	2.38	2.99
K <sub>2</sub> O	1.67	1.40	2.84	5.35
Partial Totals	98.70	98.52	98.60	98.90

**Dacite Lapilli tuffs.** Lapilli tuffs are interbedded with intermediate composition tuffs and graywackes stratigraphically beneath the Eisenbrey deposit. Stratigraphic thicknesses range from a few feet up to 75 feet. Felsic to intermediate lapilli fragments are generally well preserved although collapsed and elongated due to regional deformation. The lapilli tuff fragments consist of biotite, plagioclase, quartz, and amphibole within a matrix of biotite and amphibole. Lapilli fragments range in size from less than 0.5 inch to over 4 inches in length by 0.2 to 0.5 inches in width. Intense deformation has elongated the fragments so that they now plunge nearly vertically. Occasional fragments contain 1 to 6% disseminated pyrrhotite, pyrite, chalcopyrite, and magnetite grains.

The average mineral composition for the Eisenbrey dacite tuffs was obtained from 13 petrographic thin sections of core as shown on Table 3. These minerals consist of fine to coarse grains which have been metamorphosed into growths of subrounded to subangular grains. Minerals such as epidote and sericite are present in some examined rock thin sections. Opaque minerals consist of varying proportions of hornblende, garnet, sphene, and interstitial clay generally kaolinite. Intrusion of the gabbro sill and strong regional metamorphism have severely baked the host rock and "sweated" quartz into the matrix of the dacite tuffs. The tuffs were misinterpreted by this author and previous geologists during the 1970's as a rhyolite dome. Major oxide geochemistry needs to be conducted to quantitatively determine original rock composition.

**Anthophyllite-Magnetite Ore Horizon.** An anthophyllite-rich horizon is intimately associated with sulfide mineralization and is on strike of the iron formation outcrop (Figure 7). It is a distinctive rock consisting of sheaf-like bundles of radiating needles of anthophyllite within a fine grained, sugary, granular matrix of quartz, magnetite, antigorite, and cordierite.

The anthophyllite rock could possibly represent the altered footwall rock containing the stockwork zone. The Eisenbrey deposit has undergone penetrative deformation so that the mineralization has been stretched into a vertically plunging pencil-shaped deposit. The underlying stockwork and footwall alteration zone appears to have been transposed to a position that is now in lateral conformity with the stretched sulfide body similar to that seen at Flin Flon and Snow Lake,

TABLE 3  
MINERAL COMPOSITION PERCENTAGES OF  
VARIOUS EISENBREY ROCKS  
RUSK COUNTY, WISCONSIN

Mineral Name	Dacite Tuff	Anthophyllite Altered Rock	Mafic Tuff
Quartz	46	30	12
Cordierite		24	
Plagioclase	16		10
Anthophyllite		19	
Chlorite	6	7	12
Antigorite		10	
Epidote	1.5		1
Sericite	10		8
Muscovite	3	1.5	3
Carbonate	7		
Hornblende	2.5		2
Garnet	5.5	2.5	48
Sphene			
Andalusite			
Clay			
Magnetite		6	
Opaques	2.5	2.5	3
Totals	100	99.5	99

Manitoba (Lydon, 1984). Lydon also reported major additions of magnesium and iron to the alteration pipe and surrounding rock at Flin Flon and Snow Lake as suggested by the presence of a cordierite-anthophyllite assemblage. The anthophyllite-magnetite rock at Eisenbrey is found on either side of the northwest fold nose, partially shown in Figure 6 (Section 5500E) and Figure 7 (Section 5850E) and is similar to observations reported by Lydon (1984). This strongly suggests the Eisenbrey deposit has been isoclinally folded with stratigraphic footwall occurring on either side on the northwest fold nose. Table 4 shows the mineralogy on either side of the fold nose based upon rock thin section studies.

TABLE 4  
ANTHOPHYLLITE-MAGNETITE ROCK MINERALOGY ON EITHER OF THE NORTHWEST  
FOLD NOSE, EISENBREY DEPOSIT, RUSK COUNTY, WISCONSIN

Mineralogy	North of Fold Nose	South of Fold Nose
	%	%
Quartz	35	25
Chlorite	7	6
Sericite	3	0
Anthophyllite	15	25
Cordierite	30	20
Andalusite	2	0
Antigorite	0	20
Magnetite	6	2
Pyrrhotite	1	1
Pyrite	1	1
Total	100	100

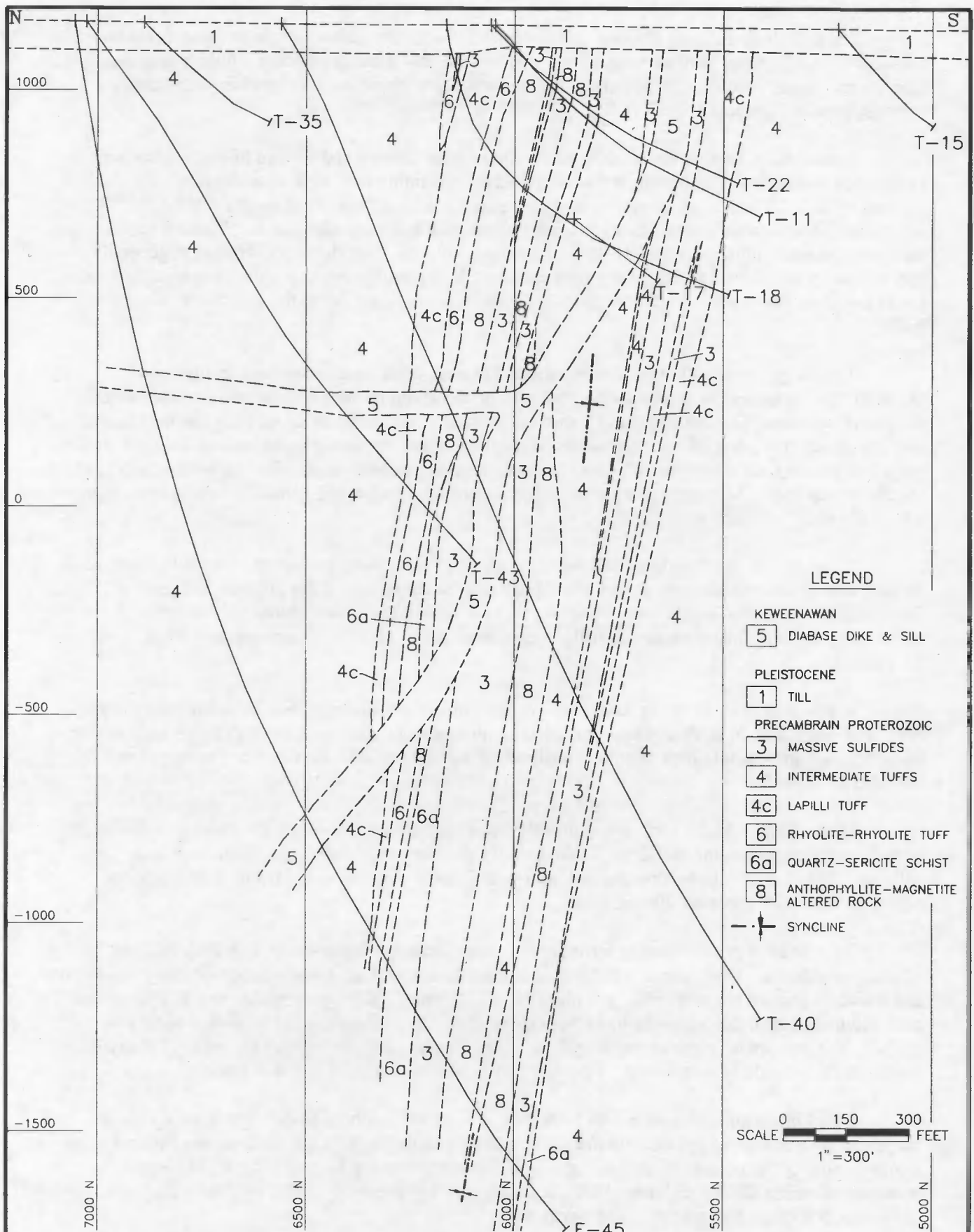


Figure 7  
 Geological Cross Section 5850E, Eisenbrey Prospect.  
 Rusk County, Wisconsin



Another distinguishing mineral is magnetite that occurs as euhedral grains up to 0.2 inch octahedrons. Magnetite content ranges from one to 15% and generally occurs within a granular mixture of quartz, cordierite, plagioclase, minor garnet, and an unknown clove-brown silicate mineral, possibly grunerite.

Immediately west of the south syncline the mineral content and texture of the ore horizon changes dramatically. The matrix is massive chlorite containing 8 to 15% magnetite as octahedral crystals up to 0.25 inch in diameter. Light gray patches or poikiloblasts of quartz, cordierite, plagioclase, and smaller magnetite crystals also occur within the chlorite matrix. These irregular intergrowths make up approximately 35% of the rock volume. Sulfide mineralization is generally low and makes up less than 2 to 5% of the rock volume. It is possible that this chlorite-magnetite horizon could represent the center of a feeder pipe that supplied mineralization to the Eisenbrey depositional basin.

**Metachert.** A few thin impure metachert horizons have been recognized in the core. Generally the metachert is closely associated with or incorporated within the above anthophyllite-magnetite horizon. The metachert has a distinctive sugary texture made up of recrystallized quartz and impurities consisting of minor amounts of plagioclase and ferromagnesian minerals. Occasionally, very fine bedding, characteristic of chert horizons reported at other deposits, has been observed in the Eisenbrey core. Magnetite and sulfide minerals are uncommon and generally average less than 5% of the rock volume.

**Rhyolite.** A rhyolite dome had been interpreted by previous geologists to have been intruded in the footwall beneath the east end of the deposit and outcrops east of the railroad bridge. Petrographic studies have indicated, however, that the rhyolite is a hard, dense almost baked dacite tuff or greywacke. Quartz content usually ranges from about 45 to 55% and averages 46%, as shown on Table 3.

A few thin rhyolite flows have been recognized and are distinguished by being extremely hard, and composed of a fine-grained to aphanitic groundmass with occasional (5%) phenocrysts of feldspar. A partial whole rock chemical analyses of a couple of rhyolite flows are averaged and included in Table 2.

**Mafic Tuffs.** Mafic tuffs are intimately associated with massive sulfide mineralization as thin beds flanking or within the sulfides. Table 3 shows that the mafic tuffs are rich in amphibole and chlorite. The rock is usually fine-grained, and well-foliated with indistinct lapilli fragments, and occurs as thin beds less than 20-feet thick.

Thin beds of predominantly ferromagnesian minerals are intercalated with much thicker beds of massive sulfides. One sample taken within the northwest fold nose was petrographically examined and found to contain chlorite (5%), anhydrite (15%), gypsum (20%), serpentine (possibly antigorite after olivine) (10%), dolomite (10 to 15%), calcite (3 to 5%), magnetite (15 to 20%), and pyrite (15%). The amount of gypsum and anhydrite varies considerably throughout the rock. Likewise serpentine is irregularly distributed. Talc has also been detected by X-ray defraction.

**Iron Formation.** The term iron formation is used at Eisenbrey to describe a rock rich in magnetite with accessory epidote, garnet and amphibole (actinolite). Thin sections were prepared on a core sample collected east on strike of the iron formation outcrop in drill hole 9. The rock consisted of quartz (25%), chlorite (10%), actinolite (20%), garnet (5-10%), epidote (10%), carbonate (5%), magnetite (20%), and pyrite (2%).

Magnetite is concentrated into thin one to two-inch thick black bands consisting of 30 to 70% magnetite. Actinolite with epidote and garnet enclose the magnetite-rich beds, whereas chlorite occurs as veinlets and disseminated grains throughout the host rock. Light gray to white beds of nearly pure quartz could represent recrystallized chert.

Iron formations have been interpreted to strike for over two miles into a series of isoclinal folds, with associated minor amounts of sulfide mineralization, along the eastern-most strike extension. Much of the Eisenbrey magnetic anomaly, particularly on the south side, is due to iron formation. It is unclear whether the iron formation in the area is one horizon that has been folded and faulted, or whether more than one unit of iron formation is present.

Quartz-Sericite Schist. A number of thin, less than 20-foot thick, quartz-sericite schist beds or alteration zones have been intersected during the 1994-1995 deep drilling program. The schists are light gray, highly foliated and in close association with sulfide mineralization located in the south syncline. Sulfide content is low within the schists, averaging about 10 to 15%. Quartz-sericite schist is the dominant lithology of the ore horizon at the Flambeau orebody, but this rock type or alteration zone is uncommon at Eisenbrey.

Gabbro. A sill or multiple sills of gabbro occur within the hangingwall of the axial portion of the steeply plunging Eisenbrey syncline axis. It consists of a medium-to coarse-grained recrystallized mixture of feldspar (35%), hornblende (35 to 40%), epidote (10%), and chlorite (5 to 10%). A chilled margin is present having a true thickness of 3 to 5 feet. Closer to the surface, the gabbro has been largely altered to chlorite (up to 60 to 65% of the rock volume).

Intrusion of the gabbro greatly elevated the temperature of the enclosing volcanoclastic and sedimentary rocks. This could account for the wide variety of amphibolite facies minerals seen in the deposit and its host rocks.

Diabase Dikes. Keweenaw diabase dikes and sills are fresh, medium-grained, holocrystalline, intergranular, non-porphyrific rock having a typical diabasic texture. The rock consists of plagioclase (35%), interstitial chlorite (25%), biotite (3-5%), muscovite (5%), hornblende (1-2%), augite (10%), olivine (10%), serpentine (2-3%), carbonate (5%), and ilmenite (3%). An 80-foot thick dike striking N 60°E and dipping 65° NW intersects the Eisenbrey deposit as shown on Figure 6. The dike splits on the east end of the West lens and also forms a sill in the footwall of the West lens (Figure 7).

Pleistocene Till. Approximately 60 feet of unconsolidated glacial outwash materials blanket the Eisenbrey deposit and surrounding area, except where removed by the downward and westward migrating Thornapple River.

## STRUCTURE

The structure of the Eisenbrey deposit is complex based upon outcrop observations, and interpretation of geophysical and drill core data. The current geometry of the deposit is interpreted to be the result of isoclinal folding with possible fault offsets. This interpretation is supported by the following observations:

- i) a one-to two-inch thick mafic tuff bed found in the outcrop east of the railroad bridge has been tightly isoclinally folded and has a near-vertical axial plunge; and,
- ii) in the same outcrop elliptically shaped rod structures that also have a vertical plunge, and S planes that show a very steep plunge to the east.

The iron formation also shows evidence of isoclinal folding as described above in subsection on Site Geology. In addition, mineral zoning briefly described in the Mineralogy subsection suggests the presence of folding due to repetition of zones within drill holes. Therefore, the deposit is interpreted to strike west from the outcrop through the East massive sulfide lens (Figure 6). A north to northwest striking fault is believed to have offset the gabbro and mineralized horizon. Further evidence for significant faulting comes from hole 4 which contains a large gouge zone where rock foliation is rotated on either side of the structure. This fault is coincident with the northwest striking magnetic response; however, offsetting relationships, if present, are unclear.

### ALTERATION

The Eisenbrey deposit has been subjected to multi-phased hydrothermal and metamorphic processes. To date, no stringer zone or alteration pipe has been definitively recognized. It is interpreted that there is a thermal metamorphic aureole caused by intrusion of a gabbro sill superimposed upon Penokean regional upper greenschist metamorphism. As a result, some unusual mineral assemblages are present, such as chlorite-tremolite-forsterite and pyroxene-garnet-quartz. Regional metamorphism has produced a suite of silicate minerals that include actinolite, albite, garnet, andalusite, anthophyllite, chlorite, cordierite, quartz and sericite-muscovite. The relative abundance of pyrrhotite is interpreted to be a product of localized thermal metamorphism.

The host rocks have not been altered by supergene processes although small patches of supergene enrichment have been cored at the top of the deposit.

### FORM OF THE DEPOSIT

The geometry of the Eisenbrey deposit is shown in plan in Figure 6; the deposit occurs as pinched and remobilized massive sulfide enlargements at fold noses within impure chert, anthophyllite, and iron formation host rocks. The isolated East lens has probable structural complications at depth whereas the west lens is a complex arrangement of two synclines open to the east with an intervening very tightly folded anticline. The south syncline is a convoluted, accordion type fold over a north-south direction of almost 200 feet.

The ore horizon continues west of the east lens, through a pyrite-sphalerite lens and into a tight syncline referred to as the northwest fold. The south limb of this syncline strikes east into a very tight anticline whose south limb returns west one half the distance of the north limb to enter into a complex and convoluted syncline known as the south fold. The fold nose within massive sulfide mineralization is approximately 170 feet north-south. The south limb may either continue south into an iron formation (Lindberg) or continue east to be intruded by the gabbro (May).

In cross section 5850 East, the massive sulfide lenses extend for at least 2500 feet below surface as near-vertical plunging rods, as shown on Figure 7. The length of the deposit, including the east and west lenses, is 3300 feet prior to folding. Isoclinal folding has compressed the once tabular deposit into an area 400 north-south by 1000 east-west.

## MINERALOGY

Base metal mineralization occurs within both pyrrhotite and pyrite matrices. Pyrrhotite is found within and on the south side of the anticline and on the west end of the south syncline nose, and minor pyrrhotite occurs on the south side of the northwest syncline. Chalcopyrite is generally associated with pyrrhotite, whereas pyrite hosts most of the sphalerite and gold mineralization. The Northwest syncline is predominantly pyrite, as well as the north side of the anticline and south side of the South syncline.

In shallow drilling the pyrrhotite occurs as massive, amorphous lenses containing irregular grains and layers of chalcopyrite. Chalcopyrite also occurs as finely disseminated grains within the matrix. Most of the copper values, however, are within the larger chalcopyrite patches, many of which halo single or clusters of pyrite cubes. Chalcopyrite can also occur as conformable blebs, some of which are irregular in shape and cross cut pyrrhotite laminations. The pyrrhotite-chalcopyrite zone is restricted to the nose of the south fold and has been intersected at depth. Figures 8 and 9 show the general distribution of copper and zinc, respectively, on the 900-foot level.

Pyrite occurs as subeuhedral to anhedral grains with interstitial sphalerite and minor chalcopyrite. Chalcopyrite is found as microscopic grains within sphalerite or as small irregular lenses interbedded with pyrite. Typical sphalerite-pyrite layering, common to many massive sulfide deposits, is present, but not well developed.

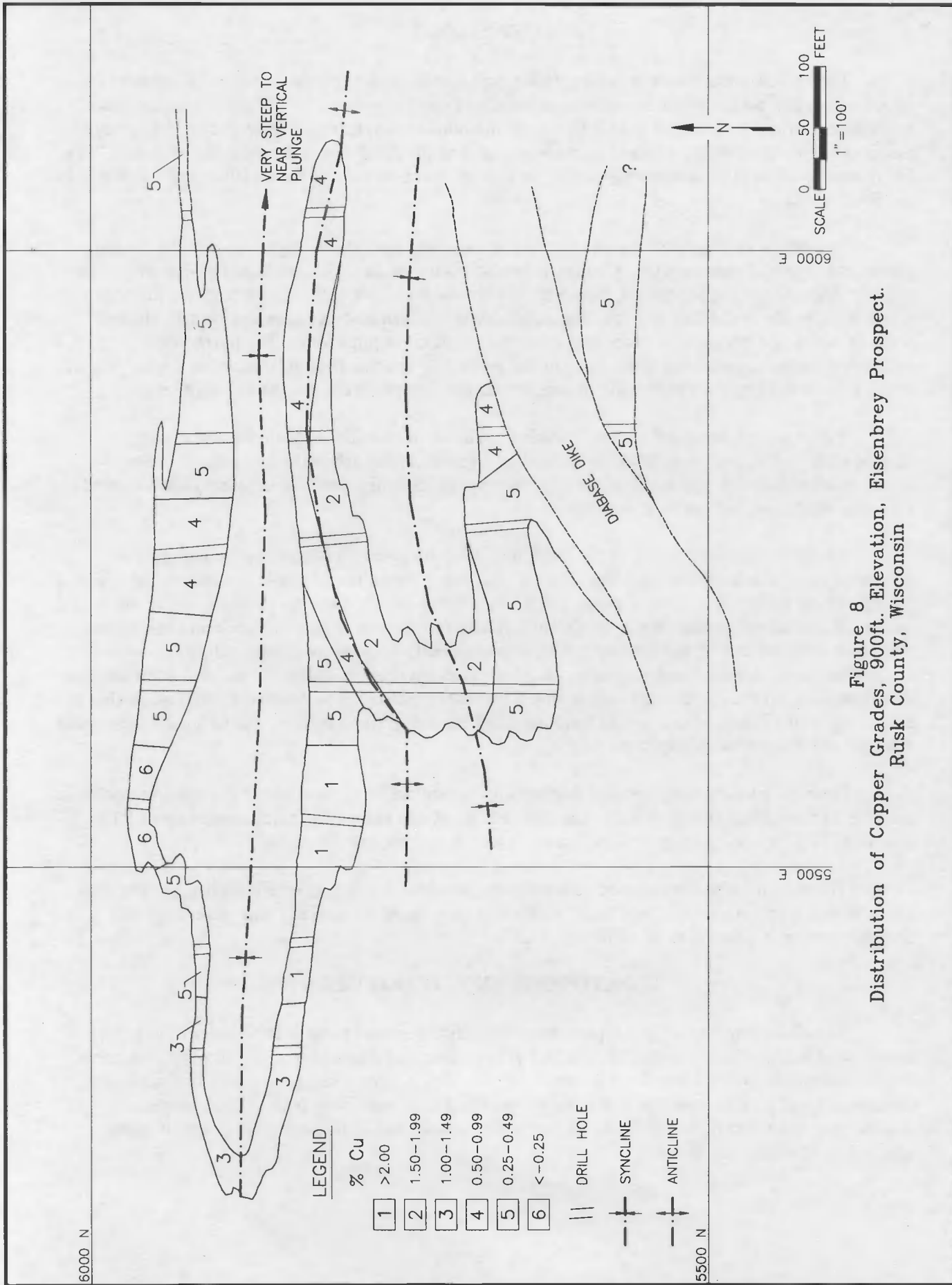
At depth and along strike of the south fold nose the pyrrhotite-chalcopyrite and pyrite-sphalerite mineral zoning becomes less distinct. Instead, pyrrhotite and pyrite are intermixed within a ragged almost shredded texture of wispy pyrrhotite patches within medium- to fine-grained subhedral pyrite. Wisps of pyrrhotite vary in size from a fraction of an inch to one to two inches. Some areas consist of large masses of amorphous pyrite with essentially no base metal mineralization, whereas some other zones contain thick sequences of cherty chalcopyrite. A distinctive mineral zone contains abundant chalcopyrite-pyrite fragments within a pyrrhotite matrix. The relatively small grain size at Eisenbrey is surprising, as one would have expected coarser grained sulfides due to amphibolite grade regional and contact metamorphism.

Near the surface there are thin interbeds of metadolomite present within the massive sulfide in the nose of the sulfide-rich anticline. The beds are about one to two feet thick consisting of 80% dolomite, 10% veined chlorite, 5% magnetite, 3 to 4 % pyrite, and 1% epidote.

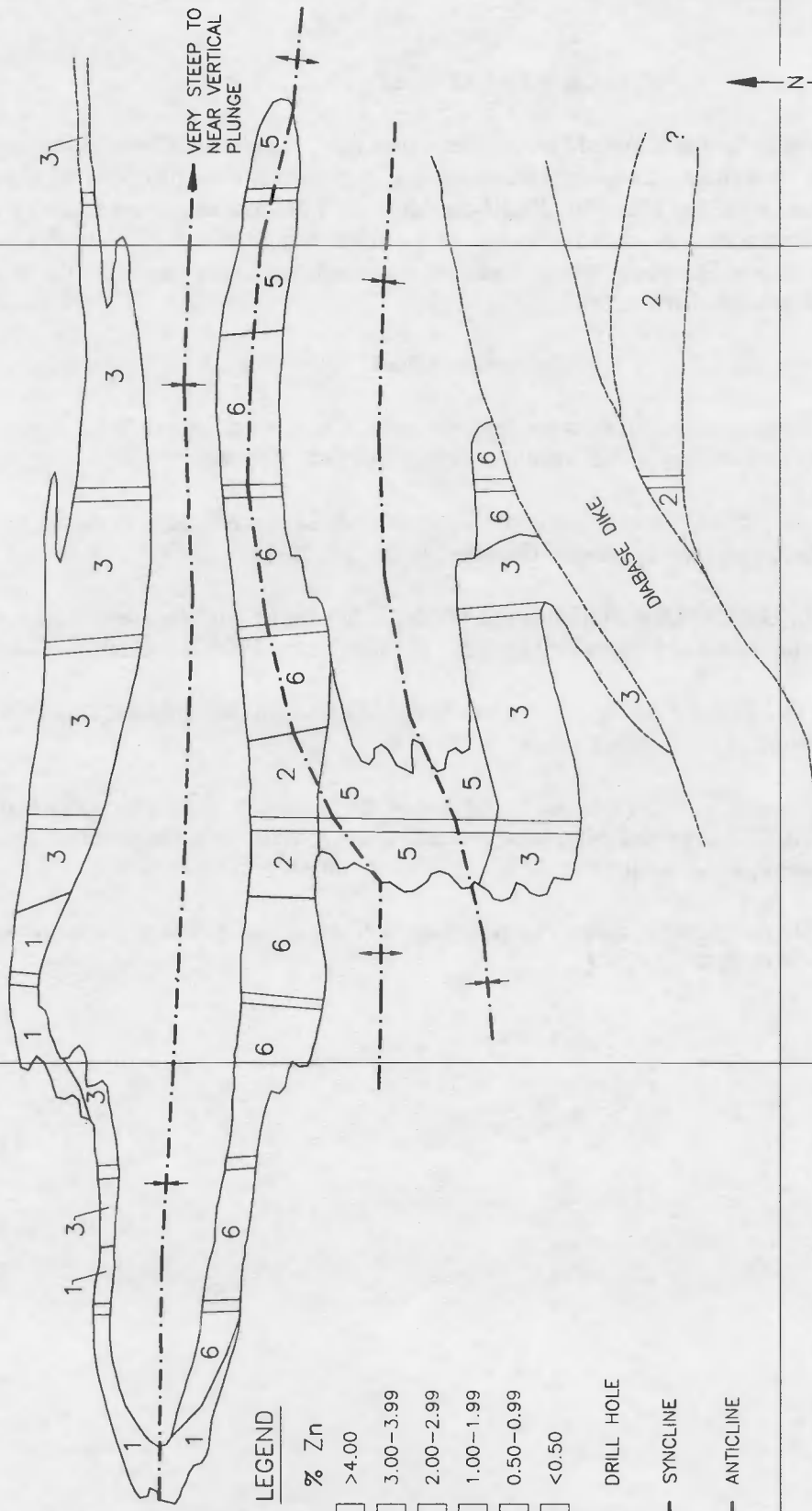
The relationships between the above mineral zones and structure of the deposit are not clear. Identification of a copper-rich "hot spot" within this very large structurally and mineralogically complex system is proving to be difficult.

## CONCLUSIONS AND COMPARISONS

The Eisenbrey deposit is a typical massive sulfide deposit in that it is hosted within a thick sequence of volcanoclastic lapilli tuff, tuff and graywackes, and capped by a gabbro sill or intrusive. It is an unusual Wisconsin massive sulfide deposit because it is very large, structurally complicated, contains unusual silicate minerals and sulfide textures, and is associated with an iron formation. Bedded magnetite occurs on the flanks of the sulfide system and as disseminated grains or blebs adjacent to or within the deposit.



6000 N



**LEGEND**

% Zn

- 1 >4.00
- 2 3.00-3.99
- 3 2.00-2.99
- 4 1.00-1.99
- 5 0.50-0.99
- 6 <0.50

|| DRILL HOLE

—+— SYNCLINE

-+ ANTICLINE

5500 N

5500 E

6000 E

SCALE  
0 50 100  
FEET  
1" = 100'

Figure 9  
Distribution of Zinc Grades, 900ft. Elevation, Eisenbrey Prospect,  
Rusk County, Wisconsin

In detail the structure, mineralogy, texture, and metal grades of the Flambeau and Eisenbrey deposits are very dissimilar. A comparison between the similarities and differences are listed on Table 5.

### ACKNOWLEDGMENTS

The author wishes to thank Tom Myatt, general manager, Flambeau Mining Company for allowing this paper to be written. Considerable advise and suggestions were provided by Russ Babcock, Stephen Dinkowitz, Jay Hammitt, Paul Schmidt, Paul Lindberg and Gene LaBerge and to Tammy Fredrickson who somehow managed to put all the comments together. Finally this paper is dedicated in memory of Ned Eisenbrey whose foresight and persistence resulted in the discovery of an interesting and significant metal resource.

### References Cited

- Babcock, R., 1996, History of Exploration for Volcanogenic Massive Sulfides in Wisconsin: Institute on Lake Superior Geology, 42nd Institute, 1996 Field Trip Volume.
- DeMatties, Theodore A., 1994, Early Proterozoic Volcanogenic Massive Sulfide Deposits in Wisconsin: An Overview: Economic Geology, v. 89, p1122-1151.
- LaBerge, G. L., 1996, General Characteristics and Geologic Setting of the Wisconsin Magmatic Terranes: Institute on Lake Superior Geology, 42nd Institute, 1996, Field trip volume.
- Lydon, J. W., 1984, Ore Deposit Models-8. Volcanogenic Massive Sulfide Deposit Part 1: A Descriptive Model; Geoscience Canada, V.11, N.4.
- May, E. R., and Dinkowitz, S. R., 1996, An Overview of the Flambeau Supergene Enriched Massive Sulfide Deposit - Geology and Mineralogy, Rusk County, Wisconsin: Institute on Lake Superior Geology, 42nd Institute, 1996 Field Trip Volume.
- Nockolds, S. R., 1954, Average Chemical Compositions of Some Igneous Rocks: Bulletin Geol. Soc. Am. 65, pp. 1007-1032.

TABLE 5  
 COMPARISON BETWEEN THE FLAMBEAU AND EISENBREY DEPOSITS  
 RUSK COUNTY, WISCONSIN

	Flambeau Orebody	Eisenbrey Deposit
<b>A. Depositional Environment</b>		
Ore Horizon	Quartz-Senecite Schist or rhyolite tuff. Metacherts common	Iron formation with bedded magnetite or disseminated magnetite with anthophyllite. Impure cherts
Host Rocks	Intermediate dacite tuffs altered to andalusite-biotite Schist with pillow lavas in stratigraphic hangingwall.	Intermediate dacite tuffs and lapilli tuffs capped by gabbro sill.
Alteration Pipe	None recognized; could be eroded	None recognized but presence suspected
Precambrian Erosion	Probably deeply eroded; looking at roots of a much larger system.	Slightly eroded; looking at the top of a very large system.
Overburden	0 to 20 feet of Cambrian sandstone and 12 to 30 feet Pleistocene Till.	60 feet of Pleistocene Till.
Outcroppings	Subcrop of weakly mineralized metachert and quartz-senecite schist under east side of Flambeau River.	Weakly mineralized iron formation, volcanoclastics, and pyroxenites on Thomapple River bank.
<b>B. Structural Setting</b>		
Folding	Structurally simple-on limb of large isoclinal fold.	Structurally complex - tight isoclinal folding.
Faulting	Strong evidence of prenecontemp - oraneous localized structures; little evidence of post depositional faults	Strong evidence of significant faulting with foliation dip changes on either side of gouge.
Foliation	Strongly Foliated	Moderately Foliated
Strike and Dip	N45° E, 75° NW; probably overturned.	E-W, dipping very steeply north or vertical with near vertical plunge.
Dikes	None	Thick diabase dikes and sills occupying probable NE regional tension cracks.
Preservation of Depositional Features	Pillows, volcanic bombs, lapillis, graben and horst features, and facies changes well preserved.	Lapillis well preserved and highly rodded.



	Flambeau Orebody	Eisenbrey Deposit
<b>C. Mineralogy</b>		
Metamorphic Grade	Upper greenschist to lower amphibolite.	Amphibolite grade.
Protore	Pyrite with chalcopyrite, minor sphalerite and trace pyrrhotite.	Pyrite with sphalerite and pyrrhotite with chalcopyrite.
Sulfide Halo	Disseminated pyrite with chert up to 300 feet wide.	Halo restricted to anthophyllite magnetite rock package. Thickness complicated by folding.
Magnetite	Trace to few percent of magnetite in mafic rocks. None associated with ore.	Several percent magnetite in some massive sulfides, host rock, and along strike in iron-formation.
Supergene Enrichment	Extensive enrichment 80 to 185 feet beneath subcrop.	Minor enrichment within 25 feet of subcrop.
Gossan	Well preserved gold, silica, iron oxide, and ankerite gossan.	Minor gossan with iron oxides and minor precious metals.
Precious Metals	High gold content associated with chalcopyrite.	Low precious metal content with gold associated with sphalerite.
Gold Cap	Precious metal cap on top of massive sulfides.	None recognized.
<b>D. Massive Sulfide Textures</b>		
Chief Sulfide texture	Well bedded with remobilized chalcopyrite in semi massive protore. Occasional sulfide or cherty fragment.	Poorly bedded. Massive pyrite and pyrrhotite with large pyrite cubes in pyrrhotite rimmed with chalcopyrite. Whispy pyrrhotite and magnetite. Numerous magnetite and cherty/volcanic fragments.
Chalcopyrite	In massive beds to ragged patches in semimassive protore	Remobilized and recrystallized around pyrite cubes, disseminated in pyrrhotite, or finely disseminated in sphalerite.
Sphalerite	Well bedded - massive beds	Interstitial grains with pyrite, weakly bedded.
<b>E. Economic Geology</b>		
Size	2400 feet long, 45 feet thick 900 feet below subcrop. Approximately 6 million tons total resource.	Approximately 1500 feet long, upto 200 feet thick and open below 3000 feet. Plus 50 million ton resource.
Protore	Insufficient size to support a mill. 3% Cu, 2% Zn.	Sufficient size but low grade. 1% Cu, 2.5% Zn.
Supergene	Economical. 1.8 million tons at 10% Cu, 0.1 opt Au.	Insufficient tonnage.

## GEOLOGICAL SUMMARY - CRANDON DEPOSIT

By A. J. Erickson, Jr.  
Exxon Coal & Minerals Co., Houston, TX

and

R. Côté  
Rio Algom Exploration Inc., Val d'or, Quebec, Canada

### INTRODUCTION

Crandon Mining Company, a Wisconsin general partnership of subsidiaries of Exxon Coal and Minerals Company (Houston, Texas) and Rio Algom Limited (Toronto, Ontario, Canada) is in the process of seeking the required local, state, and federal agreements, approvals, and permits to mine the Crandon volcanogenic zinc-copper sulfide deposit.

The deposit, located in Forest County, Wisconsin, is approximately 5 miles south of the town of Crandon, and 2 road miles east of State Highway 55, on Little Sand Lake Road.

The deposit was discovered in 1975 by an Exxon Coal and Minerals predecessor company, Exxon Minerals Company (Schmidt *et al.*, 1978; May and Schmidt, 1982; Lambe and Rowe, 1987; and Schmidt, 1991). As described by Schmidt (1991), Exxon had been active in the Lake Superior region since the late 1960's and initiated work in northern Wisconsin in 1970 with reconnaissance mapping and airborne electromagnetic surveying (INPUT). A number of targets were identified and drilled. Additional (INPUT and other) airborne surveys were flown in 1974 over areas interpreted to contain favorable felsic volcanics. This work led to the identification of other anomalies and further land acquisition, including the Skunk Lake target. Follow-up ground geophysical work was carried out in the spring of 1975 which confirmed the presence of a bedrock conductor. Drilling of the target was initiated in June 1975 and discovery was made with the first hole. The deposit was subsequently renamed the Crandon Deposit after the nearby town of Crandon. The target was the 25th prospect drilled by Exxon over a 5 year period of exploration (1970-1975) in Wisconsin after an expenditure of approximately \$2.5 million.

Since discovery, a total 340,000 feet of drilling of various types and diameters has been completed in 272 holes in and about the deposit. All interpretive work is based on this drilling as the nearest outcrops are several miles from the deposit.

### REGIONAL GEOLOGY

The deposit is hosted by early Proterozoic rock of the Precambrian Southern Province of the Canadian Shield in the east-west trending Rhineland-Ladysmith Greenstone Belt (Schmidt *et al.* 1978; May and Schmidt 1982). The belt is between 30 and 50 miles wide (N-S) and approximately 200 miles long (E-W) extending from the towns of Ladysmith in the west to Pembine in the east. (Sims, 1984, refers to the area as the Ladysmith-Pembine volcanic belt). The northern portion of the belt consists of mafic metavolcanic rocks, basalts, locally pillowed, basaltic andesites, flows, tuffs, some gabbroic rocks, and associated granites, tonalites, and granite gneiss. More felsic to mafic pillowed flows, dacitic to rhyolitic tuffs, porphyries and dikes are present in the southern portion of the belt (Sims, 1992).

The Rhinelander-Ladysmith greenstone belt forms the most northern portion of the Wisconsin Magmatic Terranes in the Penokean fold belt, south of the Niagara Fault as shown on Figure 1 (Hoffman, 1989; Sims *et al.*, 1989; Sims, 1992; and DeMatties, 1994). The magmatic terranes are complex, poorly exposed, and have been divided into three "subterrane" identified from north to south as, the Ladysmith-Pembine Belt, the Chippewa-Wausau Belt, and the Marshfield-Stevens Point Belt (Sims, 1984). More recently, Sims *et al.* (1989), and Sims (1992), combined the two northern "subterrane" into the Pembine-Wausau Terrane. The southern belt has been renamed the Marshfield Terrane.

The juxtaposed terranes and contained sulfide deposits, as shown in Figure 1, are interpreted to be the result of plate tectonic processes during the early Proterozoic. These terranes are believed to be the remnants of volcanic arc - continent and volcanic arc - volcanic arc subduction and plate collision zones.

This accretion of the plates was initially at a juncture now referred to as the Niagara Fault Zone with subsequent accretion of a second plate along the Eau Pleine Shear Zone. This deformation and accretion occurred during the Penokean Orogeny, dated at approximately 1860 to 1840 Ma (Van Schmus, 1975; Schulz, 1984; Hoffman, 1989; Sims *et al.*, 1989; Sims, 1990; Klasner *et al.*, 1991).

The recent summary by LaBerge (1994), provides a simplified discussion of these complex Proterozoic plate tectonic relationships, and the Lake Superior regional geology.

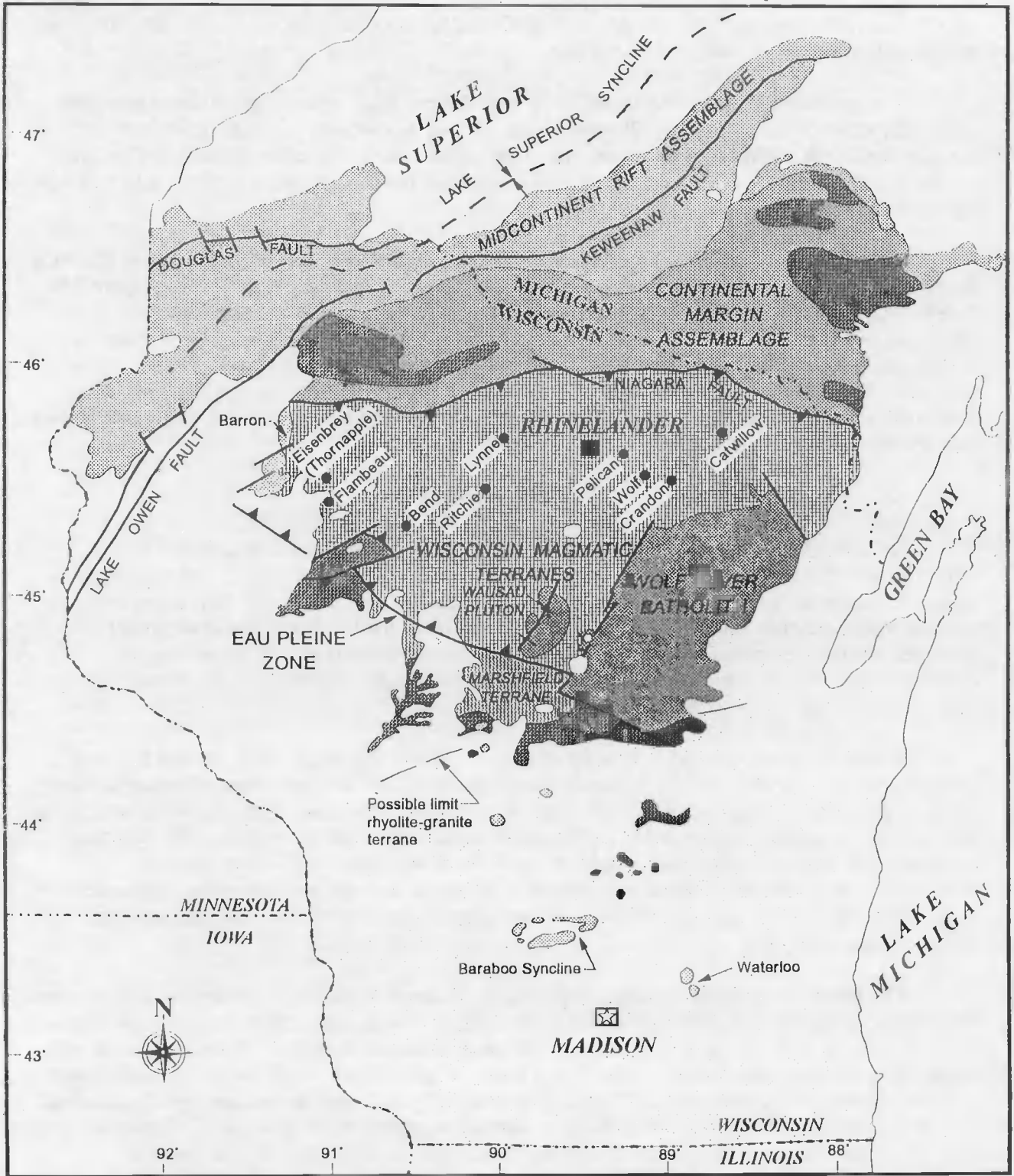
### GENERAL DEPOSIT GEOLOGY

The following details are largely summarized from the descriptions of Schmidt *et al.* (1978), May and Schmidt (1982), Rowe and Hite (1984), and Lambe and Row (1987). Their work is supplemented by more recent work by the authors. Specific citations from all individual items are commonly not included in this summary and the reader is encouraged to consult the references for further details.

The Crandon deposit is a "typical" volcanic hosted sulfide deposit as described in reviews by Solomon (1976), Franklin *et al.* (1981), or Lydon (1988), of the "primitive" zinc-copper rich type using Hutchinson's (1980) classification. The deposit consists of two major styles of mineralization 1) a syngenetic, commonly laminated, zinc-bearing, pyrite-rich, sulfide zone which is partially underlain by 2) an epigenetic, cross cutting zone of copper-bearing, quartz-pyrite-chalcopyrite stringer mineralization in altered volcanic rocks stratigraphically beneath the zinc mineralization.

Early published reserve estimates (Schmidt *et al.*, 1978; May and Schmidt, 1982; Rowe and Hite, 1984; and Lambe and Rowe, 1987) have generally included both the zinc and copper mineralization of the primary sulfide facies. The referenced tonnage is in the 55 to 65 million ton range with corresponding grades reported for this material as slightly over 1% copper, 5% zinc, and only minor amounts of lead, silver, and gold. The reserve estimate for the conformable syngenetic zinc mineralization alone is estimated as 30 million tons containing 9.4% zinc and 0.4% copper (Anon, 1994).

At the property scale, the deposit is conformably contained in a sequence of mafic, intermediate, and felsic volcanic rocks. Pyroclastic units are dominant but numerous intercalated flows have been noted within the volcanic sequence. Chert, argillites, bedded sulfides, and volcanoclastic sandstone intercalations probably indicate periods of quiescence during formation of



- Sedimentary rocks of Paleozoic age
- PROTEROZOIC**
- Middle Proterozoic (Keweenaw) mafic igneous & sedimentary rocks of Midcontinent rift system (~ 1,100 Ma)
- Anorogenic granites, syenite, & anorthosite (1470 -1525 Ma)
- Baraboo, Barron, Waterloo quartzites (age uncertain) (<1750 Ma?)
- Central Wisconsin rhyolites & granite rocks (~1,760 Ma)

- WISCONSIN MAGMATIC TERRANES**
- Island-arc metavolcanic & granitoid rocks in Pembine-Wausau terrane (1,834-1,880 Ma); Includes post-tectonic granitic rocks (1,760 Ma)
- Island-arc metavolcanic & granitoid rocks (1,835-1,890 Ma)
- CONTINENTAL MARGIN ASSEMBLAGE**
- Marquette Range Supergroup (1,820-2,100 Ma)
- ARCHEAN**
- Basement gneiss, granite, & greenstone (2600 - 3550 Ma)

- High-angle fault
- Thrust fault - Possible suture
- Sulfide Deposits

0 75 MILES

### TECTONIC MAP SOUTHERN LAKE SUPERIOR REGION

Modified after Sims, 1992

Figure 1

the volcanic pile. Syn-and post-volcanic, commonly mafic but occasionally felsic, intrusive dikes and sills constitute a small portion of the sequence.

The host volcanoclastic assemblage along with the contained sulfide deposit strike generally east-west (N85°W) and dip steeply (70°-90°) north. Relict depositional features, internal mineral zonation within the sulfide mineralization, and gross sulfide zone relationships consistently indicate a normal, north facing volcanic sequence. A small portion of the deposit on the extreme west end is steeply overturned to the south.

Rowe and Lambe (1986), have informally divided the volcanic package into a lower Hemlock Creek Group, which contains the Crandon deposit, and an upper Swamp Creek Group. Figure 2 is their reconstructed stratigraphic column and is included to provide a general summary of the lithologies and stratigraphic relationships. Detailed description of the units, discussions of the stratigraphic relationships, and interpretations of the genesis of the units are included in the above reference. Discussions here will be limited to the deposit features in the Crandon Unit with its conformable zinc mineralization, and to the stringer copper mineralization within the underlying Sand Lake Formation.

### SULFIDE DEPOSITS

As indicated, the two major mineralization types of the Crandon deposit include 1) conformable, locally laminated, syngenetic, zinc-rich pyritic sulfide lenses and 2) cross cutting, epigenetic copper-bearing stringer sulfides commonly beneath the zinc deposit. Fine grained felsic and intermediate pyritic ash and lapilli tuffs, cherts, laminated pyritic cherts, and black thinly laminated pyritic argillite are locally interbedded with the conformable sulfide mineralization. Overprinting of stringer copper zone mineralization on the zinc mineralization is occasionally seen near the base of the zinc-rich sulfide zones.

Crandon zinc mineralization consists of three or locally four sub-parallel stacked lenses of sulfide (Côté *et al.*, 1994), which are locally interbedded with tuffs and argillites. The lenses, occur either as unique horizons separated by epiclastic or pyroclastic lithologies containing lesser amounts of total sulfides, as shown on section A - A', Figure 4, or as stacked sulfide horizons with common boundaries, as shown in portions of section B - B'. The sulfide bands contain sphalerite as continuous or discontinuous laminae and patches in laminated to more massive pyrite. Laminae or seams of chalcopyrite or galena are present but less common and are often cross-cutting due at least in part to late remobilization.

The mineralization was cyclically deposited by pulses of sulfide-rich emanations in a restricted basin characterized by a shallow western half and a deeper central portion. At the eastern extremity of the deposit the sulfides thin and pinch out in the shallow end of the basin. Relationships are well illustrated on the mine level plan, Figure 3, at a depth of approximately 665 feet below surface and on cross sections A - A', B - B', and C - C' (Figure 4). Figure 5 provides an east-west longitudinal projection, showing the distribution of the zinc mineralization at a >3% zinc cutoff. The cyclicity of mineralization is shown in simplified form in the three sections as interpreted from internal stratigraphy and assay data analysis. This cyclicity has been clearly documented in recent logging and analysis of core from the latest drilling program and re-analysis of earlier drilled core.

These three main stratigraphically stacked sulfide lenses are laterally very continuous and can be traced in the majority of holes. The correlation diagram D - D' on Figure 6 highlights the internal sulfide stratigraphy and relative zinc and copper values as they relate to the specific sulfide facies

SWAMP CREEK ASSEMBLAGE

HEMLOCK CREEK ASSEMBLAGE

dg

DUCK LAKE GABBRO (dg) GENERALLY 25 M IN WIDTH.



INTRUSIVES

L: UNALTERED AND UNFRACTURED

U: UNDIFFERENTIATED. GENERALLY ALTERED DIKES OF WHICH SOME COULD BE SMALL FLOWS

ft

FOREST UNIT (ft) A SEQUENCE OF EPICLASTIC ARGILLACEOUS CONGLOMERATE AND SANDSTONE CONSISTING OF GRANITE CLASTS AND VOLCANIC CLASTS. LOCAL FLOWS AND TUFF.

pn

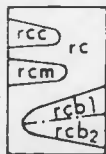
PINE UNIT (pn) A BASINAL SEQUENCE OF CHERTY TUFF. CHERT AND SILICIFIED TUFF. BECOMES MORE SERICITIC, PYRITIC, AND ARGILLITIC TO THE WEST.

ln

LINCOLN UNIT (ln) PORPHYRITIC RHYOLITIC FLOWS WITH INTERBEDDED TUFF, CHERT, AND ARGILLITE.

sk

SKUNK LAKE UNIT (sk) A BASINAL SEQUENCE OF SLUMPED AND CONTORTED CHERT AND ARGILLACEOUS TUFF LAMINAE. SOFT SEDIMENT FEATURES ABUNDANT. LOCAL INTERBEDDED CHERT OR TUFF, AND LOCALLY UP TO 10% SULFIDES.



RICE LAKE UNIT (rc) A SERIES OF VOLCANIC DEBRIS FLOWS AND EUTAXITIC ASH FLOWS.

BLUEBIRD SUBUNIT (rcb<sub>1</sub>) BLOCKY TO TABULAR CHLORITIC FRAGMENTS, (LOCALLY EXHIBITING ATTENUATION), MATRIX PREDOMINANTLY FELSIC; (rcb<sub>2</sub>) CHLORITIC FRAGMENTS MODERATELY ATTENUATED, POSSIBLY WEAKLY WELDED.

CARRIDGE SUBUNIT (rcc) DOMINANTLY WELDED ASH FLOWS ALTHOUGH DEGREE OF WELDING VARIABLE. INTERBEDDED TUFF COMMON.

MILLSTREAM SUBUNIT (rcm) BASINAL ENVIRONMENT. USUALLY CHERTY TUFF. LOCAL REWORKED TUFF. NO SULFIDES.

ok

OAK LAKE UNIT (ok) A BASINAL SEQUENCE CONSISTING DOMINANTLY OF CHERTY TUFF AND SERICITIC TUFF CONTAINING 1 TO 5% STRATABOUND PYRITE. LOCAL INTERBEDDED CHERT OR CHLORITE-SERICITE TUFF.



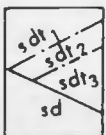
MOLE LAKE UNIT (ml) A FINE TUFF CONTAINING ONLY MINOR COARSE PYROCLASTICS. THE EAST HALF OF THE FORMATION IS A FINE CHLORITIC TUFF. THE WEST HALF IS A SILTY, HOMOGENEOUS, SERICITE-CHLORITE REWORKED TUFF, CONTAINING 0 TO 4% PYRITE. INTERBEDDED CHERT IS COMMON IN THE WEST HALF.

PROSPECT SUBUNIT (mlp) FELSIC DEBRIS FLOWS. GENERALLY 4 TO 16 MM FELSIC DEBRIS IN A FINE CHLORITIC MATRIX.

EAGLE SUBUNIT (mle) A VOLCANIC SANDSTONE CONTAINING 80% ROUNDED QUARTZ SAND IN A SERICITE-CHLORITE MATRIX.

cr

CRANDON UNIT (cr) A BASINAL SEQUENCE CONSISTING OF STRATABOUND MASSIVE SULFIDE (GREATER THAN 50% TOTAL SULFIDE), PYRITIC ARGILLITE AND PYRITIC TUFF. LOCAL THIN CHERT BEDS.



SAND LAKE UNIT (sd) FINE GRAINED TUFF WITH MINOR DEBRIS FLOWS, CHERTY TUFF AND FLOWS. GRADES WITH DEPTH INTO COARSER REWORKED TUFF AND FINE LAPILLI TUFF.

TOWNSHIP SUBUNIT (sdt) A SERIES OF VOLCANIC BRECCIAS CONSISTING OF ANGULAR, POORLY SORTED HETEROLITHIC OR MONOLITHIC FRAGMENTS. MATRICES STRONGLY SILTIC

sdt<sub>1</sub> A TRANSITIONAL BRECCIA AT THE TOP OF THE SAND LAKE UNIT, CONSISTING OF FRAGMENTS OF TUFF, ARGILLITE, CHERT AND MASSIVE SULFIDE.

sdt<sub>2</sub> VOLCANIC BRECCIA CONSISTING OF HETEROLITHIC FRAGMENTS EXHIBITING MANY STAGES OF SILICIFICATION.

sdt<sub>3</sub> VOLCANIC BRECCIA CONSISTING OF MONOLITHIC FRAGMENTS. FRAGMENTS GENERALLY WEAKLY SILICIFIED.

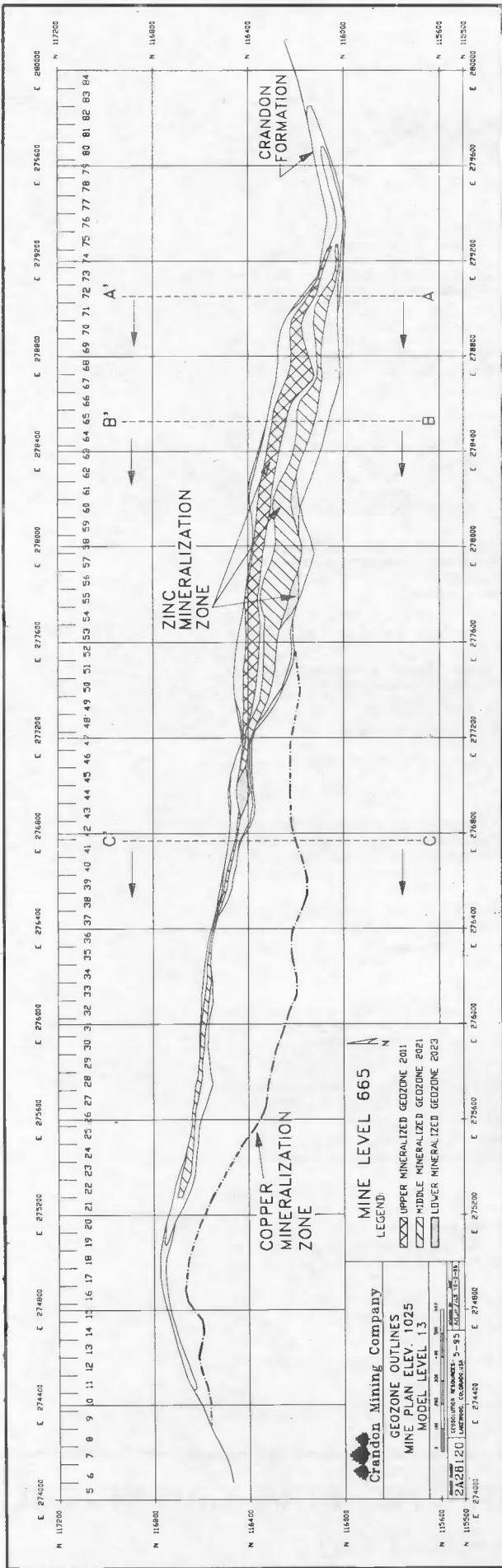
nh

NASHVILLE UNIT (nh) PORPHYRITIC BASALTIC FLOWS. LOCAL THIN TUFF BEDS.

CRANDON DEPOSIT - RECONSTRUCTED STRATIGRAPHIC COLUMN

LAMBE & ROWE (1987)

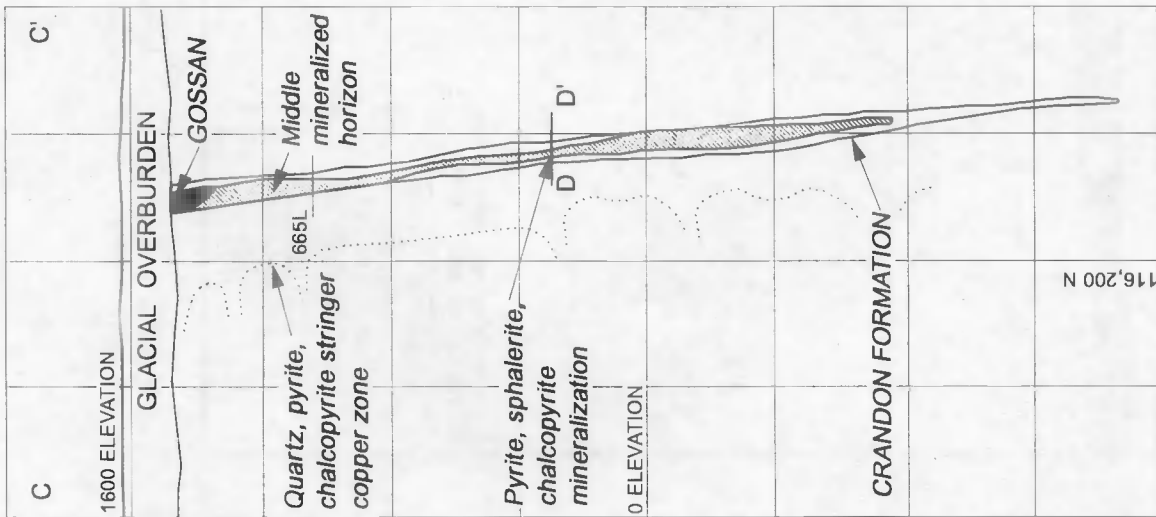
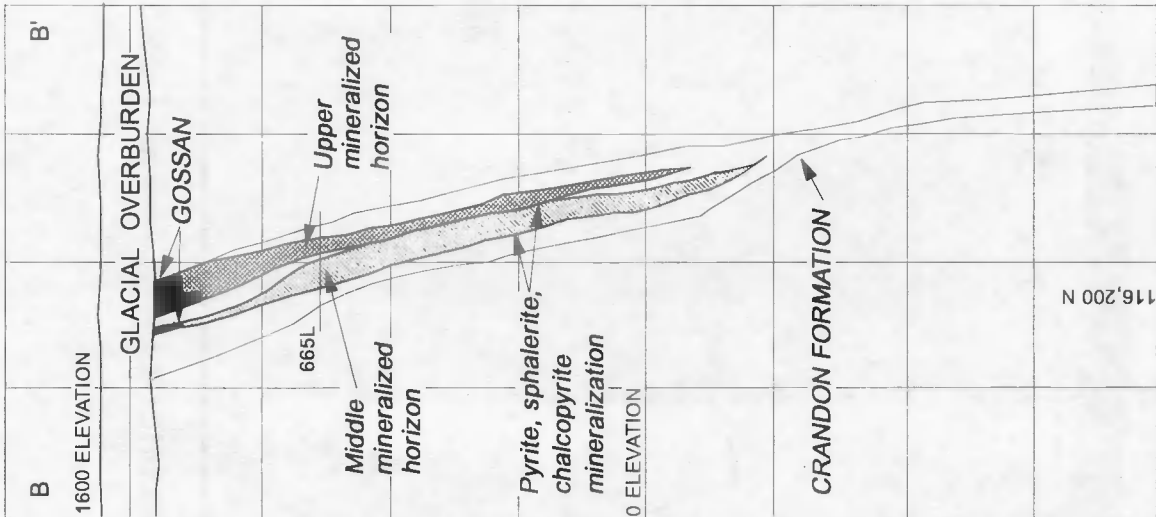
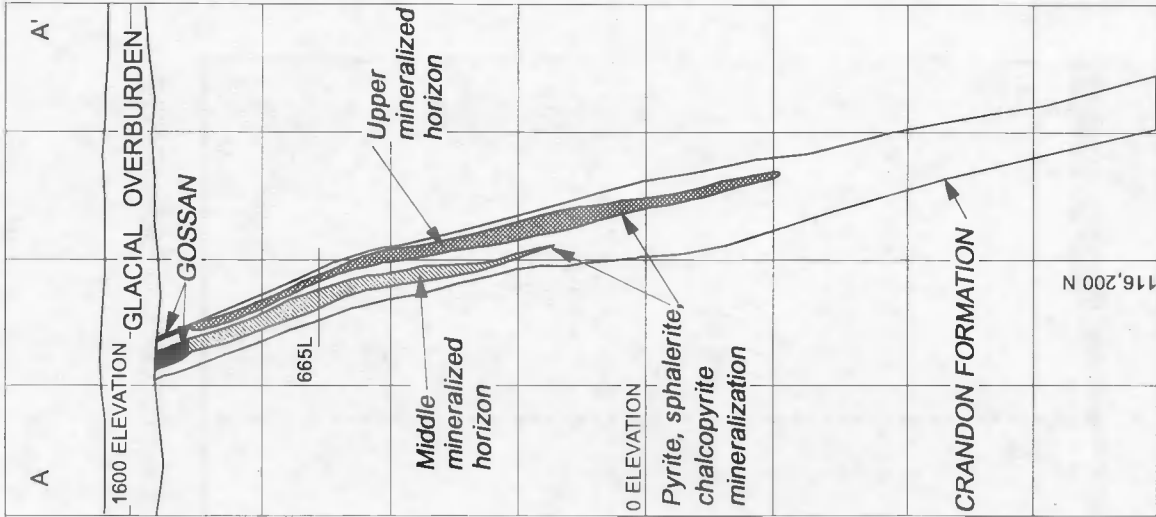
Figure 2



CRANDON DEPOSIT - CRANDON DEPOSIT MINERALIZATION ON THE PROPOSED 665 LEVEL

Figure 3

# CRANDON DEPOSIT - SIMPLIFIED GEOLOGIC CROSS SECTIONS



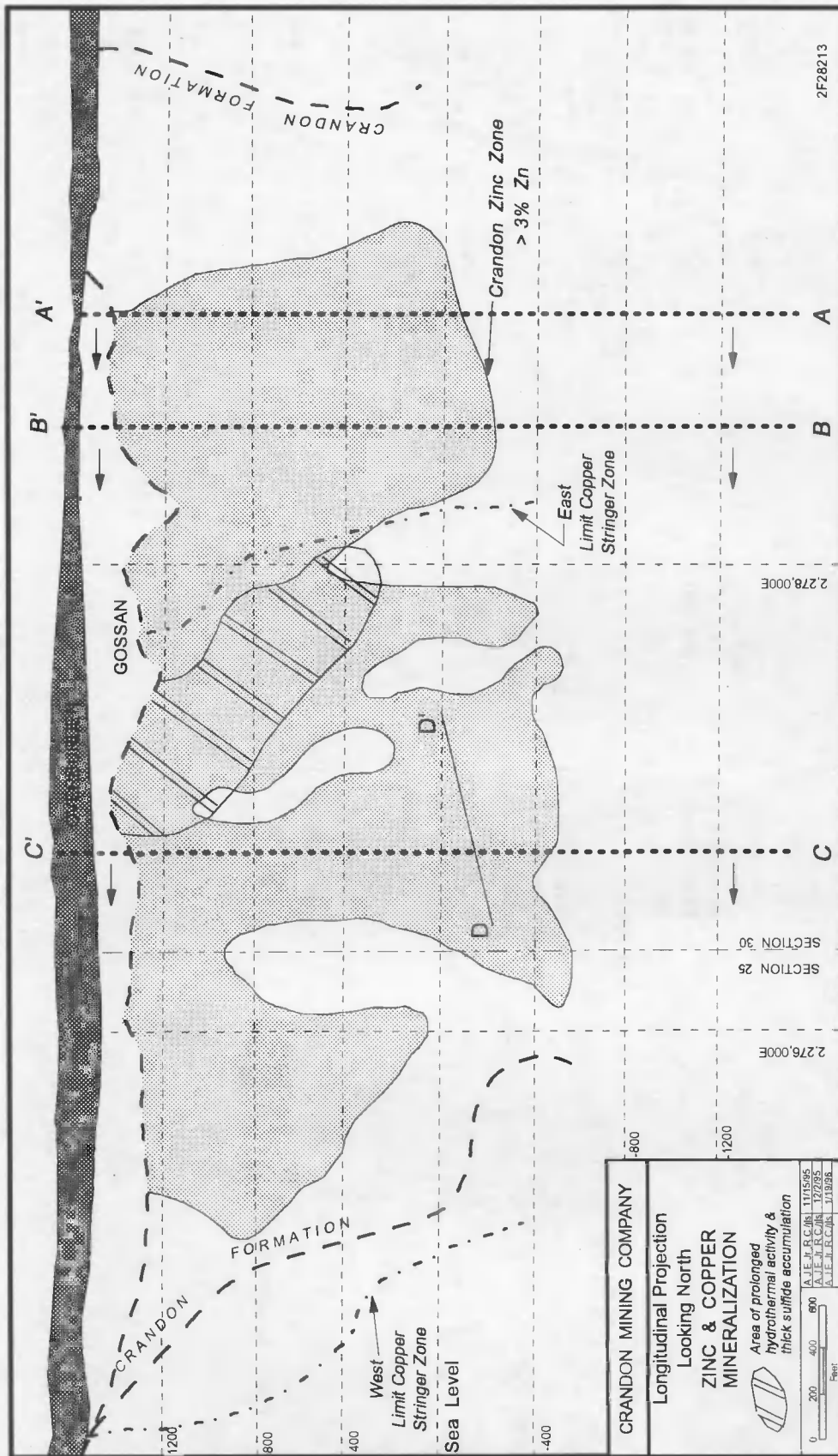
N - S SECTION A-A' 2,279,008 E  
LOOKING WEST

N - S SECTION B-B' 2,278,565 E  
LOOKING WEST

N - S SECTION C-C' 2,276,793 E  
LOOKING WEST







CRANDON DEPOSIT - EAST-WEST LONGITUDINAL PROJECTION SHOWING LIMITS OF MINERALIZATION  
 Figure 5

depicted by drill holes 137, 159, and 265. Individual lenses generally consist of an upper, zinc-rich, bedded to laminated pyrite-sphalerite ( $\pm$  galena) facies which grades stratigraphically downward into a commonly zinc-lean, poorly bedded pyritic facies. These primary textural variations and associated metal zoning are essentially repeated from one sulfide lens to the next, analogous to that described at the Mobrun deposit in the Noranda camp (La Rocque *et al.*, 1993). Typically, the lower facies consists of fine-grained colloform or spheroidal pyrite with lesser granular (in part, recrystallized) medium grained pyrite with fine interstitial sphalerite and/or fine "lacy" interstitial chalcopyrite. This lower facies may also locally include an appreciable amount (20-40%) of fine botryoidal silica gangue thought to represent a primary exhalative gel or sinter. Individual lenses generally average from 40 to 55 feet in true thickness and taper to thin horizons at the margin of the basin. Where sulfide lenses are in direct contact, the true thickness of the sulfide package may exceed 100 feet.

Stringer copper zone mineralization occurs stratigraphically beneath the zinc mineralization. It consists of multiple stages of quartz, quartz-pyrite, quartz-pyrite-chalcopyrite, locally quartz-pyrite-chalcopyrite-sphalerite, and thin pyrite veinlets. Age relationships are complex. Barren milky white quartz veinlets clearly predate the mixed quartz sulfide veinlets, whereas most thin barren pyrite veinlets post-date the quartz sulfide veinlets. This network of veinlets is localized as a semi-conformable envelope in the Sand Lake Formation "breccias" immediately below the Crandon Unit with its contained zinc mineralization as described by Lambe and Rowe (1987). Although described as mono and heterolithologic volcanic breccias, it should be noted that some of the breccia-like textures are clearly alteration features.

### SULFIDE MINERALOGY

Sulfide mineralogy is simple in both the conformable sulfide zinc zone and the footwall copper stringer zone. Pyrite is clearly the dominant sulfide in the zinc zone and may range up to nearly 100% at the base of individual sulfide lenses and in the less prevalent sub-seafloor replacement pyrite immediately beneath some of the zones of zinc mineralization. Sphalerite is the zinc sulfide. There are lesser amounts of chalcopyrite, galena, tetrahedrite, and rare pyrrhotite and arsenopyrite are present in both the zinc and copper zones. Marcasite and enargite have been reported.

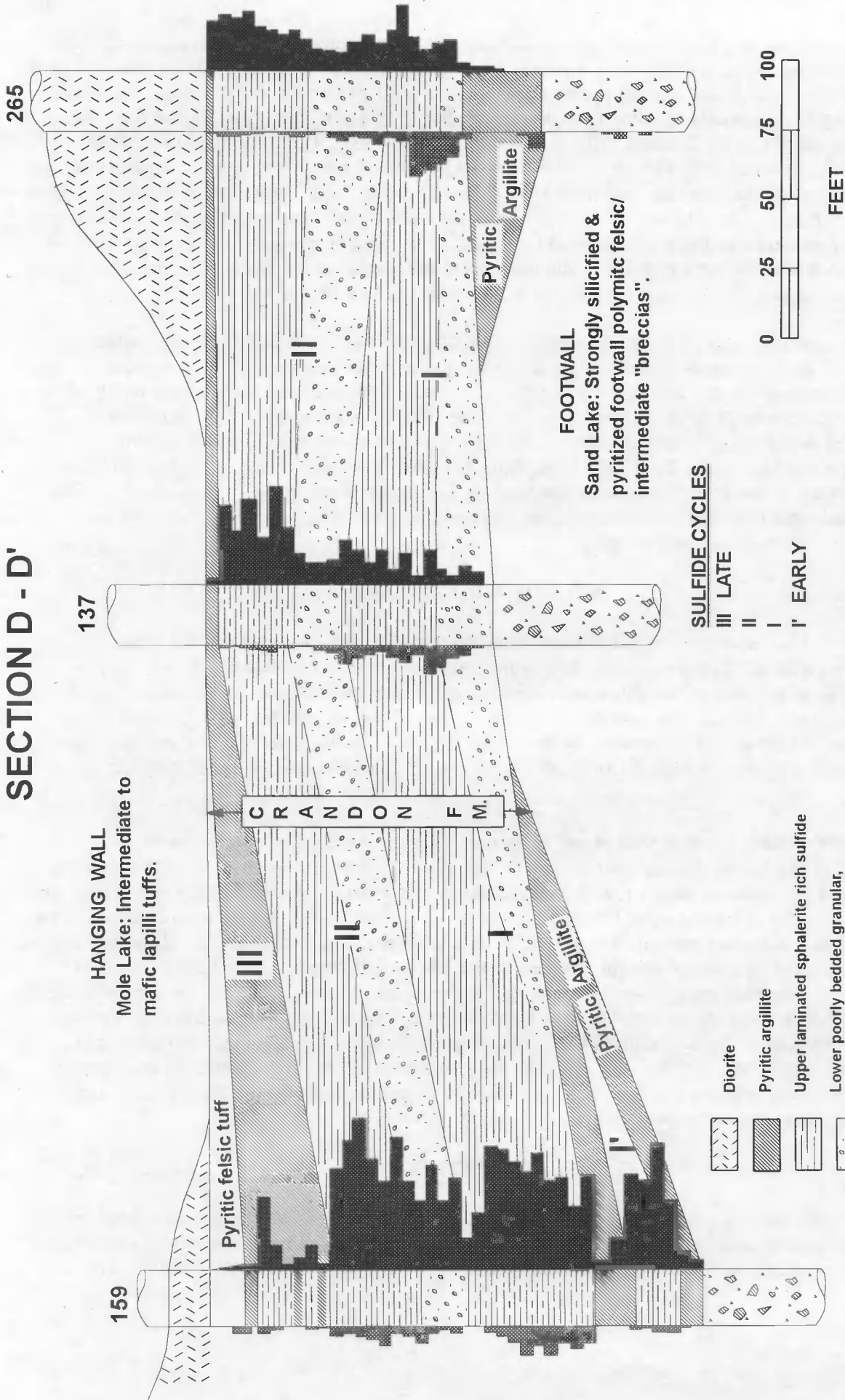
Near surface, a typical iron oxide, silica-rich gossan is present due to pre-Cambrian weathering of the sulfide mineralization. The gossan generally extends less than 100 feet below the subcrop, and is commonly only a few tens of feet thick. Very locally it extends in excess of 400 feet below the subcrop along particular lithologic horizons, or contacts within and along the margin of the Crandon Unit. A limited amount of supergene sulfide mineralization, chalcocite, covellite and rare bornite, is present beneath the gossan as well. Minor amounts of copper oxides have been noted. The supergene enriched zone is small, in part due to the proportionally low amount of copper in the primary mineralization and in part due to its removal through weathering and erosion since perhaps the middle Paleozoic. In this respect the Crandon deposit contrasts with the Flambeau deposit in western Wisconsin (May 1977). At Flambeau, the primary mineralization is generally more copper rich and the secondarily enriched ore zone was largely preserved from weathering, erosion, and Pleistocene glaciation by the presence of the Cambrian cover rock.

### ALTERATION

Synvolcanic hydrothermal alteration at Crandon is most strongly and extensively developed within the Crandon Unit and the immediate stratigraphic footwall (Sand Lake Formation) unit south of the zinc mineralization. However, alteration features are complex and commonly overlap. Footwall

# SELECTED ORE ZONE SULFIDE CORRELATION DIAGRAM

## SECTION D - D'



R. C., A.J.E. Jr., J.T.S

Figure 6

2F28526

alteration is dominated by partial to pervasive silicification, whereas lesser chloritization, sericitization, and carbonatization (mostly dolomite) are also present. Intense pyritization in zones varying in thickness from 25 to 200 feet immediately below the conformable zinc zone accompany this alteration. Limited information on the footwall stringer mineralization and the fact that erosion has left only a portion of the original deposit make it difficult to fully define a classic feeder pipe beneath the tabular zinc mineralization, as described by Lydon (1988). A zone of prolonged hydrothermal activity is inferred due to thick alteration and mineralization located approximately mid-distance between cross sections B-B' and C-C' (See Figure 5). Here an important thickness of massive and semi-massive sulfides exhibits an abundance of textural features that are interpreted to be the result of sub-seafloor replacement. Intense black chlorite alteration within the footwall Sand Lake Formation is well developed at this locality.

The "tabular appearing" footwall silicate alteration assemblage illustrated on the level plans by Lambe and Rowe (1987) suggest more intense chloritic alteration beneath the western half of the deposit, whereas to the east sericitic alteration is more abundant.

Within the Crandon Unit, some of the "pyritic argillite" in fact represents strongly metasomatized zones of magnesium-chlorite alteration within the laminated, pyrite bearing, fine epiclastic sediment. In other areas, however, the "pyritic argillite" represents pyrite-rich zones of intense black, magnesium-iron-chlorite alteration as is typically found in footwall stringer zones in volcanic-hosted sulfide deposits. This later hydrothermal alteration is both cross-cutting and locally conformable to bedding. Most commonly, it is associated with epigenetic, stringer copper mineralization and localized as multistage quartz-sulfide, or sulfide veinlets in a complex semi-conformable zone of quartz-sulfide brecciation in the footwall beneath the zinc mineralization.

## STRUCTURE AND METAMORPHIC ATTRIBUTES

The Penokean Orogeny produced a generally steep dipping attitude in the volcano-sedimentary assemblage hosting and surrounding the Crandon deposit. Bedrock units in the area of the deposit have been metamorphosed to the lower greenschist facies. The structural deformation is generally weak to moderate such that delicate primary volcanic and sedimentary textures are preserved at various localities. The resulting overprint of principal structural fabric includes a regional east-west trending subvertical dipping schistosity and the local development of longitudinal east-west shears.

The pervasive planar structure or  $S_1$  schistosity, as noted in core, is presumed axial planar to the regional fold features and is generally sub-parallel to the bedding attitudes except where small scale parasitic folding is developed. Local zones of more pronounced to strong shearing are less frequent and preferentially developed as bedding parallel features and along major lithological contacts.

Major faults have not been recognized at Crandon as shown on level plans (Figure 3) and cross-sections (Figure 4). These figures illustrate the undisturbed lateral continuity of the hanging wall contact of the deposit indicating minimal structural complications as might otherwise be indicated by marked thickening, thinning or offset due to significant folding and/or faulting. This lack of significant structural offset has been substantiated in five separate drilling programs since 1980. All holes intersected stratigraphy as anticipated, thus indicating no important structural effects.

## CONCLUSIONS

The lithological and mineralogical features of the Crandon Deposit described above are typical of many submarine volcanogenic sulfide deposits emplaced at and directly below the sea floor. Internal sulfide stratigraphy, as indicated by mappable sulfide facies, document the presence of at least three major stacked lenses, *i.e.*, pulses of pyrite-sphalerite mineralization. Long lived, both focused and diffuse discharge of metal-bearing hydrothermal fluids are indicated. These solutions percolated upward through the Sand Lake submarine volcanics to precipitate their contents at and below the Proterozoic sea floor.

The resulting concentration of the conformable pyritic, zinc-rich sulfides, uninterrupted by major structural dislocation, and the underlying discordant, copper-rich stringer mineralization is the largest known volcanic-hosted zinc copper deposit in the Rhinelander-Ladysmith Greenstone Belt.

## Acknowledgment

We would like to take this opportunity to thank T. E. Warren, Rio Algom Exploration Inc., and G. Westra, Exxon Coal and Minerals Company, for constructive comments and Crandon Mining Company, Exxon Coal and Minerals Company and Rio Algom Exploration Inc., for permission to publish this paper. Secretarial support by L. Gonzales and drafting by J. L. Shaw, Exxon Coal and Minerals Company, is greatly appreciated.

## References Cited

- Anon, 1994, Annual Report, Rio Algom Limited.
- Côté, R., Erickson, A. J., Jr., Donahue, S. V., Thresher, J. E. Jr., and Anderson, P. F., October 1994, Bedrock Hydrogeology of the Crandon Project Site: Foth & Van Dyke Memorandum, 19 p.
- DeMatties, T. A., 1994, Early Proterozoic Volcanographic Massive Sulfide Deposits in Wisconsin: An overview: *Economic Geology*, v. 89, p. 1123-1151.
- Franklin, J. M., Lydon, J. W., and Sangster, D. F., 1981, Volcanic-associated massive sulfide deposits: *Economic Geology*, 75th Anniversary Volume, p. 485-627.
- Hoffman, P. F., 1989, Precambrian geology and tectonic, history of North America: *in* Bally, A. W., and Palmer, A. R., eds., *The Geology of North America-An Overview*; G.S.A., *The Geology of North America*, v. A, p. 447-512.
- Klasner, J. S., Ojakangas, R. W., Schulz, K. J., and LaBerge, G. L., 1991, Nature and Style of deformation in the foreland of early Proterozoic Penokean Orogen, Northern Michigan: *USGS Bull* 1904-K, p. K1-K22.
- Lambe, R. N., and Rowe, R. G., 1987, Volcanic history, mineralization, and alteration of the Crandon Massive Sulfide Deposit, Wisconsin: *Econ. Geol.* v. 82, p. 1204-1238.
- LaBerge, G. L., 1994, *Geology of the Lake Superior Region*: Geoscience Press, Phoenix, AZ, 309p.

- LaRocque, A. C. L., Hodgson, C. J., and La Fleur, P. J., 1993, Gold distribution in the Moberly volcanic-associated massive sulfide deposit, Noranda, Quebec: A Preliminary Evaluation of the Role of Metamorphic Remobilization: *Economic Geology*, v. 88, p. 1443-1459.
- Lydon, J. W., 1988, Volcanogenic massive sulfide deposits Part 1: A descriptive model: Part 2: Genetic models: *in* Roberts, R. G., and Sheahan, P. A., eds., *Ore Deposit Models*, Geoscience Canada Reprint Series 3, Geol. Assn. Canada, Memorial University, St. Johns. Nfld. p. 145-181.
- May, E. R., 1976, Flambeau - A Precambrian Supergene Enriched Massive Sulfide Deposit: SME preprint 76-I-55, 35p.
- May, E. R., and Schmidt, P. G., 1982, The discovery, geology, and mineralogy of the Crandon Precambrian massive sulfide deposit, Wisconsin: *in* Hutchinson, R. W., Spence, C. D., and Franklin, J. M., eds., *Precambrian Sulfide Deposits*, H.S. Robinson Memorial Volume, Special Paper 25, Geol. Assn. of Canada, p. 448-480.
- Rowe, R. G., and Hite, R. G., 1984, Applied geology: The foundation for mine design at Exxon Minerals Company's Crandon Deposit: *in* Erickson, A. J., Jr., ed., *Applied Mining Geology*, SME, Denver, p. 9-26.
- Schmidt, P. G., 1991, Discovery case history of the Crandon Massive Sulfide Deposit, Forest County, Wisconsin: *in* V. F. Hollister, ed., *Porphyry Copper, Molybdenum, and Gold Deposits, Volcanogenic Deposits (Massive Sulfides) and Deposits in Layered Rock*, SME Case Histories of Mineral Discoveries, v. 3, p. 99-102.
- Schmidt, P. G., Dolence, J. D., Lluria, M. R., and Parsons III, G., 1978, Geologists block out Exxon's big find of Zn-Cu at Crandon: *Engineering and Mining Journal*, v. 179, p. 61-66.
- Sims, P. K., 1984, Metallogeny of Archean and Proterozoic Terrains in the Great Lakes Region - A Brief Overview: *in* Bush, A. L., ed., *Contributions to Mineral Resources Research*, 1984, USGS Bull. 1694, p. 57-71.
- Sims, P. K., (compiler), 1990, Geologic map of Precambrian rocks of Iron Mountain and Escanaba 1° x 2° Quadrangles, Northeastern Wisconsin and Northwestern Michigan: USGS Miscellaneous Investigation Series, Map I-2056.
- Sims, P. K., (compiler) 1992, Geologic map of Precambrian rocks, southern Lake Superior Region, Wisconsin and Northern Michigan: USGS Miscellaneous Investigation Series, MAP I-2185, 2 sheets.
- Sims, P. K., Van Schmus, W. R., Schulz, K. J., and Peterman, Z. E., 1989, Tectono-stratigraphic evolution of the Early Proterozoic Wisconsin magmatic terrains of the Penokean Orogen: *Can. J. Earth Sci.* v. 26, p. 2145-2158.
- Solomon, M., 1976, "Volcanic" massive sulfide deposits and their host rocks - a review and explanation: *in* Wolf, K. H., ed., *Handbook of Stratabound and Stratiform Ore Deposits*, Elsevier, Amsterdam, v. 2, p. 21-50.
- Van Schmus, W. R., 1976, Early and Middle Proterozoic history of the Great Lakes area, North America: *Phil. Tran. R. Soc. Lond. A.* 280, p. 605-628.

[The text in this section is extremely faint and illegible. It appears to be a series of paragraphs of text, possibly a letter or a report, but the content cannot be discerned.]

## **THE BEND DEPOSIT: AN EARLY PROTEROZOIC COPPER-GOLD VMS DEPOSIT**

by Theodore A. DeMatties  
and  
William F. Rowell

Geological Consultants

### **INTRODUCTION**

Exploration conducted between 1985 and 1994 by the former Jump River Joint Venture, and more recently Sharpe Energy and Resources, has identified a potentially economic copper-gold volcanogenic massive sulfide deposit in the Chequamegon National Forest of north-central Wisconsin. The deposit, known as Bend, is located in Taylor County, approximately 19 miles north-northwest of Medford, the county seat (Fig. 1). Mineral rights controlling the known deposit and its extensions are currently held under a BLM Preference Right Lease Application, BLM prospecting permits, and private leases by a joint venture consisting of Sharpe Energy and Resources, Freewest Resources and Cyprus-Amax.

Originally discovered as a single high-priority, six-channel electromagnetic (INPUT) anomaly in 1978, the property was not available to the former Jump River Joint Venture for acquisition until 1985. Drilling began in 1986 on the blind (100-120' of glacial overburden) electromagnetic target and since that time a total of 38 diamond drillholes (approximately 47,000 feet of drilling) have indicated a resource of 3.9 million short tons grading 1.87% copper, 0.09 opt gold, and 0.39 opt silver.

### **LOCAL AND REGIONAL GEOLOGY**

The Bend deposit is one in a cluster of at least three volcanogenic massive sulfide (VMS) deposits which occur within the Ladysmith district (Fig. 2). Other significant deposits in this district include Flambeau (Cu-Au), which is currently being mined, and Eisenbrey (Thornapple) (Zn-Cu) where exploration has recently (1995) been conducted; previously explored VMS showings also occur at the Schoolhouse (Cu), and Clear Creek (Cu) prospects.

This district, as well as two others which have been identified, is located in the Ladysmith-Rhineland volcanic complex. The complex lies in the Early Proterozoic Penokean volcanic belt (or Wisconsin magmatic terrane), which is a major component of the Southern Structural Province of the Canadian Shield.

The Bend deposit is hosted by a felsic center located structurally along the southern margin of a major volcanic arc and within a back-arc basin facies. Locally, the center is associated with, and occurs along the flanks of, a mafic pile succession (Fig.3). The host rock section is up to 2000 feet thick and consists of steeply dipping (upright), interbedded, schistose, rhyolitic to rhyodacitic, bedded metatuffs (sericite schist) and quartz-crystal metatuffs (quartz-sericite schist-semischist, Fig.7A) that are overlain (stratigraphic hangingwall) by an andesitic to rhyolitic (dominantly dacitic-rhyodacitic) metavolcanic flow-fragmental sequence and associated fine tuffs or metasediments (Fig. 4 and Table 1).



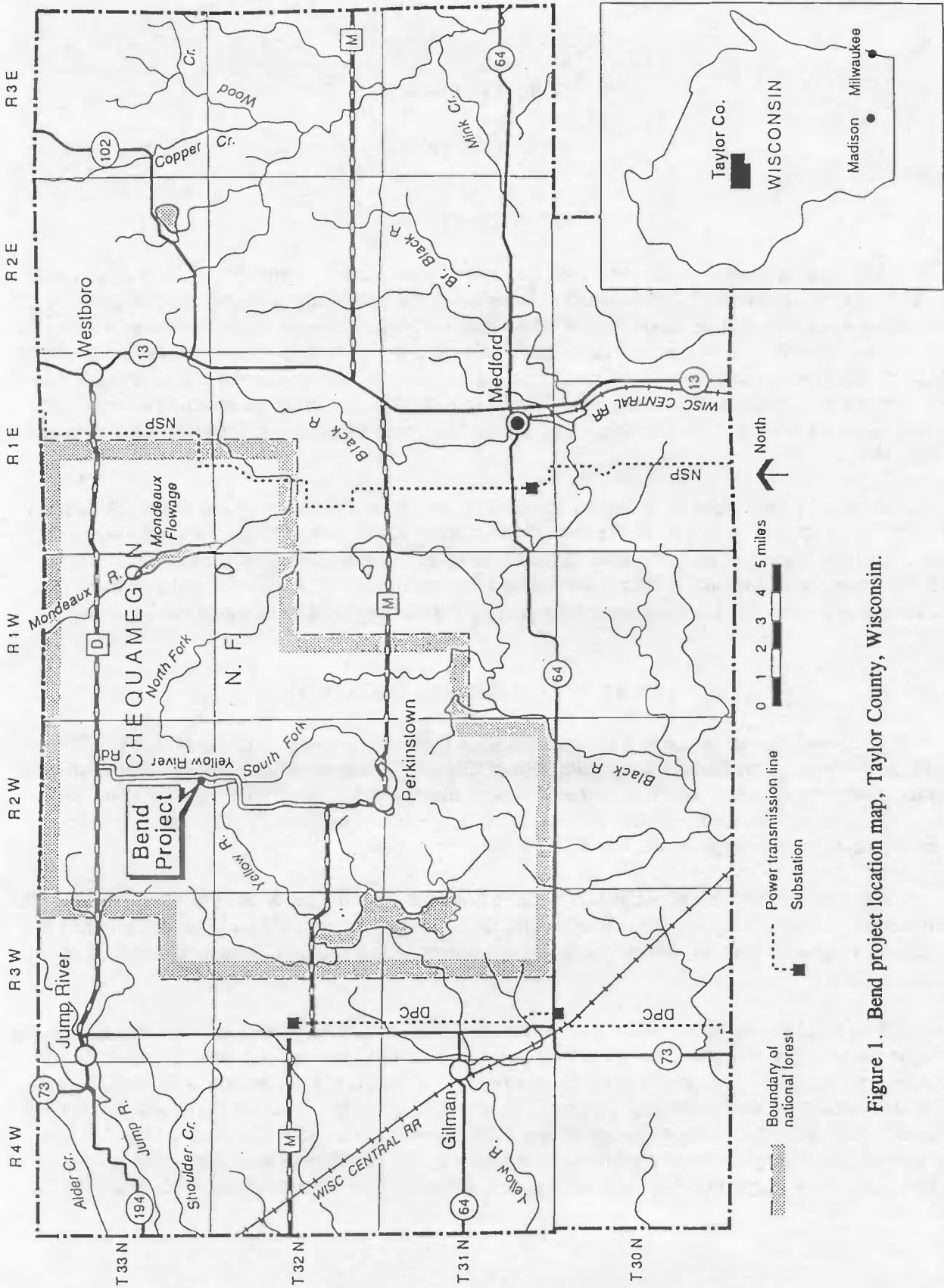


Figure 1. Bend project location map, Taylor County, Wisconsin.

Fig.1

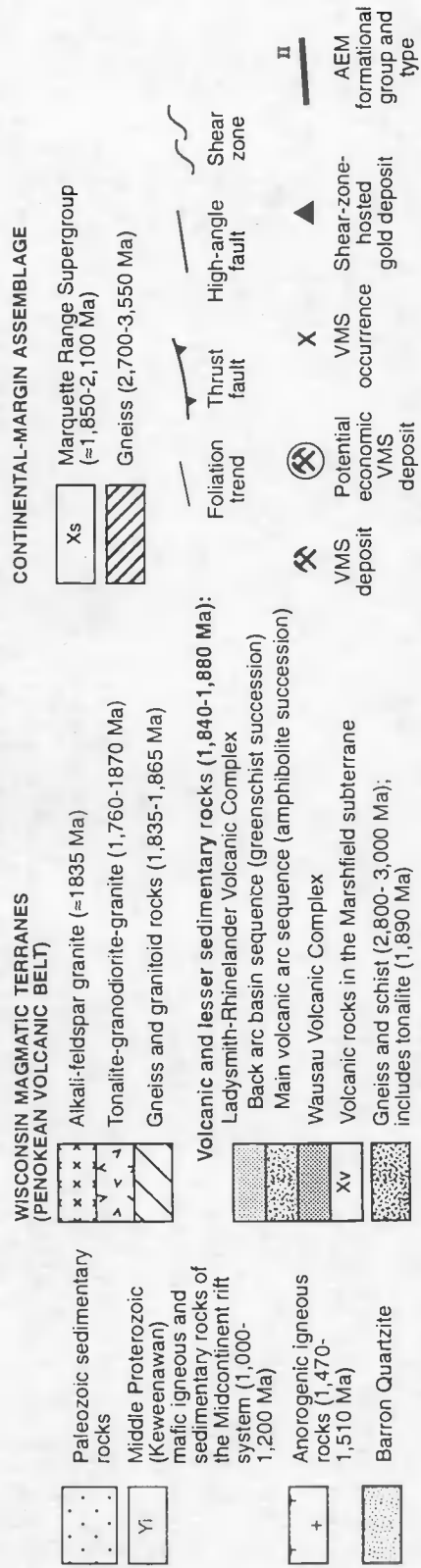
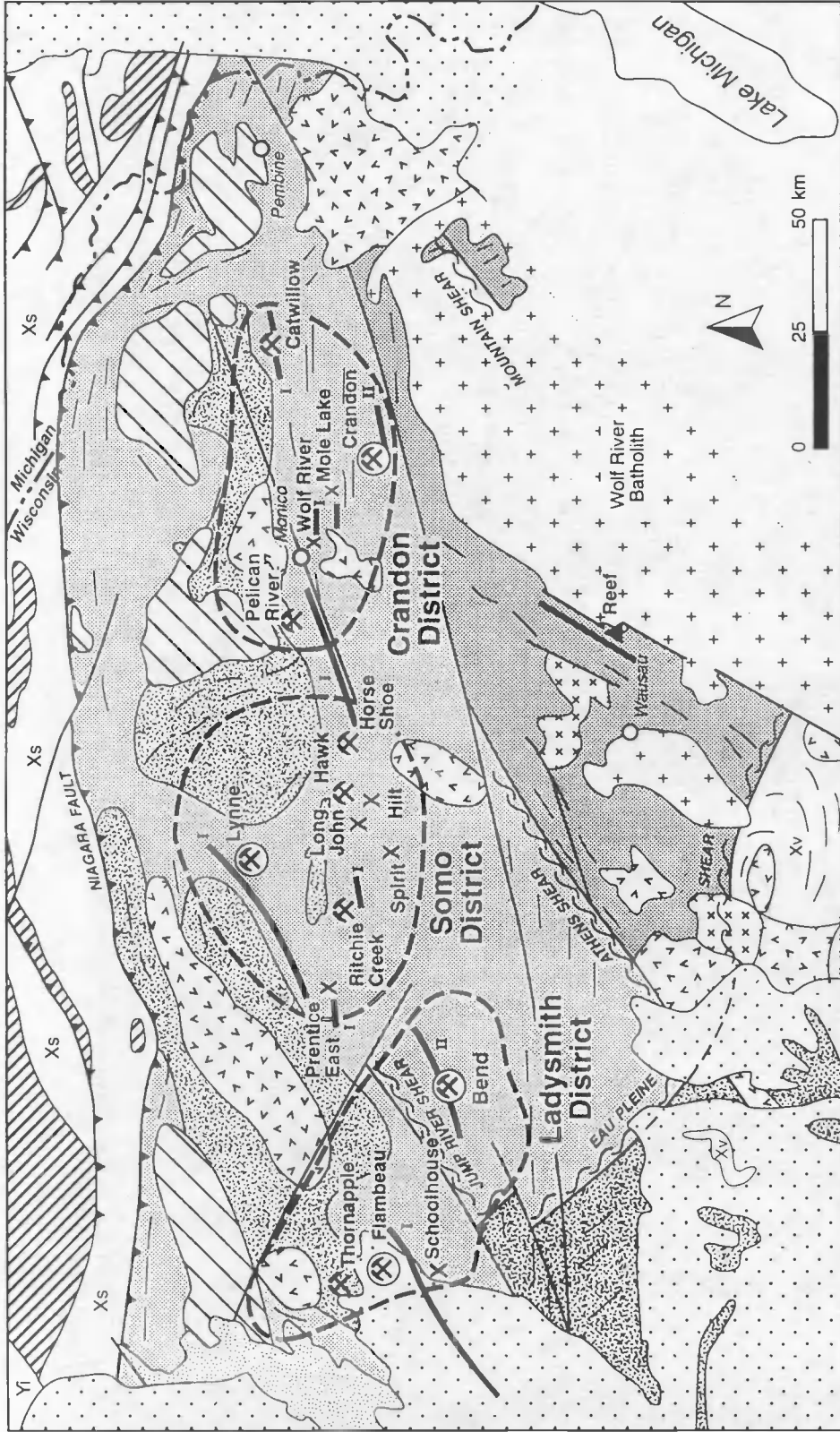


Figure 2. Geological map of northern Wisconsin showing major volcanic complexes, and distribution of VMS deposits and occurrences (modified Sims, 1989).

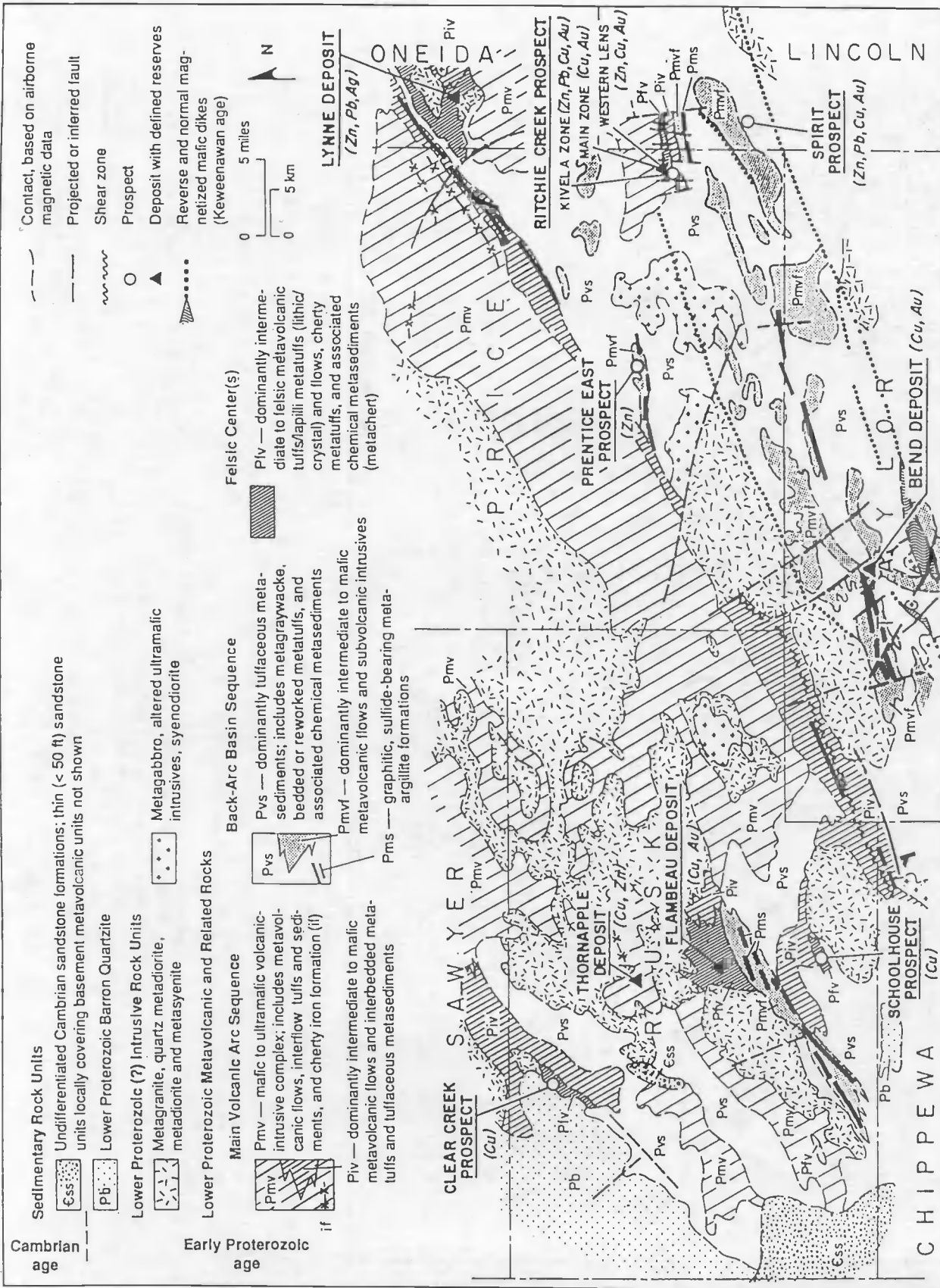


Figure 3. General geologic map of the western portion of the Ladysmith-Rhinelander metavolcanic complex (after DeMatties, 1994).



Table 1

## DESCRIPTION OF LITHOLOGIC UNITS

## VOLCANIC UNITS

## HANGING-WALL SEQUENCE (FELSIC FLOW-FRAGMENTAL COMPLEX)

<p><b>V<sub>D</sub></b> <u>INTERMEDIATE TO FELSIC FLOWS</u> (dacite to rhyodacite) Greenish gray, fine- to medium-grained, thin- to thick bedded, fractured and healed (quartz and carbonate), porphyritic (feldspar phenocrysts) and non-porphyritic metavolcanic flows and flow breccias. Interflow tuffs and sediments and interbedded siliceous and metavolcanic flows occur locally.</p>	<p><b>V<sub>A</sub></b> <u>INTERMEDIATE TO MAFIC FLOWS</u> (andesite to basaltic andesite) Dark greenish gray, fine- to medium-grained, massive, commonly porphyritic (feldspar and ferromagnesian mineral phenocrysts) metavolcanic flows and/or subvolcanic intrusives.</p>	<p><b>V<sub>R</sub></b> <u>FELSIC FLOWS</u> (rhyolite) Light gray to pinkish-white, fine- to medium-grained, massive, fractured and healed, very hard, commonly porphyritic (blue quartz eyes and feldspar phenocrysts), siliceous metavolcanic flows, subvolcanic intrusives, and flow breccias; localized well-developed flow banding?. Locally, weakly mineralized and altered.</p>
<p><b>V<sub>D-LT</sub></b> <u>INTERBEDDED FLOWS AND INTERFLOW PYROCLASTIC BEDS</u> Dominantly thin, intermediate to felsic metavolcanic flows (V<sub>D</sub>), flow breccias, and carbonate-rich interflow metatuffs and lapilli metatuffs.</p>		
<p><b>LT</b> <u>INTERMEDIATE TO FELSIC LAPILLI TUFFS</u> Greenish gray, medium- to coarse-grained, thin- to thick-bedded, carbonate-rich coarse metatuffs, lapilli metatuffs, and tuff breccias. Normal graded bedding is common. Intercalated thin intermediate to felsic metavolcanic flows (V<sub>D</sub>) locally.</p>	<p><b>T</b> <u>INTERMEDIATE TO FELSIC FINE AND COARSE TUFFS</u> Light to dark greenish gray, fine- to medium-grained, thinly bedded to laminated metatuffs and associated tuffaceous meta-sediments. Black meta-argillite laminations locally.</p>	
<p><b>CS</b> <u>TUFFACEOUS SEDIMENTS</u> Dark gray to black, fine-grained, laminated, commonly graphitic, chlorite-rich meta-argillite. Commonly sulfide-bearing. Chert laminations common.</p>	<p><b>CT</b> <u>CHERTY TUFF</u> Fine-grained, finely laminated cherty and hematitic metatuff. Chert component greater than 50%. Thin massive-sulfide beds may be present.</p>	

## MINERALIZED SEQUENCE

<p><b>XT</b> <u>ALTERED AND MINERALIZED QUARTZ-CRYSTAL FELSIC TUFF</u> Medium to light gray, fine- to medium-grained, poorly bedded, well-foliated (schistose), crystal-bearing (blue quartz eyes) quartz-sericite schist. Well-developed tuffaceous texture is preserved. Widespread stockwork sulfide mineralization is characteristic, consisting of up to 30% (commonly 1%-10%) pyrite ± chalcopyrite as disseminations, cross-cutting veinlets, and conformable bands. This unit hosts copper- and gold-bearing massive to semimassive and stringer mineralization.</p>
<p><b>XT<sub>1-3</sub></b> <u>ALTERED AND MINERALIZED CRYSTAL FELSIC TUFFS</u> Medium to light gray, fine- to medium-grained, poorly to well-bedded, weakly to well-foliated (schistose), crystal-bearing (quartz and feldspar crystals), locally fragmental quartz-sericite (±feldspar) schists and semi-schists. Widespread disseminated sulfides (pyrite ± chalcopyrite) and conformable massive to semimassive sulfide bands. Crystal tuff units are separated by thin argillite (CS) and felsic tuff (GT) beds. Unit XT<sub>3</sub> hosts copper-bearing fragmental massive sulfide and stringer sulfide mineralization.</p>

## FOOTWALL SEQUENCE


<p><b>GT</b> <u>BEDDED FELSIC TUFF</u> Gray to greenish gray, fine-grained, thinly to thickly laminated, well-foliated (schistose) sericite schist. Commonly contains disseminated pyrite, up to 5%.</p>
<p><b>MVF</b> <u>INTERMEDIATE TO MAFIC FLOWS AND INTERFLOW SEDIMENTS</u> (andesite) Dark greenish gray, fine- to medium-grained, locally laminated, foliated (schistose) chlorite schist. Carbonate alteration common.</p>

**V<sub>M</sub>** MAFIC FLOW(S) (basalt) Dark greenish gray, aphanitic to fine-grained, non-foliated, fractured and healed, nonporphyritic (massive) metavolcanic flows and/or subvolcanic intrusives


INTRUSIVE UNITS


**+** **+** SUBVOLCANIC INTRUSIVE Dark gray, medium-grained, equigranular, massive, fractured and healed, intermediate to mafic dike or sill.


SULFIDE MINERALIZATION


 **MASSIVE SULFIDE MINERALIZATION** Fine- to very fine-grained, poorly to well-bedded, locally fragment-bearing (less than 20% XT fragments), massive (greater than 50%, up to 90%) granular pyrite with varying amounts of fine chalcopryrite and tetrahedrite-tennantite intergrowths. Gangue minerals include quartz + sericite ± chlorite.

 **SEMIMASSIVE SULFIDE MINERALIZATION** 30% to 50% pyrite.

 **FRAGMENT-BEARING SULFIDE MINERALIZATION** Medium- to coarse-sized, subrounded to subangular, commonly silicified XT fragments (greater than or equal to 20%) supported in a fine-grained matrix of semimassive pyrite (30%-50%) ± chalcopryrite.









 **FRAGMENTAL SULFIDE MINERALIZATION** Medium- to coarse-sized, subrounded to subangular sulfide (py) fragments (greater than or equal to 30%) supported in a fine matrix of quartz and sericite.

 **STRINGER SULFIDE MINERALIZATION** Fine-grained cross-cutting pyrite (10%-30%) ± chalcopryrite or wispy chalcopryrite veinlets and blebs; commonly overprints massive sulfide and fragment-bearing sulfide mineralization.





 **HYDROTHERMAL ALTERATION** Includes weak to strong fine-grained black wispy chlorite alteration and weak to intense silicification.

UL - upper lens  
LL - lower lens

GEOLOGIC SYMBOLS





-  contact observed in drillhole
-  projected or inferred contact
-  fault, dashed where projected
-  relict bedding attitude
-  foliation attitude (schistosity)
-  flow breccia unless otherwise designated
-  shear zone
-  TOP direction of stratigraphic top

Level Plans

-  80° strike + dip of relict bedding
-  strike of vertically dipping bedding
-  strike of foliation (schistosity)
-  strike of vertically dipping foliation (schistosity)

Abbreviations

py-pyrite, po-pyrrhotite, cp-chalcopryrite, sp-sphalerite, tet-tetrahedrite

-  DDH significant sulfide mineralization
-  base- and precious-metal-bearing sulfide mineralization
-  Ore grade Cu
-  Ore grade Au

The felsic sequence remains open along strike to the west of the deposit, but is cut off to the east by an extensive rhyolitic dome-flow complex of unknown dimensions. In general, the felsic complex is relatively unaltered, although localized hydrothermal alteration has produced zones of moderate to intense silicification, sericitization and chloritization. Disseminated pyrite often occurs within sericitized zones, whereas stringer-like chalcopyrite is associated with black chlorite alteration.

Geophysically mappable meta-argillite formational units closely parallel or are interbedded with the felsic tuffs and the deposit. These units locally contain anomalous copper mineralization and are an important ore equivalent marker horizon that extends several miles along strike in both directions.

Regionally the felsic center may be isoclinally folded, though there is no evidence of folding in the immediate deposit area. Metamorphic grade of the succession is lower greenschist; a weak to moderately strong foliation (schistosity) has developed parallel to relict bedding in the tuffaceous units; however, many relict volcanic and sedimentary features have been preserved.

### GEOCHEMISTRY

To classify the geochemical affinity of the volcanic succession, major and trace element compositions were determined for 58 core samples taken from 12 drillholes that intersect the deposit. Twenty-two samples were from the host quartz-sericite schist (mineralized quartz-crystal felsic metatuff, designated the XT unit), 26 samples were of relatively unaltered volcanic rocks from the hangingwall sequence and 4 samples were from the felsic dome-flow complex.

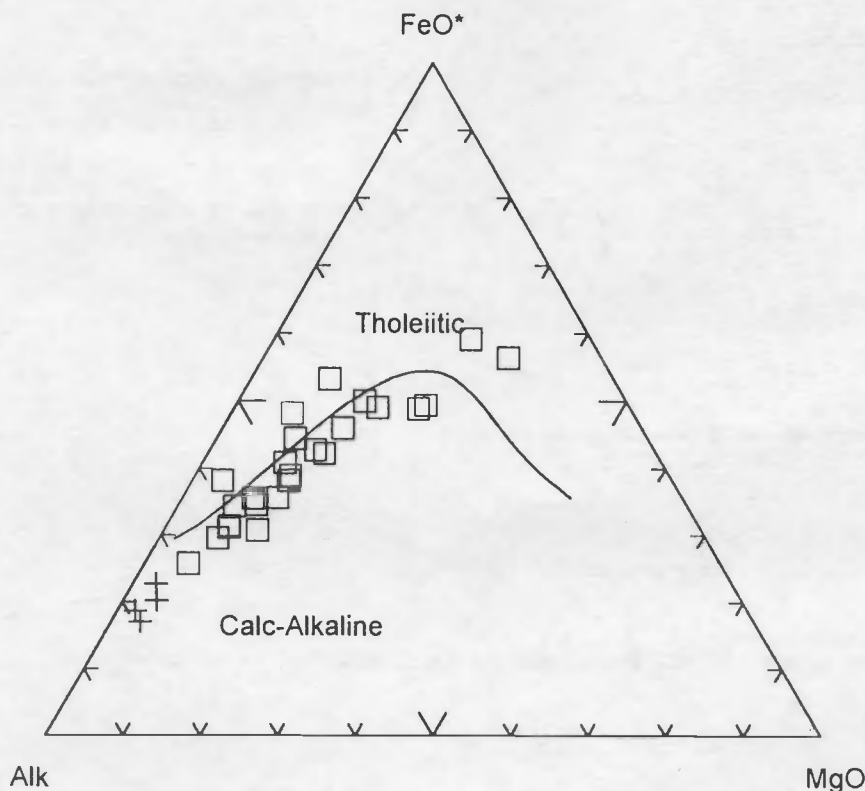


Figure 5. AFM diagram for hangingwall and felsic dome. Squares = hangingwall volcanics; Crosses = felsic dome samples.

Because the hangingwall and felsic dome rocks are generally not hydrothermally altered and have undergone only lower greenschist facies regional metamorphism, they can be classified based on major element composition. On an AFM diagram (Fig. 5) most samples plot within or near the calc-alkali field.

Limited data on  $\text{SiO}_2$  and alkali content suggests that the hangingwall sequence includes a fully differentiated rock suite ranging from basaltic-andesite to rhyolite (Fig. 6). Samples from the felsic dome complex plot primarily in the rhyolite field.

To ascertain the primary geochemical affinity of the hydrothermally altered quartz-sericite schist it is necessary to use immobile element ratios.  $\text{TiO}_2$  and Zr are generally considered to remain immobile in rocks that have been subjected to low-grade metamorphism and/or hydrothermal alteration (Pearce and Cann, 1973). If these elements have remained immobile during alteration, they should define a regression line that trends toward the origin in binary plot. The precursor composition of the altered rock can be determined by the intersection of the trend of the plot with the fractionation trend developed by less altered rocks of the sequence.

On a  $\text{TiO}_2$  vs. Zr plot (Fig. 7), rocks from the hangingwall and felsic dome define a normal differentiation trend of decreasing  $\text{TiO}_2$  with increasing Zr. In contrast, quartz-sericite schist samples plot along a linear trend toward the origin which is consistent with relative immobility during hydrothermal alteration. The regression line for the quartz-sericite schist intersects the felsic end of the fractionation trend indicating rhyolite/rhyodacite as the precursor rock type.

Immobile element plots also provide an indication of the nature and extent of mass changes due to hydrothermal alteration. Mass loss due to solution increases the relative concentration of immobile elements, whereas mass addition, such as during silicification, has the opposite effect. Samples that have undergone mass addition will plot between the fractionation trend and the origin, whereas those with mass loss will plot above the fractionation trend.

On the  $\text{TiO}_2$  vs. Zr plot, most quartz-sericite schist samples are located between the fractionation trend and the origin indicating mass dilution. Visually, it is apparent that dilution is probably related to silicification and, to a lesser extent, the addition of sulfides.

Evidence of a net silica increase can be demonstrated graphically on a plot of Zr vs.  $\text{SiO}_2$  (Fig. 8). For the hangingwall and felsic dome rocks a positive linear trend consistent with normal fractionation is apparent. In contrast, the trend of decreasing Zr with increasing  $\text{SiO}_2$  evident for the quartz-sericite schist samples indicates dilution due to silicification.

In Figure 9 it is apparent that, in addition to silicification, the quartz-sericite schist has undergone K-enrichment and Na-depletion during hydrothermal alteration. Changes in the alkali composition would have been produced during sericitization of the quartz crystal tuff precursor. Silicification must have occurred after changes in the alkali composition because sericitization produces a net quartz loss.

## MINERALIZATION

### Massive-Semimassive Sulfide Mineralization

Drilling completed thus far indicates that the bulk of the deposit consists of two steeply dipping, stacked, proximal massive (50%-90%) and semimassive ( $\geq 30\%$ ) sulfide lenses developed at



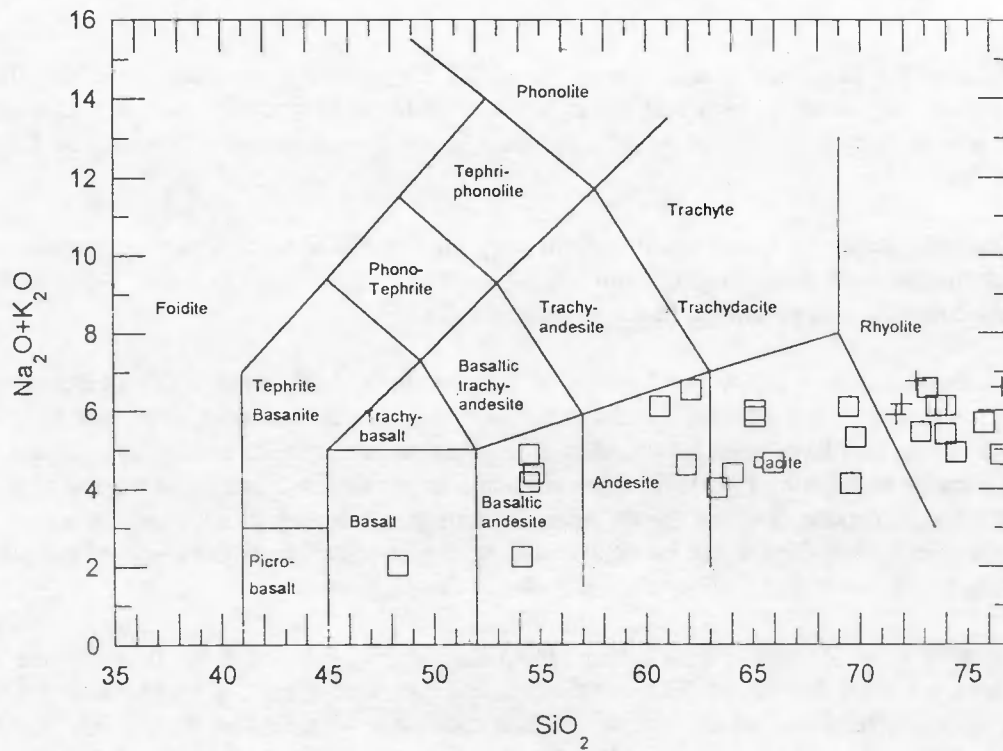


Figure 6. Volcanics from the hangingwall and felsic dome complex classified on the basis of alkali and silica content (after Lebas *et al.*, 1986). Symbols same as Figure 5.

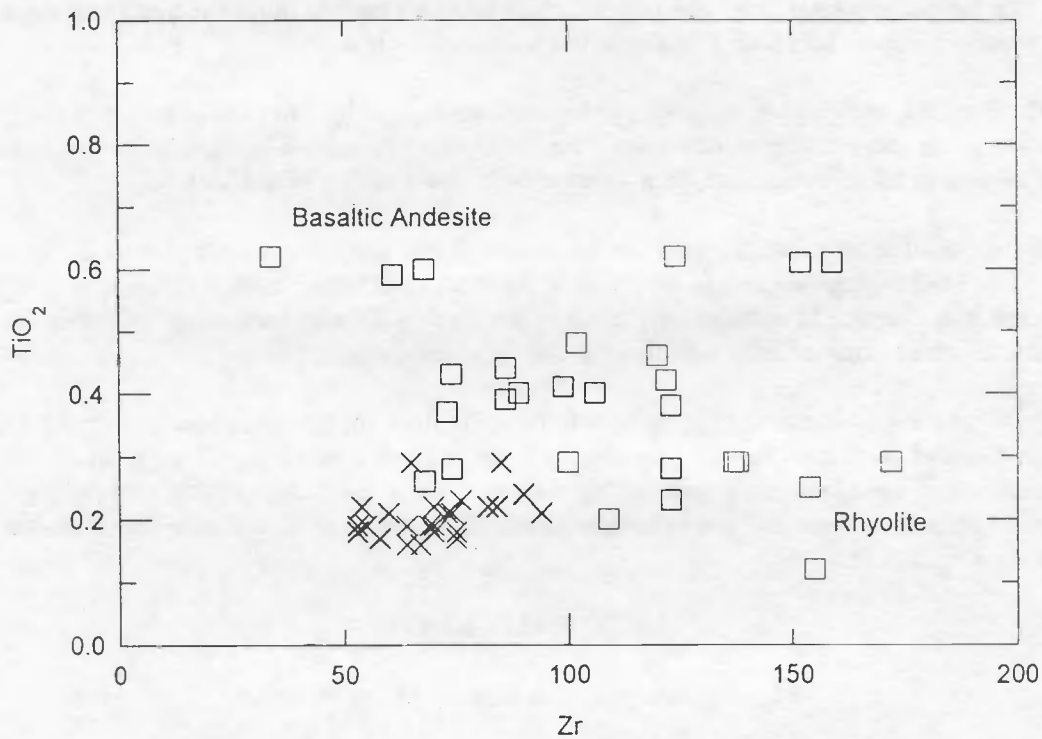


Figure 7.  $\text{TiO}_2$  vs. Zr plot for quartz-sericite schist, hangingwall volcanics and felsic dome complex. Hangingwall and felsic dome samples (squares) define a normal differentiation trend of decreasing Zr with increasing  $\text{TiO}_2$ . In contrast, quartz-sericite schist samples (X) plot along a trend toward the origin.

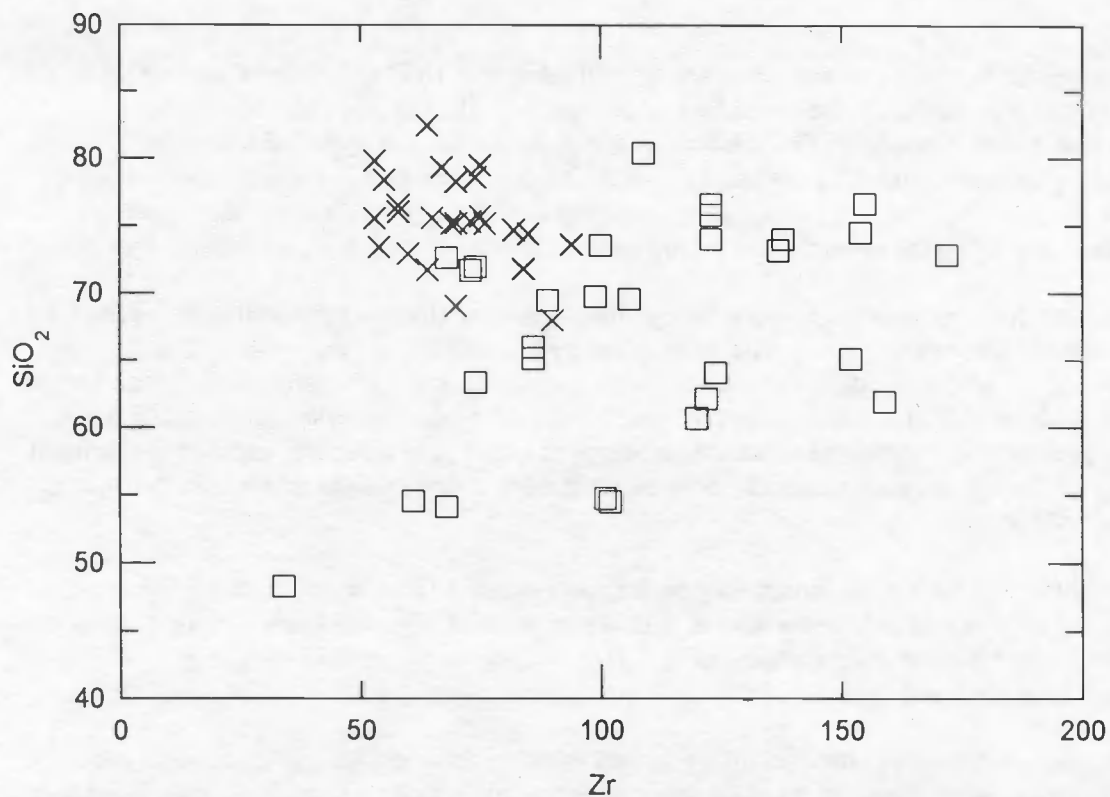


Figure 8. Plot of  $\text{SiO}_2$  vs.  $\text{Zr}$  for quartz-sericite schist, hangingwall volcanics and felsic dome. Hangingwall and felsic dome samples (squares) plot along a normal differentiation trend, while for quartz-sericite schist samples (X)  $\text{Zr}$  is diluted due to silicification.

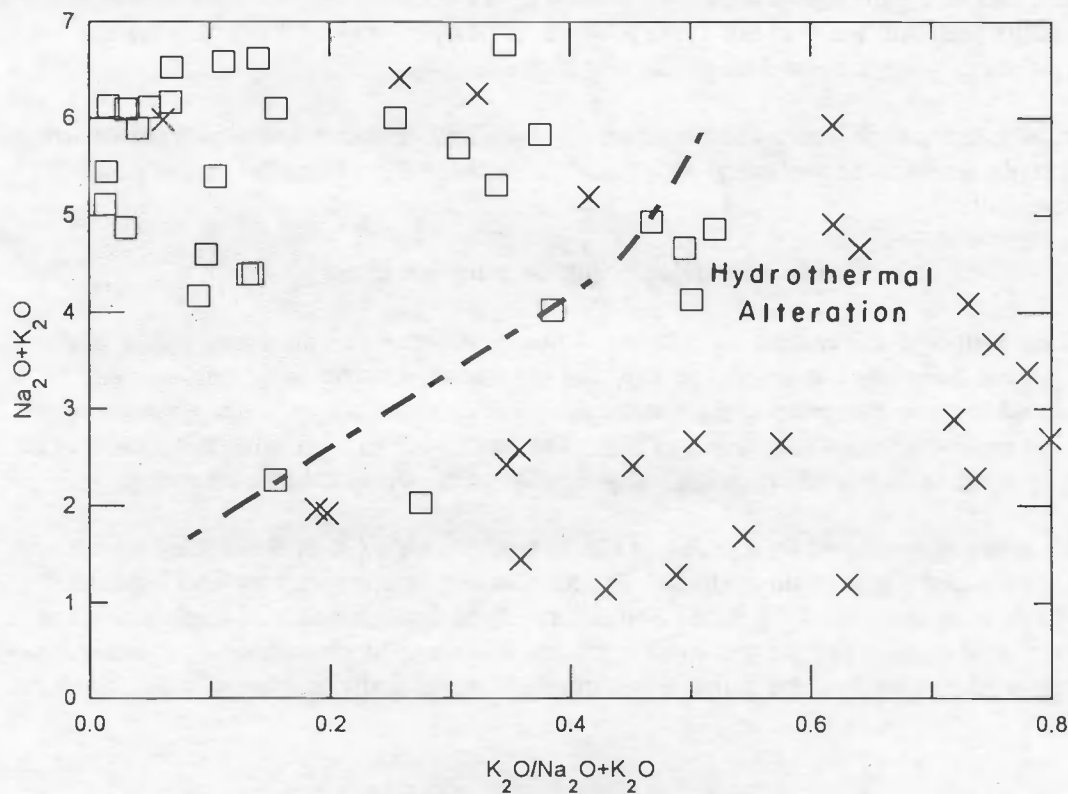


Figure 9. Plot of  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  vs.  $\text{K}_2\text{O}/(\text{Na}_2\text{O} + \text{K}_2\text{O})$  for quartz-sericite schist, hangingwall volcanics and felsic dome. Quartz-sericite schist samples (X) and Na depleted and K enriched relative to the sodic hangingwall and felsic dome samples (squares).

or near the stratigraphic top of an altered quartz-crystal felsic tuff (XT) unit. True thicknesses of the lenses range from 5 to 40 feet. The lower lens is thickest near the center of the deposit but interfingers with quartz-crystal tuff (XT) down dip and along strike; the upper lens is more continuous along dip and strike (Fig. 10 and 11). Both lenses extend to subcrop and are overlain by 100-120 feet of Chippewa end moraine. Other stratigraphically lower massive sulfide lenses are known, particularly along the eastern flank of the deposit, but have not been well defined by drilling.

Each lens contains medium to very fine grained, granular (locally recrystallized), pyrite with varying amounts of interstitial chalcopyrite  $\pm$  tetrahedrite-tennantite  $\pm$  arsenopyrite  $\pm$  bornite  $\pm$  chalcocite and  $\pm$  gold tellurides. Gangue minerals include quartz, carbonate (calcite), and sericite. Petrographic analysis indicates that chalcopyrite and bornite also occur as exsolutions within pyrite grains. The presence of tetrahedrite-tennantite, arsenopyrite, and gold tellurides explains the unusual geochemistry of the mineralization, which includes anomalous concentrations of arsenic, antimony, bismuth, and tellurium.

Individual beds within the lenses may be fragment-bearing (altered and unaltered quartz-crystal tuff); the stratigraphically lower lens is massive or exhibits vague bedding, whereas the upper lens is generally well bedded and laminated (Fig. 12B). Sedimentary features, such as graded bedding, have been observed in drill core.

The pyritic lenses are connected by a fragment-bearing semimassive sulfide zone (a debris apron) that has been overprinted by poorly developed epigenetic copper and gold stockwork-stringer mineralization (Fig. 10 and 11). The semimassive sulfide zone is characterized by a fine pyrite matrix which supports subrounded to angular, silicified quartz-sericite schist clasts that, in general, range from 2 to 10 cm in diameter. The zone thickens where the two lenses converge up dip toward the center of the relict sulfide mound. Isopach data suggests that the original mound developed within and along the flanks of a paleotopographic high formed by a thickening of the quartz-crystal tuff unit. The double plunge (east and west) of the upper massive sulfide lens may be a primary feature produced by paleotopographic control of sulfide deposition.

Near the subcrop both lenses exhibit evidence of shallow oxidation and supergene enrichment. A thin ( $\leq 5'$ ) replacement zone containing secondary chalcocite and bornite after primary sulfides is known from drilling.

#### Stockwork-stringer sulfide mineralization

Stockwork-stringer mineralization consists of fine cross-cutting chalcopyrite and/or pyrite  $\pm$  chalcopyrite  $\pm$  gold tellurides (calaverite, petzite, and krennerite) anastomosing veinlets-veins (Fig. 12C). In addition to overprinting the semimassive sulfide zone, wispy chalcopyrite stringers locally cross-cut bedded massive sulfide (Fig. 12D). The stockwork-stringer mineralization may be accompanied by weak to strong silicification and generally weak, wispy chlorite alteration.

Both lenses are enveloped by a pyritic stockwork sulfide halo ( $\leq 30\%$  sulfides) which extends an undetermined distance along strike. The halo, which is associated with widespread pervasive sericitization, consists of pyrite disseminations, discontinuous bands or laminations and veinlets that are cross-cutting and parallel to foliation and bedding. Stockwork-stringer mineralization developed stratigraphically below the major lenses grades both vertically and laterally into the halo.

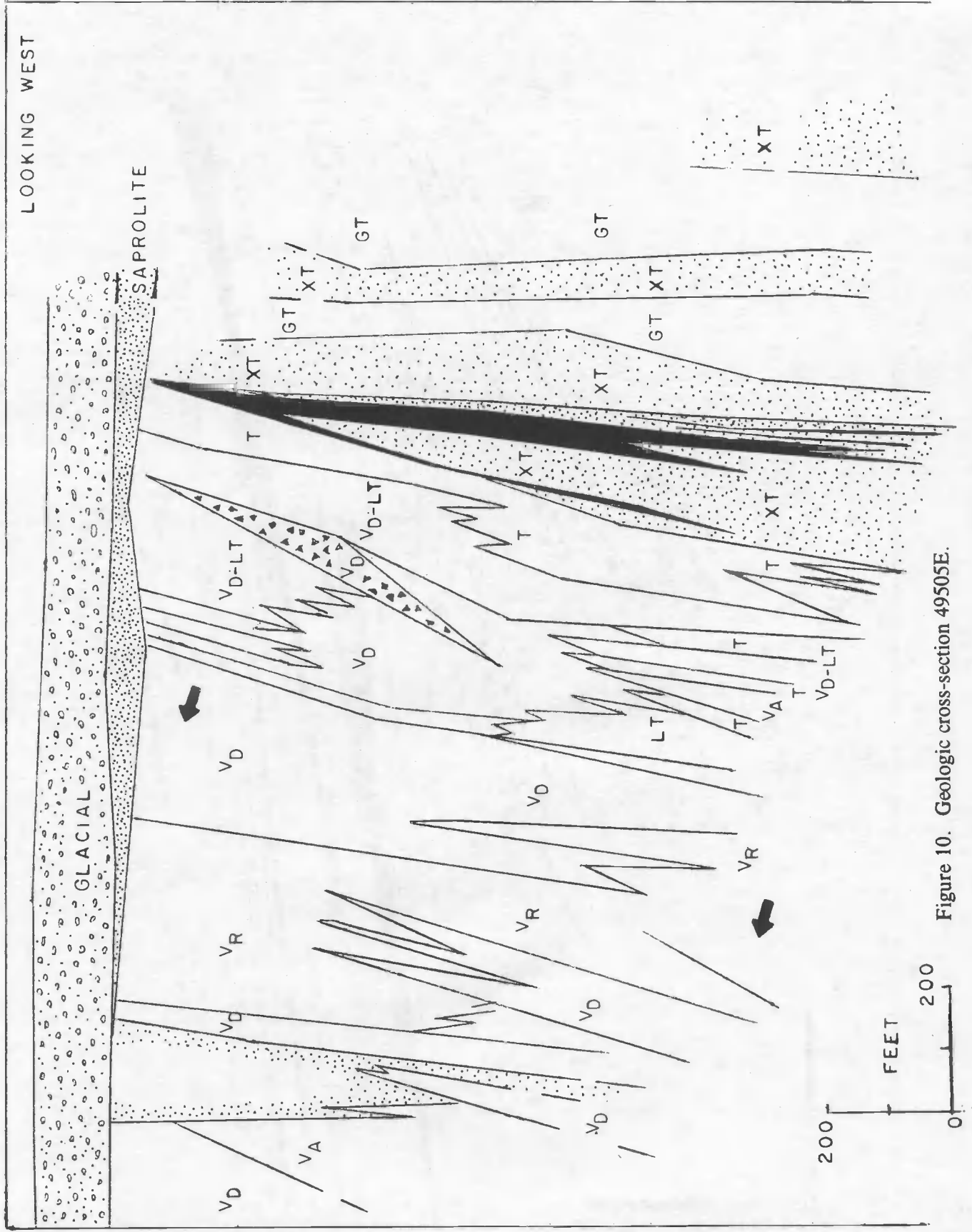


Figure 10. Geologic cross-section 49505E.

LOOKING WEST

GLACIAL

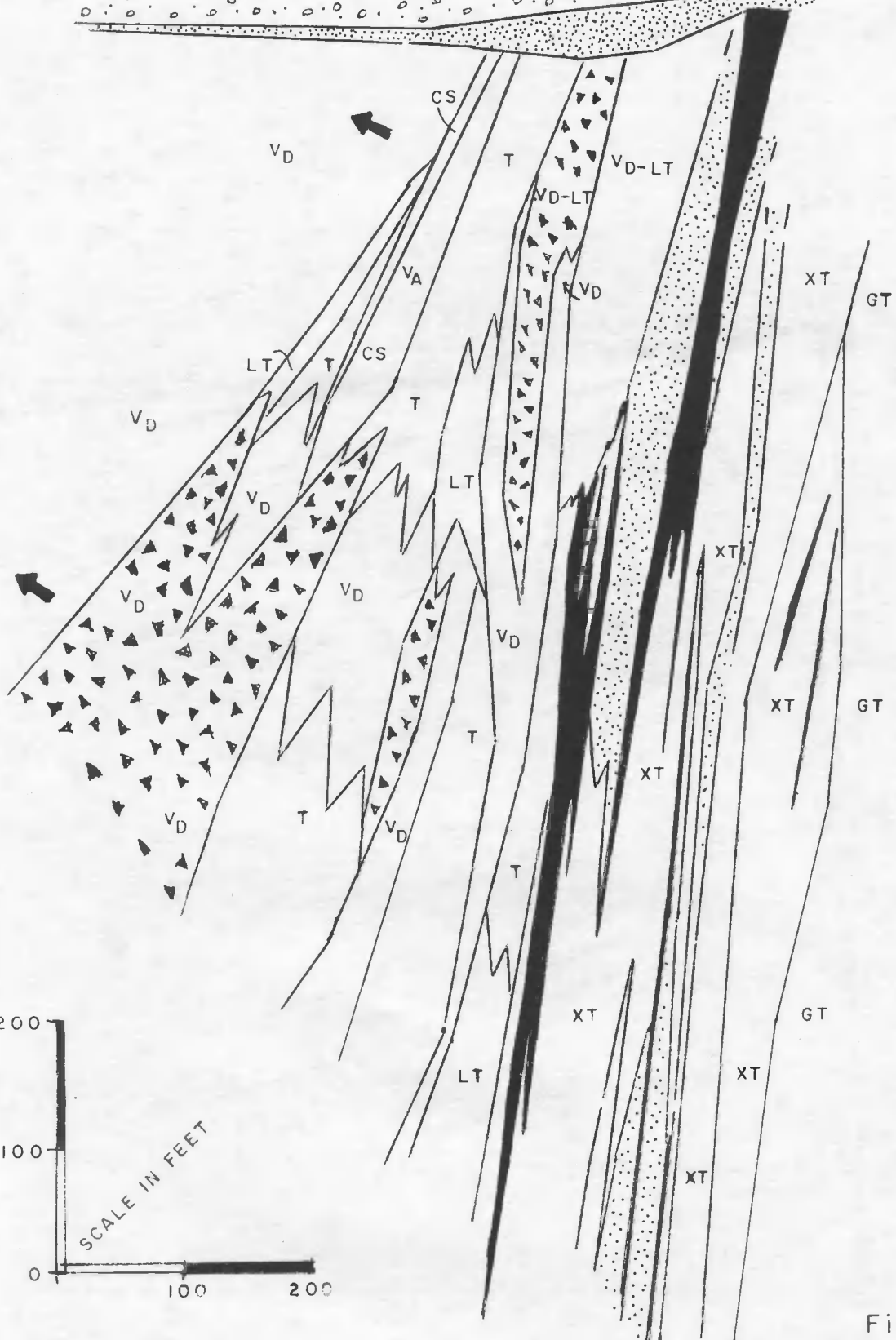


Fig. II

## Copper-Gold Distribution

The deposit, classified as copper-type VMS mineralization (DeMatties 1994), contains only minor amounts of zinc and, therefore, has not developed any zonation of base metals. However, the deposit does exhibit distinct copper-gold zoning patterns, i.e. development of copper-rich massive sulfide lenses accompanied by several prominent parallel gold zones.

In the massive sulfide mineralization hypogene copper grades exhibit a significant increase stratigraphically upward from the lower to upper lens. The well-bedded stratigraphically upper lens contains the highest copper grades in the deposit. This copper distribution may have resulted from hypogene enrichment by stratigraphically upward migration or "refining" during multiple copper-gold hydrothermal pulses within the developing sulfide mound.

The highest gold values in the system occur stratigraphically below each lens as semiconformable ore-grade ( $\geq 0.1$  opt) gold assay zones (designated as the "tuckunder" and lower gold zones). These zones, which developed in the enveloping stockwork-sulfide halo, appear to be stratigraphically controlled and have continuity along strike and down dip. Locally, structures cross-cutting the halo host auriferous quartz-carbonate veins containing gold-silver tellurides that assay in the multiple ounce-per-ton range. The frequency of cross-cutting gold-silver mineralized structures is unknown at this time.

Widespread gold values  $\geq 0.01$  opt have been found throughout the stockwork sulfide halo. Higher values can form poorly developed stratiform assay zones of limited down dip or lateral extent.

## POTENTIAL ORE RESERVES

A potential copper ore reserve (copper zone) is contained in the two stacked lenses, semimassive sulfide zone, and associated stringer mineralization. The zone contains accessory amounts of gold and silver reported as gold and silver telluride minerals. Where the lenses coalesce, the copper zone may total 70 feet in thickness. Overall dimensions of the zone include a strike length ranging from 1100 feet at the subcrop to 1800 feet at depth and a thickness which varies from 10 to 70 feet; it has been tested to a depth of 2000 feet.

A 1994 estimate calculated a drill indicated resource of 3.3 million tons grading 2.05% copper, 0.07 opt gold and 0.41 opt silver (estimate includes "tuckunder" gold zone). A high-grade core in the center of the copper zone contains 1.42 million tons grading 3.11% copper, 0.07 opt gold and 0.41 opt silver. The copper zone remains open down dip and down plunge to the west; it appears to terminate against the domal complex along its eastern margin.

In addition to the copper zone, ore potential exists in the adjoining lower gold assay zone, which is characterized by pyritic gold mineralization with minor copper and silver values. Though poorly defined, it is estimated (1994) to contain a resource of 602,850 tons grading 0.885% copper, 0.21 opt gold, and 0.26 opt silver. The zone remains open in all directions.

## EXPLORATION POTENTIAL

In addition to expanding the identified resource down dip and down plunge, there is good potential for discovery of additional VMS deposits along strike to the east where the ore-equivalent horizon has been located. The horizon is represented by a section of laminated to thin bedded hematitic cherty tuffs (tetsusekiei), meta-argillites (commonly graphitic or sulfide-bearing) and

A



A. Altered felsic quartz-crystal metatuff (quartz-sericite schist) host rock, productive XT unit. Note flattened and elongated blue (dark gray in photo) quartz eyes which characterize this unit.

B



B. Bedded and laminated massive sulfide from the upper lens of the copper zone. Relict bedding features are well preserved. Large host rock fragment (quartz-sericite schist) is draped by bedding. Darker laminae are tetrahedrite-tennantite.

C



C. Pyritic stringer mineralization cross cutting quartz-crystal tuff.

D



D. Fine chalcopyrite stringer mineralization (light gray) overprinting massive pyritic sulfide, copper zone.

E

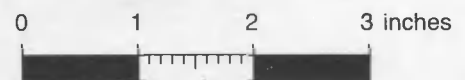


E. Laminated cherty hematitic metatuff (tetsusekiei) that stratigraphically overlies the deposit along its eastern flank. The light laminae are the tuffaceous (sericite-rich) component whereas the darker laminae represent the exhalative (quartz-hematite) component.

F



F. Mineralized argillite. Note fine discontinuous pyrite-chalcopyrite laminations (light gray).



copper-bearing massive sulfide beds (Figs. 12E and 12F). Although the horizon is interrupted by the felsic dome, geophysical surveys suggest it reappears again on the northeastern margin of the complex and extends along strike for nearly 5000 feet. Several isolated electromagnetic anomalies have been identified along the trend of the horizon. These targets remain untested.

### Acknowledgments

The author would like to acknowledge Sharpe Energy and Resources for permission to release these data. Also thanks are extended to Mark Burdick who prepared the illustrations.

### References Cited

- DeMatties, T. A., 1994, Early Proterozoic massive sulfide deposits in Wisconsin: an overview: *Economic Geology*, v.89, p. 1122-1151.
- LeBas, M. J., LeMaitre, R. W., Streckeisen, A., and Zanettin, B., 1986, A Chemical Classification of Volcanic Rocks Based on Total Alkali Silica Diagram: *Journal of Petrology*, v. 27, p. 745-750.
- Pearce, J. A. and Cann, J. R., 1973, Tectonic Setting of Basic Volcanic Rocks Determined Using Trace Element Analyses: *Earth and Planetary Science Letters*, v. 1, p. 290-300.
- Sims, P. K., Van Schmus, W. R., Schulz, K. J., and Peterman, Z. E., 1989, Tectonic-stratigraphic evolution of the early Proterozoic Wisconsin magmatic terranes of the Penokean Orogen: *Canadian Journal of Earth Sciences*, v.26. p 2145-2158.





## **GEOLOGY OF THE LYNNE BASE-METAL DEPOSIT, NORTH-CENTRAL WISCONSIN, U.S.A.**

by Glen W. Adams

Geological Consultant  
Rhineland, Wisconsin

### **ABSTRACT**

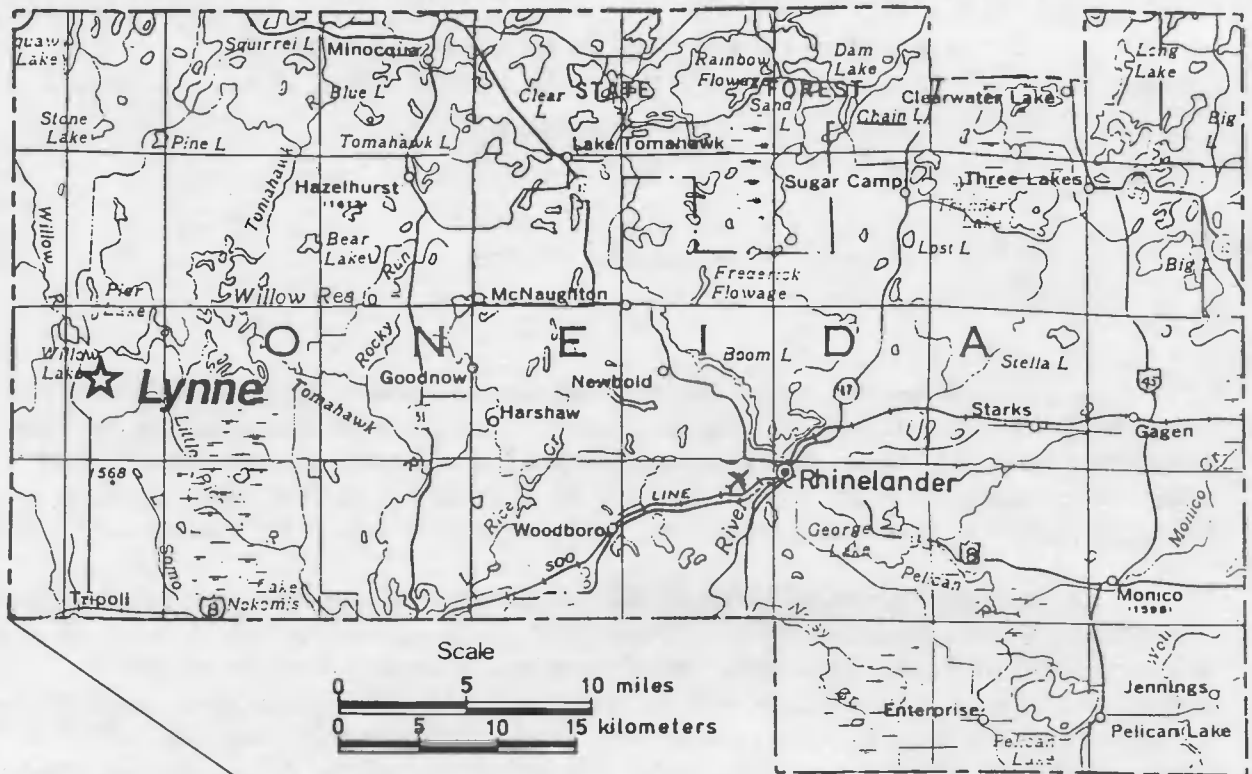
The Lynne polymetallic deposit was discovered in early 1990 by Noranda Exploration Inc., in north-central Wisconsin, U.S.A. The deposit is the most recent base-metal discovery in the Early Proterozoic, Rhineland-Ladysmith greenstone belt and has a reported open-pit reserve of 5.61 million tons grading 9.27% Zn, 0.47% Cu, 1.71% Pb, 2.38 opt Ag, and 0.021 opt Au. Mine permitting procedures have been suspended and the future of the deposit is uncertain.

The Lynne deposit consists of four stacked, strataform massive to semi-massive sphalerite-rich bodies hosted within a predominantly felsic sequence of subaqueous volcanic and volcanoclastic rocks, volcanic-derived wackes and tuffs, and chemical sediments. Unusually abundant amounts of carbonate rocks are directly associated with the sulfide ore. The Lynne stratigraphy is underlain by an intrusive tonalite body that locally disrupts and intrudes the lowest sulfide unit. No definitive stringer zone or alteration pipe has been identified; however, a broad alteration assemblage, similar to other volcanogenic massive sulfide deposits, envelopes the immediate host rocks. Skarn-style mineralization is associated with carbonate rocks along the flanks of the sulfide bodies. Metal zoning compatible with volcanogenic massive sulfide deposits is present. Although the Lynne deposit has characteristics of both volcanogenic massive sulfide and skarn-type deposits, a volcanogenic model is preferred.

### **INTRODUCTION**

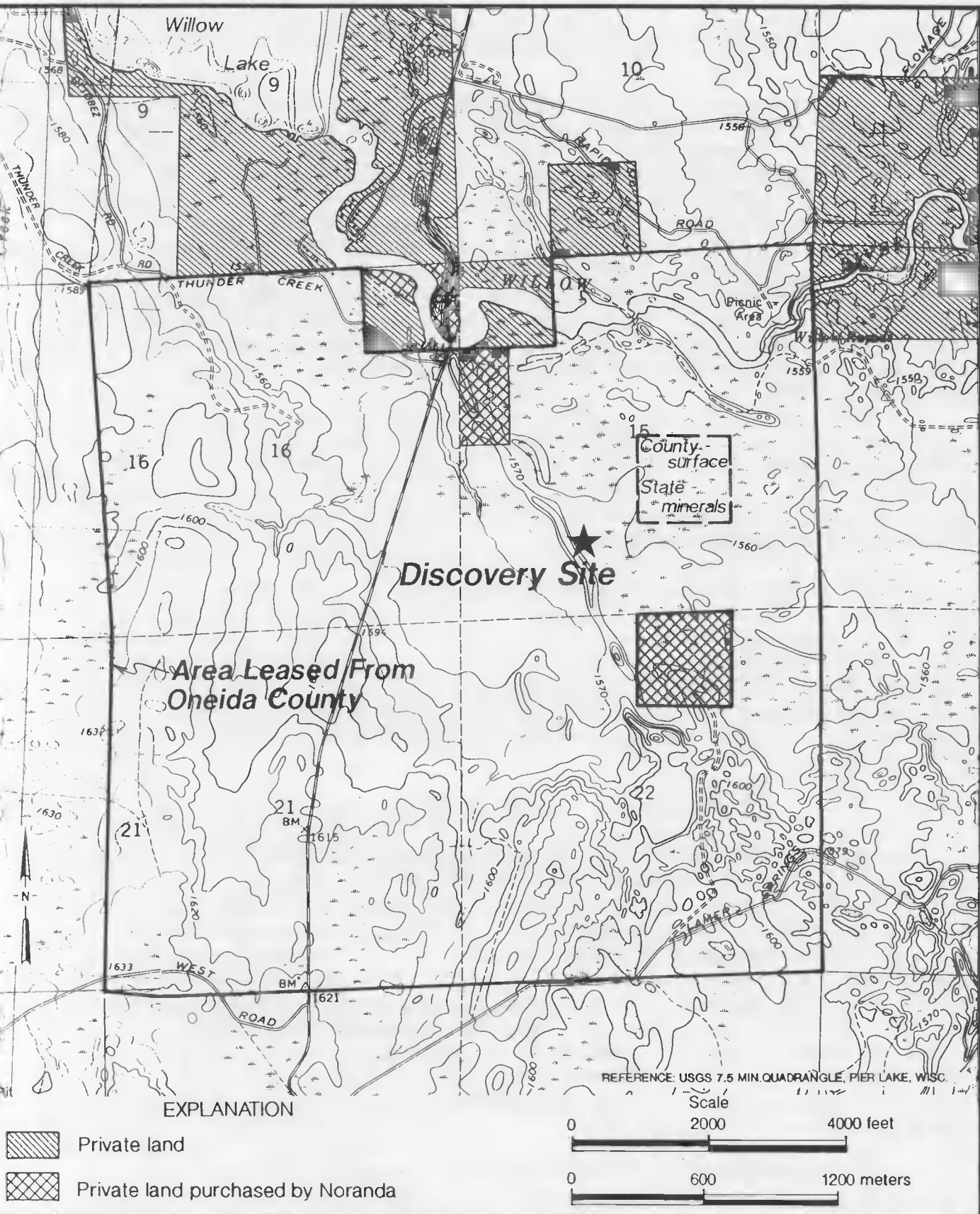
The Lynne polymetallic deposit is located in Lynne Township approximately 25 miles west-northwest of Rhineland in north-central Wisconsin (Figure 1). The deposit site is approximately nine miles north of State Highway 8 and the small town of Tripoli. All-weather paved and gravel roads access the project area and the Wisconsin Central Railway has a siding at Tripoli.

The Lynne deposit occurs on Oneida County surface and mineral lands that are under lease to Noranda Minerals Wisconsin Corp. (Figure 2). Subsequent to the discovery of the deposit in January, 1990, 138 drill holes were drilled to delineate the Lynne massive sulfide body and conduct stratigraphic tests in the immediate deposit area. In January, 1992, a Notice of Intent To Collect Data and Proposed Scope of Study was filed with the Wisconsin DNR as Noranda's initial step in the involved Wisconsin mine permitting process. The deposit is intimately associated with an area of wetlands that would be disturbed by mining. On October 23, 1993, Noranda suspended all permitting activity, citing uncertainties surrounding DNR wetlands and lake-bed designation issues and metal prices. All surface disturbances related to the exploration and initial permitting procedures were reclaimed as of January, 1996 and the future of the deposit is uncertain. All Noranda's county mineral leases on the Lynne deposit remain in good standing.



**Figure 1**

Location Map  
 Lynne Base-Metal Deposit  
 Oneida County, Wisconsin



**Figure 2**

**Noranda Mineral Lands  
Lynne Base-Metal Deposit  
Oneida County, Wisconsin**

## REGIONAL GEOLOGY

The Lynne deposit is located in the central part of the Rhinelander-Ladysmith greenstone belt, a belt of Proterozoic, volcanic and sedimentary rocks within the Southern Province of the Canadian Shield. The Rhinelander-Ladysmith greenstone belt (Figure 3), is the informal designation for the northern part of the Pembine-Wausau terrane of Sims *et al.* (1989). It is approximately 50 miles wide and extends roughly 150 miles in an east-west direction across northern Wisconsin and the central Upper Peninsula of Michigan. Rocks within the greenstone belt range in age from 1,860 Ma to 1,889 Ma (Sims *et al.*, 1989), and have been affected by the Penokeon Orogeny, resulting in locally intense folding, major faulting, thermal metamorphism, and granitic plutonism. Widespread Pleistocene glacial deposits mantle much of the greenstone terrane resulting in minimal outcrop exposure. On the west the greenstone belt is overlain by Late Proterozoic quartzite and Paleozoic sandstones, while on the east there is an onlap of Early Paleozoic sandstone and carbonate rocks. In-depth reviews of the Rhinelander-Ladysmith Greenstone belt are presented in this volume by DeMatties and by LaBerge.

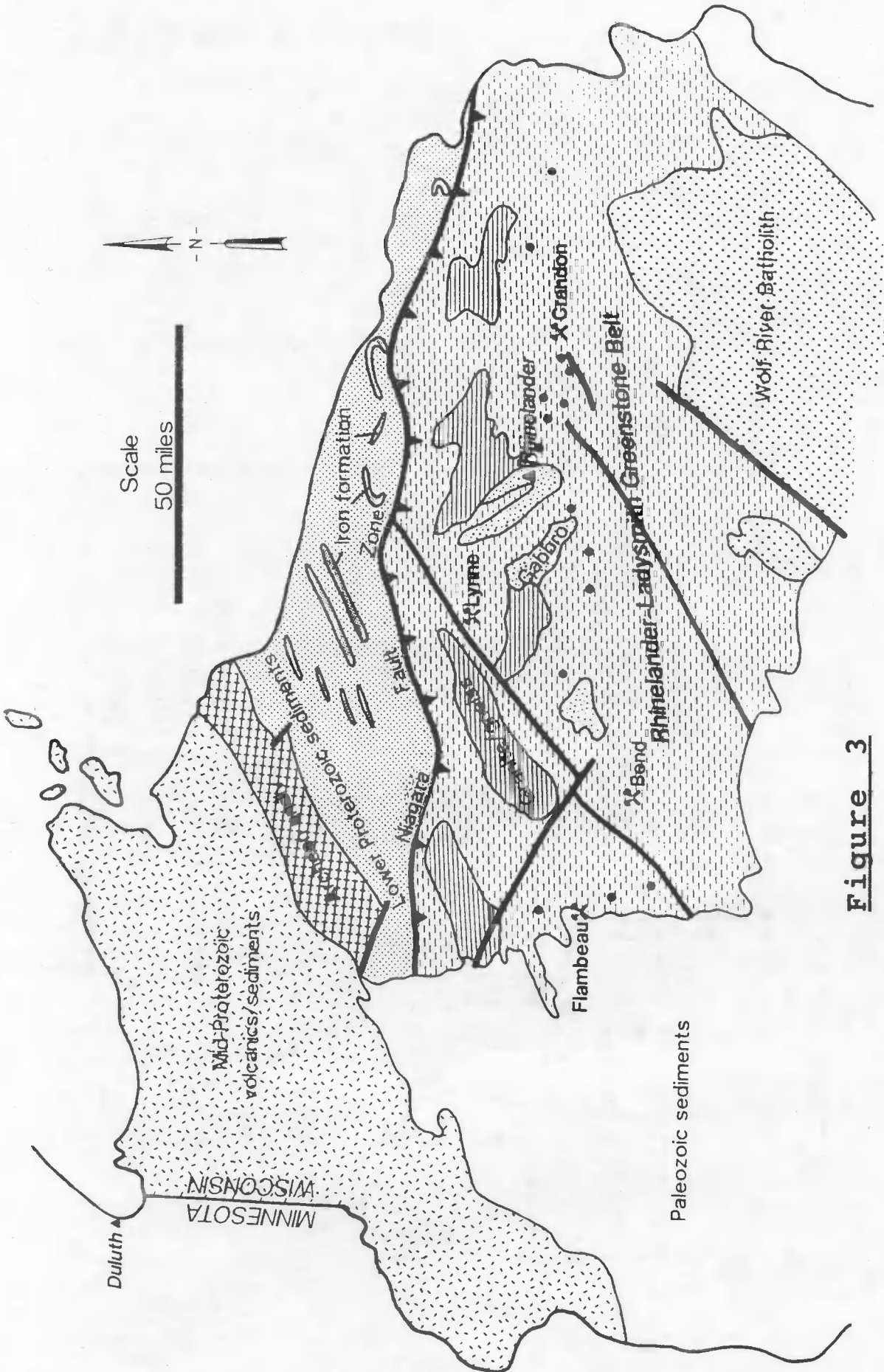
Mineral exploration over the past 30 years, dominated by airborne geophysical surveys, has identified over two dozen significant base-metal massive sulfide occurrences scattered throughout the Rhinelander-Ladysmith greenstone belt (Figure 4). The Flambeau mine, currently in production, and three other potentially economic occurrences, the Crandon, Bend, and Lynne deposits, all occur within the Rhinelander-Ladysmith greenstone belt.

Geologic knowledge of the Lynne deposit area is very limited due to poor outcrop exposure. Regional airborne E.M. and magnetic data and scattered drill hole information suggest that the general geology of the Lynne area consists predominantly of mafic to intermediate volcanic rocks with at least one felsic eruptive and intrusive event, represented by the lithologies in the immediate Lynne deposit area. The felsic volcanic-related rocks associated with the Lynne deposit predominate over mafic to intermediate rocks by a significant amount. The increase of felsic volcanic rocks in the Lynne deposit area is common to other significant base-metal occurrences in northern Wisconsin and elsewhere (DeMatties, 1994).

### LYNNE DEPOSIT DISCOVERY HISTORY

The Lynne deposit is the most recent major base-metal discovery in Wisconsin. However, at least two exploration companies were aware of the Lynne airborne E.M. anomalies up to 14 years before its discovery. Exxon Minerals identified isolated anomalies over what is now the Lynne deposit from an airborne E.M. survey flown in the mid 1970's. Because the mineral rights covering the anomalies were owned by Oneida County, and unattainable at that time, no serious interest was given to the target. Kerr McGee conducted an airborne E.M. survey over the area in the early to mid-1980's following up on anomalous lake sediment samples taken about two miles southeast of the deposit. They too had detected the Lynne E.M. response; however, Oneida County lands were still not available for mineral leasing. Not until Oneida County made their mineral lands available for lease through competitive sealed bid in 1989, did the lands hosting the Lynne deposit become attainable. Unfortunately, by this time neither Exxon Minerals nor Kerr McGee were still actively exploring in Wisconsin.

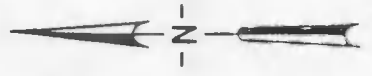
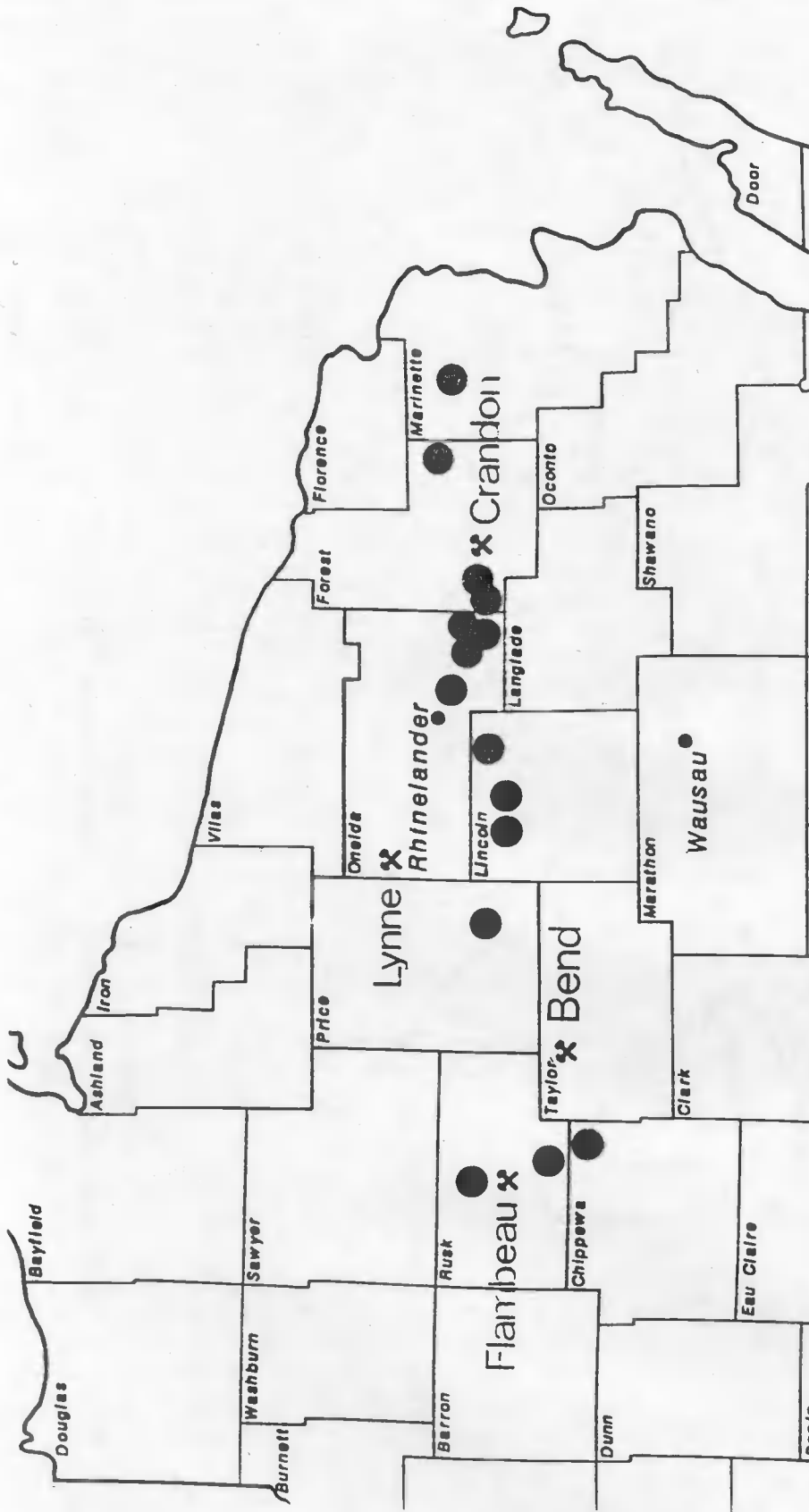
Noranda Exploration remained active in the state on the belief that Wisconsin's greenstone belts hosted additional base-metal deposits. Noranda's staff was experienced in Wisconsin exploration and knew of the Lynne airborne E.M. anomalies. Noranda's perseverance paid off when, in May



**Figure 3**

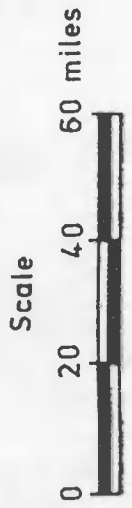
**Schematic Geology  
Rhinelander-Ladysmith Greenstone Belt  
North-Central Wisconsin**

● Massive sulfide occurrence



**Figure 4**

Massive Sulfide Occurrences  
North-Central Wisconsin



1989, they were the successful bidder on four sections of Oneida County mineral lands in Lynne Township.

Initial ground geophysical surveys conducted by contractor Rodney Ikola and Associates, and later by Noranda staff, revealed a moderate to strong E.M. anomaly with an associated strong out-of-phase E.M. component (Figure 5), which was initially attributed to an overburden response. Gravity data indicated a relatively low, but anomalous, gravity response of about 0.8 milligals. On January 6, 1990, after two failed attempts to penetrate 56 feet of glacial overburden, the Lynne massive sulfide deposit was intersected in the first of two initial drill holes (Adams, 1990). Discovery hole W90-1 intersected 128 feet of zinc-rich massive sulfides followed by a second hole, drilled 150 feet to the north of the first hole, which stayed in relatively massive sulfides for over 375 feet (Table 1). It was now understood that the large out-of-phase E.M. response was caused by widespread, relatively poorly conductive, massive sphalerite mineralization. The massive orebody corresponds with the main strong in-phase E.M. anomaly of Figure 5. The narrow in-phase E.M. anomaly southeast of the orebody is not related to sulfide mineralization.

On June 19, 1990, Noranda publicly announced the discovery of the Lynne deposit. After 18 years of exploration, the drilling of several promising massive sulfide occurrences, and the expenditure of several millions of dollars in Wisconsin, Noranda appeared to have a massive sulfide deposit with commercial potential. Reported reserves of 5.61 million tons grading 9.27% Zn, 0.47% Cu, 1.71% Pb, 2.38 opt Ag, and 0.021 opt Au (American Mines Handbook, 1995), are considered recoverable by open pit methods.

In 1990, Noranda flew a detailed airborne E.M. survey over the Lynne deposit and surrounding region defining additional attractive targets. To date no other discoveries have been made, although the exploration potential is favorable. In early 1993, Noranda Exploration Inc. closed its Wisconsin exploration office sighting a general unfavorable mineral exploration and development climate in the state.

## GEOLOGY AND MORPHOLOGY OF THE LYNNE DEPOSIT

The area hosting the Lynne deposit is covered by 40 to 75 feet of unconsolidated glacial till. Lithologies, alteration and structure of the orebody and its host rocks are derived from drill hole information and detailed ground and airborne geophysical data. The only known outcrop within several miles of the deposit is an area of moderately foliated granitic rock occurring in, and adjacent to, the Willow River about 4000 feet northeast of the orebody. There is evidence of an oxidized cap on the ore deposit.

The Lynne ore body consists of four strataform, massive to semi-massive, stacked, polymetallic, sulfide bodies with an aggregate thickness of approximately 325 feet in the central part of the ore zone. The sulfide bodies exhibit abrupt thickening and coalescing in the core of the ore zone with ore dissipating relatively quickly on the flanks. Sphalerite is the predominant sulfide mineral followed in abundance by pyrrhotite, pyrite, galena, and chalcopyrite. Gold occurs in the lower sulfide body and in association with skarn mineralization on the flanks of the deposit along with magnetite. Silver mineralization occurs in the central to upper part of the ore body. Metal zoning occurs as a relative enrichment of copper toward the base of individual sulfide units. Metal zoning also occurs as a progression of relative copper and iron enrichment toward the base of the composite sulfide deposit, grading upward into strong zinc mineralization followed by concentrations of lead and silver in the upper parts of the ore zone. The sulfide-bearing zone has a strike length of approximately 1300 feet and both the ore deposit and its host rocks strike in a general east-southeast



**Table 1**

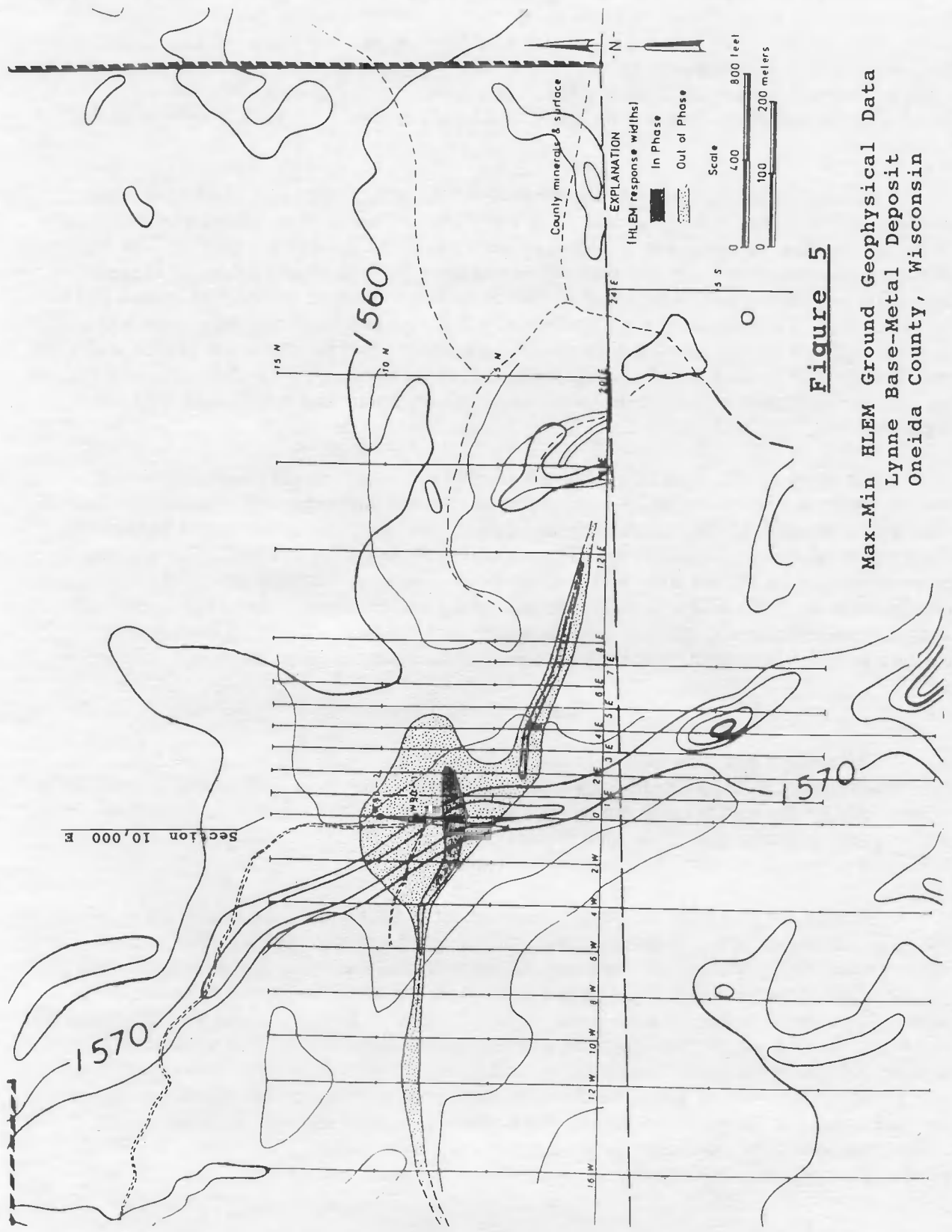
**Assay Results From Drill Holes W90-1 & W90-2  
Lynne Base-Metal Deposit  
Oneida County, Wisconsin**

Composite Zones from Drill Hole W90-1

From (Ft)	To (Ft)	Width (Ft)	Zn %	Cu %	Pb %	Ag opt	Au opt
135.50	150.70	15.20	34.78	0.38	3.64	0.608	0.010
150.70	168.20	17.50	5.02	0.83	0.36	0.293	0.012
168.20	197.20	29.00	34.44	0.88	3.13	1.104	0.006
205.40	263.50	58.10	22.17	0.58	3.83	1.435	0.014
135.50	263.50	128.00	22.71	0.64	2.95	1.039	0.011

Composite Zones from Drill Hole W90-2

From (Ft)	To (Ft)	Width (Ft)	Zn %	Cu %	Pb %	Ag opt	Au opt
55.00	66.60	11.60	18.59	0.05	8.47	8.558	0.016
102.60	242.30	139.70	6.41	0.17	2.82	10.746	0.014
250.90	320.60	69.70	21.64	0.54	2.82	1.257	0.012
320.60	350.20	29.60	2.79	0.12	0.77	0.901	0.012
372.20	405.50	33.30	4.71	0.16	0.29	0.498	0.009
405.50	439.00	33.50	11.20	0.74	0.76	0.844	0.018
55.00	439.00	384.00	8.45	0.26	2.09	4.736	0.012



**Figure 5**

Max-Min HLEM Ground Geophysical Data  
 Lynne Base-Metal Deposit  
 Oneida County, Wisconsin

direction dipping northeasterly at about 40 degrees. Graded beds within the host rocks indicate that the stratigraphy is upright with tops to the northeast. The zinc-rich sulfide bodies lie within a subaqueous, volcanoclastic, sedimentary and carbonate-rich sequence of rocks. Drill hole data from host rocks indicate a general coarsening of pyroclastic material to the north, or down-dip, suggesting a more proximal location to a possible volcanic eruptive source in that direction. The lowest sulfide-rich horizon of the deposit is underlain, and locally disrupted and cut off, by an intrusive tonalite body.

The deposit and its host rocks show no major structural complexities. East to southeast striking, vertical to sub-vertical, fracture zones exhibit minor movement in stratigraphy within and down-dip from the ore zones, and according to Kennedy (1992), postdate the tonalite. The fracture zones are commonly filled with rhyodacite dikes and less often with basaltic dikes. A shallow depression or trough occurs in the upper surface of the tonalite beneath the thickest, central part of the ore deposit. There has been some speculation that the fracture zones may have some relationship to this trough-like feature, and that the fracture zones, and possibly the depression in the tonalite, are genetically related to the deposition of sulfide mineralization (Adams, 1991). Both structural features may represent remnants of a down-dropped, or graben-like, feature that helped to localize ore deposition.

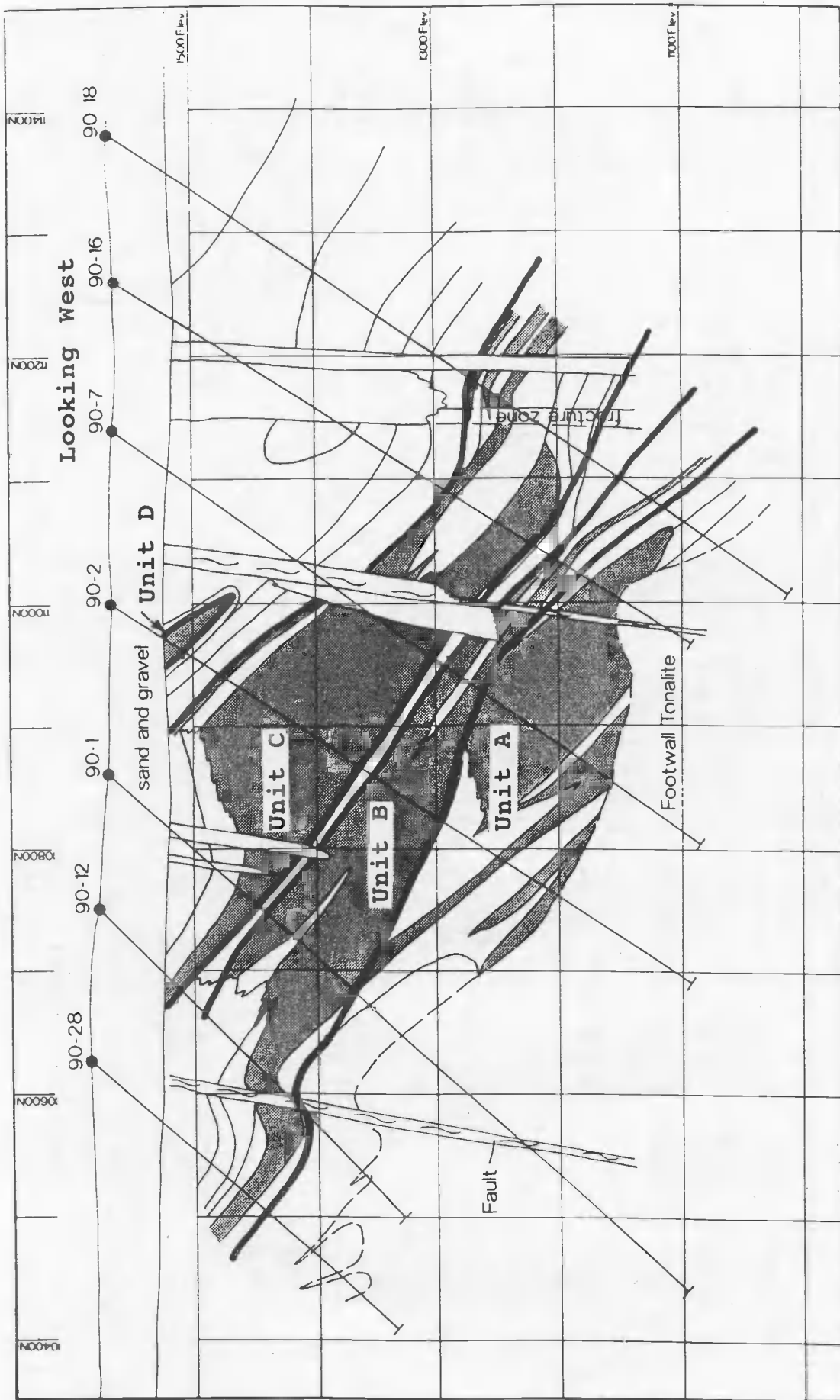
The entire lithologic package, although variably altered and locally affected by contact metamorphism and skarnification, is metamorphosed to greenschist metamorphic rank. Evidence of retrograde alteration of higher temperature minerals to lower temperature minerals is widespread. Chlorite and talc-bearing alteration assemblages occur in the lower parts of the Lynne stratigraphy; however, no distinct stringer zone or alteration pipe is evident. A pervasive alteration assemblage does occur in the enveloping host rocks. Because of the unusual combination of base-metal and alteration assemblages, and the host rock lithologies, the Lynne deposit exhibits characteristics common to both volcanogenic massive sulfide and carbonate-related skarn, deposits.

### Sulfide Mineralization

The massive and semi-massive strataform lenses of the Lynne ore deposit are divided into four separate zones or units based on physical, or discrete compositional, differences (Adams, 1990; Adams, 1991). The sulfide lenses are designated as units A through D with A being the lower-most, and progressing stratigraphically upward to units B, C, and D (Figures 6 and 7).

#### Unit A

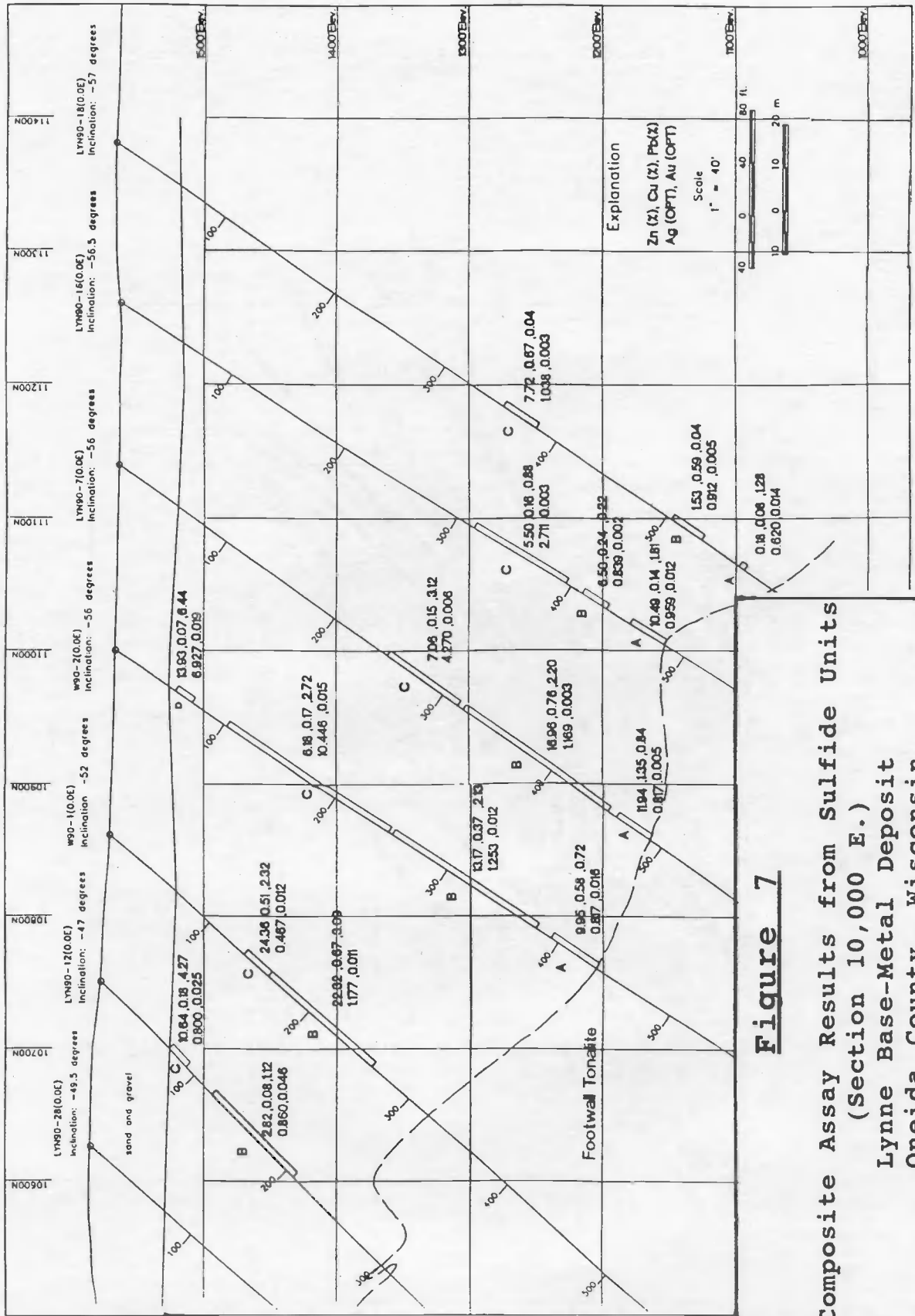
Sulfide Unit A exhibits the greatest lateral extent of all the zones and reaches up to 60 feet in thickness, although it is locally disrupted and intruded by the foot-wall tonalite. The zone is a pyritic, massive sphalerite body enriched in chalcopyrite and pyrrhotite relative to the other zones. Over 50 percent of the copper and over 30 percent of the gold content of the ore deposit occurs in cherty, chloritic, pyrrhotitic massive to semi-massive sulfide portions of this unit (Kennedy, 1992). Partially enveloping the unit is a talc-rich assemblage containing disseminated to massive sulfides with Mg-chlorite, phlogopite and lesser tourmaline, serpentine, cummingtonite, and galena (Kennedy *et al.*, 1991). Also present locally within the alteration envelope is stringer-like and disseminated sphalerite and pyrrhotite. An extensive barren zone of this alteration assemblage, with laminated cherts containing disseminated pyrrhotite, pyrite and minor magnetite laminae, continues up to 300 feet along strike and down-dip from Unit A.



**Figure 6**

Sulphide Units  
 (Section 10,000 E.)  
 Lynne Base-Metal Deposit  
 Oneida County, Wisconsin

Looking West



**Figure 7**

Composite Assay Results from Sulfide Units  
 (Section 10,000 E.)  
 Lynne Base-Metal Deposit  
 Oneida County, Wisconsin

### Unit B

Narrow intervals of carbonate rock, with local skarn-type mineralization, separate units B and A. Sulfide mineralization in Unit B differs strongly from Unit A in that it occurs in association with lenticular masses of chemical sedimentary rocks including calcareous and siliceous facies. Disseminated sphalerite and pyrite is ubiquitous to the carbonate host rocks, and massive to semi-massive sphalerite, with lesser galena and subordinate chalcopyrite, forms lenses up to 50 feet thick. The composite thickness of Unit B reaches approximately 150 feet in the central part of the ore body. Unit B contains over 50 percent of the total deposit tonnage and almost 60 percent of the total zinc content of the deposit (Kennedy, 1992). Thin beds of carbonate-rich volcanoclastic and sedimentary rocks within the unit are pervasively replaced by calc-silicate minerals. Sphalerite, and to a lesser extent pyrrhotite and pyrite, are disseminated throughout the carbonate host rocks. The carbonate rocks are relatively planar bedded near the base of the unit becoming increasingly disrupted toward the top. Carbonate beds tend to be finer grained and well bedded off the flanks of Unit B.

### Unit C

Narrow beds of barren volcanoclastic wackes or tuffs and a rhyolitic sill separate units B and C. Unit C is approximately 160 feet thick and consists predominantly of contorted, folded, or disrupted calcareous chemical sediments that can be divided into two zones. The lower calcareous zone is about 50 feet thick and consists of marble with massive to semi-massive sphalerite and galena. The upper 110 feet of the unit is calcareous, but within the upper 50 feet it becomes extremely siliceous containing cherty layers and diopside-rich cherts. Sulfide mineralization in the upper part of Unit C consists of disseminated to semi-massive sphalerite, pyrite and galena. A large proportion of the deposit's silver content occurs in the upper siliceous part of Unit C in the form of native silver, tetrahedrite, and argentiferous galena. Here, silver content averages over 100 ounces per ton for several tens of feet. As with Unit B, this unit shows a relative abundance of chalcopyrite toward the base of the sulfide assemblages. An envelope of diopside-garnet-pyrrhotite-magnetite skarn mineralization occurs on the south side of the lower part of Unit C and on the upper part of Unit C in association with rhyolite sills (Kennedy, 1992).

### Unit D

Unit D, the uppermost sulfide unit, is a massive to semi-massive zone of sphalerite with accessory galena and appreciable chalcopyrite in siliceous, cherty, chemical sediments. This unit is truncated by the bedrock surface and grades rapidly down-dip into barren volcanoclastic sediments. The unit is separated from the underlying unit C by a 50-foot thick, rhyolitic sill.

## **Host Rocks**

The rocks hosting the Lynne deposit (Figure 8), have had little in-depth investigation with the exception of work done by Kennedy (1992), who, in conjunction with Noranda's predevelopment staff, studied the immediate host-rocks and their alteration assemblages as part of the deposit delineation drilling program. Much of the following information on the host rocks is drawn heavily from Kennedy (1992), and the findings of the predevelopment staff.

Kennedy (1992) has divided the Lynne deposit host rocks into five units consisting of, in ascending order, the Lower Rhyolite, the ore-bearing Lynne Horizon, the Upper Rhyolite, the Upper VCS and the Hanging Wall Unit. Subsequent to the deposition of this felsic volcanic-rich sequence, the rocks were intruded by a probable subvolcanic tonalite body that partially ingested and disrupted the lower surface of sulfide Unit A.

### Lower Rhyolite

The Lower Rhyolite consists of massive to poorly sorted, rhyolitic lapilli to ash tuff containing abundant pumice fragments and locally poorly graded beds of fine ash tuff. Dark green to black chloritic material is common as veinlets and irregular masses. Kennedy (1992) interprets this lithologic package as a sequence of subaqueous debris flows. Angular and shattered coarser felsic lapilli fragments suggest possible local autobrecciation of rhyolitic flow rocks.

The Lower Rhyolite interfingers with the stratigraphically higher Lynne Horizon north of the orebody but is absent from the immediate vicinity of the orebody either due to non-deposition or incorporation into the intruding tonalite. Rhyolitic tuffs with distinctive angular lapilli clasts occur north of the orebody and approximately one mile south of the orebody, suggesting that this unit may be relatively widespread.

### Lynne Horizon

The Lynne Horizon hosts the Lynne ore deposit and consists of a sequence of predominantly volcanoclastic, detrital, and chemical sedimentary rocks with lesser interlayered intermediate to felsic volcanic flow rocks and minor rhyolitic crystal tuffs. The horizon is up to 320 feet thick and extends over one-half mile east of the ore deposit. The volcanoclastic rocks consist of greywackes and laminated siltstones of volcanoclastic or reworked volcanic material interbedded with and grading into crystal to crystal-lithic tuffs.

Carbonate-rich sediments, characteristic to this horizon, and lesser laminated cherts occur over 1300 feet away from the orebody and increase in abundance and thickness toward the orebody where they exceed 200 feet thick in the center of the ore deposit (Kennedy, 1992). The bulk of the carbonate rocks are directly associated with the massive to disseminated parts of the sulfide ore zones where they are partially or mostly replaced by sulfide minerals. Some partial replacement continues for a considerable distance away from the main orebody to the north and east where it is often associated with an envelope of potassic and magnesium alteration. On the flanks of the Lynne Horizon the carbonates are often well bedded, while less sulfide-rich carbonate zones within and between the main ore zones are commonly laminated though often disrupted and contorted. The carbonate rocks form sharp contacts with overlying volcanoclastic horizons.

Descriptions by Kennedy *et al.* (1991), Kennedy (1992), and Kennedy and Donnelly (1992), suggest that the carbonate assemblages at Lynne show considerable compositional variations. Dolomitic rocks are the most abundant, and directly associated with base-metal mineralization, while limestones are associated with barren or poorly developed sulfide mineralization on the eastern and western flanks of the deposit. The tendency of more Mg-carbonate toward the central part of the orebody, combined with Mg-silicate alteration assemblages in the immediate host rocks, could denote Mg-metasomatism related to carbonate build-up and ore formation. Since the initial drill holes into the ore body, it has been speculated that the buildup of carbonate material is directly associated with ore deposition (Adams, 1990). The carbonate rocks are relatively restricted to a north-northeast-trending basal feature (Kennedy, 1992), which coincides with the thickest part of the sulfide ore body, suggesting a direct relationship between the ore body and a carbonate build-up.

### Upper Rhyolite

The Upper Rhyolite unit consists of rhyolite crystal and crystal lithic, lapilli tuffs and massive rhyolite with minor interlayers of dacite and andesite, and thin basal horizons of greywacke and chert. The unit is over 300 feet thick north of the orebody and thins southward where it becomes interlayered with the ore stratigraphy. Rhyolitic sills that intrude the ore body are similar to massive rhyolites in the Upper Rhyolite. Epidote-rich skarn is associated with some of the rhyolitic sills on

the west edge of the ore body, suggesting a possible correlation between the intrusion of narrow rhyolite sills of the Upper Rhyolite and the formation of skarn mineralization.

#### The Upper VCS Unit

The Upper VCS Unit consists of volcanic-derived greywacke and laminated siltstone with increasing amounts of andesite as the horizon is traced northward. The updip southerly projection of the horizon is represented by the narrow, upper-most, silicious sulfide Unit D. In the immediate vicinity of the orebody, the Upper VCS Unit is less than 100 feet thick but thickens to over 200 feet to the north and west. Iron sulfides commonly occur in this unit as fracture fillings within 100 feet of the orebody, and form sulfide-rich laminae associated with magnetite in siltstones. Chlorite, epidote and minor actinolite alteration minerals are common.

#### Hanging Wall Unit

The Hanging Wall Unit is a mixture of felsic to mafic tuffs, heterolithic wackes and agglomerates, or conglomerates. Characteristic to this unit are clast-supported agglomerates containing beige to pink lapilli-sized rhyolitic clasts. The wackes contain lapilli-sized rhyolitic to andesitic clasts and plagioclase and quartz crystals in a mafic groundmass. Interpretations by the Noranda pre-development team suggest that the unit may be a series of debris flows that appear to dissipate to the north and are therefore derived from a southerly source area.

#### Tonalite

The tonalite underlies the Lynne ore and host-rock stratigraphy. It has an irregular upper contact that dips at a shallow angle to the northeast. The tonalite intrudes and disrupts the lower part of sulfide Unit A, displacing and enclosing parts of the unit. Flexures in the overlying stratigraphy appear to be associated with a northeast-striking trough in the tonalite surface. The intrusive is often porphyritic with quartz ovoids and euhedral, zoned plagioclase crystals in a fine-grained, commonly graphic, matrix (Kennedy and Donnelly, 1992). Within 50 feet of the contact, the tonalite is characterized by a granophyric texture. Low temperature alteration is common in the tonalite, but is strongest in association with local fracturing or faulting. Within 35 feet of the tonalite, local recrystallization of adjacent volcanic and volcanoclastic rocks occurs and a hornfels texture is sometimes present (Kennedy and Donnelly, 1992). The magnetic response associated with the known area of tonalite grades into a relatively constant regional magnetic low south of the deposit that is interpreted as a large granitic body.

#### **Alteration**

There does not appear to be a distinct alteration pipe, or stringer zone, beneath or adjacent to the Lynne deposit as is common to other volcanogenic massive sulfide deposits (Franklin *et al.*, 1975; Franklin *et al.* 1981). It is possible that the subvolcanic tonalite body has engulfed and destroyed any pre-existing alteration stringer zone. There is, however, an alteration mineral assemblage associated with the lower Lynne ore stratigraphy and the stratigraphically higher encompassing host rocks.

Talc-rich zones up to 25 feet thick occur beneath and grade into the lower massive sulfide Unit A, and talc-rich zones up to 15 feet thick separate zinc-rich ore from skarn and marble units along the northern flank of the orebody (Kennedy, 1992). Local stringer-like veins and disseminations of sphalerite and pyrrhotite occur within Mg-chlorite and muscovite-rich talcose rocks associated with the lower parts of sulfide Unit A (Adams, 1990; Kennedy, 1992). Observations by the Noranda predevelopment team (personal communication), reveal a Mg- and K-rich secondary mineral assemblage extending laterally up to 1300 feet down-dip, and over 2000 feet east, in the footwall rocks of the orebody, and within several hundred feet of the orebody, feldspar in tuffs of the



Upper Rhyolite and the Upper VCS Unit are altered to muscovite and chlorite. These criteria support a broad alteration assemblage similar to semiconformable alteration zones found in conjunction with several world-wide volcanogenic massive sulfide occurrences described by Franklin *et al.* (1981). Tonalite in contact with the orebody, on the other hand, appears to be little altered, suggesting a post-alteration intrusive event.

### Skarn Mineralization

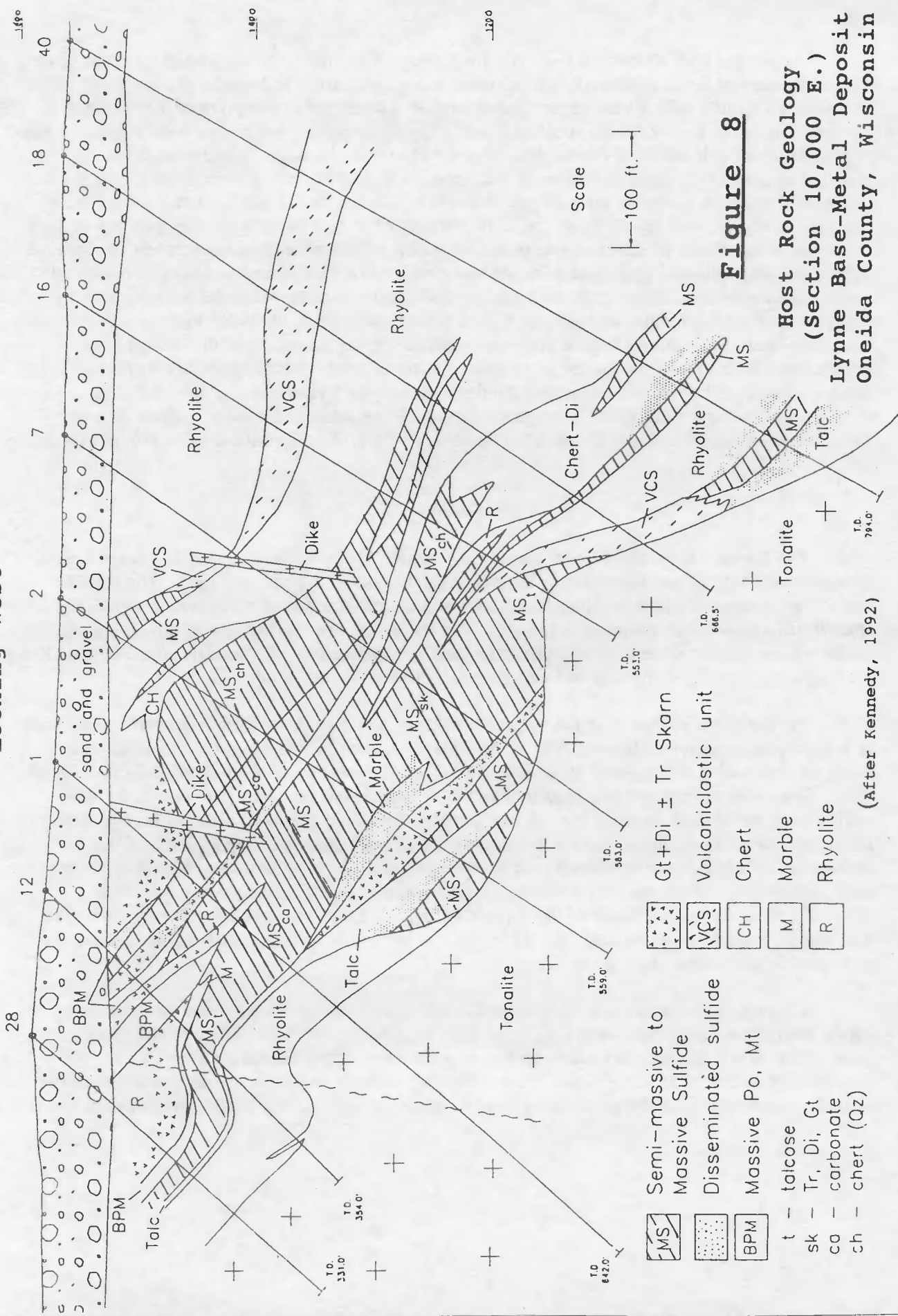
The abundant calc-silicate mineral assemblage associated with the Lynne deposit is uncommon to volcanic-related massive sulfide deposits. It is apparent that the skarn-style of mineralization is directly related to the anomalous amount of carbonate rock associated with the orebody. The most intensive skarn mineralization is associated with the extensive replacement of carbonate along the up-dip flanks or projected edges of the orebody (Figure 8). Here pyrrhotite and magnetite are also locally abundant, especially along the southern edges of the orebody. Quartz-diopside skarn assemblages are characteristic of the upper parts of the deposit and epidote skarn occurs in conjunction with intrusive rhyolitic sills within the orebody (Kennedy, 1992). Skarn mineralization is seldom associated with base-metal ore, but the highest ore-grade gold concentrations have a direct skarn relationship (Adams, 1991; Kennedy, 1992).

No other known massive sulfide occurrence in the Rhineland-Ladysmith greenstone belt is associated with such abundant carbonate material. DeMatties (1990) describes possible carbonate-rich exhalites at the Ritchie Creek occurrence, and significant dolomitic units make up part of the Crandon deposit stratigraphy (Lambe and Rowe, 1987). Franklin *et al.* (1975) refer to a dolomitic host rock package for the Mattabi deposit in the Sturgeon Lake camp of northwestern Ontario. The significant skarn assemblage associated with the Lynne deposit makes this one of the most unique base-metal deposits of the Rhineland-Ladysmith greenstone belt.

### Proposed Genetic Model for the Lynne Deposit

Although the Lynne deposit has characteristics of both volcanogenic massive sulfide and skarn-related deposits, it is believed that the supporting evidence is sufficient to suggest a volcanogenic origin for deposit. A sulfide depositional scenario is proposed whereby a graben-like depression, perhaps developed in conjunction with a caldera collapse feature, forms on the flank of a felsic volcanic complex centered to the northeast of the present-day Lynne deposit. The association of the near-vertical fracture zones in the Lynne stratigraphy, and the trough-like depression in the tonalite surface, with the rapid thickening of the core of the ore deposit, may represent remnant features of the postulated graben. Within the confines of the down-dropped block of felsic volcanic rocks, and using bounding growth faults as conduits, volcanic vents may have began an effusive build-up of carbonate-rich chemical sediments. Either syndepositionally, or closely following the carbonate build-up, solutions rich in zinc, with subordinate lead, silver, copper and gold, replaced much of the central portion of the carbonate mound. At least four episodes of metal infusion prevailed over the deposition of volcanoclastic and chemical sedimentary material within the graben complex. As the sulfide deposition evolved, the relatively abundant copper and iron dropped out of solution, both at the onset of each sulfide event, and throughout the entire sulfide depositional period, and was supplanted by zinc with progressively increasing amounts of lead and then silver. Coincident with the evolution of metal-bearing solutions was the progression from carbonate-rich toward silica-rich chemical sedimentary facies. The confines of the proposed graben feature may account for the stacked layering of chemical sedimentation and sulfide deposition.

Looking West



- MS Semi-massive to Massive Sulfide
- MS<sub>ch</sub> Disseminated sulfide
- BPM Massive Po, Mt
- t talcose
- sk Tr, Di, Gt
- co carbonate
- ch chert (Qz)
- CH Chert
- M Marble
- R Rhyolite
- + Tonalite
- + Gt+Di ± Tr Skarn
- + Volcaniclastic unit
- + Chert
- + Marble
- + Rhyolite

**Figure 8**

Host Rock Geology  
 (Section 10,000 E.)  
 Lynne Base-Metal Deposit  
 Oneida County, Wisconsin

(After Kennedy, 1992)

Associated with a resurgence of volcanic activity, the sulfide-bearing stratigraphy was covered with a sequence of felsic to intermediate, volcanic flow, pyroclastic, and epiclastic rocks, and intruded by rhyolitic sills. At the same relative time, or subsequent to this point in the volcanic history of the area, a subvolcanic, tonalitic mass intruded the base of the graben feature and its metal-rich sequence of volcanics and chemical sediments. During its intrusion, the tonalite could have engulfed an alteration pipe associated with the graben-bounding fracture system leaving only the more widespread wallrock alteration assemblage. Associated either with the intrusion of the tonalite, the intrusion of higher level rhyolitic sills, or a combination of both, a skarn-style alteration assemblage developed in the flanks of the carbonate mound in which sulfide mineralization was less pronounced. Pyrrhotite, magnetite and gold mineralization was produced or remobilized in association with this event. Later movement reactivated the bounding faults and subsequent bimodal intrusive activity filled some of the fault zones with dikes. It is of course unknown if additional massive sulfide bodies were deposited in this graben feature prior to, or following, the formation of the current Lynne sulfide units, their possible existence being either destroyed by the intruding tonalite or erosion. Since the geological environment favored the deposition of the Lynne deposit, it is likely, as substantiated by base-metal camps throughout the world, that additional massive sulfide deposits formed in conjunction with the Lynne felsic build-up of the prolific Rhinelander-Ladysmith greenstone belt.

### Summary

The Lynne base-metal deposit consists of a series of four strataform, massive to semi-massive, sphalerite-rich sulfide bodies containing accessory galena, silver, copper, and gold. The deposit is hosted by a dominantly felsic volcanoclastic and sedimentary sequence of rocks with a significant amount of carbonate-rich chemical sediments. The immediate ore-bearing stratigraphy is overlain by felsic to intermediate volcanic flow, pyroclastic, and epiclastic rocks. An intrusive tonalite underlies the Lynne stratigraphy disrupting and intruding the lower-most sulfide unit.

No definitive alteration or feeder pipe is evident; however, an alteration assemblage common to volcanogenic massive sulfide deposits world-wide, is present in the deposit's immediate host rocks. Metal zoning is suggested by relative copper enrichment toward the base of individual sulfide units. Deposit-wide metal zoning occurs as a relative enrichment in copper and iron in the lower sulfide units, an upward increase in zinc, and the development of galena concentrations and strong silver enrichment in the upper parts of the deposit. There is a corresponding evolution from carbonate-rich rocks lower in the sequence to more siliceous chemical sediments higher in the host rock stratigraphy. Skarn-type mineralization is characteristic to the carbonate-rich host rocks, especially along the up-dip flanks of the deposit and locally associated with intrusive rhyolitic sills. The highest concentrations of gold, and an increase in pyrrhotite and magnetite mineralization, are associated with the skarn-type assemblage.

Characteristics common to volcanogenic massive sulfide and skarn-related deposits occur within the Lynne deposit lithologic sequence. Data suggest that the main sulfide mineralizing events were related to a volcanogenic-related, carbonate-generating, hydrothermal system. Skarn development in carbonate rocks within the main sulfide orebody and its lateral equivalents may be related to the intrusion of the subvolcanic tonalite, the rhyolite sills, or a combination of both events.

### Acknowledgements

The author strongly acknowledges the contributions of the Lynne predevelopment team of L. Kennedy, T. (Harding) Kennedy, J. Schaff, A. Zielinski and T. Suszek for their contributions to the author's knowledge through reviews, reports and conversations during the delineation of the Lynne deposit. Special recognition is due Larry Kennedy, author of the Noranda summary report, from which much of the descriptive text regarding alteration assemblages and host rock lithologies was taken. The management of Noranda Exploration Inc. is also acknowledged for their philosophy of exploration persistence and their confidence in the Superior District staff. I also thank Noranda Exploration Inc. for permission to publish this paper.

### References Cited

- Adams, Glen W., 1990, Lynne Base-Metal Discovery, North-Central Wisconsin: New Discoveries in North America Session, Northwest Mining Association 96th Annual Meeting, Spokane, Washington, transcript, 18 p.
- Adams, Glen W., 1991, Lynne Base-Metal Discovery: The Minnesota Prospector, Vol.1, No. 5, p. 2-7.
- AMERICAN MINES HANDBOOK, 1995, Noranda Exploration Inc., Company Profiles, Southam Magazine and Information Group publishers, p.167.
- DeMatties, T. A., 1990, The Ritchie Creek Main Zone: A Lower Proterozoic Copper-Gold Volcanogenic Massive Sulfide Deposit in Northern Wisconsin: Economic Geology, Vol. 85, p. 1908-1916.
- DeMatties, T. A., 1994, Early Proterozoic Volcanogenic Massive Sulfide Deposits in Wisconsin: An Overview: Economic Geology, Vol. 89, p. 1122-1151.
- Franklin, J. M., Lydon, J. W. and Sangster, D. F., 1981, Volcanic-Associated Massive Sulfide Deposits: ECONOMIC GEOLOGY 75th ANNIVERSARY VOLUME, p. 485-627.
- Franklin, J. M., Kasarda, J., and Paulsen, K. H., 1975, Petrology and Chemistry of the Alteration Zone of the Mattabi Massive Sulfide Deposit: Economic Geology, Vol. 79, p. 63-79.
- Kennedy, L. P., Harding, T. A., Schaff, J. H., and Zielinski, A. M., 1991, The Lynne Massive Sulfide Deposit, Oneida County, Wisconsin: Annual Institute on Lake Superior Geology, 37th, Eau Claire, Wisconsin, 1991, p. 63
- Kennedy, L. P., 1992, Lynne Project Summary Geologic and Geotechnical Report: unpublished report, Noranda Exploration, Inc., Rhinelander, Wisconsin, 29 p.
- Kennedy, L. P., and Donnelly, M. E., 1992, Geology of the Lynne Zn-Pb-Cu-Ag Deposit, a Proterozoic Massive Sulfide, Oneida County, Wisconsin: unpublished report, Noranda Exploration Inc., Rhinelander, Wisconsin, 3 p.
- Lambe, R. N., and Rowe, R. G., 1987, Volcanic History, Mineralization, and Alteration of the Crandon Massive Sulfide Deposit, Wisconsin: Economic Geology, Vol. 82, p. 1204-1238.
- Sims, P. K., Van Schmus, W. R., Schulz, K. J., and Peterman, Z. E., 1989, Tectono-Stratigraphic Evolution of the Early Proterozoic Wisconsin Magmatic Terranes of the Penokean Orogen: Canadian Journal of Earth Sciences, Vol. 26, p 2145-2158.

