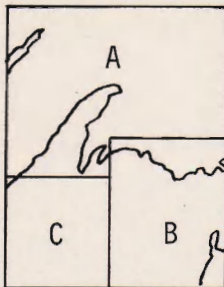


TWENTY-FIRST ANNUAL INSTITUTE
ON LAKE SUPERIOR GEOLOGY

Northern Michigan University
Marquette, Michigan

April 30 - May 4, 1975



NASA, ERTS-1, MSS SENSOR: (4, 5, 6, 7) .46-.82 μ , Prints obtained by photographing color composites using Kodak Panatomic X film and a wratten 25 (red) filter.

- A - DATE: 9-28-73, HOUR: 4:12.5, SCALE: 1/3,369,000
ALTITUDE: 911,200 METERS, SUN ELEVATION: 36°
SUN AZIMUTH: 151° , PHOTOGRAPH NUMBER: 1,432,161,255
- B - DATE: 9-9-73, HOUR: 4:08.0, SCALE: 1/3,369,000
ALTITUDE: 916,100 METERS, SUN ELEVATION: 44°
SUN AZIMUTH: 145° , PHOTOGRAPH NUMBER: 1,413,160,805
- C - DATE: 2-8-73, HOUR: 4:26.4, SCALE: 1/3,369,000
ALTITUDE: 912,700 METERS, SUN ELEVATION: 26°
SUN AZIMUTH: 147° , PHOTOGRAPH NUMBER: 1,576,161,025

On both covers, better drained sandy moraines and outwash plains have lighter tones, reflecting second and third growth vegetation composed predominantly of grass with scattered jackpine and aspen or of maple, aspen, and red oak forest. Lower, wetter areas appear darker on the photographs because the vegetative cover consists primarily of black spruce, tamarack, and cedar.

Direction of Valders ice sheet movement is demonstrated by the drumlin and outwash plaque area between the Escanaba and Menominee Rivers. The pattern suggests that the Valders ice may not have extended farther west than Iron Mountain. Fluting shown in till plain in the east central and south eastern part of photograph C may have been left by pre-Valders ice.

1975

NORTHERN MICHIGAN UNIVERSITY
75th ANNIVERSARY

TWENTY-FIRST ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY
PROCEEDINGS



held at
NORTHERN MICHIGAN UNIVERSITY
Marquette, Michigan
April 30-May 4, 1975

Edited by

FILLMORE C. F. EARNEY and JOHN D. HUGHES

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21st Annual
INSTITUTE ON LAKE SUPERIOR GEOLOGY
Northern Michigan University
Marquette, Michigan
April 30--May 4, 1975

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ANNUAL BANQUET GUEST SPEAKER

Dr. Richard J. Anderson, Associate Director--Energy Program,
Battelle Memorial Institute, Columbus, Ohio 43201

ACKNOWLEDGEMENTS

The general planning committee and editors gratefully acknowledge: the assistance and facilities provided for the Institute meeting by Dr. John X. Jamrich, President of Northern Michigan University; the help of Cleveland-Cliffs and Associated Companies in hosting of planning sessions and field trips and for assistance in the publication of the Proceedings; the excellent programs developed by the field trip organizers and guides; the efforts of Eugene S. Sinervo in reproducing the numerous figures contained in the field guides; the aid of Leo T. Deschaine in duplicating the manuscript; the help of Professor John P. Farrell in obtaining aerial photos displayed on the covers of this volume; the work of Linda Greenberg in typing the final manuscript for the Proceedings; and the assistance of Joanne Boyum, Beatrice Hughes, and Delores Ohlson in preparing an outstanding program for the ladies in attendance as guests at the Institute meeting.

PROGRAM

TUESDAY, APRIL 29, 1975

8:00 p.m. Pre-Institute Field Trip No. 3 (Jacobsville Sandstone)
Convenes in Fisher Hall, Rm. 138, Michigan Techno-
logical University, Houghton, Michigan

WEDNESDAY, APRIL 30, 1975

12:30 - Early Registration, University Center, Northern
1:00 p.m. Michigan University (NMU), Marquette, Michigan

1:00 p.m. Pre-Institute Field Trip No. 5 (Empire Mine) Departs
from University Center, NMU

6:00 - Early Registration, Ramada Inn, 412 West Washington
8:00 p.m. St., Marquette, Michigan

7:00 - Get Acquainted Evening (Cash Bar) Ramada Inn,
10:00 p.m. 412 West Washington St., Marquette, Michigan

THURSDAY, MAY 1, 1975

7:00 a.m. Breakfast for Presenting Authors, Charcoal Room
University Center, NMU

7:30 - Registration
9:30 a.m. University Center, NMU

Morning Co-Chairmen: University Center
Session W. H. McIlwaine &
M. S. Walton

8:00 - Dr. John X. Jamrich WELCOME
President, NMU

8:15 - D. J. Johnson Petrology and Tectonic Setting
of the Hemlock Formation, Iron
County, Michigan, p. 3.

J. R. Mangham The Petrology and Structure of
the Mellen Gabbro Complex Near
Hurley, Wisconsin, p. 4.

x

	M. L. Cummings	Structure and Petrology of Precambrian Amphibolite, Big Falls County Park, Eau Claire County, Wisconsin, p. 5.
	J. Wood	Ultramafic Metavolcanics and Their Geologic Setting in the North Spirit Lake Area, Ontario, pp. 6-7.
9:50 - 10:05		COFFEE
10:05-	N. W. Jones	A Reconnaissance Study of the Chipman Lake "Carbonatite Complex," Ontario, p. 8.
	E. I. Smith	Minerology and Chemistry of the Precambrian Marquette Rhyolite, Green Lake County, Wisconsin, p. 9.
	P. K. Sims & Z. E. Peterman	Mobility in Reactivated Precambrian W Basement Gneisses, Marenisco-Watersmeet Area, Northern Michigan, pp. 10-11.
11:15 - 12:00		Poster Session
12:00 - 1:00		LUNCH
<u>Afternoon Session</u>	Co-Chairmen: J. O. Kalliokoski & D. D. Yardley	University Center
1:15 -	F. W. Holcomb	The Bedrock and Overburden Geology of the Eastern Part of the City of Houghton, Michigan, p. 12.
	J. T. Mengel & E. H. Meitzner	Slope Stability and Land Use Planning on the Red Clays of the Lake Superior Basin, Douglas County, Wisconsin, p. 13.
	S. C. Nordeng & B. M. Hamil	Mine Waste and Dredge Spoil Distribution Patterns in the Bottom Sediments of Lake Superior Northwest of the Keweenaw Peninsula, Michigan, pp. 14-15.

	A. M. Johnson & H. O. Sorenson	Michigan Upper Peninsula Middle Silurian Limestones: Geology and Resource Potential, pp. 16-17.
2:50 - 3:05		COFFEE
3:05 -	M. A. Gere	Variation of Samples Along Strike Within a Brecciated Amygdaloid, Caledonia Mine, Ontonagon County, Michigan, pp. 18-19.
	E. W. Heinrich	Hydrothermal Alteration of the Mississagi Conglomeratic Quartzite, Pronto Mine, Blind River, Ontario, p. 20.
	D. G. Meineke	Base Metal Exploration in Northern Minnesota, pp. 21-22.
	K. B. Rundman & S. Gembolis	Metallography of Michigan Native Copper, pp. 23-24.
4:20 - 5:00		Poster Session
4:40 -	W. F. Cannon	U.S.G.S. Computer Display of the Marquette Range
<u>Evening</u>		
5:30 - 6:30		SOCIAL HOUR (Cash Bar) Ramada Inn, 412 West Washington St., Marquette, Michigan
6:30 -	Guest Speaker Richard J. Anderson	ANNUAL BANQUET Ramada Inn "Tomorrow's Energy Supply -- A Formula for Survival"

FRIDAY, MAY 2, 1975

7:00 a.m.		Breakfast for Presenting Authors Charcoal Room, University Center, NMU
<u>Morning Session</u>	Co-Chairmen: S. Goldich & G. F. West	
8:00 -		Announcements
8:15 -	J. Mancuso, M. Loughheed, R. Seavoy & R. Shaw	The Significance of the Cherty Iron-Formation, Baraga Basin, Michigan, p. 25.

	E. Dimroth	Paleo-Environment of Iron-Rich Sedimentary Rocks, p. 26.
	M. S. Lougheed & J. Mancuso	The Biogenic Origin of Precambrian Iron-Formations, p. 27.
	R. F. Bacon	Geological Modeling of Gravity Features, Northeastern Marquette County, Michigan, p. 28.
9:50 - 10:05		COFFEE
10:05 -	G. E. Frantti	A Review of the Copper Country "Earthquakes" of 1905 and 1906, Houghton County, Michigan, p. 29.
	L. O. Bacon	Bouguer Gravity Map, Western Half of Michigan's Upper Peninsula, p. 30.
	J. H. Karl	The Wisconsin Aeromagnetic Mapping Project, p. 31.
	S. Chaudhuri	Geochronology of Upper and Middle Keweenaw Rocks of Michigan, p. 32.
11:20 - 12:00		Poster Session
12:00 - 1:00		LUNCH
<u>Afternoon Session</u>	Co-Chairmen: G. D. Aho & J. D. Hughes	University Center
1:10 -	D. T. A. Symons	Paleoaphebian Polar Wander and Paleomagnetism of the Gowganda Formation, p. 33.
	L. J. Pesonen & H. C. Halls	Paleomagnetism of Keweenaw Diabase Dikes from Baraga and Marquette Counties, Michigan, p. 34.
	C. P. Ervin & M. G. Mudrey	Extension of Vermilion District Lamprophyres into Western Minnesota from Geophysical Observations, p. 35.
2:20 - 3:00		Poster Session
4:00 -		Field Trip No. 2 (Greenstone) Departs from University Center, NMU

SATURDAY, MAY 3, 1975

8:00 a.m.

Field Trip No. 4 (Marquette
Iron Range)

Field Trip No. 6 (Empire Mine)
Depart from University Center,
NMU

SUNDAY, MAY 4, 1975

4:00 p.m.

Field Trip No. 2 (Greenstone)
Returns to University Center,
NMU

ABSTRACTS

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PETROLOGY AND TECTONIC SETTING OF THE
HEMLOCK FORMATION, IRON COUNTY, MICHIGAN

D. Jay Johnson, Department of Geology and Geological Engineering,
Michigan Technological University, Houghton, Michigan 49931

ABSTRACT

A six square mile area of the Hemlock Formation (Secs. 31, 32, and 33, T44N, R32W and Secs. 4, 5, and 6, T43N, R32W) in Iron County was mapped. The area was chosen because the top 7,000 ft. of the Hemlock Formation outcrops particularly well.

The Hemlock Formation is a thick series of volcanic rocks of Middle Precambrian age which surrounds the "Amasa Oval." The thickness of the Hemlock ranges from a maximum of about 23,000 ft. on the west side of the oval to about 2,500 ft. on the east side. The increased westward thickening appears to be due to proximity to the source of the volcanics.

The mapping shows about 5,000 ft. of the Hemlock to be interlayered hyaloclastites (formerly called "agglomerates") and minor amounts of pillow lavas. This is overlain by about 2,000 ft. of subaerial massive to amygdaloidal flows containing at least one fluvial conglomerate. The mapping also shows two crystal tuffs of about 200 ft. thickness, one near the top and one at the base of the hyaloclastites.

THE PETROLOGY AND STRUCTURE OF THE
MELLEN GABBRO COMPLEX NEAR HURLEY, WISCONSIN

J. R. Mangham, Department of Geology, University of Wisconsin,
Madison, Wisconsin 53706

ABSTRACT

The Mellen Gabbro Complex lies on the south side of the Lake Superior Syncline and outcrops along a zone approximately five miles wide and thirty-five miles long, striking approximately N 70° E, dipping northwest, and extending nearly to the Michigan-Wisconsin border at a point five miles northwest of Hurley, Wisconsin. The complex is a sill-like body of gabbro of tholeiitic composition, associated with abundant intrusions of granophyre. It is a layered body with dark olivine gabbro grading into leucogabbro, gabbro, and gabbro-norite, and anorthosite near the top (north). The olivine gabbros have, throughout their extent, well developed rhythmic layering nearest the bottom and planar flow structure in the form of parallel oriented plagioclase laths. Chemical evidence shows a trend of iron enrichment with increasing height in the gabbro, and field work shows evidence of multiple intrusion--such as inclusions of dark olivine gabbro in leucogabbro. Structural and chemical data, the "younging" trend toward the top of the complex, and the large volumes of granophyre exposed suggest differentiation from the same melt and transgressive flow up the flank of the incipient syncline. Thus, later differentiates would appear as separate intrusions and would tend to concentrate higher on the flank and possibly be absent closer to the axis of the syncline.

STRUCTURE AND PETROLOGY OF PRECAMBRIAN AMPHIBOLITE, BIG FALLS COUNTY PARK, EAU CLAIRE COUNTY, WISCONSIN

M. L. Cummings, Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706

ABSTRACT

Precambrian amphibolite gneisses and schists associated with the "Chippewa amphibolite complex," crop out at Big Falls County Park in Eau Claire County, Wisconsin. Four lithologic units include: 1) banded amphibolite gneiss (b.a.g.) with alternating hornblende-rich and plagioclase-rich bands, 2) amphibolite schist (a.s.) of hornblende- and cummingtonite-bearing bands, 3) transition gneisses (t.g.) of two textural patterns, a) lenticular segregations of plagioclase and hornblende and b) fine bands of plagioclase and hornblende, and 4) feldspathic gneiss (f.g.) with greater than 80 percent plagioclase.

Structure and petrology indicate three deformational phases accompanied by recrystallization; however, relict textures are commonly observed. Garnet porphyroblasts, wrapped by compositional foliation, and rootless intrafolial folds of compositionally banded rock are remnants of the first deformational phase. The second deformational phase produced folding and faulting while mineralogy of hornblende, plagioclase and locally garnet indicate amphibolite facies conditions. Crystallization of hornblende with blue-green Z axial color and epidote indicate epidote-amphibolite facies conditions during the third deformational phase. Shear zones and a cross-cutting schistosity formed during the third deformational phase.

Mg/(Mg+Fe) ratios are higher for hornblende from the a.s. unit (0.54) than from the b.a.g. unit (0.44), while the same ratio in garnets from the a.s. unit (0.12) are lower than in the b.a.g. unit (0.20). K_2O / Na_2O ratios for the b.a.g. unit and the a.s. unit are extremely low (0.103 and 0.075, respectively). Whole rock analyses for the b.a.g. unit indicate high Al_2O_3 and CaO at 24.6 and 13.7 weight percent respectively, and low total femic constituents (8.3 weight percent). Composition of the b.a.g. and a.s. units suggest mafic igneous parentage ranging from gabbro to anorthositic gabbro.

ULTRAMAFIC METAVOLCANICS AND THEIR GEOLOGIC
SETTING IN THE NORTH SPIRIT LAKE AREA, ONTARIO

J. Wood, Geological Branch, Ministry of Natural Resources,
Queens Park, Toronto, Ontario

ABSTRACT

Stratiform ultramafic rock units near the northeastern boundary of the early precambrian North Spirit Lake-MacDowell Lake metavolcanic-metasedimentary belt show evidence of a magmatic origin in the form of spinifex textures, chilled and fractured contacts, and pillow structures; these are considered to be lava flows. Rare narrow spinifex textured units that cross-cut the flow rocks are considered to be intrusions. Bedded ultramafic interflow rocks are thought to be of sedimentary origin.

The sequence of ultramafic flows has a minimum thickness of 650 meters and shows well preserved textures and structures along a 1.6 km. strike length. Minimum flow thickness is in the order of 1 m. Maximum thickness is not known because of outcrop limitations, but exceeds 5 meters. Flows with a thickness of 4 meters best display the six internal zones identified by Pyke and others (1973). All flow units exhibit a chilled and fractured top. The immediately underlying spinifex textured zone is generally present but only on a microscopic scale in the thin flows. Underlying the spinifex zones, the peridotite zones are well developed. The base of a flow unit generally is chilled.

Serpentine, chlorite and opaque minerals have replaced most of the pyroxene crystals in the peridotitic parts of flows. Olivine crystals have been replaced by serpentine and carbonate; the ground mass is comprised of serpentine, chlorite, talc, carbonate, and opaque minerals. In the spinifex zones, skeletal olivine crystals have been replaced by chlorite, serpentine, and carbonate; pyroxene crystals (small skeletal) by tremolite and opaques; and the ground-mass by tremolite and carbonate.

Five chemically analyzed samples yielded values of MgO (recalculated anhydrous) between 24.5 percent and 36.9 percent and TiO_2 contents below 0.4 percent. $\text{CaO} / \text{Al}_2\text{O}_3$ ratios range from 1.0:1 to 1.5:1 and values of K_2O are 0.02 percent or less.

The ultramafic flows occur at the stratigraphic top of a predominantly volcanic sequence. Rocks associated with the ultramafic flows are mafic and felsic metavolcanics and banded quartz-magnetite iron formation. The ultramafic flows are overlain unconformably by clastic metasediments and intermediate to felsic metavolcanics. They may hence offer potential for stratigraphic correlation between the North Spirit Lake and adjacent metavolcanic-metasedimentary belts.

The ultramafic rocks offer potential not only for nickel and copper mineralization, but also for gold (D.R. Pyke 1974). These rocks will be studied in further detail during the 1975 field season.

REFERENCES

Pyke, D.R. 1974.

Watabeag River Area, District of Cochrane and Timiskaming, pp. 94-98, in: Summary of Field Work, 1974, by The Geological Branch, edited by V. G. Milne, D. F. Hewitt, and K. D. Card, Ontario Division of Mines, MP59, 206 p.

Pyke, D.R., Naldrett, A.J., and Eckstrand, O.R., 1973.

Archean Ultramafic flows in Munro Township, Ontario, Bull. Geol. Soc. Amer., V. 84, pp. 955-978.

A RECONNAISSANCE STUDY OF
THE CHIPMAN LAKE "CARBONATITE COMPLEX," ONTARIO

Norris W. Jones, Department of Geology, University of Wisconsin-
Oshkosh, Oshkosh, Wisconsin 54901

ABSTRACT

The Chipman Lake Complex is located about 18 miles north-east of Longlac, District of Thunder Bay, Ontario. There are no published descriptions of the Complex, although it has been referred to by Gittins (in Tuttle and Gittins, 1966, Carbonatites) and by Barker (in Sørensen, 1974, The Alkaline Rocks) as a carbonatite complex. This report, based on reconnaissance field studies and thin section examination, describes the Complex and questions its interpretation as a carbonatite.

The Complex is circular in plan, small (diameter of two miles), and has a strong magnetic anomaly associated with it. It appears to consist almost entirely of an alkali-lime syenite, which locally grades to monzonite. Magnetite content of the syenite appears to be highest near the center and lowest near the margins of the magnetic anomaly. Foliation is pronounced near, and parallels, the contact with the surrounding amphibolite.

Syenite is the oldest rock in the Complex. Others are (oldest to youngest): hornblendite and biotite-hornblendite masses, feldspar and granite pegmatite dikes, felsite dikes, basalt-diabase dikes, and carbonate (mostly dolomite) veins. The carbonate veins are up to two feet wide, occur throughout and outside of the intrusion, and at one location also contain chalcedony. They are interpreted as veins (hydrothermal) rather than dikes (magmatic).

Although the Chipman Lake Complex has certain features characteristic of carbonatite complexes, most of the rocks exposed are not normally associated with carbonatites. On the basis of available information, it is suggested that Chipman Lake is not a carbonatite complex.

MINERALOGY AND CHEMISTRY OF THE PRECAMBRIAN
MARQUETTE RHYOLITE, GREEN LAKE COUNTY, WISCONSIN

Eugene I. Smith, Division of Science, University of Wisconsin-
Parkside, Kenosha, Wisconsin 53140

ABSTRACT

The Marquette inlier consists of texturally variable rhyolite flows and breccias, showing cyclic variation in mineralogy and chemistry, overlain by an ash-flow tuff. The sequence is steeply dipping (50° to 85° southeast) and is overturned. The flows are cut by a 100 m. wide andesite dike. The top of the exposed section is a 650 m. thick coarsely porphyritic rhyolite containing angular plagioclase (7%), quartz (10%), and perthite (18%) in a fine-grained devitrified matrix (65%). The rhyolite shows a decrease in $\text{Na}_2\text{O}/\text{K}_2\text{O}$ (0.91-0.75) and K/Rb (302-253) and an increase in Rb/Sr (1.29-1.45) from bottom to top of the unit, suggesting active differentiation during eruption. It shows no noticeable stratigraphic breaks and is an ash-flow tuff. The tuff is underlain by a 1400 m. thick section of rhyolite flows which show cyclic changes in mineralogy and chemistry. The variation from a phenocryst poor (14%) plagioclase unit to a phenocryst rich (35%) quartz, plagioclase and perthite unit is repeated three times. This cyclic change is reflected chemically by Rb/Sr ; Rb/Sr is less than 1 for the quartz, plagioclase, perthite units, and greater than 1 for the plagioclase units. The lowest flows in the exposed sequence are sodic with $\text{Na}_2\text{O}/\text{K}_2\text{O}=1.1$ to 1.3, whereas units stratigraphically above are potassic with $\text{Na}_2\text{O}/\text{K}_2\text{O}=0.7$ to 0.9. A common source for all units is indicated by common trace element chemistry, and flow direction studies which suggest flow to the southeast for all sampled Marquette rhyolite units.

The Marquette rhyolite can be chemically distinguished from other Precambrian rhyolite and granite inliers in south central Wisconsin. Twenty-one new chemical analyses show that these inliers can be divided into three chemical groups: (1) high CaO ($1.28 \pm 0.23\%$) rhyolite (Marquette); (2) low CaO ($0.23 \pm 0.14\%$), high Na_2O ($4.56 \pm 0.13\%$) rhyolite (Berlin and Utley inliers); and (3) high K_2O ($5.68 \pm 0.25\%$), low CaO ($0.43 \pm 0.08\%$) rhyolites and granites (Endeavor, Observatory Hill, Montello and Red Granite inliers). The Marquette inlier can be further distinguished from the other inliers by higher Al_2O_3 , MgO , Pb , Ba , V , Cu , Sr , and lower K_2O , Cr , La , Y , and Zr .

MOBILITY IN REACTIVATED PRECAMBRIAN W BASEMENT GNEISSES,
MARENISCO-WATERSMEET AREA, NORTHERN MICHIGAN

P. K. Sims and Zell E. Peterman, U. S. Geological Survey, Denver, Colorado
80225

ABSTRACT

Rb-Sr data on migmatitic gneisses that form the cores of antiforms or domes surrounded by metamorphosed Precambrian X (middle Precambrian) strata in the Marenisco-Watersmeet area, northern Michigan, show that the rock systems have been severely disturbed by complex tectonic and thermal events subsequent to primary crystallization; but the pattern is consistent with an interpretation that Precambrian W (lower Precambrian) gneisses, which formed the basement on which the bedded succession was deposited, were internally metamorphosed and partly mobilized during their reactivation in Precambrian X time.

Disturbance of the rock systems is indicated isotopically by lowering of the whole-rock Rb-Sr ages of many samples of the gneisses from 2600 m.y. or older to about 1800 m.y. and by scattering of the data points, although some of the points can be fitted to secondary isochrons. Probably the major mechanism of the disturbance was redistribution of previously accumulated radiogenic Sr, which is indicated by the high initial $^{87}\text{Sr}/^{86}\text{Sr}$ of the resultant isochrons.

Judged from the structural relationships and petrography of the gneisses, the migration of radiogenic Sr resulted from cataclasis, recrystallization and the local introduction of K-feldspar during reactivation of the gneisses in Precambrian X time. The strong internal dynamothermal metamorphism was accompanied by metamorphic segregation and/or partial melting, which produced at least some of the leucosome of the migmatitic gneisses and probably also the small granitic pegmatite bodies that intrude adjacent Precambrian X rocks. However, both the field relationships and the Rb-Sr data argue against large-scale partial melting, for large bodies of relatively homogeneous granite are lacking and the leucosome is not strongly enriched in Rb and depleted in Sr, as would be expected for anatectic granitic magmas derived at crustal levels.

The gneiss at Marenisco (Presque Isle Granite) was not tectonically reconstituted during its reactivation, for the bedded rocks truncate the steep foliation in the crustal area of the antiform and metadiabase dikes that were intruded and metamorphosed after development of the foliation are not deformed. However, a concordant foliation possibly was imposed in the gneiss at Watersmeet (Wolf Lake Granite of Allen and Barrett, 1915) at the gneiss-cover boundary; if so, this body was relatively more plastic than the gneiss at Marenisco during its rejuvenation.

In general, the relative degree of mobility of the gneisses, as indicated by the Rb-Sr systematics, correlates with the regional metamorphic zoning pattern in the Precambrian X bedded rocks: the bodies having the most disturbed rock systems (gneiss at Watersmeet and granite near Thayer of Fritts, 1969) are surrounded by garnet-grade metamorphic rocks and the one having the least disturbed rock system (gneiss at Marenisco) is surrounded by biotite-grade or lower metamorphic rocks. This relationship suggests that the metamorphism in this region might be directly related to reactivation of the basement gneisses--a problem that deserves much further study.

THE BEDROCK AND OVERBURDEN GEOLOGY OF THE EASTERN
PART OF THE CITY OF HOUGHTON, MICHIGAN

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ABSTRACT

Bedrock geology, overburden thickness and character, surface and subsurface drainage, and existing mine openings, trenches, and rock piles have been mapped in the eastern part of the city of Houghton on base maps having a scale of 1" = 100' and a contour interval of two feet. A systematic evaluation has been made of the manner in which these factors affect land planning and utilization.

The city of Houghton is situated on a steep rocky north facing hillside that trends almost normal to the strike of the underlying bedrock formations. The bedrock geology consists of basalts and interbedded conglomerates of the Portage Lake Volcanic Series of Middle Keweenawan age. The sequence generally strikes N30°E and dip to the northwest at approximately 55°. The flows vary in thickness, the larger (+100'), massive, more resistant parts of the basaltic lava flows form distinct linear ridges, whereas the amygdaloidal flow tops and interbedded conglomerates form the bedrock lows.

The overburden varies considerably in thickness, and ranges in character from gravels on the lower slopes to the sandy silts near the top of the slope. Subsurface drainage is poor, roughly parallel to the strike of the flows. Wet surface conditions are dependent on the bedrock slope, angle of fault to the strike of the flows, changes in overburden and bedrock geology, and the presence of mine openings and trenches.

SLOPE STABILITY AND LAND USE PLANNING ON THE RED CLAYS
OF THE LAKE SUPERIOR BASIN, DOUGLAS COUNTY, WISCONSIN

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ABSTRACT

The purpose of this study was to establish guidelines for land use and development on the upland clay plain of Lake Superior along stream valleys and the shoreline of Lake Superior. A secondary objective was the development of an investigative approach which can be easily used in other areas of cohesive soil.

An inventory of bank slopes in the study area showed a wide range of slope angles with the severity and type of failure closely related to the specific slope angle.

The flatest slopes in the Quaternary red clay sediments range from 5 to 10 degrees. These slopes develop in areas of minimum disruption by natural or human agencies. Typical slopes along youthful stream valleys range from 10 to 15 degrees and have convex profiles. These slopes generally show active failure by soil creep. Slopes steeper than about 15 degrees fail by shallow translatory sliding, and as the inclination approaches 20 degrees failure occurs by deeper rotational slides.

The most rapid erosion can be observed along the lake shore where the coast line is retreating at a rate of two to five feet per year. At this time almost the entire Douglas County shoreline is in a state of accelerated erosion and gravity failure.

Design and zoning guidelines for construction set-backs, highway slopes, and other engineering works can be established by recognizing the functional relationship between the slope angle and the downslope erosion and transport mechanism.

This study provides a flexible basis for the establishment of slope set-backs in zoning and land use planning and eliminates some of the subjectivity commonly found in the preliminary planning and design of slopes and embankments for engineering projects.

The analysis of geologic and pedologic data justified one very vital assumption--that reasonably uniform and homogeneous soil conditions exist in the study area. It must be emphasized that the method of study and analysis has general application, but the results of study in a specific area can be applied outside that area only with extreme caution.

MINE WASTE AND DREDGE SPOIL DISTRIBUTION PATTERNS
IN THE BOTTOM SEDIMENTS OF LAKE SUPERIOR
NORTHWEST OF THE KEWEENAW PENINSULA, MICHIGAN

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ABSTRACT

Sediment distribution patterns in Lake Superior along the northwest shore of the Keweenaw Peninsula, Michigan, were studied by sedimentological and mineralogical analyses of bottom samples taken at depths between 0 and 80 meters along transects at right angles to the shoreline. Samples were screened for grain size distributions, classified for shape and roundness under the microscope, and classified by Munsell color and spectral reflectivity. Mineral separates were made with an isodynamic magnetic separator. Grain size distributions and mineral content were used to characterize sediment and chart the dispersal patterns of stamp mill waste derived from the beach and dredge spoil removed from the Keweenaw Waterway by the U.S. Army Corps of Engineers and dumped into the lake about a mile offshore of the north entrance of the waterway.

The mill waste is derived from dumps situated on the beach at Freda about six miles southwest of the waterway entrance. Plumes of the fine silt fraction of this material are prominent in the nearshore water during periods of high wind and waves. These plumes find their way into the waterway borne on currents generated by water pile-up in the mouth of the entry. The mill waste can migrate several miles southward along the waterway in this manner. The waste consists of finely ground ophitic basalt, the result of comminution of native copper ores milled at Freda. This material is noticeably darker in color, finer and more angular in texture than the natural bottom sediment. The abrupt contrast between the purple-red basalt and the buff-colored natural bottom sediment derived almost completely from weathering of the Freda Sandstone which outcrops along the shore, makes tracing of the movement of the mill waste relatively easy. The high pyroxene and magnetite content of the basalt allows it to be readily separated from the quartz sand by means of the isodynamic separator. The natural beach sand is very poor in heavy minerals so the magnetic separation gives a good quantitative assay of the amount of mill waste present in the sediment.

The dredge spoil characteristically consists of a mixture of the natural sediment and the finer fractions of the mill waste, along with relatively large amounts of plant debris washed into the waterway by runoff. This material has been sampled and characterized in the same way as the mine waste, and is readily identified in the bottom sediments.

A noteworthy characteristic of the sediments sampled is the almost total absence of clay-size fines. The mill wastes deposited along the shoreline contain few fines, this fraction being washed out during the deposition and apparently carried to deeper portions of the lake. In the Keweenaw Waterway, fines from the stampmill wastes are deposited on the bottom of the upper portions of Portage Lake. Laboratory experiments indicate that the basalt continuously produces fines by combined chemical and mechanical weathering but in the sediment transport process these are removed and carried in suspension. The deeper samples from the Lake Superior bottom show increasing amounts of fine fraction below depths of about 70 meters. Natural sediments on the lake bottom range in character from normal beach sand to what appears to be sub-areal dune sand.

Data collected have been subjected to various statistical tests and correlations. Computer generated maps of the various sediment parameters have been correlated with distributions of aquatic organisms and heavy metals. The resulting maps and their interpretations constitute part of the environmental impact statement for the disposal of dredge spoil from the Keweenaw Waterway.

MICHIGAN UPPER PENINSULA MIDDLE SILURIAN LIMESTONES:
GEOLOGY AND RESOURCE POTENTIAL

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ABSTRACT

Progress on evaluation of high purity Paleozoic limestones in the eastern Upper Peninsula is reported. This project is a cooperative venture between the Institute of Mineral Research, Michigan Technological University, and the Michigan Geological Survey. High priority was attached to this project because of land-use considerations and the economic significance of these resources. The limestones being studied underlie land of high recreational value and constitute an important present and future source of fluxstone for the steel industry. High purity reserves should be defined so they are not lost or their utilization impaired through improper land-use decisions. Present knowledge is inadequate to outline reserves; the most recent comprehensive work was done prior to 1915 (Smith, 1915).

Two carbonates are being evaluated; the Engadine dolostone and the Fiborn member of the Hendricks formation, Burnt Bluff Group, a high calcium limestone. During the 1974 field season, nine cores were diamond drilled from outcrop of the Hendricks formation, along a strike length of 100 miles in Schoolcraft, Mackinaw and Chippewa Counties. Careful selection of drilling sites required only shallow coring depths to evaluate the nearly flat-lying strata (regional dip is southerly 50 ft./mile).

Initial results from core logging suggest that economic thicknesses of higher purity limestones are present in Mackinaw and the western part of Chippewa Counties. Partial dolomitization of strata to the east and more extensive dolomitization to the west limit economic potential of the Fiborn limestone. Results of this study will be published later this year by the Michigan Geological Survey when analyses of split cores are completed.

During the forthcoming season, field work including drilling will be continued on the Engadine dolostone formation.

Previous workers in the Silurian have classified the strata into a time stratigraphic framework based on lithology, fossil evidence and relative stratigraphic position (Ehlers and Kesling, 1957; Ehlers, 1973). These careful studies were essential prerequisites to this evaluation program.

Speculation that the Silurian section may represent a shelf margin, carbonate-evaporite sequence, is also considered. Sheldon (1963) proposed this model for contiguous Niagaran strata on Manitoulin Island lying to the east, in Ontario. Both lithology and areal distribution of Niagaran strata in Northern Michigan are consistent with a carbonate-evaporite model. Stratigraphic relationships between units interpreted as reef, algal-flat, evaporite, etc., would require a transgressive sequence of deposition.

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VARIATION OF SAMPLES ALONG STRIKE WITHIN A BRECCIATED
AMYGDALOID, CALEDONIA MINE, ONTONAGON COUNTY, MICHIGAN

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ABSTRACT

Thirty-one selected samples were collected, mostly at 100-foot intervals, along a 2,900-foot drift parallel to a horizontal structural contour (strike) within the Knowlton Amygdaloid of the Caledonia Mine, near Mass, Ontonagon County, Michigan. The Knowlton Amygdaloid is referred to in the literature as being, at least in part, a brecciated flow within the Portage Lake Lava Series of middle Keweenawan age.

Thin sections and polished sections were made from each sample and examined through petrographic, metallographic and binocular microscopes. The polished sections were also used as hand samples for rough megascopic classification.

The percentages of individual minerals and mineral assemblages within the samples were tabulated and compared with the same mineral assemblages in other samples. Cross correlations were made between associated minerals and also the amount of the specimen consisting of amygdules, vesicles, and veinlets. The grain sizes of plagioclase and pyroxene and the sizes of the amygdules were compared between specimens.

Comparison of the correlation charts showed that twenty-nine of the thirty-one samples appear to confine themselves to seven general groups, based upon megascopic appearance, which are also similar in microscopic and mineralogical characteristics.

It is concluded that differences among the seven sample groups are due to the flow being of a brecciated character. Therefore, all samples in one group could be from within breccia blocks, another group could represent interstitial material, and a third group may have been affected by adjacent veinlets and resorption.

Some characteristics which seem apparent from working with this brecciated amygdaloid and which may extend to other brecciated flows are:

- 1) When several samples look alike megascopically, they will, most likely, be very close in microscopic characteristics, so rough grouping can be done with hand specimens.
- 2) Sample variation would, most likely, be as varied if a brecciated flow were to be sampled nearly continuously over a short horizontal distance as it would be if sampled over a prolonged distance, as in this study. Some thin sections and polished sections examined showed a variation in a distance of less than an inch or so.
- 3) The presence of copper appears to be independent of any of the samples' other mineralogical variables. This agrees with findings presented by Butler and Burbank in U.S.G.S. Professional Paper 144.

HYDROTHERMAL ALTERATION OF THE MISSISSAGI CONGLOMERATIC QUARTZITE, PRONTO MINE, BLIND RIVER, ONTARIO

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ABSTRACT

The Pronto uranium deposit, the first mine developed in the Blind River - Elliot Lake district of Ontario, is a completely atypical example of the classic uranium-thorium-pyrite mineralization disseminated throughout the matrix of meta-conglomerate as represented by the other deposits in the district. In 1956, beginning on the third level, mining encountered very widespread non-conglomeratic ores which persisted through the lowest (sixth) level, at times providing as much as 40 percent of the rock mined. Originally regarded as arkosic quartzites and graywackes, the non-conglomeratic ores have been demonstrated to represent conglomerate altered hydrothermally in various ways.

The hydrothermal rocks show four different contact relations to the conglomerates: 1) selective replacement, 2) gradational, 3) faulted, 4) brecciated. Hydrothermal ores flank both sides of a major, west-northwest trending, diabase dike and are restricted to areas of faulting; they are themselves faulted and sheared.

Types of hydrothermal rocks include: 1) albitized conglomerates, 2) albitites (some pyritic), 3) chloritic albitites, 4) chloritites, and 5) carbonate rocks (both calcitic and dolomitic). Some dolomitic varieties have coarse dolomite ovoids pseudomorphous after quartz pebbles. Locally, vugs in altered rocks contain dark calcite crystals enclosing sulfides (pyrite, pyrrhotite, chalcopyrite, galena, and sphalerite).

In altered ores uranium values tend to be concentrated near footwall contacts and generally run two to four times mine grade. However, ore thicknesses in altered ore are markedly reduced compared to those of adjacent conglomerate.

Three genetic hypotheses must be considered: 1) The conglomeratic ores are syngenetic and have been modified by hydrothermal alteration. 2) The conglomeratic ores are epigenetic and were subsequently modified hydrothermally. 3) The conglomeratic and hydrothermal ores are contemporaneous.

BASE METAL EXPLORATION IN NORTHERN MINNESOTA

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ABSTRACT

Minnesota has traditionally been known for its extensive iron deposits in the Lower and Middle Precambrian iron-formations of the northern part of the state. Iron deposits in the Lower Precambrian (Algoma type) iron-formations were first explored and mined in 1875 and 1884, respectively. Except for unsuccessful gold prospecting, no significant exploration for metals other than iron was done in northern Minnesota until the early 1950's.

In 1948, copper-nickel mineralization was first discovered in the Duluth Gabbro Complex. This discovery has resulted in an intensive search for these magmatic copper-nickel deposits from the early 1950's to the present. The exploration to date in the Duluth Gabbro Complex has mainly been concentrated in the basal contact area. This exploration has been done by geologic observations and projections, but geophysical and geochemical methods have been applied, especially geophysics, in areas of limited outcrop.

Based on currently available data, a resource estimate (Bonnichsen, 1974) has been made of the copper-nickel in the most intensely explored region of the Duluth Gabbro Complex. This estimate indicated, at a cutoff of 0.50% combined copper-nickel (Cu+Ni), a resource of 5.8 billion tons of mineralized rock with an average grade of 0.84% (Cu+Ni).

In the late 1960's, in addition to the Duluth Gabbro Complex, exploration geologists became interested in the Lower Precambrian (Archaen) volcanic belts' volcanogenic massive sulfide and comagmatic intrusive deposits. These deposits have, and continue to be, intensively explored. The exploration of the Archean volcanic belts has been done much the same as that in northwestern Ontario. Because of the extensive Quaternary deposits overlying these belts, exploration targets are usually selected by airborne electromagnetic and magnetic methods. From these surveys, targets are selected for ground follow-up geophysics and subsequent drilling if these results are favorable.

The Archean volcanic belts of northern Minnesota do have a good potential for the occurrence of economic deposits. A survey of the immediate area surrounding northern Minnesota, in southeastern Manitoba and northwestern Ontario shows that seven base metal mines have been developed or are in the process of development since 1969 in Archean volcanic belts.

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METALLOGRAPHY OF MICHIGAN NATIVE COPPER

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ABSTRACT

Even though millions of tons of native copper have been removed from various mines of Michigan's Keweenaw Peninsula, very little metallographic work, beyond the brief studies of Drier and Hendrickson, has been done on native copper.

This paper reports on a more extensive study of samples from the Baltic and Isle Royale poor rock piles, and of unlocated mass copper specimens from the Seaman Mineralogical Museum. Because the grain size was found to be quite coarse, most samples could be studied directly in hand specimen, or under low magnification. For this study metallographic preparation of the samples involved cutting and then consecutive grinding on 120, 180, 240, 320, and 600 grit papers. The surfaces were then cleaned and the samples placed in a tray of nitric acid for about 15 seconds. To prevent immediate tarnishing, they were next soaked in a ten percent solution of $(\text{NH}_4)_2\text{S}_2\text{O}_8$ for about one minute, washed in warm water, dried, and the surface coated with a thin film of clear glycerin. This preserves a fresh study surface for about one hour.

Native copper particle size can be defined as the size of the individual unit, or piece, of native copper. Grain size is represented metallurgically as that crystallographic unit that has either direct lattice continuity or lattice continuity through simple twinning. According to this definition, a copper particle four inches in diameter may consist of a few grains, the largest of which may exceed two to three inches in size.

To prepare a surface for study under higher magnification (greater than 15X), the specimen is ground, as before, to the 600 grit stage. Then the sample is polished for 36 seconds under a current of 2 amperes in an electrolytic solution consisting of 500 cc water, 50 cc propanol, 250 cc ethanol, and 250 cc phosphoric acid. Finally, the sample is washed with alcohol and dried.

All of the copper shows extensive twinning. In addition, several specimens show striations within individual grains which represent small variations in crystallographic orientation within the original grains. Both of these defects could have been produced in the growth process. In one instance, electrolytic etching showed

a very high population of etch pits adjacent to a boundary. These etch pits may be evidence of the presence of dislocations in the native copper. The origin of the dislocations is not certain; however, one could imagine their presence being due to either deformation resulting from relative shear between the silicate wall rock and the copper particle or damage incurred in metallographic preparation.

Some samples of copper show numerous small inclusions, about 0.05 mm in diameter, that have so far not been identified.

The present evidence does not permit one to decide whether the large grain size originated at the time the copper originally formed, or whether it might be due to grain boundary migration during some post-depositional period of heating.

THE SIGNIFICANCE OF THE CHERTY IRON-FORMATION,
BARAGA BASIN, MICHIGAN

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ABSTRACT

A Middle Precambrian chert and carbonate rock section (Iron-Formation) is exposed in a number of localities in Baraga County. The maximum measured thickness is 70' near the Huron River in Section 1, T. 51 N., R. 30 W. In north-eastern Baraga County the iron-formation was deposited unconformably on granitic basement, but to the southwest it lies conformably upon a quartzite. More than 1100' of black slate overlie the iron-formation.

Two distinct sequences make up the chert and carbonate rock section: a cherty-iron formation and an overlying volcanoclastic sequence. The cherty-iron formation is composed of chert, calcite, ferroan calcite, and ferroan dolomite-ankerite with minor chlorite, hematite, pyrite, and carbonate-apatite. The volcanoclastic sequence consists of tuffs, breccias, and lapillistones, interbedded with black, carbonaceous, pyritic chert.

We propose that the cherty iron-formation and the volcanoclastic sequence in the Baraga Basin correlate respectively with the Greenwood Iron-formation Member and the Clarksburg Volcanics Member of the Michigamme Formation on the Western Marquette Range.

PALEO-ENVIRONMENT OF IRON-RICH SEDIMENTARY ROCKS

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ABSTRACT

Actualistic methods should be applied to the interpretation of the formative environment of iron-rich sediments. Iron-rich sediments may be classified in two basic classes; the iron-rich shales (most sulfide iron-formations and the sideritic clay ironstones) and chemical sediments with limestone-type textures (cherty iron-formation and Minette-type iron ores).

Methods for the environmental recognition of fine-grained terrigenous sediments (Reineck and Singh, 1973) may be applied to iron-rich shales. Iron-rich shales occur intercalated between fine-grained, thin-bedded, distal turbidites in deep basinal environments; intercalated between proximal reef-debris turbidites in shallow inter-reef basins (for example Meggen, Germany); or in peritidal settings (for example some copper ores of Zambia).

Massive pyrite bodies pose some special problems. Many massive pyrite bodies grade into black shales and may have formed from sapropelites by the action of sulfate-reducing bacteria. These should be treated like pyritiferous shales. Other pyrite bodies are related to volcanic centers and may be analogs to the sulfide muds of the Red Sea. Analysis of the volcanogenic facies of the over- and underlying volcanic rocks may provide the best way to study their formative environment. Some volcanogenic sulfide bodies have been deposited in water less than 100 meters deep.

Facies of cherty iron-formations and of Minette-type iron ores may be defined by their sedimentary textures and structures (Chauvel and Dimroth, 1974). These are readily interpreted by comparison with recent limestone facies (Bathurst, 1971; Milliman, 1974).

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THE BIOGENIC ORIGIN OF PRECAMBRIAN IRON-FORMATIONS

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ABSTRACT

The initial particulate composition of iron-formation is quite restricted. It is composed of calcium carbonate, opal, and organic debris.

Carbonate algal microspheres are the source of initial calcium carbonate, although a very minor source is from carbonate tests of another microorganism. A secondary but major source of carbonate is produced as submicron grains by carbonate bacteria metabolizing organic debris. Their metabolic process produces ammonia, which creates a very high pH micro-environment; this condition precipitates a carbonate from ambient water. We consider this to be a biochemical process.

Opal is derived from the tests of several types of silica secreting organisms. The tests are easily comminuted by water agitation to produce a slurry. Only rarely are tests accumulated as laminae in quiet water, and even more rarely incorporated within laminae deposited as slurry.

During periods of quiet water, anaerobic conditions exist at the mud and water interface. Under these conditions sapropel from algal hash and opal complex, in variable proportions, to produce amorphous "greenaloid." This material is sufficiently cohesive to produce granules during subsequent water turbulence.

Because of intermittent transport of particles and the variable mixing of aerobic and anaerobic water, the various components are subjected to one or more cycles of residence in oxidizing or reducing environments.

Ferrous iron is introduced during the period of deposition, and prior to lithification. Most of the carbonate is sideritized and "greenaloid" production involves ferrous iron complexing, probably owing to presence of iron bacteria. Sulphate reducing bacteria were present in some "greenaloid," as biogenic pyrite is a common component in greenalite.

Data for events and products produced during progressive diagenesis were presented last year at these meetings and the sequences culminating in production of magnetite and hematite remains, in our opinion, as being correct.

GEOLOGICAL MODELING OF GRAVITY FEATURES,
NORTHEASTERN MARQUETTE COUNTY, MICHIGAN

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ABSTRACT

On the basis of approximately 575 new gravity readings, the area N.W. of Marquette shows a pattern of steep gravity gradients forming strong intersecting lineations. The lineations have been modeled, using surface geology as compiled by Bodwell (1972), to represent near-vertically block faulted masses of Archean granitic basement rock.

A large central positive anomaly, nearly rhombohedral in shape, as defined by strong gradients, is interpreted to represent a down-dropped block of basement rock that contains lower Precambrian greenstones, which is now covered by Middle Precambrian meta-sediments. This structure is approximately 6 km in depth.

Major Bouger gravity lineations, representing for the most part faulted block margins, correlate well with lineations observed in aeromagnetic maps. These magnetic features probably represent the emplacement of Keweenaw diabase dikes along fault boundaries.

Gravity model interpretations of the structure for the Northern Complex confirm the structural model for Penokean tectonics that was put forth by Cannon (1972).

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A REVIEW OF THE COPPER COUNTRY "EARTHQUAKES"
OF 1905 AND 1906, HOUGHTON COUNTY, MICHIGAN

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ABSTRACT

Two Copper Country seismic events of 26 July 1905 and 26 May 1906 appear in the records as earthquakes. The 1905 shock is thought to be the strongest recorded seismic event in the northern mid-continent and includes in its effects the shifting of a residence on its foundation and ground fissuring. The 1906 shock was reported to have registered on a seismograph at Cleveland, Ohio, and includes in its effects the twisting of nearby railroad tracks and ground fissuring. Both events were assigned Modified Mercalli Intensities of VIII which is striking for their locations in a nonseismic stable craton.

The epicentral locations of these events are close to the Keweenaw Fault which is a major geologic feature extending from the Upper Peninsula of Michigan to Wisconsin where it merges southwesterly with other structures in the mid-continent gravity high. Nuclear power site investigating teams which are looking at possible sites in the midwest along this mid-continent structure are concerned because of the possibility that, if these earthquakes represent adjustments in tectonic stress along the Keweenaw Fault, similar events might occur elsewhere along the alignment in the future.

We have reviewed the historical descriptions and contemporary newspapers' accounts of the 1905 and 1906 principal events and related them to the development of local underground mines. The "felt" areas are smaller than expected for earthquakes of intensity VIII. The areas of greatest disturbance correlate with the areas of underground mine workings. Though the primary cause of the events may be adjustment in regional stresses along the Keweenaw or related faults, instability induced by mine workings modified the local damage and might have triggered the initial disturbances.

BOUGUER GRAVITY MAP, WESTERN HALF
OF MICHIGAN'S UPPER PENINSULA

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ABSTRACT

This paper provides an updating of previous gravity work, incorporating data from the last few years in the areas north and south of the Marquette trough, as well as offshore data from Wold (1972).

Major gravity anomalies are related to rock types having density contrasts with adjacent rocks. Major gravity features reveal such major structural features as the Marquette trough, the western portion of the Menominee range, the Keweenaw Bay graben(?) and other major features such as the trace of the Keweenaw fault. Minor features associated with some of the major features indicate areas where more detailed exploration work needs to be done.

THE WISCONSIN AEROMAGNETIC MAPPING PROJECT

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ABSTRACT

To date, in an area centered north of Wausau, about 12,000 line miles have been aeromagnetically mapped and organized by USGS ~~into~~ 15' topographic quadangles. The survey is flown on north-south flight lines with a one-half mile spacing at a radar altitude of 500 feet above the ground using a proton magnetometer. Digitally collected data is computer processed using a two dimensional 4x4 point polynomial interpolation from which 100 gamma contour levels are generated for producing subsequent computer graphic output. About 200 contour maps on four different popular scales have been produced along with downward continued maps and specialized perspective presentations.

Preliminary interpretation indicates the magnetic data correlates well with the known geology in the Tigerton, Wausau, and Wolf River batholith areas. The aeromagnetic maps are published by the Wisconsin Geological and Natural History Survey and are available from them at a nominal fee.

GEOCHRONOLOGY OF UPPER AND MIDDLE KEWEENAWAN
ROCKS OF MICHIGAN

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ABSTRACT

Additional Rb-Sr ages determined for Keweenawan rocks of Michigan have been useful in the understanding of Keweenawan igneous activity. The whole-rock Rb-Sr isochron for Bear Lake felsite, 6 miles north of Hancock, yielded an age of 1007 ± 25 m.y. and an initial Sr (87/86) ratio of 0.705 ± 0.001 . This apparent age for the felsite sets a minimum time of deposition for the Freda Sandstone. A whole-rock sample from Mt. Houghton rhyolite provided an age of 1038 m.y., whereas a similar determination for Copper City rhyolite yielded an age of 1040 m.y. A muscovite separate from the Jacobsville Sandstone indicated an apparent Rb-Sr age of 1745 m.y., whereas the associated biotite separate in the same sample was found to be 1110 m.y. old.

PALEOAPHEBIAN POLAR WANDER AND
PALEOMAGNETISM OF THE GOWGANDA FORMATION

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ABSTRACT

The paleomagnetism of sediments from the Huronian Gowganda Formation was studied for 16 sites near Elliot Lake, Ontario, in the Southern Geologic Province. The sediments retain a stable remanence acquired during diagenesis some 2.29 b.y. ago. The calculated paleolatitude of 62° favours a polar glacial till mode of deposition for the thick tillite members rather than a subpolar periglacial dropstone mode. The Gowganda pole position is located at 123° W, 65° N, ($\delta_p - 10.6$; $\delta_m - 11.7$). This agrees with unpublished data contained in studies on other Huronian strata; these findings may require a radical change in previously published conclusions on Paleoaphebian wander paths. Further, it suggests that either the limits for Huronian glaciation proposed by Young (1973) are wrong or that the Bear and Slave Provinces had not yet been added to the Churchill, Superior and Southern Provinces.

PALEOMAGNETISM OF KEWEENAWAN DIABASE DIKES
FROM BARAGA AND MARQUETTE COUNTIES, MICHIGAN

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ABSTRACT

Preliminary paleomagnetic results on the Keweenawan Baraga-Marquette dike swarm in Michigan yield a paleomagnetic pole which differs significantly from an early measurement by Graham (1953). Graham's original data, which were obtained from 2 dikes without rigorous magnetic cleaning, yielded a pole position (Lat. 45° N, Long. 99° W), which plots close to the projected apex of the Logan Loop (a prominent excursion, that occurred 1.2 to 1.1 b.y. ago in the Precambrian apparent polar wander path for North America).

A remeasurement of the Baraga-Marquette dikes was thus undertaken to verify the location of this potentially important pole position. In the present study 120 oriented rock samples were collected from 12 diabase dikes. Paleomagnetic data from these samples reveal a Natural Remanent Magnetization (NRM) several times larger than the induced component (Q varies from 1 to 12). Alternating field demagnetization shows that the NRM is magnetically hard ($J_{200}/J_0 \geq 0.5$) and directionally stable up to 1000 oe peak field. The mean remanence direction for 49 specimens after a cleaning field of 200 oe is: $D = 121^{\circ}$, $I = -69^{\circ}$, $\alpha_{95} = 2.4^{\circ}$, yielding a pole position of Lat. 52° N, Long. 147° W. This pole is about 30° of arc farther west than Graham's determination and is not significantly different from pole positions obtained for the reversely magnetized Logan sills.

EXTENSION OF VERMILION DISTRICT LAMPROPHYRES INTO
WESTERN MINNESOTA FROM GEOPHYSICAL OBSERVATIONS

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ABSTRACT

Positive gravity and magnetic anomalies characteristic of lamprophyres of the Lower Precambrian Vermilion district, northern Minnesota, are also discernible on geophysical maps in glacially covered areas in western Minnesota. This suggests an extension of a lamprophyre province from the Vermilion district into western Minnesota along the 48th parallel.

Analysis of coincident gravity (20 mgal) and magnetic (1000 gamma) anomalies near Fosston, Polk County, shows the source to be an elongate body (1.9 by 4.8 km) in bedrock beneath the glacial drift (122 m thick). The model source is a vertical prism extending from the basement surface to an unknown depth. Attempts to flare the top of the gravity model suggest that flaring is minor or nonexistent. The interpreted density and susceptibility contrast of the source are approximately 3.1 g/cc and 0.0025, respectively.

Small bodies of syenitic rocks, lamprophyres, and lesser granitic rocks are common in the western part of the Vermilion district, and in adjacent areas to the west that are not covered by drift. They intrude the Lower Precambrian metavolcanic and metasedimentary sequences, and less commonly the metasedimentary-metavolcanic rocks north of the Vermilion fault. Analysis of exposed bodies in the Vermilion district, and of buried bodies in western Minnesota, suggest shallow emplacement with a relatively minor amount of erosion.

The lamprophyres are melanocratic or mesotype rocks that contain euhedral ferromagnesian glomeroporphyroblasts in a microgranular groundmass that tends to have a panidiomorphic texture. The lamprophyres can be classed mainly as metavogesite and metaspessartite. Petrographic and chemical aspects of these rocks are presented by Geldon (1972) and by Sims and Mudrey (1972).

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- Sims, P.K., and Mudrey, M.G., 1972, Syenitic Plutons and Associated Lamprophyres, Geology of Minnesota, Cent. Vol. Minn. Geol. Surv., pp. 140-152.

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FIELD TRIPS

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GLACIAL GEOLOGY

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GREENSTONE

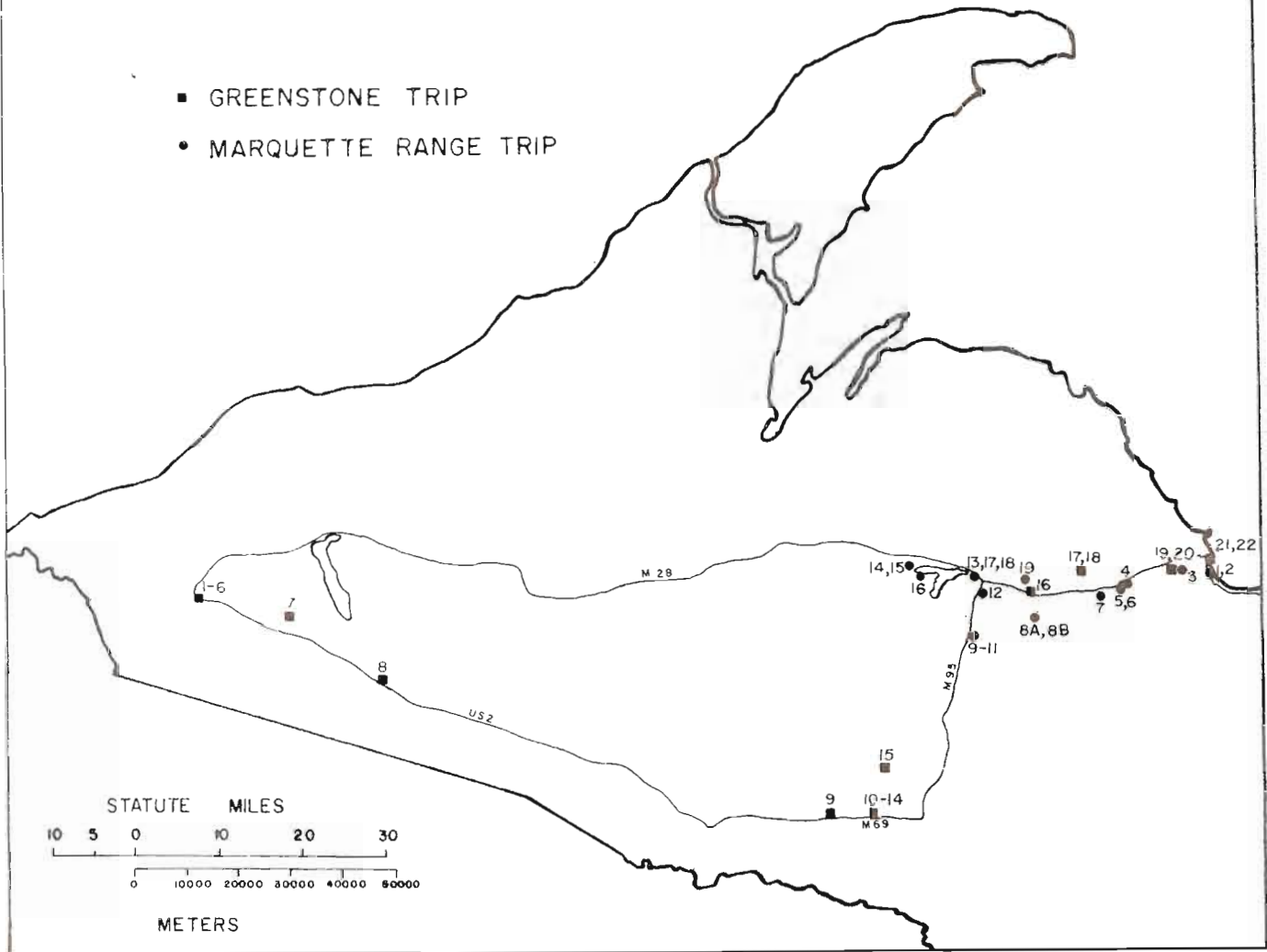
By

W. C. Prinz, J. E. Gair, and W. F. Cannon

U.S. Geological Survey

Reston, Virginia

- GREENSTONE TRIP
- MARQUETTE RANGE TRIP



Introduction

The success in recent years of mineral exploration in Precambrian greenstone terranes has heightened interest in greenstone belts of the Canadian Shield. This period of increasing interest in greenstones has coincided with the last stages of mapping of greenstones in the Upper Peninsula of Michigan by the U.S. Geological Survey in cooperation with the State of Michigan; this cooperative program has been in existence since World War II. It, therefore, seems particularly appropriate at this time that an entire field trip of the Institute be devoted to a broad examination of greenstones in the Upper Peninsula.

The trip will include representative examples of major greenstone units of middle and early Precambrian (Precambrian X and W) age that extend from the Gogebic Range on the west to some of the most easterly exposures in the Marquette Range. These greenstone units span 500 million or more years. The distribution and stratigraphic position of the major greenstone units are shown on the map and correlation chart (Figs. 1 and 2). Parts of published topographic maps accompany the following sections of this report and show the exact locations of field trip stops. The selected references listed at the end of the guidebook contain geologic maps of the respective areas.

The field trip will begin on the Gogebic Range and proceed across the Marenisco-Watersmeet area, the Iron River-Crystal Falls district, and eastern Iron County, into the Marquette district.

Gogebic Range, Gogebic County Archean Greenstone, Wakefield area

Metamorphosed volcanic rocks of Archean age (Precambrian W) form a belt 1 to 3 miles across and 10 miles long (east-west) along the southern edge of the Gogebic iron range in the vicinity of Wakefield, Michigan. These rocks are intruded on the south and west by quartz monzonite, also of Precambrian W age, and are overlain with angular unconformity on the north and east by the iron-bearing Precambrian X sequence of the Gogebic range. The eastern two-thirds of the belt of Archean volcanic rocks is mainly mafic to intermediate flow and pyroclastic rocks but contains sparse felsic rocks. The western third is made up of intermediate to felsic schist. These rocks generally strike west to northwest and dip steeply to the south. Northeast trends are rare. Tops of the units face south, except possibly in the northern part of the belt where evidence for top directions is equivocal.

The mafic to intermediate flows commonly show ellipsoidal (pillow) structures or are amygdaloidal. Most are andesitic to dacitic in composition. The series of flows is apparently about 10,000 feet thick, but it may have been repeated by undetected faults. Mafic to intermediate pyroclastic rocks are commonly interbedded with the flows in units as much as several hundred feet thick. A pyroclastic unit possibly 3,000 to 4,000 feet thick extends from Wakefield eastward for $1\frac{1}{2}$ miles and apparently underlies the mafic flows. The pyroclastic rocks range from fine-grained tuffs to lapilli tuffs to volcanic conglomerates and breccias containing boulders as much as 4 feet across. Some tuffs are thin bedded and slaty; others are thick bedded and relatively massive. Sparse felsic rocks are also interbedded with the mafic flows and apparently form thin, predominantly pyroclastic units, although they are poorly exposed.

Felsic rocks become more abundant to the west, and the western third of the Archean volcanic belt is composed wholly of schist of felsic to intermediate composition. In this western area, the outcrop belt of felsic schist is 8,000 to 10,000 feet across; this probably represents the maximum thickness of felsic rocks.

The volcanic rocks in the Wakefield area represent the remnants of the central and upper parts of what was once probably a much larger differentiated volcanic pile. The andesitic flows in the Wakefield area are similar to flows found in the central parts of more completely exposed Archean volcanic piles in Canada. They pass upward (southward) and westward into felsic rocks typical of the upper parts of Archean volcanic piles. The thickening of felsic schists to the west suggests that the Wakefield area lies on the east side of a center of felsic eruption. Basaltic flows typical of the base of Archean volcanic piles are not exposed in the Wakefield area, although they may lie at depth to the north or may have been removed by erosion prior to deposition of the Precambrian X rocks.

The Archean rocks were regionally metamorphosed before deposition of the rocks of Precambrian X age. The metamorphic grade of the Archean rocks increases from chlorite grade (greenschist facies) in the north and east to garnet grade (amphibolite facies) in the south and west. The rocks of Precambrian X age were metamorphosed to chlorite grade during the Penokean orogeny (post-Precambrian X) at which time retrograde minerals were formed in some of the Archean rocks. Thus, weakly metamorphosed rocks of Precambrian X age rest unconformably on more highly metamorphosed rocks of Precambrian W age (see Stop 5).

The Archean rocks are cut by dikes of metadiabase of Precambrian X age and by dikes of unmetamorphosed diabase of Precambrian Y age.

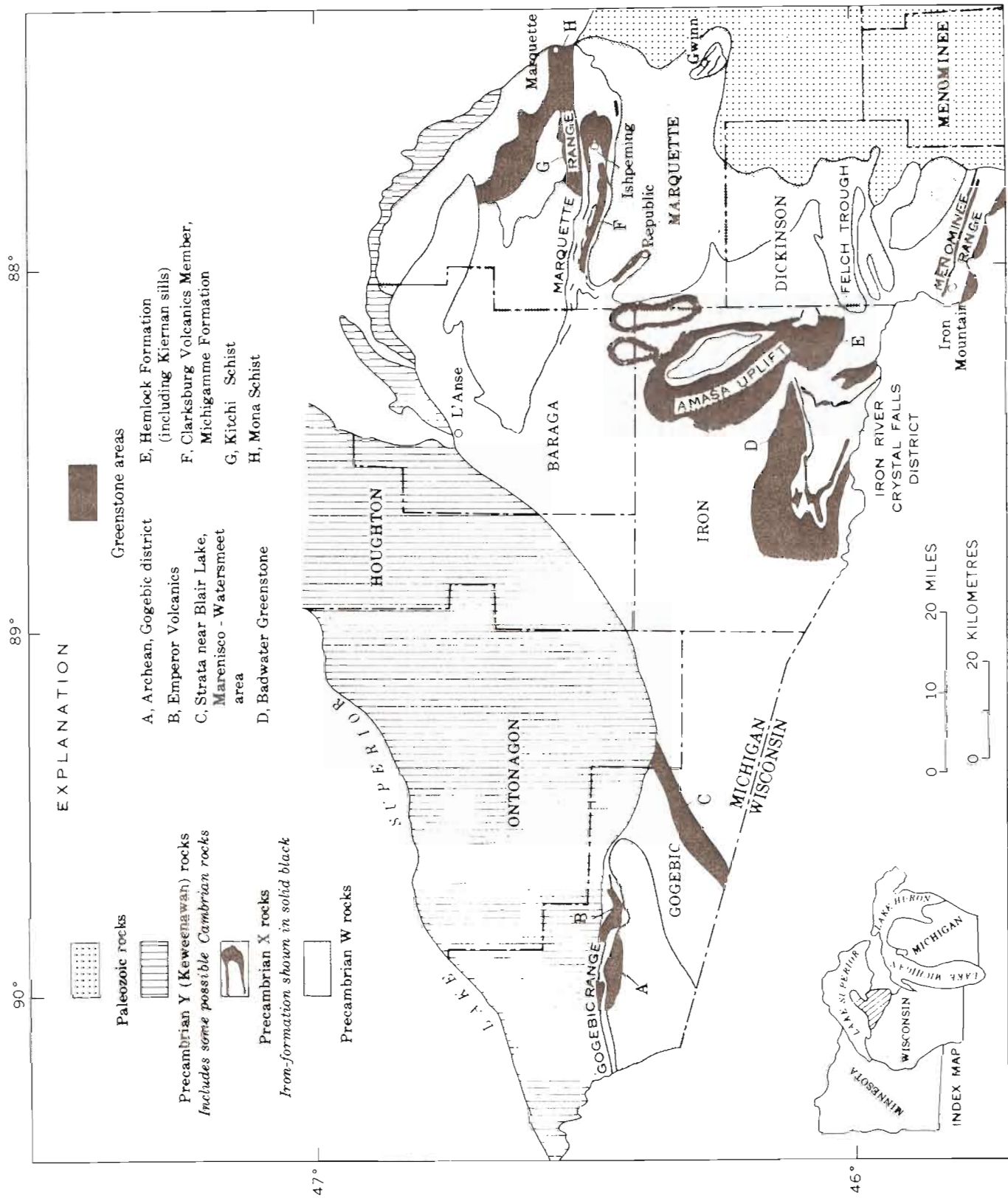
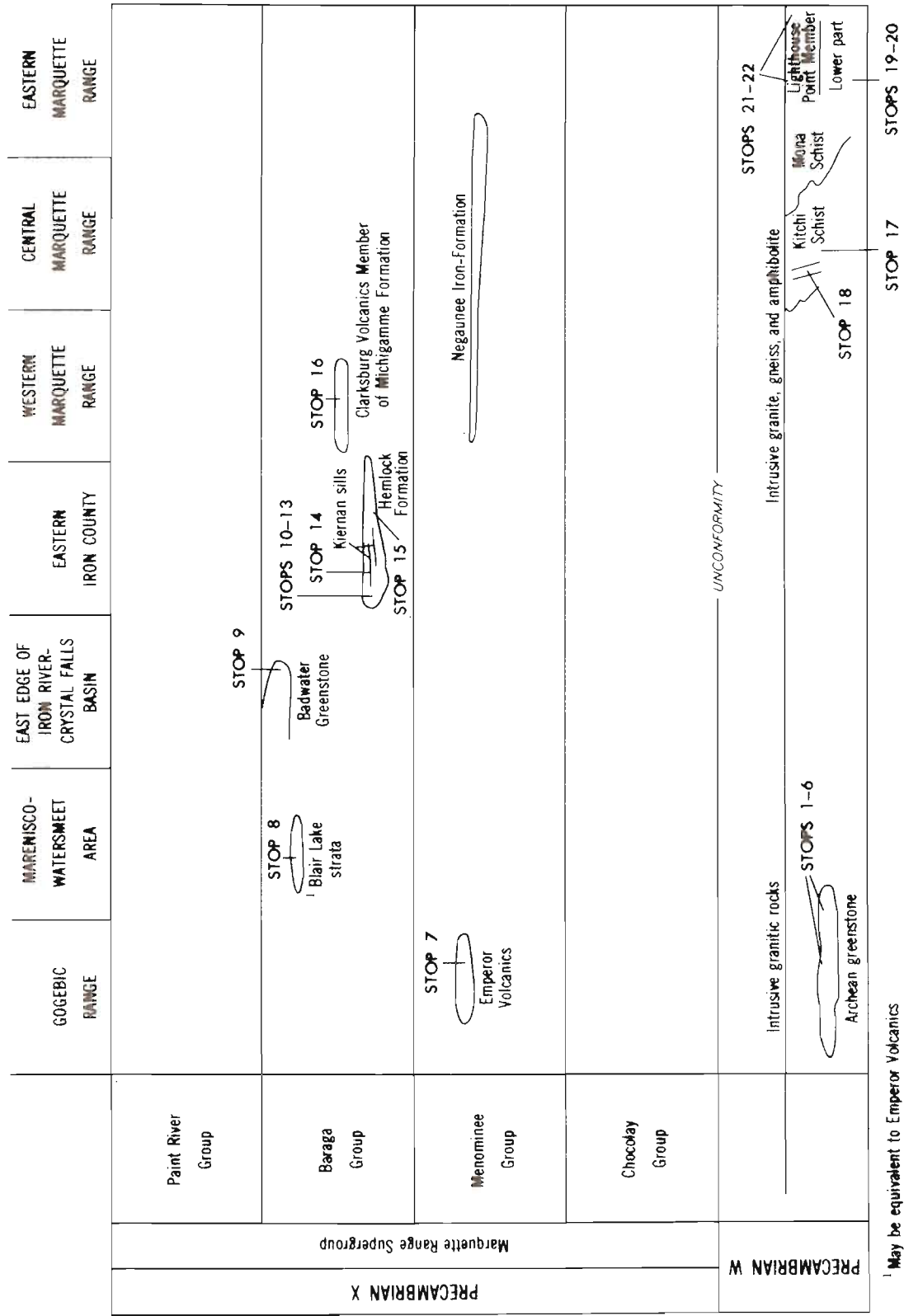


Figure 1--Generalized geologic map of western Upper Michigan.

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¹ May be equivalent to Emperor Volcanics

Figure 2--Correlation chart of units to be seen on field trip.

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The area of the field trip lies at the center of the belt of Archean volcanic rocks where the lithology is changing from predominantly mafic in the east to felsic in the west and where the metamorphic grade is changing from low to the northeast to high to the southwest. Field trip stops 1-6 are shown on a part of the Wakefield 7½-minute quadrangle (see next page). The geology of this area has been mapped by Prinz and Hubbard (1975); the area to the east by Trent (1973), and that to the west by Schmidt (1972).

Stop 1 (Fig. 3). Ellipsoidal flows. Road cut along U.S. Rte. 2, 3.0 miles east of Wakefield.

The rocks here are of low metamorphic grade (greenschist facies) and are composed of fine-grained albite-oligoclase, quartz, epidote-zoisite, and chlorite. Some samples also contain carbonate, pale amphibole, and biotite.

Ellipsoidal (pillow) structures are well-exposed in the glacially polished outcrop on the south side of the highway. The flows strike about N. 65° W. and dip steeply to the south. Tops face south.

Discontinuous thin fragmental zones are exposed on the top of the outcrop on the north side of the highway. The fragments in these zones are rounded and up to a couple of inches across. Although the fragments weather to a much lighter color than the matrix does, in thin section little difference in composition is apparent.

Stop 2 (Fig. 3). Felsic pyroclastic rocks. Low outcrop ½ mile west-southwest of Stop 1.

This is a poorly exposed and relatively thin unit in a predominantly mafic sequence. Mafic to intermediate flows crop out on the ridge 500 feet to the north and 900 feet to the south. The metamorphic grade here is low, like that of the rock at Stop 1. The rock is composed principally of quartz and feldspar (albite-oligoclase and some K-feldspar), variable amounts of carbonate, fine-grained epidote, chlorite, biotite, and muscovite. The rock is dacitic to rhyodacitic in composition. Pyrite is generally abundant in this unit, particularly on the dump of a test pit along the fence line 300 feet west of the outcrop.

Stop 3 (Fig. 3). Mafic to intermediate pyroclastic rocks. Road cut along U.S. Rte. 2, 1.4 miles east of Wakefield.

This outcrop is near the southeastern edge of a thick pyroclastic unit that crops out in an area extending ½ mile north to the base of the Precambrian X rocks and 1½ miles west to the west edge of Wakefield. The rock in the road cut varies from thin

to thick-bedded massive or slaty tuff to coarser grained lapilli tuff containing fragments of andesite and of broken feldspar, commonly highly altered to sericite. Clastic quartz, locally abundant carbonate, and some chlorite are other constituents of this unit. The metamorphic grade is low, like that at the first two stops.

Coarser grained pyroclastic rocks with fragments to $\frac{1}{2}$ inch across are exposed in the woods on the knob just north of the highway. Bedding in the pyroclastic rocks here strikes northeast and dips steeply to the southeast. At two places (not in this outcrop), relations suggest that the tops of these beds face north as opposed to the south facing tops of the mafic flows to the south and east. We'll buy a beer for anyone who can find convincing evidence for top directions in this outcrop.

Stop 4 (Fig. 3). Felsic schist. Road cut and outcrop 1.1 miles south of Wakefield.

The rocks exposed here are lineated quartz-biotite-feldspar schists. They contain both plagioclase (albite-oligoclase) and K-feldspar, and the feldspars are partly to mostly altered to sericite. The rocks also contain some chlorite and muscovite and sparse garnet. Although the mineralogy of these rocks is relatively simple, variation in grain size and relative abundance of the minerals defines laminae as much as 2 feet thick that probably represent original bedding. These rocks are rhyodacitic in composition. They are probably equivalent to the felsic pyroclastic rocks seen at Stop 2 but are of higher metamorphic grade. This outcrop is part of a much thicker felsic unit than that at Stop 2. Felsic schist extends from here 1,500 feet north to the ellipsoidal flows to be seen at Stop 5 and probably for 3,500 feet south to the mafic pyroclastic rocks at Stop 6. This belt of felsic schist maintains a width of 5,000 to 10,000 feet for at least $3\frac{1}{2}$ miles along strike to the west, but it narrows rapidly to the east.

Stop 5 (Fig. 3). Ellipsoidal flows. Quarry 0.8 mile south of Wakefield. (Walk east along driveway; follow streamers up west-facing slope to top of quarry, across the top of the quarry, and south down the east side of the quarry back to the driveway. WARNING--the rock along the top of the quarry may be slippery, particularly if it is wet; WALK CAREFULLY.)

Felsic schists, similar to those seen at Stop 4, crop out on the lower part of the slope on the way to the top of the quarry. The main purpose of this stop, however, is to examine ellipsoidal flows at the top of the quarry which are higher metamorphic grade

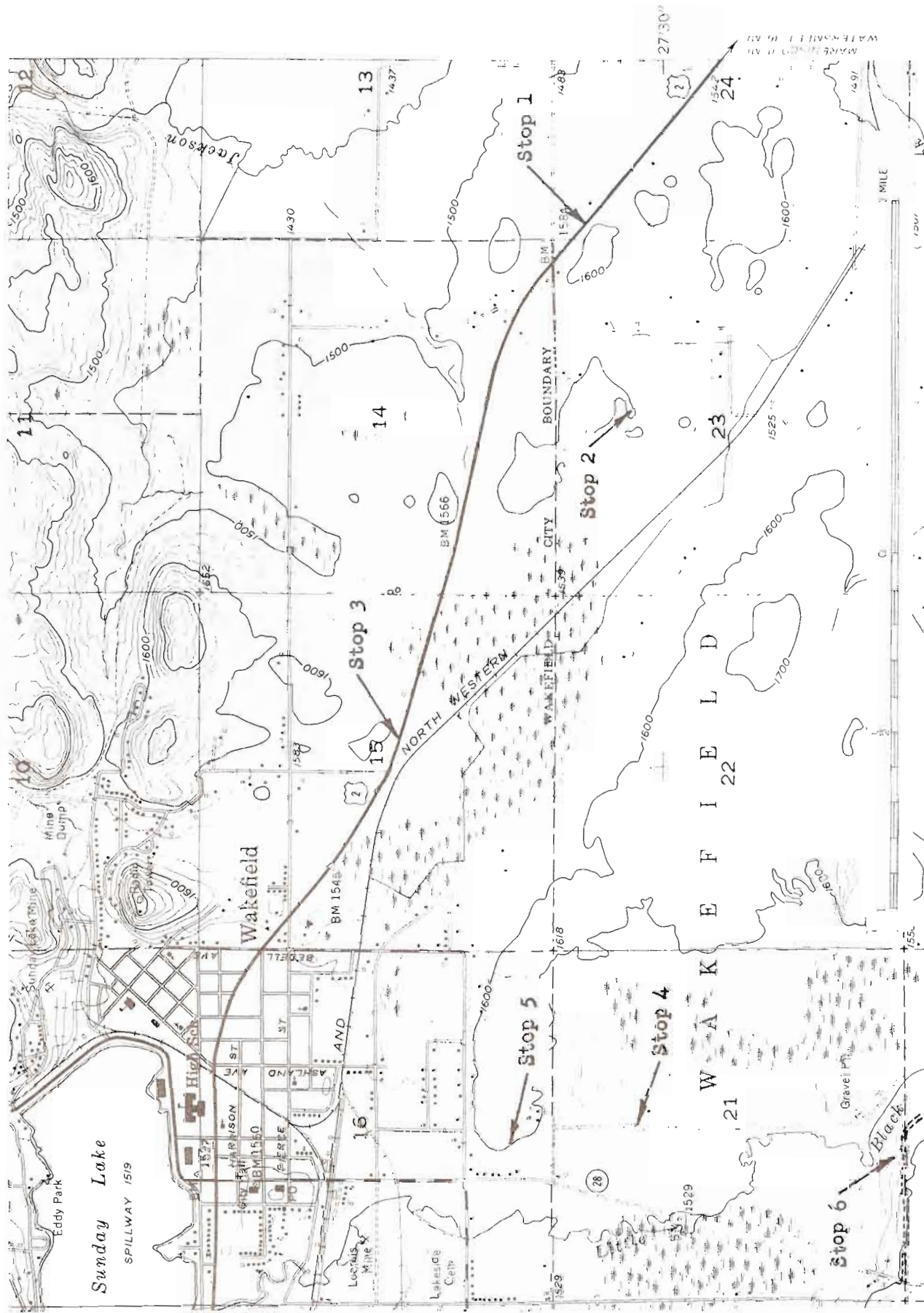


Figure 3--Stops 1-6. Archean Greenstone, Wakefield Area. Wakefield 7-1/2 quadrangle.

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(amphibolite facies) than those seen at Stop 1. The flows here are composed mainly of untwinned feldspar showing sericitic alteration, quartz, and green pleochroic amphibole that is commonly poikiloblastic. Some samples contain carbonate, but none contain epidote. A few samples contain chlorite that probably formed as a retrograde mineral during the less intense later Penokean regional metamorphism. The base of the Precambrian X rocks, which are only weakly metamorphosed, is only about 500 feet north of the quarry. Amphibole along the selvages of the pillows is commonly coarser grained than that in the interior. This is undoubtedly a metamorphic phenomenon in which metamorphism has caused a reversal in the relative grain size; originally the selvages would have been finer grained than the interiors of the pillows. The tops of these flows face southwest. The contact between flows and overlying felsic schist has a northerly strike on the slope to the west of the quarry, but it swings around to a southeast trend around the quarry. Outcrops north of the quarry (not to be visited on the trip) show some amygdaloidal structures and interbedded pyroclastics and are cut by a dike of unmetamorphosed diabase.

Stop 6 (Fig. 3). (optional). Mafic to intermediate pyroclastic rocks.
Outcrop 1.9 miles south of Wakefield.

The rocks at this stop are of higher metamorphic grade (amphibolite or epidote-amphibolite facies) than the equivalent rocks seen at Stop 3 and are the most accessible exposures of coarser grained pyroclastic rocks. The low outcrop at the top of the slope is coarse volcanic breccia with angular to subangular fragments of metaandesite in an amphibolitic matrix. The fragments range from a few inches to 4 feet across and some are amygdaloidal. They are stretched out parallel to a strong northwest-plunging lineation. The fragmental texture is very distinct on surfaces parallel with the lineation. Both the matrix and the clasts are composed of quartz, green amphibole, and sericitized feldspar containing some epidote, carbonate, and chlorite. The clasts contain less amphibole and more quartz and epidote than the matrix. The rock is finer grained and more felsic to the north (down the slope) and shows a compositional layering. It is probably metamorphosed bedded tuff. The metatuff is cut by a dike of medium-grained quartz monzonite, probably an offshoot of the main quartz monzonite pluton $\frac{1}{2}$ mile to the south.

Marenisco-Watersmeet area, Gogebic County
Blair Lake strata (Precambrian X)

The Precambrian X sequence between Marenisco and Watersmeet consists of interbedded metamorphosed sedimentary and volcanic units (Fritts, 1969). The sedimentary units are mainly graywacke and slate; the volcanic units are mafic flows and pyroclastics. A thick volcanic unit, called "strata near Blair Lake" by Fritts (1969) will be examined on this trip. The Blair Lake strata are about 7,500 feet thick and consist of mafic ellipsoidal flows and pyroclastics and some thin interbedded graywacke, quartzite, and iron-formation. The Blair Lake rocks are probably equivalent to the Badwater Greenstone of the Iron River-Crystal Falls district or to the Emperor Volcanics of the east Gogebic Range.

Stop 8 (Fig. 5). Mafic ellipsoidal flows and pyroclastic rocks.
Road cuts along U.S. Rte. 2, 12 miles east of
Marenisco and 15 miles west of Watersmeet (see
map on next page).

The stop is in mafic volcanic rocks in the lower part of the Blair Lake strata. The rocks here have been metamorphosed to garnet grade (amphibolite facies). They have been recrystallized to amphibolite containing varying proportions of green amphibole, quartz, and untwinned feldspar. Biotite or carbonate are abundant in some samples. Epidote is rare, generally occurring with quartz in amygdules or veinlets. Rarely, the feldspar is sericitized. Although the rocks have been recrystallized, original structures are remarkably well preserved in many places. Pyroclastic rocks are the most abundant. They range from thin-bedded metatuffs to coarse volcanic breccias containing fragments as much as 5 feet across. The mineralogy from bed to bed or between fragment and matrix is the same or similar; the differences are in grain size and relative proportions of the major minerals. Ellipsoidal and amygdaloidal structures are typical of the flow units. The ellipsoidal structures are particularly well-exposed on the southwest side of the highway near the northwest end of the road cuts. The unit strikes northeast and dips steeply to the southeast. Tops face southeast.

Gogebic Range, Gogebic County
Emperor Volcanics (Precambrian X)

Mafic to intermediate flows, volcanic breccias, and tuffs are interbedded with and overly the upper part of the Ironwood Iron-formation in the eastern part of the Gogebic Range (Prinz, 1967; Trent, 1973). These rocks, called Emperor Volcanics, extend from 6 miles east of Wakefield eastward for 8 miles to the head of Copps Creek, which is 6 miles north of Marenisco. The volcanics have a maximum thickness of 5,000 feet. The Emperor Volcanics are truncated on the west by an unconformity at the base of the Keweenaw flows (Precambrian Y) and on the east by an unconformity at the base of the Copps Formation as used by Prinz (1967) (Precambrian X); they were thus once more extensive and possibly thicker than they are today. Although the unit is well exposed, exposures are relatively inaccessible; the easiest one to reach is at Stop 7.

Stop 7 (Fig. 4). (optional). Volcanic breccia. Outcrop 5 miles north of Marenisco (see map on next page). Follow the road north from Marenisco to its end at a clearing that was once the site of a logging camp; walk north along old log road for 800 feet; outcrops are east and west, but the one to the east is the more accessible.

The outcrop is coarse volcanic breccia. Large andesitic or dacitic fragments are set in schistose matrix of essentially the same composition. The metamorphic grade here is low (greenschist facies).

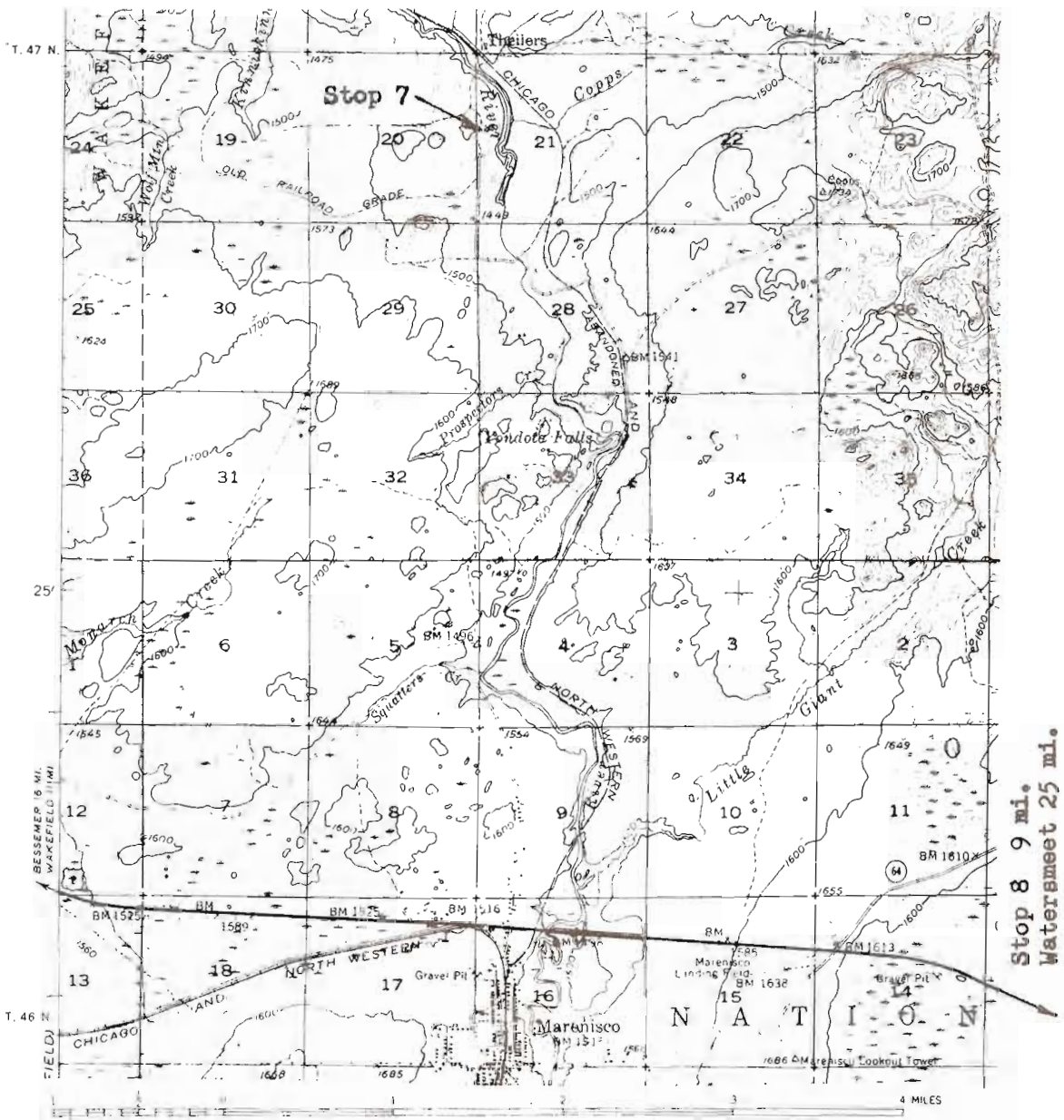


Figure 4--Stop 7. Emperor Volcanics, East Gogebic Range.
Marenisco 15-minute quadrangle.

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Iron River-Crystal Falls district, Iron County
Badwater Greenstone (Precambrian X)

Stop 9 (Fig. 6). Badwater Greenstone. Outcrop $1\frac{1}{2}$ miles northwest of Crystal Falls (see map on next page).

The Badwater Greenstone is composed mainly of metamorphosed mafic flows, commonly showing ellipsoidal structures, and some interbedded pyroclastic rocks--tuff and agglomerate. The Badwater lies between the Michigamme Formation below and the Dunn Creek Slate of the Paint River Group above. It is structurally conformable with both units. The stop lies in the so called "north belt" of Badwater Greenstone, which has been mapped and described by James, et al. (1968, p. 31-32). In the north belt, the Badwater has an average thickness of 15,000 feet and has been traced for 25 miles along strike west of the stop, but it pinches out $2\frac{1}{2}$ miles to the east. Pillows, which are well exposed along the south side of the knob at the stop, face uniformly south along the north belt. Rocks are of low metamorphic grade (greenschist facies).

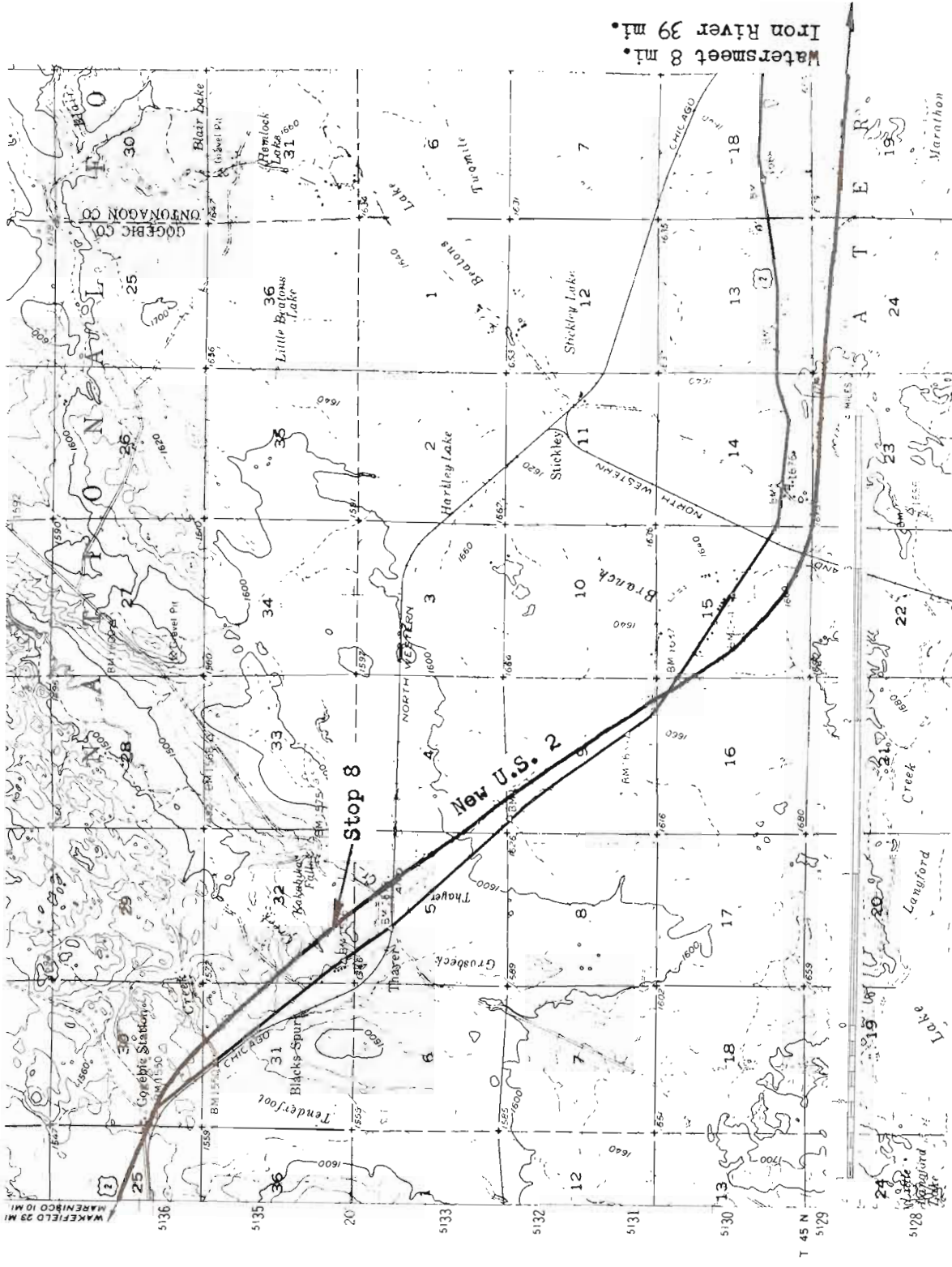


Figure 5--Stop 8. Blair Lake Strata, Marenisco-Watersmeet area. Thayer 15-minute quadrangle.

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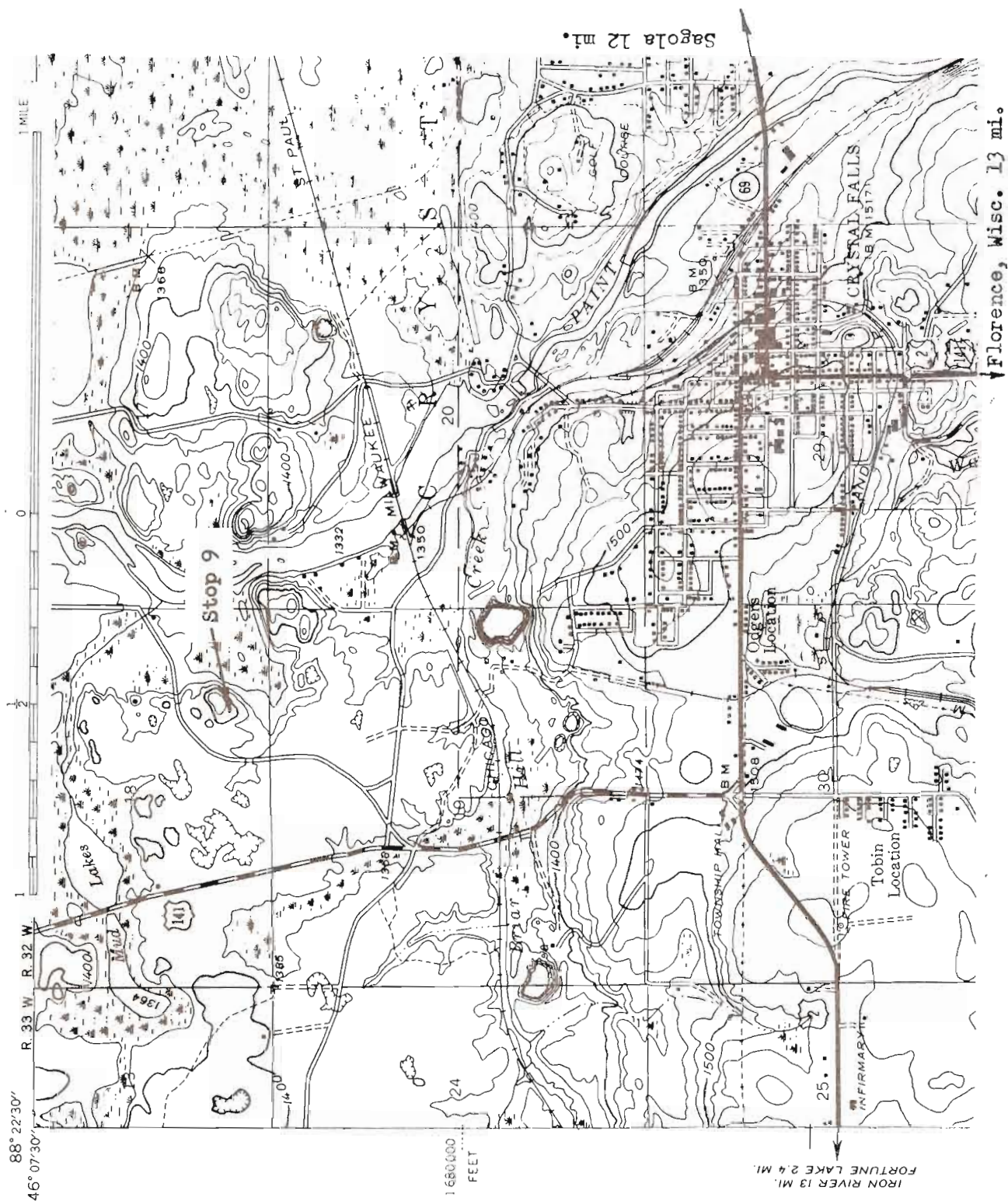


Figure 6--Stop 9. Badwater Greenstone, Crystal Falls area. Crystal Falls 7-1/2 minute quadrangle.

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Crystal Falls District, Eastern Iron County
Hemlock Formation and West Kiernan sill
(Precambrian X)

The Hemlock Formation occurs in a belt that completely surrounds the Amasa oval. The Amasa oval is an uplift about 12 miles long and as much as 3 to 4 miles wide in northeastern Iron County and has a core of Precambrian W granitic and gneissic rock. The Hemlock Formation consists mainly of a thick series of altered mafic flow rock, tuff, and agglomerate, forming massive to schistose and slaty greenstone. Ellipsoidal (pillow) and amygdaloidal structures are common. The Hemlock evidently was a thick volcanic pile consisting of interbedded subaerial and submarine mafic flows and agglomerates and interspersed thin mafic ash beds, lapilli tuffs, and sedimentary rocks. Felsic tuff and possibly flows occur sporadically in the volcanic pile. As a result of the Penokean regional metamorphism at the end of Precambrian X time, the mafic volcanic rocks in parts of the formation have been converted into schist units rich in biotite, hornblende, and epidote. Rocks at the field trip stops are all in the chlorite zone (lower greenschist facies) of metamorphism. Narrow belts of slate (not shown on field trip) are interbedded with the volcanic rock in some places. Graywacke (not shown on field trip) is present in a few places, and is generally interbedded with slate. One small area in the Hemlock Formation near the Mansfield Location on the Michigamme River contains a zone of ferruginous pyritic slate and iron-formation--the Mansfield Iron-bearing Slate Member--which has been mined for iron ore in the past. Rhyolitic felsite layers (now metarhyolite) are characterized by "eyes" of opalescent blue quartz.

One of the striking features of the Hemlock Formation is a great reduction in its thickness from west to east across the Amasa oval and beyond. On the west flank of the oval the Hemlock has a thickness somewhat in excess of 20,000 feet; 3 to 4 miles to the east on the east flank, the maximum thickness is about 2,300 feet, and 6 miles farther east, on the east side of the Sagola basin, there is no Hemlock Formation. The thick deposits and coarse fragmental layers on the west flank of the Amasa oval suggest that centers of volcanic eruption were west of the oval.

Prior to Penokean folding and metamorphism, two thick tabular bodies of diabase-gabbro, the Kiernan sills, were intruded into the present south and southwestern parts of the Hemlock Formation. Within the upper and thicker West Kiernan sill, differentiation took place by crystal fractionation and gravity settling after intrusion of the mafic magma. Ultramafic zones formed near the bottom of the sill and small late-stage pegmatitic differentiates (not shown on field trip) accumulated in the upper part of the sill. The diabase-gabbro and the more mafic differentiates were altered to greenstone during Penokean metamorphism.

Stops in the Hemlock Formation and West Kiernan sill are described below (see Figs. 7 and 8). Stops 10-13 will be completed the first day before returning to Iron River for the night; Stops 14-15 will be made on the morning of the second day. Stops 10-12 and 14 are in the Lake Mary 7½-minute quadrangle (Bayley, 1959); Stops 13 and 15 are in the Kiernan 7½-minute quadrangle (Gair and Wier, 1956). Following Stop 15 the trip will proceed to the western Marquette Range.

Stop 10 (Fig. 7). Ellipsoidal, fragmental, and amygdular greenstone. Road north from Michigan Hwy. 69 to Mansfield Location, 4 miles east of city of Crystal Falls. Small, low outcrop, northwest side of road approximately 7/8 mile southwest of 3-way road junction near Mansfield Location.

The succession from the southeast edge of the outcrop at the road to the west edge is ellipsoidal greenstone overlain by a layer of fragmental greenstone, overlain in turn by an amygdular zone. Note convex pillow surfaces that provide evidence that the stratigraphic tops face west.

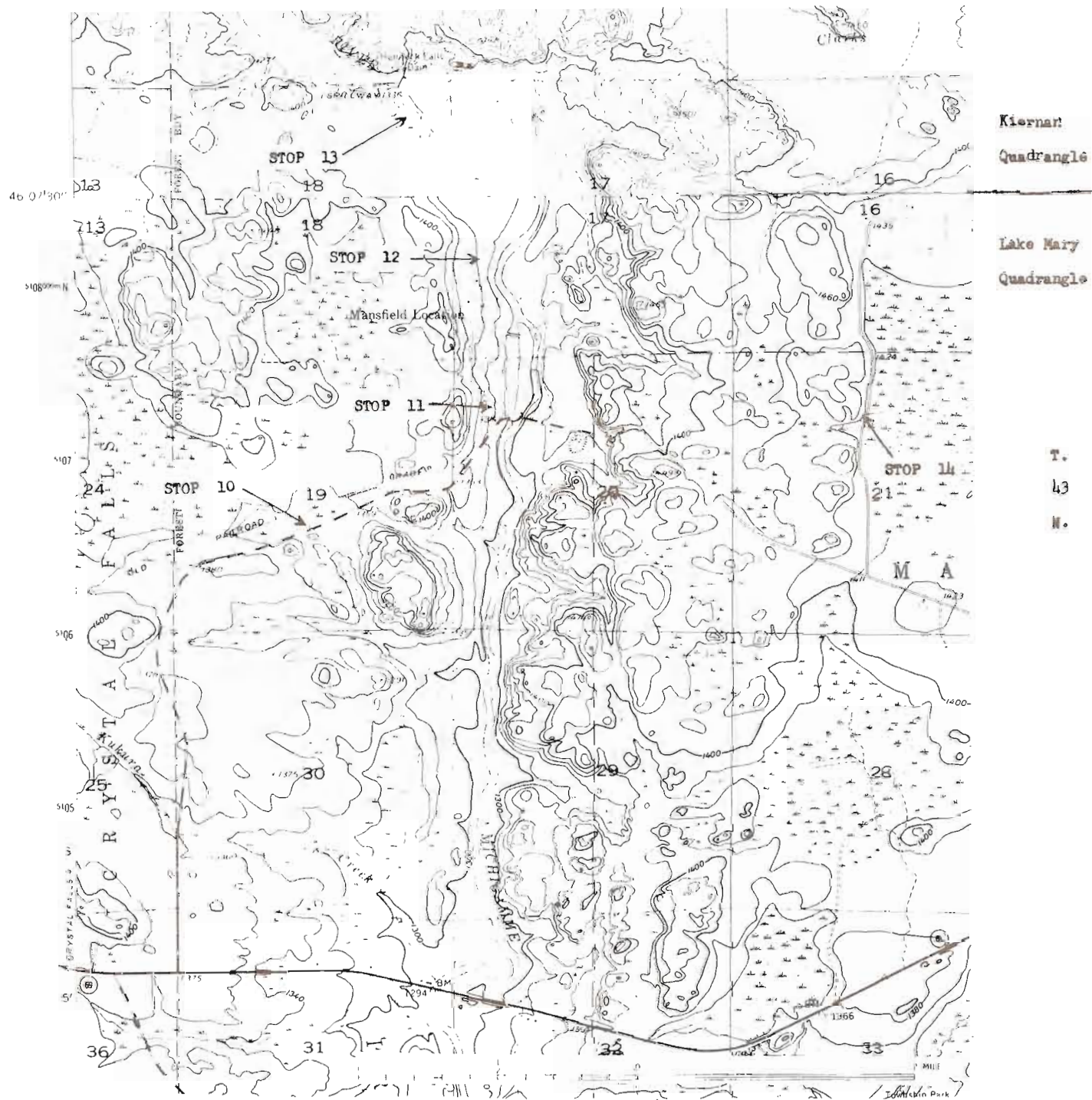
Stop 11 (Fig. 7). Ellipsoidal and massive flow greenstone; Mansfield Iron-bearing Slate Member of Hemlock Formation; volcanic agglomerate. Start at 3-way road junction near Mansfield Location. Observe outcrops west of road, northwestward from the junction, and the different lithologies on the mine dump.

Ellipsoidal greenstone just west of junction is in sequence with massive flow greenstone. Some pillows are elongate and may represent a small amount of downdip flowage after emplacement. Some pillows are unusual in having little or no selvage at their margins. Proceed on foot about 1,000 feet northwestward to vicinity of old Mansfield mine shaft. There on mine dump may be seen fragments of volcanic agglomerate as well as various ferruginous rocks--Mansfield Iron-bearing (pyritic) Slate Member, oxidized ferruginous volcanic rock (slate?), and laminated soft iron ore.

Stop 12 (Fig. 7). Volcanic agglomerate (conglomerate). Road north from Mansfield Location. Outcrops west of road, about 2,000 feet north of mine dump at Stop 11.

Mafic agglomeratic greenstone contains round cobbles up to 6 inches in diameter and some angular fragments of laminated mafic volcanic(?) rock. These rocks are on strike with those observed at Stop 11.

Stop 13 (Fig. 7). Fragmental tuffaceous greenstone and massive (flow?) greenstone. Road north from Mansfield Location to vicinity of dam at Michigamme (Hemlock) Falls (Michigamme River). Outcrops approximately 1,000 feet south of dam.



R. 31 W.

Figure 7--Stops 10-14. Mafic metavolcanic rocks, Hemlock Formation and West Kiernan Sill, near Mansfield Location, Lake Mary and Kiernan 7-1/2 minute quadrangle.

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Volcanic layers trend north-northwest and dip steeply westward on southwest flank of Amasa uplift. One layer consists mainly of small angular rock fragments and probable lapilli ($\frac{1}{2}$ inch and less). This layer overlies massive flow(?) greenstone

SECOND DAY

Stop 14 (Fig. 7). Basal part of West Kiernan sill. Road between Mansfield Location and Kiernan.

The West Kiernan sill here trends north and dips steeply west in conformity with the enclosing Hemlock Formation on the far south-west flank of the Amasa uplift. The average composition of the sill is gabbroic but the basal part (east side) of the sill at this stop is ultramafic because of gravity settling of early-formed very large crystals of pyroxene. This settling took place while the magma body was essentially flat-lying as originally emplaced in the Hemlock Formation. During subsequent Penokean folding and metamorphism, the sill and enclosing rocks were steeply tilted, and pyroxene was altered largely to amphibole. In the chlorite metamorphic zone, as here, the amphibole typically is tremolitic or actinolitic. Dense fine-grained greenstone near the east edge of the outcrop represents the chilled border zone at the base of the sill.

Stop 15 (Fig. 8). Metarhyolite, Hemlock Formation. About $\frac{2}{5}$ mile west of road between Kiernan and Lake Ellen.

This stop is at the south end of a belt of metarhyolite, $\frac{1}{2}$ mile or more long and at least several hundred feet thick, located on the southeast flank of the Amasa uplift. Although contacts with other rocks in the Hemlock Formation are not exposed, drill cores of somewhat similar rocks 2 miles to the south, just southeast of Kiernan junction, suggest that metarhyolite is interlayered or interfingering with mafic volcanic rocks. The metarhyolite now is a mixture of fine-grained and medium-grained quartz and sericite. Phenocrysts of blue quartz "float" in a fine-grained groundmass of quartz and sericite. Under the microscope, the "quartz eye" phenocrysts are seen to be bipyramidal and partly resorbed--typical of quartz crystals formed early in the cooling of felsic lava. A common metamorphic feature of this rock (seen with the microscope) is pseudomorphs of original feldspar that are now quartz shot through with tiny flakes of sericite. Note: By wetting the rock you will be better able to see the blue quartz.

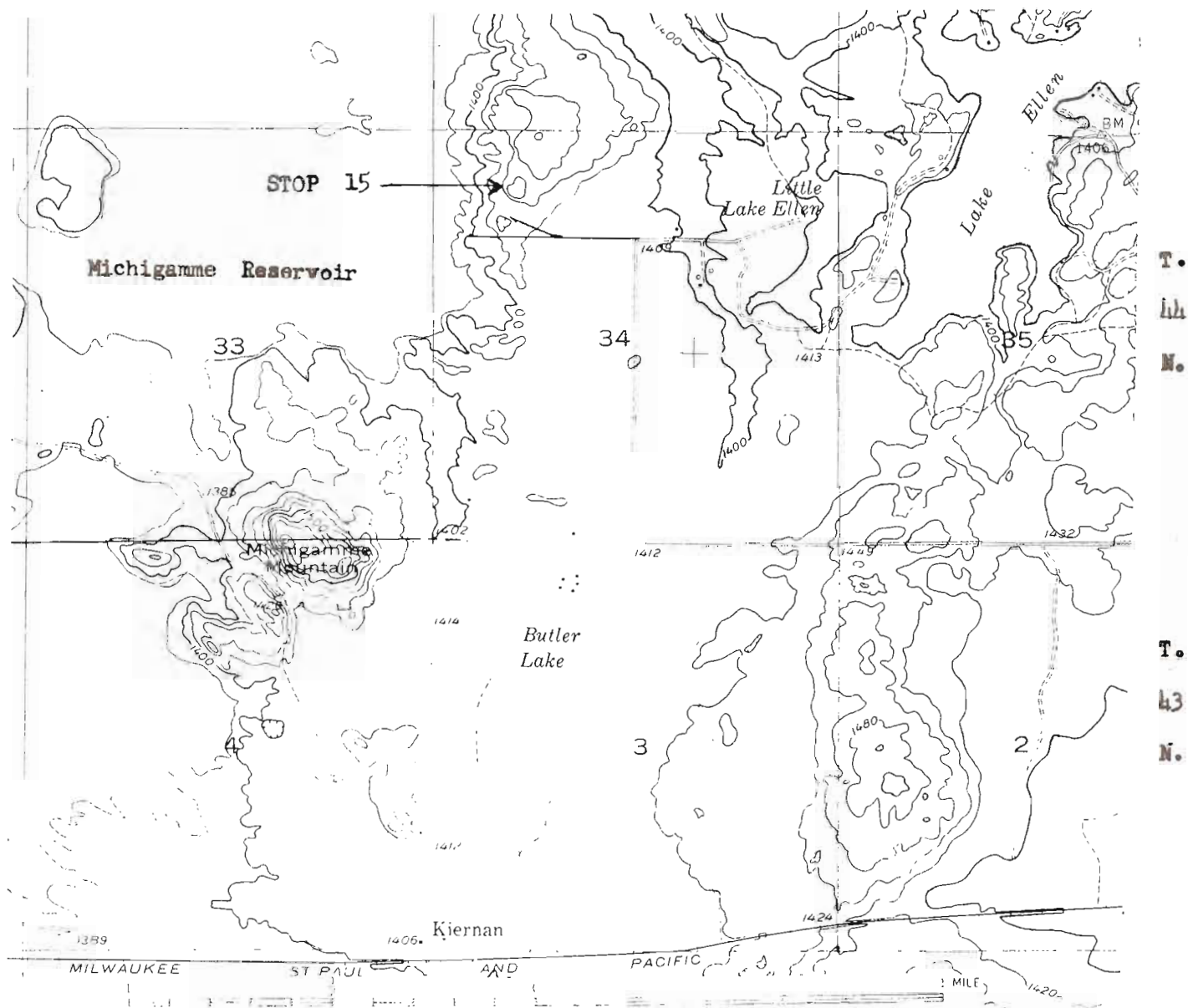
Western part of Marquette district

Stop 16 (Fig. 9). Clarksburg Volcanics Member of Michigamme Formation (Precambrian X)

The Clarksburg Volcanics Member is a relatively local unit preserved only along the south limb of the Marquette trough along a strike length of about 20 miles. The formation is primarily mafic pyroclastic rocks and lesser amounts of intermediate pyroclastic rocks, mafic flow rocks, argillaceous sedimentary rocks, and iron-formation. The presence of lenses of iron-formation throughout the volcanic pile indicates that deposition was submarine. The Clarksburg is about 2,000 feet thick near Stop 16 but is absent at the equivalent stratigraphic horizon on the north limb of the Marquette trough only about 1 mile away (perhaps about 2 miles if the rocks were restored to their pre-folding position). Thus the Clarksburg seems to have formed in this area as a cinder cone having slopes at least 10-15° to the north.

Outcrops at the stop show typical bedded pyroclastic units. Bedding from a few centimeters to a few tens of centimeters thick is expressed principally by variations in grain size, the largest clasts being about 20 cm long. Clasts of mafic rocks are by far the most abundant lithologic type. Argillaceous and cherty sedimentary rock clasts are rare. Pyroclastic units characteristically have a high percentage of calcite replacing the finer grained matrix. During weathering the calcite is destroyed relatively rapidly and, as a result, the rubbly pyroclastic nature of these rocks is very prominently shown, as is well illustrated by the more weathered parts of the exposure north of the railroad tracks. In this area the rocks were metamorphosed to garnet grade. Original mafic minerals were converted to amphibole and biotite; plagioclase, presumably originally of intermediate anorthite composition, was converted to albite and calcite. In spite of relatively intense recrystallization, the original pyroclastic texture is very well preserved, commonly even at microscopic scale.

South of the railroad tracks is a small exposure of iron-formation typical of material that forms numerous lenses throughout the pyroclastic rocks. Lenses are typically a few tens of meters thick and a few tens of meters thick and a few hundreds of meters long. The rocks exposed here are interlayered magnetic biotite-rich argillite and siliceous beds, which, unlike chert beds in most iron-formations, contain abundant fine grained muscovite. The presence of this muscovite and a relatively high Al and Mg content of the iron-rich layers suggests that low levels of clastic sedimentation persisted throughout deposition of the iron-formation.



R. 31 W.

Figure 8--Stop 15. Metarhyolite, Hemlock Formation. Off road between Kiernan junction and Lake Ellen, Kiernan 7-1/2 minute quadrangle.

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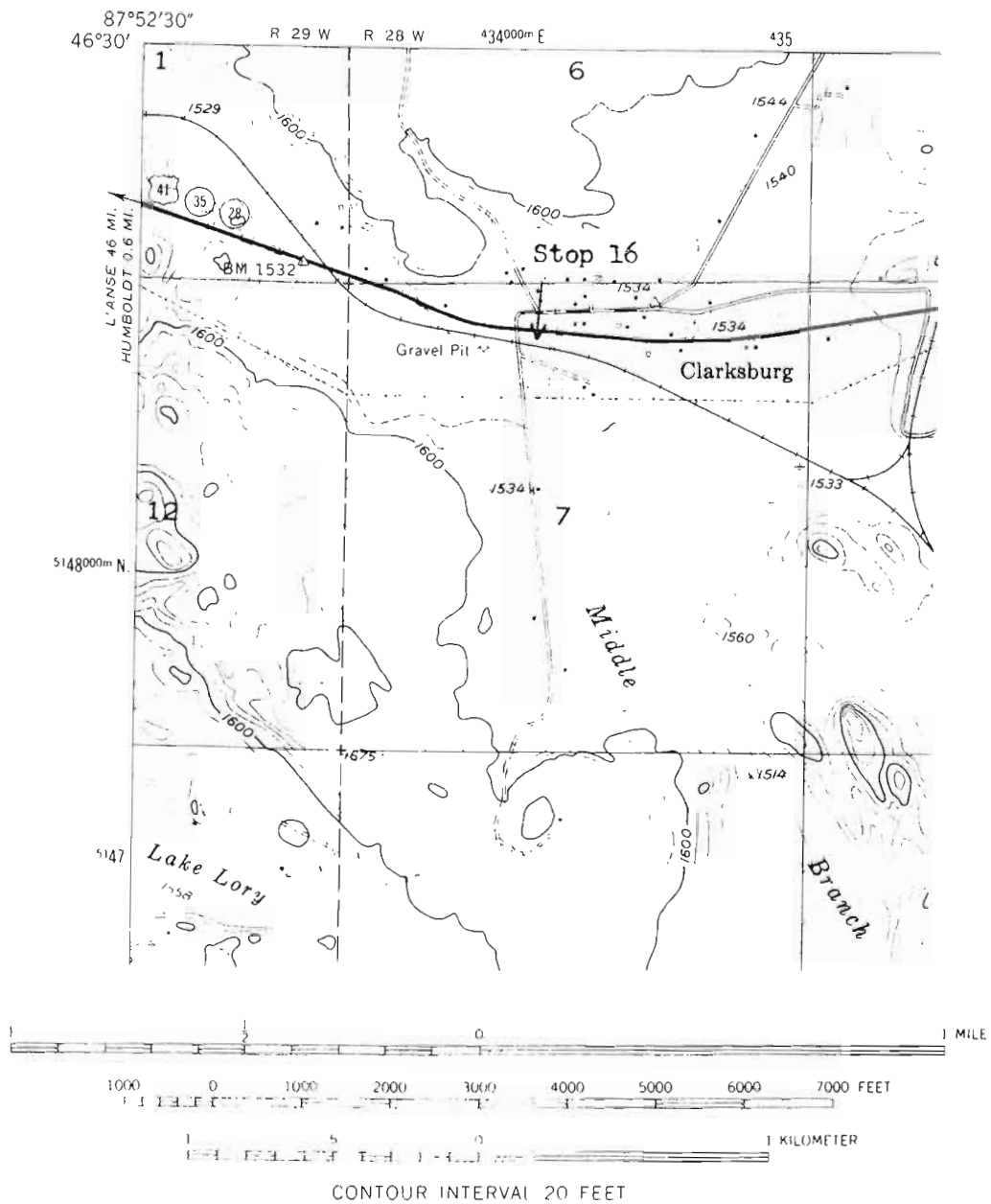
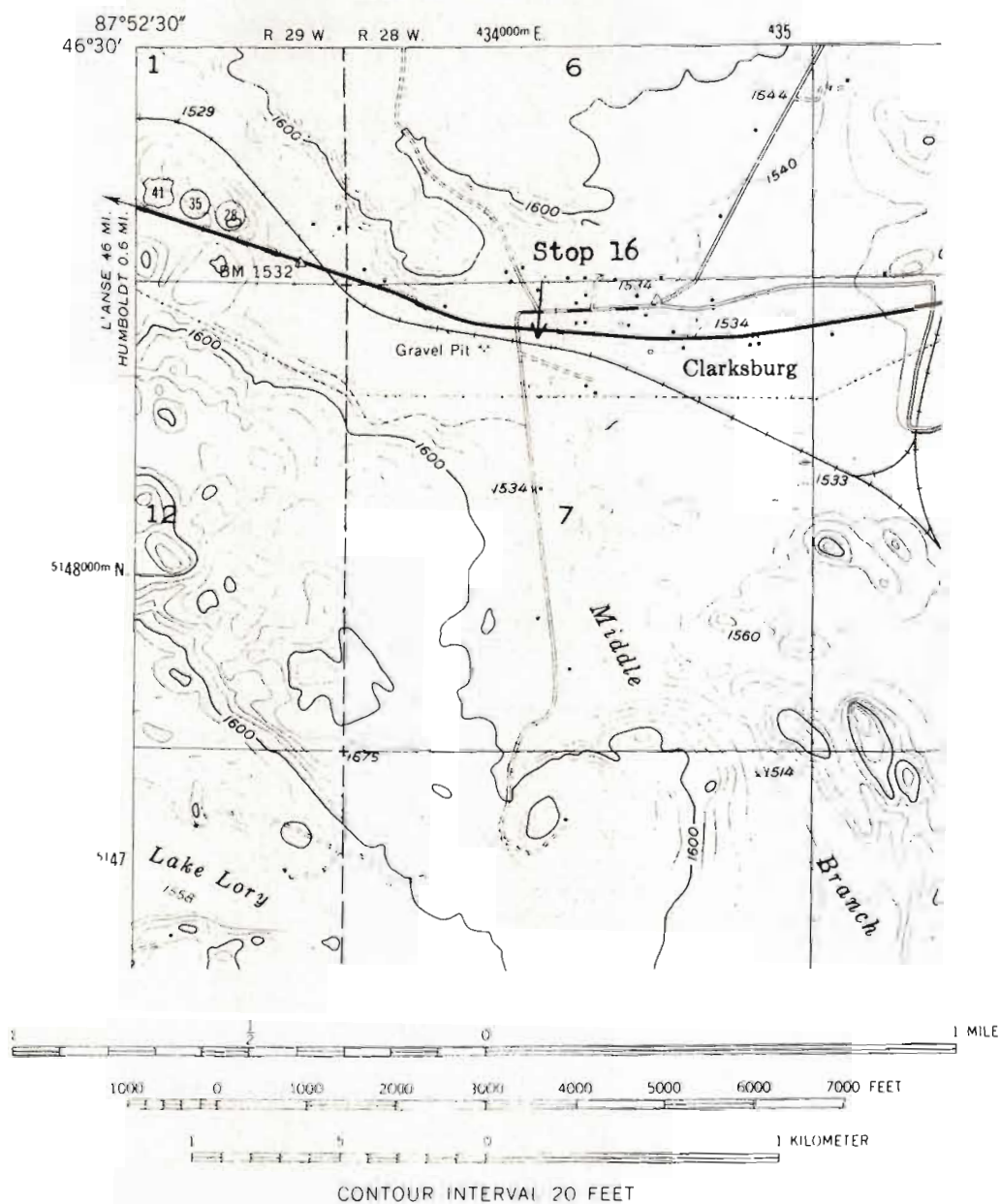


Figure 9--Stop 16. Clarksburg Volcanics Member of Michigamme Formation, western part of Marquette district. Greenwood 7-1/2 minute quadrangle.

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Central part of the Marquette District



north of the road to the mine. About 180,000 tons of ore were mined between 1882 and 1897 which, according to Broderick (1945), contained tetrahedrite, pyrite, chalcopyrite and minor amounts of other sulfides and carried .2 oz. of gold and .9 oz. of silver per ton. In addition, pyritic schist adjacent to the quartz veins (similar to material on dump) contains .13 oz. of gold and .7 oz. of silver per ton. Broderick estimated that there is about eight times as much of the second type of ore (never mined) as of the vein type. The mine workings are 800 feet deep and exploration drilling from the bottom of the workings indicates that mineralized rock extends at least several hundred feet deeper, thus considerable gold reserves remain.

Eastern Part of Marquette District
Mona Schist (Precambrian W)
Stops 19-22 (Figs. 11 and 12)

The Mona Schist forms part of the basement of Precambrian W age in the Marquette district. Basement rocks underlie infolded Precambrian X rocks of the Marquette trough and are exposed in relatively uplifted areas north and south of the trough. The basement rocks are more than 2.6 billion years old and consist of two major types--older metavolcanic rocks and younger intrusive granitic rocks. In general, the volcanic rocks immediately underlie the north side of the Marquette trough in the east half of the Marquette district and form a belt several miles wide. The granitic rocks bound this belt on the north and evidently assimilated parts of the Mona Schist. On the south side of the Marquette trough, the granitic Precambrian W rocks directly underlie Precambrian X rocks of the trough, except at the very east end of the district where a wedge of Precambrian W metavolcanic rock (Mona Schist) intervenes.

The metavolcanic rocks belong to two west-trending formations north of the trough: Mona Schist in the eastern third of the district consists of greenstone, amphibole schist, chloritic schist, and metafelsite; and Kitchi Schist, mainly in the central part of the district, consists largely of agglomeratic and tuffaceous metadacite. The lower part of the Mona trends toward the Kitchi, and the upper part of the Mona passes north of the Kitchi. The two formations are probably separated by faults in most places, if not all places. The Mona Schist is considered here to be part of a large volcanic pile; but, in exposures through a strike distance of about 20 miles, essentially no change in the nature of the rock indicates the configuration or overall dimensions of the pile or the position of the Mona with respect to eruption centers. The deposits, having rather uniform west and west-northwest trends and top directions uniformly to the north, probably all are one flank of a pile that originally had a diameter of at least 50 miles and a thickness of as much as 5 miles. The Kitchi possibly represents deposits close to an eruptive center.

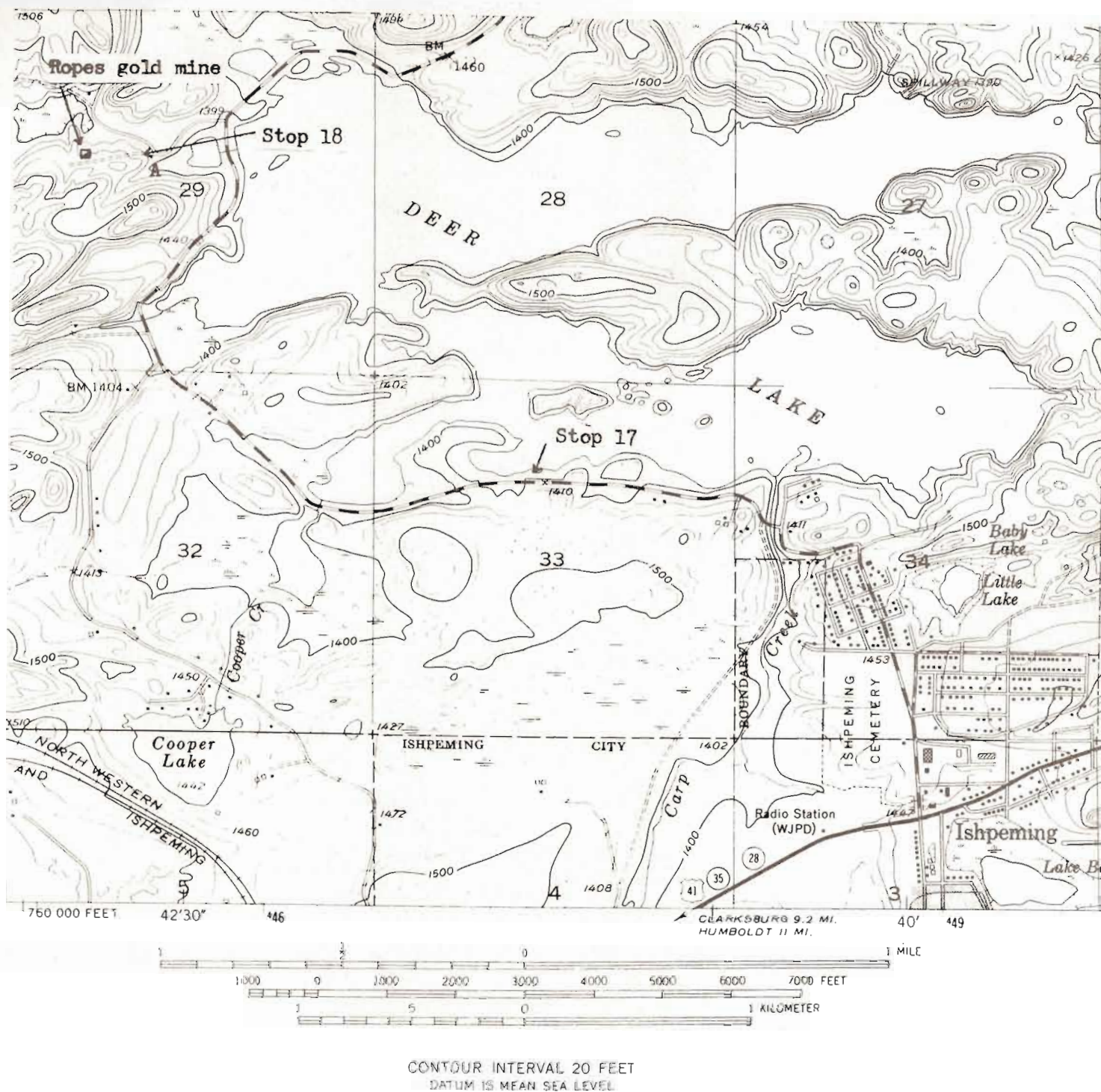


Figure 10--Stops 17-18. Kitchi Schist and serpentinized peridotite (Ropes Gold Mine), central part of Marquette district. Negaunee SW 7-1/2 minute quadrangle.

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Age relations of the Kitchi and Mona are uncertain, however, and quite possibly the two formations are of different ages and formed around different eruptive centers. Kitchi Schist has been seen at Stop 17 and will not be discussed further.

Mona Schist to the north of the Marquette trough consists of two principal units, a lower predominantly massive and ellipsoidal metabasalt and an upper layered amphibole schist and chloritic and sericitic schist and slate, the Lighthouse Point Member. The estimated thickness of the formation in different parts of the area is 13,000 to 25,000 feet. Thin layers of mafic fragmental rocks and of quartz-sericite felsitic slate and porphyritic quartz-feldspar-sericite schist are intercalated in a few places with mafic flow layers in the lower unit. Sericitic schist and slate of the Lighthouse Point Member is interpreted as metamorphosed felsic tuff or coarser pyroclastic rock and the layered amphibole schist of the Lighthouse Point Member as metamorphosed layers of mafic tuff. The Lighthouse Point Member is about 5,000 to 9,000 feet thick. Some light-colored sericite-quartz-feldspar rock having definite volcanic fragmental textures occurs within the belt of chloritic and sericitic schist and slate but is not accessible for the field trip (the best exposures were victims of a shopping center). Stratigraphic tops identified by pillow structures in the lower unit persistently face to the north. Thus, the indicated sequence of volcanic deposition was first mafic flows interspersed with a few brief felsic ash falls and felsic and mafic pyroclastic deposits, followed by alternate felsic and mafic ash falls (sericitic and chloritic schist and slate of the lower Lighthouse Point Member), followed by layers of mafic tuff.

Penokean metamorphism, the last to affect rocks in the area, was at the level of the chlorite zone (lower greenschist facies) in the eastern part of the Marquette district. However, the north half or so of the Mona Schist--that is, the amphibole schist of the Lighthouse Point Member--is in the biotite zone (epidote-amphibolite facies). Metadiabase dikes that cut the amphibole schist are metamorphosed in the chlorite zone reflecting Penokean metamorphism, so the higher metamorphic grade of the amphibole schist is believed to have been established before the dikes were emplaced and before Penokean metamorphism, probably during intrusion of the granite to the north during Precambrian W time.

Small amounts of pyrite, generally well under 1 percent, are present in the Mona greenstone, scattered through the rock in small grains. In a few places thin veins of quartz-carbonate may contain a fraction of a percent of pyrite or chalcopyrite. No significant amount of sulfide mineralization, however, has been found in the Mona Schist in the course of the detailed outcrop-by-outcrop mapping of the Marquette and Negaunee 7½-minute quadrangles in which much of the formation occurs. Reports by Gair and Thaden (1968) and Puffett (1974) contain geologic maps and detailed descriptions of these rocks.

Stop 19 (Fig. 11). Ellipsoidal and massive flow greenstone, lower part of Mona Schist. North of Marquette County Road 492, about $3\frac{1}{2}$ miles SW of city of Marquette. Marquette $7\frac{1}{2}$ -minute quadrangle (see map on next page).

Examine glaciated exposure of ellipsoidal (pillow) greenstone beneath powerline; bedding trends east-west and dips steeply north. This outcrop contains the largest single pillow observed in the Mona Schist; it is about 11 feet in length in the outcrop (diameter?). The pillows commonly have a chilled fine-grained shell and in places the margins are amygdular. Zones of ellipsoidal greenstone in the lower part of the Mona Schist are generally less than 100 feet thick and appear to be lenticular and discontinuous. Ellipsoidal structures such as these are considered to be evidence of submarine extrusion. Adjacent massive flow rock may have been shielded from contact with seawater by a shell of the ellipsoidal rock. Note the northward direction of stratigraphic tops indicated by the convex tops of pillows and the pillow "roots" directed stratigraphically downward. Proceed SW along power line back to County Road 492, passing outcrops of massive flow greenstone. These exposures are typical of those in the lower half of the Mona Schist.

Stop 20 (Fig. 11). (optional). Contact between Mona Schist (Precambrian W) and Enchantment Lake Formation (Precambrian X). Road east from Marquette County Road 492 to Enchantment Lake, $1/8$ mile north of lake. Marquette $7\frac{1}{2}$ -minute quadrangle.

Mona Schist to the north is in nearly vertical contact with conglomerate of the Enchantment Lake Formation to the south. The Mona Schist dips steeply north whereas the Enchantment Lake Formation dips vertically to steeply south. Mona Schist is sheared within about 50 feet of the contact; north of the zone of shearing the Mona is massive flow greenstone. The stratigraphic top of the Mona is to the north, as indicated by pillow structures, the nearest of which is about 3,000 feet west of this stop. The stratigraphic top of the Enchantment Lake Formation, on the other hand, is to the south. Thus, the Precambrian X and W rocks are structurally back-to-back (or bottom-to-bottom). It is possible that the Mona Schist was completely upside down at the time the Enchantment Lake Formation was deposited on it, and was then rotated to its present steeply dipping position during folding of the Precambrian X rocks. However, the geometry involved in tilting or rotating the 3 mile-thick section of Mona Schist is simpler if it is assumed that the Mona had been tilted to about its present attitude before deposition of the Precambrian X rocks and then was moved vertically as a unit during subsequent deformation of the Precambrian X rocks. Accordingly, the present contact between the Mona Schist and the Enchantment Lake Formation would have formed essentially by shearing.

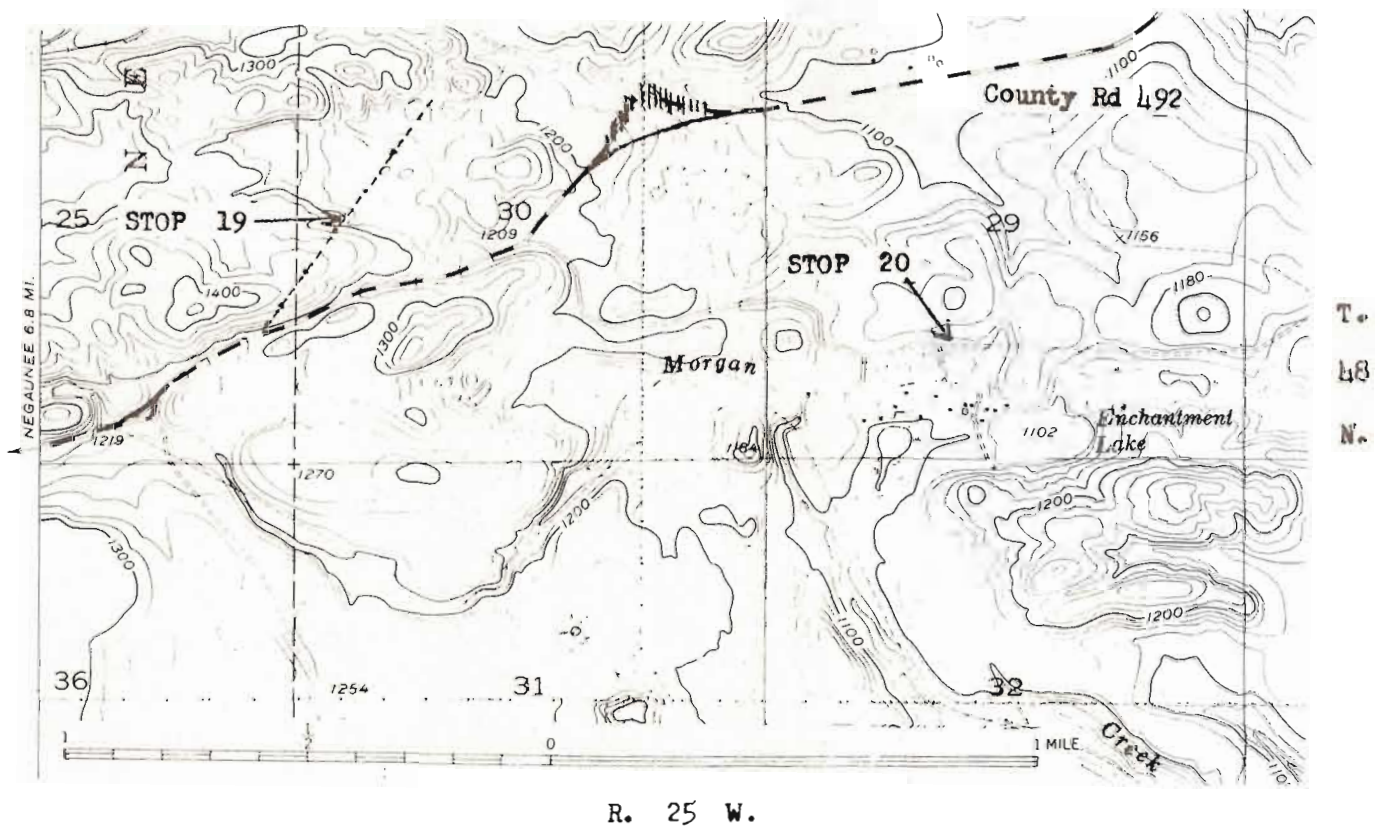


Figure 11--Stops 19-20. Lower Part of Mona Schist, 3-4 miles southwest of city of Marquette, Marquette 7-1/2 minute quadrangle.

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Stop 21 (Fig. 12). Chloritic and sericitic slate (phyllitic rock), Lighthouse Point Member of Mona Schist. Western part of city of Marquette (Trowbridge Park), north of U.S. Hwy. 41 (see map on next page).

The chloritic and sericitic rock forms a knob on which is located a large storage tank for the Marquette water supply. The dark and light phyllitic rocks are closely interlayered in places and are in the belt of schist and slate forming the lower part of the Lighthouse Point Member of the Mona Schist. The rocks trend west and dip vertically or steeply north. The foliation is accordant or nearly so, with layering in the overlying amphibole schist. The thickness of this lower unit of the Lighthouse Point Member changes greatly from about 300 feet at the east end of the belt at Lake Superior to 2,800 feet 5 to 6 miles to the west. The light-colored phyllitic rock probably was derived from fine-grained felsic volcanic ash, an interpretation based on the association in this same belt of flinty quartz-sericite rock having the chemical composition of rhyolite and felsic pyroclastic rock (latter rock not shown on field trip). The texturally similar but dark-colored chloritic phyllite was probably fine-grained pyroclastic rock of mafic composition.

Stop 22 (Fig. 12). Chloritic slate and schist; layered amphibole schist, Lighthouse Point Member of Mona Schist; mafic and felsic intrusive rocks. Lighthouse Point, east edge of city of Marquette.

Starting near the end of the breakwater, proceed north and stratigraphically upward from fissile chloritic rock into the layered amphibole schist. The rocks of the Lighthouse Point Member here strike west and dip steeply north. The fissile chloritic rock is representative of the belt of slate and schist forming the lower part of the Lighthouse Point Member. Here at the east end of the belt the lower unit of the Lighthouse Point Member is about 300 feet thick at most. The layered amphibole schist is characterized by compositional banding and a strong schistosity parallel to layers. Layers typically are in the form of tabular lenses, 1-3 inches thick and 10-30 feet long. They are believed to have formed as beds of mafic tuff and to have been modified subsequent to deposition by shearing, boudinage, metamorphic recrystallization, and possibly by a small amount of metamorphic differentiation. The thickness of the amphibole schist ranges from about 4,500 to 6,500 feet. Chemically the rock is equivalent to basalt. Typical mineral assemblages in the amphibole schist consist of blue-green hornblende and oligoclase-andesine. The increase in metamorphic grade of the Mona Schist from lower greenschist facies (chlorite zone) a mile or less to the south to epidote amphibolite facies here is attributed to the intrusion of granite exposed 1 to 2 miles to the north.

Diabase of Precambrian Y age, metafelsite of probable Precambrian W age (possibly offshoots of granite to the north), and metadiabase of Precambrian X or late Precambrian W age intrude the metavolcanic rocks on Lighthouse Point.

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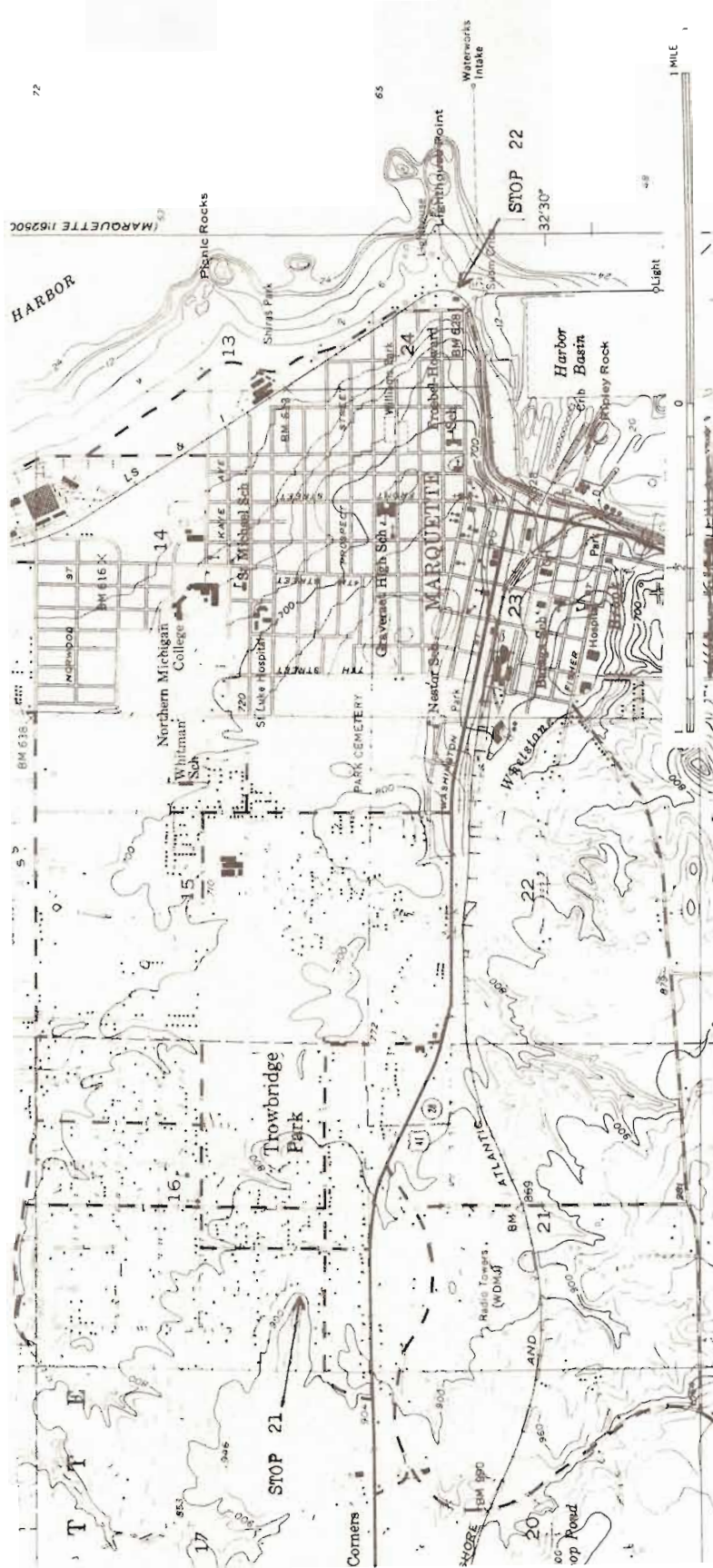


Figure 12--Stops 21-22. Lighthouse Point Member of Mona Schist, City of Marquette.

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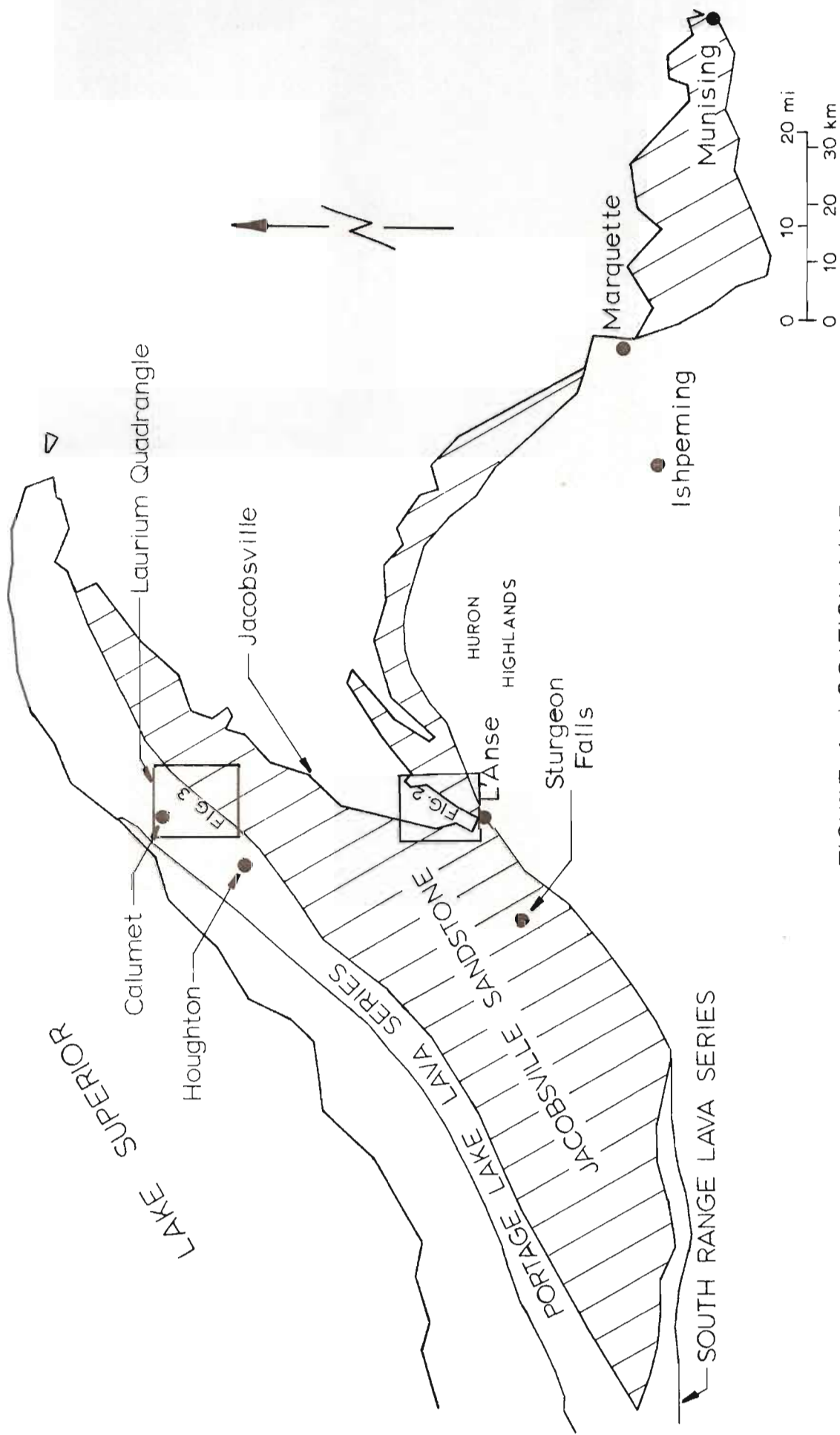


FIGURE 1. LOCATION MAP

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The Jacobsville Sandstone: Evidence
for a Lower-Middle Keweenaw Age

By

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Institute of Mineral Research
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Houghton, Michigan

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INTRODUCTION

The report and incorporated field trip logs which follow are based upon a four year study of the Jacobsville sandstone (JS). This investigation has been supported by state funds provided to the Institute of Mineral Research, Michigan Technological University. The twofold objective of this study is to (1) develop criteria which serve to distinguish between different strata, or series of strata, within the JS and (2) develop an in-depth data source which can be employed in the evaluation of potential mineral deposits within or underlying the JS.

Sedimentological methods were developed during the course of these investigations for the purpose of determining the depositional environment of the first cycle sediments comprising the JS. These methods, based primarily upon statistical grain size analysis, are believed to be generally applicable to red bed sequences of many ages. Results of grain size analysis, which supplement the following field descriptions and interpretations, will be published later.

This presentation consists of three essential parts: (1) a photo essay preceding the (2) field trip, and (3) an updated, more detailed version of a paper presented by the writer at the 20th Annual Institute on Lake Superior Geology (Babcock, 1974). An environmental model for the JS in the Keweenaw Bay/Peninsula region is presented.

The distribution and regional setting of Jacobsville exposures precludes easy access, observation, and field interpretation for the following reasons: (1) the area underlain by these red beds is very large (2) outcrops are few, widely scattered, and mostly two dimensional, and (3) most areas of high percentage exposure are within partly cliff-walled, steep-sided ravines or cliffs bordering Lake Superior which are virtually inaccessible. In the later two cases, gross horizontal and/or vertical control is restricted to such a degree that field relationships are obscure. Exceptions exist near Point Isabel, on the Keweenaw Peninsula, and on the tip of the Huron Peninsula, at Point Abbaye (Figure 1). At these two locations, continuous pavement exposures may be traversed for over a kilometer along the Superior shoreline.

A 45 colored slide photo essay was shown before the field trip. This supplementary presentation should facilitate interpretation of the six outcrop areas visited by providing (1) a regional frame of reference wherein the two outcrop groups can be placed and (2) a greater degree of visual continuity than has been heretofore available. It is hoped that problems of the latter type can be alleviated somewhat in the above manner. In this context, Hamblin (1958, p. 10) stated that more recent disagreements concerning the age of the JS have resulted "...because the authors were unable to examine enough outcrops to establish a regional picture for the problem." A loan copy of this presentation cross-referenced to this text, complete with brief descriptions and photographs, has been placed on file at the Institute of Mineral Research.

The writer hopes that the study results which follow will provide impetus for further studies concerning the Jacobsville and supplement the findings of Hamblin (1958).

GENERAL GEOLOGY AND REGIONAL SETTING

The Jacobsville sandstone is an excellent example of a red bed sequence. This sequence is one of the thickest and most extensive sedimentary units in the Michigan Upper Peninsula. Descriptions which follow are confined to the 3900 km² area of major interest west of the Marquette/Baraga county line. The type section at Jacobsville (Figure 1) was the site of active dimension stone quarries just before turn of the century.

Mesa-valley terrain best describes the geomorphological characteristics of the JS in the study region. Deep valleys, more or less filled with glacial drift, separate mesas capped by relatively resistant, flat-lying sandstones. Mesa-valley terrain is well-developed immediately northwest of Dillman Park (Stop 3) and southeast of the Laurium quadrangle (Figures 1, 2, and 3).

Based upon proprietary information, the Jacobsville sequence is comprised of upper, middle, and lower members in much the same manner as the Bayfield sequence and the Freda sandstone; i.e., the lower member is thicker and more immature, sedimentologically, than the upper member and the thin middle member is more mature than either the upper or the lower member. Exposures in the study region represent portions of the upper-most horizons of the upper member of the J.S. However, possible exceptions exist on the western and northern flanks of the Huron Highlands (Figure 1).

PREVIOUS WORK

Hamblin completed a regional investigation of the Jacobsville sandstone for the PhD degree which was subsequently published as a bulletin by the Michigan Geological Survey (Hamblin, 1958). Results of heavy mineral studies and sedimentological properties of the JS in the Keweenaw Bay area were completed by Denning (1949) and Tolunay (1970), respectively. Geophysical investigations in the study region include Bacon (1960, 1964, 1966), Bacon and others (1968), and Aho (1971).

The age of the Jacobsville sandstone of Lane and Seaman (1907) has been a controversial subject for over 150 years. During the period 1821 to 1916, this red bed sequence was ascribed ages ranging from Middle Cambrian to Triassic. Most correlations have been based primarily upon striking similarities exhibited by many red bed sequences, regardless of geological age. Hamblin (1958) concluded that the JS was Lower and/or Middle Cambrian. More recently, the Jacobsville has been ascribed an Upper Keweenawan age based, in part, on some similarities to the Bayfield sandstones of Northern Wisconsin.

Wadsworth (1884) presented field evidence which showed that the uppermost beds of the Jacobsville and lowermost flows of the Portage Lake Lava Series (PLLS) were interbedded. Trenching operations below Douglass Houghton Falls in the Hammell Creek Section, shown in Figure 3, revealed that the lowermost trap of the PLLS was a melaphyre two feet thick dipping 20°NW which was underlain and overlain conformably by sandstone beds. This evidence was disputed, sight unseen, by other geologists, and finally discounted altogether.

Wadsworth noted there were two schools of thought about the age of the Jacobsville--one claiming that the sandstone was the same relative age as the Portage Lake Lavas; the other, younger. However, Wadsworth and his contemporaries agreed that the Jacobsville was of Potsdam (Middle Cambrian) age or younger. In my opinion, his evidence was discounted because if the lavas actually overlay the sandstone, the entire lava series and overlying Upper Keweenawan sediments would have to be Paleozoic or younger in age. Wadsworth lamented (Whitney and Wadsworth, 1884, p. 485):

"It is a remarkable circumstance that, while this evidence is so clear and explicit, the more recent writers have avoided any mention of it, but have endeavored to discuss the subject on theoretical grounds chiefly."

What is even more remarkable is that this statement is still applicable. I have not found any evidence to indicate that Wadsworth's observations have ever been field checked.

Hal Hubbard presented evidence here at the Institute in 1967 and 1968 which indicated that the South Range Lava Series (SRLS) differs lithologically, magnetically, and in areal distribution from the Portage Lake Lava Series (Figure 1). Furthermore, he noted that in the Ironwood area near the left side of Figure 1, the older SRLS is stratigraphically separated from the younger PLLS by more than 7000 ft. of sedimentary rocks. Hubbard believed that these sediments represent the Jacobsville sequence and stated (1968, p. 35):

"The Jacobsville sandstone is unconformable on the lower member of the South Range Traps east of Lake Gogebic and at Sturgeon Falls, Michigan. This unconformity has been used by nearly all writers to demonstrate that the Jacobsville sandstone is younger than the Portage Lake Lava Series."

In the Sturgeon Falls area (Figure 1), massive facies sandstones of the Jacobsville sequence overlie basalts of the South Range Lava Series. These flat-lying predominantly lacustrine sands are separated from the underlying basalts, which dip about 10°NW, by a pronounced erosional unconformity (Hamblin, 1958). Results of the present investigation indicate that these sandstones comprise a portion of the uppermost stratigraphic horizons of the Jacobsville. It therefore seems evident that most of the strata comprising both the South Range Lava Series and Jacobsville sequence must be considered erosional and/or non-depositional in the Sturgeon Falls area. Furthermore, as noted by Hubbard (1968), relationships between the sediments and volcanics in this area have absolutely no bearing on the relative age relationships between the JS and the PLLS.

Results of my investigations are in accord with the findings of Wadsworth (1884) and Hubbard (1967, 1968). Quite frankly, I feel the evidence presented herein cannot be conveniently discounted by the geological dogma which has heretofore prevented rational discussion and re-evaluation of PLLS-JS structural and stratigraphic relationships.

FIELD TRIP LOGS

The first group of JS exposures to be viewed are located in the L'Anse area of the Keweenaw Bay 15' quadrangle map (Figure 2). From south to north, exposures at the first three stops comprise portions of a lateral sequence/facies change from the fluvial, through the deltaic, and into the lacustrine depositional environment. Table 1 summarizes basic facies parameters in terms of sediment type, depositional environment, and facies equivalent of Hamblin (1958) and Allen (1970). From oldest to youngest stratigraphically and laterally from near-to far-source, Allen's basic red bed cyclothem consists of: conglomerate (A), sandstones (B_1) cross-bedded (B_2) flat-bedded (B_3) cross-laminated, alternating beds (C), and siltstones (D).

The following brief description of JS exposures in the Keweenaw Bay region is presented in order that the first group of outcrops may be placed into a regional framework. Colored slides of most of these exposures were shown during the photo essay preceding this field trip.

Approaching the Figure 2 map area from the northeast, commencing at the Marquette/Baraga county line, the JS consists primarily of near-source, B_1 facies, lenticular sandstones. About 2 km west of the mouth of the Huron River, a large channel structure, over 300 m wide, unconformably overlies similar JS fluvial sandstones. Along the coast, west of this channel in section 11, T.52N., R.30W., an adit was driven at lake level along a copper-bearing vein. At Point Abbaye, on the tip of the Huron Peninsula, large trough cross-bedded B_1 sandstones contain barite zones, concretions, and fracture fillings (Babcock, 1969). About 1.4 km west of the tip, at Ruona's camp, B_1 facies sandstones unconformably overly D facies siltstones. A similar sequence, with up to 35° of angular unconformity, is present in the northwest-facing coastal cliffs at Pequaming (Figure 2).

The L'Anse Red Rocks, Stop 1 on Figure 2, is a large channel structure lying unconformably upon Upper Huronian slates. On the west side of Keweenaw Bay, C facies alternating beds comprise sections at Stops 2 and 3. These beds, which dip gently and become finer-grained northward, exhibit north to northwest sediment transport directions. Sediment transport directions are locally fault-block controlled.

Massive, B_2 facies, flat-bedded sandstones comprise the Dillman Park section north of Stop 3, the type section at Jacobsville, and all but the northernmost exposures along the western shore of Keweenaw Bay on the east side of the Keweenaw Peninsula. Traverse Island is comprised of alternating beds, $C = B_1 + B_2 + D$. Uppermost B_1 facies beds exposed here consist of gently folded, very competent quartzites. On the southeast side of the island, chrome mica (fuchsite) was found along a bleached fracture zone. A similar alternating bed sequence is present near the mouth of the Tobacco River north of Gay. Northeast of Gay, at Bruneau Park, B_2 facies, well-sorted fine sandstone unconformably

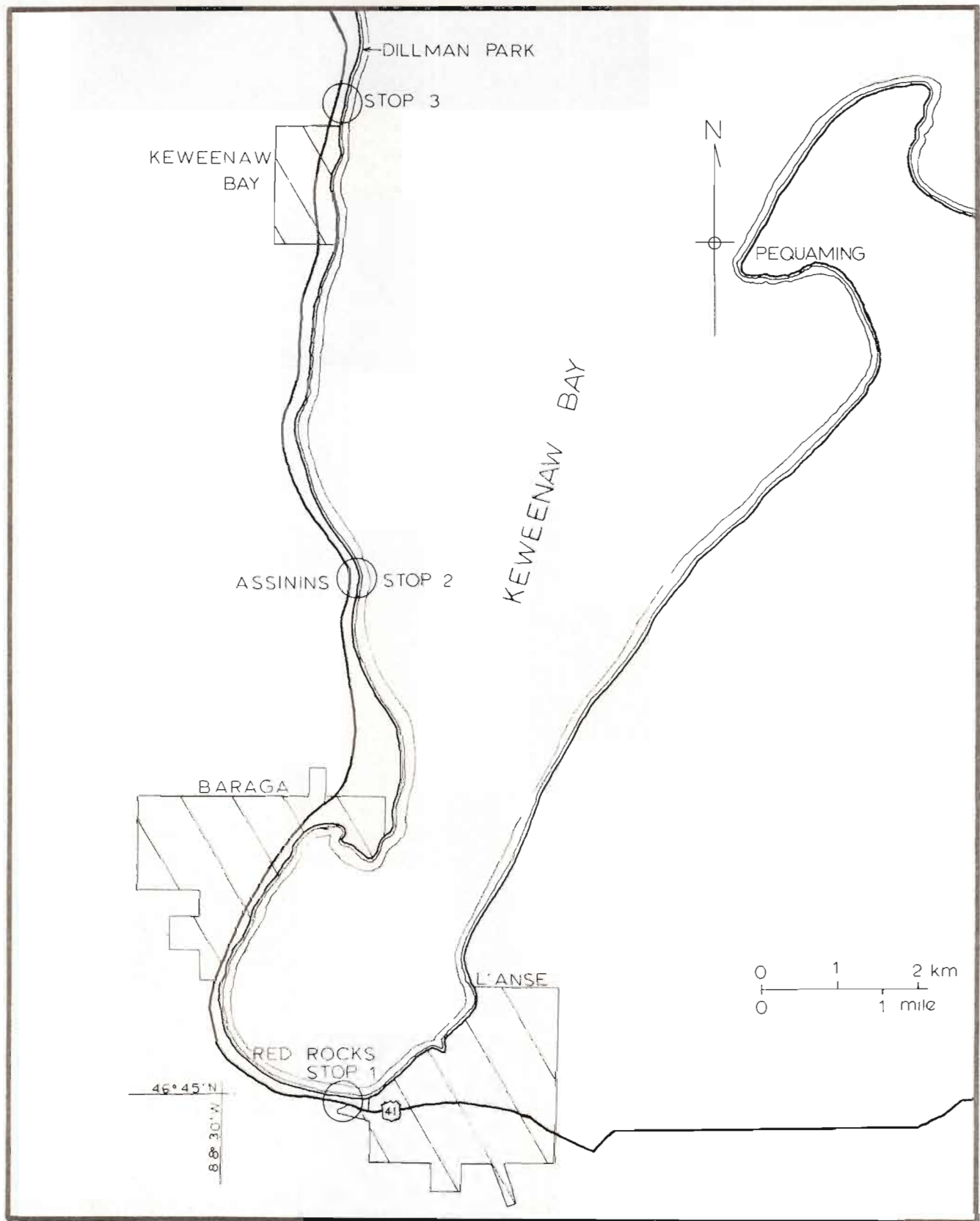


FIGURE 2 L'ANSE, MICHIGAN, AREA

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TABLE 1. SEDIMENTARY PARAMETERS OF JACOBSTOWN RED BED SEQUENCE EXPOSURES
ALONG THE SOUTHERN AND WESTERN SHORE OF KEWEENAW BAY, MICHIGAN

Location/Stop	Depositional Environment	Sediment Type	Facies Equivalents	
			Allen (1970)	Hamblin (1958)
L'Anse Red Rocks/1	Fluvial: main channel	Sand Gravel	B ₁ A	Lenticular sandstone Conglomerate
Assinins/2	Fluvial - deltaic	Sand	C(=B ₁ +B ₂ +D)	-
Village of Keweenaw Bay/3	Deltaic - lacustrine	Sand	C(=B ₂ +D)	-
Dillman Park Jacobsville	Lacustrine	Silty Sands	B ₂	Massive sandstone

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overlies D facies siltstone. Between Bruneau Park and Point Isabel, B₁ facies sandstones unconformably overlie B₂ facies sandstones of the "Old Marble Cake" (OMC) disturbed bedding horizon at or within a few meters above and below lake level (602 feet). The OMC marker horizon occurs at an elevation of 815 feet in the Pilgrim River (Chassell quadrangle, near the center of Sec. 26, T.54N., R.34W.) and on Gooseneck Creek (Laurium quadrangle, section 28, T.55N., R.33W.).

B₃ facies sandstones, which comprise about 43% of the Upper Keweenaw Freda sandstones (Hamblin, 1961), are rare in the exposed and subsurface JS. A few minor occurrences of B₃ facies units, interbedded with B₂ facies lacustrine sandstones, are noted in the cliffs along the western shore of Keweenaw Bay between Jacobsville and Gay.

Stop 1: L'Anse Red Rocks

The L'Anse Red Rocks are located in Section 7, T.50N., R.34W., about 2 km southwest of L'Anse (Figure 2). Here, a thick section (12 m±) of Jacobsville sands and gravels were deposited in a fluvial channel which unconformably overlies the Michigamme slate. These sandstones are essentially flat-lying, arkosic, medium-grained, variably bleached, and exhibit cross- and disturbed bedding. Authigenic biotite and muscovite, on bedding plane partings, and kaolinitic cement characterize these sandstones. According to Hamblin (1958), the sediment transport direction here is about N 60°±15° W. A conglomerate of variable thickness (0.1 to 1.1 m) lies just above the basal contact and at least four thin pebble horizons are exposed in the cliff on the south side of the highway. The matrix of these conglomeratic horizons is best described as a granite wash.

The basal contact is about one meter above mean lake level. Murray (1955) describes grooving and other features on the Michigamme surface here as of possible glacial origin.

Over 350 pebbles and cobbles derived from conglomeratic horizons in this exposure were classified by lithic type and measured. The observed maximum clast size is 17 cm (large cobble). Most rock types present are similar to those exposed a maximum distance of 25 km away towards the south and east. In order of decreasing abundance, pebble lithologies are vein quartz, quartzite, iron-formation and chert, Michigamme slate, pyllite, and argillite, and hornblende schist. Five distinct types of quartzite are present. One variety, a coarse-grained yellow-grey quartzite, contains discoidal plates and elongated blades and chips of Michigamme slate. This quartzite, of post-Huronian/pre-Jacobsville age, is not known in outcrop. Many of the chert pebbles present in this and other sections bordering Keweenaw Bay exhibit a thin tan-yellow iron oxide coating which appears to have been partially removed by abrasion during transport. This coating is believed to represent a peri-glacial desert varnish. The existence of this coating could be construed as strong evidence supporting a glacio-fluvial origin of the Jacobsville as proposed by Murray (1955).

Disturbed bedding structures of the type exposed here are identical to those of tectonic origin described by Allen and Banks (1972) and Jones (1965). Well-developed diapiric injection structures and disturbed bedding are present at several locations around Keweenaw Bay and near

the contact zone between the JS and PLLS in the Laurium quadrangle. Disturbed bedding identical to that exposed here will be seen later in the lower conglomerate section at Dover Creek (Stop 4, Figure 4). Several slides of these features were shown in the photo essay preceding this trip. The most pronounced of these features are stratigraphically limited to a zone immediately above and/or below a marked unconformity within the uppermost Jacobsville. These structures and the associated unconformity constitute an important time (marker) horizon. Both are believed to be manifestations of a period of regional block faulting.

A normal fault is present near the west end of the cliff, on the south side of the road, west of a culvert. This zone strikes about N15-20°W, dips about 55° WSW, and exhibits a minimum estimated vertical displacement of 3 to 4 m. Note that pebble beds on the east side are absent on the west (downthrown) side of the fault. Hamblin (1958) describes 13 minor normal faults of the major set (N15-20°E) in the Keweenaw Bay region which have an average displacement of about 3 m. The downthrown side of these faults, and those of the N70°W set are invariably on the Keweenaw Bay/ Lowlands side. The fault zone here is variably bleached and contains, in places, a thin (2 cm) veinlet of calcite and minor kaolinite. The red-fluorescence of this calcite is attributable to a minor manganese content. Here, as at Pequaming and east of Skanee, minor copper mineralization is noted along the fault zone. Veins and veinlets in these sets also cut the Copper Harbor conglomerate, Nonesuch shale, and Freda sandstone on the west side of the Keweenaw Peninsula and exhibit the same association between red-fluorescent calcite and copper mineralization.

Stop 2: Assinins/Tribal Center

The Assinins section is located in section 15, T.51N., R.33W. (Figure 2). The upper portion of this section is exposed above the railroad grade; the lower part, on the beach. In order to conserve time, we will be viewing only the beach exposures. The beach section is approximately 90 m long, 5 m thick, consists of at least 10 distinct beds, and is best described as a somewhat complex, though monotonous, alternating bed sequence of white medium-grained sandstones and red to maroon silty sandstones and siltstones. Grain size distributions of the former orthoquartzitic beds are typically fluvial-deltaic; the latter unbleached beds, deltaic and/or (mixed) lacustrine. At least one bed of flat-bedded, B₂ facies, lacustrine sandstone is present.

Contrary to first impressions, the bleached fluvial-deltaic orthoquartzitic (FDOQ) sands constitute interbeds within the red to maroon deltaic silty sands and silts (DSST) comprising the lowermost portion of the beach exposures. However, the reverse appears true in the upper part of this section. In the beach exposures, lowermost FDOQ beds either lens out completely or exhibit a facies change into the more poorly-sorted DSST beds. Some FDOQ beds are noted to gently sag into underlying DSST beds.

Beds in the Assinis section dip 3° to 8° N (avg. 5° N). With the exception of a few FDOQ beds in the lowermost part, most beds and, hence, the entire section also thicken to the north. Sediment transport directions are N20-30°W.

Most FDOQ beds average about one meter thick. Both FDOQ and DSST type beds exhibit an increasing mean grain size upsection, i.e., they coarsen upward. This factor, and the relative increase in volume of FDOQ beds and concomitant decrease in volume of DSST beds toward the top suggest that this section is part of a prograding deltaic sequence. This progradation may be attributable to uplift in the source area (towards the present south-southeast) and/or subsidence (towards the present north-northwest) further "offshore". We will be viewing a predominantly lacustrine section at Stop 3, about 3.5 km north of this section.

FDOQ beds exhibit kaolinite cement in the uppermost 5-10 cm, authigenic quartz overgrowths, low angle cross-bedding, and occasional "floating" quartz pebbles 1-4 cm in size. The upper surface of some FDOQ beds exhibit shale pebbles and/or shale pebble casts pressed into a thin slip of mud and/or a rippled dune-bed configuration of shallow water origin. This latter feature is well developed on the top of the large block under the white pines.

The widely to thinly laminated DSST beds exhibit small bleached spots and authigenic muscovite and/or biotite on bedding plane partings.

Denning (1949) notes the existence of a fault at the north end of these exposures, near the south boundary of the cemetery.

Stop 3: Village of Keweenaw Bay

At this stop, located near the center of section 34, T.52N., R.33W., we will examine a low coastal ledge. Time and safety considerations preclude visiting the main exposures which comprise the cliff below Grover C. Dillman Park, about 0.5 km north of here (Figure 2). Colored slides of the massive bedded, B_2 facies, lacustrine sandstones comprising the large cliff were shown before the field trip. The section to be viewed dips under the main cliff exposures and, as at the previous stop, is an alternating bed sequence which dips about 5° N and thickens to the north.

These exposures consist of a DSST-type bed, up to 1.5 m thick, overlain by and incorporating FDOQ-type interbeds. One such interbed, best described as a "shoestring sand" is wholly enclosed within the DSST unit. This interbed has a due northwest-trending major axis and rapidly pinches out northeast and southwest. From all appearances, sands comprising this bed were literally flushed out of a narrow channel into off-delta waters. This completely bleached FDOQ-type interbed served as the loci for bleaching of the enclosing DSST-type bed. Note the bleached rim around this sandstone. As such, this bed constitutes an excellent example of iron-removal bleaching by solutions which locally, passed through relatively well-sorted more permeable beds.

Ripple marks on top of this FDOQ-type bed dip 21° NE, perpendicular to the main sediment wedge axis, and indicate that extensive slumping took place soon after deposition. These slightly asymmetric oscillation ripple marks exhibit a spacing of about 8.0 cm and an amplitude of about 1.0 cm. Although this spacing is greater and amplitude less than those reported by Hamblin (1958) as characterizing B₂ sandstones of the western shore of Keweenaw Bay, environmental criteria calculated using the equations of Tanner (1971) yield identical results. At confidence levels between 70 and 86%, these ripple marks were generated in about 1.2 m of water, with a wave height of about 20 cm, and a fetch of about 236 km. The wind direction was from the (present) northwest; nearly opposite the (present) sediment transport direction. Tanner (1971) notes that a ripple mark spacing of 4-5 cm separates, with fairly good reliability, small lakes and ponds from large lakes and seas.

The highest density of well-exposed JS' sections in the region is located in the Laurium quadrangle (Figure 3), where many ravines cut the southeast facing scarp within which the JS and PLLS are in contact. At least 100 m of more or less continuous JS section are exposed in each of the following ravines: Gooseneck, Quincy, Dover, and Natural Wall. The latter two sections, and that of an unnamed creek between them, comprise the second group of outcrops to be viewed.

Stop 4: Hungarian Falls on Dover Creek

Hungarian falls is located about 1 km west of the village of Hubbell near the common corner of sections 11, 12, 13 and 14, T.56N., R.33W. Parking facilities and trails at this site are maintained by the Department of Natural Resources. At and below the main falls a 50 m thick section of friable sandstones, unlaminated mudstones, and pebble to cobble conglomerates of the uppermost JS are exposed in the bed of Dover Creek. This relatively undisturbed section was measured with a Jacob's staff marked off into 10 cm intervals.

Figure 4 is a simplified stratigraphic column of the Hungarian Falls exposures. The measured portion of this section, and a diagrammatic profile of same, are shown on the right; the overlying unmeasured portion on the left. Sandstone beds are shown blank; mudstones, solid black; conglomerates, pebble pattern; and lava flows, V stippling. Disturbed bedding horizons are shown with a wavy line and injection structures are designated "i".

Proceeding upstream along the trail on the northeast rim of the ravine, the trail splits. Along the lower trail, near the bottom of the ravine, the lower conglomerate horizons shown on Figure 4 are exposed on the southwest side of and within the creek bed. Here, moderately west-dipping mudflows, sandstones, and mudflow conglomerates are overlain by a paraconglomerate and sandstone beds. The conglomerates dip $18-20^{\circ}$ NW and may thus be considered more or less conformable to flows of the PLLS at the top of this section. On the upstream end of these exposures, a north-trending channel structure cuts through the conglomerates. The cut and fill relationship between conglomerates and sandstones is well-defined here. Note that the more or less flat-lying sandstones have "filled in the dip difference" between the conglomerates and the horizontal. The depositional sequence exposed here is interpreted as follows: (1) uplift of highlands to the west with attendant mudflows transported eastward and deposited on the toe of an alluvial fan

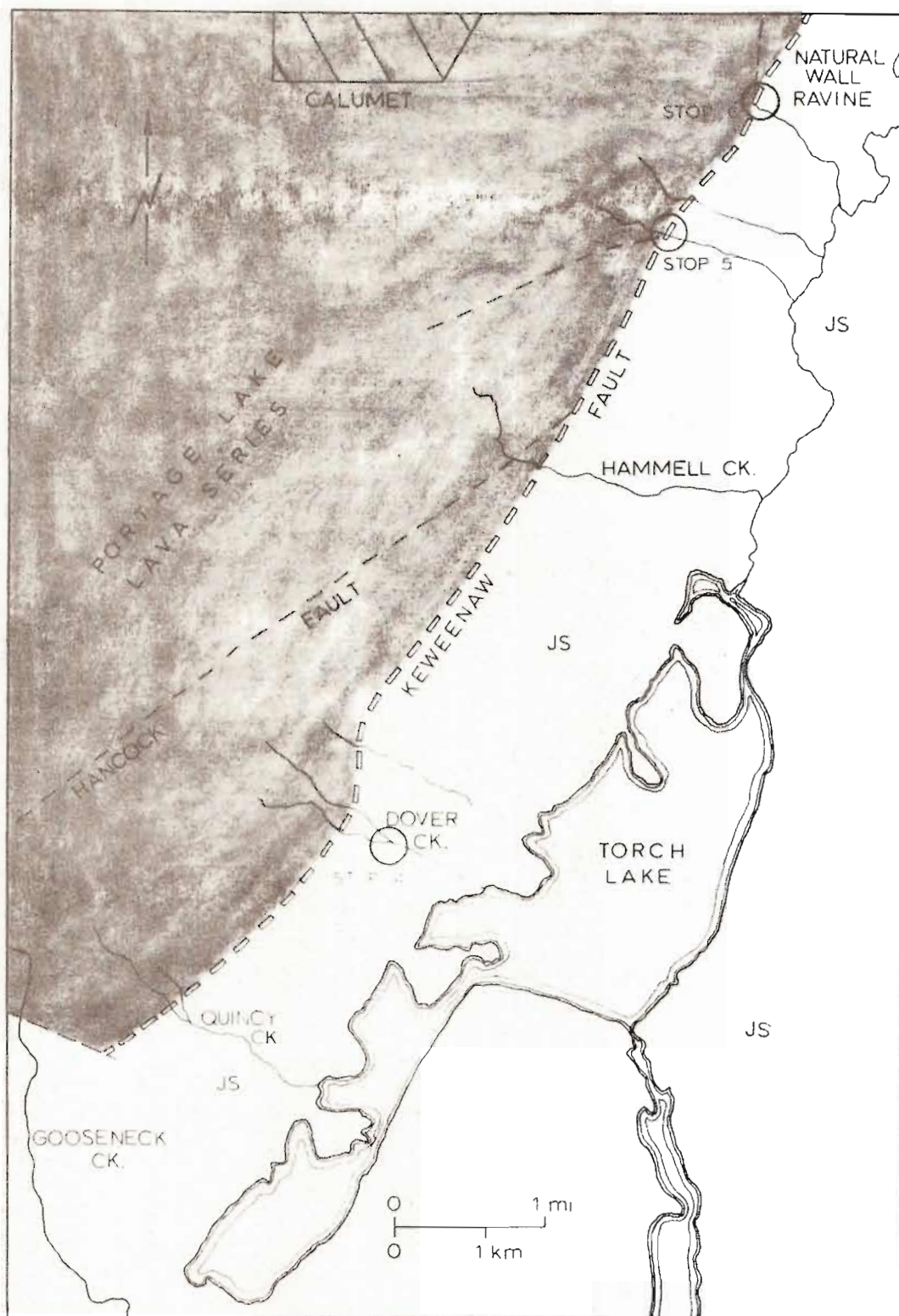
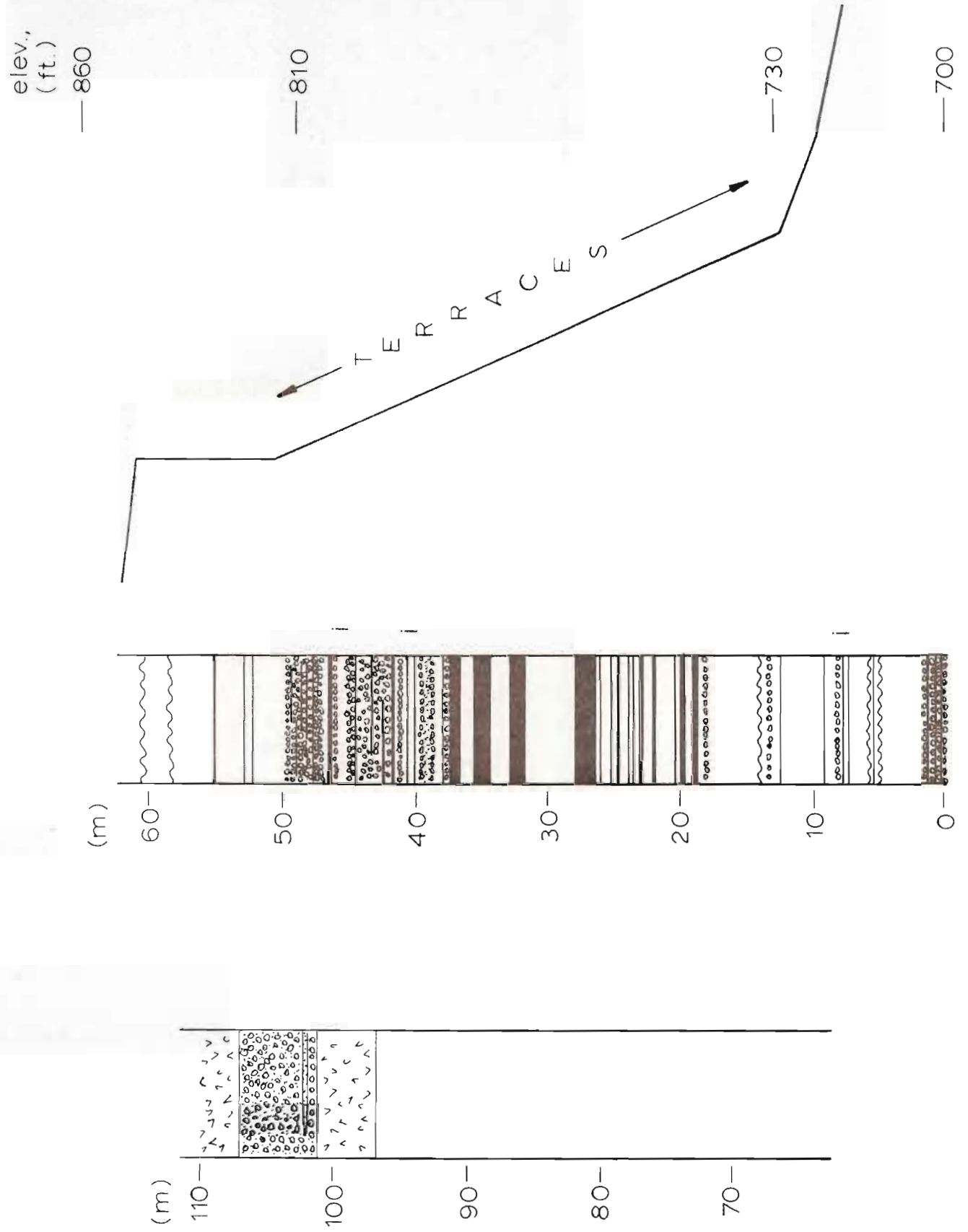


FIGURE 3. LAURIUM QUADRANGLE,
MICHIGAN

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FIGURE 4. DOVER CREEK - HUNGARIAN FALLS SECTION



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flanking these highlands, (2) subsidence of the western highlands, and (3) deposition of channel sands from a southern source area. Cross-bedding, disturbed bedding, and injection structures are noted in these channel sandstones. Based upon descriptions of identical structures, the latter two features are believed to be of the gravity-loading type which were triggered by earthshocks (Jones, 1965; Allen and Banks, 1972). Disturbed bedding, similar to that exposed here was seen previously at the L'Anse Red Rocks (Stop 1).

Proceeding upstream, additional section is exposed on the southwest wall and in terraces comprising the lower portion of the smaller of the two main falls. The larger falls, covered for the most part with talus blocks, can be observed from the viewing platform. Time does not permit viewing exposures between the base of the main falls and the JS-PLLS contact zone shown on Figure 4.

Terraces of the southwest side of the main falls are comprised of mudstones, sandstones, and conglomerates. Mudstones comprise about 11 m of the measured portion of the section; conglomerates, 9.5 m. Although there is about 200 m of horizontal distance between the top of the upper conglomerate and the first measured bed of the lower conglomerate, this section appears to thicken by at least 40% towards the northwest, upstream. This is a gross estimate because of the lateral component involved, absence of good horizontal and vertical control, and the fact that average bed thickness cannot be measured in many instances because the beds are extremely lenticular.

Fluvial channel structures, unlaminated mudstones, and the highly irregular relief beneath mudstone and conglomerate beds should be noted in the terraced portion of the section. A 0-13 cm thick layer of authigenic muscovite and biotite is present beneath one of the thicker mudflows near the center of the terraced section. The grain size distribution of these friable conglomerates are identical to those of mudflow and mixed mudflow-channel origin from Recent alluvial fans in California described by Bull (1962). These conglomerates have a clay to sand size matrix and contain pebbles and cobbles of diverse lithologies similar to conglomerates of the PLLS. Mudflow sediments are deposited by non-Newtonian mechanisms which entail laminar flow with negligible turbulence. Inverse and inverse-normal grading, which characterize mudflows, can be seen in this section. The bases of these sedimentary flows were surfaces of essentially zero net shear: a thin mud slip is usually all that separates these units from the uneroded upper portion of the underlying bed. Mudflows and mixed mudflow-channel deposits exhibit pebbles, cobbles, and/or boulders with major and semi-major axes parallel or subparallel to bedding. Pure mudflows do not exhibit cross-bedding or imbrication. Sediment transport directions in the measured portion of the section range between N15°E and due east. Based upon imbrication studies, Hamblin and Horner (1961) postulated a source area for PLLS conglomerates southeast of the JS-PLLS contact zone. In my opinion, the above and numerous other lines of geological and geophysical evidence suggest that their interpretation should be re-examined.

Cross-bedded channel sandstone overlies the upper conglomerate at the top of the terraced portion of this section. Fluvial and lesser wave-modified lacustrine sandstones comprise the unmeasured portion of this section. Very well-sorted, high quartz beds of the latter type pinch out rapidly downstream, whereas, conglomerates and mudstones of the underlying measured section pinch out rapidly downstream between the main falls and the parking area.

The distribution, geometry, lithology, and sedimentological properties of beds comprising the measured section indicate that these exposures represent a cross-section through the toe (distal portion) of an alluvial fan.

Stop 5: Unnamed Creek South of St. Louis Exploration

This section is located in a shallow ravine about 400 m south southeast of St. Louis exploration near the center of the south line of the SE $\frac{1}{4}$, (Section 19), T.56N., R.32W. east of Laurium (Fig. 3). Proceeding downstream, outcrops of the lowermost PLLS are exposed. In this section, the Copper City flow or "Big Trap" of old usage, is about 125 m thick and lies no more than 100 m stratigraphically above the JS-PLLS contact.

A somewhat epidotized PLLS-type conglomerate is exposed between the Copper City flow and the contact. This mafic conglomerate contains angular to poorly-rounded clasts up to 10 cm in size of Lower Keweenaw volcanics in a lithic fragment matrix. Conglomerate of identical appearance is exposed about 400 m north of here and above Douglas Houghton Falls on Hammell Creek 2.8 km south-southwest of this section. Unlike PLLS conglomerates higher up in the section, this unit is not best-described as felsitic, i.e., it resembles the Baltic (No. 3) and St. Louis (No. 6) conglomerates which are apparently, in part, time equivalent in this region.

The basal flow of the PLLS in this section is a maroon colored, very fine-grained, chloritic melaphyre ("trap"). The upper amygdaloidal zone contains abundant chlorite and a copper-colored mica similar in appearance to that present on the surface of pebbles in the L'Anse Red Rocks. Abundant chlorite and small poorly-developed agates characterize the basal amygdaloidal zone. Thin calcite veinlets cut the basal portion of this melaphyre and the uppermost Jacobsville quartzite beds. A 40 cm-thick zone of shattered melaphyre chips separates the basal melaphyre from conformably underlying JS quartzite beds.

Proceeding downstream from the small falls at the contact, dips exhibited by sandstone and conglomeratic JS beds beneath the quartzite progressively increase from 34°, to 48°, 64°, and 78° WNW. Farther downstream, a covered interval is encountered, then JS beds with N60°E, 78°SSE and N35°E, 35°ESE orientations. The latter beds have orientations virtually identical to those in the JS-PLLS contact zone. JS beds 120 m downstream and points farther eastward are essentially flat-lying. From these data, and the existence of similar though larger structures at Natural Wall (Stop 6) and other locations, the above mentioned covered interval is interpreted as the shattered core of an anticlinal flexure. The latter two JS beds cited

above represent portions of the east limb of this structure. Absence of gross vertical and horizontal control precludes presentation of a diagrammatic cross-section of this structure.

Stop 6: Natural Wall Ravine

The Natural Wall ravine is located about 3 km east of Calumet (Figure 3). Unlike the relatively undisturbed section at Hungarian Falls (Stop 4), here the uppermost JS has been folded into an asymmetrical antiformal structure. Figure 5 is a diagrammatic 1:1 cross-section of these exposures. Access to these exposures is provided by trails to the ravine and along the northeast rim. A steep trail near the midpoint of the rim trail leads to the bottom of the ravine.

Essentially flat-lying beds of mudstone, sandstone, and conglomerate are exposed in the streambed, downstream from the trail to the bottom (Figure 5) and on the south side of the access road on the north side of the ravine. Flat-lying units in the streambed are separated from steeply east-dipping beds of the eastern limb of the anticline by a covered interval, believed to be a shatter zone, about 15 m wide. The so-called "Natural Wall" consists of a relatively resistant bed, about 1 m thick, comprised of fine-grained, well-sorted, lacustrine sandstone deposited above wave base in about 0.5 m of water. These data are based upon grain size analysis of sands comprising this bed and application of the equations of Tanner (1971) to ripple mark casts on the base of this bed. The natural wall unit is located about one third of the way downstream from the anticlinal core to the shatter zone within a nearly 125 m thick section of conglomerates, mudstones, and similar sandstones.

Within the anticlinal core of this south-plunging structure, the west limb dips about 40° ; the east limb, 60° . Beds above the core are shattered. However, beds within the core are simply folded. On the basis of appearance, there is little doubt that these beds were folded prior to induration. Upstream from the core, cross-bedding tops point upstream; downstream, they point downstream. About 70 m upstream from the core, in the JS-PLLS contact zone, a basal melaphyre is overlain by a PLLS-type conglomerate which is in turn overlain by a porphyritic rhyolite. This rhyolite exhibits pseudo- or true flow banding and could be of either extrusive or intrusive origin.

Two sections southwest of Natural Wall ravine were examined by the writer. Time does not permit viewing these sections during the field trip. Both are located within 400 m of Stop 6 and exhibit a well-exposed JS-PLLS contact which appears to dip 10° to 30° W. Beds of the uppermost Jacobsville show large-scale bedding features with extremely variable strikes and dips within the contact zone. From outward appearance, these beds were plastically deformed prior to complete induration. The southernmost section contains a 2-3 m thick bed of sandstone about 25 m above the base of the PLLS. This bed exhibits attributes of both the JS and PLLS sedimentary types, i.e., it appears to be transitional. In many respects, this unit resembles the mixed-type quartzite present on the Mayflower mine dump, which is located about 2 km north of this section.

There exists no bed-by-bed continuity within the lowermost PLLS between these two sections and/or the sections at Stops 5 and 6. At the last two stops, and one of the above mentioned unnamed sections, a basal melaphyre is present at the contact. However, the PLLS-type conglomerate present at Natural Wall is absent in the two southernmost of these four sections. This unit is present at the contact in a bowl-shaped ravine south of Stop 6. Rhyolite/felsite is present only in the Natural Wall section.

UPPERMOST JS/LOWERMOST PLLS CONGLOMERATES

Conglomerates, mudstones, and sandstones of the Dover Creek section (Stop 5) are similar to those at Natural Wall ravine (Stop 6) and all other exposed sections between them. Uppermost JS conglomerates were noted in all but the two most southerly of the nine sections investigated.

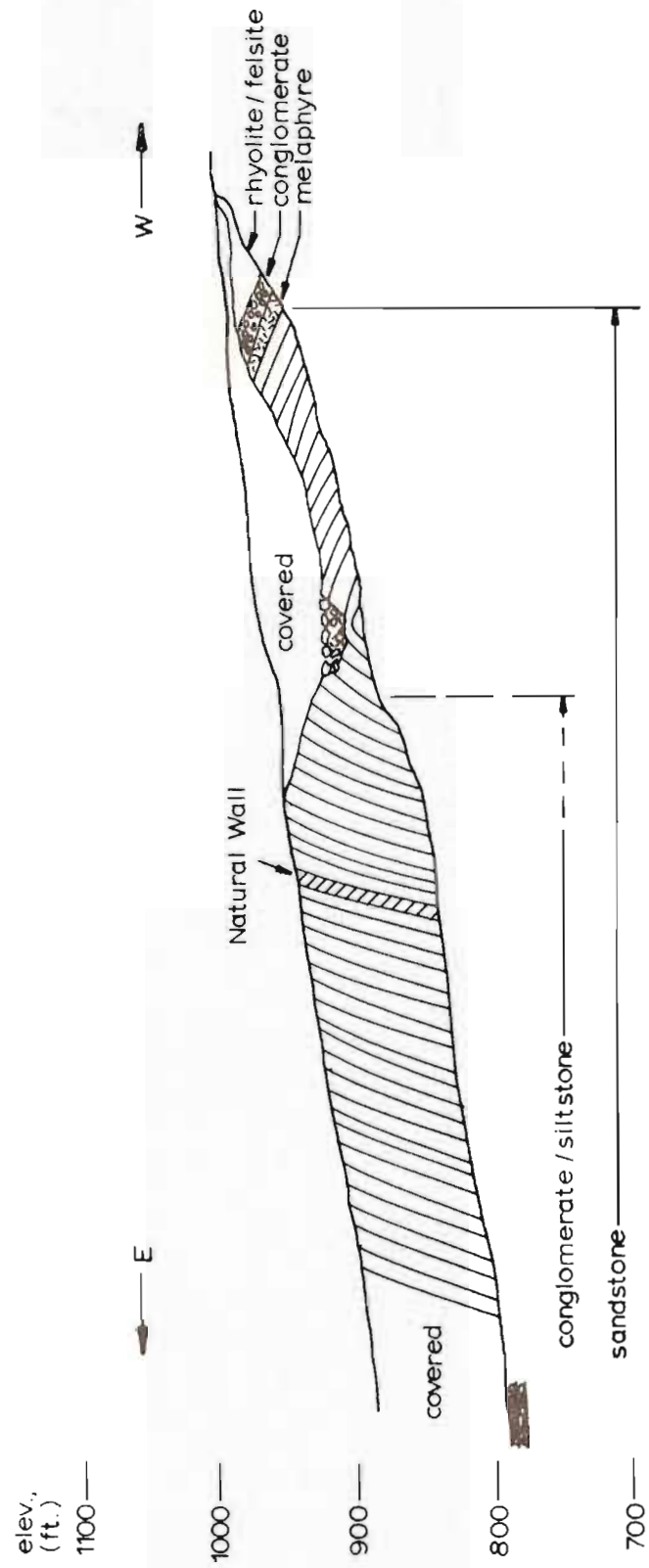
Field measurements of maximum clast size in uppermost JS conglomerates were performed in six sections. From Dover Creek to the northernmost section at Natural Wall, there is a more or less progressive increase from large cobble (22 cm max.) to medium boulder (80 cm max.) size over a distance of about 9 km along strike.

The thickness of 36 uppermost Jacobsville conglomerates were measured in the Dover Creek, St. Louis Hill, and Natural Wall sections, i.e. at Stops 4, 5, and 6. Observed values comprise an odd-numbered arithmetic progression 1, 3, 5, 7, 9:

	Cycle	Beds (n)	avg. (cm)	Frequency Distribution (approx.)
(base)	1	19	51	3
	3	11	158	2
	5	2	247	1
	7	3	345	
	9	1	460	
	n_T	= 36	131	

Computed averages exhibit a maximum difference range from theoretical base cycle multiples of $\pm 3.5\%$. The minimum computed probability that these values constitute a random sequence is 377,000 to one. These data indicate that the bed thicknesses of mudflow conglomerates within uppermost JS alluvial fans are in large part tectonically controlled. Evidence that the depositional rate was equivalent to the subsidence rate in the Keweenaw Peninsula during Middle Keweenawan time was presented by Nordeng and Babcock (1968). The regional distribution of stratigraphic marker beds and correlative mesocycles within the uppermost JS suggests that the bed thickness frequency distribution cited above is a manifestation of differential subsidence rate frequency. Thus, there seems little reason to believe that the following is coincidental: maximum/average bed thickness ratios for these 36 conglomerates and similar data on massive, B_2 facies, lacustrine sandstones of the uppermost JS (Hamblin, 1958, p. 43) are 3.5 and 3.6, respectively.

FIGURE 5. NATURAL WALL RAVINE
(diagrammatic X-section at 1:1)



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Mudflow conglomerates, unlike those deposited as streamfloods, beach gravels, etc., exhibit statistically significant correlations between bed thickness and maximum clast size. Alluvial fan mudflow conglomerates in the "New Red" sandstone (Permo-Triassic) of western Scotland have bed thickness/maximum clast size ratios between 4.3 and 7.5 to 1 (correlation coefficients = 0.65 to 0.91, $n = 12$ sites; Steel, 1974). Treating the above 36 JS conglomerates as a single population, the value computed for this ratio is 12.5 to 1 (correlation coefficient = 0.86).

Based upon maximum clast size-slope-distance from source data on Recent alluvial fans by Blissenbach (1952), uppermost JS and lowermost PLLS-type conglomerates were probably deposited between six and 16 km from their source. Distribution, geometry, and sediment transport criteria indicate JS conglomerates were deposited on coalescing alluvial fans. The major portions of these fans lay towards the west of the contact zone within an area now occupied by Middle and Upper Keweenawan rocks.

North of the Laurium quadrangle, variable amounts of mafic pyroclastic debris are present in lowermost PLLS conglomerates. In the Mohawk quadrangle, a felsite conglomerate exhibits a facies change into a lapilli tuff as the contact is approached, i.e. proceeding southeast. These exposures are located in the bed of an intermittent stream on the north side of the Fulton-Gay road, as shown on the Mohawk geologic quadrangle map near the center of the NE $\frac{1}{4}$ of section 35, T.57N., R.32W. (Davidson and others, 1955). Volcanic agglomerates are exposed at several locations along the contact in the Mount Bohemia - Bete Gris Bay region in T.58N., R.27W. and R.28W. In addition, "ashbed" type flows with scoriaceous tops occur within the lowermost PLLS immediately north of Natural Wall (Butler and Burbank, 1929, plate 22). Ashy material of this type is present on the Mayflower mine dump.

The writer concurs with Hubbard (personal communication, 1974) in the belief that pebble to boulder size clasts of volcanic rocks in Upper and Middle Keweenawan sediments, and the uppermost JS, were derived from a Lower Keweenawan terrain.

STRUCTURE

The south-plunging antiformal structure at Natural Wall Ravine lies on or near the southern projection of the Mayflower fault. Data presented by Butler and Burbank (1929) and annual reports of the Mayflower-Old Colony Mining Company (1899-1924) indicate that this fault zone lies within the axial plane of the Mayflower anticline. Diamond drilling and drifting in the Mayflower area, immediately to the north of the Natural Wall area, showed the presence of flows dipping from 10° to 30° E. The Mayflower anticline opens towards the north from the Natural Wall area, involves beds of the uppermost 200 m of the JS and lowermost beds of the PLLS below the Copper City flow, and is truncated by the Allouez Gap Fault.

The Allouez Gap fault, other mapped faults, and photo-derived lineaments define the Allouez Fracture Zone. Two larger structures, similar to the Mayflower anticline, are symmetrically disposed about the Allouez Fracture Zone (Figure 6). Three structural blocks, delimited by low-angle "splays" radiating from the JS-PLLS contact zone, are shown in Figure 6. The Hancock, Mayflower, and Suffolk faults, best described as axial plane shatter zones, define the northwestern (basinward) extent of these three blocks. Western limbs of these three asymmetrical structures are steeply dipping; eastern limbs or sides exhibit moderate dips. The Hancock block is monoclinical, i.e. unlike the two smaller blocks, it does not exhibit an eastern limb. Major transverse fault zones with variable dip-slip and rotational components appear to more or less truncate the open ends of the three blocks. Structural data concerning these features, derived primarily from Butler and Burbank, (1929, plates 18, 19 and 22), are summarized below:

Block	Subsurface Dips		Surface Dips (east limb)
	(west limb)	(east limb)	
Hancock	40-52°NNW	8-23°NNW	25°W-15°E
Mayflower	45-72°W	0-30°E	0±5°E, W
Suffolk	49-72°NW	0-8°SE	0±

The Hancock and Natural Wall flexures plunge toward the basin margin on their closed ends in the JS-PLLS contact zone, i.e., towards the north-east and south, respectively. The plunge exhibited by these two flexures is consistent with their location relative to major transverse fracture zones and the fact that the Keweenawan thickens towards the northeast, along the peninsula, because of an increased subsidence rate (Nordeng and Babcock, 1968).

The northwestern limbs of the Hancock, Mayflower, and Suffolk flexures are steeply dipping. However, the antiformal flexure in the south St. Louis section (Stop 5) is more or less symmetrical and the Natural Wall Structure (Stop 6) exhibits a steeply dipping east limb. In addition to these five, at least two other antiformal flexures exist within the JS-PLLS contact zone; one on the north side of the Lake syncline, the other in the Victoria Dam region. These two structures are located about 72 km and 86 km southwest of the center of the Laurium quadrangle, on the southwest side of the Firesteel and Ontonagon River Fracture Zones, respectively.

JS-PLLS CONTACT RELATIONS

The following discussion of the JS-PLLS contact zone is limited to beds 10 m above and below the exact contact in the Laurium quadrangle. Brief discussion of a typical stratigraphic section across the contact zone and detailed bed-by-bed correlations between sections are precluded by lithologic, stratigraphic, and structural complexities and the absence of good horizontal and vertical control.

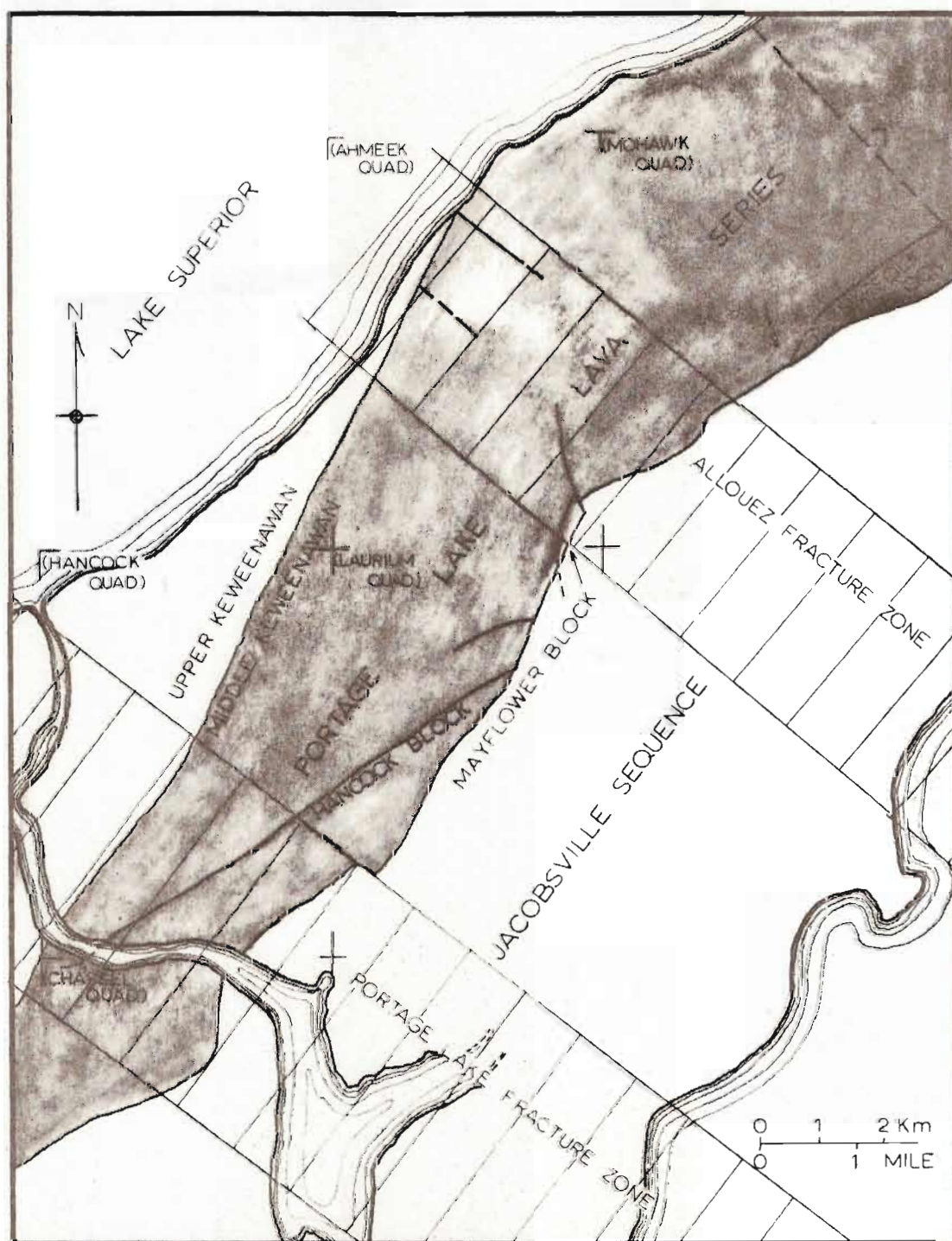


FIGURE 6 GROSS STRUCTURES IN THE PORTAGE LAKE, MICHIGAN, AREA

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Beds within the contact zone are extremely lenticular. The exact location of the contact is covered in some of these sections. The dip of individual beds ranges between 10° W to vertical except in the St. Louis Hill - Natural Wall sections (Stops 5 and 6) where steeply east-dipping beds are exposed. However, the steepest dips locally are usually found outside the immediate contact zone within the uppermost JS.

A minor lacustrine transgression from the east marks the top of the JS in the Laurium quadrangle. Beach gravels and/or high-quartz beach sands are now represented by quartzites in four of the nine sections examined. These beach sand matrix conglomerates appear restricted to the contact zone yet exhibit pebble-boulder lithologies indistinguishable from those present in uppermost JS and lowermost PLLS conglomerates. Sandstones, comprised of fluvial and/or wave-modified fluvial sands, are present in the other five sections. Mudstones are absent.

In seven sections, the lowermost PLLS flow is a fine-grained maroon-colored trap. This melaphyre is overlain, in six sections, by a conglomerate with a characteristic PLLS-type lithic fragment matrix. The sub-angular to well-rounded pebble to boulder sized clasts in this conglomerate consist predominantly of fine-grained porphyrites and other Lower Keweenaw type volcanics. Early workers called this unit the "contact conglomerate". This conglomerate is not shown on the geological map of the Laurium quadrangle by Cornwall and Wright (1956). However, reinterpretation of available drill logs in the Portage Lake area and field evidence, suggests that conglomerate (pu) mapped in the Chassell quadrangle by White (1956), and the "contact conglomerate" exposed in the Laurium quadrangle are indeed equivalent. Other units in the lowermost PLLS include additional melaphyres, lesser ophites, and the aforementioned rhyolite.

Other than Wadsworth's (1884) field data, the only evidence of interbedding between sediments of the JS and volcanics of the PLLS in the Laurium quadrangle is that shown in the log for DDH no. 11 of the Torch Lake drill section (Butler and Burbank, 1929, pl. 21). At the bottom of this hole, a 24 m thick bed of Jacobsville sandstone overlies about 15 m of shattered ophite within the contact zone.

ENVIRONMENTAL MODEL

The distribution of massive facies lacustrine sandstones in the Keweenaw Bay/ Peninsula area (Figure 1) indicates that a lake was centered near the axis of the Jacobsville outcrop area. The occurrence of predominantly fluvial sands comprising exposures in the Laurium quadrangle and those adjacent to the Huron Highlands suggests that alluvial fans existed along the basin margins northwest and southeast of this paleo-lake.

Based upon the ripple mark data in the description for Stop 3, one may envision a relatively large paleo-lake, during uppermost JS time, which lay off towards the north of this location. The one meter depth contour appears to have coincided with the present western shore of Keweenaw Bay. Onshore winds, blowing towards the (present) south and southeast, produced these and other abundant ripple marks which characterize Hamblin's massive bedded sandstones. Mud cracked ripple marks confirm the shallow water depths computed from Tanner's (1971) equations.

Ripple marks along the western shore of Keweenaw Bay in B₂ facies JS beds exhibit environment values identical to those of the lower part of the Morrison formation (Jurassic) on the Colorado plateau in northern New Mexico (Tanner, 1971). These two virtually identical environments were the site of relatively large very shallow lakes within rapidly subsiding intercratonic basins. Dimensions of these lakes are believed to have been 50-100 km or more long, 20-40 or more km wide, and no more than a few meters deep. In my opinion the lateral and stratigraphic persistence of these ripple-marked lacustrine beds preclude the existence of an arid or semi-arid climate during uppermost JS time.

A laterally persistent, arkosic, marker bed has been defined in the JS of the Keweenaw Bay/ Peninsula region. On the basis of field appearance and laboratory analysis of its grain size distribution characteristics, this bed has a sheetflood, streamflood, or deltaic origin, depending upon where samples are taken. This marker bed constitutes an important aquifer which normally yields 5 to 20 gallons of water per minute. Sometimes the water is artesian. I have designated this unit the "microcline marker grit", because it contains diagnostic, tan-yellow, coarse sand to granule-sized clasts of maximum microcline with brilliant cleavage flashes. These microcline clasts, which constitute 10 to 50% of the detritus in this bed, indicate that chemical breakdown of feldspathic material did not occur in uppermost JS time. Water wells on either side of Otter Lake, 9 km northwest of Stop 3, encountered this unit at an elevation of 700 feet. This marker occurs at exactly the same elevation within the Quincy Creek section in the Laurium quadrangle (Figure 3). The two occurrences are separated by a distance of 22 km. This observation and the above-mentioned data regarding the extremely shallow lacustrine environment in the Keweenaw Bay region, constitute evidence that the fluvial/lacustrine plain on which the uppermost JS was deposited was incredibly flat.

Selley (1970 ; p. 43) presents four sedimentary-tectonic models of alluvial environments. Based upon data presented in this paper, the Jacobsville appears to be an example of the following general type: "Sequences, thousands of feet thick, deposited in fault-bounded troughs within continental shields." More specifically, Selley describes this alluvial environment as occurring

"...in fault-bounded troughs often closed from the sea either within mountain chains or continental shields. These deposits, often thousands of feet thick, are generally coarse braided alluvium generated from fans on the marginal fault scarps. They may pass laterally into meandering alluvium or directly into lacustrine deposits in the trough center. These deposits are often interbedded with volcanic rocks which erupted along the marginal faults. Examples of this model include the Triassic Newark: Connecticut Trough complex of northwest North America, the Devonian Midland Valley of Scotland, the Precambrian Dala and Jotnian sandstones of Scandinavia, and possibly the Torridonian."

Red bed sequences of the JS type appear restricted to a very definitive period within a tectonic framework of active rifting. More specifically, these continental sediments characterize the initial breakup stage between cratons, or on a larger scale during later periods of crustal evolution, continents. The Triassic Newark Group, of the "trailing edge" continental margin type, was deposited during the initial breakup of Pangaea, i.e., the opening of the North Atlantic (Dietz and Holden, 1970). The intra-continental, intercratonic Colorado Plateau basin wherein the Morrison formation was deposited is pre-Cretaceous (Jurassic), i.e., a possible manifestation of the initial phase of the major world wide crustal rifting period. The uppermost JS is believed of initial Middle Keweenaw rifting age. Volcanics are either interbedded with or laterally disposed time equivalents of the Morrison and Newark Groups sediments. Herein, I have cited evidence that a similar relationship exists between the JS and PLLS.

CONCLUSIONS

Jacobsville conglomerates in the Laurium quadrangle are stratigraphically at the top of the sequence and have not been dragged up from the base of the Jacobsville within the zone of the Keweenaw fault as stated by Hamblin (1958). The sedimentology, geometry, distribution, and regional setting of these conglomerates indicate they were deposited on coalescing alluvial fans located within a rapidly subsiding rift zone. This setting is believed analogous to that of the Lake Precambrian Torridon Group of northwest Scotland. According to Selley (1970), alluvial fan apices of the Torridon red beds lay along the line of the Minch fault.

The source of uppermost JS conglomerates was located a relatively short distance, 16 km or less, towards the west of the contact zone in a region now occupied by Middle and Upper Keweenaw rocks. Several lines of evidence presented by Hubbard (1971) and within this paper indicate that the Minnesota Precambrian craton, which apparently separated from the Michigan craton during Middle Keweenaw time, was a major source of the coarse clastic debris comprising uppermost JS and lowermost PLLS conglomerates of the study region.

The JS more or less conformably underlies and is locally interbedded with the PLLS in the Laurium and adjacent quadrangles.

Numerous lines of evidence suggest that the so-called Keweenaw fault may be considered as a natural zone of weakness at the interface between a thick sedimentary sequence and an even thicker volcanic series. I believe that this zone more or less defines the southernmost and easternmost incursions of Portage Lake lavas and sediments onto a tectonically stable shelf of flat-lying Jacobsville sediments bordering the pre-Keweenaw interior highlands of the western and central portions of the Upper Peninsula of Michigan.

The Keweenaw fault defines a zone of rate of change of subsidence; a loci of structural adjustments along a basin margin hinge associated with active rifting during Middle Keweenaw time. Much of the folding, tilting, and faulting in and near this zone appears to have taken place

before the uppermost JS was indurated, i.e., relatively soon after it was deposited. Structures within this hinge zone involve beds of the JS and PLLS. The Hancock, Mayflower, and Suffolk blocks comprise the basinward side or limb of buttress-type structures; the former is monoformal, the latter two are antiformal flexures. These structures were formed by compressional adjustments contemporaneous with active subsidence accompanying the deposition of the PLLS. In the Laurium and adjacent quadrangles, these adjustments took place within a zone about 2 km wide on the basinward side of the immediate JS-PLLS contact. Faulting and folding is not confined to the trace of the JS-PLLS contact. Similar antiformal structures exist northeast and southwest of the Laurium quadrangle. The JS-PLLS contact is not simply a zone of high angle reverse and/or normal faulting as proponents of the Keweenaw Fault concept would have us believe. In addition to variably northwest-dipping reverse and/or normal faulting, the structural style of this zone incorporates axial plane shatter and fault zones, within antiformal and lesser synformal flexures, which radiate at low angles from the contact zone. Furthermore, the writer has found no evidence to suggest that the lowermost PLLS is in part time equivalent to the SRLS (South Range Lava Series) or that two red bed sandstone sequences of markedly different age are present in the region investigated.

The tectonically active period immediately preceding the initial outpourings of the PLLS is marked by a regional unconformity within the uppermost JS of the study region.

The areal distribution of fluvial and lacustrine sandstones and tectonic setting of the JS are consistent with an environmental model based upon similar red bed sequences ranging in age from Precambrian to Triassic.

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MARQUETTE IRON RANGE

By

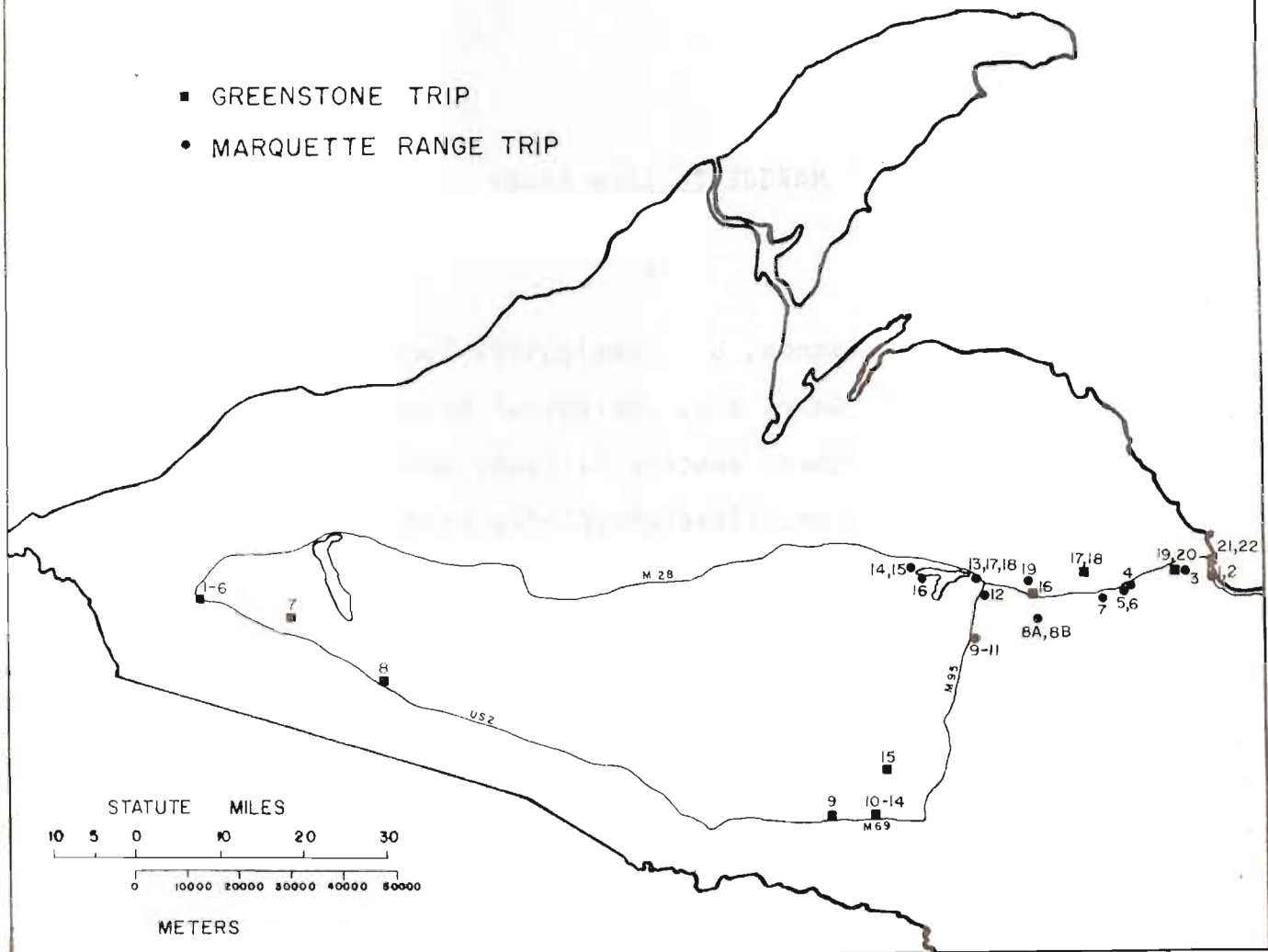
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- GREENSTONE TRIP
- MARQUETTE RANGE TRIP



Introduction

The Marquette Range has been the site of numerous field trips over the past decade, as a great many geologists have had the opportunity to examine this area first hand, and we are sure many members of the Institute have toured the area at least once. Nevertheless, we feel that still another Marquette Range trip is warranted because of heightened interest over the past few years in the mineral resources of the area, because of the influx of new geologists, and because of information from continuing research in the area.

This one-day trip must necessarily miss some of the classical exposures known by many who have visited the area previously. It is designed principally to study the stratigraphic succession of part of the Marquette Range Supergroup and the history of the area that can be inferred from the nature of the sediments. The trip will also illustrate aspects of the deformation and metamorphism of these rocks during the Penokean orogeny and will briefly examine some of the underlying basement rocks. Of the 19 stops, 7 have not been visited on previous trips; the remaining 12 have been part of one or more previous Institute trips. We hope, for people who may have attended the earlier trips, that a second visit will be worthwhile; those of us who have seen these exposures many times seldom fail to notice something new on each visit, and we feel confident that this will be true for this trip, also.

The trip will examine the section, as nearly as possible, from the base upward. In some cases this is not logistically convenient and departures from stratigraphic order are noted in descriptions of individual stops.

Marquette Range Supergroup

The Marquette Range Supergroup consists of four groups, from oldest to youngest, the Chocolay, Menominee, Baraga, and Paint River Groups. The three oldest are preserved in the Marquette trough, whereas the Paint River Group is preserved only in the Iron River-Crystal Falls district to the southwest. The sedimentation of the supergroup records a progressive change in tectonic conditions from a stable craton (Chocolay Group) through a sedimentary basin with mild tectonism (Menominee Group) to a highly active tectonic basin (Baraga Group) as the long-stable Superior craton was reactivated at the onset of the Penokean orogeny.

Details of the stratigraphic section and the correlation of units in the Marquette area with units elsewhere in northern Michigan are shown in Table 1.

Original lithologic types have been altered, probably about 1.9 b.y. ago, by progressive metamorphism. Isograds determined by H.L. James¹ are shown in Figure 1.

Chocolay Group

The Chocolay Group was deposited on a stable cratonic basement of Precambrian W greenstone and granitic rocks. Little evidence remains about the nature of the land surface at the beginning of deposition, but a long period (~800m.y.) of erosion between late Precambrian W tectonism and Chocolay deposition and the blanket-like nature of sedimentary units suggest the area was peneplaned.

The Group consists principally of a transgressive sequence of basal orthoquartzite, the Mesnard Quartzite (stop 1), overlain by slate and dolomite of the Kona Dolomite (stop 2). Locally, a unit of conglomerate, graywacke, arkose, and slate, the Enchantment Lake Formation, partly of glacial origin, is at the base of the section; it will be seen at Stop 3. Gray slate of the Wewe Slate overlies the Kona Dolomite, but it will not be seen on this trip.

These units are preserved only in the east end of the Marquette Range. They are truncated by an unconformity at the base of the overlying Menominee Group near Negaunee, Michigan, but are correlated with and may have been originally continuous with similar rocks in other parts of northern Michigan.

Stop 1 (Fig. 2). Mesnard Quartzite (Precambrian X) and Jacobsville Sandstone (Precambrian and (or) Cambrian).

At this stop Mesnard Quartzite, the basal orthoquartzite unit of the Chocolay Group, is exposed along the shore of Lake Superior and is overlain, with angular unconformity, by the Jacobsville Sandstone.

White-weathering vitreous Mesnard Quartzite in beds 4 to 8 inches thick strikes eastward and dips 80°S to vertically. Cross-beds and ripple marks indicate top directions to the south, in conformance with the position of the quartzite on the north limb of the Marquette trough. Reddish Jacobsville Sandstone dips 10-15° eastward to southeastward and is visibly in contact with the Mesnard. Remnant patches of Jacobsville are plastered against the north side of the quartzite outcrop, and on the south side the contact is steep. Evidently, during deposition of the Jacobsville, the Mesnard at this

¹H.L. James, 1955, Zones of regional metamorphism in the Precambrian of northern Michigan: Geol. Soc. America Bull., v. 66, pp. 1455-1488.

			Marquette Range	Iron River- Crystal Falls District	Menominee Range	Gogebic Range
Precambrian Y	Keweenaw		Intrusive diabase	Intrusive diabase	Intrusive diabase	Volcanic, intrusive, and sedimentary rock
Precambrian X	Marquette Range Supergroup	Paint- River Group		Fortune Lakes Slate Stambaugh Formation Hiawatha Graywacke Riverton Iron-Formation Dunn Creek Slate		
		Beraga Group	Michigamme Slate Bijiki Iron- Formation Member Clarksburg Volcanics Member Greenwood Iron- Formation Member Goodrich Quartzite LOCAL UNCONFORMITY OR DISCONFORMITY	Badwater Greenstone Michigamme Slate Amasa Formation Hemlock Formation	Badwater Greenstone Michigamme Slate	
		Menominee Group	Negaunee Iron-Formation Sismo Slate Ajibik Quartzite UNCONFORMITY OR DISCONFORMITY		Vulcan Iron-Formation Felch Formation.	Ironwood Iron-Formation Palms Quartzite
		Chocoley Group	Wewe Slate Kona Dolomite Mesnard Quartzite Enchantment Lake Formation UNCONFORMITY	Saunders Formation UNCONFORMITY(?)	Randville Dolomite Sturgeon Quartzite Fern Creek Formation UNCONFORMITY	Bad River Dolomite Sunday Quartzite UNCONFORMITY
Precambrian W			Gneiss Greenstone	Greenstone (stratigraphic position uncertain)	Gneiss	Gneiss Granite

Table 1. Stratigraphic sections of the Marquette Range Supergroup and correlation of units in the upper peninsula of Michigan.

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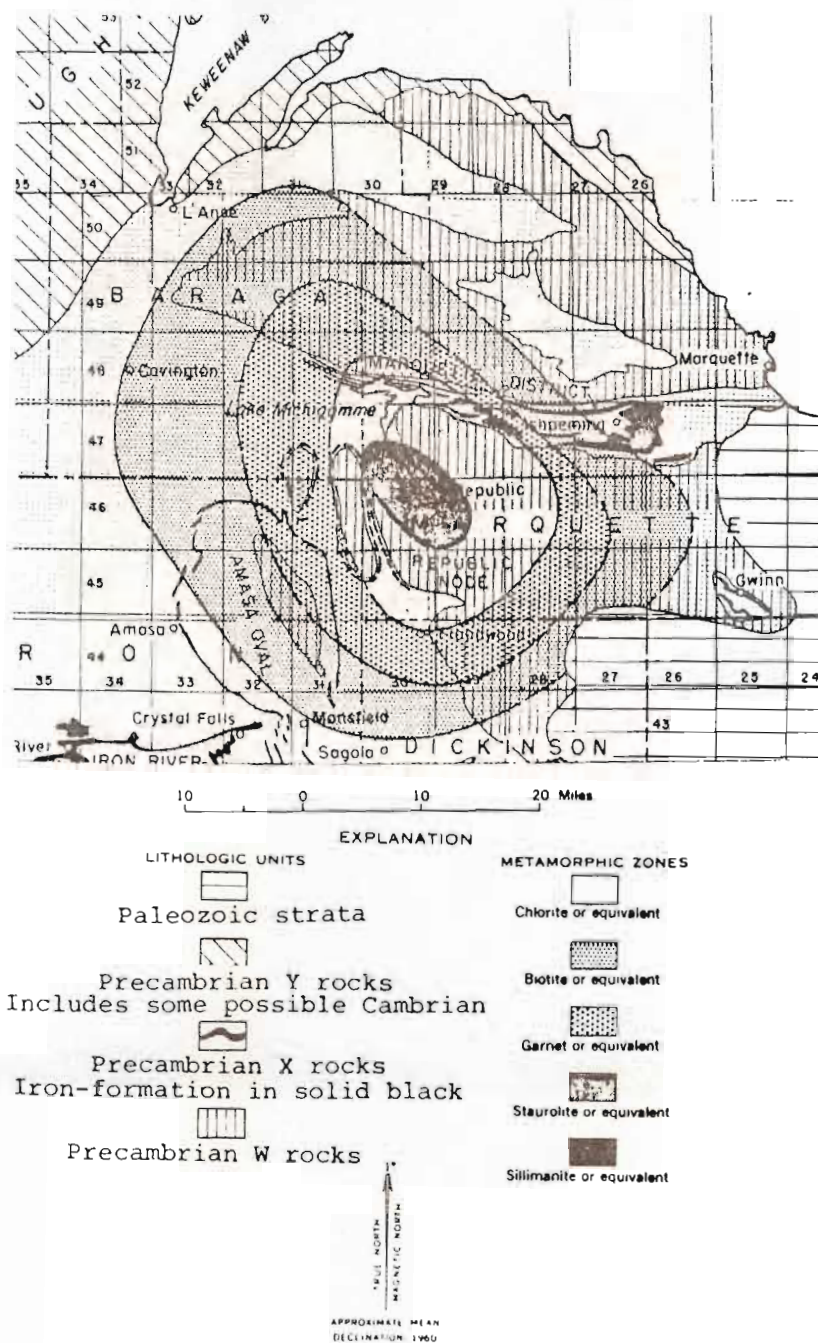


Figure 1. Map showing zones of Penokean regional metamorphism in the Marquette region. (from H.L. James, 1955, Zones of regional metamorphism in the Precambrian of northern Michigan: Geol. Soc. America Bull., v. 66, p. 1455-1488.)

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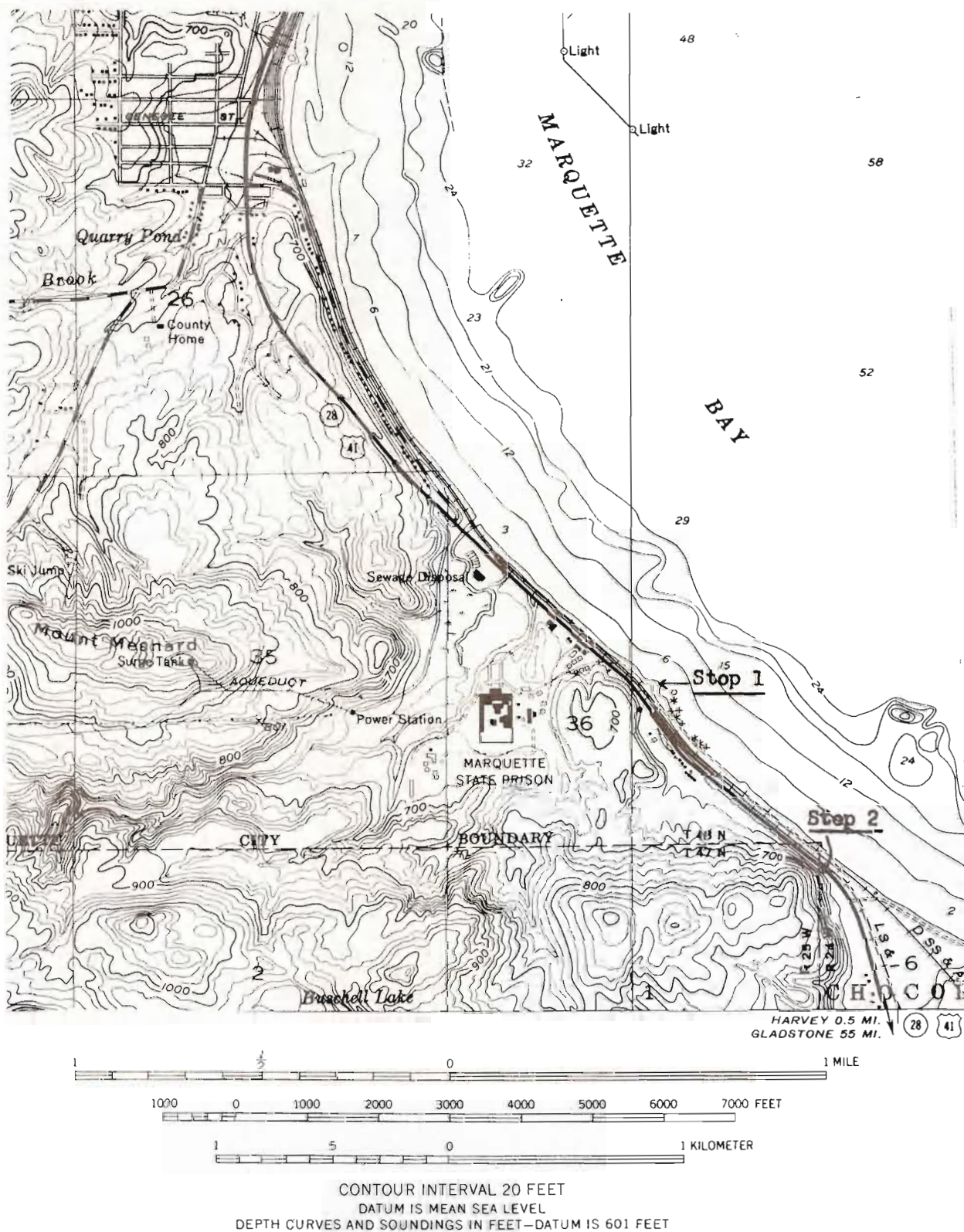


Figure 2. A portion of the Marquette 7½-minute quadrangle, showing the location of stops 1 and 2.

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place formed a topographic ridge, much as it does now. Flat-lying Jacobsville is on the flank of Mt. Mesnard, about 3/4 mile west of here and 370 feet above lake level, which indicates a pre-Jacobsville topographic relief and ruggedness approximately the same as or greater than that adjacent to the present shore of Lake Superior.

Note the smooth, polished (glacial?) rock surface being exhumed from beneath the Jacobsville. Near L'Anse, Michigan, the pre-Jacobsville surface is strongly striated (glacial?).

An interesting feature of this outcrop is the great number of percussion marks on the surface of the Mesnard Quartzite. These were formed as the outcrop was battered by storm-tossed cobbles, but when did they form? Do storm waves on the present lake reach the top of this outcrop? Were they more likely formed in a slightly higher-level glacial lake, or could they have formed during Jacobsville transgression?

Stop 2 (Fig. 2). Kona Dolomite.

The Kona is mostly dolomite, in part algal, but contains lesser amounts of fine- to medium-grained clastic rocks.

The northwest half of the large road cut on the west side of U.S. 41 exposes mainly thinly laminated green, pink, and maroon slates in the lower part of the Kona. These rocks dip steeply southward with some undulation and are strongly cleaved. Cleavage bedding relationships indicate that these rocks are north of a synclinal axis and cleavage bedding intersections plunge eastward. Thin layers of reddish or maroon quartzite and dolomite, as much as 4 feet thick, are interbedded in the slate. Pods of vein quartz are common in parts of the slate and, in general, are aligned with the rock cleavage. Southeastward and stratigraphically upward in the road cut, dolomite beds become more common in the slate, and a thick bed of reddish brown ferruginous dolomitic quartzite is exposed 60 to 150 feet from the southeast end of the road cut. At the southeast end, a trail leads westward uphill about 50 feet to a cliff in which can be seen large domed algal structures in Kona Dolomite. At the base of the slope, almost directly below the algal structures, gentle folds in the dolomite plunge about 35° E. From this place southward, bedding dips to the north and cleavage bedding relationships indicate that the synclinal axis is to the north. The axis of the east-plunging syncline, therefore, passes through the exposure of algal structures. The slate in the Kona on the south limb of the syncline is only about half as thick as that on the north limb; this difference is attributed to faulting on the south limb.

Stop 3(Fig. 3). Enchantment Lake Formation.

The Enchantment Lake Formation is a discontinuous unit at the base of the Marquette Range Supergroup. It consists of conglomerate, graywacke, arkose, and slate is believed to be, at least partly, of glacial origin. It is conformably below the Mesnard Quartzite.

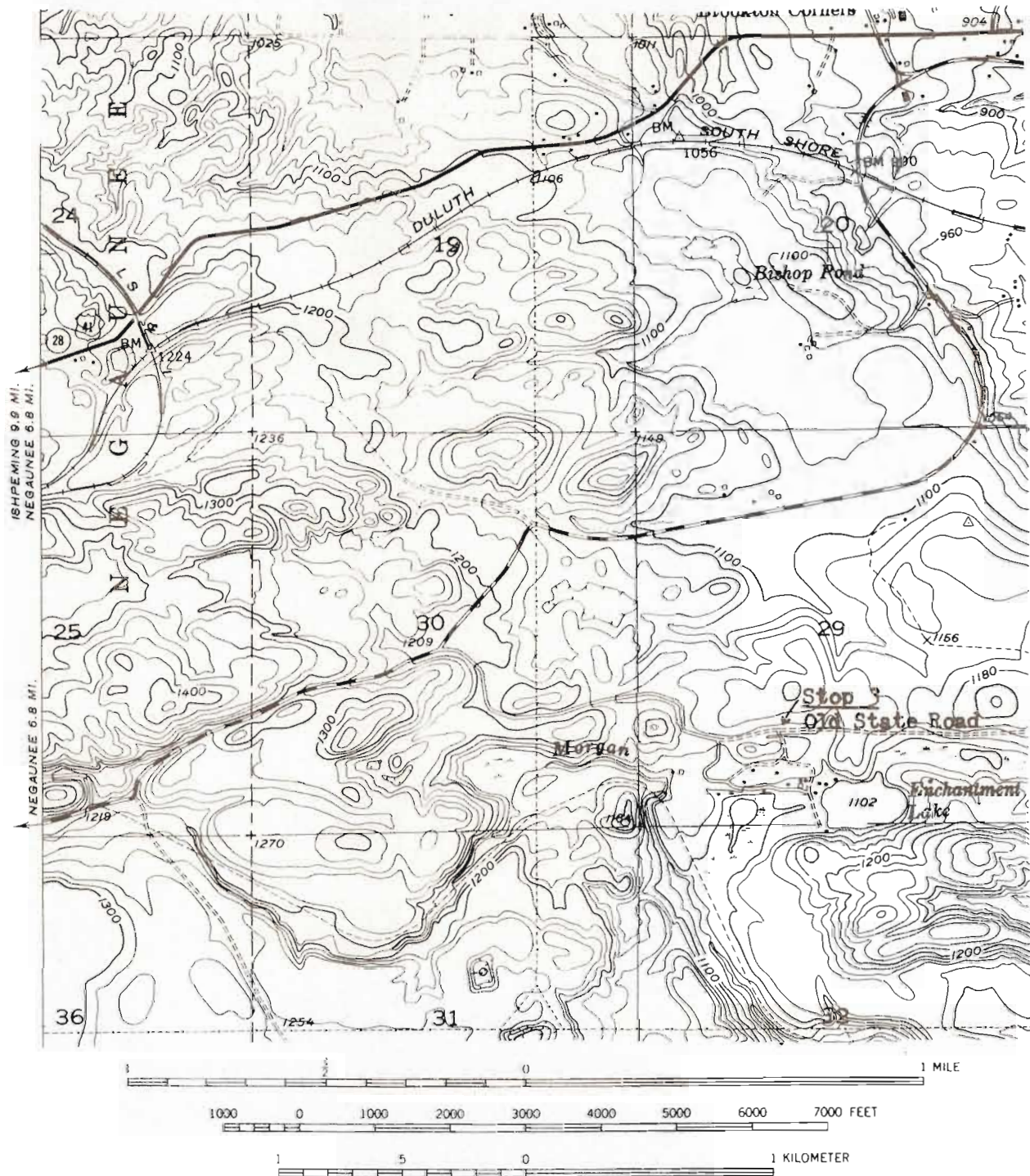
Immediately north of the Old State Road are several exposures of basal conglomerate of the Enchantment Lake Formation, containing fragments of tonalitic gneiss and greenstone. The matrix is rich in chlorite. The conglomerate can be seen in sharp vertical contact with slaty greenstone of the underlying Mona Schist (Precambrian W). Within 100 feet north of the contact, the Mona Schist becomes comparatively massive. Both the greenstone and the conglomerate are strongly foliated near the contact, and steeply plunging to vertical lineations are common on foliation surfaces.

The contact of Mona Schist (Precambrian W) and the Enchantment Lake is interpreted to be a fault. In addition to the highly sheared nature of the contact, the two units are "back to back"; pillows in the Mona on nearby outcrops indicate top directions to the north, whereas the Enchantment Lake and overlying units face south and are nearly vertical. We believe the present attitude of the Enchantment Lake is a result of draping of the sediments over a vertically rising fault block of the Mona. The alternate explanation that the Mona was overturned prior to Enchantment Lake deposition and was subsequently folded back to vertical seems less likely.

Menominee Group

The Menominee Group overlies the Chocoday Group with low-angle unconformity. West of Negaunee, where the Chocoday Group is completely eroded, the Menominee Group lies on Precambrian W rocks. Like the Chocoday Group, (the Menominee) is principally a transgressive sequence of basal quartzite (Ajibik Quartzite, stop 4) overlain by slate and argillite (Siamo Slate, stop 4) which grades upward into Negaunee Iron-formation (stops 5,6,7,9,10,13).

A question to ponder while examining these rocks is: why is the initial transgressive sequence, the Chocoday Group, relatively poor in iron, thus culminating in deposition of Ca and Mg carbonate rocks, whereas the succeeding transgressive sequence, the Menominee Group, is greatly enriched in iron, thus culminating in deposition of iron-formation? Most geologists now agree that weathering of a land mass is the most likely source of iron in the iron-formation, but if that is truly the case, why did the land mass contribute so little iron during Chocoday deposition and so much during Menominee deposition?



CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

Figure 3. A portion of the Marquette 7½-minute quadrangle showing the location of stop 3.

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One explanation might be that thick iron-rich residual deposits formed on land during the very stable condition under which the Chocolay Group formed. The Negaunee Iron-formation contains clastic lenses that we interpreted to reflect minor tectonic instability. Deposition of the iron-formation was shortly followed by more prominent instability during deposition of the Baraga Group. The onset of this orogenic or epiorogenic movement may have rejuvenated streams, resulting in the rapid erosion of iron-rich residual material and thus accounting for the pulse of iron deposition now recorded in the Negaunee Iron-formation.

Stop 4 (Fig. 4). Ajibik Quartzite and Siamo Slate.

The Ajibik Quartzite is exposed in roadcuts on both sides of U.S. 41 near point (a) on Figure 4. It is the basal quartzite of the Menominee Group and here overlies Mesnard Quartzite exposed in cuts just to the east. The geology here has been mapped in detail by Puffett,² and he described the Ajibik as gray vitreous quartzite and lesser amounts of conglomerate, slate, and graywacke. Near the base of the unit is a distinctive granule bed, about 10 inches thick, containing pebbles as much as one inch in diameter. It is overlain by about 4 feet of distinctly crossbedded quartzite. These units have been important as marker beds demonstrating that the Ajibik gradually truncates underlying units. A distinctive staining feature in these roadcuts is concentric bands of fine-grained manganese minerals and hematite. They resemble Liesegang rings and probably resulted from diffusion of dark-colored minerals. Where incompletely developed, some of the features resemble crossbeds.

The Siamo Slate is exposed in a roadcut on the south side of U.S. 41 near point 4(b), Fig. 4.

Typical Siamo Slate is exposed here on the north limb of the Marquette synclinorium, about 450 to 600 feet above the Ajibik Quartzite and roughly 1100 feet below the Negaunee Iron-formation. The Siamo is a pelitic rock containing quartz, chlorite, and sericite. The fresh rock is dark- to light-gray or gray green. The slate tends to weather to gray brown or pale yellow brown. Beds that contain some sideritic(?) carbonate weather reddish brown. Bedding strikes generally westward and dips 50 - 60 S., but its orientation varies locally on drag folds. This is well shown in the low outcrop on the northwest side of the highway. A very characteristic feature of the Siamo, which is prominently displayed in the road cut, is the interbedding that is generally gray green or a lighter gray than the slate. This clastic rock contains varying amounts of quartz and feldspar and

²W.P. Puffett, 1974, Geology of the Negaunee Quadrangle, Marquette County, Michigan: U.S. Geol. Survey Prof. Paper 788, 53 p.

argillaceous matrix minerals. Feldspathic quartzite or arkose is most abundant, but graywacke, sericitic quartzite, and graywacke-like rock in a carbonate-muscovite matrix also occur in the exposure. At both the southwest end and near the northeast end of the road cut, 20 to 25 feet of arkosic rocks occur in beds 1 to 5 feet thick. Interbedded in the slate that it exposed between these thicker zones of arkosic rocks are thin graywacke or other clastic beds, 1 to 6 inches thick. On the south side of the road cut, tightly folded slate is in contact with thick monoclinaly dipping arkosic rock.

Note that the prominent cleavage cutting the slate layers in the central part of the road cut dips southward more steeply than the bedding. The cleavage bedding relationships indicate that a synclinal axis is to the south and this is consistent with this exposure being on the north limb of the synclinorium. The cleavage evidently is a product of the major deformation that occurred near the end of Precambrian X time.

Lenses of graywacke or sericitic quartzite that transect the slate bedding are a peculiar feature at this locality. It cannot be stated with certainty whether these are clastic dikes or faulted segments of normal beds. Dikes, undoubtedly clastic, which cut Siamo Slate a few miles southeast of Negaunee have no consistent orientation but bend irregularly as they cross the slate. In the road cut, on the other hand, the rather consistent parallelism and near parallelism of the clastic lenses and cleavage in the slate suggest that the lenses are segments of beds that were broken and differentially shoved into the slate along or close to surfaces of shearing during the late Precambrian X deformation. Somewhat similar differential slippage is indicated along the contact between the tightly folded slate and monoclinaly dipping arkosic rock on the south side of the exposure. C. Powell has suggested that the clastic lenses are dikes emplaced along cleavage during tectonic dewatering.³

Quartz-chlorite-sericite assemblages in the Siamo are characteristic of pelitic rocks in the chlorite zone or the lower part of the greenschist facies of regional metamorphism. The Siamo Slate here, therefore, is of low metamorphic grade.

Negaunee Iron-formation

The Negaunee Iron-formation contains a great variety of lithologic types, depending on variations in sedimentary environment, differences in diagenetic alteration, and varying degrees of metamorphism. Much of the formation was originally cherty carbonate and iron-silicate rock such as at stop 5. At least part of the jaspilite units (banded reddish chert and hematite) are probably primary oxide

³ C. McA. Powell, 1969, Intrusive sandstone dikes in the Siamo Slate near Negaunee, Michigan: Geol. Soc. America Bull., v. 80, pp. 2585-2594.

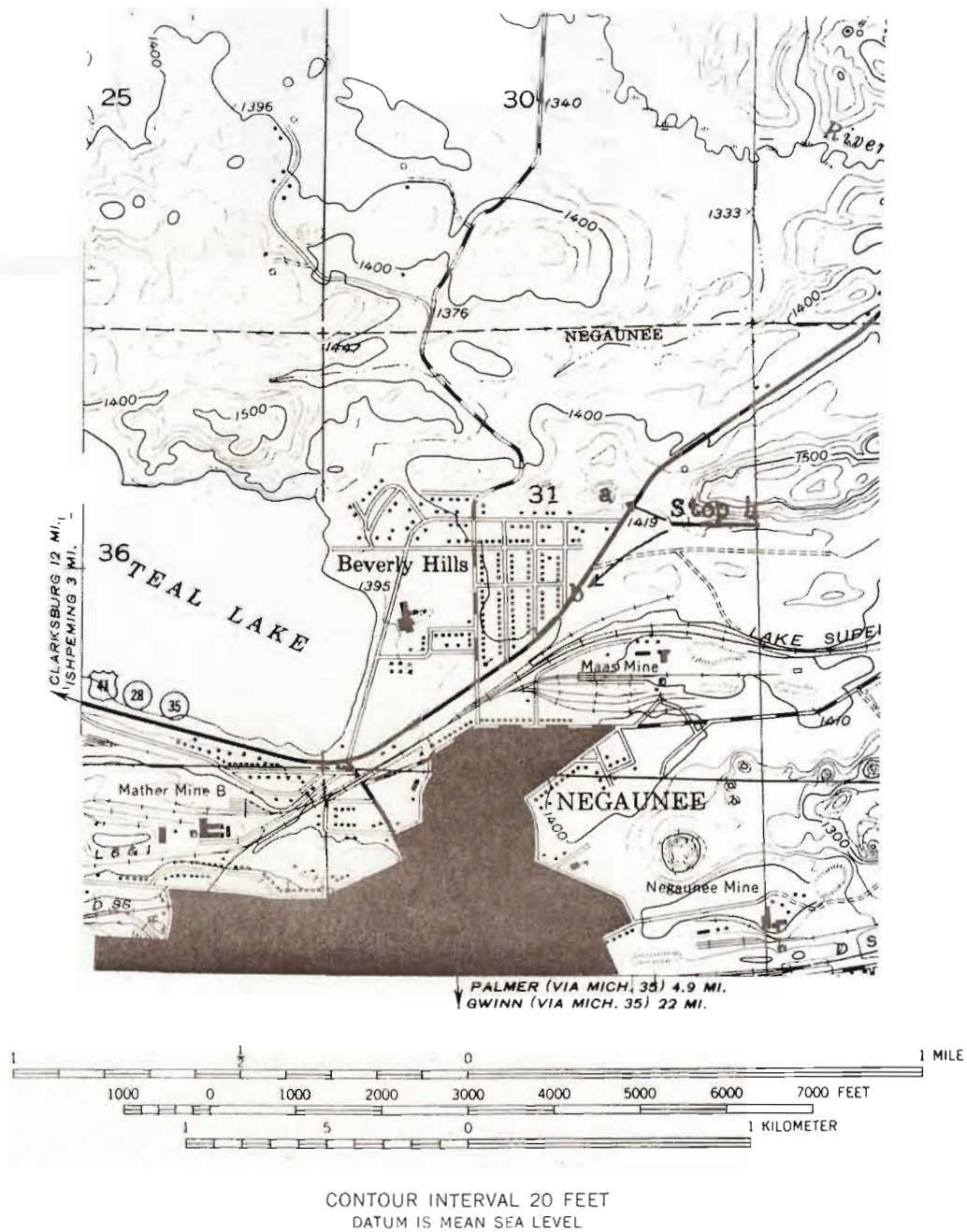


Figure 4. A portion of the Negaunee 7-1/2 minute quadrangle showing the location of stop 4.

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facies material (see stop 10) but elsewhere, such as at Jasper Knob (stop 7), jaspilite may have formed by the weathering of carbonate iron-formation shortly after deposition. At higher metamorphic grades, iron carbonate and silicate rocks such as minnesotaite are recrystallized to grunerite, resulting in magnetic gruneritic schist such as at stop 13.

The Negaunee is the principal iron-bearing unit in the Marquette Range. It has produced large quantities of high-grade secondary ores, but now such ore is recovered only at the Mather mine which can be seen to the west of stop 4. Since the mid-1950's, concentrating-grade ore has become the principal source of iron and presently about 12 million tons of concentrates are produced annually.

The Negaunee is believed to contain at least 2 billion tons of concentrating-grade ore mineable and processable with existing technology. The total iron resource is probably at least an order of magnitude larger.

Note: The geology at stops 5, 7, and 10 were prepared in collaboration with H. L. James for a previous I.L.S.G. guidebook; the descriptions used here are based largely on that work.

Stop 5 (Fig. 5). Negaunee Iron-formation near Athens mine.

Rock typical of the lower part of the Negaunee Iron-formation is exposed in the road cut. Sills of greenstone (metadiabase) less than 1 foot (30 cm) thick can be seen in the iron-formation along the south side of the road. The exposure shows a typical example of the carbonate facies of iron-formation.

The iron-formation here consists mainly of alternating laminae of sideritic carbonate and fine-grained quartz (chert), but some layers contain as much as 15 percent minnesotaite, which imparts a greenish color, and some layers contain a small amount of magnetite. Laminae characteristically range from paper thin to about half a centimeter in thickness. Layers are not pure; the quartzose layers, in particular, tend to have crystals of carbonate scattered through them. In the fresh rock the darker gray-green laminae are the richer in carbonate and minnesotaite. At this stop note the fine grain size, which is characteristic of the iron-formation in the low-grade (chlorite) metamorphic zone in the eastern part of the Marquette synclinorium.

This exposure provides striking examples of the effects of surface weathering oxidation, and replacement of sideritic iron-formation. The weathering oxidation effects have taken place within a relatively few years since the present cut was made. Oxidation replacement has advanced inward from cracks and exposed surfaces, first causing the conversion of layers richer in carbonate into yellow-brown to reddish brown goethitic iron oxide, and eventually changing even quartzose laminae into iron oxide, as indicated by the continuous zones of rusty iron oxide replacing both sideritic and quartzose laminae within a few millimeters of access surfaces. These surficial effects are rudely analogous to those that occurred in carbonate-facies iron-formation during the growth of bodies of soft earthy hematite in synclines and other "upward-facing" structural settings. The replacement of quartz (chert) by iron oxide, such as seen in the Athens road cut, occurs more readily and extensively in finer grained iron-formation than in coarser grained iron-formation. The presence of finer grained rock has been an important factor contributing to the greater development of soft earthy iron ore in the eastern part of the Marquette district than in the western part, where, owing to higher grades of metamorphism, quartz grains are as much as 50 times larger than in the eastern part of the district.

Stop 6 (Fig. 5). Negaunee Iron-formation at the South Jackson Pit.

The exposures in the South Jackson Pit are the upper part of the Negaunee Iron-formation. Here the weathering-oxidation such as seen at stop 5 is much more widespread. The iron-formation is well oxidized and is characterized by irregular replacement, principally by hematite. This locality is the most significant locality where manganese minerals, principally manganite and pyrolusite, are found with hematite. The iron-formation here averages 2% manganese. Selected ore produced from the Lucy mine (about .7 mile to the southeast) contained as much as 11% manganese.

Stop 7 (Fig. 6). Negaunee Iron-formation at Jasper Knob.

Classic exposures of the jaspilitic upper part of the Negaunee Iron-formation may be seen on Jasper Knob. These exposures are in the central part of the Marquette synclinorium, north of the major fold axis of the district.

The iron-formation characteristically has alternating thin beds and lenses of steel-gray, dark-blue-gray, dark-gray, or black specular hematite and bright-red hematitic fine-grained cherty quartzite. Beds commonly range in thickness from a fraction of a millimeter to about 2 centimeters, and fine internal laminations can be seen in the thicker layers. Specularite plates are strongly oriented parallel to bedding in the hematitic layers. Excellent colored illustrations of this

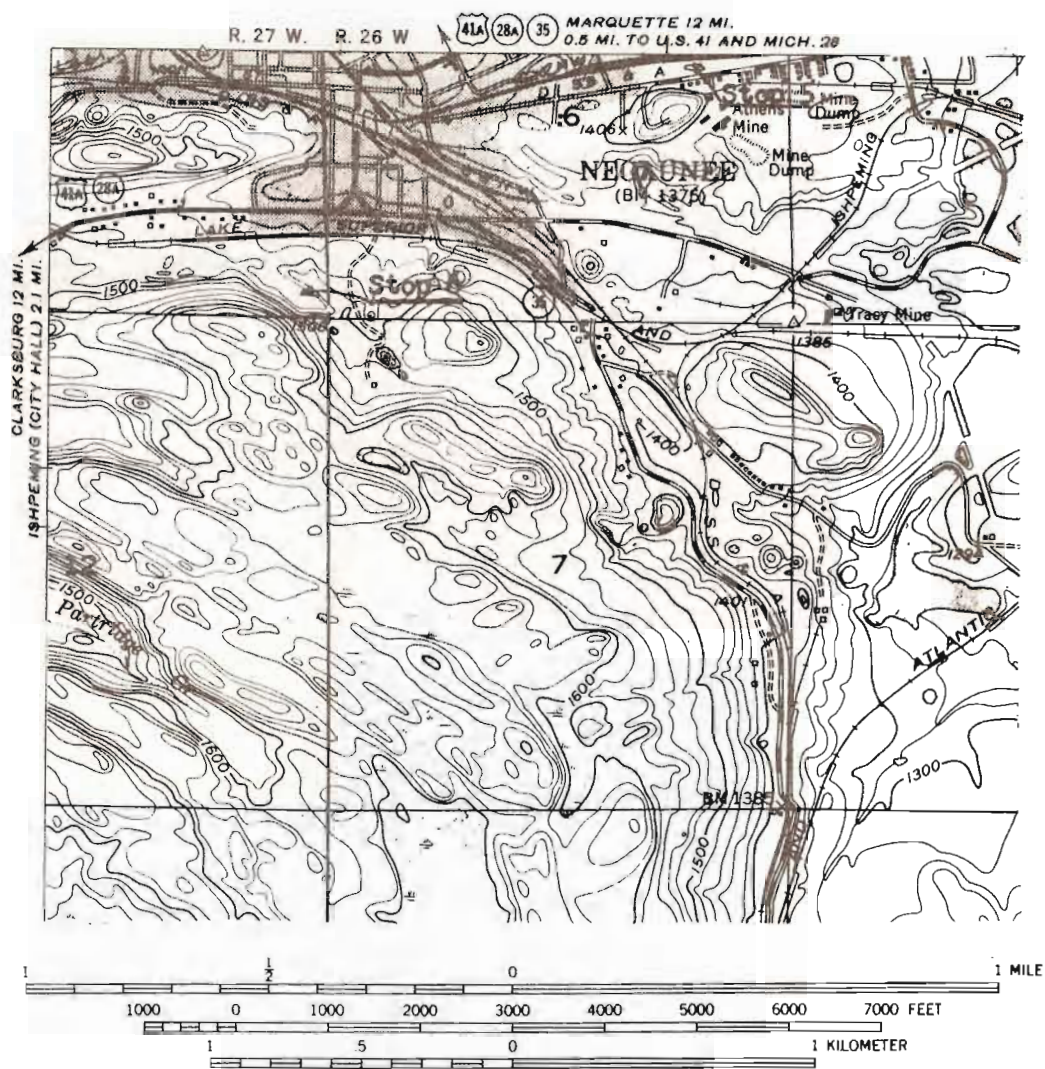


Figure 5. A portion of the Palmer 7½-minute quadrangle showing the location of stops 5 and 6.

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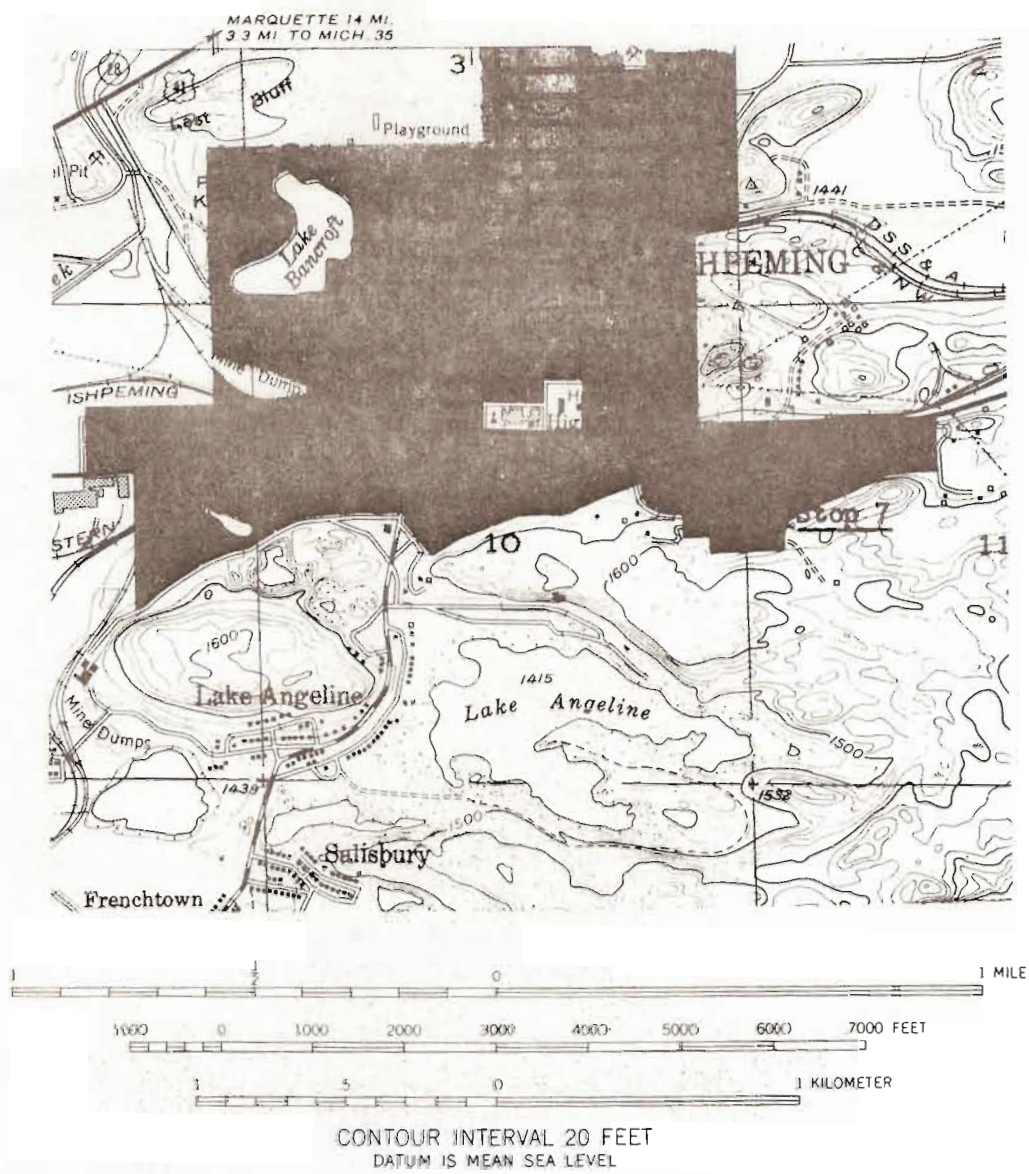


Figure 6. A portion of the Ishpeming 7½-minute quadrangle showing the location of stop 7.

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rock have been published in U.S. Geological Survey Monograph 28.⁴

Folds having drag folds on their limbs and themselves being drag folds on the limb of a still larger fold are strikingly shown in most exposures. Fold axes are horizontal to gently plunging. In cross section the south limbs of individual anticlinal drag folds commonly are longer than the north limbs, indicating that the major synclinal axis passes south of Jasper Knob.

Small breccia zones occur in the iron-formation at this locality. Along them the comparatively brittle reddish cherty (jasper) layers in particular have been fragmented. Fractures have been healed mainly by crystalline hematite. Some of the breccia zones may correspond in orientation to axial plane cleavage.

Two principal theories have been advanced for the origin of the jaspilitic iron-formation at Jasper Knob. One theory advocates oxidation of a siderite-chert iron-formation during the post-Negaunee erosional interval and its recrystallization to specularite-quartz during the late Precambrian X orogeny and metamorphism. This theory would account for patches of jaspilite in carbonate-facies iron-formation which are present near contacts between the two rocks as, for example, in the Cliffs Shaft mine about 1/2 mile northwest of here. The second theory advocates a primary origin for the iron oxide, either as depositional hematite or as magnetite derived by diagenetic modification of depositional oxides. The rock here resembles megascopically, particularly in the very even bedding, magnetite-rich facies of iron-formation rather than hematitic facies, which is characteristically irregularly bedded and oolitic.

Compare the material here with that at Kloman mine (stop 10, Fig. 8).

Stop 8 (Fig. 7). Precambrian W granitic rocks near Greenwood Reservoir.

The two principal granitic units forming the Precambrian W southern complex will be seen here. Near point 8A (Fig. 7) Compeau Creek Gneiss is exposed in a large roadcut. The Compeau Creek Gneiss is generally medium- to coarse-grained and mostly granodiorite or tonalite. It is characteristically both compositionally and structurally heterogeneous at outcrop scale. Here, it varies from massive rocks with faint banding or schleiren expressed by variations in percentage of mafic minerals, mostly biotite, to rather well foliated gneiss. Clots of biotite are common and in places are aligned in the foliation. Relict garnet cores can be found in some clots. Toward the northeast end of the road cut, the Compeau Creek Gneiss is cut by a nearly vertical dike of Precambrian X metadiabase.

⁴ C.R. Van Hise, and W.S. Bayley, 1897, The Marquette Iron-bearing District of Michigan: U.S. Geol. Survey Mon. 28, 608 p.

Near point 8B (Fig. 7) the Bell Creek Gneiss is exposed in low outcrops south of the road. The Bell Creek is a very coarse-grained rock, mostly adamellite characterized by abundant megacrysts, of microcline microperthite as much as about 2 inches long. The rock is compositionally homogeneous over very large areas. Megacrysts are commonly aligned to define a foliation which, in turn, defines regional folds having wavelengths of many miles.

The Compeau Creek Gneiss intrudes Bell Creek Gneiss at many localities and is clearly the younger of the two units, but both units together define a Rb/Sr isochron of about 2.7 b.y., as determined by W.R. VanSchmus.

Greenwood Reservoir

The Greenwood Reservoir is a prominent new land mark near stop 8 (See Fig. 7). It was created in 1973 by the Tilden Mining Company to provide a constant source of water for the concentrating plant requirements. The water surface approximates 1400 acres. The Reservoir area is open to the public for fishing, boating, hiking, and other recreational activities. The agreement with the Michigan Department of Natural Resources provides that, at all times, the discharge downstream to the Middle Branch of the Escanaba River will be at least three times the minimum low flow observed by stream gauging over many years. An interesting feature of the system is the multiport discharge system in which any combination of four vertically arranged ports may be utilized to mix waters of varying temperatures and oxygen content.

Stop 9 (Fig. 8). Republic Mine.

We will make a brief stop at the public lookout to view an active open-pit mining operation. The public lookout is located at the north end of the principal part of the Republic mine. As the viewer faces the pit looking south, the ore dips vertically or steeply to the right. The ore zone, the upper jaspilite unit of the Negaunee Iron-formation, is about 300 feet thick near the north end of the pit but reaches as much as 500 feet thick near the keel of the Republic syncline where the pit turns to the west and largely passes out of sight. The lookout is nearly on the Negaunee-Goodrich contact, and good exposures of thick bedded Goodrich Quartzite can be seen in the pit to the right (west) of the ore. To the left (east) is a high vertical wall formed by the upper contact of a metadiabase sill in the Negaunee. Note the wire mesh stabilization of the wall using rock bolts. The new primary crusher is located in this material and has a 2777-foot long inclined conveyor gallery connecting the crusher to the plant site. The floor of the pit is 520 feet below the level of the land surface at which mining started.

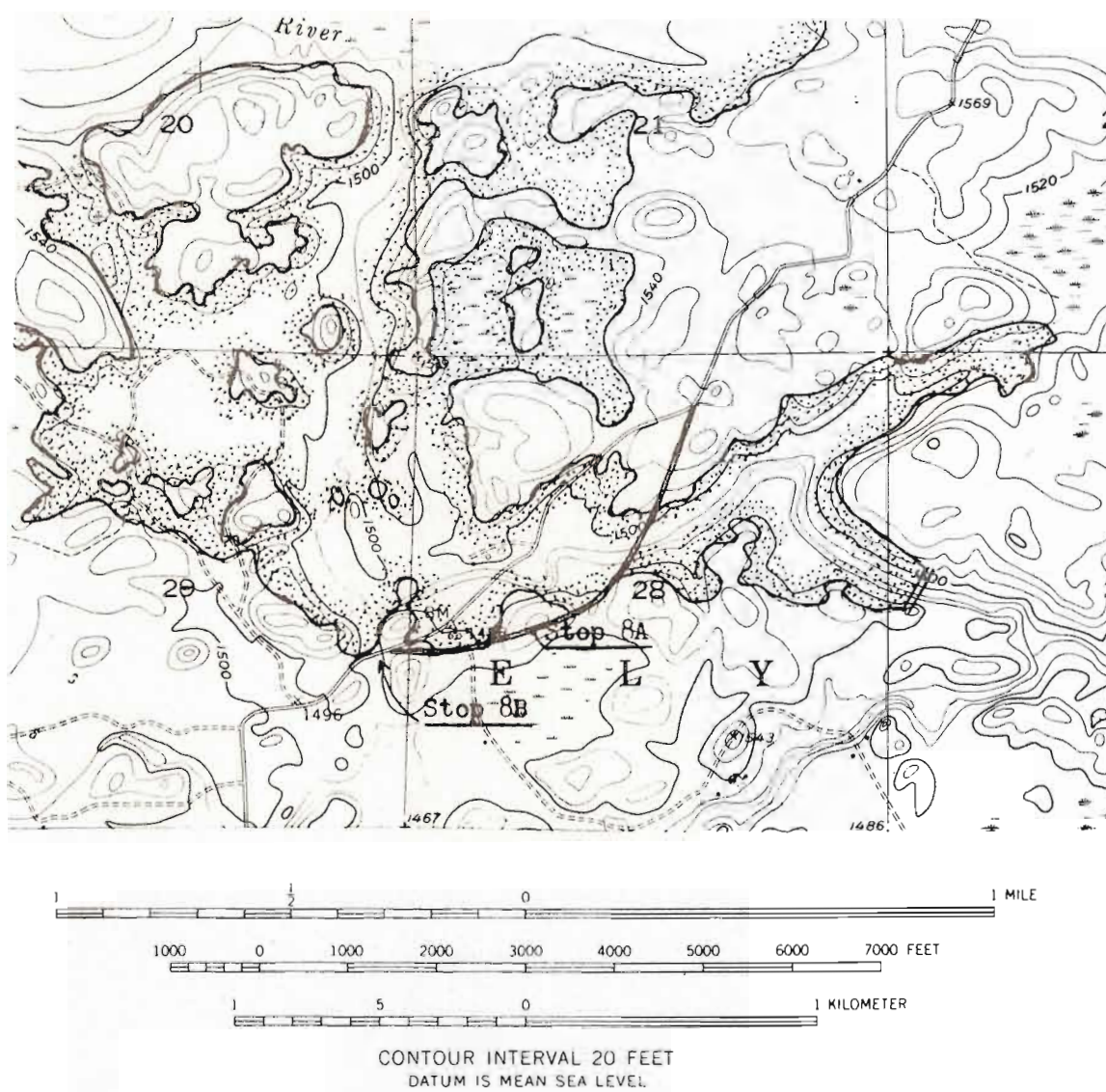


Figure 7. A portion of the Greenwood 7 1/2-minute quadrangle showing the location of stops 8A and 8B.

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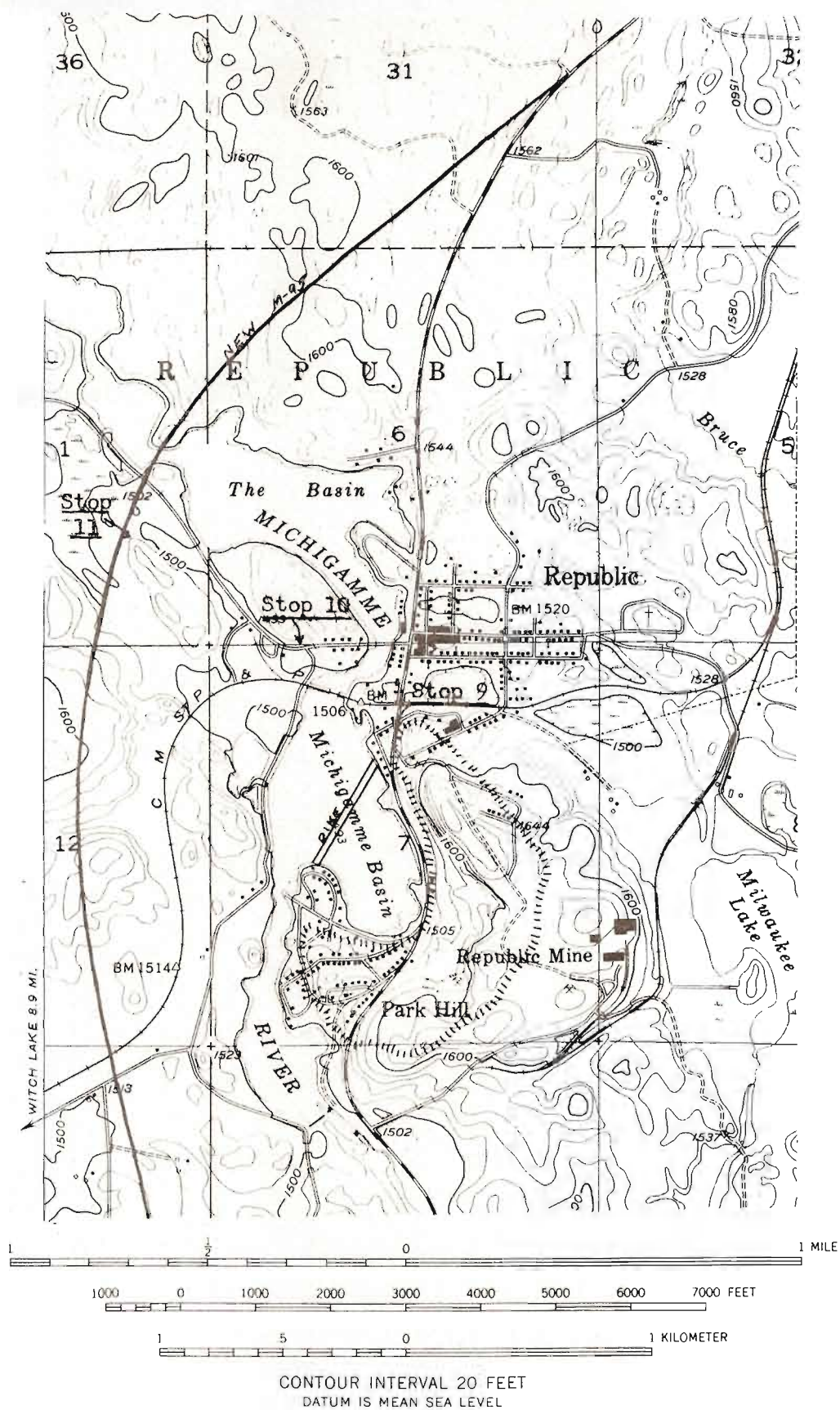


Figure 8. A portion of the Republic 7½-minute quadrangle showing the location of stops 9, 10, and 11.

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Stop 10 (Fig. 8). Negaunee Iron-formation at Kloman Mine.

A large, glacially polished outcrop near the abandoned Kloman mine provides an exceptionally good exposure of the commercial taconite horizon near the top of the Negaunee Iron-formation and contains several features of petrologic interest.

The outcrop is on the northeast limb of the Republic syncline. The rocks strike about N. 45° W. and dip vertically. Several lithologic types of iron-formation are complexly interbedded; the detailed section is illustrated in Figure 9. As a point of reference, the large steel eye bolt set into the outcrop corresponds to the horizon at 42 feet on the section in Figure 9.

These rocks illustrate a marked lateral facies change from the Republic pit, which is directly along strike about 3,000 feet to the southeast. Whereas the ore horizon in the Republic pit is entirely jaspilite, with a few tens of feet of chert-magnetite iron-formation at the base, the ore horizon here contains many units of chert-magnetite and chert-magnetite-silicate iron-formation interbedded with the jaspilite.

A close correspondence between bedding characteristics and mineralogy suggests that the present mineralogy, although a product of sillimanite-grade metamorphism, reflects original differences in the sediments, particularly in oxidation states.

Hematite-bearing units are typically wavy-bedded and contain red or maroon jasper, much of which is oolitic. This is in contrast to magnetite-rich and silicate-bearing units which are typically even-bedded and contain no hematite, jasper, or oolites. Presumably, the wavy-bedded hematitic rocks were deposited in relatively shallow water, above wave base, where currents were sufficiently intense to produce disturbed bedding and oolites, and where the water was sufficiently oxygenated to result in a thoroughly oxidized sediment. The even-bedded magnetite and silicate rocks, on the other hand, are presumed to have formed in deeper water, below wave base, where a combination of quiet bottom conditions and relatively unoxidized water allowed the accumulation of incompletely oxidized iron minerals in uniform layers. If this is so, the rocks here indicate deposition in progressively shallower water having several fluctuations either in depth of water or depth of wave action to produce the interlayering of lithologies in the transition zone between the dominantly ferrous sediments at the base of the section and the ferric sediments at the top of the section.

The close correspondence between bedding characteristics and mineralogy is convincing evidence that these rocks represent a primary oxide facies of iron-formation and that the specularite and magnetite

are metamorphic derivatives of primary hematite and magnetite, respectively, or precursor minerals having similar oxidation states. Some minerals, here considered as primary, may have formed by diagenetic changes shortly after deposition; however, the oxidation state of each bed must reflect the composition of bottom or interstitial water, for adjacent beds may be of markedly different oxidation states.

The rocks here were metamorphosed to sillimanite grade during the Penokean orogeny, as indicated by the coarse grain size of chert and by mineral assemblages in nearby pelitic rocks. Of particular interest at this outcrop is the lack of equilibration of oxidation states between adjacent units in spite of the intense metamorphism. Dominantly hematitic units are in direct contact with dominantly magnetitic units, and, although hematitic beds are nowhere in direct contact with silicate-bearing beds, they are separated by only thin chert beds in many places. These relationships attest to the inability of metamorphic fluids to induce widespread oxidation or reduction of solid phases and are a classic illustration of rocks in which the chemical potential of oxygen was controlled by the solid phases during metamorphism.

The Negaunee Iron-formation will be seen again at stop 13 (Fig. 11).

Baraga Group

The Baraga Group contains two formations, the Goodrich Quartzite and Michigamme Formation. The Michigamme, the youngest unit in the area, includes a complex and extremely thick sequence of rocks and by itself is many times thicker than the entire underlying section.

The group was deposited with low-angle unconformity over the Menominee Group or locally, where the Menominee Group was completely eroded, lies on Precambrian W rocks.

Deposition began with a transgressive sequence of basal conglomerate and quartzite (Goodrich) and gradually was dominated by fine-grained carbonaceous mud and iron-formation (lower part of Michigamme Formation), although volcanic rocks (Clarksburg) formed locally. Eventually, rapid deposition and subsidence resulted in a vast volume of turbidite deposition (upper slate member of Michigamme Formation).

Stop 11 (Fig. 8). Michigamme Formation (lower slate member).

Tightly folded schist of the lower slate member of the Michigamme Formation is exposed in a roadcut on the east side of highway M-95 near the axis of the Republic syncline. The rock here is iron-rich metasediments, now consisting of biotite-garnet-amphibole schist

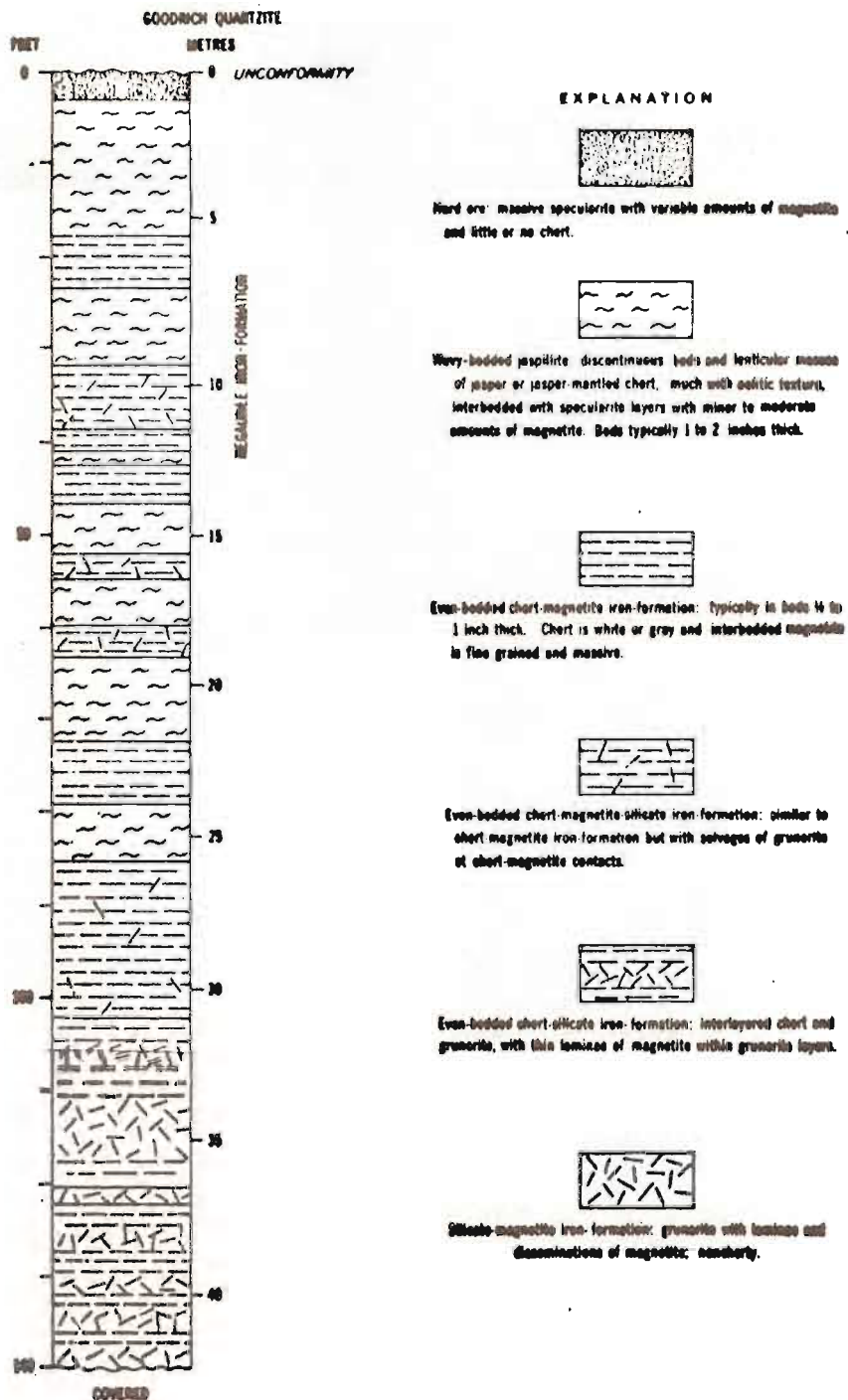


Figure 9. Stratigraphic Section of Negaunee Iron Formation near Kloman Mine, Republic, Michigan.

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that contains a few inch-thick layers of impure quartzite. Although the rocks are in the sillimanite zone of metamorphism, sillimanite is not present here because of the lack of appropriate aluminous source materials. Minor folds having amplitudes much greater than wavelengths and greatly attenuated limbs are common and reflect the geometry of the major syncline whose preserved keel is deeper than it is wide at this point and becomes deeper to the northwest. Folding is markedly noncylindrical at outcrop scale; domains of homogeneous strain are commonly only a few square feet. Most minor folds plunge northwest in accordance with the regional synclinal axis but plunges vary from about 15° SE to 60° NW.

Near the north end of the outcrop a thin (1 to 3 inches) quartzite bed is repeated many times by minor folds. Axes of adjacent folds only a few inches apart have plunges that diverge by as much as 60° . This noncylindrical geometry may be a result of an earlier fold set in the sedimentary rocks that formed prior to and was strongly overprinted by the folding of the Republic syncline (See stops 15 and 16 for a discussion of the earlier folding).

Stop 12 (Fig. 10). Humboldt tailings basin.

We will stop briefly to examine the progress being made in revegetating tailings from Humboldt Mine.

The Humboldt Mine was an active taconite property from 1953 to 1970. When the west tailings basin became static, a comprehensive revegetation program was initiated by The Cleveland-Cliffs Iron Company, Manager for the Humboldt Mine, in cooperation with the Forestry Department of Michigan Technological University. The tailings consist principally of chert, with minor amounts of hematite and sericite, and average about 50 per cent minus 325 mesh. The north part was planted in 1972 and the south part in 1973. The grasses are alfalfa, rye, orchard grass, timothy, fescue, clover, and wheat.

Stop 13 (Fig. 11). Negaunee Iron-formation and metadiabase sill at Champion relay tower.

Smooth glaciated outcrops north of the relay tower provide excellent exposures of grunerite-magnetite iron-formation which is the dominant lithologic type of Negaunee Iron-formation in the western Marquette Range. This stop is not in proper stratigraphic sequence; rather we will visit it at this point in the trip as a compromise to allow seeing the best available exposures with a minimum of travel.

The rock here consists of medium- to coarse-grained grunerite and lesser amounts of magnetite. Layering (relict bedding) is shown by variations in grunerite/magnetite ratios. Most of the rock is free of chert but in places it changes abruptly along strike to cherty iron-formation. In such places it is clear that much of the grunerite has formed at the expense of chert and it thus seems likely that the precursor iron-mineral was mostly siderite.

Grunerite may form by metamorphism either from Fe-carbonate or other Fe-silicate. Fe-carbonate is favored here because a reaction such as $\text{Fe-carbonate} + \text{silica} + \text{H}_2\text{O} \longrightarrow \text{grunerite}$ would consume large amounts of chert, as has occurred here.

Near the base of the relay tower, a zone rich in garnet and hornblende lies along the contact of a metadiabase sill and the iron-formation. One or both of these minerals commonly forms a nearly continuous rind a few inches thick between the iron-formation and metadiabase and presumably resulted from chemical diffusion between the two rock types during metamorphism.

Stop 14 (Fig. 12). Goodrich Quartzite.

Basal conglomerate of the Goodrich Quartzite is exposed along the north aise of U.S. 41. The conglomerate here is typical of much throughout the range in that it contains two distinctly different types of clasts. The greatest proportion of the clasts are from the immediately underlying Negaunee Iron-formation and are generally subangular to subrounded. They have probably not been transported far. Well-rounded clasts of vein quartz comprise the second type. They are probably derived from a Precambrian W terrane and their well-rounded nature suggests they have been transported farther than iron-formation clasts. Other rock types which could be ascribed to a Precambrian W terrane are exceedingly rare. This, along with the rarity of feldspar in the lower few hundred feet of the Goodrich, suggests that the Precambrian W source area was undergoing intense chemical weathering and the quartz was the only major mineral not broken down; quartz veins were the only rock type resistant enough to form pebble-size clasts.

A controversial feature of this outcrop is the origin of elongated west-trending troughs. The troughs are about 1 foot deep and 2-3 feet apart. Because they trend parallel to regional fold axes, some would interpret them as tectonic features. However, adjacent troughs are in places superimposed, the overlying trough truncating bedding in the underlying trough, and many are supratenuous, the amplitude of the trough decreasing upward. These features indicate that the troughs are of sedimentary origin.

Stop 15 (Fig. 12). Michigamme Formation, upper slate member.

Rocks in the upper slate member of the Michigamme Formation are well exposed in several outcrops in abandoned farm fields east of Spruce River road. "Slate", as used by some authors, is a misnomer for these rocks; most are massive to schistose metagraywacke. These rocks are, in places, well bedded and bedding is especially well shown by staurolite-rich units. Tight folds trend about N. 80° W. and are part of a regional fold set developed in Precambrian W rocks in many

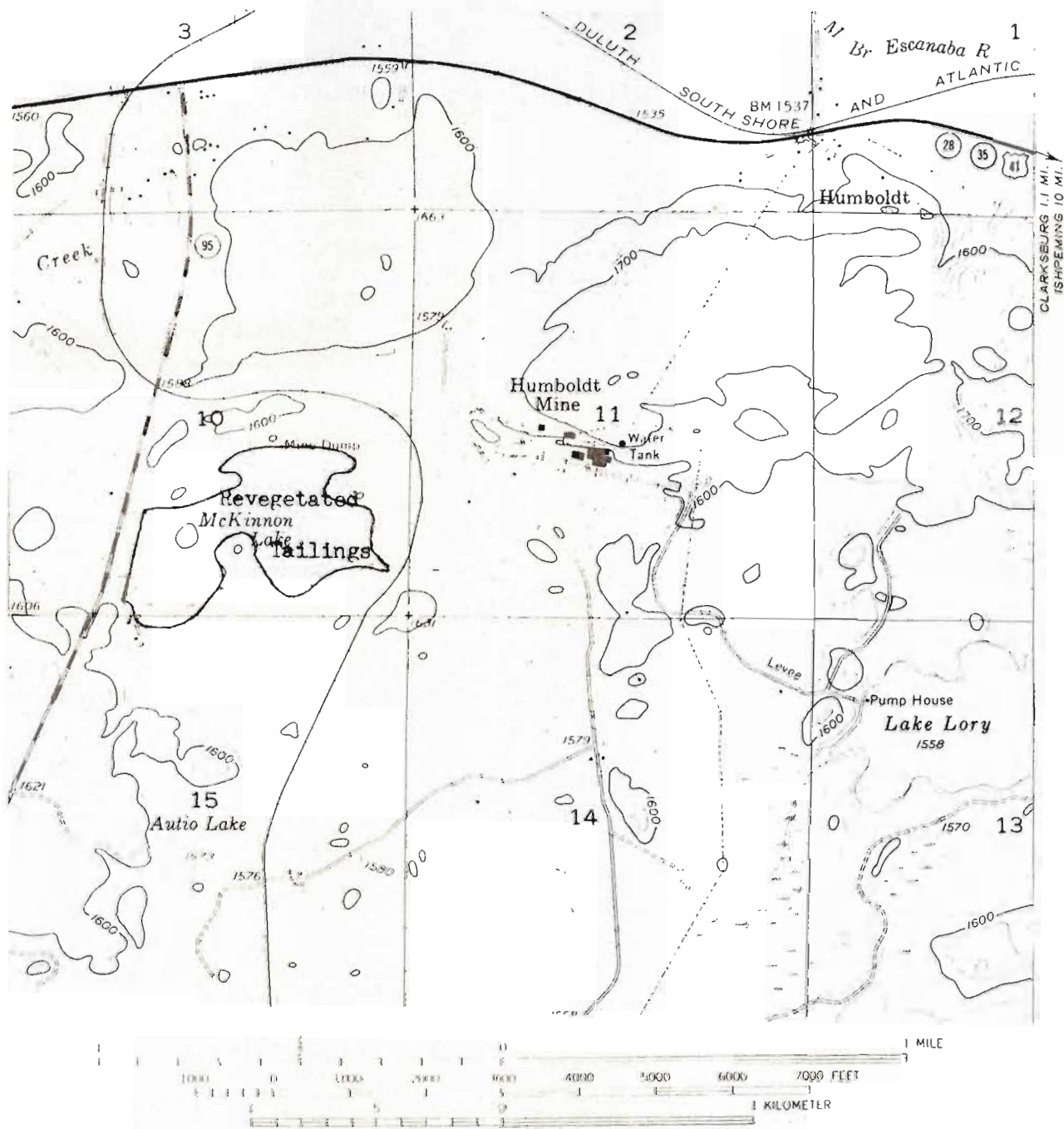


Figure 10. A portion of the Republic 7 1/2-minute quadrangle showing the location of the revegetated tailings at Humboldt mine (stop 12).

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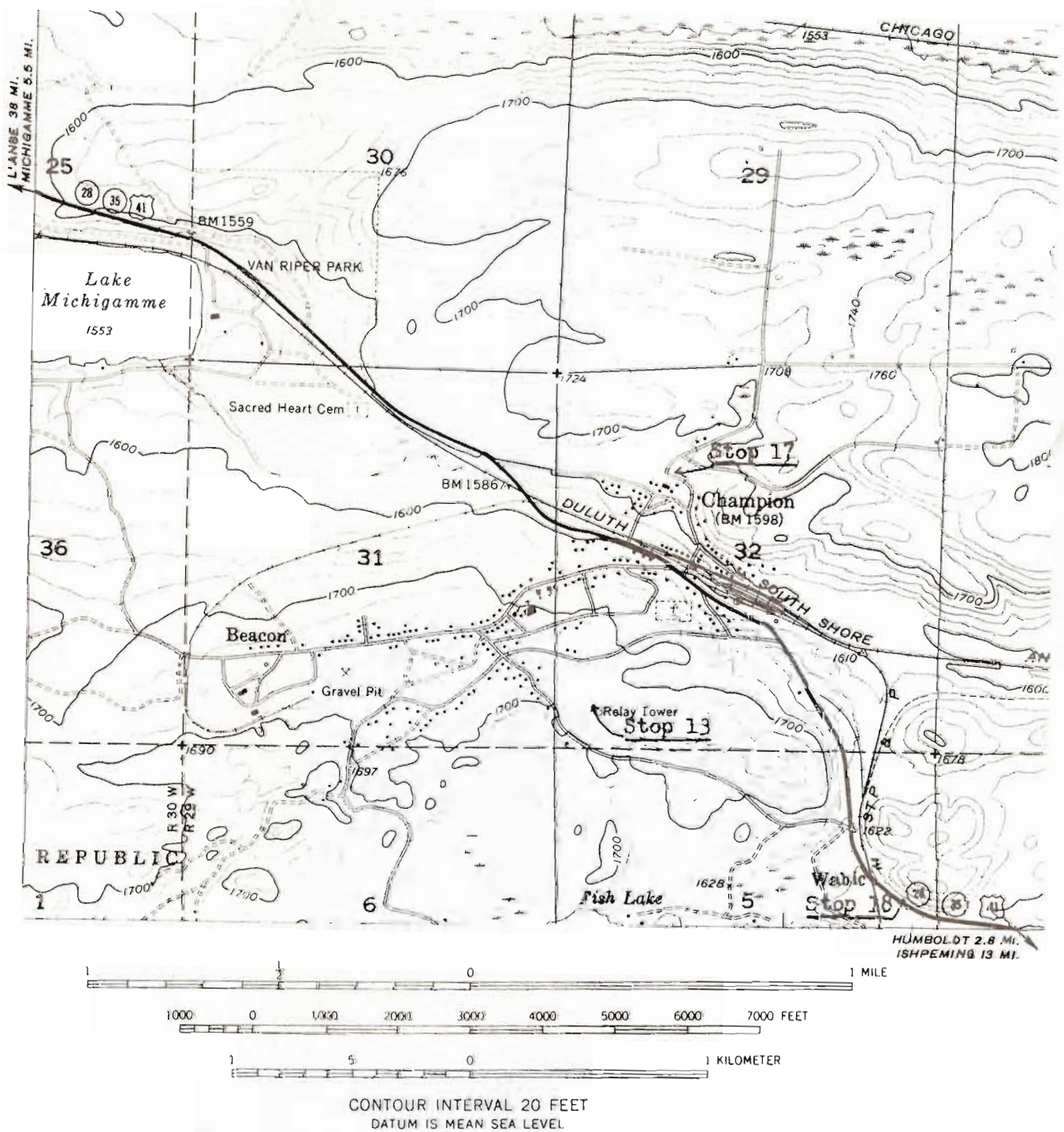


Figure 11. A portion of the Champion 7½-minute quadrangle showing the location of stops 13, 17, and 18.

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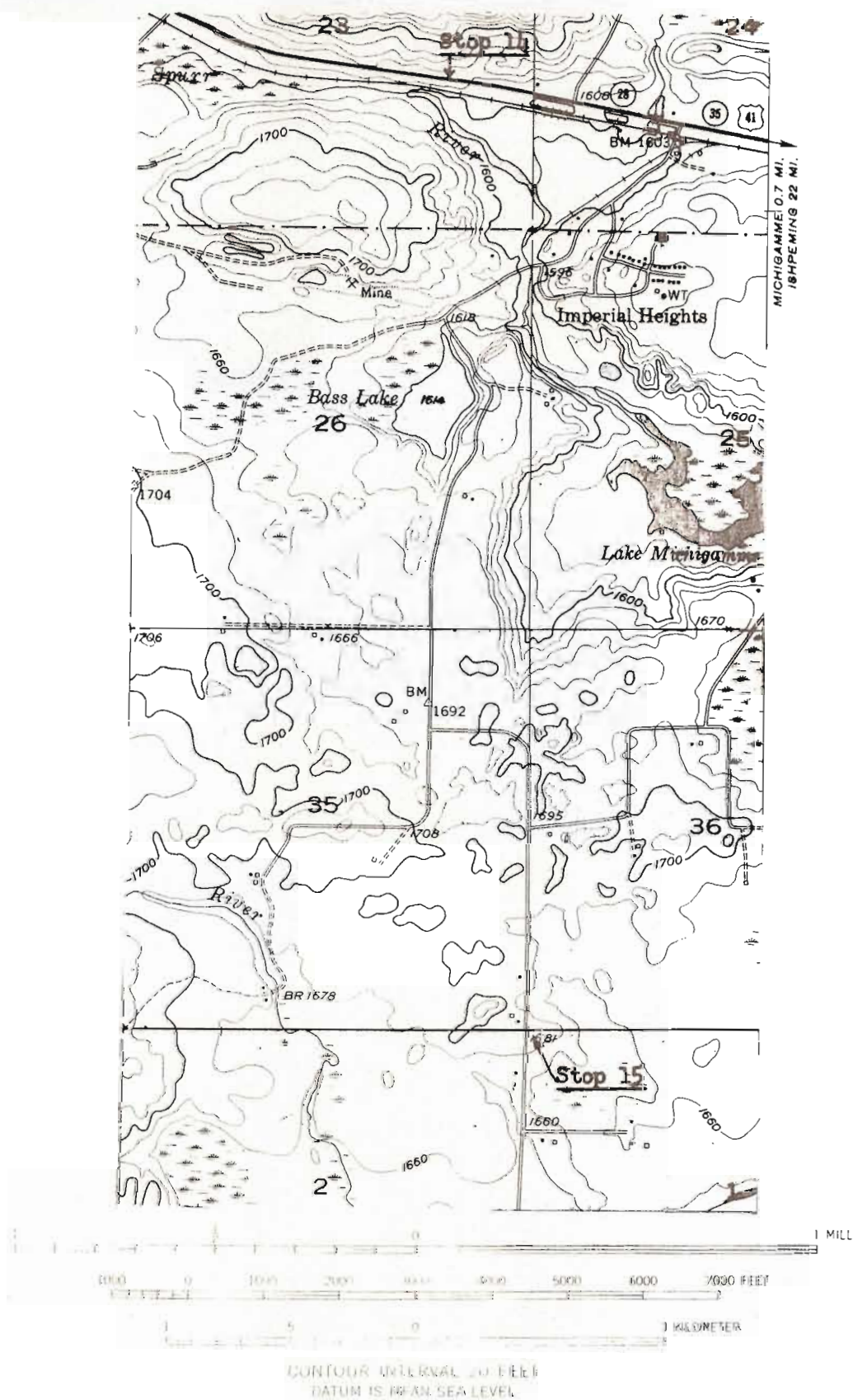


Figure 12. A portion of the Three Lakes 7½-minute quadrangle showing the location of stops 14 and 15.

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parts of northern Michigan. Precambrian W basement rocks contain no recognizable effects of this deformation and thus folding is believed to be thin skinned, affecting only Precambrian X rocks. It occurred prior to basement controlled deformation responsible for regional structures such as the Marquette trough and the Republic syncline. (see stop 16 for additional discussion)

Graded bedding is common in the upper slate member although not convincingly preserved here. To the west near Covington, Michigan, a minimum thickness of about 3 miles for a graded-bedding sequence can be demonstrated; the true thickness may be much greater. By this time in the depositional history, the originally stable craton was greatly mobilized and deeply buried as ensialic eugeo-synclinal deposits accumulated to great thickness.

Stop 16 (Fig. 13). Michigamme Formation, upper slate member.

In this outcrop, structures formed during the two major deformational events are superimposed. The rock is muscovite schist and contains penetrative axial plane foliation formed during the thin-skinned folding preserved at stop 15. There, about 3 miles from the nearest basement uplift, these early folds and foliation were not reformed during younger basement controlled deformation, but here, only 1.5 miles from the uplifted basement block bounding the north limb of the Marquette trough, deformation of the sediments during that uplift has produced a second set of penetrative features. These are crinkle folds in the early foliation and a fracture cleavage in the axial plane of the Marquette trough.

A third minor deformation is shown by northwest-trending nearly vertical kink bands that deform all other tectonic elements.

Stop 17 (Fig. 11). Iron-formation in lower slate member of Michigamme Formation.

This unit was previously thought to be part of the Bijiki Iron-formation Member, which lies between the upper and lower slate members of the Michigamme Formation. In light of recent mapping we now believe it to be a unit within the lower slate member. Near Champion, the lower slate member is mostly massive gray to black quartzite with at least one, and probably more, units of iron-formation generally enclosed in an envelope of black pyritic slate.

The iron-formation is exposed here on the south limb of the Marquette synclinorium, about 1/4 mile south of the major axis and about 3/4 mile north of the south margin. The total width of the synclinorium in this vicinity is only about 2-1/4 miles. This exposure occurs in the staurolite zone of regional metamorphism that rings the Republic sillimanite node (see map of metamorphic zones, Figure 1).

Original laminations, ranging from less than a millimeter to several centimeters in thickness, are remarkably well preserved in spite of the complete recrystallization and nearly completely new mineralogy resulting from metamorphism. The layers now consist of felted masses of grunerite containing minor magnetite and quartz. In one zone, which approximates bedding in attitude, grunerite has formed spherulites which have diameters as much as 3 millimeters. Thin veins of grunerite cut the rock in several places.

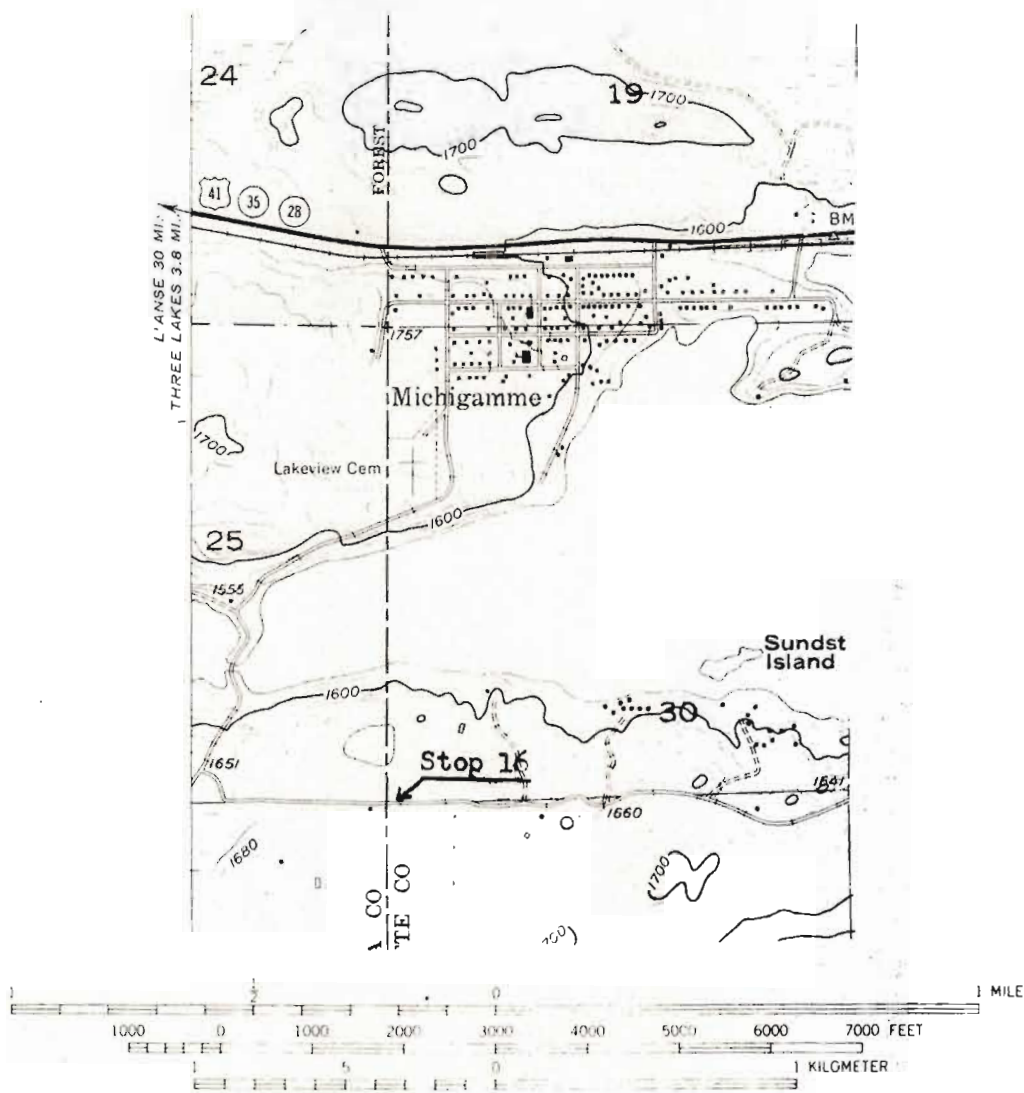
The premetamorphic iron-formation might have been rich in either iron carbonate or iron silicate (greenalite?). Either the silication of original siderite by the combining of its iron with chert and the loss of its carbon dioxide or the recrystallization of low-temperature iron silicate could have produced the grunerite. The fact that cores of relict quartz (chert) are present in some layers suggests that the siderite + quartz reaction predominated; the quartz cores represent excess silica over that needed to react completely with original siderite.

Stop 18 (Fig. 11). Clarksburg Volcanics Member of Michigamme Formation.

The Clarksburg Volcanics Member is a local unit restricted to a strike length of about 15 miles along the south limb of the Marquette trough. They are nearly all pyroclastic rocks, the overwhelming volume of which is mafic, but here they also contain a few layers of intermediate to felsic crystal tuff and locally abundant graywacke. In this outcrop layering is prominent, and pyroclastic textures are well preserved in spite of staurolite-grade metamorphism. A puzzling feature here is the coarse-grained apparently gabbroic texture of some of the mafic units. If this is truly a gabbroic texture, why are the volcanic rocks so coarse grained and what is the origin of subtle compositional layering within the mafic units?

Stop 19 (Fig. 14). Structural relationships in Broken Hills area.

The final stop of the field trip illustrates the structural style of the final major phase of Precambrian X deformation in the Marquette Range. After deposition of the Marquette Range Supergroup and after its thin-skinned deformation, blocks of Precambrian W basement rocks rose along steep faults. The principal structural basins, such as the Marquette trough, formed over relatively downdropped parts of the basement. The Broken Hills area is a scale model of larger regional structures. Here the high east-trending ridge east of the road is underlain by an upthrust slab of Precambrian W basement granitic rocks. The sediments of the Marquette Range Supergroup are molded around this slab to form a west-plunging anticline. A few hundred feet east of the road, the Ajibik Quartzite on the north is in contact with granite to the south. The Ajibik dips about 80°S. beneath the granite.



CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

Figure 13. A portion of the Michigamme 7½-minute quadrangle showing the location of stop 16.

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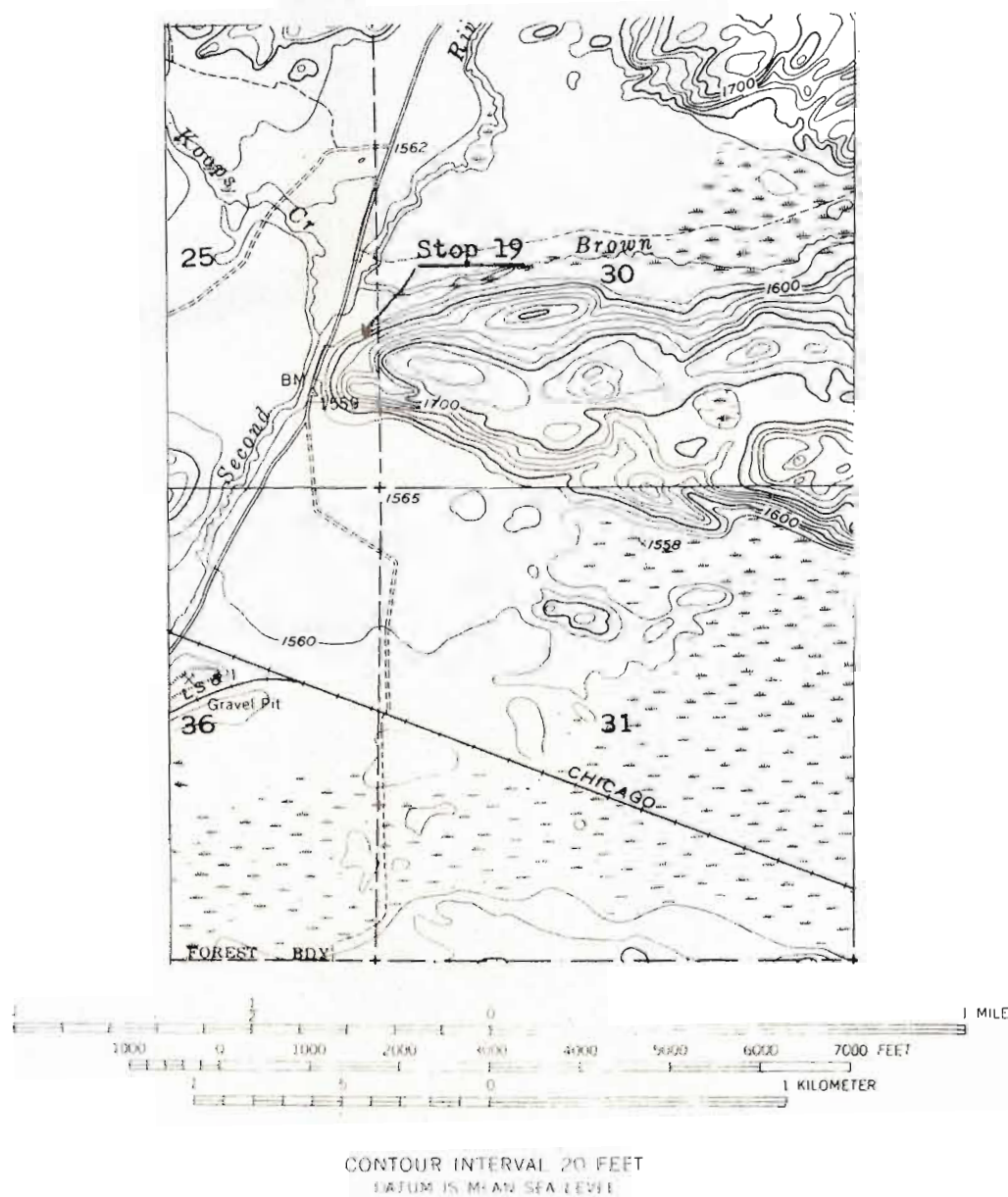


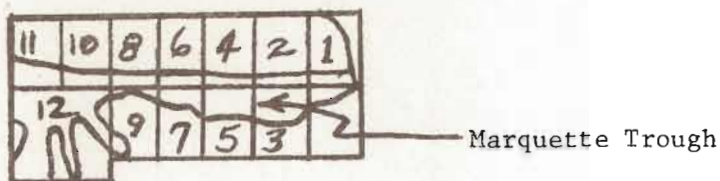
Figure 14. A portion of the Diorite 7 $\frac{1}{2}$ -minute quadrangle showing the location of stop 19.

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The granite is highly sheared within a few feet of the contact and less sheared farther south, although shear foliation is developed to some extent across most of the ridge. The Ajibik is not obviously sheared near the contact, but the general absence of bedding and a few traces of highly distorted bedding suggest that the basal part of the Ajibik also underwent severe internal deformation. Evidently, as basement rocks failed largely by faulting or less commonly in zones of distributed shear, the sedimentary rocks were ductile enough to flow and thus were molded around rising basement fault blocks without themselves being faulted.

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Geology compiled from
U.S. Geological Survey Maps
and Reports



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THE EMPIRE MINE AND MILL
PALMER, MICHIGAN

By

T. Wentworth Slitor and Gerald Kulbieda

Empire Iron Mining Company

Palmer, Michigan

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ABSTRACT

The Empire Mine is an iron ore mining, concentrating, and pelletizing complex operated by The Cleveland-Cliffs Iron Company, Manager for the Empire Iron Mining Company owned by Inland Steel, McLouth Steel, International Harvester, and Cleveland-Cliffs. The mine is located in Palmer, Michigan, on the Marquette Iron Range, approximately two miles south of Negaunee in Michigan's Upper Peninsula.

The ore is mined by conventional open pit methods utilizing shovels with bucket capacities from 6 to 11 cubic yards and trucks with capacities from 75 to 150 tons. Three rotary drills with 12½" or 15" bits are utilized for production drilling. AN/FO (ammonium nitrate-fuel oil mixture) Prills or aluminized slurries are used as the blasting medium. The blasted crude ore is hauled to a 60" by 89" gyratory crusher where the ore is reduced to minus nine inches. The crushed material is then conveyed either to the crude ore storage facility or to the outside crude ore surge pile for later reclamation. Waste rock and overburden are hauled to areas outside the iron formation for dumping and segregation. The yearly production of crude ore mined is approximately 16.8 million long tons at a daily average of 46,000 long tons. Approximately 7.3 million cubic yards of waste rock and overburden are removed annually at a daily average of 20,000 cubic yards.

The concentrating flowsheet consists of two stages of closed circuit autogenous mills (21 separate lines), two stages of magnetic separator concentration, and one step of hydraulic concentration that uses flotation as a final upgrading step. Twelve balling drums and three grate-kiln pelletizing units convert the concentrates into high quality pellets.

The Empire Mine commenced operation late in 1963 and has been expanded in two stages. The first expansion was completed in 1966, increasing annual pellet production from 1.6 to 3.4 million long tons per year. The second expansion completed late in 1974 brought the property to its present capacity of 5.3 million long tons of pellets per year. The pellets are shipped by rail from the mine site to Escanaba or to Marquette where they are transferred to lake freighters for shipment to the steel mills.

The Empire orebody lies stratigraphically in the lower portion of the Negaunee Iron Formation (part of the Menominee Group, Middle Precambrian). Regionally, the orebody is located on the southeast limb of the Marquette Synclinorium. The elongated synclinorium opens and plunges to the west for a distance of 35 miles and attains a width of approximately 5 miles north-south.

Metamorphism occurred with the intrusion of tonalite and granodiorite in Late Precambrian when the Marquette Synclinorium was formed. The Empire orebody falls within the chlorite zone (near the boundary of the biotite zone) whereas the Republic orebody at the west end of the synclinorium falls within the sillimanite zone.

The Empire orebody has been divided into the following facies (Fig. 1):

- Upper undifferentiated iron formation
- Iron formation and clastic interbeds
- Magnetite-chert-carbonate iron formation
- Magnetite-carbonate-silicate-chert iron formation
- Lower undifferentiated iron formation

The formation dips 30 to 40 degrees west-northwest and strikes north-northeast (Fig. 2). Extensive faulting has occurred with some apparent displacements of several hundred feet and has been accompanied by the intrusion of chloritic dikes along some of the fault zones. Jointing is prominent and studies indicate at least four joint sets. The amount of soluble iron is very uniform and commonly ranges between 32% and 35% whereas the magnetic iron varies from 0% to 34%.

For improved efficiency in the milling and pelletizing processes, it is essential that a uniform crude ore feed be maintained within certain limits. As each of the facies react differently in the milling process, a crude ore blending and truck allocation program incorporating a remote computer terminal has been developed to aid pit supervisors in blending the crude ore to prevent wide swings in weight recovery, feed rates, grade, and silica. A terminal (consisting of an IBM 3270 tube display and typewriter console and IBM 3284 printer) located in the pit office allows access to the IBM 370 computer in the Data Processing Department of Cleveland-Cliffs Iron Company at Ishpeming. The blending process has two basic modes of calculation to select:

1. Simple Blend Calculations

In this mode, the program calculates the resultant blend when shovels are assigned to ore blocks at specified production rates.

2. Optimum Blend Calculations (Polypod Testing)

In this mode, shovels are assigned to ore blocks, but the production from each shovel is determined by the program to minimize the differences in ore analyses between the resultant blend and a specified target blend. The "Goodness" of the blend is determined by a mathematical function which uses the differences between resultant and target blend analyses in determining the value of the function.

Once the shovel-ore block combinations and percentage (tonnage) required from the ore blocks are determined from the blending polypod runs, the truck allocation portion of the program can be initiated. The truck program will specify how the available trucks should be allocated to supply the intended blend.

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EMPIRE MINE

IDEALIZED CROSS SECTION

LOOKING N-E

VERTICAL SCALE 1"=400' JULY 1971

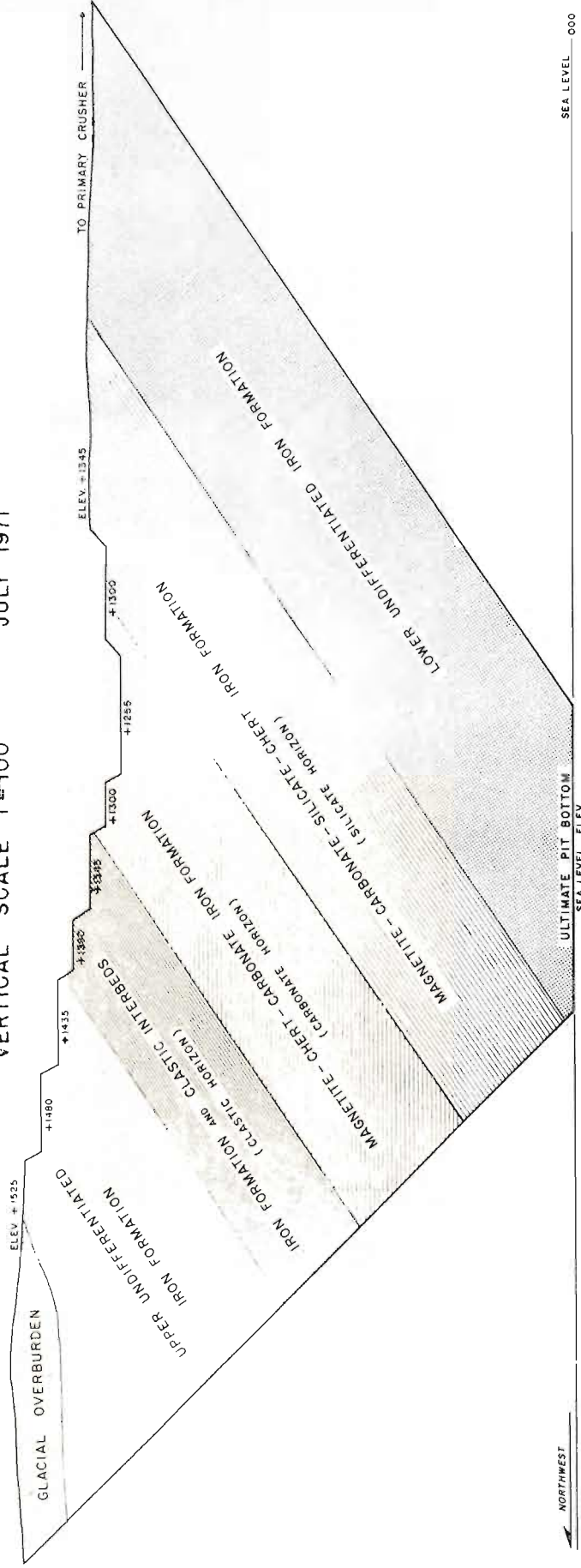


Figure 1

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SURFACE GEOLOGY OF EMPIRE MINE SECTION 19, T.47N., R.26W., MARQUETTE COUNTY, MICHIGAN

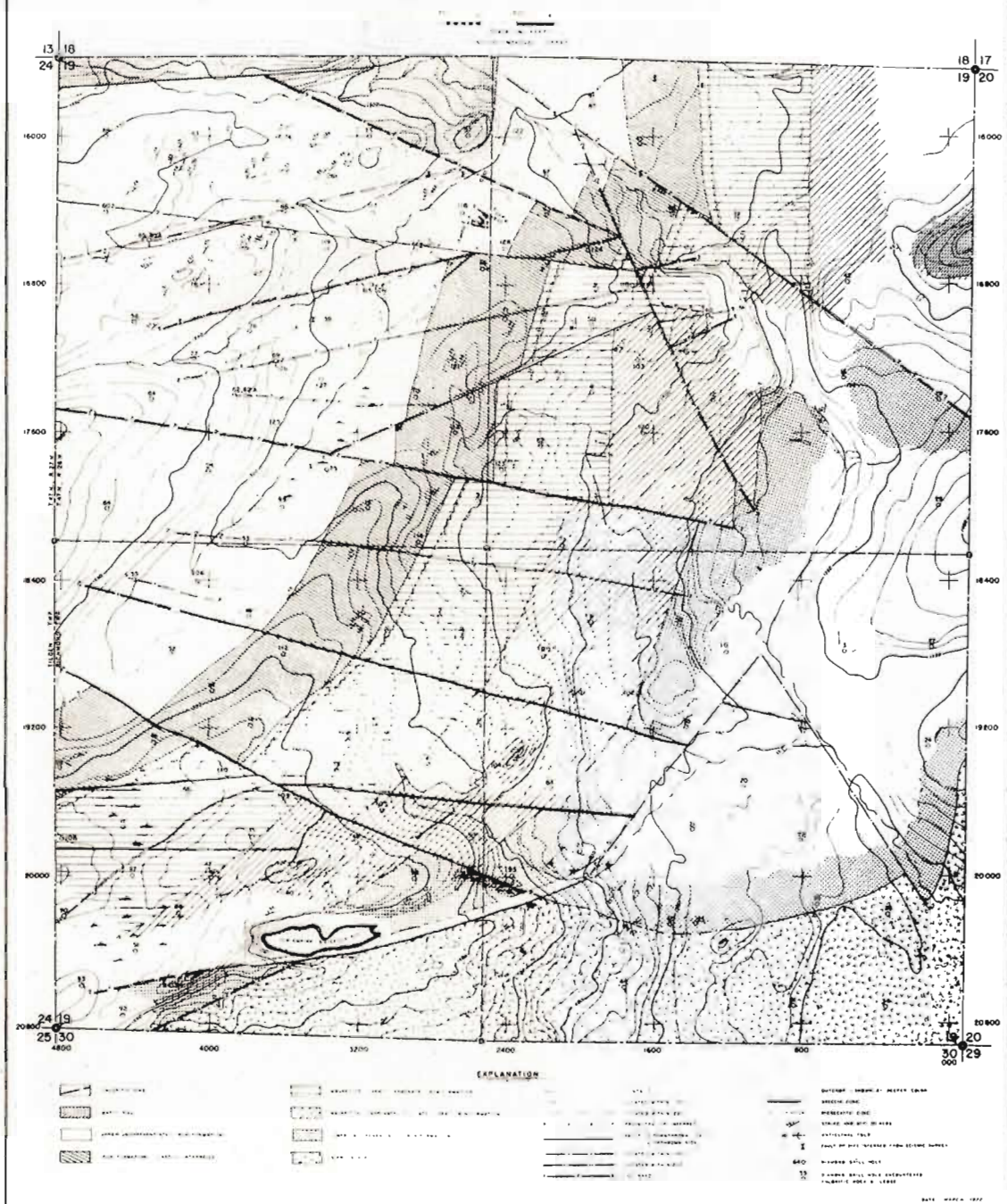


Figure 2

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OUTLINE OF EMPIRE IRON MINING COMPANY FIELD TRIP
FOR THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

1. Assemble in display room for viewing models and flowsheets of the Empire pit, concentrator, and pellet plant. Specimens of all the major facies of the Empire orebody, selected drill core specimens, geologic maps, sections, and examples of Empire ore blending and truck allocation runs will be displayed.
2. A slide presentation by Dr. Tsu Ming Han (Senior Research Scientist for the Cleveland-Cliffs Iron Company) on sedimentary and metamorphic features occurring in the Empire orebody with emphasis on the origin of the Negaunee Iron Formation.
3. Tour of the Empire pit (a detailed synopsis of pit stops will be handed out prior to the pit tour). The tour will include stops at available major ore facies, stops showing some of the structural, sedimentary, and metamorphic features, and stops to view mining and crushing operations.
4. Tour of Empire concentrator and pellet plant.

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SUPPLEMENT

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THE MARQUETTE MINERAL DISTRICT OF MICHIGAN

by

Burton H. Boyum
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The Cleveland-Cliffs Iron Company
Ishpeming, Michigan

SUMMARY

The Marquette Mineral District of Michigan is distinctive for its thick series of Middle Precambrian rocks, known as the Marquette Range Supergroup. It is also notable as the site of the first discovery of iron ore in the Lake Superior Region in 1844. Iron mining has attracted settlers and developers and the industry has accounted for the economic base of Marquette County and adjacent counties since 1845. A total of 423,278,906 long tons of iron ore has been produced and shipped without interruption through 1974. The greater part of the iron ore production has come from the Negaunee Iron-Formation in the principal part of the Range and the Cascade Range. Lesser amounts were produced in the Gwinn area and from the Bijiki Iron-Formation near Champion and Michigamme. Production, until the 1950's, both by open pit and underground methods, was of high-grade "direct-shipping" quality. Concentration and agglomeration (pelletizing) have increased in proportion until in 1974, it accounted for 96% of the iron ore production. The current rate of production is 14.5 million long tons annually with significant reserves indicating many years of future production. Also of economic interest has been the production of sand, gravel, dolomite and gold. Copper mineralization is known as well.

The Marquette Mineral District is characterized by the Middle Precambrian Marquette Range Supergroup found in a westerly plunging syncline bordered by granitic and mafic metavolcanic rocks of Lower Precambrian age. The Supergroup is made up of metasediments: quartzites, argillites and slates, dolomite and several iron-formations. Keweenaw diabase intrusives are found throughout the District. Sandstone, thought to be Upper Precambrian, is found in Marquette. To the southeast are found Cambrian and Ordovician sediments which continue to the east and south. Sandstone and limestone overlying the Gwinn area have been called Cambrian or Ordovician. Glacial deposits of Pleistocene age are found extensively. Figure 1 shows the location of the Marquette Mineral District.

GENERAL SETTING

The Marquette Mineral District of Michigan is located in Marquette County and the east central portion of Baraga County. Marquette County is the largest county in Michigan, being 1,210,920 acres (490,053 hectares). Geographically, it consists of rolling to rugged topography. Highlands rise some 600 to 1200 feet (180 to 365 meters) above Lake Superior (mean sea level elevation +602 feet or 183 meters). The average elevation in the vicinity of the mining towns of Ishpeming and Negaunee is +1400 feet (425 meters) while the highest point, called Firetower or Signal Hill, is +1875 feet (572 meters). The area is heavily forested--

with numerous lakes and swamps. The watershed in Marquette County drains to Lake Superior and to Lake Michigan from these highlands. Since the early days, these highlands have been called "ranges" or "iron-ranges" where iron mining has been done. The three principal cities are Marquette (County seat and port), Ishpeming and Negaunee. In addition to the mining and related activities (suppliers, railroads, services), education (Northern Michigan University), government (principally K. I. Sawyer Air Force Base), forest products and tourism augment the area's economic base.

HISTORICAL SETTING

The Indian population was probably sparse in the District. They could have traveled through the area, bartering with the first miners in the region who worked the native copper in the Keweenaw Peninsula as far back as 3800 years ago (Drier and DuTemple, 1961). The first Europeans to visit the Upper Peninsula were the French explorers, Brulé and Grenoble in 1622. They referred to the natives as "Algonquin" whose language was similar to those they knew in the Ottawa River area. The local tribes were Chippewa and Ojibway. Brulé and Grenoble reported their findings to Quebec City. The reports stimulated interest and visits by fur traders, missionaries and voyageurs. In the summer of 1668, Father Jacques Marquette founded the permanent mission at Sault Ste. Marie, Michigan. In September, 1669, he was posted to the Holy Spirit Mission, Chequamegon Bay. He made trips to Sault Ste. Marie in 1670 and 1671. It is believed that he and his party camped at or near Lighthouse Point on these trips. In 1673, he and Louis Joliet explored the Mississippi River down to its junction with the Arkansas River. He died May 18, 1675, and was buried near St. Ignace. His name has been given to the city, county and the mineral district in recognition of his work among the natives and for the European settlers. Figure 2 shows the map, published in Paris in 1672, made by Fathers Allouez and Dablon with assistance from Father Marquette. We are told that their unit of reference was the distance they could paddle per day. It is interesting to note that fear of the Iroquois caused the French to avoid the Lower Peninsula, as it was not visited until 1669. The next 170 years were marked with sporadic fur trading in this vicinity.

While Michigan was still a territory, a reconnaissance was organized under Governor Lewis Cass which explored the Upper Peninsula, Wisconsin and Minnesota in 1820. The party included Henry Rowe Schoolcraft, Mineralogist, and David Douglass, Topographer. They were at Granite Point, Marquette, June 23, 1820.

In 1837, Michigan became the 26th state in the Union. Fortunately, it named Dr. Douglass Houghton to be the first State Geologist who fortunately convinced the U.S. Government that the Federal Land Subdivision Survey should have geological mapping as an adjunct. The Indian Treaty of LaPointe, 1842, opened the Upper Peninsula to the white men. On September 19, 1844, a Government Survey Party under Mr. William A. Burt was running the east line of Section 1, 47-27 (now Mather Mine "B" Shaft property). A younger brother of Douglass Houghton, Jacob, noted erratic compass behavior. They sought the cause and found, as recorded by Douglass Houghton, "Spathose and magnetite ores abounding." Because of the magnetic problems he had encountered earlier, Burt had invented his famous solar compass. Later, in 1846, Burt wrote: "It may be reasonably inferred that not more than one-seventh of the

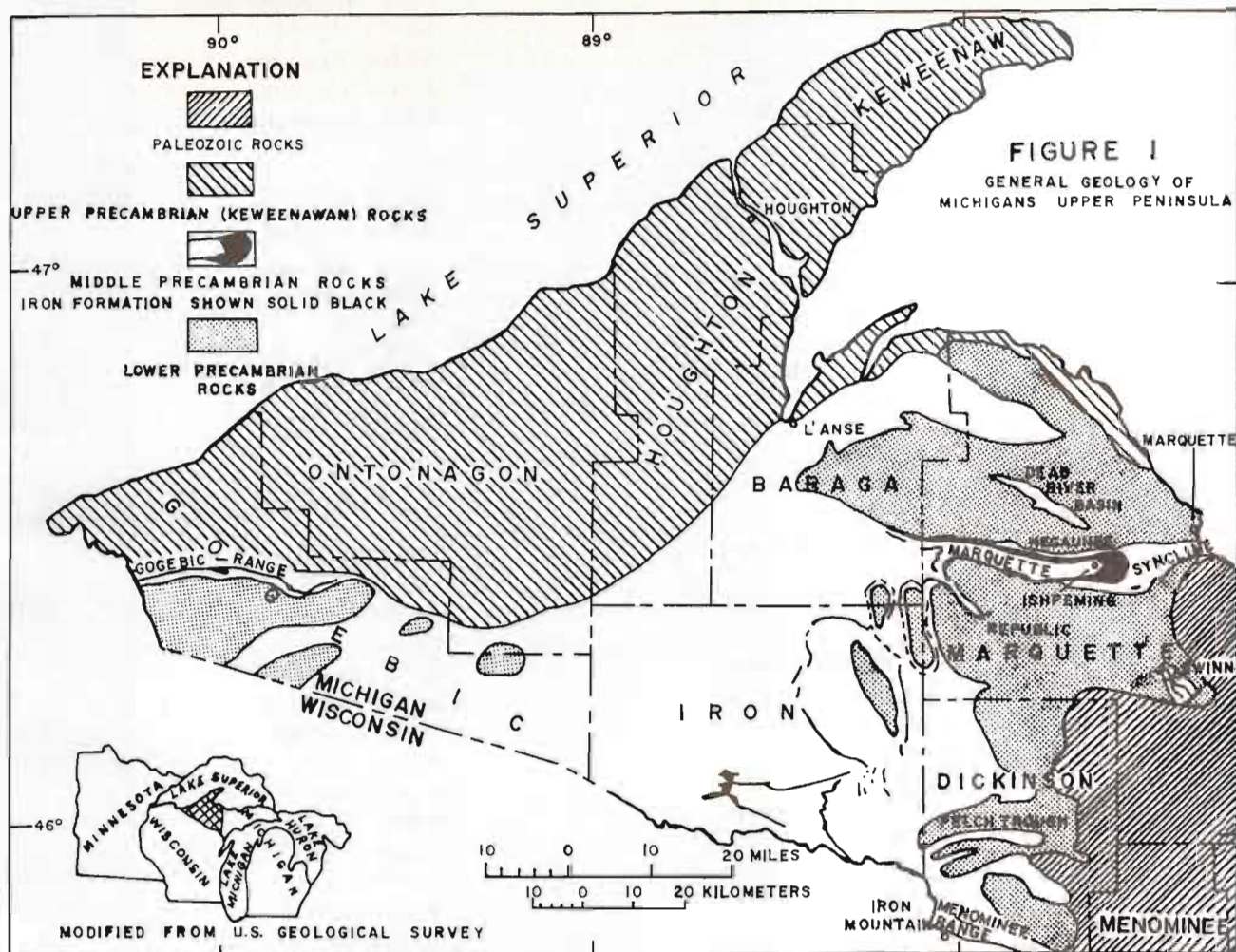


Figure 1 -- General Geology of Michigan's Upper Peninsula.



Figure 2 -- Jesuit map of Lake Superior - 1672.

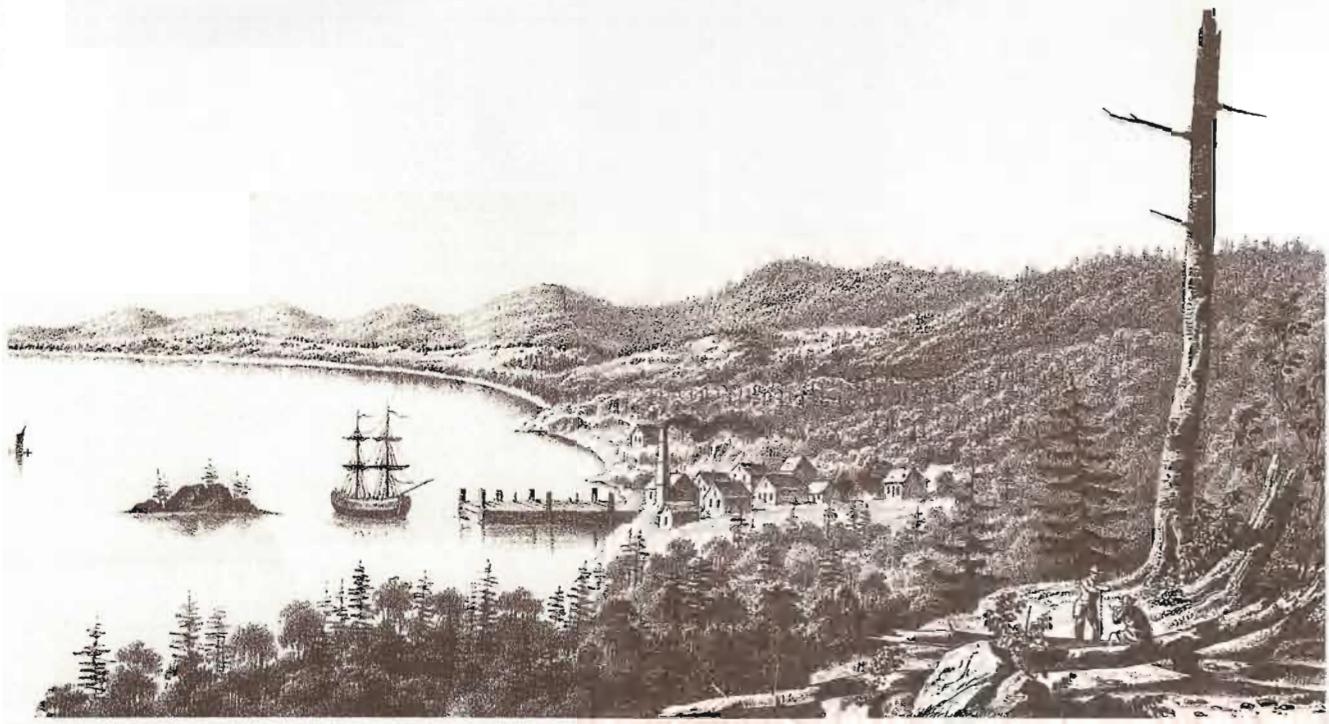


Figure 3 – Marquette, 1851. From Foster and Whitney, Volume II, Frontispiece.
Note Ripley Rock out from Commercial Dock.

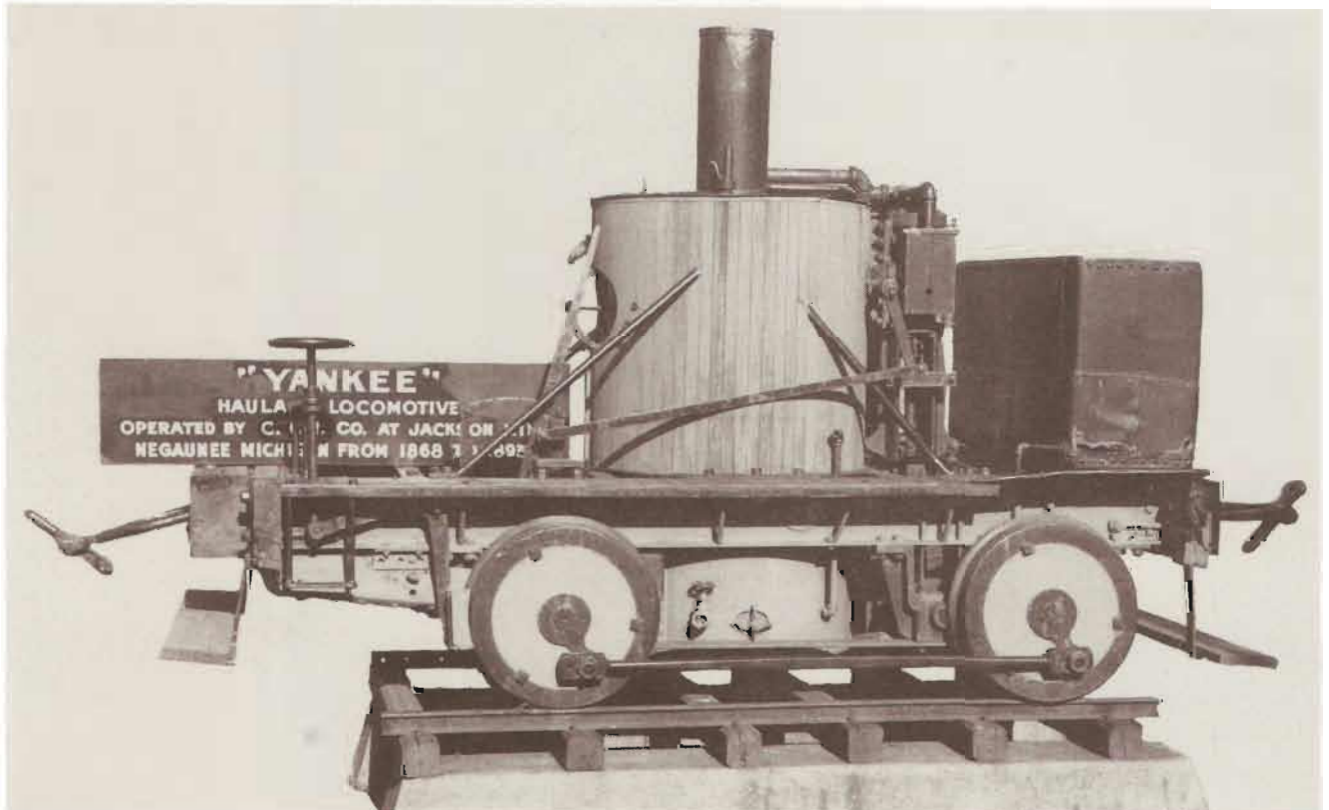


Figure 4 – The "Yankee" Locomotive used by the Jackson Iron Company from 1868 to 1893.

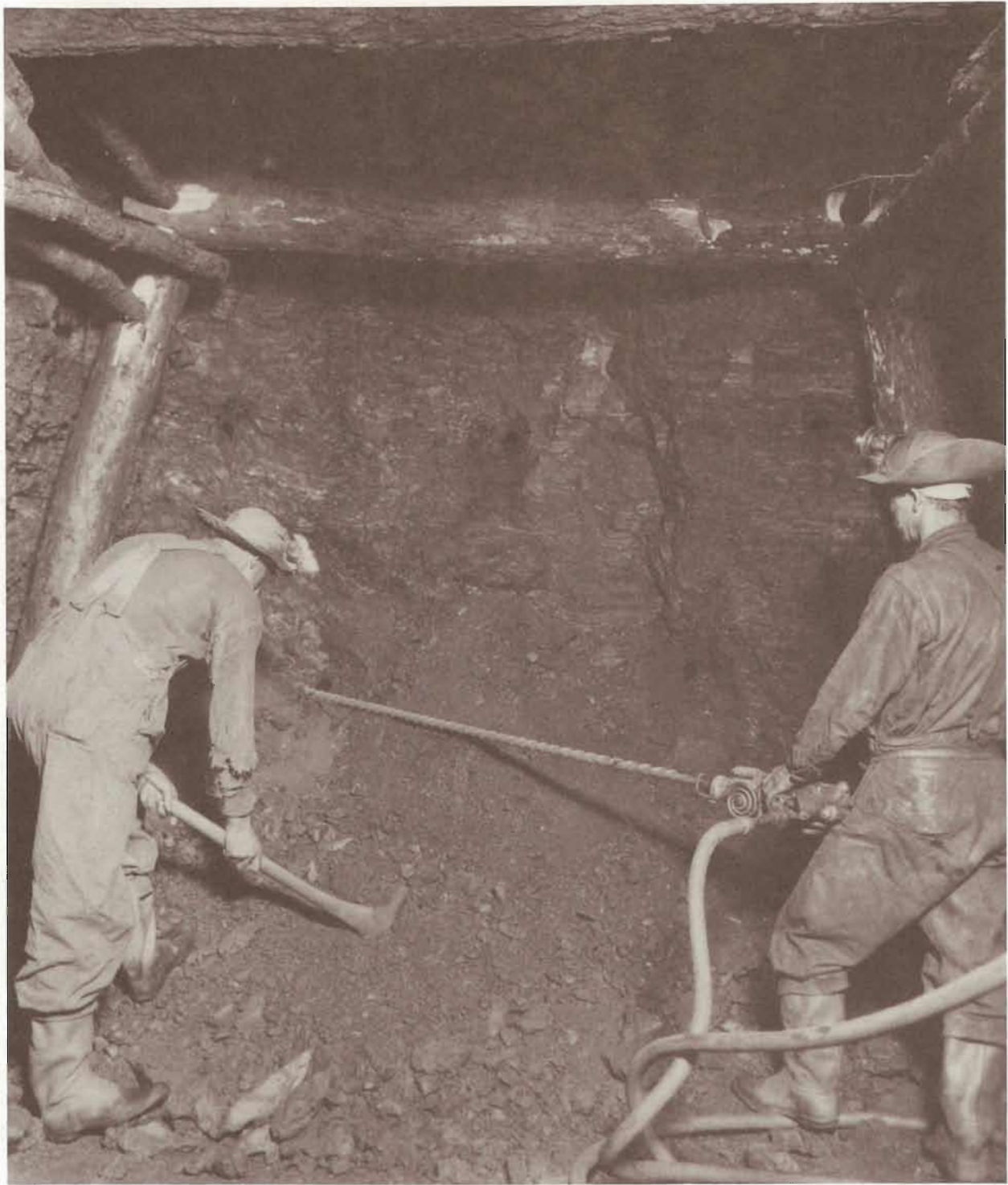


Photo courtesy of Marquette County Historical Society

Figure 8 – Negaunee Mine Top Slicing, circa 1920.

Photo courtesy of Marquette County Historical Society

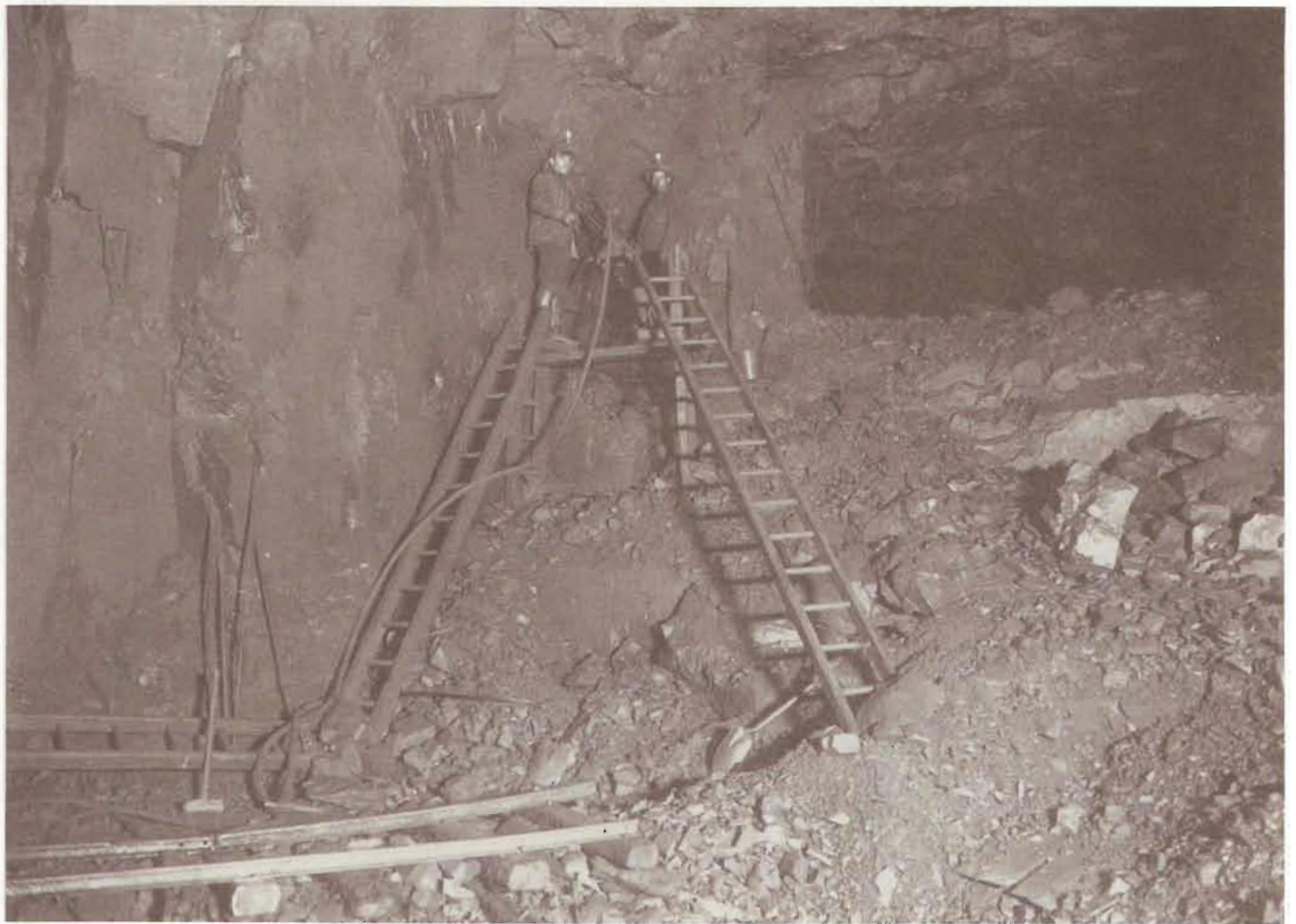


Figure 7 – Cliffs Shaft Mine Room and Pillar Stoping, circa 1895.

Figure 6 - North Jackson Mine Number 3 Pit. Inclined skip road in rear, circa 1890.

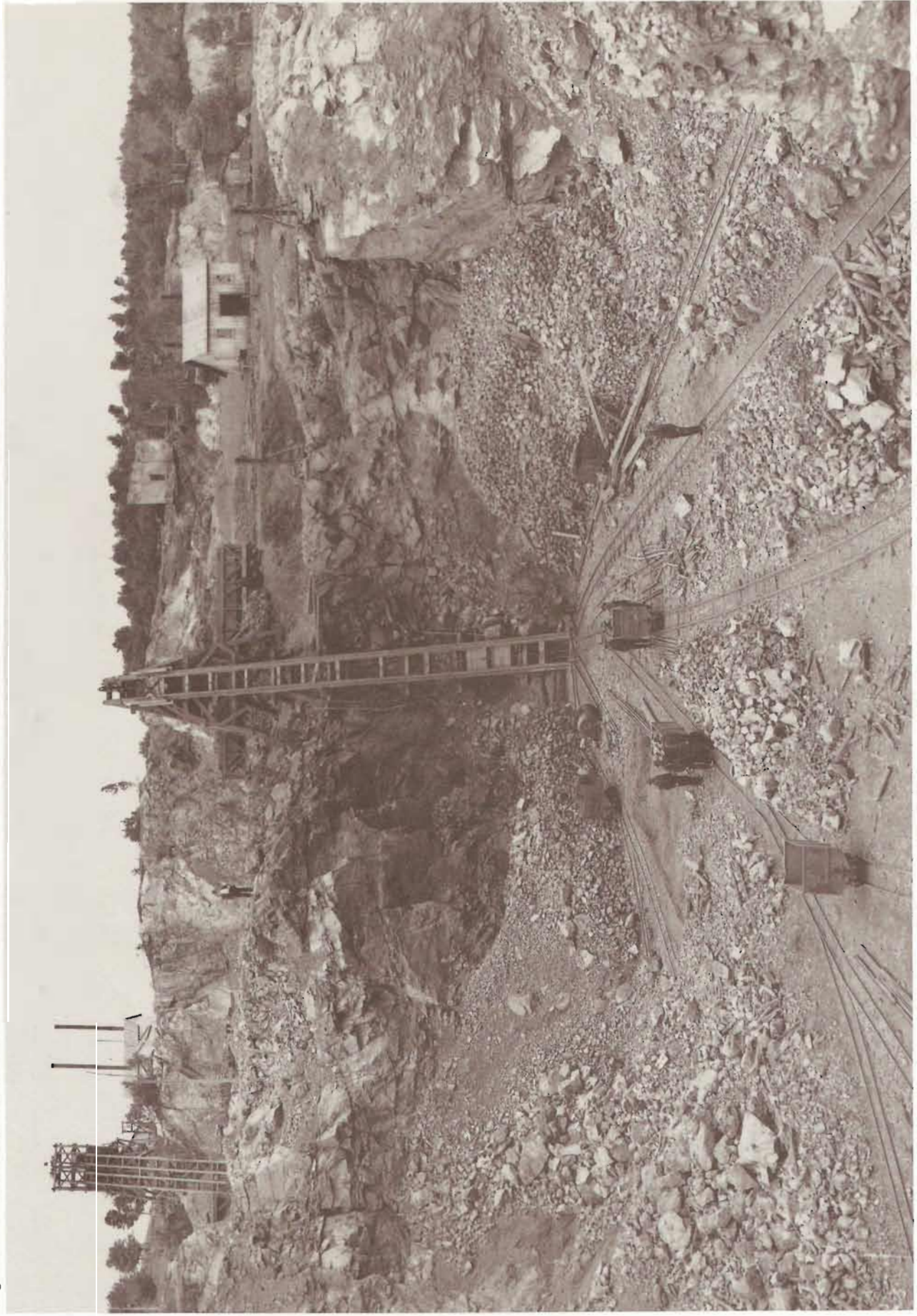




Figure 5 – Open pit operations, 1860. North Jackson Mine, Number 1 Pit. Photo courtesy - The Cleveland-Cliffs Iron Company.

down. For a number of years, Cliffs conducted extensive geological and metallurgical research on the oxidized Negaunee Iron-Formation at the Tilden Mine. A joint program with the U.S. Bureau of Mines, Minneapolis, led to the successful development of the selective flocculation-flotation process. The Tilden Mine came on stream in 1974.

The application of these taconite-type processes to low-grade iron-formation have meant the transformation of the Marquette Range from an annual production rate of 4 to 5 million to 14.5 million long tons in 1975. Further expansion to 21.3 million long tons per year is likely before the end of the decade, making the Range a significant source of iron ore to the United States and Canadian steel companies who have joined The Cleveland-Cliffs Iron Company in these ventures. A significant factor in these developments has been the Michigan Legislature's adoption of two "specific" tax acts to aid and encourage these low grade and pelletizing properties.

As noted earlier, the decision to emphasize the shipping of iron ore, rather than charcoal iron, goes back to 1851-1852. However, charcoal furnaces continued to put out significant tonnages approximating one and a half million tons from 1848 to 1893. Noteworthy were the Pioneer Plant at Negaunee and the Fayette Furnace. The latter is well worth the visit to Fayette State Park (Department of Natural Resources) near Rapid River.

GEOLOGIC SETTING

The principal rock units of the Marquette Mineral District are Precambrian in age. The dominant series, both geologically and economically, is termed the Marquette Range Supergroup of Middle Precambrian age. This series is underlain both to the north and the south by Lower Precambrian mafic metavolcanic and granitic rocks. Both the Lower and Middle Precambrian rocks are metamorphosed in varying degrees. Also, they are intruded by Keweenaw dikes. These Lower and Middle Precambrian rocks are overlain locally by a sandstone thought to be Upper Precambrian, and sandstones and limestones of Cambrian and Ordovician age, and lastly, by glacial deposits of Pleistocene age.

The Marquette Range Supergroup is found in a westerly trending and plunging synclinorium, opening to the west (Figure 9). In the western part of Marquette County, the south limb is folded into a lesser syncline, called the Republic Trough. The Marquette Range Supergroup continues to the west and south into Baraga, Iron and Dickinson Counties. The Cascade Range, found to the southeast near Palmer, is a faulted section of the main synclinorium.

Two other major structures are recognized on the Marquette Range: The Dead River Basin which lies to the north of Negaunee and the Gwinn, or Swanzey, Basin which is located some 20 miles (32 kilometers) to the southeast of Negaunee. The rocks of these two basins are correlated with the Marquette Range Supergroup.

Structurally, the Lower and Middle Precambrian rocks are assigned to the Southern Province of the great Canadian Shield (Leech et al., 1963).

RÉSUMÉ OF GEOLOGIC MAPPING

The Marquette Mineral District has been mapped and described in considerable

The initial iron mining on the Marquette Range was in Negaunee and Ishpeming, following the finding of ore at or near surface (Figure 5). This open pit mining proceeded in depth, using inclined hoisting "skip-roads" (Figure 6) and, later, shafts. Rapidly, the whole of the Marquette iron range, including the Cascade and Gwinn Districts, was explored by mapping, test pitting and diamond drilling and developed. By 1880, most of the ore was being produced from underground mines. Early mining methods included open stoping, room and pillar stoping and square-set mining, depending upon the strength of the ore and other "ground conditions" (Figure 7). Top slicing was developed by 1890 (Figure 8), with sub-level caving following. Large-scale block caving was studied and introduced at properties in Negaunee and Ishpeming in 1950. At this writing, the Mather Mine is one of two underground iron mines still operating on the U. S. side of the Lake Superior Region.

Understandably, the iron ore miners devoted their exploration and development efforts to finding the high-grade or "direct-shipping" ores. These ores were natural concentrations found in the host rock of leaner iron-formation. Investigations disclosed the practicality of crushing and grinding the iron-formation to liberate the ore minerals so that concentration (and agglomeration) make a marketable product. As early as the 1880's, several attempts were made to develop economic processes. The great American inventor, Thomas A. Edison, built a magnetic separator at the Humboldt (Edwards) Mine in 1888. Technically, it was a successful process for concentrating the magnetic iron-formation, producing 893 long tons of concentrates before it burned in 1889; it was not rebuilt. The Jackson Mine in Negaunee, long famous as the site of the original discovery of Lake Superior iron ore and an important producer of high quality iron ore, ran into grade problems and built a concentrator. Various Minnesota properties had used simple to complex processes to upgrade intermediate grade ores using "washing", heavy media and other hydrogravimetric means. The Mines Experiment Station, Minneapolis, with E. W. Davis and others, did much significant research leading to the magnetic "taconite" concentration and agglomeration. The Reserve Mine in Minnesota was the first such commercial development, first producing in 1955.

Cleveland-Cliffs studied both the Negaunee and Bijiki Iron-Formations from 1945, opening the present Research Laboratory in 1950. The first large-scale plant (relatively speaking) was the Ohio Mine, west of Michigamme, in the Bijiki Iron-Formation. From 1952 to 1960, a heavy media plant produced 745,620 long tons of concentrate. Meanwhile, research on concentration of the specular hematite at Humboldt and Republic was perfected utilizing a froth flotation method of concentration. These plants first began to produce concentrates in 1954 and 1956, respectively. Both plants produced concentrates only. Agglomeration by pelletizing was pursued by researchers; their efforts led to the development of the Marquette Range's first straight-grate pellet plant, which was constructed at Eagle Mills in 1956. Cliffs then built grate-kiln systems at Humboldt in 1960 and at Republic in 1961. Research on the magnetic iron-formation at the Empire Mine led to the first magnetic taconite-type plant going into production in 1963.

In 1954, Cliffs built the Ore Improvement Plant at Eagle Mills to upgrade various underground mines' ores by drying, crushing, screening and heavy media processes. The next development was the Pioneer Plant, built in 1965 to pelletize Mather Mine underground ores. Further expansions also took place at the Republic and Empire Mines. The Humboldt Mine ceased mining operations in 1970 but continued to pelletize Republic Mine ore concentrates after the Eagle Mills plant was shut

inland to the mines. John Westren secured a Michigan Act in 1850 to build "The Iron Bay (Marquette) and Carp River Plank Road Company". Work started and by March 14, 1855, the Iron Mountain Railway Company was incorporated and took over the Plank Road Company. Operations started November 1, 1855, and continued two years before passing out of existence. Meanwhile, a similarly named railroad, incorporated February 22, 1855, as "The Iron Mountain Railroad Company", started operations in 1857. On December 27, 1856, the "Bay de Noquette and Marquette Railroad" was incorporated to provide rail traffic to Lake Michigan. It took over the Iron Mountain Railroad in 1859. The line to the west was the "Marquette and Ontonagon Railway", incorporated February 6, 1857. The road to L'Anse was completed on December 16, 1872. These became the Duluth, South Shore and Atlantic (D.S.S. & A.) and later the Soo Line. The "Peninsula Railroad Company" (C. & N.W. Ry.) built a road from Escanaba to Negaunee in 1864. In 1895, The Cleveland-Cliffs Iron Company and the Pittsburgh and Lake Angeline Mining Company formed the "Lake Superior and Ishpeming Railway" (L.S. & I. Ry.) completing the line to Presque Isle August 12, 1896. In 1924, the "Marquette and Southeastern" and "Munising" railroads were consolidated into the L.S. & I. Ry., totalling 164 miles of trackage. Locomotives were used in the open pits as well as on the ore haul (Figure 4).

The story of the Marquette Mineral District would not be complete without reference to the "Iron Range and Huron Bay Railroad" from Champion to Huron Bay. Between 1891 and 1896, over 3 million dollars were spent on forty miles of grade, track, rolling stock and a complete ore dock. One locomotive made the trip, but no ore was ever hauled on this railroad. It was sold and dismantled in 1901, a complete loss to its stockholders!

The Jackson Iron Company built the first ore dock in Marquette in 1855 where the present Marquette Dock Company is located. The Lake Superior Iron Company built a dock that same year at the foot of Baraga Avenue (Figure 3). In 1857, the same company built a much bigger dock near the site of the present Soo Line dock built in 1932 (Number 6). Numerous docks were built and rebuilt. The L.S. & I. dock (Number 1) at Presque Isle was built as a wooden structure in 1896. It was rebuilt as a concrete structure and put in service in 1912, designated Number 2.

The Cleveland Iron Mining Company made the first substantial shipment of 1,447 tons in 1855. The growth of the iron mining on the Marquette Range can be seen by the following table of annual shipments from Marquette and Escanaba:*

1856	11,597	1930	3,450,643
1857	25,626	1935	3,150,170
1860	104,971	1940	5,920,463
1865	166,636	1945	4,585,436
1870	779,233	1950	4,955,002
1880	1,436,876	1955	5,907,642
1890	2,640,652	1960	5,498,497
1900	3,205,437	1965	8,527,407
1910	3,891,540	1970	10,674,445
1920	3,466,878	1974	9,067,724

*A small amount was shipped from L'Anse 1875-1885.

number of iron ore beds were seen during the survey of the Township lines; and if this district of Townships be subdivided with care in reference to mines and minerals, six times as many more will probably be found. If this view of the iron region of the Northern Peninsula of Michigan be correct, it far excels any other portion of the United States in the abundance and good qualities of its iron ores."

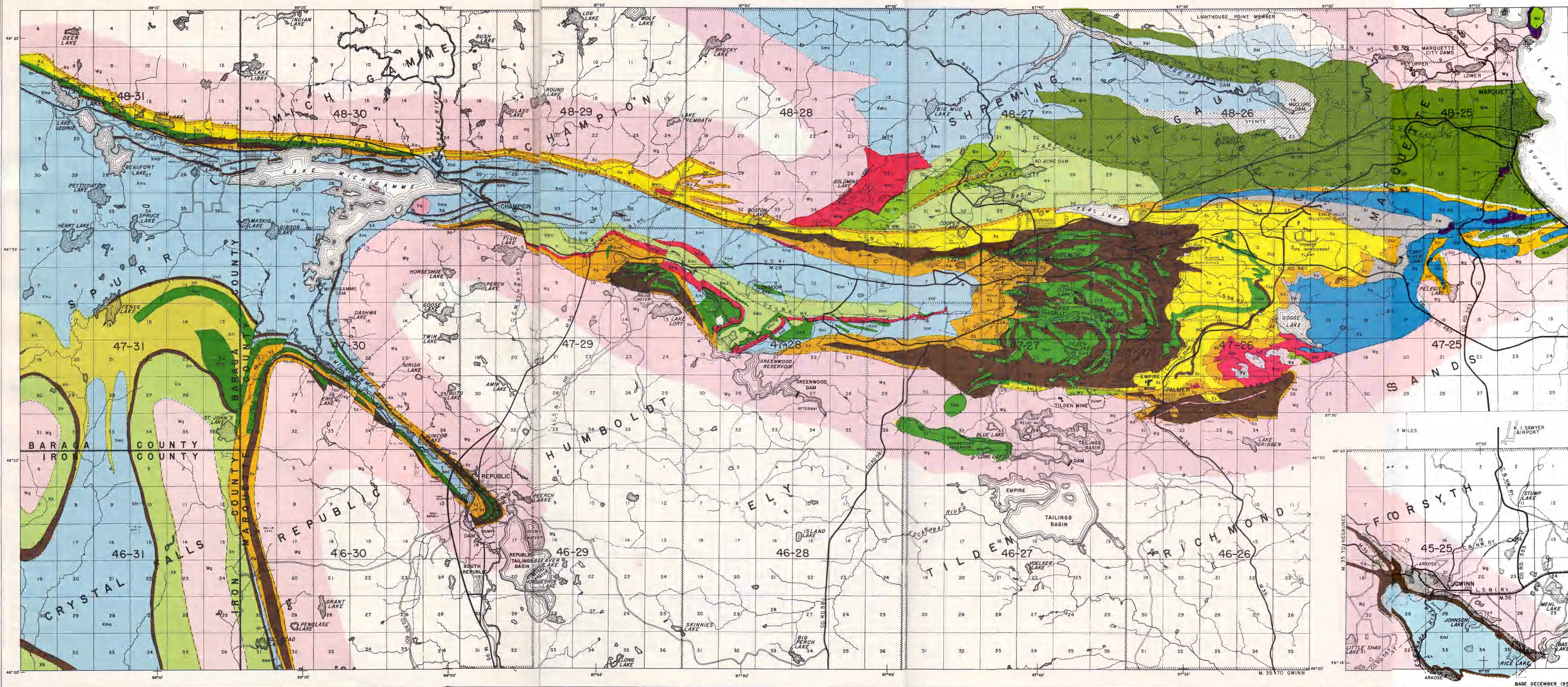
Word of the iron ore discovery spread through the state and elsewhere during that winter. In 1845, a group of men from Jackson, Michigan, formed the Jackson Mining Company. The treasurer, Philo Everett, and his associates, reached Teal Lake in June. The story is told that the Indian chief, Marji-Gesick, showed them the high-grade hard ore under the stump of a fallen pine tree. Other companies formed, such as the Cleveland Iron Mining Company on November 9, 1847, the Marquette Iron Company in March, 1849, and the Lake Superior Iron Company on March 13, 1853.

The initial mining effort was directed towards producing ore for charcoal furnaces to make pig iron. The Jackson Mining Company built a forge on the Carp River in order to utilize water power. In addition, the site was en route to the Marquette harbor, although there was no lakeside settlement at the time. The first bloom was made on February 10, 1848. On January 12, 1847, Carp River Forge settlement became the first post office in what is now Marquette County. Other charcoal furnaces were built in 1850 by the Marquette Iron Company in the City of Marquette (then called Worcester; settled July 10, 1849) where front Street and Baraga Avenue intersect (Figure 3). Another furnace was located at the mouth of the Carp River by the Cleveland Iron Mining Company.

The first recorded shipment from the port of Marquette consisted of six barrels of ore on July 7, 1852. The rapids at Sault Ste. Marie created a problem which the Northwest Company attempted to alleviate by building a small lock for canoes and small craft in 1797. Pressure was exerted on the United States Government as early as 1839 to construct a dam and lock. Three times in the 1840's, the Senate passed a bill for construction, only to be defeated in the House. The great Senator, Henry Clay, is reputed to have said the locks would be "a work quite beyond the remotest settlement of the United States if not in the moon!" The bill was passed finally and approved by President Millard Fillmore on August 26, 1852, spurred on by the iron and copper developments. Despite all the construction problems, the first Soo Lock was opened in June, 1855. By this time also, it had become apparent that the ore rather than charcoal iron should be the commodity to be shipped to markets in the industrially developed portions of the United States. Once the Soo Locks were opened, both the iron and copper ranges grew rapidly. Geologic reconnaissance was extended throughout the Lake Superior Region, resulting in the discovery of other major ranges:

Menominee-East	1874	(Vulcan)
Vermilion	1878	
Menominee-West	1882	(Iron River)
Gogebic	1885	
Michipicoten	1889	
Mesabi	1889	
Cuyuna	1904	

Just as the Soo Locks were a key factor in developing the Upper Peninsula's copper and iron resources, so was the building of railroads from Lake Superior

LEGEND
GEOLOGIC COLUMN OF THE PRINCIPAL DISTRICT
MODIFIED FROM U.S. GEOLOGICAL SURVEY

CENOZOIC	PLEISTOCENE	GLACIAL DEPOSITS	
		GL	AGE UNCERTAIN-FOUND AT GWINN
PALEOZOIC	ORDOVICIAN	CS	JACOBSVILLE SANDSTONE-AGE UNCERTAIN
		Yd	DIABASE-UNALTERED DIKES AND PLUGS
UPPER "Y"	KEWEENAWAN	Xtl	STRATA NEAR FENCE LAKE-ARGILLITE, QUARTZITE, CONGLOMERATE
		Xh	FENCE RIVER FORMATION-MAGNETIC SILICATE IRON-FORMATION
PRECAMBRIAN	MIDDLE PRECAMBRIAN "X"	Xm	HEMLOCK FORMATION-VOLCANIC ROCKS, FLOWS AND PYROCLASTICS
		Xm	BIJIKI IRON-FORMATION-CHERTY SILICATE IRON-FORMATION, LOCALLY ENRICHED
MARQUETTE RANGE SUPERGROUP FORMERLY "HURONIAN" OR "ANIMKIE"	BARAGA GROUP	Xm	UPPER SLATE MEMBER-METAGRAYWACKE, SCHIST, BLACK SLATE
		Xm	IRON-FORMATION-CHERTY SILICATE IRON-FORMATION, LIKE BIJIKI BUT WITHIN LOWER SLATE
LOWER "W"	CHOCOLAY GROUP	Xm	CLARKSBURG VOLCANICS-MAFIC TO INTERMEDIATE PYROCLASTICS
		Xm	GREENWOOD IRON-FORMATION-MAGNETIC SILICATE IRON-FORMATION
MARQUETTE RANGE SUPERGROUP FORMERLY "HURONIAN" OR "ANIMKIE"	MENOMINEE GROUP	Xm	LOWER SLATE-BLACK SLATE, IMPURE QUARTZITE, ARGILLITE
		Xg	GOODRICH QUARTZITE-QUARTZITE, CONGLOMERATES, ARGILLITE
MARQUETTE RANGE SUPERGROUP FORMERLY "HURONIAN" OR "ANIMKIE"	CHOCOLAY GROUP	Xg	NEGAUNEE IRON-FORMATION-CARBONATE, SILICATE AND OXIDE IRON-FORMATION, LOCALLY ENRICHED
		Xg	SIAMO SLATE-ARGILLITE, SLATE, GRAYWACKE-CONTAINS GOOSE LAKE IRON-FORMATION (Xsg)
MARQUETTE RANGE SUPERGROUP FORMERLY "HURONIAN" OR "ANIMKIE"	CHOCOLAY GROUP	Xg	AJIBIKI QUARTZITE-QUARTZITE, LOCAL CONGLOMERATE BEDS
		Xg	CHOCOLAY GROUP-SLATE, SCHIST, QUARTZITE AND GRAYWACKE
MARQUETTE RANGE SUPERGROUP FORMERLY "HURONIAN" OR "ANIMKIE"	CHOCOLAY GROUP	Xg	WEWE SLATE-GRAY SERICITIC AND QUARTZ-SERICITE SLATE
		Xg	KONA DOLOMITE-VARIOUS COLORED MASSIVE DOLOMITE AND CHERTY DOLOMITE
MARQUETTE RANGE SUPERGROUP FORMERLY "HURONIAN" OR "ANIMKIE"	CHOCOLAY GROUP	Xg	MESNARD QUARTZITE-VITREOUS WHITE QUARTZITE
		Xg	ENCHANTMENT LAKE-REANY CREEK FORMATION METASEDIMENTS
MARQUETTE RANGE SUPERGROUP FORMERLY "HURONIAN" OR "ANIMKIE"	CHOCOLAY GROUP	Xg	PALMER GNEISS-SHEARED, COMMINUTED, GRANITE AND AMPHIBOLITE GNEISS
		Xg	GRANITE ROCKS-COMPEAU CREEK AND BELL CREEK GRANITIC ROCKS
MARQUETTE RANGE SUPERGROUP FORMERLY "HURONIAN" OR "ANIMKIE"	CHOCOLAY GROUP	Xg	SERPENTINITE-MASSIVE TO SHEARED SERPENTINIZED PERIDOTITE
		Xg	METAGABBRO COMPLEX-METAGABBRO, METABASALT, MINOR FELSIC VOLCANIC ROCK
MARQUETTE RANGE SUPERGROUP FORMERLY "HURONIAN" OR "ANIMKIE"	CHOCOLAY GROUP	Xg	MONA SCHIST-MAFIC FLOWS, MASSIVE TO ELLIPSOIDAL
		Xg	KITCHI SCHIST-INTRUSIVE ROCKS, MINOR MAFIC FLOWS

SCALE IN MILES
SCALE IN KILOMETERS

FIGURE 9



detail. The first period of significance is the 1840-1850 era when reports were made by Douglass Houghton, various "mineral agents", Bela Hubbard, J. W. Foster and J. D. Whitney. T. S. Hunt (1861) and J. P. Kimball (1865) were the first to ascribe the term "Huronian" to the Middle Precambrian rocks of the Marquette Range. The second State Geological Survey was organized in May, 1869, under Alexander Winchell as State Geologist. Under this revitalized regime were the studies of Major T. B. Brooks (1873) and C. Rominger (1881), being Volumes I and IV, respectively, of the Michigan Geological Survey. Also worth noting was the initiation in 1879 of the series of Reports of the Commissioner of Mineral Statistics (Michigan) with data for 1877-1878. These continued for a number of years and are most informative concerning the iron and copper mining. C. R. VanHise published the first of many papers on the Marquette District in 1890 and continued through 1897 when Monograph XXVIII of the United States Geological Survey was published. Numerous geologists worked for the U.S.G.S. over these years. Of note was the work of Henry L. Smyth, starting with 1893 on the Republic Trough. In July, 1899, he became associated with The Cleveland-Cliffs Iron Company as Geological Consultant, continuing uninterrupted until April, 1927. During Professor Smyth's regime, he founded the Geological Department at Cliffs (1900), the first to be organized by a private mining company in the Lake Superior Region, to the best of our knowledge. E. E. White was named Chief Geologist in 1909. He was succeeded by Edwin L. Derby, Jr. (1916 to 1954), Burton H. Boyum (1954 to 1965) and Gerald J. Anderson (1965 to the present time).

The U.S.G.S. continued its extensive mapping and in 1911 they published Monograph LII, a classic among classics! The chief editors were Charles R. VanHise and Charles K. Leith. Work continued by both the Michigan and United States Geological Surveys, and by the mining companies' staffs as well as graduate students.

The Marquette Mineral District has been restudied by the U.S.G.S., during the period of 1955 through 1975, as part of its long-range program. Principal investigators have been Harold L. James, J. E. Gair, W. F. Cannon, Lorin Clark, R. E. Thaden, W. P. Puffett, John S. Klasner, George C. Simmons and Carl E. Dutton. The work has been done in cooperation with the Michigan Geological Survey.

STRATIGRAPHIC COLUMN

The legend of Figure 9 constitutes a schematic summary of the stratigraphic column of the Marquette Mineral District. As noted, it is modified from the United States Geological Survey and reflects mapping and drill hole data by the mining companies and by graduate students and faculty.

As noted earlier, Hunt (1861) and Kimball (1865) were the first to use the term "Huronian", following the work of the Canadian Geological Survey. This usage continued until H. L. James (1958 and 1972) proposed a new subdivision of the Precambrian to be lower or early, middle, and upper or late. He also noted that the group called Huronian was correlated better with the Animikie of northern Minnesota. This nomenclature continued until 1970, when Cannon and Gair proposed the term "Marquette Range Supergroup". In 1972, James (and the U.S.G.S.) initiated the alphabetical designation "W" for "early", "X" for "middle", and "Y" and "Z" for "late" Precambrian, as an "interim" scheme. This designation is incorporated in this summary.

Figures 10 and 11 depict the spatial relations of those rocks and the iron ore occurrences near Negaunee and Ishpeming.

The descriptions that follow for the various members of the stratigraphic column are drawn from recent publications by the United States Geological Survey. For simplicity in presentation, descriptions are drawn from these publications without specific reference. However, grateful acknowledgement is made to the various authors of the U.S.G.S. and the bibliography contains a complete reference to these various publications.

LOWER PRECAMBRIAN

General

Lower Precambrian rocks of the Marquette Mineral District include the Kitchi and Mona Schists, a Metagabbro Complex, Serpentinite, Compeau Creek and Bell Creek Granitic Rocks, the Dead River Pluton and the Palmer Gneiss. These rocks are found to the north, the east and the south of the Marquette Range Supergroup synclinorium.

Kitchi Schist

The Kitchi Schist is principally a pyroclastic rock with fragments ranging from less than 20 millimeters to more than 125 millimeters in diameter. Some of these fragments are well rounded and others are angular. It has been termed latite to dacite in composition. Siderite and calcite are common. Age relationships with the Mona Schist are not clear but it is felt that it may be approximately the same age as the lower member of the Mona Schist. Age determinations indicate ranges in excess of 2.6 billion years.

Mona Schist

The Mona Schist is made up principally of greenstone, commonly having ellipsoidal structures. North of the synclinorium, the Mona Schist consists of two principal units: the lower is predominantly massive and ellipsoidal metabasalt, and the upper is layered amphibole, chloritic and sericitic schist. In the Marquette area, this is referred to as the Lighthouse Point member. In the Negaunee Quadrangle, the equivalent is divided into the Nealy Creek member and a sheared rhyolite tuff member. The thickness of the Mona Schist is complicated by the intrusion of the Dead River Pluton as well as by shearing and folding in the Lighthouse Point member. Estimates range from 13,000 to 25,000 feet (4,000 to 7,700 meters). The Lighthouse Point member is thought to range from 5,000 to 9,000 feet (1,500 to 2,750 meters). Large, well developed pillow structures are common in the lower member of the Mona Schist. Lengths range from one to four feet and thickness from one to three feet. In general, the elongation is parallel to the foliation, being close to east-west, and dips are steeply to the north.

Metagabbro Complex

This consists of metagabbro, metabasalts and minor felsic volcanic rocks. These are irregularly shaped bodies, including one plug-like mass that underlies the Picnic Rocks at Shiras Park.

Granite Rocks

This group is known as the Compeau Creek Gneiss and the Bell Creek Gneiss. In the Marquette area, this is found to be principally foliated tonalite and

granodiorite with various dark chloritic, biotitic and hornblendic varieties with amphibolite. Granite is rare. In the west central portion, the Compeau Creek Gneiss is generally a medium to coarse grained granodiorite or tonalite. The Bell Creek Gneiss is a granitic gneiss with some mafic gneiss. The rock is homogeneous over large areas. Age relationships would suggest that the Compeau Creek Gneiss intrudes the Bell Creek Gneiss at a number of localities. The rubidium-strontium age determination suggests about 2.7 billion years (W. R. VanSchmus).

Palmer Gneiss

The Palmer Gneiss is shown separately in the stratigraphic column. Recent work by the U.S.G.S., however, (Gair and Simmons, 1968, and Gair and Thaden, 1968) suggests that this may be the same general age as the Bell Creek and Compeau Creek Gneiss, being a metamorphosed equivalent.

MIDDLE PRECAMBRIAN

General

The Marquette Range Supergroup comprises a significant series of Middle Precambrian rocks found in the Marquette Mineral District. As noted earlier, these were called Huronian for many years and then later renamed Animikie, until 1970 when Cannon and Gair proposed the term "Marquette Range Supergroup". The Marquette Range Supergroup has been divided into four principal groups:

Paint River Group
Baraga Group
Menominee Group
Chocolay Group

The three oldest are found in the Marquette synclinorium and the Paint River Group is found in the adjacent area to the west-southwest, essentially in the Iron River-Crystal Falls Districts. The following is quoted from W. F. Cannon (1973), indicating the tectonic framework of sedimentation of the Marquette Range Supergroup: "Deposition began (section 1) with stable shelf deposits, now quartzite, dolomite, and slate of the Chocolay Group. After mild uplift, sedimentation continued in a mildly active miogeosynclinal environment (section 2). The sediments compose the Menominee Group which contains most of the major iron-bearing units of Michigan. In the Marquette Range, fault uplift of basement rocks began during this period (Gair, 1967). This event is here considered to be the beginning of the Penocean orogeny. This period was closed by general uplift and erosion and possibly local deformation, although some areas remained submerged (J. E. Gair, oral communications, 1970). Bailey and others (1966) gave evidence of rather intense folding in the Menominee Range during this uplift. The area then submerged and the Baraga and Paint River Groups were deposited in a eugeosynclinal environment. These groups consist of a graywacke-shale assemblage and abundant mafic volcanic rocks, mostly submarine, and iron-formations which, except for the Riverton Iron-Formation (James and others, 1968), are thin and of only local extent. Intrusion of a suite of diabase sills and dykes may also have occurred at this time (VanHise and Bayley, 1897). These may be the intrusive equivalent of the volcanic rocks rather than post-depositional intrusions, as has been commonly assumed by most recent authors. Recent trace element data from the Marquette Range support this old but commonly overlooked conclusion. The total sedimentary column was probably 5 miles thick or more in

many areas and was deposited on previously deformed and metamorphosed, largely granitic, peneplaned terrain. The deep burial of previously stable granitic crustal material presents one of the most interesting and largely unexplored tectonic phenomena in the Lake Superior region. The Paint River Group is the youngest Middle Precambrian unit known in Michigan; its deposition was probably followed rapidly by major Penokean uplift and deformation."

CHOCOLAY GROUP

The Chocolay Group consists of the Enchantment Lake-Reany Creek Formations, the Mesnard Quartzite, the Kona Dolomite, the Wewe Slate and the non-differentiated Chocolay Group series. It is the feeling of the U.S.G.S. that there was a period of perhaps 800 million years of erosion of the underlying Lower Precambrian felsic and mafic metavolcanic rocks.

Enchantment Lake-Reany Creek Formation

These are discontinuous units at the base of the Marquette Range Supergroup. Enchantment Lake Formation is found near Marquette while the Reany Creek is found near Negaunee. Each has a base of conglomerate, grades through arkose to graywacke to chloritic slate. It is suggested that the environment may have been one in which glaciers were active. Puffett (1969) suggests that the isolated boulders in the slate were believed to have been ice rafted.

It is difficult to determine the maximum thickness of these formations although, in the vicinity of Enchantment Lake, it would appear to be approximately 500 feet (150 meters).

Mesnard Quartzite

This formation is a thick massive vitreous quartzite which is generally light gray, but which also displays two shades of pink and light red in some areas. Numerous veinlets of quartz and hematite cut the quartzite. Ripple marks and cross-bedding are widespread. Maximum thickness appears to be in the neighborhood of 500 feet (150 meters).

Kona Dolomite

This is essentially a fine to medium grained pink-gray crystalline siliceous dolomite with some interlaminated argillaceous and arenaceous phases. Hematite staining locally gives a color of pinkish to reddish hue. Algal structures are found in the dolomite. These have been modified by recrystallization but are generally characterized in plan view by dusty hematite rings or quartz rings around carbonate cores. These domes of algal colonies range in width from one inch to as much as six feet.

Silicification of the Kona Formation has occurred widely in the dolomite, siliceous dolomite and the argillaceous layers. This is accompanied by fine grained hematite so that the resulting rock is a jasperoid.

Taylor (1972) estimates the maximum thickness of 2,600 feet (800 meters). His mapping has divided the formation into seven members. He noted that this deposition, as with much of the Chocolay Group, reflects stable shelf environment of deposition, in part, lagoonal. The algal structures, wave and current sedimentary structures and the reddish color of many of the beds, suggest open

marine, shallow water and oxidizing conditions. Locally, a portion of the Kona contains a significant amount of sulfide mineralization. This will be discussed later in the report under the economic section.

Wewe Slate

The Wewe Slate is light to dark gray greenish to salmon colored. Although the Wewe Slate has been considered to be of detrital origin, and the greater part of it appears to be so, in a few localized areas there is some evidence of a complete or partial volcanic origin. Its maximum development occurs immediately east of Eagle Mills where it would appear that its thickness has reached 3,000 feet (920 meters).

MENOMINEE GROUP

The Menominee Group is principally a transgressive sequence of sediments overlying the Chocoday Group with a low angle unconformity in the eastern portion of the synclinorium and to the west. It lies on that portion of the Chocoday Group that has not been eroded and on Precambrian "W" rocks. The Menominee Group consists of the basal Ajibik Quartzite overlain by argillites, graywackes and slates of the Siamo Group and, in turn, by the Negaunee Iron-Formation. The latter is one of the major iron-formations of the world. Viewed in perspective, the Chocoday Group followed a long period of erosion and glacial activity and consisted of clastics with the carbonate rocks of the Kona followed by more clastics; then came the Menominee Group, continuing with clastics and terminating with the great thickness of the Negaunee Iron-Formation. The various land masses that were supplying the clastics and also the weathered material for the other sediments, contributed very little iron until Negaunee time. Weathering conditions must have been conducive to the liberation of substantial amounts of iron. Locally, there are clastic lenses in the Negaunee Iron-Formation which may reflect minor tectonic instability, but it is remarkable to note the great thickness of this relatively uniform chemical sediment.

Ajibik Quartzite

For the most part, this consists of massive quartzite with minor amounts of argillaceous and conglomeratic material. In appearance, the Ajibik resembles the Mesnard Quartzite. It does, however, display distinctive concentric stainings which probably are Liesegang rings. There is also a distinctive granule bed near the base of the Ajibik Formation. Estimates of the thickness of the Ajibik range from about 600 to 1,250 feet (180 to 380 meters).

Siamo Slate

The Siamo Slate consists of dark gray to light gray argillite, slate, graywacke and quartzite. Slaty cleavage is common to conspicuous. Locally, there are carbonate rich layers and also beds of conglomerate. There is also an unexposed magnetic section some 500 to 1,000 feet above the base of the Siamo. This has been correlated with the Goose Lake member proposed by Tyler and Twenhofel (1952). Noteworthy, too, are the clastic dikes found in the Siamo Formation. Material composing the clastic dikes is similar to that of the graywacke

beds in the formation. Maximum thickness of the Siamo has been estimated to be from 600 to 1,250 feet (180 to 380 meters).

Negaunee Iron-Formation

The Negaunee Iron-Formation is the most significant member of the entire stratigraphic column. It is the principal host rock for the direct-shipping type iron ores of the District and it is itself the ore for the modern mining-beneficiation operation. In general, it may be said to be similar to most other Middle Precambrian iron-formations of the Lake Superior Region. It is, however, remarkable for its relative lack of argillaceous and arenaceous facies. The maximum stratigraphic thickness is attained in the Negaunee-Ishpeming area where studies suggest thicknesses in excess of 3,500 feet (1,300 meters). These thickness estimates have been made by taking into consideration possible duplication through faulting and also by deducting the thickness of the various intrusive sills. In Negaunee, at the east and northeast portions of the synclorium, there is a transition zone from the Siamo to the Negaunee Iron-Formation in which there are interbedded argillaceous lenses and iron-formation. Some clastic zones are found in the southeast portion near Palmer. Considered in its entirety, there is a remarkable lack of distinctive stratigraphic features that might be used for correlating and distinguishing the various portions of this great thickness. The alteration of the iron-formation and the ore occurrences and their genesis are covered in subsequent portions of the paper.

BARAGA GROUP

In the principal part of the Range, the Baraga Group is made up of two members: the Goodrich Quartzite and the Michigamme Formation. The Michigamme Formation is further divided into a lower slate, with three iron-formation members; the Clarksburg Volcanics; and an upper slate. West of the central portion, near the Marquette County-Baraga County line, the members of the Hemlock Formation, the Fence River Formation and Strata Near Fence Lake occur which are equivalent to the lower part of the Michigamme Formation.

At the end of the deposition of the Menominee Group and before the deposition of the Baraga Group, there was a period of erosion which locally removed part or all of the Menominee Group. In a sense, the lithology of the Baraga Group parallels that of the Menominee Group which has a basal quartzite working up in through an argillaceous sediment and then through iron rich members. The Baraga Group, however, shows evidence of volcanism in the pyroclastics of the Clarksburg member. Furthermore, the Baraga Group iron-formation members are much thinner and are overlain by great thicknesses of graywackes and black shales or argillites.

Goodrich Quartzite

The Goodrich Quartzite is typically a light to medium gray thick bedded quartzite. Goodrich consists of conglomerates and interbedded argillites which locally display extensive ripple marks. In most localities, the basal conglomerate is made up of fragments of the Negaunee Iron-Formation. Elsewhere, fragments of vein quartz are found, suggesting that the weathering process was such that only a durable detritus is reflected in the conglomerate. The Negaunee-Goodrich contact has been reported to have up to 15 degrees angular discordance, but commonly there is very little noticeable discordance in the extensive exposures

in the Cliffs Shaft Mine. The Goodrich Quartzite grades upward into a banded argillite which is transitional to the lower argillite member of the Michigamme Formation. The thickness of the Goodrich Quartzite varies considerably. However, the greatest thickness is in the area of Ishpeming and immediately west of Ishpeming where thicknesses are believed to exceed 1,500 feet (460 meters).

Michigamme Formation

The Michigamme Formation was previously called the Michigamme Slate. However, it has been renamed because so many of the lithologic units within the formation are not slate. Estimates of the total stratigraphic thickness vary considerably but it can be noted that the Michigamme Formation is undoubtedly the thickest member of any in the Marquette Range Supergroup. For details of the Michigamme Formation with reference to the rocks found to the west and to the southwest, the reader is referred to Cannon and Klasner (1975). The Lower Argillite member, as noted above, is a transition from the Goodrich Quartzite. Exposures are limited; however, diamond drill core suggests that the rock is more coarse grained near the base and becomes progressively finer grained and also more iron rich near the top. Maximum thickness is indicated at approximately 1,500 feet (460 meters) for the Lower Argillite.

Greenwood Iron-Formation

This is gray-green to light colored banded magnetic silicate iron-formation with interbedded bands of argillaceous clastic material. It is exposed only on the south limb of the synclinorium but ground magnetics suggest that it also occurs on the north limb. The Greenwood Iron-Formation varies from the Negaunee Iron-Formation in that it contains clastic material and does not contain as much iron. The thickness on the south limb is estimated to range from 500 to 1,200 feet (150 to 365 meters).

Clarksburg Volcanics

These are mafic pyroclastic rocks consisting of metatuff and meta-agglomerate in layers ranging from six inches to one foot (150 to 300 millimeters). The weathered surface commonly is buff colored and has a rubbly appearance. The primary mafic minerals have been altered by metamorphism. The meta-agglomerate is mineralogically similar to the tuff, but it contains large fragments, some of them as much as 300 millimeters in diameter. The fragments themselves are principally tuff, pumice and scoraceous basalt. Thin bands of argillite are found throughout the exposures. Most of them, however, are too small to show at a map scale. Note the asymmetrical relationship of the Clarksburg in that it, too, is found only on the south limb.

Iron-Formation

Another iron-formation is found in the sequence essentially similar to the Greenwood Iron-Formation member. It is a weakly magnetic silicate iron-formation with only occasional chert bands. It also has considerable amounts of detrital material.

Upper Members

This consists of a variety of graywacke, argillites, quartzites, conglomerates and black carbonaceous, pyritic slate with some siltstone. Cannon and Klasner (1975) have published a summary of the "Stratigraphic Relationships within the Baraga Group of Precambrian Age, Central Upper Peninsula, Michigan" and relate the general stratigraphy of the western part of the Marquette Mineral District and its relationships to the central part of the Upper Peninsula, extending into Baraga and Iron Counties. They say:

"Clearly, lateral facies changes occur within distances of a few kilometers to a few tens of kilometers, resulting in many units of only local extent. The correlation of many of these units between well studied areas in the Marquette Trough to the north and Iron and Dickinson Counties to the south has been conjectural, largely because detailed maps linking these areas were lacking."

This summary presents the interpretation of the various facies relationships between the many local units in the Baraga Group.

Bijiki Iron-Formation

The Bijiki Iron-Formation is an intermediate unit in the Michigamme Formation and lies between the lower and upper members. It is believed that the primary sediment was essentially a cherty sideritic iron-formation similar to the Negaunee Iron-Formation. The lower portion is metamorphosed cherty silicate iron-formation, while the upper part is oxidized and locally enriched in certain structural features. High-grade shipping ore was once produced both in the Champion area and in the area west of Michigamme. Mining was done both by open pit and underground methods. Thicknesses ranged from 100 to 200 feet (30 to 60 meters). Over 4 million tons of ore were shipped from mines in the Bijiki Iron-Formation.

Other Members

As noted in the stratigraphic column, there are other members related to the Hemlock Formation and one called the Fence River Formation that are thought to be equivalent to the lower part of the Michigamme Formation, as described by Cannon and Klasner (1975).

PAINT RIVER GROUP

Harold James (1958), in the U.S.G.S. Professional Paper 314-C, describes the Paint River Group that overlies the Baraga Group. This series is found to the southwest of the Marquette Mineral District.

Gwinn District

The Gwinn District is located to the southeast of the main Marquette Range synclinorium (see Figure 9). The following column has been modified from Allen (1914):

Paleozoic		Ordovician Cambrian	Limestone and sandstone
Precambrian	Late	Keweenaw	Intrusives
	Middle	Baraga	Princeton Series Ferruginous slate, cherty quartzite and graywacke conglomerate
		Menominee	Gwinn Series Dark gray slate, graywacke Iron-Formation Dark gray to graphitic slate
	Early		Granite, greenstone

Some geologists have speculated that the iron-formation in the Gwinn District is correlative with the Bijiki Iron-Formation rather than the Negaunee. Insufficient work has been done on this District to be that definitive. Also, it is not known definitely that the limestones and sandstones are Paleozoic, as no fossils have been found.

Metadiabase

A variety of metadiabase and metagabbro form dikes, sills and irregular shaped bodies in the various members of the Lower and Middle Precambrian rocks. In general, these are green to dark green rocks and generally medium to coarse grained. They have, however, been metamorphosed. They are found in dikes of varying thickness and where the dikes are thin, they are fine grained.

Large masses of the metadiabase are found in the Negaunee and Ishpeming areas within the Negaunee Iron-Formation. VanHise and Leith (1911) note:

"Within the iron-bearing formation, there are numerous intrusive masses of 'greenstone', really diabase and its altered equivalents. These occur in the form of both dikes and bosses, and many of the latter are of large size, running up to masses 2 miles or more in extent. These rocks are especially prevalent in the broad area of the iron-bearing formation near Ishpeming, where they occupy between one-third and one-half of the area. In many places the greenstones intrude the sedimentary series in a roughly laccolithic fashion. In consequence of this, where the two have been folded together their relations are roughly similar to those of sedimentary formations, but when examined closely, the greenstones are always found to cut the Negaunee Formation to a lesser or greater degree."

The sill-like relationships of the intrusives within the iron-formation are not always as apparent from surface exposures as they are from diamond drilling and underground workings. Underground Hole #440, drilled in 1893 from the 1,000 foot level of Number 4 Shaft, Cleveland Hematite Mine, was studied by

H. L. Smyth. This hole was directly under a major surface exposure of metadiabase. He concluded the intrusive was sill-like.

A general average for their thickness in the Ishpeming-Negaunee area would be of the order of 400 feet (120 meters), with a maximum of 700 feet (210 meters). For a number of years, mining company personnel have used them, over short distances, as horizon markers. This practice is described by Gair and Simmons (1970). Puffett (1974) concludes that the metagabbro is probably Early Precambrian in age. The metadiabase may be of several ages; some may be definitely Early Precambrian or Middle Precambrian. He believes that the diabase is of Keweenaw age.

KEWEENAWAN

Diabase

The diabase is found principally as dikes that intrude virtually every rock unit of Lower and Middle Precambrian age. It is normally dark brown to black, fine to medium grained, and weathers a rusty brown color. It is noted, too, that the diabase is frequently magnetic while the metadiabase is not. Ground and aerial magnetic surveys normally show these as narrow negative anomalies.

Jacobsville Sandstone

Near Marquette, a few scattered exposures of a sandstone are found which correlate with the Jacobsville of the Keweenaw Peninsula. It is essentially a reddish or reddish brown friable feldspathic lenticular sandstone with intercalated lenses of red or gray conglomerate and reddish shale. In general, the dip angle does not exceed 15 degrees and cross-bedding is common. The age of this material is not known definitely. It has been assigned both to the Keweenaw age and also to Early or Middle Cambrian. Larry L. Babcock (1974, 1975), from studies in the type locality and along the Keweenaw Peninsula, ascribes it to Lower-Middle Keweenaw age.

PALEOZOIC

Cambrian and Ordovician Limestones and Sandstones

Reference has already been made to the limited limestone and sandstone exposures near Gwinn. There is no question that Paleozoics are found nearby (see Figure 1), as they are found extensively to the east and south of the Marquette Mineral District. These extend to the Lower Peninsula where their extensive development in the Michigan Basin is found.

CENOZOIC

Pleistocene Glacial Deposits

The Marquette Mineral District was extensively glaciated. The principal glacial deposits in the highlands were from the Cary substage of the Wisconsin stage which retreated about 13,000 years ago. The Valders substage did reach the Marquette area to an elevation of perhaps 1,000 feet or more above sea level. John D. Hughes (personal communication) suggests that there were low stages in the Lake Michigan and Lake Huron basins at the time the ice border withdrew from

the Michigan shoreline of Lake Superior between Marquette and Whitefish Bay. Withdrawal of the ice permitted eastward drainage of the Superior basin and brought an end to Lake Duluth, the name given to the very high stages. A retreat in the North Bay area initiated the low stages and may have contributed to the formation of Lake Chippewa in the Michigan basin and Lake Stanley in the Huron basin. The first eastward drainage from the western Superior basin entered the Au Train-Whitefish spillway by flowing across a rocky highland that borders the Au Train River valley near Lake Superior. The initial flow took place when the ice border had retreated to a point within 8 miles of the present Lake Superior shore and uncovered a pass across the highland at an elevation of 1,050 feet above sea level. From the top of the highland, the water distended swiftly into the Au Train-Whitefish lowland. As the ice border on the highland withdrew toward the north, a succession of progressively lower spillways was uncovered until the lowest, at an elevation of 820 feet, was opened. When the ice border on the highland had retreated 6 miles from the first point of eastern drainage, the outlet was uncovered which was then at least 40 feet below the Au Train-Whitefish lowlands sill, and must relate to the eastern drainage toward the St. Mary's River that followed a path between the Michigan-Lake Superior slope and the ice border. The surface of Green Bay and Lake Michigan was at a very low level at the end of Lake Duluth times, or must have reached the low level before the Au Train-Whitefish lowland was abandoned as a spillway. According to Dorr and Eschman (1970), the last of the ice barriers melted about 9,500 years ago, thus initiating "post-glacial time". About 3,200 years ago, the St. Clair outlet was lowered to give rise to the present Lake Michigan-Lake Huron surface. Lake Superior became a separate lake at an elevation of approximately 602 feet above sea level.

Orogeny

Seaman (1944) suggested two periods of orogeny following Michigamme time which he called Sibley and the Superior (or Republic) which preceded Keweenaw times. The Superior would correspond to the Penokean Orogeny, as noted by W. F. Cannon (1973), "The Penokean Orogeny in Northern Michigan". The term was introduced by Blackwelder in 1914. Continuing work by the United States Geological Survey over the past 30 years has helped to define the structural style and orogenic sequence of the Penokean Orogeny as pre-Keweenaw-post-Marquette Range Supergroup. The summary by Cannon (1973), reviews both the structural geology and the regional metamorphism. For some time, mining company geologists had used the relative metamorphic order to assist in the exploration for potential concentrating ores. The paper by H. L. James (1955) was essentially a regional reconnaissance study. Later detailed work has done little to change the pattern which he described. Figure 12 shows the nodes and zones of the Penokean regional metamorphism and is modified from James and Cannon.

Both the Republic and Peavey nodes reach the sillimanite zone. It is interesting to note that the greater part of the "soft" iron ore is found in the Ishpeming and Negaunee areas which is in the chlorite to biotite zones. The metamorphic isograds cross the geologic structures at high angles in many areas. This suggests that the metamorphism is post-deformation.

Of considerable interest is the paper by James and Clayton (1962), relating mineral formation temperatures to their oxygen isotope fractionation. Some samples from the Marquette Range were tested, specifically from the Athens and Greenwood Mines and the Republic District. They tentatively conclude: 1) on the

basis of internal consistency and consistent relations to the mineralogic evidence of metamorphic zoning, the isotopic data yields at least a fair approximation of temperatures of metamorphism through the garnet zones; 2) the temperature of metamorphism for the chlorite zone reaches approximately 200° C., that of the biotite zone approximately 275° C., and that of the garnet zone approximately 350° C.; and 3) the rocks in the staurolite and sillimanite zones (upper part of the epidote amphibolite facies and amphibolite facies, respectively) were formed at temperatures above 350° C., and the present isotopic composition of the oxygen of these rocks is due to retrograde equilibration during temperature decline.

In 1945, the writer noted various occurrences of dickite and chrome nontronite in underground mapping in the mines in the Negaunee area. These were submitted to J. W. Gruner, who published a paper concerning them in 1946. Samples were also supplied to Stanley Tyler. The paper by Bailey and Tyler (1960) describes a number of these minerals.

PRIMARY IRON-FORMATIONS

Since the time of Douglass Houghton, students of iron-formations have speculated over the nature of the primary sediment and its subsequent alteration. Monograph LII treats the subject from page 500 to 520, inclusively. Particularly significant is the summary of Harold L. James (1954) on sedimentary facies of iron-formation, which emphasizes the four basic facies: carbonate, sulfide, oxide and silicate. Quoting from pages 246 and 247:

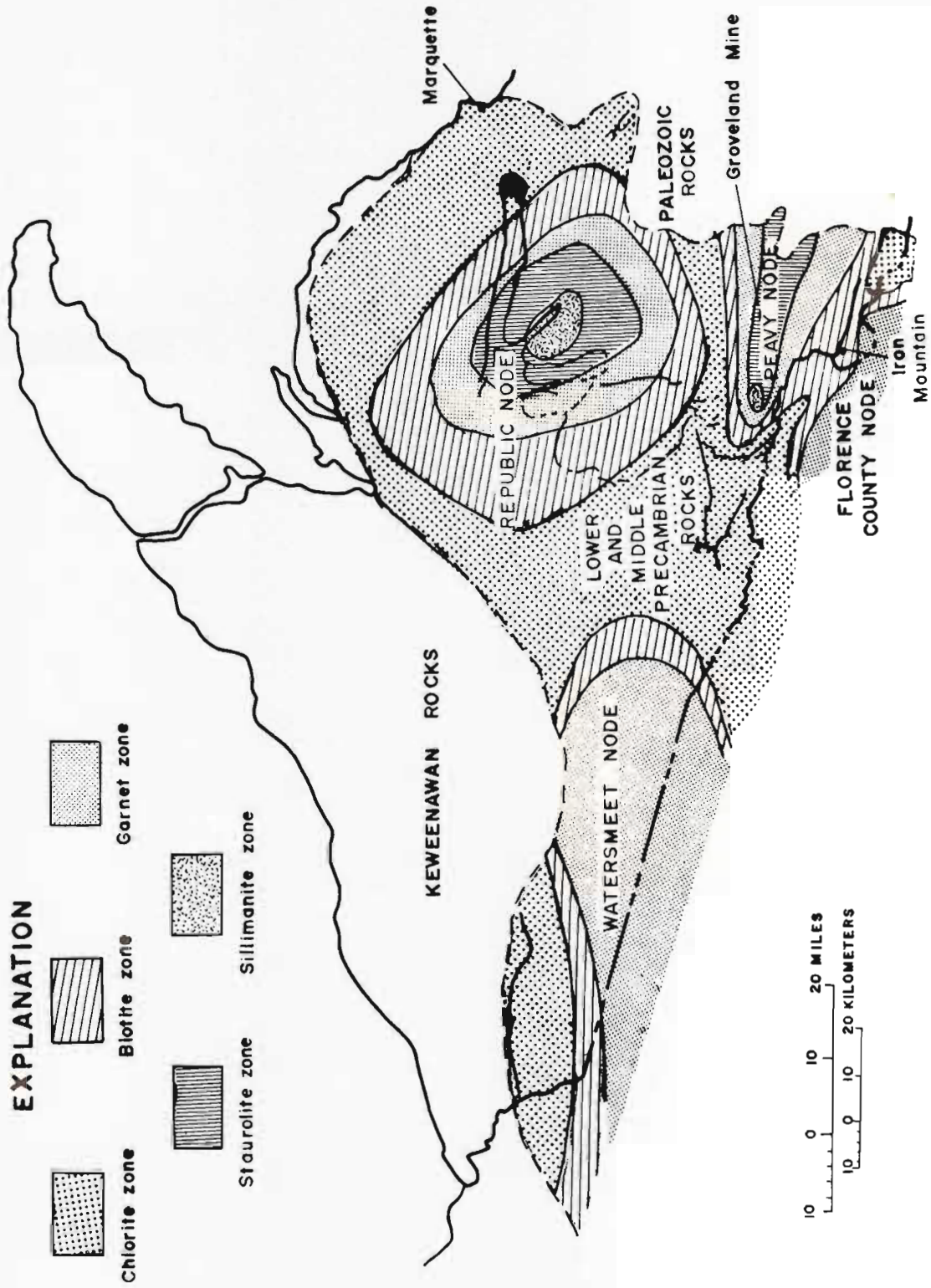
"As might be expected, the lithologies encountered in the field are more complex than those suggested by generalized theoretical considerations. Four clearly defined end members — sulfide, carbonate, silicate, and oxide — make up a large part of the iron-formations. But many of the rocks were deposited in fluctuating environments, with resultant interlayering and modification of contrasting materials; others were strongly modified by diagenesis under chemical environments much different from those existing during deposition; still others owe some of their properties to clastic additions during chemical sedimentation. These factors make pigeon-hole classification of the present rock units a difficult task, but at the same time the preserved record furnishes valuable evidence with respect to relative stabilities of the minerals and the nature of the depositional and burial environments.

"The sulfide, carbonate, and oxide (hematite) facies stand in well-defined theoretical and field relationships to one another. The analysis by Krumbein and Garrels ... shows that there is little or no overlap of stability fields. This is borne out by field evidence; except for diagenetic modifications ... pyrite, carbonate, and hematite are mutually exclusive within a given layer of iron-formation. Also, since the chemistry of depositional environments does not change radically within short periods of time, interbedding, if present, is between adjacent types — that is, between sulfide and carbonate or between carbonate and oxide — rarely if ever between sulfide and oxide.

"The silicate facies does not appear to occupy a fixed position in terms of Eh, the major environmental control. Iron silicate apparently of primary

FIGURE 12

MAP SHOWING NODES AND ZONES OF
PENOEAN REGIONAL METAMORPHISM



Modified from James (1955) and Cannon (1973)

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origin is present as interstitial material or as discrete layers in rocks composed dominantly of sulfide, carbonate, or oxide. However, it occurs most abundantly in rocks with layers that contain either oxide or carbonate. This association suggests that the optimum environment for its deposition is one that lies, with respect to Eh, near the boundary zone between oxidizing and reducing. But other factors, such as addition of clastic material, probably are involved in the formation of the silicate rocks."

Other significant references are Boyum, Anderson and Han (1955), Anderson and Han (1956), Lepp and Goldich (1964), Han and Villar (1965), Han (1966), together with the papers published in November, 1973, in the Bulletin of the Society of Economic Geologists, reflecting the conference held at the University of Minnesota, November 10-12, 1972. Noteworthy is the summary by R. W. Bayley and H. L. James (pages 934-959) and S. S. Goldich (pages 1126-1134) as well as the other papers in this publication. Diagenetic-metamorphic replacement features are covered by Han (1971). The paper by James I. Drever (1974), "Geochemical Model for the Origin of Precambrian Banded Iron-Formations", as indicated in the title, contains an interesting suggestion for the source of the iron.

As noted earlier, the Negaunee Iron-Formation is noteworthy for its great thickness and relative uniformity in the eastern part of the synclinorium, as well as the fact that the principal facies is the carbonate facies. Photomicrographs accompanying this paper illustrate a number of these features.

T. D. Waggoner (1972) pointed out the local stratigraphic correlation of the lower part of the Negaunee Iron-Formation based upon lithology, mineralogical assemblages, grain size, color and metallurgical response. These correlations reflect not only the primary sediment but also metamorphic effects over short distances.

Alteration of the Negaunee Iron-Formation

Much of the bulk of the Negaunee Iron-Formation has been altered by oxidation and enrichment, as well as metamorphism. There are areas of virtually unaltered iron-formation. The average iron content of this material approximates 26%, dried. Where the iron-formation has been oxidized, the average approximates 31% iron, dried, taking the whole Range into consideration. Locally, in the Negaunee area, the average is somewhat higher, approaching 35%. The average weighted crude ore feed for the various beneficiating properties considered over the life of mine in terms of acid soluble iron is as follows:

Empire Mine	33%
Tilden Mine	36%
Republic Mine	37%
Cascade Project	37%

As noted above, the principal facies found in the Negaunee Iron-Formation is the carbonate facies. The stages in alteration include the oxidation of the carbonate normally to hematite or to goethite. As oxidation and enrichment progress, more of the chert is replaced by iron oxides. On the Marquette Range, for the most part, this is a volume-for-volume metasomatic replacement. This contrasts with the Mesabi Range, for example, where extensive slumping is

is noted in the formation of high-grade orebodies. In numerous instances, it is possible to follow the primary bedding from little altered iron-formation into ore. In some instances, the replacement is selective and in other cases, it is highly irregular, crossing the bedding at high angles. The only area of incomplete volumetric replacement has been noted in the North Lake District, particularly at the Barnes-Hecker Mine where large openings were known to occur.

The oxidation and enrichment of the Negaunee Iron-Formation have extended to great depths. The folding of the Marquette Range synclinorium was accompanied by the development of a strong joint system which locally increases the permeability of the iron-formation. Exploration by diamond drilling and by underground workings in recent years has indicated that the oxidation and the enrichment extend to far greater depths than thought by earlier studies. Drill holes have cut rich material in an excess of 57% iron, dried, to depths of over 5,000 feet from the present land surface. The deepest hole drilled so far on the Marquette Range reached a depth of 6,365 feet and was NX size (3-inch diameter). This hole encountered oxidation and enrichment to the bottom. We assume that the post-Baraga oxidation and enrichment to ore took place in late Precambrian time. Undoubtedly, erosion of overlying rocks took place since that time, reducing the depths to what we observe now.

The alteration of the Negaunee Iron-Formation and the other iron-formations on the Range have all been affected by the regional metamorphism (see Figure 12). Locally, the iron-formations have been altered to silicate complexes. The several papers by Tsu-Ming Han provide detailed descriptions of these various mineral assemblies. Variations can be anticipated because of the variety of possible primary facies (carbonate vs. oxide vs. silicate vs. sulfide), the variety of participating fluids, specific structural conditions and lack of isotopic equilibrium together with retrograde metamorphism. Variations in metamorphic degree, too, can be expressed by the relative increase in grain size, both of the quartz and of the ore minerals (see Table I).

Ore Occurrences

The accepted definition of the word "ore" is "a mineral or group of minerals from which a metal or metals can be extracted at a profit". Over the years, the direct-shipping ores, particularly in the Lake Superior Region, have had a base iron content of 51.5% iron, natural (moisture included). Since the 1950's, the grade of the iron content of the direct-shipping ores has tended to be higher, reflecting the competition of foreign ores as well as the concentrates and agglomerates. In recent years, their grades have been in the range of 54 to 56.5% iron, natural.

Four principal types of ore have been produced and shipped from the Marquette Iron Range. They are:

- High-grade direct-shipping "soft" ores
- High-grade direct-shipping "hard" ores
- Siliceous ores
- Concentrates and agglomerates (pellets) from iron-formation

TABLE I
Indicators for Metamorphic Grade in Precambrian Sedimentary Iron-Formations

GEOLOGICAL PROCESS	ORE MINERAL INCLUSIONS	CHARACTERISTICS OF SILICATES	HEMATITE-MAGNETITE RELATIONS
DIAGENESIS			
LOW GRADE METAMORPHISM	Very abundant	Decreasing number of hydroxyl ions in silicates → SHEET SILICATES Minnesotaitite Stilpnomelane Chlorite	Sharp increase of ore mineral size → MAGNETITE STABLE Magnetite replacing Hematite
MEDIUM GRADE METAMORPHISM	Appreciable	DOUBLE CHAIN SILICATES Grunerite Cumingtonite Actinolite Hornblende	SPECULARITE STABLE Specularite replacing Magnetite
HIGH GRADE METAMORPHISM	Common to fairly common	DOUBLE CHAIN SILICATES Amphiboles SINGLE CHAIN SILICATES Pyroxene	MAGNETITE STABLE Magnetite tending to replace Specularite

From Tsu-Ming Han (1966)

Page 1 of 1

Table 1: Summary of the data

Year	Value
2010	100
2011	110
2012	120
2013	130
2014	140
2015	150
2016	160
2017	170
2018	180
2019	190
2020	200

Table 2: Summary of the data

Year	Value
2010	100
2011	110
2012	120
2013	130
2014	140
2015	150
2016	160
2017	170
2018	180
2019	190
2020	200

Table 3: Summary of the data

Year	Value
2010	100
2011	110
2012	120
2013	130
2014	140
2015	150
2016	160
2017	170
2018	180
2019	190
2020	200

Table 4: Summary of the data

Year	Value
2010	100
2011	110
2012	120
2013	130
2014	140
2015	150
2016	160
2017	170
2018	180
2019	190
2020	200

Table 5: Summary of the data

Over the years, the miners noted the distinction of the two principal types of high grade ores: soft and hard. The soft ores have porous, friable, and earthy to semi-plastic characteristics. The minerals are principally hematite, goethite with minor amounts of martite (locally some are still magnetite), some unreplaced chert and, locally, silicates. The hard ores are hard, dense, and compact with low porosity. The iron minerals are compact to specular hematite and magnetite. Soft ores tend to be dark red to reddish blue through to orange and yellow when there is a high proportion of goethite. The hard ores are blue, blue-black to reddish black, steel gray to reddish dark blue. The partially enriched iron-formation found with the soft ores tend to have white to gray chert and were called "soft ore jasper". The iron-formation found with the hard ores was called "hard ore jasper" and has bands of red chert to gray or black chert. The red chert is the jaspilite.

The siliceous ores were enriched hematitic and goethitic iron-formation found along the south limb of the main synclorium or in the Cascade Range. These tended to have approximately 38% iron with a roughly equivalent amount of silica. There is a limited market for this material. It is used to control the basicity of the slag in the blast furnace.

The concentration and agglomeration of the iron-formation has already been discussed. As noted, this type of ore product constituted 96% of the production for the year 1974 from the Marquette Mineral District.

Soft Ores

Approximately 57% of the total production of the Marquette Range through the year 1974, including the Cascade and Gwinn Districts, has been of the soft ore type of high-grade direct-shipping ores. The greater part of these occurred in the basal portion of the Negaunee Iron-Formation and in the eastern part of the District. Figures 10 and 11 illustrate typical occurrences. These deposits may be as thick as 260 feet (80 meters) normal to the bedding and have considerable lateral extent. Typically, they are formed in upward facing or open structures formed by folding, faulting or some combination of structural configuration, including faults occupied by dikes.

The ores, apparently without exception, are found in a "host" of oxidized and enriched iron-formation. The lower contact of the orebodies was on the transition zone from the Siamo Slate to the Negaunee Iron-Formation. As noted earlier, there are several occurrences of interbedded argillite in the iron-formation near the base of the Negaunee Iron-Formation. In some cases, the iron-formation between these argillite layers was replaced to form high-grade ore and, in many cases, both these argillites and any adjacent intrusives were highly altered, some to the extent of being of ore quality.

Of minor importance from a tonnage viewpoint, but of interest from a structural viewpoint, are local soft orebodies found in "ore types" which are chimneys of ore extending some distance vertically, cutting the stratification of the iron-formation. These pipes were 200 to 300 feet across

and were localized at the intersection of two or more vertical intrusives cutting the iron-formation. This type of ore has been characterized by its low phosphorus content and by the ground conditions that the miners refer to as "heavy ground".

Elsewhere throughout the Negaunee Iron-Formation, some soft orebodies were found near the hanging wall lying on top of the metadiabase sills. In one instance (Section 16 Mine), the soft ore on top of the sill came up to a contact with the hard ore (E. L. Derby, Jr., personal communication). This ore type is of irregular distribution, both as to its occurrence and its thickness. These deposits were found to the south of Ishpeming toward the axis of the Range synclinorium. Most of these properties were active around the turn of the century and it was an important ore source at that time. The ore appears to be post-metadiabase sills and, in some cases, the sills themselves are highly altered. In general, we can say structural controls appear to be similar to that of the ore lying on the footwall contact. In general, the ores were high in iron content and low in phosphorus and sulfur.

As noted earlier, the mineralogy of the soft ores is relatively simple, essentially hematite and goethite with some martite and unreplaced chert. While most of them were earthy to plastic, there were variations and gradations to a semi-hard ore. Locally, at the Negaunee Mine and at the Mather Mine "A" Shaft were types that were very similar to the hard ore. Other minerals which appear to be post-ore are gypsum, kaolin, dickite and chrome nontronite as well as minor amounts of other clay minerals (Bailey and Tyler, 1960). The gypsum, kaolin and dickite appear to be filling the interstitial volumes of porosity as the latest minerals while the chrome nontronite is generally in veins. The gypsiferous zones occur in definite elevation zones (near the present sea level), cutting across the stratification of the iron-formation and also across the orebodies in a tilted tabular-like occurrence.

The soft ore found in the Bijiki Iron-Formation and also in the iron-formation at Gwinn is generally similar to the occurrences described for the Negaunee Iron-Formation. The ratio of goethite to hematite was much higher in the Bijiki soft orebodies while the hematite was the principal mineral in the Gwinn ore occurrences. The Gwinn orebodies were found near the base of the iron-formation. In the case of the Bijiki ores, some of the soft ores occurred with a footwall of silicate iron-formation. In both instances, the orebodies were found in some structural configuration, folding and/or faulting. In the case of the Bijiki occurrences, the oxidation seemed to terminate under the overlying Michigamme Formation, much like the Biwabik Iron-Formation under the Virginia Slate on the Mesabi Range.

Hard Ores

The production of hard ores amounts to 16% of the total iron ore produced through 1974 on the Marquette Mineral Range. With the exception of a few minor occurrences noted above, the vast majority of the hard ores was found in

the upper part of the Negaunee Iron-Formation and generally immediately below the contact with the Goodrich Formation. The hard ores are made up of hard, dense, compact to specular hematite and magnetite. The orebodies are found within well oxidized and locally enriched iron-formation, generally of the jaspilite or magnetic silicate type iron-formations. Remnants of jaspilite or gray hematitic cherty iron-formation may be found within the ore. This jaspilite is, in turn, underlain by a sideritic iron-formation or, in some cases, by a silicate iron-formation. Laterally, the hard ore grades along the bedding into jaspilite and, in turn, into the cherty carbonate iron-formation. Also, locally, remnants of the cherty carbonate iron-formation can be found surrounded by jaspilite. In other cases, the orebodies lie on top of the irregular intrusive metadiabase. Structural relationships indicate that much of the metadiabase predates the Goodrich Quartzite. In other cases, the relationship is not that clear. Commonly, the upper contact of the hard ore is with the conglomerate, with varying thickness, or an argillite, either of which grades rapidly into the quartzite. In one occurrence in the Cliffs Shaft Mine, the writer mapped seven alternating layers of conglomerate and argillite. Locally, the conglomerate itself is of ore grade with both the pebbles and the matrix being hematite. The intrusives which cut the hard ore are quite frequently confused with the argillite of the Goodrich Formation. Both materials are fine grained and highly altered, making identification difficult.

As noted earlier, there was an extensive period of erosion at the end of the Menominee Group before the deposition of the Baraga Group. Thus, the Goodrich-Negaunee contact is an erosion surface but there appears to be little or no angular discordance. It would appear that the structural folding observed in the Cliffs Shaft Mine, for example, did not exist prior to the deposition of the Goodrich.

The most easterly hard ores are found at the Jackson Mine and it was this deposit that was found by Burt's survey party in September, 1844. Hard ore is found again at the east end of Ishpeming where the hard ore crops out, being part of the very extensive Cliffs Shaft Mine ore occurrence. There are no active hard ore mines on the Marquette Range at the present time. The last two remaining active properties, the Cliffs Shaft Mine and the Champion Mine, closed in 1965 and 1967, respectively. The Cliffs Shaft Mine was the largest of all, having produced over 27,740,000 tons of premium hard ore. The workings occurred under the greater part of the city of Ishpeming. The structure was that of a westerly plunging syncline having a crossfold under the town of Ishpeming, bringing the ore close to ledge surface adjacent to the distinctive headframes, which are still standing. Other important properties include the Lake Superior Hard Ore, south of the Cliffs Shaft Mine, the Greenwood, Humboldt and Champion Mines, all along the south limb, the Republic Mine in the Republic fold and the Michigamme Mine on the north limb near the west end of the Range. The Republic Mine produced 8,563,170 tons, reaching a depth underground of some 4,000 feet along the plunge, or 2,800 feet vertically (1,200 and 850 meters, respectively).

Not only is there less porosity and permeability in the hard ores but this also occurs in the overlying Goodrich Formation. The ore can be said to be in tight structural traps. The writer has been underground in several old mines that

had flooded and were reopened. One could find places in the old workings where the air compressed and a high-water "reaction" rim could be noted in the roof of the stope, showing that the compressed air could not escape.

Concentrating Ores

A general summary of the "concentrating" ores is provided on page 195. The following descriptions are taken from G. J. Anderson (1968):

Humboldt Mine

The first property on the Marquette Range and in Michigan to utilize fine grinding to obtain liberation and concentration of the iron minerals was the Humboldt Mine. Locally, the structural pattern consists of a north-south monocline dipping westward. Dips range from nearly vertical on the northern and southern portions to approximately 55 degrees in the central area.

The hanging wall consists of a quartzite that is, in part, conglomeritic and argillaceous. An alternating series of mafic intrusives and unoxidized silicate iron-formation forms the mining footwall.

The ore section consists of a specular hematite-chert in the upper part and a specular hematite-magnetite-chert in the lower part. Visible subordinate minerals include sericite, muscovite, tourmaline, garnet, apatite, and chloritoid. Locally, sericite is a major mineral.

The mill flowsheet included three stages of crushing and two stages of grinding in rod and ball mills. Liberation of the specular hematite and magnetite was essentially achieved at minus 65 mesh. Concentration of the iron oxides was by froth flotation, and the chert was depressed. The ore was pelletized. Operations started at this property in 1954 producing concentrates. Pelletizing started in 1960 and reached a capacity of almost 900,000 tons per year. Mining ceased in 1970 and the pellet plant has processed Republic Mine concentrates since that time.

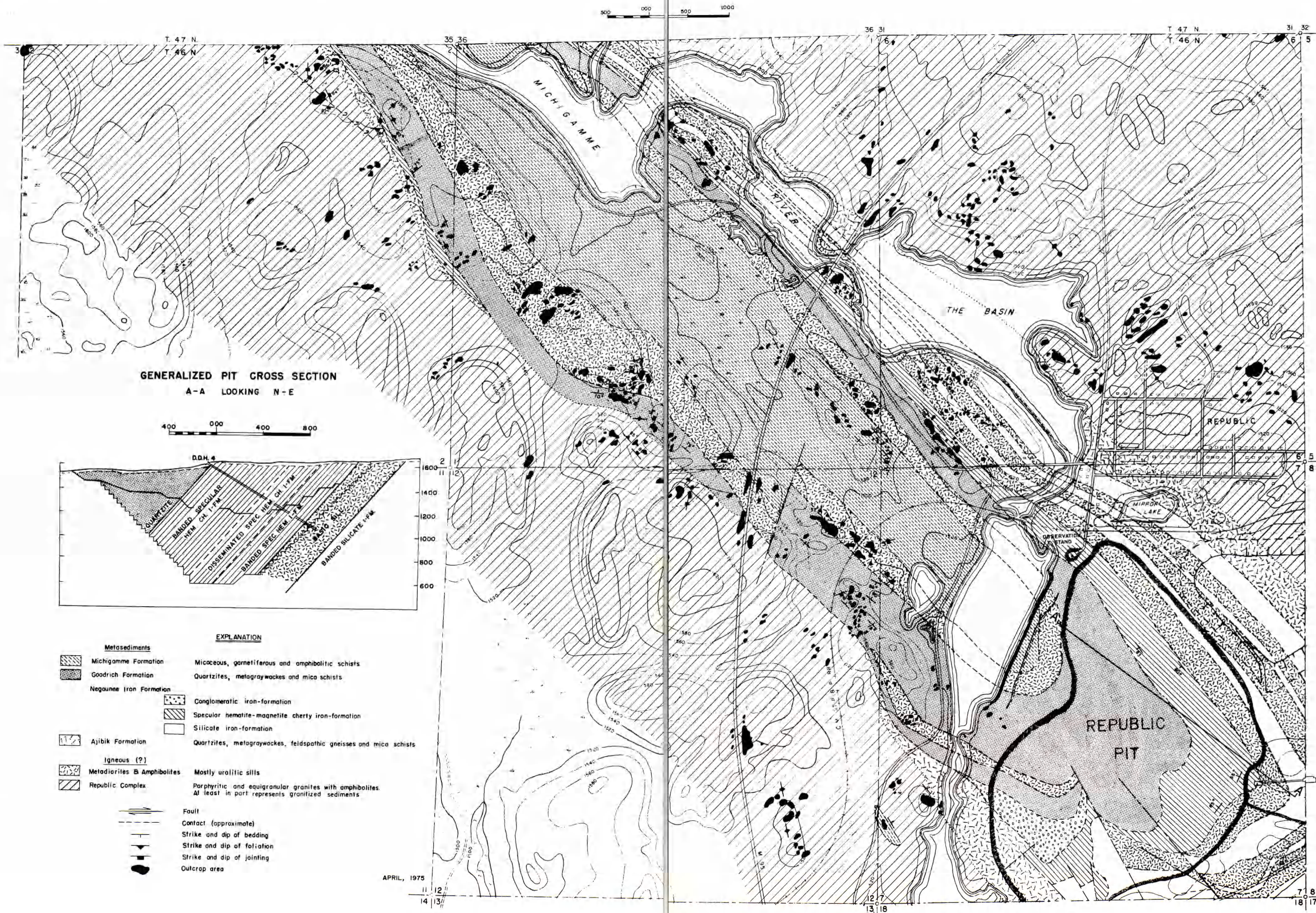
Republic Mine

The Republic deposit is located near the southern extremity of a tightly folded syncline known as the Republic Trough that extends southeasterly off the main Marquette Range synclinorium (see Figure 9). Like the Humboldt, the Republic orebody is located immediately below the Goodrich Formation (see Figure 13). The dip of the orebody ranges from 45 degrees near the plunging end of the trough to nearly vertical along the north limb of the trough. The orebody is a tabular mass 400 to 600 feet thick and is being mined along a strike length of 6,000 feet. Information from underground workings of the "Old" Republic hard ore mine indicates that the specularite iron-formation extends downdip over 3,000 feet. Economic conditions will dictate how deep the orebody may be mined.

The iron-formation at the Republic Mine is subdivided into four basic lithologic types according to major mineral constituents. These include a specular

GEOLOGY OF THE REPUBLIC MINE AREA

FIGURE 13



hematite-chert-muscovite conglomerate member at the base of the Goodrich Formation and, in descending order, a specular hematite-chert, a magnetite-chert and a magnetite-grunerite-chert. The upper three members constitute the ore feed for the Republic concentrator. The magnetite-grunerite-chert, although not being mined at present, is a potential ore reserve of fine-grained magnetite that may be utilized by a different flow scheme at some future date. The magnetite-grunerite iron-formation is cut by a series of sill-like amphibolite intrusives. At present, the mining footwall at Republic is either amphibolite intrusive or magnetite-grunerite iron-formation.

The flowsheet at the Republic Mine is essentially the same as at the Humboldt Mine except that, in addition to conventional flotation, the Republic mill employs a final hot-flotation process to upgrade the concentrates to produce a 65% iron pellet. Annual production is 3.5 million tons of pellets, of which 900,000 tons are pelletized at the Humboldt Mine.

Empire Mine

The Empire Mine and Plant is the first of its kind constructed to treat magnetite ores in Michigan. This property was placed in production in 1963 to concentrate a magnetite-rich portion of the Negaunee Iron-Formation that occurs in the Palmer area (see Figures 9 and 14). The ore occurs in a monoclinial fold which dips about 35 degrees to the northwest. Dike-filled transverse faults cut the monocline into blocks. The apparent stratigraphic thickness of iron-formation in the Empire area is about 3,000 to 3,500 feet. Ore is now being mined from an area 5,600 feet long and 4,800 feet wide. Diamond drill hole information indicates good concentrating ores to a depth of 1,100 feet.

The iron minerals in the Empire ore are magnetite, iron carbonates, iron silicates, martite, and earthy hematite with minor goethite and pyrite. The economic iron mineral is very fine-grained magnetite with a common size range of 400 to 800 mesh (0.037 mm to 0.019 mm). Geologic mapping and ore-dressing tests indicate four types of ore from the hanging wall towards the footwall: 1) magnetite-chert-arenaceous iron-formation, 2) magnetite-chert-carbonate iron-formation, 3) magnetite-chert-silicate iron-formation, and 4) magnetite-chert-silicate-carbonate iron-formation (see Figure 14). The orebody is within the Negaunee Iron-Formation. The hanging wall rock stripping consists largely of lean sub-economic iron-formation that occasionally may contain ore material, and the footwall of the orebody is mainly a silicate iron-formation. The actual mining limit differs according to the amenability of the iron-formation material to make a suitable grade and give a satisfactory iron recovery. (Plates I-D and E illustrate ores from the Empire Mine.) Liberation of the magnetite is achieved at a grind of 90% minus 500 mesh, or about 0.032 mm. The ores are ground in an autogenous circuit and concentrated by magnetic separation and siphonsizers. Amine flotation is utilized for final upgrading to produce a plus 63% iron pellet. Annual production rate is 5.3 million tons of pellets.

Tilden Mine

The Tilden Mine is the most recent property to be developed on the Marquette Range. It is found on the south limb of the synclinorium (see Figures 9 and 15). The area is rugged and includes the highest point in Marquette County, Signal or

Firetower Hill (+1875 feet or 572 meters). Stratigraphically, the major area of mining is approximately in the middle third of the Negaunee Iron-Formation. The general strike is almost east-west (N. 80° E.) and the dips are to the north-west at 30 to 40 degrees. Numerous metadiabase sills and dikes are found. The sills pinch and swell, being concordant with the formation bedding in many places and cutting the bedding elsewhere.

A significant structural feature associated with the orebody is the Palmer Fault which marks the footwall. The lower third of the Negaunee Iron-Formation has been faulted off to the east with an apparent horizontal movement of over four miles. The fault has a uniform east-west strike and from diamond drill data indications are that it dips 55 to 60 degrees to the north. The footwall consists of a chlorite schist. Northwest trending rotational faults offset both the iron-formation and the metadiabase sills. Faults may contain occasional chlorite-carbonate dikes and are definitely of a later age than the sills.

Most of the faults show some lateral movement as revealed by offsets of the iron-formation sill contacts. In most observations, the western block has moved to the northwest in relation to the eastern block. Three of the faults cut across the east-west footwall fault and indicate that the northwest-southeast fault system was active both prior to and after the east-west movement.

The major minerals in the Tilden ore body are martite, a pseudomorph of hematite after magnetite, and silica in the form of a fine-grained chert. Some of the chert bands contain ultra-fine hematite which imparts a red color, prompting the term jaspilite for some ore zones. Minor amounts of fine-grained earthy hematite, a product of secondary oxidation of the carbonate and silicate minerals, are common throughout the formation and in a few localized areas it is the pre-dominant iron bearing mineral.

A remnant magnetite-carbonate chert zone outcrops in the east end of the West Pit and rakes downdip at about 45 degrees to the northeast. A second magnetite-carbonate body occurs under the large sill around Tilden Lake. Most of the carbonate occurs as siderite with only minor amounts of ankerite. Drilling has revealed that secondary oxidation decreases and the primary minerals of magnetite and iron carbonates increase with depth.

Iron oxide grain sizes range from sub-micron to +100 microns with an average between 15 and 22 microns for most of the martitic zone. Much of the orebody mineral assemblage is characterized by aggregates of grains which form distinct bands alternating with chert bands.

The large clastic unit, although lens shaped and irregular in thickness, is considered a synchronous unit and has been used extensively in the correlation study. Unfortunately, secondary oxidation has eliminated direct mineralogical correlations with other units in the formation. Trace element analysis was attempted in hopes of establishing the identity of individual units but failed due to the complete redistribution of ions in the oxidized facies.

Exploration and metallurgical research have gone on for years. In 1963, a pilot plant program was initiated with the U. S. Bureau of Mines in Minneapolis,



A. Cherty Carbonate I-Fm.
Thin Section 200X Athens Mine
Magnesium iron carbonate
granules, various shades;
chert, white

Magnetite lamina alternating
with silicate-carbonate

Silicate-carbonate

Silicate-chert containing
some carbonate

Magnetite lamina alternating
with magnetite-chert-
carbonate-silicate

Chert-silicate containing
carbonate and magnetite

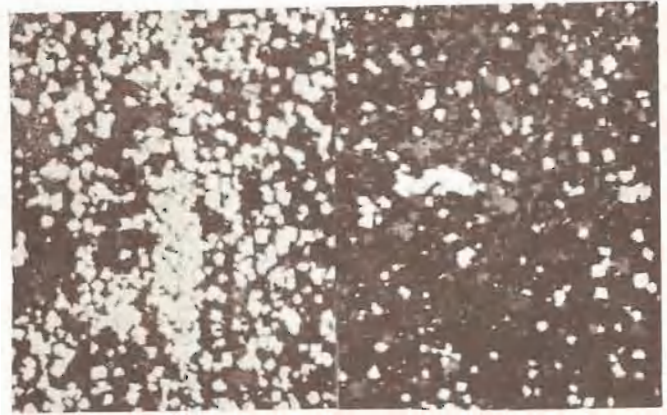
Magnetite lamina alternating
with magnetite-chert-
carbonate-silicate



B. Mag. Chloritic Clastic I-Fm.
Thin section 100X Empire Mine
Coarse magnetite and quartz
granules with chloritic
groundmass



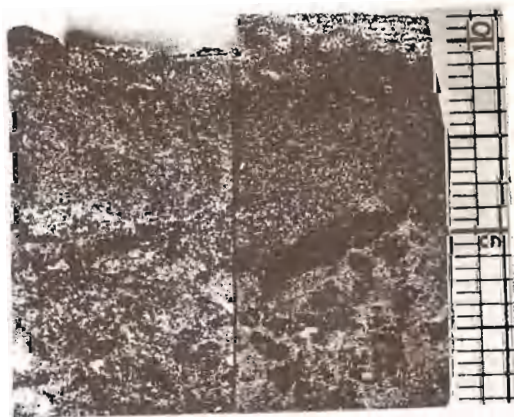
C. Mag. Grunetic Cherty I-Fm.
Thin section 100X Republic Mine
Grunetite, gray; chert, dusty
white; magnetite, black



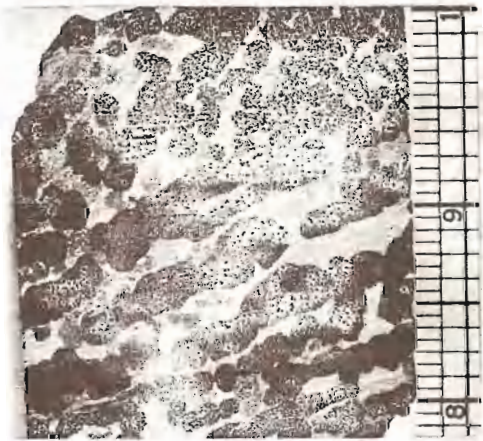
D. Polished slab of Iron-Formation
Natural scale

E. and F. Pol. Sec. 100X

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G. Marititic Cherty Clastic I-Fm. Natural size



I. Cherty Goethitic I-Fm. Natural size



K. Specularitic Cherty I-Fm. Pol. Sec. 100X - Hematite, white; chert, black



H. Same - Pol. Sec. 100X Maritite, white; magnetite, whitish gray; chert and quartz, dark gray



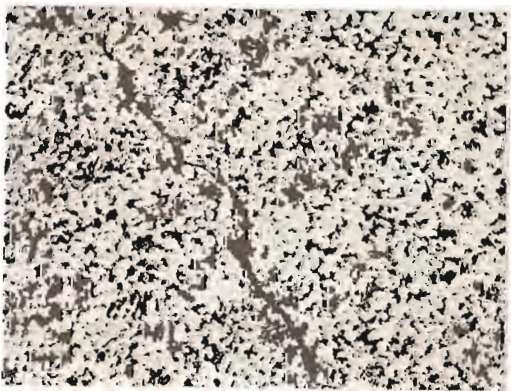
J. Same - Pol. Sec. 100X Maritite, white; goethite, gray; chert, dark gray; and pits, black



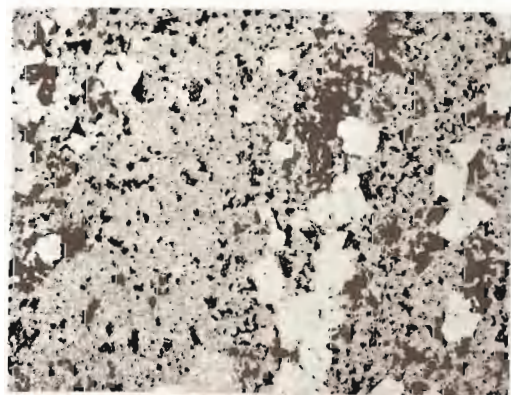
L. Magnetitic Specularitic Cherty I-Fm. Pol. Sec. 100X Hematite, white; magnetite, gray; chert, dark gray

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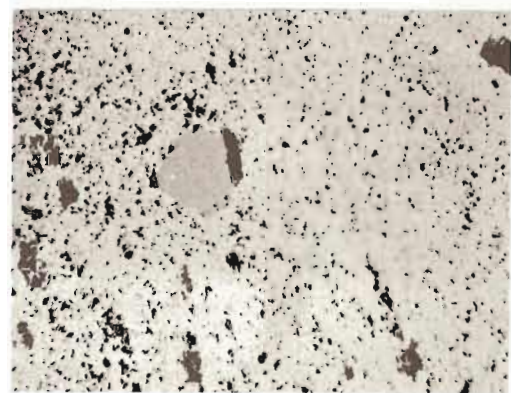
Plate III - Photomicrographs



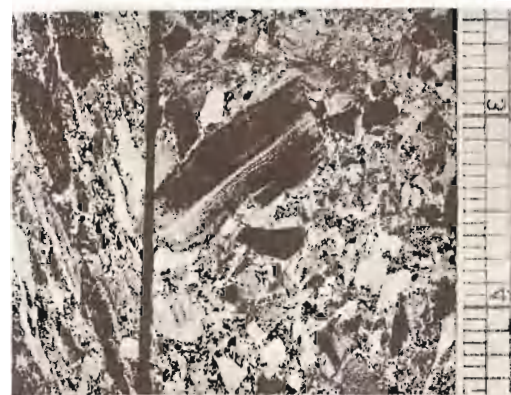
M. Mather soft hematite.
Hematite white.
Pol. sec. 100x.



O. Mather soft martitic ore.
Martite, white, chert,
dark.
Hematite, greyish white.
Pol. sec. 100x.



Q. Cliffs-Shaft hard hematite
Hematite, white; and
Magnetite, greyish white.
Pol. sec. 100x



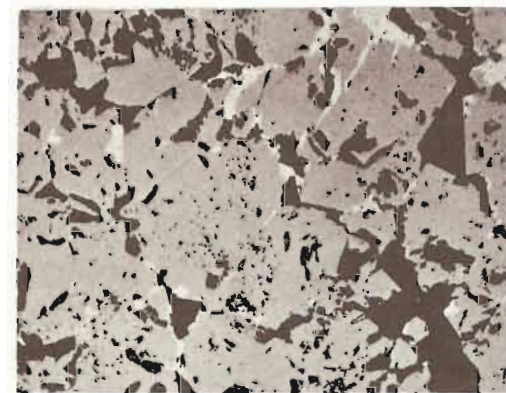
S. Cliffs-Shaft ore
conglomerate.
Natural size.



As M. 500x
Hematite, white; and
gangue and pores, dark
grey.



P. Mather hard martitic ore.
Martite, white; pore,
black.
Pol. sec. 100x.



R. Cliffs-Shaft Magnetite.
Magnetite, greyish white;
hematite, white; gangue,
dark grey, and pit black.
Pol. sec. 100x



T. As S. Pol. sec. 100x
Hematite, greyish
white; martite, white;
gangue, dark grey.

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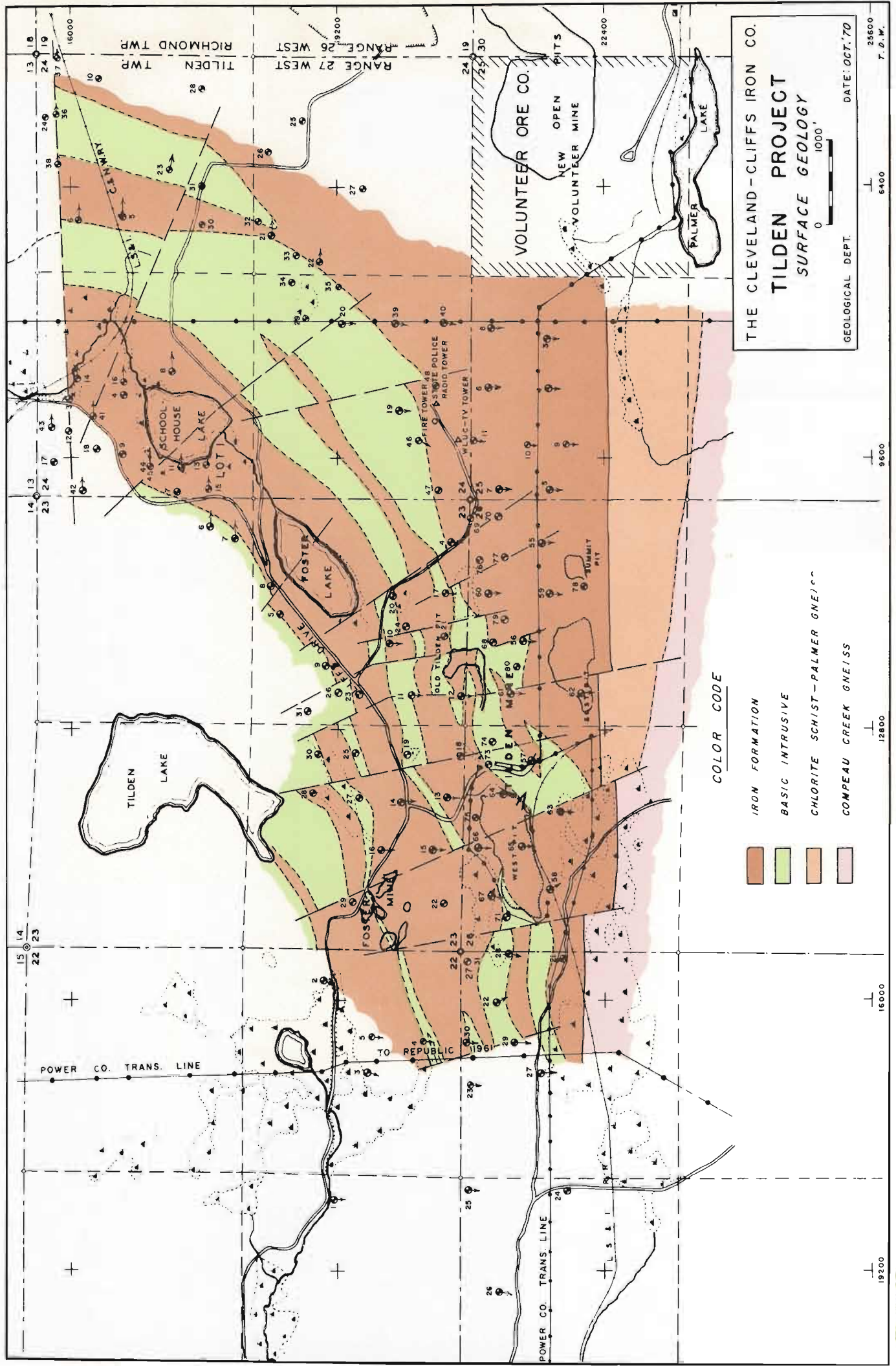


Figure 15

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Minnesota. The program was expanded in 1966 and pilot plant work carried out from 1968. The Joint Venture was announced in May, 1972. Concentrate and pellet production started in October and December, 1974, respectively. The initial facility is designed for an annual production rate of 4.0 million tons.

The concentrating process differs from that of Republic or Empire Mines. It utilizes a selective flocculation and flotation system. The ground ore is conditioned and pumped to thickener tanks where starch selectively flocculates the iron oxides. Sodium silicate is used to disperse the fine siliceous material. The deslimed iron rich underflow from the thickeners is combined, conditioned and distributed to rougher flotation cells for concentration. Four scavenger stages follow the rougher stage with the final underflow pumped back to the rougher stage. Rougher underflow moves to the concentrate thickeners and then to the filters. The filtered product is balled and pelletized.

GENESIS OF THE HIGH-GRADE ORES

There has been no universal agreement on the origin of the high-grade ores of the Marquette Iron Range. There are differences of opinion regarding both the method and the timing of the enrichment of the hard ores as opposed to the soft ores. The soft ores are discussed first.

Soft Ores

Certain features are common to most hypotheses of the origin of the soft ores:

1. Fracturing of the iron-formation was important in that it permitted access for the solutions that oxidized the primary iron-formation, removed silica and transported the iron which replaced much of the silica.
2. The silica was removed, presumably, by the same solutions that carried the iron. Inasmuch as no remnants of the removed silica have been identified on the Marquette Range, it is assumed that it was carried to the ancient surface and removed.
3. The orebodies are found only in the Negaunee, Bijiki and Gwinn Iron-Formations. Other rock types in the column may have been altered and enriched locally, but no significant tonnage of high-grade soft ore has been found in any of the other geologic members.
4. The soft orebodies are found lying on the respective stratigraphic footwalls and on the metadiabase sheets in "trough-like" or "open-facing" structures. These less permeable members may be folded and/or faulted, but appear to act as "bottom" surfaces.
5. The major structural controls of folding, faulting and most intrusives were pre-ore. Some intrusives may be post-ore and, according to some observers, some faulting and possibly some of the folding are post-ore.
6. Few of the deeper major orebodies extend to ledge surface up the dip or up the pitch, but the oxidation of the iron-formation adjacent to the orebodies definitely does extend to ledge.

7. Any hypotheses must account for the circulation of a hydraulic system which extends to depths of over 6,000 feet from the present surface.

8. Most soft ores contain varying amounts of clay mineral assemblages that indicate temperatures higher than normal ground-water temperatures. The relation of these clay minerals to the iron minerals is not conclusive. They are not established as being definitely contemporaneous.

Cold Water Origin

Monograph XXVIII reviewed the various ideas of soft ore origin and advanced the basic cold water hypothesis. The agent of oxidation, solution of silica, and introduction of iron was oxygen-bearing ground-water. The iron which replaced the silica was derived from other portions of the iron-formation. In 1935, C. K. Leith *et al.* (pages 24-26), modified the hypothesis by proposing that the chemical activity of the circulating ground-waters had been increased by heating due to Keweenaw lavas and intrusives. They also observed that oxidation is found at a greater depth than would be expected of normal ground-water circulation, even under mountainous conditions.

Hydrothermal Origin

In 1926, J. W. Gruner proposed a hydrothermal origin for Vermilion Iron Range ores. In 1929, he extended this hypothesis to the formation of high-grade ores throughout the Lake Superior region. Gruner's hypothesis stressed the greater dissolving power of hot water on silica. The thermal conditions would stimulate hydraulic circulation. On the basis that most of the Lake Superior intrusives were basic and therefore relatively "dry", objections were raised to the idea that these waters were juvenile. In 1937, he published his "modified theory" which proposed that the ore-forming fluids were principally meteoric waters which had been heated by igneous emanations. He conceded, also, that not all of the introduced iron came from these emanations. Gruner explained the observed differences in resultant ore types as being related to differences in primary iron-formation, structural conditions, temperatures of the water, and relative quantities of emanations. Tyler (1949) reviewed the possible hydrothermal origin, as did Mann (1953). Arguments against these ideas were advanced by James (1953), although he did not address the Marquette Range occurrences specifically.

Summary on Soft Ore Genesis

The theories of Leith and Gruner are not too dissimilar. Aside from Gruner's "emanations", the ore-forming process is almost the same, the differences being only a matter of degree. The geometry of the soft orebodies is significant when emphasizing the complicated "plumbing" of the hydraulic systems. Many of the orebodies are found on the "open" side of structural traps. Some have no apparent relationship to the present surface.

The mineralogy may be significant also. Recent microscopic work by Tsu-Ming Han has found appreciable martite in the soft ores, as shown in Plates III-O and P. The semi-hard ores found in the soft orebodies are essentially

made up of equigranular martite, some of which contains traces to appreciable magnetite remnants. Han suggests that the martitization was contemporaneous with the soft ore formation.

Lastly, as pointed out above, some of the clay minerals suggest temperatures higher than those of normal ground-waters. The writer noted dickite and chrome nontronite in the Marquette Range ores in 1945, as described by Gruner (1946). The paper by Bailey and Tyler (1960) describes dickite, kaolinite (non-definitive), nacrite, talc, pyrophyllite, 1M and 2M₁ muscovite, lizardite, clinochrysotile, Al-serpentine, dioctahedral and trioctahedral chlorite, dioctahedral and trioctahedral montmorillonite, palygorskite, and regular interstratifications of chlorite-montmorillonite, as well as the non-clay minerals apatite, alunite, gypsum, calcite, and rhodochrosite. Bailey and Tyler state on pages 155 and 156: "In summary, both the synthesis data and the evidence provided by field relationships for similar clays elsewhere in the world suggest that the clay mineral assemblage in the Michigan iron ores is primarily the result of hydrothermal activity. . . . The intimate association of the clay minerals with the iron ore suggests that these differences may also extend to the origin of the ore itself."

As noted earlier, the soft ores are found in the chlorite zone of metamorphism.

Hard Ores

The hard ores are more complex than the soft ores. There may be two or more modes of origin and times of formation. Significant features are:

1. The hard ores are found in the upper 200 feet of the Negaunee Iron-Formation. Most commonly, the hard ore is at the Goodrich contact.
2. The hard ores are in "closed" structures, such as anticlinal flexures, under less permeable rocks.
3. Commonly, the iron-formation adjacent to the ore is the "oxide-facies" - jaspilite, the reddish, pinkish banded chert the miners once called "hard ore jasper".
4. Hard ores tend to have equigranular iron minerals, little to no porosity, few vugs and no botryoidal textures.
5. The magnetite ores are commonly in discontinuous masses in specularitic iron-formation and ore. The chert associated with magnetite ore is gray rather than reddish. In some areas magnetite orebodies and magnetitic iron-formation are traversed by quartz veins containing tourmaline, very coarse specularite and crystalline siderite with minor pyrite, sphalerite and chalcopyrite. Babcock (1966 and 1974) has found an extensive suite of minerals at the Champion Mine, including manganese-bearing garnets, cummingtonite, tremolite-actinolite, schefferite and rhodonite and diopside-hedenbergite-johannsenite series of pyroxenes. Also found were molybdenite, kutnahorite, andalusite, sheelite, powellite and anhydrite. He emphasized the magnetite-jacobsite series.

6. Frequently the hard ores extend down into the iron-formation as "droppers", appearing to have been formed by replacing the iron-formation.

7. Locally, at the Goodrich contact, some massive hard ore contains detrital quartz which suggests that the original iron minerals may have had a similar detrital origin.

8. Above the hard ores and at the base of the Goodrich, one finds conglomerates of varying thickness. The conglomerate may contain much detrital chert or quartz, and some ore fragments that appear to have been ore at the time of deposition.

9. Dynamic metamorphism is suggested to have been responsible for the formation of the specular hematite in the ores and adjacent iron-formation.

10. No hard ore is found in the Bijiki or Gwinn Iron-Formations.

Hypotheses of Hard Ore Origin

Monograph LII (pages 278-279) outlines a possible origin and time sequence of ore formation. The upper portion of the Negaunee Iron-Formation was exposed to weathering and concentration (mechanical classification?) to produce an iron rich product. Burial by Goodrich and later formations followed. After the deposition of the Michigamme Formation, the Marquette Range Supergroup sediments were folded, faulted and intruded. The metamorphism associated with the structural deformation formed the hard ores from the weathered ores.

Post-Keweenaw erosion re-exposed the Negaunee and Bijiki Iron-Formations. They were altered by ground-waters to form the soft ores, as outlined earlier. Since the soft ores were formed after the dynamic metamorphism, they do not display the specular hematite and other features of the hard ore.

The objection to this concept centers on the "weathered-surface" origin for all of the hard ores. It is necessary to postulate some introduction of iron to explain both the geometry and detailed features of many hard orebodies. This introduction of iron must have been accomplished before or during metamorphism. The hydrothermal school of thought would ascribe much of the hard ores to replacement of the iron-formation by high-temperature solutions.

J. E. Gair (U.S.G.S. Open File 74-227, 1974) concluded from his study at the Cliffs Shaft Mine:

- "1. The spatial association of jaspilite and hard ore suggests that they are related in origin, and that the relationship is controlled in some way by the contact (erosion surface) separating the Goodrich Quartzite and Negaunee Iron-Formation. Relict iron-formation laminations in the hard ore indicate that the ore-grade concentration of iron was accomplished by a direct replacement of iron-formation, especially of the cherty laminations.
- "2. At least some jaspilite in the Cliffs Shaft Mine was derived by alteration of carbonate iron-formation, and the proximity of jaspilite to the pre-Goodrich erosion surface suggests that the alteration was the result of weathering.

- "3. An oxide iron-formation corresponding to the present jaspilite, and ore-grade concentrations of iron corresponding to the present bodies of hard ore existed prior to the Penokean regional metamorphism and prior to Goodrich deposition. The presence in basal Goodrich conglomerate of fragments of jaspilite and hard ore indicates that both materials are essentially pre-Goodrich in age. The recrystallized fabric of jaspilite and hard ore shows that their iron-oxide composition was already established when metamorphism took place.
- "4. The position of intrusive greenstone bodies dipping under orebodies, suggests an analogy with some existing bodies of soft iron ore formed from carbonate iron-formation, in which underlying intrusive rock provided a barrier to the downward movement of ground-water that led to a build-up of concentrations of secondary iron oxide above the barrier — between the barrier and the erosion surface. Masses of mafic intrusive rock emplaced in the iron-formation before the post-Negaunee, pre-Goodrich erosion interval could have had the same effect during that interval. However, not all intrusive bodies are clearly pre-erosion interval in age; some appear to have come later. The magnetite present in many bodies of hard ore adjacent to contacts with intrusive greenstone apparently is a product of contact metamorphism, so is not readily explained unless the intrusive rock was emplaced after the ore-grade concentration of iron had taken place. The simplest explanation is that mafic intrusive bodies were emplaced before and after the erosion interval, and before regional metamorphism."

W. F. Cannon (1973), in his paper entitled, "High-Grade Magnetite Deposits at Republic, Michigan: Their Bearing on the Genesis of Marquette Range Hard Ore", states:

"The magnetite-rich ore is probably of hydrothermal origin and because Penokean regional metamorphism is the only recognized post iron-formation thermal event, the fluids were probably derived by dehydration and decarbonatization of the iron-formation and underlying rocks during progressive regional metamorphism which reached sillimanite grade at Republic.

"The localization of the ore at the top of the Negaunee Iron-Formation might be explained through the buffering action of the iron-formation on the oxygen fugacity of the fluids. As fluids (considered here as H_2O for simplicity but probably also CO_2 rich) are expelled during metamorphism and pass upward through the rock section, they will contact first the relatively reduced magnetite-silicate and magnetite-carbonate units in the lower part of the Negaunee and will tend toward an equilibrium oxygen fugacity (f_{O_2}), such as Point 1 on Figure 1, determined by a buffer curve such as Curve A, and will contain concentrations of ferrous and ferric iron species appropriate for that f_{O_2} and temperature. As fluids pass upward and contact the jaspilite, a redox reaction must occur in which the jaspilite is partly reduced by the conversion of specularite to magnetite and the fluids are oxidized to achieve an f_{O_2} , such as Point 2, determined by the hematite-magnetite buffer (Curve B). The increased f_{O_2} of the fluids and consequent lower solubility of ferrous iron species and the oxidation of some ferrous iron to less soluble ferric species results in the precipitation of magnetite. Textures clearly indicate that

silica was removed during the hydrothermal activity and the magnetite presumably was precipitated in its place. Because the equilibrium f_{O_2} of the buffered assemblages is very small (10^{-40} to 10^{-20} atm for the probable conditions of metamorphism), small volumes of rock can buffer very large volumes of fluid, and the system can remain buffered until all hematite in the jaspilite is converted to magnetite.

"I propose that the magnetite-rich ore has formed by: 1) the reduction of hematite to magnetite during a hematite-magnetite buffer reaction; 2) the precipitation of magnetite from hydrothermal (metamorphic) fluids as the fluids were oxidized during that buffer reaction and the solubility of ferrous iron was decreased.

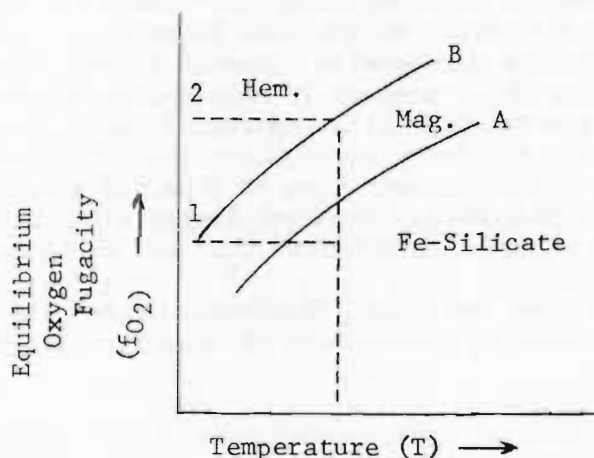


Figure 16. T - f_{O_2} diagram showing relative positions of hematite-magnetite buffer curve and a buffer curve determined by the equilibrium: quartz + magnetite = Fe-silicate. Points 1 and 2 illustrated differences in f_{O_2} controlled by the buffered assemblages at constant T .

(Cannon's Figure 1; see quoted text)

"The formation of magnetite-rich ore appears to require a restricted set of conditions:

- 1) Metamorphism must reach at least biotite grade, although most orebodies and all large ones are in garnet or higher grade.
- 2) Iron-formation with mostly ferric iron, such as jaspilite, must be physically above iron-formation with abundant ferrous iron.
- 3) A stratigraphic or structural trap capable of concentrating the flow of fluids must be present. The Goodrich Quartzite and metadiabase sills and dikes were apparently relatively impermeable, and the Megaunee-Goodrich contact near anticlinal crests and dike-quartzite intersections were favorable loci for ore formation.

"The absence of any of these three conditions inhibits the formation of magnetite-rich ore."

EXPLORATION FOR ORE

Volume I of the revived Michigan Geological Survey, written by Major T. B. Brooks (1873), has Chapter VII entitled "Explorations (Prospecting for Ore)" which begins with a section entitled, "How Failures Have Occurred, and How to Avoid Them". He presents a colorful summary of the hard lessons that were learned about finding mines since iron ore was first discovered in 1844. Mapping of outcrops and test pitting are described, as well as sampling. Geophysics figured early in the exploration program. In fact, it was the deflection of the compass needle that caused Burt's party to seek the source and thus discover the iron ore in 1844. Much use was made of the dip-needle or "Swedish mining compass" as it was sometimes referred to. Brooks cautions, however, "Worthless ores often attract the needle just as strongly as merchantable ones" (page 204).

Figure 17 shows the first illustration of "aerial" geophysics in which the enterprising student of the magnetic field climbed a pine tree to some 94 feet above the surface, taking observations every 10 feet. For a number of years, routine geologic mapping was accompanied by dip-needle surveys. In the 1930's, the tripod-mounted Hotchkiss Superdip came into vogue. This was followed by more sophisticated magnetometers. The airborne magnetic survey was developed during World War II in connection with submarine detection. Various aerial surveys were made of the Upper Peninsula, both by State and Federal governments and by private companies. The latest is GP-Map 894, "Aeromagnetic Map of Michigan and the Adjacent Great Lakes".

Other geophysical techniques conducted on the Marquette Range included gravimetric surveys, refraction seismic work and electromagnetic induction. Limited research was done also on resistivity and self-potential surveys. Both ground and airborne radioactivity surveys have been conducted as well.

The diamond drill was invented by Jean R. Leschot, a Swiss engineer living in Paris, in 1862. Brooks reports that the first diamond drill on the Marquette Range was used in 1870 at the Lake Superior Mine, Ishpeming. The first recorded drilling by the Cleveland-Cliffs group was Hole No. "A" in Section 10, 47-27, part of the Cliffs Shaft Mine. The hole was started on March 15, 1877, with 76 feet of surface material and bottomed at a depth of 628 feet on February 15, 1878, without encountering ore. A second drill was positioned a short distance away at a new location for Hole No. "B" which was started June 1, 1877, with 74 feet of surface material and had a high-grade ore run from 400 to 460 feet and was completed in July of 1878.

The diamond drill was used extensively throughout the Lake Superior Region and many important improvements were made through the ingenuity of the mining company personnel and drill contractors. The double-tube core barrel was introduced in the 1930's. From its inception up to 1940, the diamond bits consisted of hand-set black diamonds. In 1940, the first mechanically set bortz

bits were introduced. Black diamonds continued to be used, however, for another decade. During World War II, Cliffs employed 8 men as "setters". The Geological Department of the Jones and Laughlin Steel Corporation did extensive research in core recovery and made important innovations in the design of the swivel-type double-tube core barrel. Both Jones and Laughlin and Cleveland-Cliffs pioneered the use of bentonite muds for penetrating the overburden and for stabilizing wall conditions in bedrock. The oil field type of electrologging was also tried (Boyum, 1957 - "Schlumberger Electro-logging of Small Diameter Drill Holes on the Marquette Range, Michigan"). Geochemical sampling has also been conducted in selected locations as non-ferrous reconnaissance in the Mineral District.

MINE SUBSIDENCE

As noted in the historical summary, a number of the properties progressed from open pit mining to underground and substantial volumes of iron ore have been recovered by underground mining methods. Due to the varying ground conditions overlying the ore, mine subsidence has occurred. Extensive studies have been made by both the mining companies and the United States Bureau of Mines. Various geophysical techniques have been applied also to measure stress accumulations. These various studies are summarized in a paper by Boyum (Subsidence Case Histories in Michigan Mines, 1961).

MINED LAND RESTORATION

Michigan Act #92 - P.A. of 1970 is known as the "Mine Restoration Act". It was passed by the Michigan Legislature to apply to certain mining operations in Michigan in making plans for the restoration of certain mined lands and planning for their end use. A certain amount of mine restoration activity has gone on since the 1800's; however, the program was accentuated in the 1960's. In 1967, The Cleveland-Cliffs Iron Company initiated discussions with the staff of the Michigan Technological University at Houghton, Michigan, for certain interdisciplinary cooperative studies with the mining company. This resulted in revegetation studies at both the Republic and Humboldt Mines and has been applied to other properties as well.

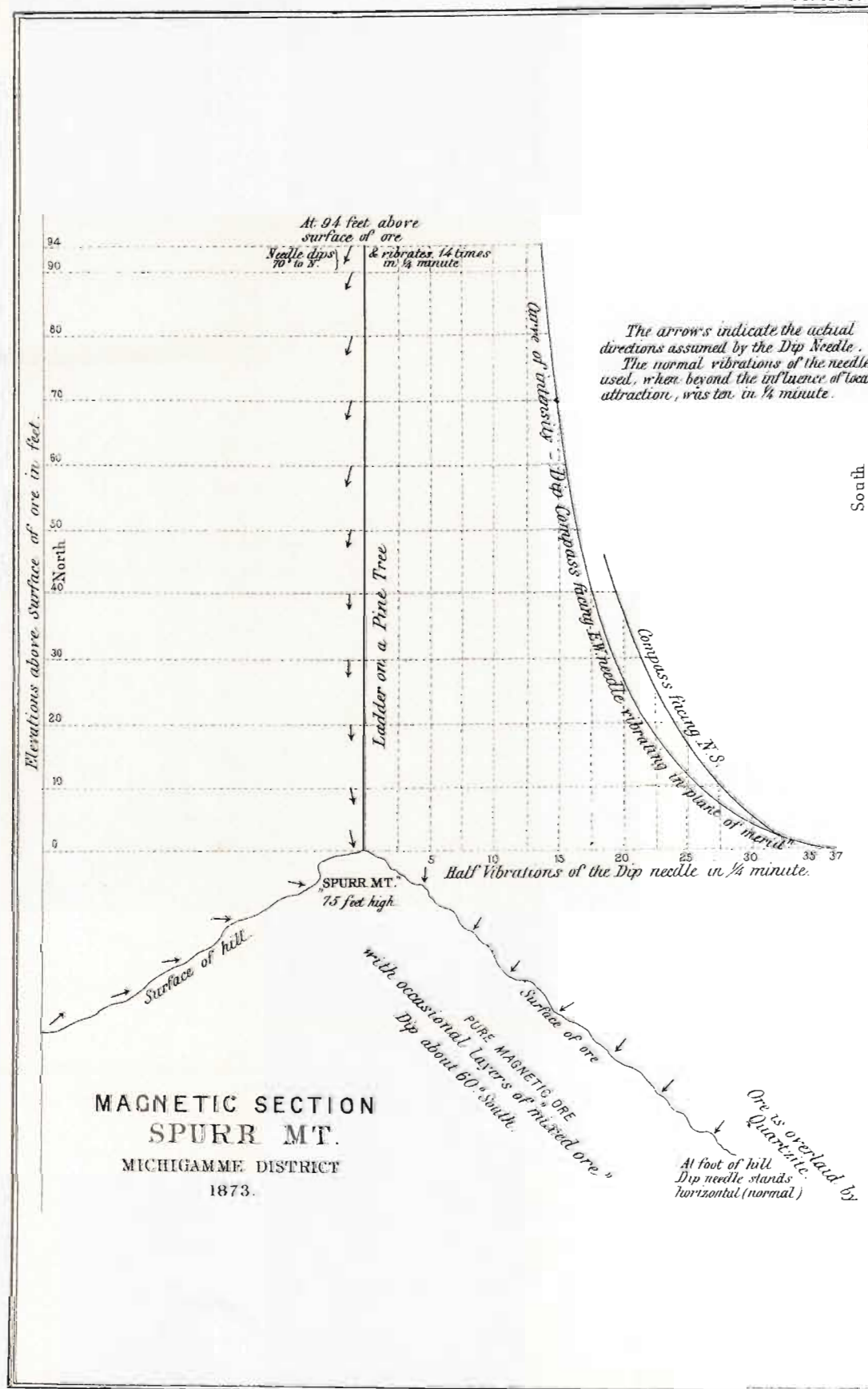
Increasing attention has been paid to the quality of air and water in connection with the mining activities, as well as land use. The Greenwood Reservoir, created in 1973 as part of the overall Tilden Mine project, is an outstanding example of the cooperative work between the mining companies and the State of Michigan to assist industry in its development and, at the same time, add a feature that is beautiful to see and a source of important recreational activities for the citizens.

OTHER MINERAL OCCURRENCES

North of Ishpeming and the Marquette Range Supergroup is an area referred to as the Ishpeming Gold Belt. Two principal properties, the Ropes Gold Mine and the Michigan Gold Mine, had gold values. The Ropes Gold Mine is described by T. M. Broderick (1945), "Geology of the Ropes Gold Mine, Marquette County,

Figure 17 - First "Aerial" Magnetics on Marquette Mineral District
North-South Section, Looking East

Pl. XVI.



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Michigan." A total of \$703,000 worth of gold was produced from this operation during the period from 1883 to 1897. At that time gold was \$20.00/ounce. Willard A. Bodwell (1972), "Geologic compilation and non-ferrous metal potential, Precambrian section Northern Michigan", has summarized a number of these various occurrences.

The mineralization is found in a body of volcanic fragmental rock within a peridotite. The principal production came from a zone of several en echelon quartz veins up to 38 feet thick (11 meters) terminating at the peridotite contact. Later exploration by Calumet and Hecla indicated a zone of gold values with disseminated pyrite in altered volcanics. This pyrite zone forms a halo around the nucleus of the quartz veins adjacent to the old Ropes Mine workings. Their exploration indicated over one million tons of material averaging 0.13 ounces of gold and 0.7 ounces of silver per ton to a depth of 850 feet (260 meters) below surface.

Significant amounts of uranium oxide have been detected in the iron-formation on the Marquette Range and in the Gwinn District. R. C. Vickers (1956) has reviewed the thorium-rich monazite that occurs in conglomeratic layers in the Goodrich Quartzite in the Cascade District.

Occurrences of copper sulfide have been found in the Kona Dolomite. G. Lynn Taylor (1972), in his thesis entitled "Stratigraphy, Sedimentology and Sulfide Mineralization of the Kona Dolomite" has reviewed these occurrences. He states, "The beds containing sulfide mineralization, as well as several other beds stratigraphically higher in the Kona Dolomite, are postulated to have deposited under 'sabkha' type conditions. The chloride-rich brines, generated by such an environment are thought to have transported copper ions in a chloride complex through the middle quartzite bed of the lower quartzite member which acted as an aquifer. The brines, refluxing through this quartzite, spreading westward, upward, and downward, replaced syngenetic pyrite by sequence of copper sulfides to give a concentric zonal distribution of bornite, chalcopyrite, and pyrite around a central lens of chalcopyrite situated in the middle quartzite bed."

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The writer has enjoyed preparing this summary, with particular emphasis on both the geology and the history of the Marquette Mineral District. To quote E. A. Allen, "The good old days were awful!"

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Prominent cultural features that appear on the back cover include the Inland Lime and Stone Company quarry and port facility north of Lake Michigan, the Michigan Limestone Operation (United States Steel Corporation) quarry and port facility near Cedarville, and the Bethlehem Mines Corporation quarry and port facility on Drummond Island. The Michigan Limestone Operation near Rogers City is visible in the Lower Peninsula. The small white triangle, south of Whitefish Bay, is Raco Air Field. The length of each runway, from corner to corner, is 1,680 meters.

A considerable quantity of suspended clay may be seen entering the St. Mary's River from the Munuscong River. The sediment plume clearly extends into the northern part of Lake Huron. The source of clay is the lacustrine clay plain of Lake Algonquin which is extensively tilled in Chippewa County, to the south of Sault Ste. Marie.

The prominent light patch about 80 kilometers west of Whitefish Bay is the Grand Sable Bank, an area of unstable dunes that are migrating inland over glacial outwash.

Fracture patterns in the shield area north and east of Sault Ste. Marie are clearly displayed.

NASA, ERTS-1, DATE: 5-4-73, HOUR: 3:58.10, SCALE: 1/3,369,000
ALTITUDE: 915,000 METERS, WAVE LENGTH RANGE (5).6 TO .7 μ
SUN ELEVATION: 53°, SUN AZIMUTH: 138°

NASA, ERTS-1, DATE: 5-5-73, HOUR: 4:03.30, SCALE: 1/3,369,000
ALTITUDE: 915,100 METERS, WAVE LENGTH RANGE (5).6 TO .7 μ
SUN ELEVATION: 54°, SUN AZIMUTH: 138°