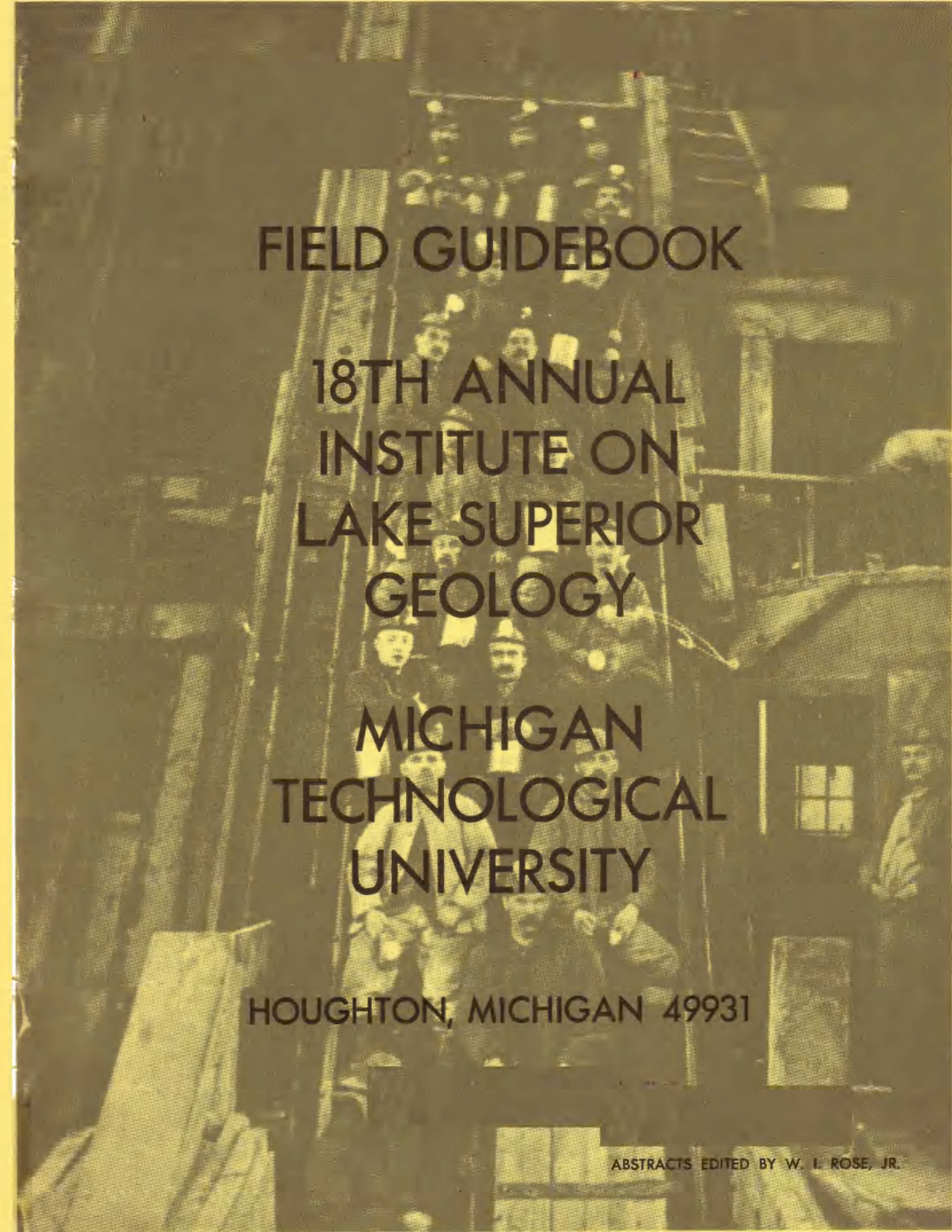




FIELD GUIDEBOOK

18TH ANNUAL
INSTITUTE ON
LAKE SUPERIOR
GEOLOGY

MICHIGAN
TECHNOLOGICAL
UNIVERSITY

HOUGHTON, MICHIGAN 49931

ABSTRACTS EDITED BY W. I. ROSE, JR.

FIELD TRIP A

Penokean orogeny in the central
and western Gogebic region, 1/ 2/
Michigan and Wisconsin

by

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This trip visits localities (Figure 1) selected to give a general idea of the Precambrian X 3/ (middle) stratigraphic succession (Figure 2), and the structural relationships of this succession to older and younger rocks. Two points will be emphasized: 1) the simplicity of deformation in the western part of the Gogebic district at the close of Precambrian X (middle) time, and 2) the very low metamorphic grade of some Precambrian X (middle) strata near Ramsay.

The southeastward increase in deformation complexity from Bessemer to the Marinesco area seems to correspond nicely with a deformation-intensity gradient in the Marquette area and also in the western Mesabi-Emily-Cuyuna area in Minnesota, to form a northern limit to the Penokean orogen.

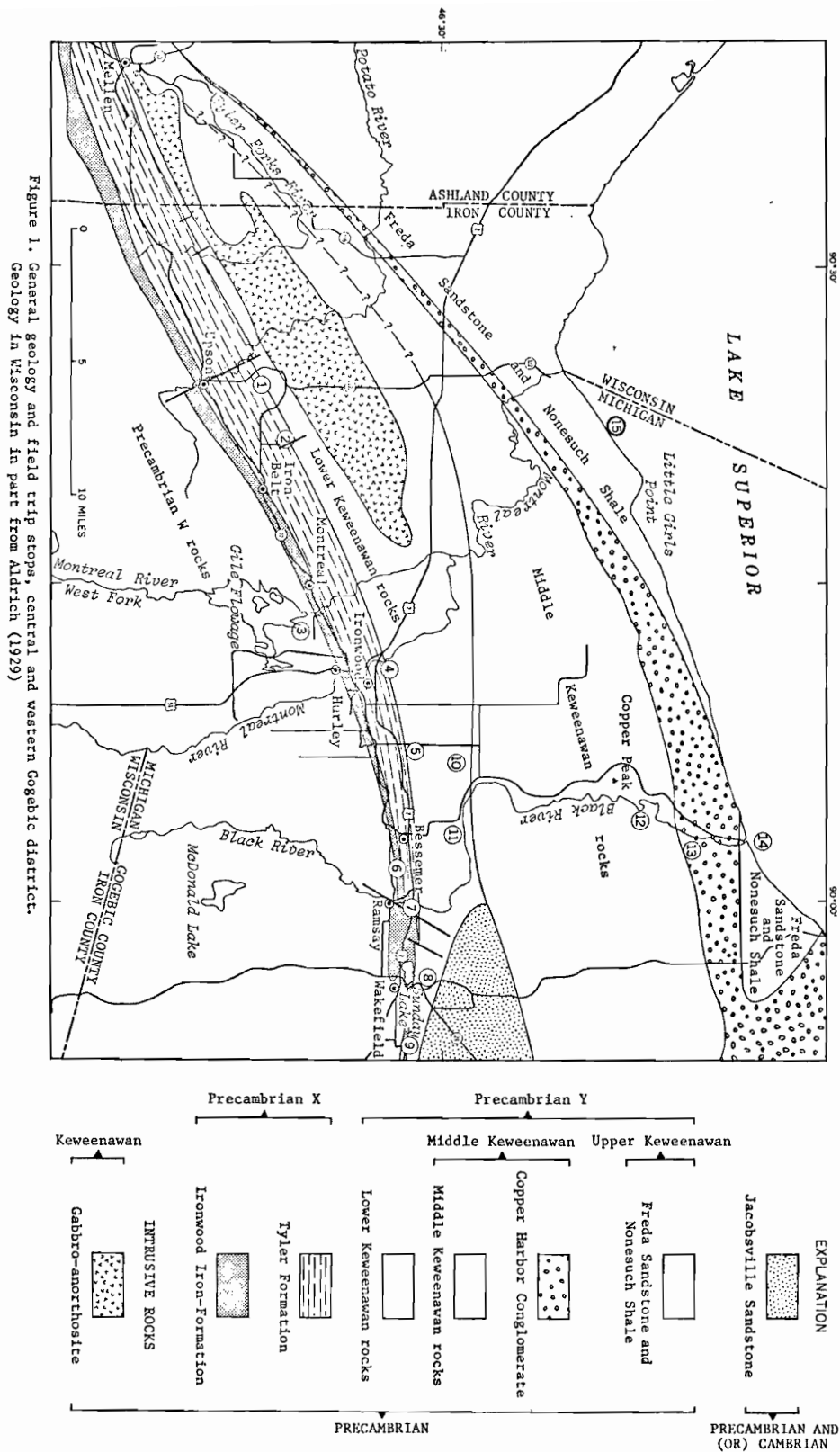
Many more stops are described than can be visited in the time permitted for the Institute on Lake Superior Geology field trip. It is hoped that these extra stops will be useful for student field trips and others who may visit the area later. We plan to make stops 4 through 9, if time permits.

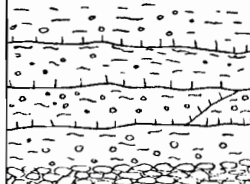
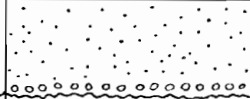
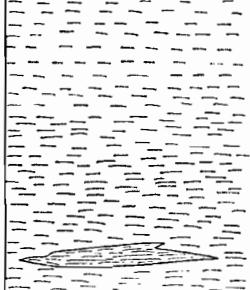
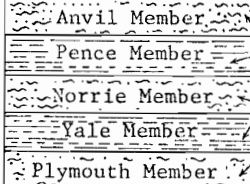
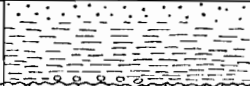
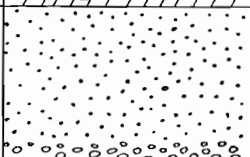
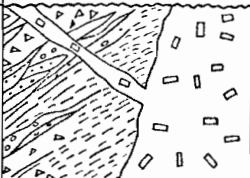
1/ Work done in cooperation with the Geological Survey Division of the Michigan Department of Conservation.

2/ Publication authorized by the Director, U.S. Geological Survey.

3/ An interim scheme for subdivision of Precambrian time recently adopted by the U.S. Geological Survey:

Precambrian Z - base of Cambrian to 800 m.y. (formerly considered late Precambrian)
Precambrian Y - 800 m.y. to 1,600 m.y. (formerly considered late Precambrian)
Precambrian X - 1,600 m.y. to 2,500 m.y. (formerly considered middle Precambrian)
Precambrian W - older than 2,500 m.y. (formerly considered early Precambrian)



Precambrian Y (upper)	Lower Keweenaw (?)	ca. 20,000'		Volcanics along Powder Mill Creek Intermediate to felsic lava flows, uncommon basalt flows; except in lower 5000 ft thin basalt flows with a few intermediate flows. Pillow lavas at base
		ca. 300'		Bessemer Sandstone of Seaman (1944) Quartz arenite with abundant matrix; conglomeratic at base
Precambrian X (middle)	Baraga Group	9500' maximum		Tyler Formation Light - to dark - gray plagioclase- rich fine-grained sandstone, argil- laceous siltstone, and argillite. Lowermost 1000 ft is partly ferruginous and has lenses of lean cherty iron-formation
	Menominee Group	450'-950'		Ironwood Iron-Formation Mostly thin-bedded cherty carbonate iron-formation Mostly thick wavy bedded cherty iron- formation
		400'-450'		Palms Formation Sericitic argillite; red-brown quartzite at top
	Chocolay Group	400'		Bad River Dolomite Gray to buff dolomite and cherty dolo- mite. Stromatolitic structures common. Found in both east and west parts of Gogebic district, <u>absent</u> in center
		150'		Sunday Quartzite Mainly white, gray, and red vitreous quartzite, and conglomerate at the base. Known only in the eastern Gogebic
Precambrian W (lower)				Precambrian W (lower) complex Sedimentary-volcanic ("greenstone") sequence, partly metamorphosed to foliated hornblende gneiss, intruded by quartz monzonite and pegmatite

Generalized stratigraphic section in central and western Gogebic district

Figure 2

Keweenaw geology is not part of the field trip, but several kinds of volcanic rocks are so well exposed at several easy to-get-to places that a brief description is included for reference by teachers leading field trips and for others interested in volcanic rocks.

Descriptions of stops 1 through 7 and stop 9 were prepared by Schmidt; the rest were prepared by Hubbard.

Stop 1 Coarse conglomerate near the base of the lower Keweenaw.

Location: Near Upson, Wisconsin, about 200 feet south and 500 feet west of the NW cor. NW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 7, T. 45 N., R. 1 E.

Conglomerate cobbles are as much as 15 cm in diameter and well rounded; they range from closely packed to "floating" in finer matrix. Materials are mainly white quartz (+ 40%), red, pink, and brown quartzite (+ 40%), and iron-formation (+ 20%). I have not been able to find the actual base in a brief visit to this place.

Good exposures of the lowermost flows along Powder Mill Creek are on the low hill to the north.

Stop 2 A small but good exposure of the unconformable contact of the Tyler Formation (Precambrian X (middle)) and the Bessemer Sandstone of Seaman (1944) (Precambrian Y (upper)).

Location: Near Iron Belt, Wisconsin, 500 feet due south of NW cor., NW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 4, T. 45 N., R. 1 E. This outcrop is $\frac{1}{2}$ mile due west from gravel pit on country road along east side, sec. 4 (Figure 3).

A conglomerate containing pebbles as large as 5 cm which consist mainly of quartz and quartzite rests directly on gray laminated argillite of the Tyler Formation. A few tens of feet lower in the section, the Tyler Formation is partly silty to finely quartzitic. Volcanics of the type along Powder Mill Creek form the ridge 500-700 feet to the north.

Stop 3 Stretched volcanic breccia and tuff of Precambrian W (lower) greenstone unit. Although not related to the theme of this trip, this is an unusually interesting exposure and is included for use by student field trips.

Location: In Gile, Wisconsin, in the SW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 34, T. 46 N., R. 2 E. (Figure 4). Drive to the boat landing at the south end of Gile and hike to the top of the bluff overlooking the lake southeast of the landing.

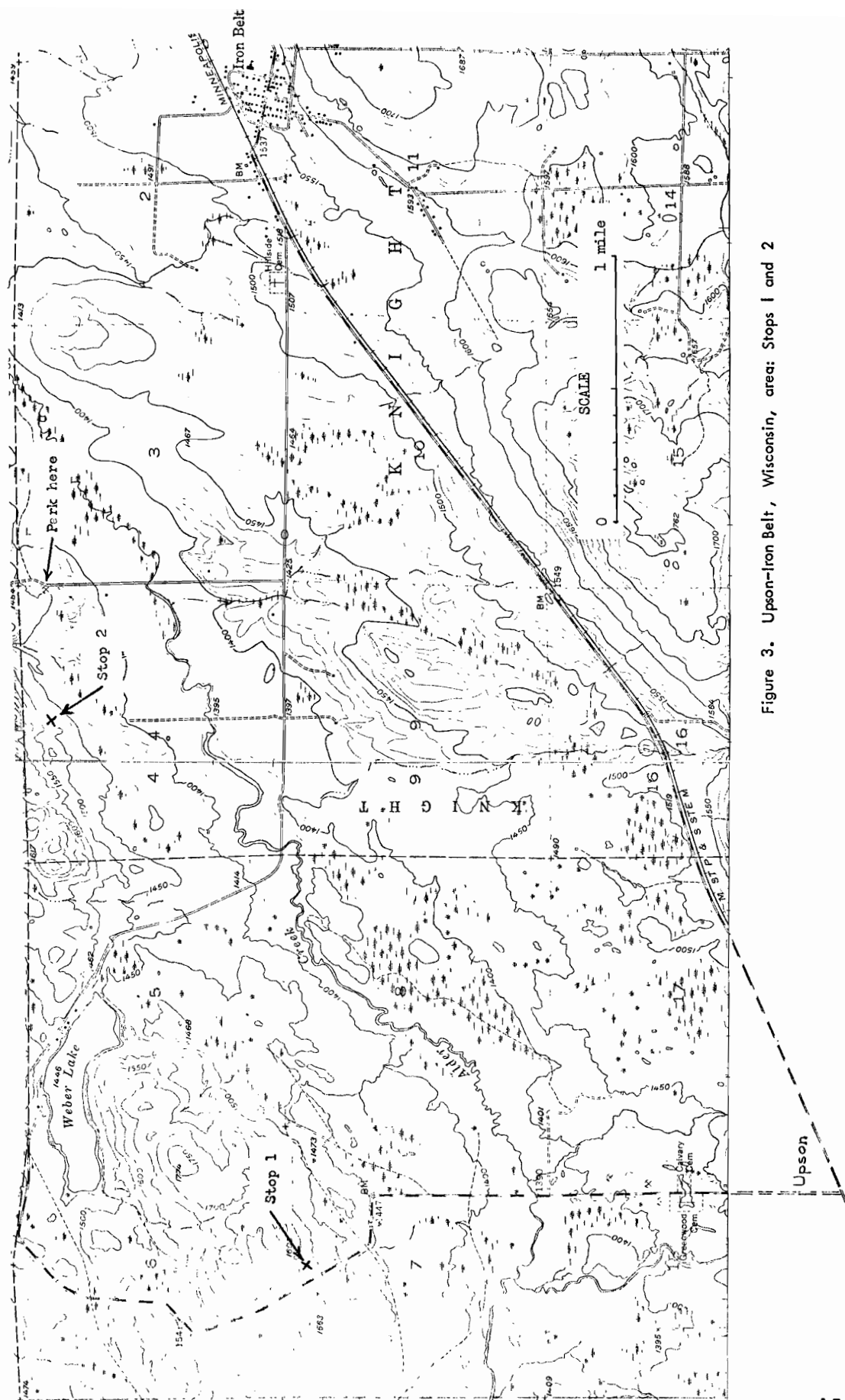


Figure 3. Upson-Iron Belt, Wisconsin, area: Stops 1 and 2

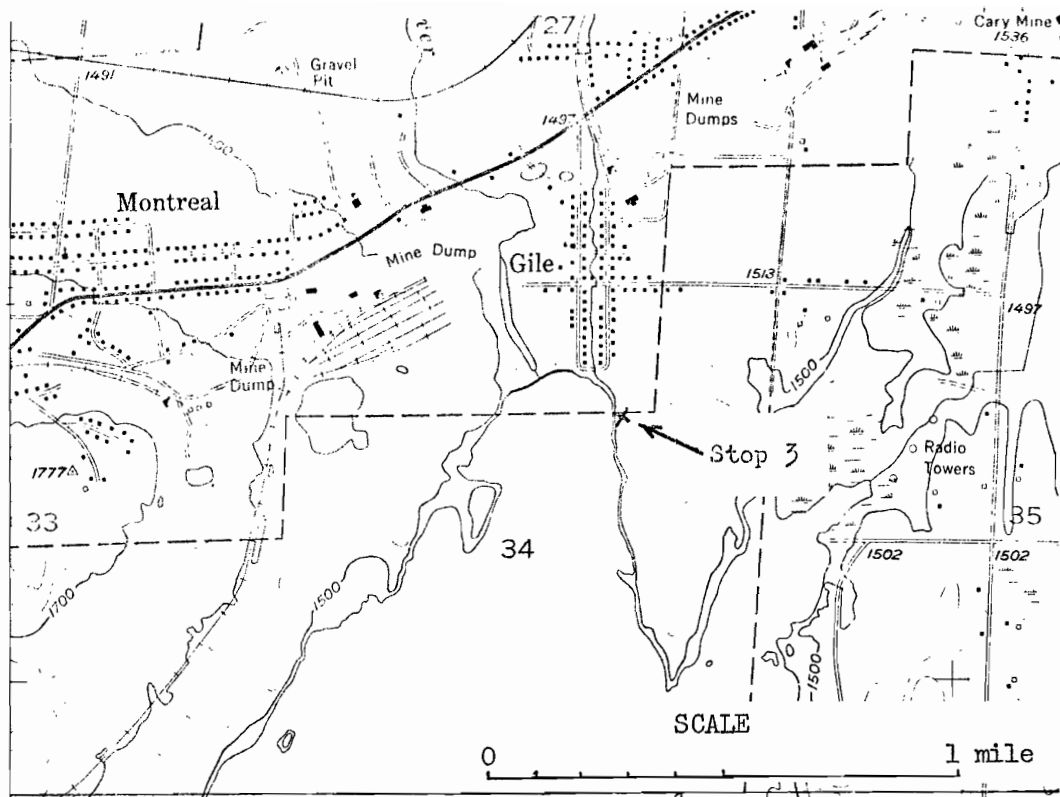


Figure 4. Gile, Wisconsin, area: Stop 3.

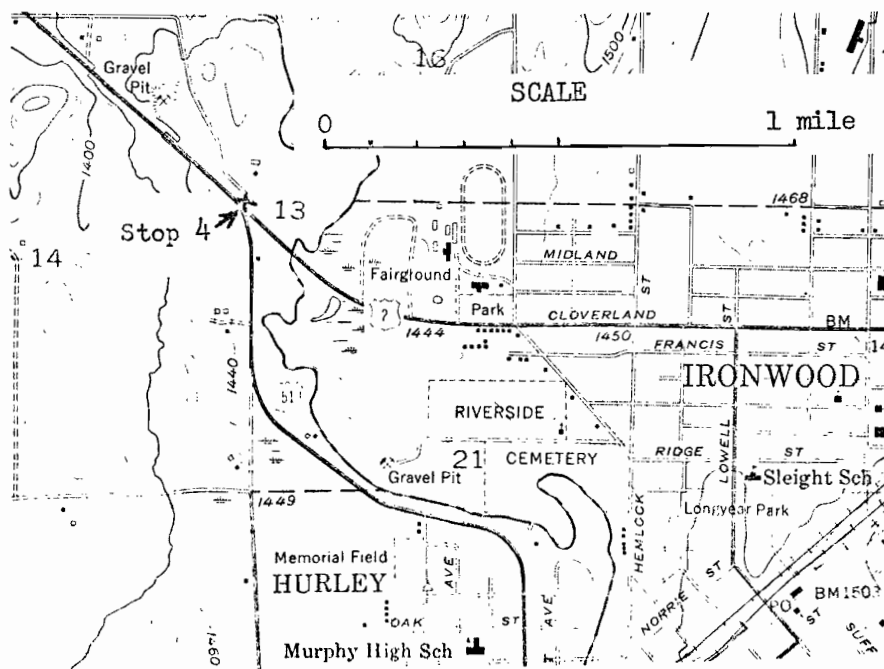


Figure 5. Hurley, Wisconsin, area: Stop 4.

The greenstone here consists of coarse pyroclastic material and layers of fine tuff. The sequence is folded and elongated perhaps as much as tenfold. Textural details are thoroughly smeared in the direction of elongation, but in a plane perpendicular to this direction delicate details are very well preserved.

As I have seen neither this coarse pyroclastic phase nor deformation like this elsewhere in the area, this outcrop may be rather anomalous. Some parts of the greenstone unit elsewhere are argillite and siltstone, and some good pillow lavas are present, but the commonest types are nondescript fine hornblendic schists that are difficult to categorize as metaflows, metatuffs, etc.

For 1 to 2 miles southeast of this point, the greenstone is progressively metamorphosed to a foliated hornblende gneiss.

Stop 4 Representative exposure of the Tyler Formation.

Location: Hurley, Wisconsin, on U. S. Highway 2 beneath overpass at junction with U. S. Highway 51.

This locality is high in the Tyler Formation in an area where the unit is perhaps 7,000 feet thick. It thickens westward to a maximum of 9,500 feet in Wisconsin and thins eastward to an area east of Ramsay where it was entirely removed before the start of Keweenaw deposition. The amount of thickening by folding of this formation isn't known. Most geologists examining the Tyler have probably looked for evidence of folding, but except for the drag fold mapped by Felmlee (1970) east of Mellen, I know of none that have been found. The steep north dip may be the result of tilting as a block rather than being part of a fold limb. Atwater (1938), described structural evidence for folding that he saw at two localities, one 3 miles southwest of here and one 3 miles to the east (Figure 6). I think you can see cleavage like this here. What does it mean in relation to major deformation style?

The lowermost 1,000 feet of the Tyler Formation is partly very ferruginous and some is iron-formation; some strata look like these, but the whole aspect of the basal part is somewhat different, especially east of Ironwood. There may be places near Mellen, Wisconsin, where "normal" Tyler Formation like this rests directly on the Ironwood Iron-Formation. I have found very little data about the part 1,000-2,000 feet above the base; above that, all rocks in the normally poor field outcrops are represented in this roadcut.

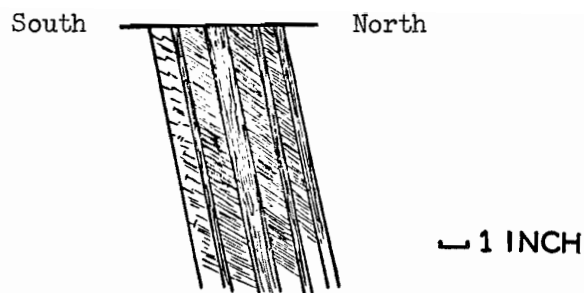


Figure 6. Vertical section of the Tyler Formation in sec. 13, T. 47 N., R. 47 W., Michigan, showing anomalous(?) relationship of bedding and cleavage, adapted from Atwater (1938, Figure 3, p. 169). Atwater was puzzled because this relationship seemed to indicate the bedding is overturned and that there is an anticline to the north.

The dark slaty argillite seems more abundant here than in natural exposures where there is probably a bias toward the stronger siltstone beds. Note the flakes of shiny carbon on some layers in the fine siltstone. Perhaps these are of organic origin; if so, do they represent a crude fossil form?

The low-grade metamorphic changes that have affected this outcrop are probably almost all Keweenawan, and the intensity of these changes increases westward to a maximum 25-40 miles distant. To the east near Ramsay, the metamorphic grade of Precambrian X (middle) rocks is very low; the grade then increases eastward. Age of metamorphism in the eastern Gogebic is generally assumed to be "Penocean", but lower Keweenawan volcanic rocks at Silver Mountain (sec. 1, T. 49 N., R. 36 W., Houghton County, Michigan), 70 miles from here, are, I believe, definitely metamorphosed. Thus, there must also be a center of Keweenawan metamorphism somewhere to the east, and any evaluation of metamorphic history to the east must take the two possible times of metamorphism into account.

Although the effects of Penocean metamorphism were weak near Ironwood, and especially at Ramsay, they were strong a few miles to the south, and this southward increase in metamorphic grade is well documented by the changes in the mafic dikes. Previously metamorphosed dikes show the retrograde effects of this period, and there are also younger dikes only affected by this period. West of McDonald Lake (Figure 1), where the degree of metamorphism reached during this period equals that of the next older stage, distinction between the effects of the two is impossible.

Stop 5 Base of volcanics like those typically exposed along Powder Mill Creek.

Location: Near Ironwood, Michigan. A low rock knob in pasture near county road, NW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 12, T. 47 N., R. 47 W. (Figure 7).

Pillow lava at the base of volcanics along Powder Mill Creek rests on quartzite of Bessemer Sandstone of Seaman (1944). You can find places where the soft muddy sediment was squeezed up between rubbly blocks on the sole of the flow. Note the small outcrop(?) of flow stratigraphically lower than the main quartzite area. It may indicate this quartzite is one of the lenses that occur above the base of the Powder Mill Creek section.

Careful examination of this contact along strike shows that it is offset by many north-trending right-lateral faults having 10-300 feet displacement. These seem to die out southward, displacing the iron-formation less than the Keweenaw strata, and only few displace the top of the Precambrian W (lower) basement.

Stop 6 The surface between Precambrian W (lower) and the Precambrian X (middle), the nature of the Palms Formation, and some of the Ironwood Iron-Formation.

Location: The old Palms and Anvil mines near Bessemer, Michigan, in the N $\frac{1}{2}$ sec. 14, T. 47 N., R. 46 W. (Figure 8).

Stop 6a The pre-Palms surface and the nature of the lowermost Palms(?) sediments.

Location: Old railroad cut south of the old Palms mine.

Although the pre-Palms surface seems to have been a very simple flat plane on a large scale, it had a very interesting microrelief. To some extent this is visible at most exposures, but none show the strange irregularities better than this one.

This surface dips about 65° N. in this immediate area; directly to the north, the dips of the lowest Keweenaw strata are 70°-75° N. The basal Keweenaw strata are consistently parallel to or as much as 15° steeper dipping than the Precambrian X (middle) rocks in this part of the district.

The Precambrian W (lower) rock here is a foliated gneiss which I interpret to be the metamorphic equivalent of the old greenstone complex. (The Precambrian W (lower) porphyritic quartz monzonite intrusive to which the metamorphism is related is well exposed to the west near the old Puritan and Geneva mines. Interesting and puzzling migmatites occur 3,500 feet east of here on the highest rock ridge in the community of Anvil).

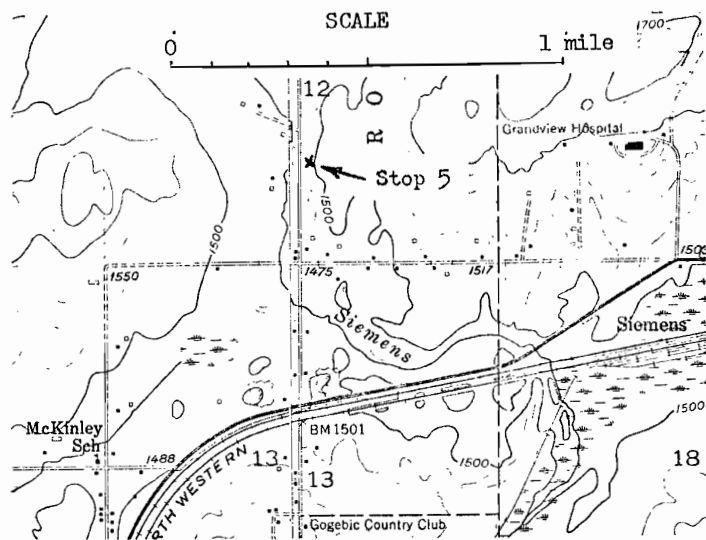


Figure 7. Ironwood, Michigan, area: Stop 5.

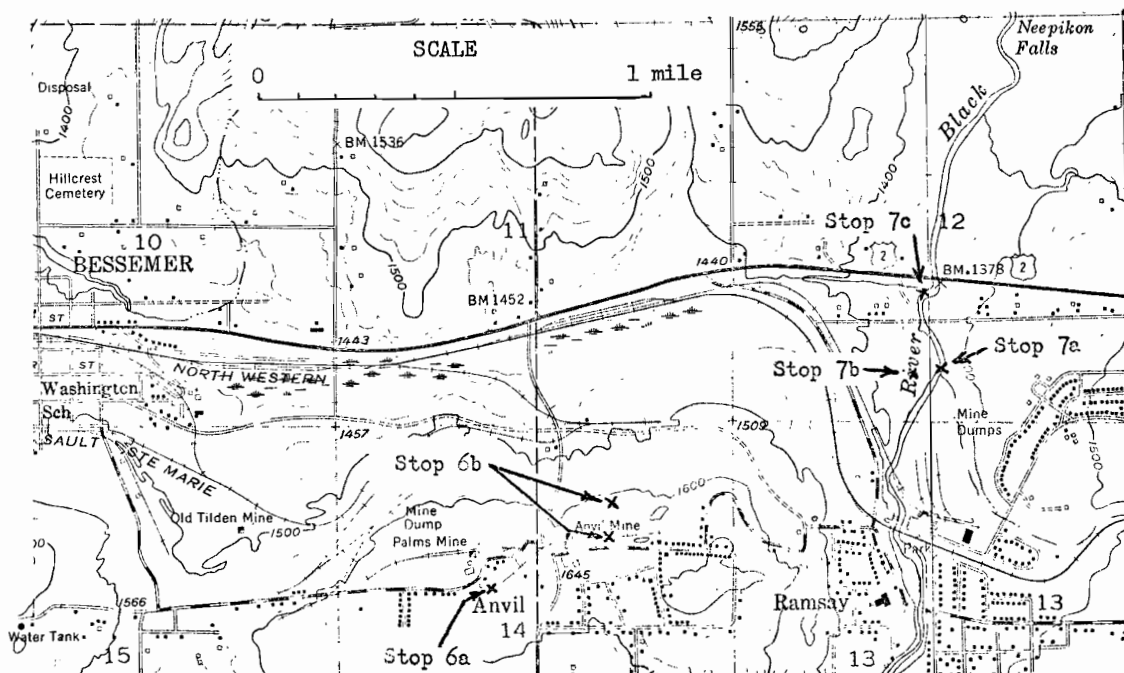


Figure 8. Bessemer-Ramsay area, Michigan: Stops 6 and 7.

Depressions in the old rock surface contain material that is different from the gray argillite and silty argillite that normally forms the base of the Palms Formation. The depressions contain fragments of the underlying rock, as large as 30 cm. in diameter, and also many well-rounded pebbles of quartz, jasper, and chert. The pebbles are commonly found in small crevices or cracks in the crystalline rock.

Crevices and sheltered depressions in the surface of the underlying rock surface are identical to the protected sites at the base of the Pokegama Formation where Cloud and Licari (1972) found well-preserved Gunflintia minuta Barghoorn, and other nannofossils. None of my thin-sections contain algal filaments but none were cut of sheltered crevice material.

The depressions are mostly lined or filled with a laminated siliceous rock, some of which is chert. At the Newport mine, some of the laminated chert is granular and somewhat resembles iron-formation. The granules are 0.5-1.0 mm. in diameter, and most are mixtures of chlorite and chert or chlorite and calcite; a few are all chlorite and some are all chert or red jasper.

Is this laminated chert really basal Palms Formation? Van Hise and Leith (1911, p. 227-228) interpreted what was probably some of this material as an isolated patch of Sunday Quartzite. Did the Sunday Quartzite and Bad River Dolomite cover this surface, later to be stripped away or were they just not deposited here? There is much chert in the Bad River Dolomite. Was that the source of the cherty cobbles at the base of the Palms Formation?

Northward from this exposure to the vicinity of the old Palms mine, you can see the argillite-siltstone phase of the lower + 400 feet of the Palms Formation and the + 100 feet of quartzite at the top.

Stop 6b Facies of the Ironwood Iron-Formation.

Location: North of old Anvil mine.

As in the Gunflint and Biwabik Iron-Formations and Trommald Formation, the Ironwood Iron-Formation is made up of subunits of distinctly contrasting lithology (the traditional "slaty" and "cherty" types). Here you will be able to see thick-bedded granular cherty iron-formation of the lowermost Plymouth Member and thinly laminated sideritic iron-formation of the Yale Member. Both here and at the stop along the

Black River, the iron-formation is little metamorphosed, and the mineral composition of the unoxidized material is very different from the iron-formation to the east and west. It is a good place to sample and study "primary" iron formation because it is about as little altered after lithification as any you can see in the Lake Superior region. The main primary iron mineral here is siderite; silicates and oxides are both sparse.

The base of the Plymouth is marked by a persistent 1-5 foot layer of algal chert and jasper, overlain by a few feet of thinly laminated argillaceous iron-formation that does not normally crop out (the "Footwall Slate"). Stromatolitic structures are common in the basal algal layer, but they are not nearly as complex and well-preserved as some in the Mesabi district. Small granules are common within the laminae of the inverted-cup structures themselves. Peculiar forms, of probably organic origin, of types described by LaBerge (1967) are common in the granules. Material you collect here is considerably less metamorphosed but has undergone more surface alteration than material LaBerge used from the Vicar mine 7 miles east of here.

The main wavy-bedded part of the Plymouth constitutes 1/2 to 3/4 of the member and it has been perhaps the most important ore-bearing interval in the Ironwood Iron-Formation. Relatively thin blankets of ore at the base of this unit occupy more bedding-surface area than do ores at higher horizons. These strata are made up of wavy-bedded and lenticular layers of granular chert, from less than 1 cm. to more than 30 cm. thick, interbedded with uneven thin-bedded ferruginous layers as much as 5 cm. thick, called separators.

In unoxidized iron-formation, the wavy chert beds contain much less iron than the separators, possibly as little as 10%-20%, though I know of no analytical work on individual layers.

In iron-formation of low metamorphic grade, unoxidized chert layers can be found for analysis, but the thin-bedded separators are oxidized and leached to great depths -- I have never seen unaltered separators of low metamorphic grade. (At higher grades good sample material is common.)

Here the wavy-bedded chert layers contain silica and siderite, sparse hematite (primary, I think), and very sparse green chlorite as the only primary silicate. Here, more than along the Black River, a little stilpnomelane has replaced chlorite and perhaps other minerals as the lowest grade secondary iron-silicate.

The upper part of the Plymouth (ca. 50-75 feet thick) is mostly more uniform and in persistent layers 1 to 3 cm. thick. Some layers are granular and some are plain chert. There is a persistent thin jaspery interval near the top of the member. Central Gogebic jaspers are colored by red-reflecting "dust" particles ca. 0.0005 mm. in diameter, whereas jasper from Ishpeming in the Marquette district is colored by hematite in minute crystal platelets.

The dust in Gogebic jaspers tends to be aggregated into spheres 0.008 - 0.016 mm. in diameter. These are similar to the "type E" structures of LaBerge, who believed them to be of organic origin.

The Yale Member is mostly thin-bedded chert-carbonate iron-formation and also contains a few granular wavy-bedded layers, a tuffaceous bed, and black argillite that is partly pyritiferous. Parts of the succession are missing in some places but here the member is 206 feet thick. Although the Yale is partly oxidized to great depths, unoxidized masses are common in surface exposures, and you can inspect a variety here. Good surface exposures of unoxidized thin-bedded chert-carbonate and chert-silicate iron-formation are common in the Gogebic and in other Lake Superior districts too.

The primary minerals of this facies are almost entirely chert and carbonate with local pyrite where sedimentary conditions were right. (Where some magnetite is present higher in the formation, I think it is mostly or entirely metamorphic.)

Successively higher members in the iron-formation repeat these general lithologic types with certain characteristic variations in each member.

Stop 7 Ironwood-Tyler relationships and mineralogy of unmetamorphosed(?) iron-formation.

Location: In bed of Black River south of U. S. Highway 2 (Figure 8). Park at bridge on secondary road 600 feet south of Highway 2. Ironwood-Tyler transition is best seen on east bank; lithologic types in iron-formation on west bank. River is heavily polluted, avoid contact with the water.

Stop 7a Ironwood-Tyler contact relationships.

Location: Walk 600 feet upstream from secondary road on east bank of river. The contact we are considering is transitional and is 50-100 feet north of the sewer outfall.

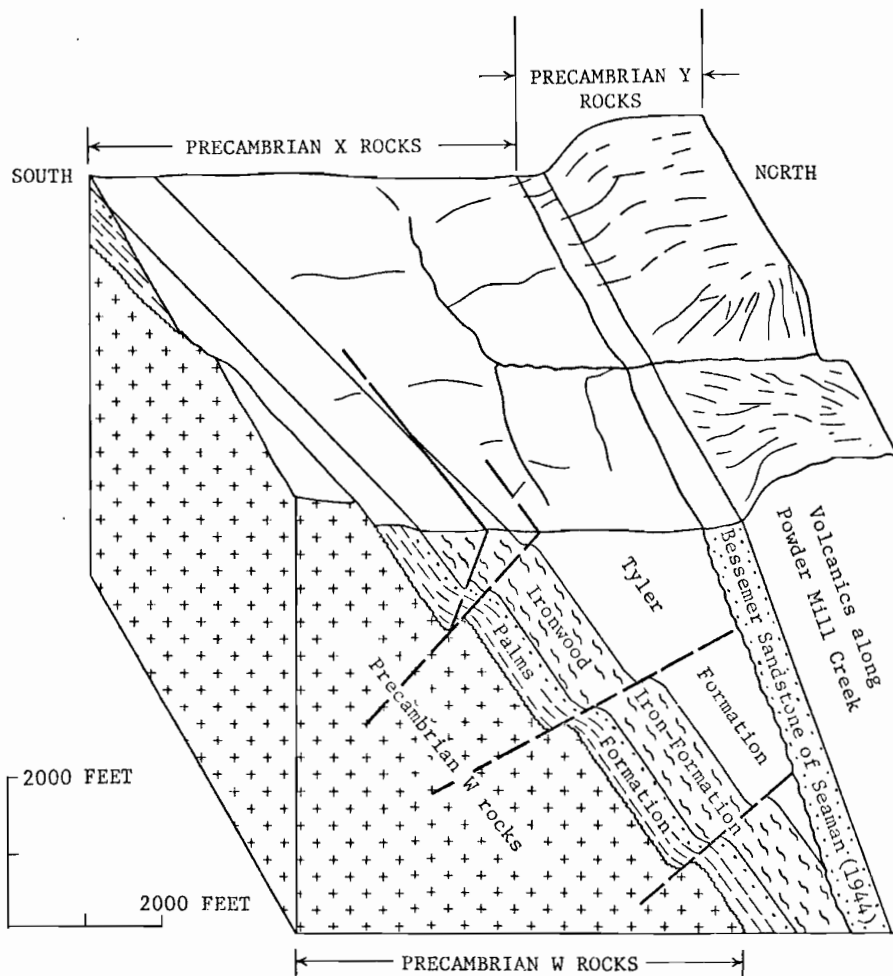
Presumably these thin-bedded carbonate iron-formation strata are at the top of the Anvil Member and are overlain by ferruginous quartzite at the base of the Tyler Formation. This is the only place in the central Gogebic district where the contact is well exposed; it may be one of the few places in the whole district.

Considerable structural displacement is required to account for the contact this far north; presumably the displacement was on the Ayer fault, a south-dipping strike fault identified in drill holes and mine workings. East-trending faults are common here and eastward; they are about perpendicular to the bedding, and most are upthrown on the north side (Figure 9). These faults can be recognized in the Precambrian X (middle) and at the Precambrian X-W (middle-lower) boundary, but the Precambrian W (lower) lacks internal markers for tracing the faults. The absence of faults of this type in the Keweenaw strata indicates that the deformation was before Keweenaw time when the Ironwood and Tyler were close to horizontal or gently south-dipping (lower part, Figure 9). East is also the major dike direction; some dikes are on faults, but many have no stratigraphic displacement associated with them. I think that step faulting is the only clear expression of Penokean deformation in the Gogebic district west of Wakefield and that it may have produced much of the 10,000 feet of uplift at Wakefield indicated by differential erosion of the Tyler Formation. Step faulting is locally common within the Marquette district as a result of Penokean orogeny.

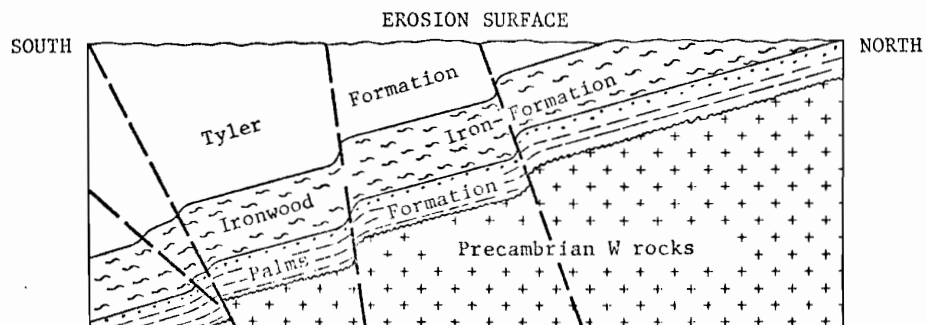
Thin-bedded carbonate iron-formation occurs above the thick-bedded "typical" Anvil Member and below the Tyler Formation only in this general part of the district, and this is the only outcrop I know. These thin-bedded strata are the ones that Hotchkiss (1919) placed at the base of the "Pabst Member", beneath the basal conglomerate but above the unconformity. Atwater (1938) put them in the Ironwood Iron-Formation as the topmost beds of the Anvil. Atwater did not believe that a major unconformity separated the Ironwood and Tyler; I interpret the formations to be gradational and sedimentation to have been continuous in the central Gogebic. Trent believes that field relationships indicate an unconformity at this horizon on the east Gogebic. Post-Penokean erosion removed this part of the section for 7 miles between our areas, thus making it difficult to resolve the problem across this gap.

Mining company cross-sections prepared from subsurface data support an interpretation of this contact as the top of the Ironwood Iron-Formation. However, one alternative interpretation

Figure 9



Generalized diagram of the relationship of Precambrian rocks in the central Gogebic district



Hypothetical post-Penokean pre-Keweenaw cross-section on same surface as front of block diagram above

merits our consideration. At the Puritan Mine, 4 miles to the west, the only underground workings to penetrate far up into the Tyler Formation went through a thin-bedded siliceous carbonate iron-formation 450 feet above the base of the Tyler, and this may be that unit. The thin-bedded iron-formation here contains almost 4 percent Al_2O_3 .

Regardless of our exact stratigraphic positions, these observations are valid at this locality:

- 1) The lower part of the Tyler Formation is iron-rich. Change from Ironwood to Tyler sedimentation took place by influx of clastic material into a basin during chemical precipitation of iron. The end of iron deposition was later during Tyler time.
- 2) The siliceous fragments and pebbles sparsely present in the Tyler Formation here are like material that has been called a basal conglomerate, although at many places much more fragmental material is present close to the contact. To my knowledge, the Tyler Formation is nowhere as sandy as here.

Stop 7b Jaspersy granular chert and chamositic thin-bedded iron-formation, very little metamorphosed.

Location: Test pit dump in brushy woods, about 500 feet S. 75 W. from sewer outfall area, stop 7a; in SE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 12, T. 47 N., R. 46 W.

This is the least metamorphosed iron-formation I have seen in the Lake Superior region. I think it may even be less metamorphosed than material from Kakabeka Falls in the Gunflint district. Radiating or feathery chalcedonic quartz is common in the granular chert, and a profusion of minute spherulitic forms can be seen in the 5 to 25 μ range. Traces of bright-green chlorite are present in many granules.

The thinly laminated silicate iron-formation gave an X-ray pattern for chamosite. A pleochroic golden-brown silicate, probably stilpnomelane, is present in small amounts. There is no minnesotaite here or in more altered material a few miles to the west where stilpnomelane is fairly common. My conclusion is that stilpnomelane may be partly diagenetic, but it is more likely entirely metamorphic in origin. Minnesotaite is certainly only metamorphic and has a threshold temperature slightly higher than stilpnomelane under natural conditions---a temperature that was not reached in the Ironwood-

Ramsay segment of the Gogebic Range.

This material gives you a good idea of how mild the metamorphism resulting from the Penokean orogeny was in part of the Gogebic district; in fact, some might argue that this rock is unmetamorphosed.

Examine a thin section of the granular jasper when you get home. Can this hematite be anything but primary in origin?

Stop 7c Carbonate-sulfide granular iron-formation and anthraxalite in Tyler Formation.

Location: West bank of Black River south of U. S. Highway 2 bridge; NE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 12, T. 47 N., R. 46 W.

The dark-brown pitchy carbon material here has an X-ray pattern that fits best with something in the meta-anthracite range. Some of the traces I have made are just about the same as from anthraxalite collected near the Ontario Hydro station below Kakabeka Falls. The whole comparison of patterns was disappointingly inconclusive, however.

Neither the carbonate-sulfide granular iron-formation nor the anthraxalite have been described from anywhere else in the Gogebic. If unfaulted, the stratigraphic position here is 200 to 300 feet higher than the "upper" iron-formation in the Puritan mine; this is stratigraphically lower than the highest part of the Tyler Formation penetrated in that mine.

The Tyler Formation is only 2,000 to 2,500 feet thick here and is missing less than 2 miles eastward. Keweenaw beds north of here dip 5° to 15° steeper than beds at this locality (Figure 9).

Stop 8 Lower Keweenaw flows and their attitude.

Location: Road cut and quarry along Michigan State Highway M-28, about one-quarter mile northeast of Sunday Lake, Wakefield, Michigan (Figure 10).

The northward dip of these lower Keweenaw flows is a little steeper than the dip of the Precambrian X (middle) sedimentary rocks that are unconformable beneath them. Because the difference in attitudes is small, the unconformity that separates Keweenaw rocks from Precambrian X (middle) rocks cannot be shown in an outcrop. The unconformity is shown clearly by areal relationships. The underlying Tyler Formation thins eastward from near the

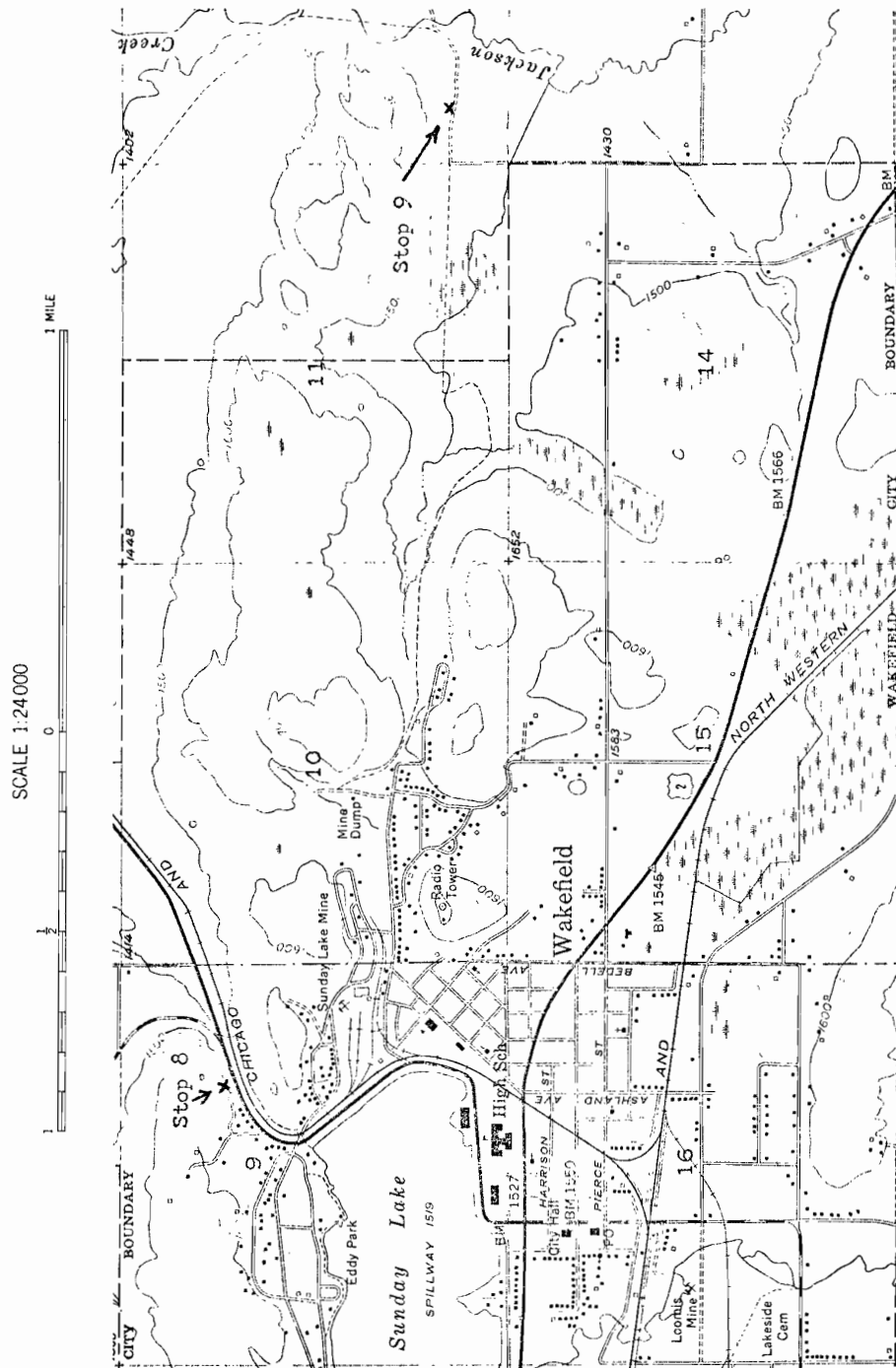


Figure 10. Wakefield, Michigan, area: Stops 8 and 9.

Montreal River (stop 4) where it is about 7,000 feet thick. On the Black River (stop 7), the Tyler is about 2,000 feet thick, and it is completely eroded away east of the road to Indianhead Mountain (about two miles east of the Black River.). Eastward, the Ironwood Iron-Formation is eroded, and south of this stop as much as three-quarters of it may have been eroded before the Keweenaw rocks were deposited.

The dips of the lower Keweenaw flows increase northward (Figure 11), and in exposures about 7,000 feet stratigraphically above this one, the flows are slightly overturned. Because the progressive upward increase in dip of the Precambrian X (middle) and lower Keweenaw rocks is a regional relationship, it is inferred that the differences in dip are related to deposition of the rocks and that the central parts of the depositional basins of both Precambrian X (middle) and lower Keweenaw rocks were to the south. The center of the depositional basin of the middle and upper Keweenaw rocks was to the north.

The rocks at this stop are weakly metamorphosed, but they are more metamorphosed than the middle Keweenaw volcanic rocks. Chlorite is abundant in the matrix of the rocks and causes the greenish color. The changes in metamorphic grade of the lower Keweenaw rocks may be sympathetic with those of the Precambrian X (middle) rocks, and the metamorphic grade increases westward from the Black River. In samples of the lower Keweenaw flows systematically collected in Wisconsin, actinolite is rare near Michigan and becomes progressively more abundant westward toward Mellen, where it is abundant.

Stop 9 Metamorphosed thin-bedded iron-formation, Keweenaw strata resting on Ironwood Iron-Formation.

Location: Vicar mine dump, SW $\frac{1}{4}$ sec. 12, T. 47 N., R. 45 W., east of Wakefield (Figure 10).

This mine dump is a good place to collect samples of unoxidized metamorphosed thin-bedded iron-formation. Although still only within the "chlorite zone," the metamorphic grade at the Vicar mine is the limiting grade above which direct-shipping ores did not generally form from iron-formation. Both minnesotaite and stilpnomelane are abundant here (Mann 1953, p. 261).

The choice of this location for the study of "primary" iron-formation mineralogy by Huber (1959) was unfortunate. Mann (1953) also thought the minerals present here were typical of

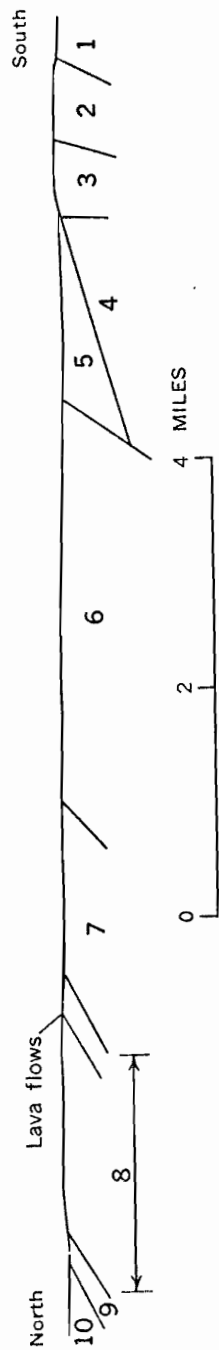


Figure 11. North-south geologic section just west of Black River

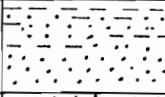
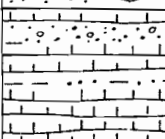
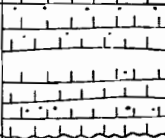
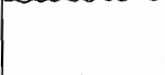
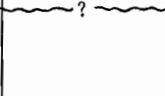
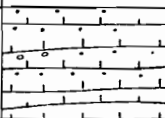
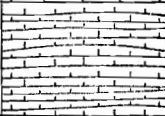
Precambrian Y (upper)				Upper	12,000' +		10 Freda Sandstone Reddish-brown lithic sandstone interbedded with siltstone
					550'		9 Nonesuch Shale Gray lithic sandstone and siltstone
					1600'-6000'		8 Copper Harbor Conglomerate Reddish-brown lithic conglomerate and sandstone; intermediate lava flows at Great Conglomerate Falls on the Black River
				Middle	0-9500'		7 Unnamed formation Grayish intermediate to mafic lava flows interbedded with lithic sandstone, siltstone, and conglomerate; uncommon felsic flows
					8000' - 13,000'		6 Portage Lake Lava Series Grayish mafic to intermediate lava flows, uncommon reddish-brown felsic flows, and lithic sandstone and conglomerate
				Lower	?		5 Nonmagnetic rock Covered by till
					ca 10,000'		4 Rock having magnetic properties similar to unit 3 Covered by till
					4500'		3 Lava flows along Powder Mill Creek Bluish-gray intermediate lava flows and reddish-brown felsic flows; felsic flows become more abundant upward
					5000'		2 Basalt flows along Powder Mill Creek Greenish-gray basalt flows and rare intermediate flows
					ca 300'		1 Bessemer Sandstone of Seaman (1944) Quartz arenite with abundant matrix; conglomerate at base

Figure 12. Stratigraphic section of Keweenaw Series, Ironwood area, Michigan

the whole producing range, but in fact a metamorphic grade this high may be reached going westward only at the very western end of the producing range in Wisconsin.

I have looked at only two thin-sections of Powder Mill Creek flows near here, and I think they are metamorphosed about the same as the iron formation. Is all the iron-formation metamorphism post-Penokean here? Where was the metamorphic center? Careful comparisons of metamorphic grades in the Keweenaw flows and the Precambrian X (middle) rocks is the really nitty-gritty of regional metamorphic study in the Gogebic, but the flows have generally been judged to be "unmetamorphosed" by field examination. I find, however, that determinations of comparative grade in such contrasting rock types is very difficult at this grade.

Stop 10 Intermediate volcanic rocks.

Location: Siemen's Creek in R. 47 W. north and south of the line between T. 47 N. and T. 48 N. (Figure 13).

Rhyodacite and trachyandesite flows are typical rocks in the upper part of the lower Keweenaw section (Figure 12). Most of the rocks are aphanitic. The flows are thicker, averaging about 80 feet and reaching a maximum of 200 feet thick. The flow tops are autobrecciated, and the vesicule fillings differ from those in the lower Keweenaw rocks. Note chalcedony at the northern falls. The rocks are bluish gray rather than greenish gray. A reddish-brown felsite flow (quartz latite) is well exposed south of the township line. It has massive flow-banded rock at the base and vesiculated rock in the upper part. The rocks are overturned.

Stop 11 Lower Keweenaw intermediate flow with glomeroporphyritic texture.

Location: Roadcut near the south line of sec. 33, T. 48 N., R. 46 W. (Figure 13).

Glomeroporphyritic texture (clotted phenocrysts, here plagioclase) is well developed only in the lower Keweenaw volcanic rocks. Several flows with this texture occur in the lower Keweenaw section, and they are useful as stratigraphic marker beds. The texture is informally called "turkey-track" or "chicken-track" porphyry.

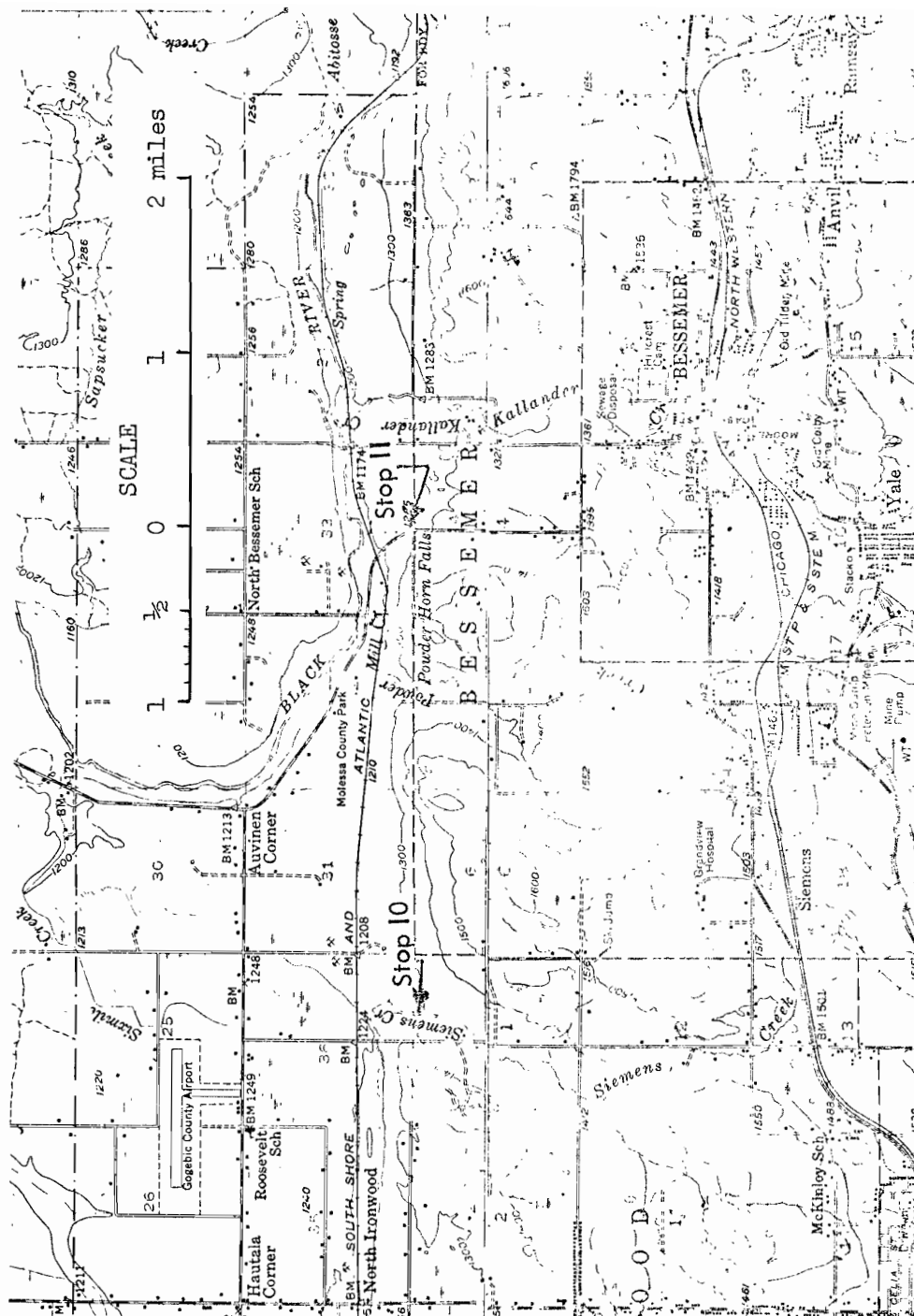


Figure 13. Bessemer area: Keweenawan geology stops 10 and 11.

Stop 12 Middle Keweenawan rocks of the "unnamed formation" of Johnson and White (1969).

Location: Meander loops near Algonquin Falls, Black River, NE $\frac{1}{4}$ sec. 29, T. 49 N., R. 46 W., (Figure 14, stop 12). An abandoned logging road can be followed from the Black River Parkway to the Black River. It joins the parkway where the parkway begins to bend west, about 1.1 miles north of Copper Peak.

The rocks here are more mafic than the typical rocks of the "unnamed formation" farther east and include rocks with ophitic texture, which are not common in the "unnamed formation." Such rocks are common in the underlying Portage Lake Lava Series. The middle Keweenawan volcanic rocks differ in appearance from the lower Keweenawan volcanic rocks. The middle Keweenawan rocks are coarser grained and contain less chlorite. The flows are thicker, the vesicles are much more irregular, the flow tops are rougher, and some tops have a sheeted structure. The exposures at Algonquin Falls are unusually good.

A flow with ophitic texture and containing pyroxenes increasing in size toward the middle is completely exposed in the westernmost part of the western meander loop. A narrow fault zone occurs just to the east, and a fault sliver in the zone forms an island in the river. East of the fault zone, the river flows along the top of a porphyritic flow which has unusually large phenocrysts at the eastern meander loop. Down section, a flow-top breccia is well exposed. Below that is a conglomerate that contains abundant pebbles of volcanic rocks. The more mafic rocks are derived from the lower Keweenawan rocks. Note that they do not resemble the enclosing rocks closely. Farther downstream, just below the falls which is really a rapids, is cross-bedded lithic sandstone. Such sandstones have been called arkoses in the Lake Superior region, but they contain very little feldspar. Above the sandstone is a flow with many flow units or several very thin flows. Just above the western end of the sandstone, one flow margin laps against another.

POISON IVY is common in sunny places along the river bank.

Stop 13 Copper Harbor Conglomerate (Figure 11, Unit 8).

Location: U.S. Forest Service recreational area at Gorge Falls-Potawatami Falls, near north end of Black River Parkway (Figure 14).

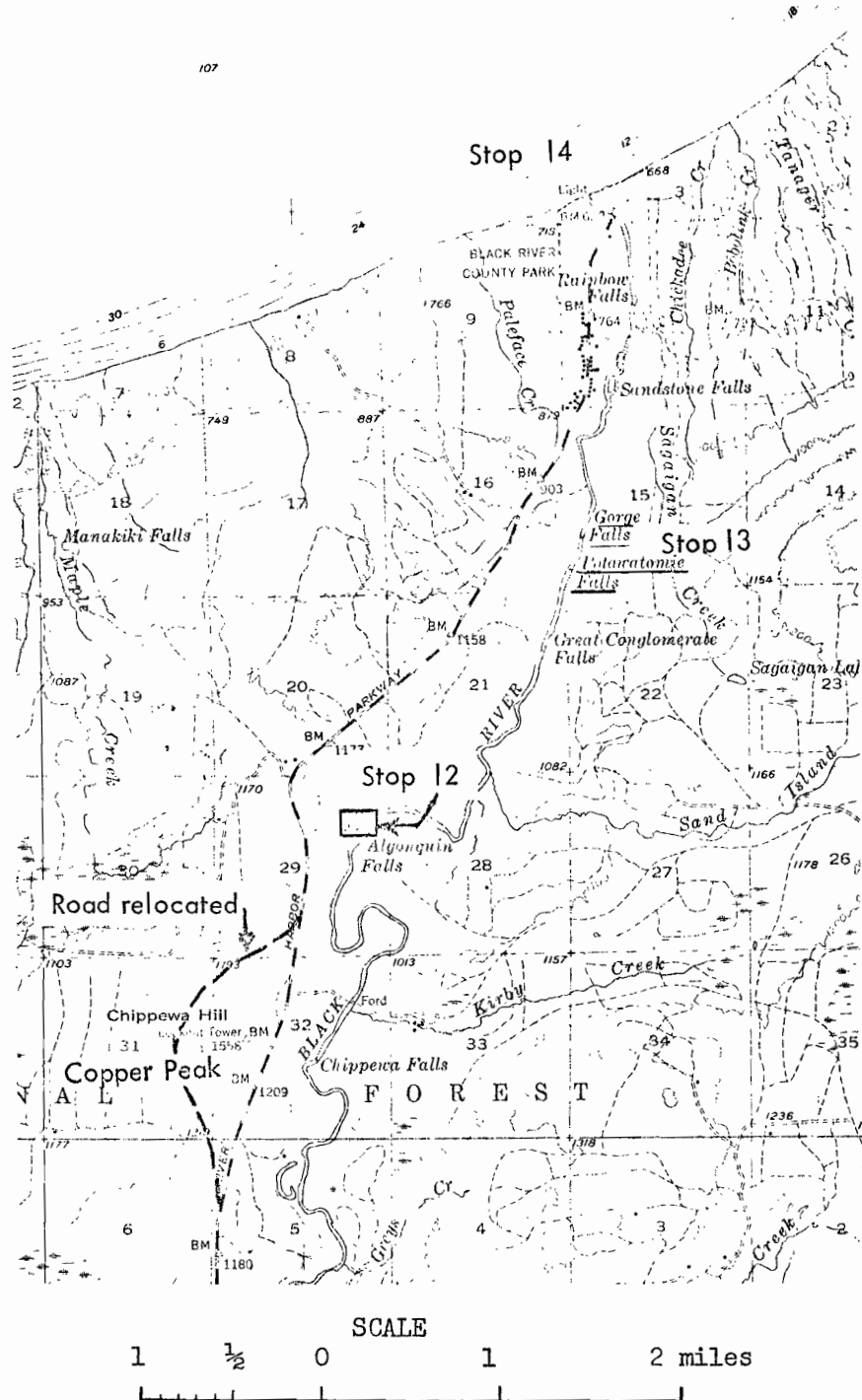


Figure 14. Copper Peak area: Keweenawan geology Stops 12 through 14.

The Copper Harbor Conglomerate is composed of detritus of lower Keweenawan volcanic rocks in most places, but farther west it also includes pebbles of pre-Keweenawan rocks. The felsic rocks in the pebbles resemble types of rocks found in both lower and middle Keweenawan volcanic rock sequences, but the intermediate pebbles are from rock types found only in the lower Keweenawan sequence. Rocks that occur only in the middle Keweenawan sequence are not represented among the pebbles. The lack of middle Keweenawan rock types indicates that the Portage Lake Lava Series is not the source of the pebbles, as was formerly believed.

A structural terrace is exposed downstream from the George Falls Forest Service service area.

Stop 14 The Nonesuch Shale (Figure 11, Unit 9).

Location: West side of Black River Harbor, north end of Black River Parkway.

Evenly laminated very fine sandstone and siltstone are typical of the Nonesuch Shale.

Stop 15 The Freda Sandstone (Figure 12, Unit 10).

Location: Power House near the mouth of the Montreal River and along the shore from the mouth of the Montreal River to Little Girls Point (Figure 1).

The upper part of the Freda is predominately fine to very fine sandstone that is crossbedded and interlayered with massive to laminated siltstone. The Freda Sandstone has been called an arkose, but the rock contains very little feldspar. Lithic sandstone is probably the best name, but it would fit the term graywacke as defined by many classifiers. These are stream-deposited rocks.

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FIELD TRIP B

Guide to Penokean deformational style
and regional metamorphism of the
western Marquette Range, Michigan*

by

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** Publication authorized by the Director, U.S. Geological Survey

GUIDE TO PENOKEAN DEFORMATION STYLE AND REGIONAL METAMORPHISM
OF THE WESTERN MARQUETTE RANGE, MICHIGAN

The Marquette Range in the central northern peninsula of Michigan is an east-west synclinorium of metasedimentary and metavolcanic rocks of Precambrian X* age bounded on the north and south by crystalline rocks of Precambrian W age.

In the past, attention has been focused largely on the eastern part of the range because of the relatively good exposures and concentration of economic iron deposits in that area. During the past few years, however, our studies in the western part of the Marquette Range have shown some previously unrecognized features and have helped unravel the sequence of Penokean deformation and metamorphism of Precambrian X age.

The exposures seen on the field trip illustrate the section of rocks of Precambrian X age in the western Marquette Range and their multiphase deformation and metamorphism. The trip begins in the sillimanite zone of James' (1955) Republic metamorphic node (see isograds on fig. 1), where the rocks in the Republic syncline are well exposed in and around the Republic open-pit iron mine. This relatively narrow syncline serves as a scale model of larger synclinal structures in Michigan. The trip proceeds westward from Republic toward zones of lower metamorphic grade and examines folded and metamorphosed sedimentary rocks and iron ore near the towns of Champion, Michigamme, and Alberta, Michigan.

Geologic setting

The general geology of the western Marquette Range and the location of field trip stops is shown in figure 2.

Stratigraphy.--Precambrian W: Rocks of Precambrian W age are divided geographically into the northern complex composed of the rocks north of the Marquette synclinorium, and the southern complex, composed of rocks south of the Marquette synclinorium (Van Hise and Bayley, 1897). Although there has been general agreement on the age of the northern complex, the age of the southern complex was debated by several authors (Swanson, 1930; Zinn, 1931; Lamey, 1931, 1933, 1934, 1935) who favored a late Precambrian X age for the granitic rocks. Recent age determinations (Aldrich and others, 1965; Woolsey, 1971) and detailed mapping (Cannon, 1971 a,b) leave little doubt that most granitic rocks in the southern complex are of Precambrian W age.

The southern complex contains at least two major units of granitic rocks, two migmatitic horizons, and at least four ages of mafic rocks. It is intruded by at least three ages of mafic dikes and at least one age of pegmatite. By far the most abundant rock type, however, is a coarsely porphyroblastic quartz monzonitic gneiss.

* The recently proposed system of Precambrian time nomenclature is used in this report. Rocks older than 2.5 b.y. are termed Precambrian W; those between 2.5 and 1.6 b.y. are termed Precambrian X, and those between 1.6 and 0.8 b.y. are termed Precambrian Y.

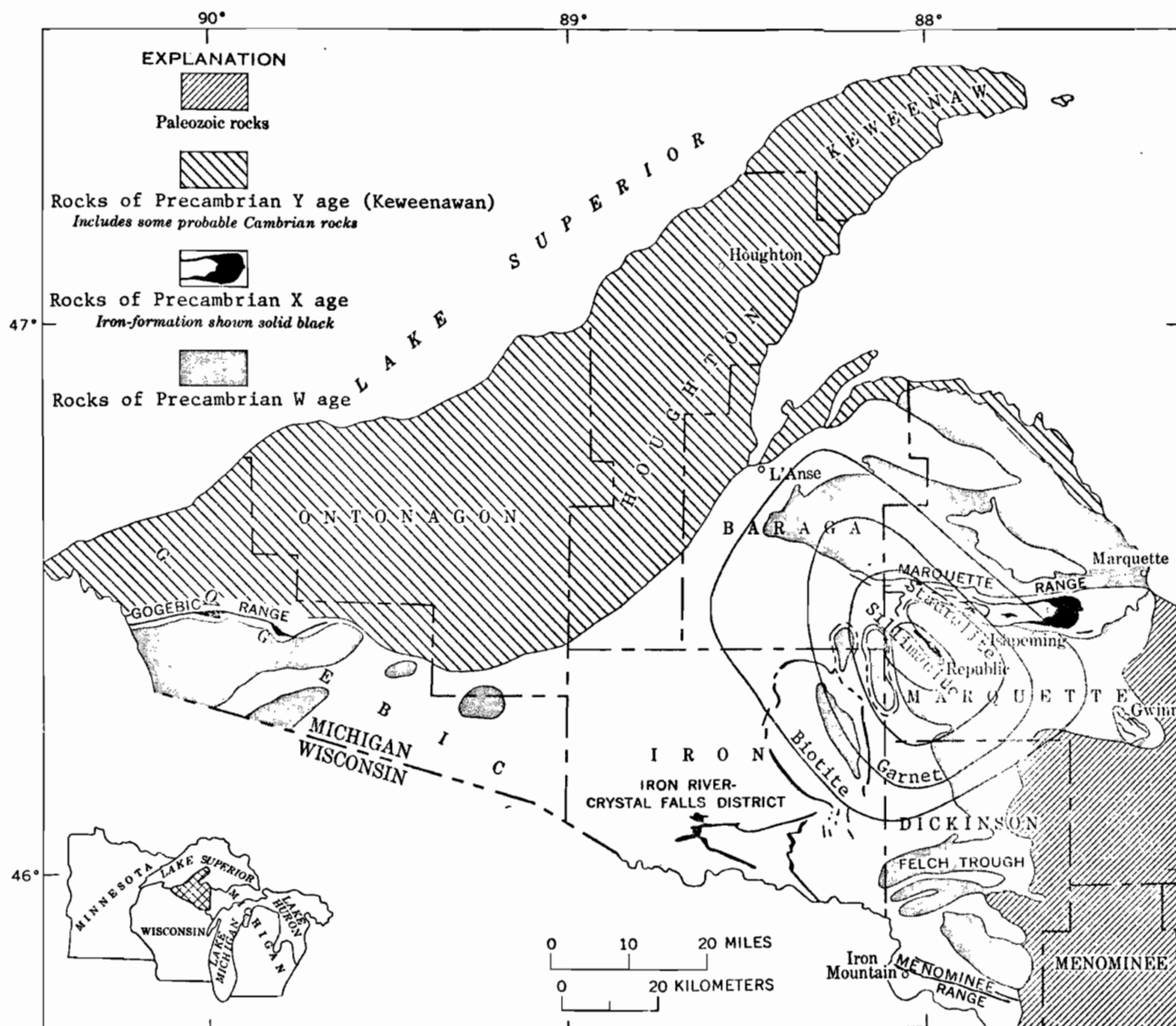


Figure 1.--Geologic sketch map of the northern peninsula of Michigan showing the Marquette range and the isograds of the Republic metamorphic node from James (1955).

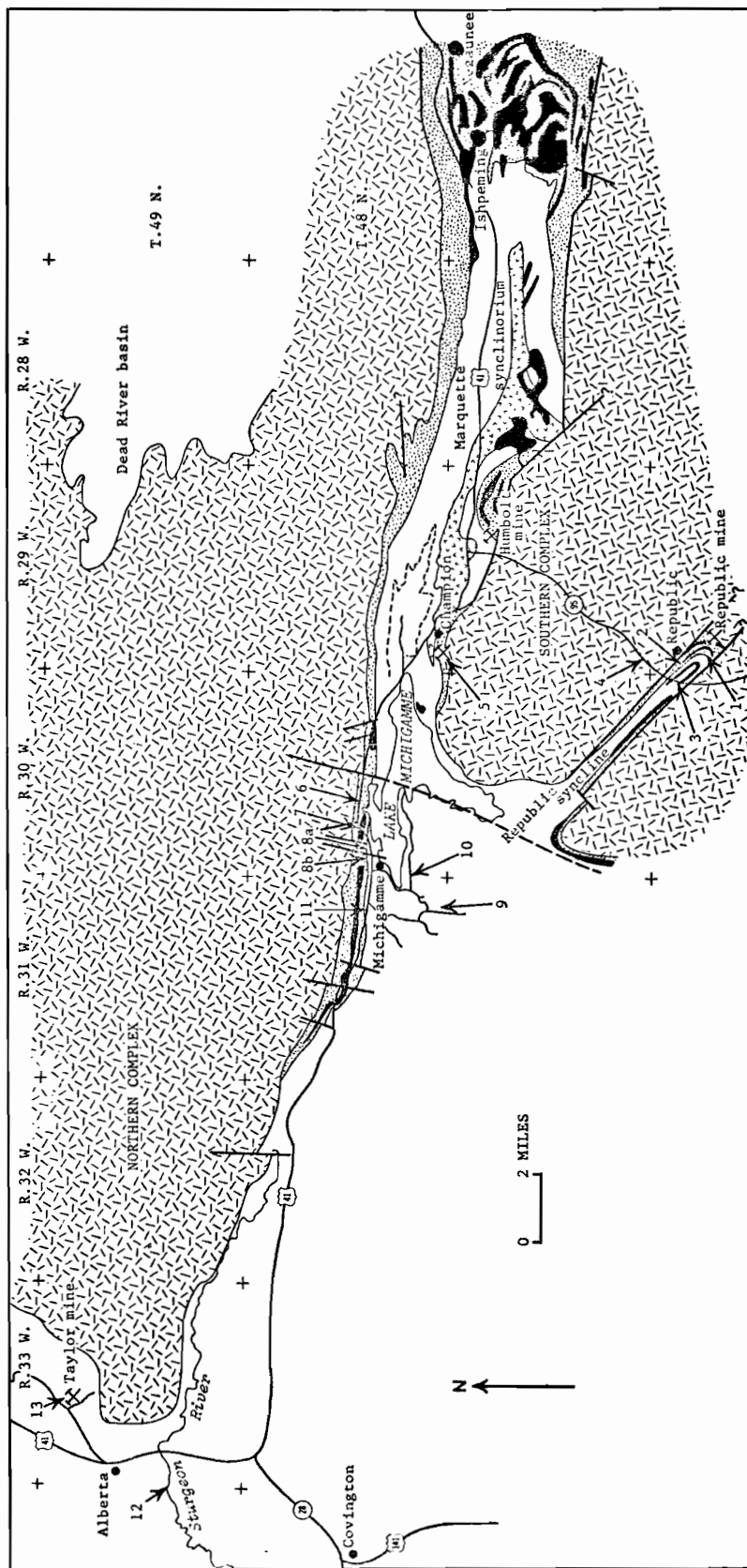
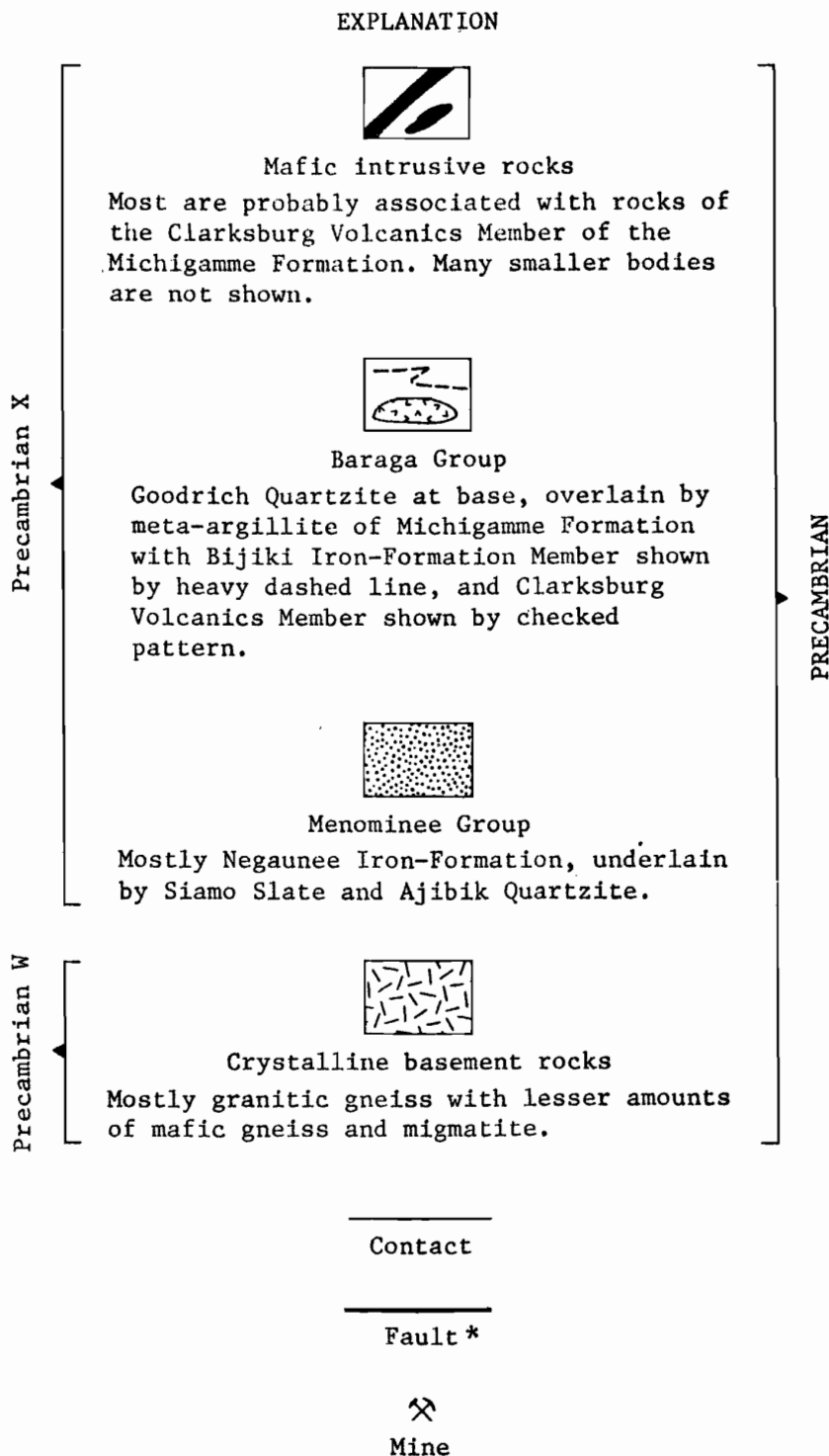


Figure 2.--Geologic map of the western Marquette Range. Compiled from Boyum (1964), Cannon (1971 a,b), Simmons (1971), maps supplied by United States Steel Co., and unpublished thesis maps by W. Rodwell and J. Klasner, Michigan Technological University, Houghton, Michigan.

Figure 2, Legend



*Contact between Precambrian W and Precambrian X rocks is shown to be a fault in most areas of recent detailed mapping. It is probably a fault in many other areas, as well, but is not shown as such in areas where the nature of the contact is still in doubt.

		SUPERGROUP, GROUP, FORMATION, AND (OR) MEMBER		DESCRIPTION		
PRECAMBRIAN	Precambrian Y					
			Diabase	Nonmetamorphosed diabase dikes		
	Precambrian X			Pegmatite	Coarse-grained-microcline-quartz-muscovite rocks. Relatively rare but most abundant near Republic.	
				Metadiabase	Amphibolitic rock, much with relict diabasic texture. Mostly as sills in Precambrian X rocks and dikes in Precambrian W rocks. Much is probably associated with rocks of the Clarksburg Volcanics Member of the Michigamme Formation.	
		Marquette Range Supergroup	Baraga Group	Michigamme Formation	Upper slate member	Metapelite and metagraywacke.
					Rijiki Iron-Formation Member	Mostly cherty silicate iron-formation.
					Lower slate member	Metapelite and metagraywacke with some pyritic carbonaceous slate.
					Clarksburg Volcanics Member	Mafic pyroclastic rocks with intercalated meta-argillite and iron-formation.
					Greenwood Iron-Formation Member	Cherty silicate iron-formation.
			Menominee Group		Goodrich Quartzite	Massive to banded protoquartzite with conglomerate near base.
		UNCONFORMITY				
				Negaunee Iron-Formation	Mostly cherty silicate iron-formation with oxide iron-formation near top.	
				Siamo Slate	Laminated metapelite.	
				Ajibik Quartzite	Banded to massive, light-colored quartzite.	
		UNCONFORMITY				
Precambrian W			Gneiss of northern and southern complexes	Complex of granitic and mafic gneiss.		

Figure 3.--Stratigraphic column for the western Marquette Range, Michigan.

Various lithologies are known from the eastern part of the northern complex, which has been studied in detail. However, only relatively massive, medium- to coarse-grained granitic rocks will be seen in the field-trip area adjacent to the Marquette synclinorium.

In spite of the proximity of the two complexes there is an apparent lack of similarity in details of their geology.

Precambrian X: Rocks of Precambrian X age in northern Michigan are divided into four groups which, from oldest to youngest, are the Chocolay, Menominee, Baraga, and Paint River Groups (James, 1958). These together constitute the Marquette Range Supergroup (Cannon and Gair, 1970). A stratigraphic section for the western Marquette Range is shown in figure 3.

The Marquette Range Supergroup was deposited unconformably on deeply eroded, and probably peneplaned, Precambrian W Basement, but the contact with the basement is now a fault in much of the western Marquette Range. The Chocolay Group, prominent in the eastern Marquette Range, pinches out to the west and is absent in the field-trip area.

The Menominee Group, the oldest Precambrian X unit present in the western Marquette Range, contains sedimentary evidence of tectonic instability on at least a local scale. After deposition of the Menominee Group, a period of uplift and erosion resulted in deep dissection of the sediments and complete removal in some areas. Where removal was complete, the Baraga Group now lies directly on the basement. The Baraga Group was deposited in a highly active tectonic environment. The clean quartz sands at the base of the group are overlain by graywacke-shale sequence, mafic volcanic rocks, and iron-formations of the Michigamme Formation which, south of the field-trip area, is overlain by thick masses of Badwater Greenstone, and the graywacke-shale-iron-formation assemblage of the Paint River Group (James, 1958).

Structure.-- The Marquette synclinorium and Republic syncline have cores of Precambrian X sedimentary rocks flanked by Precambrian W basement rocks. The Marquette synclinorium trends nearly east, and the Republic syncline, a subsidiary structure south of the synclinorium, extends southeast from the south end of Lake Michigamme to the village of Republic. East of the village of Champion, the Marquette synclinorium is relatively narrow, ranging from 2 to 5 miles in width, but west of Champion, it broadens and loses definition. Although the rocks on the north limb continue in a westward trend, the rocks on the south limb have south and southwest trends, and the synclinorium opens to the southwest into a broad basin, whose structure and stratigraphy are poorly known.

Axial planes of Penokean folds in the Precambrian X sedimentary rocks are nearly vertical, and fold axes plunge at generally low angles (as much as 45°). Cleavage is well developed in many units. Folds in Precambrian W gneiss are cut by swarms of metadiabase dikes which are not folded but which were metamorphosed during the Penokean orogeny. These folds, which must predate the Penokean, are believed to have formed during one or more

Precambrian W orogenies and are not related to Penokean deformation. Recent interpretations of the structure of the Marquette synclinorium and Republic syncline (Gair and Thaden, 1968; Cannon, 1971) propose that the synclines of Precambrian X rocks occur in grabens in Precambrian W rocks and are similar to structures to the south, in Dickinson County (James and others, 1961).

Regional metamorphism. Regional metamorphism began during deformation but culminated after deformation. A few mafic dikes cut folds in the metasedimentary rocks. They are not themselves folded, but they are metamorphosed to regional grade.

The metamorphic zones mapped by James (1955) are shown in figure 1. Rocks of the Marquette Range extend through the metamorphic spectrum from chlorite to sillimanite grade. The field trip visits biotite- to sillimanite-grade rocks.

Because little regional deformation took place after metamorphism, the present erosion surface approximates an isobaric surface and the isograds define isotherms. The metamorphism is a low-pressure type characterized by andalusite-bearing and sillimanite-bearing assemblages.

Economic geology. The western Marquette Range has been a continuous producer of iron ore for more than 100 years from about 40 mines. All are now inactive except for the Republic open-pit taconite operation which annually produces more than 3 million tons of iron ore pellets from about 10 million tons of crude ore and has the largest total production of all mines in Michigan.

Most of the production in the western Marquette Range came from the Negaunee Iron-Formation and iron-rich conglomerate phases of the immediately overlying Goodrich Quartzite. The Bijiki Iron-Formation Member of the Michigamme Formation was a producer of lesser importance, yielding high-grade limonitic ore similar to the soft ores of the Negaunee Iron-Formation in the eastern Marquette Range. Until 1955, all operations in the Negaunee Iron-Formation in the western Marquette Range recovered high-grade hard ore which consists of mixtures of specular hematite, magnetite, and martite. This hard ore is polygenetic and consists of both metamorphosed soft ore and hydrothermally deposited iron oxides. Since the mid-1950's, however, low-grade concentrating ore has become dominant. This ore, which occurs in uppermost horizons of the Negaunee Iron-Formation, is banded cherty or jaspery rock with bedded or disseminated specular hematite, magnetite, and martite, and to a lesser extent, banded chert-magnetite rock.

The concentrating ore forms the ore horizon presently exploited at the Republic mine but was first exploited at the Humboldt mine, which was active from 1954 to 1970 and had a peak annual production of nearly 1 million tons of pellets.

More complete summaries of the economic geology and ore genesis have been given by Boyum (1964) and Anderson (1968)

The Penokean orogeny

Definition of term. In recent years the term "Penokean" has been applied to the orogeny that occurred in late Precambrian X time in the southern province of the Canadian Shield. In the Marquette Range, the Penokean orogeny included the folding and faulting of the Marquette Range Supergroup, uplift of blocks of Precambrian W basement rocks, regional metamorphism, and pegmatite dike emplacement. Age determinations by Goldich and others (1961) and Aldrich and others (1965) indicate an age of 1.9 b.y. for metamorphism and pegmatite dike emplacement, two of the last Penokean events in the Marquette Range.

Regional Penokean deformation. Considerations of gross geometry of Penokean structures in northern Michigan (Cannon, 1971c) place constraints on possible deformational styles and suggest a sequence of deformation which is consistent with detailed structural analyses in the western Marquette Range and the Republic trough.

The regional Penokean structures in northern Michigan are uplifts of Precambrian W rocks; Precambrian X rocks are in intervening structural basins, which range in geometry from broad synclinal basins to tightly infolded synclines. A great divergence in trends of regional structures suggests that these structures are products of vertical tectonism rather than regional horizontal compression. Many uplifts of Precambrian W rocks are cut by swarms of diabase dikes which are metamorphosed by Penokean regional metamorphism and are correlated with pre-Penokean intrusive and extrusive mafic rocks in the Precambrian X section. The pre-Penokean age and undeformed nature of these dikes indicate that the Precambrian W rocks in which they occur were not internally deformed during Penokean folding of the adjacent Precambrian X sedimentary rocks. The Precambrian W rocks must have moved as fault blocks, and the structural style defined by James and others (1961) for parts of Dickinson County is probably applicable to most of the northern Michigan.

Folds within the Precambrian X rocks indicate that their deformation differs from the deformation of Precambrian W basement rocks in two important respects: 1) The Precambrian X rocks have undergone a very substantial internal deformation and horizontal shortening which has not occurred in the basement rocks. 2) Folds in Precambrian X rocks trend west and west-northwest, in contrast to the divergent trends of structures involving the basement.

Penokean deformation in Michigan, therefore involves at least two phases of folding:

- 1) Deformation of Precambrian X sedimentary rocks, probably the result of gravity sliding; fold axes trended west and west-northwest. This phase requires at least one décollement surface at, or near, the base of the Precambrian X sedimentary section.

- 2) Block uplift of Precambrian W basement rocks passively draped the earlier folded Precambrian X rocks into basins between the uplifts. This produced a second set of folds that are especially tight in some narrower synclines.

In some areas, the trends of these two ages of folds diverge at high angles and are easily separable. In the western Marquette Range, however, the trends are within about 20° of each other. As a result, the folding sequence was recognized only recently through detailed structural analyses in the Republic trough, Lake Michigamme, and Taylor mine areas. The results of these detailed studies are briefly discussed in the following paragraphs. Table 1, which summarizes the deformational events associated with the Penokean orogeny, should be referred to while reading the following detailed structural descriptions.

Penokean structures in the Republic trough. The Republic trough is an F_2 structure consisting of a syncline of Precambrian X rocks of the Marquette Range Supergroup flanked by Precambrian W granitic gneiss. The geology of the southeast end of the trough is shown in figure 4. The trough trends N. 45° W. and formed as a result of infolding associated with the rising of Precambrian W granitic rocks that bound the trough on either side. F_2 folding of the sedimentary rocks was very intense, and F_1 structures have not been recognized because of either complete overprinting by F_2 deformation or the original absence of these structures.

The F_2 tectonite fabric is defined by northwest-striking nearly vertical cleavage and by northwest-plunging minor folds which reflect, respectively, the axial plane and fold axis of the Republic trough. Numerous steep faults have formed subparallel to the axial plane near the keel of the fold and are well shown in the Republic open-pit mine.

Structural trends of Precambrian W rocks are parallel to the trend of the Republic trough and may have controlled the trend of the faults responsible for the trough. At the keel of the trough the Precambrian W trends are truncated by the rocks of the Marquette Range Supergroup, and the contact is interpreted as the unconformity between the Precambrian W and X rocks which has been tilted northwest during F_2 deformation.

Descriptions for stops 1, 2, and 3 contain more detailed information on this area.

Penokean structures at Lake Michigamme and Taylor mine. New information regarding deformation resulting from the Penokean orogeny has been gathered through detailed studies in the Lake Michigamme and Taylor mine areas. Both these areas are characterized by intense folding of the Precambrian X rocks.

The Marquette synclinorium and the anticline formed by the wrapping of the Marquette Range Supergroup around the west end of the northern complex are regional F_2 structures formed by the vertical movement of the northern and southern complexes. The Precambrian X rocks of the Marquette Range Supergroup here contain structures related to these regional F_2 structures as well as to an earlier F_1 regional deformation and a later F_3 deformation.

TABLE 1
Sequence of Penocean deformation
in the western Marquette Range area

EVENT	EVIDENCE
(F ₁) Development of regional folds and cleavage, possibly caused by large-scale gravity slides off an ancestral Penocean Range.	(S ₁) Cleavage schistosity and fold axes strike N. 70° W. Injections of silt and sand along cleavage planes suggest that sediments were unconsolidated during F ₁ deformation
(F ₂) Second phase of deformation caused by movement of granitic complexes as rigid blocks.	(S ₂) and L ₂) Crinkle folding of S ₁ caused S ₂ fracture cleavage. Intersection of S ₂ with S ₁ resulted in L ₂ lineations trending approximately east. The occurrence of shear zones between granite masses and metasedimentary rocks, and abundant shearing in the mafic sills within the metasedimentary rocks indicate late-stage movement between granitic blocks and the sedimentary rocks.
(F ₃) Third phase of deformation, possibly caused by continued rise of granitic complexes.	(S ₃) and (L ₃) Deformation of S ₁ , S ₂ , and L ₂ by kink-bands, visible on certain outcrops in Lake Michigamme area, and folding of L ₂ lineations in the Taylor mine area.
Post-Penocean north-south faulting	North-trending shear zones, magnetic discontinuities, and physiographic features such as stream lineaments, indicate faulting. The faulting is post-Penocean in age because the shear zones have not been affected by Penocean metamorphism.

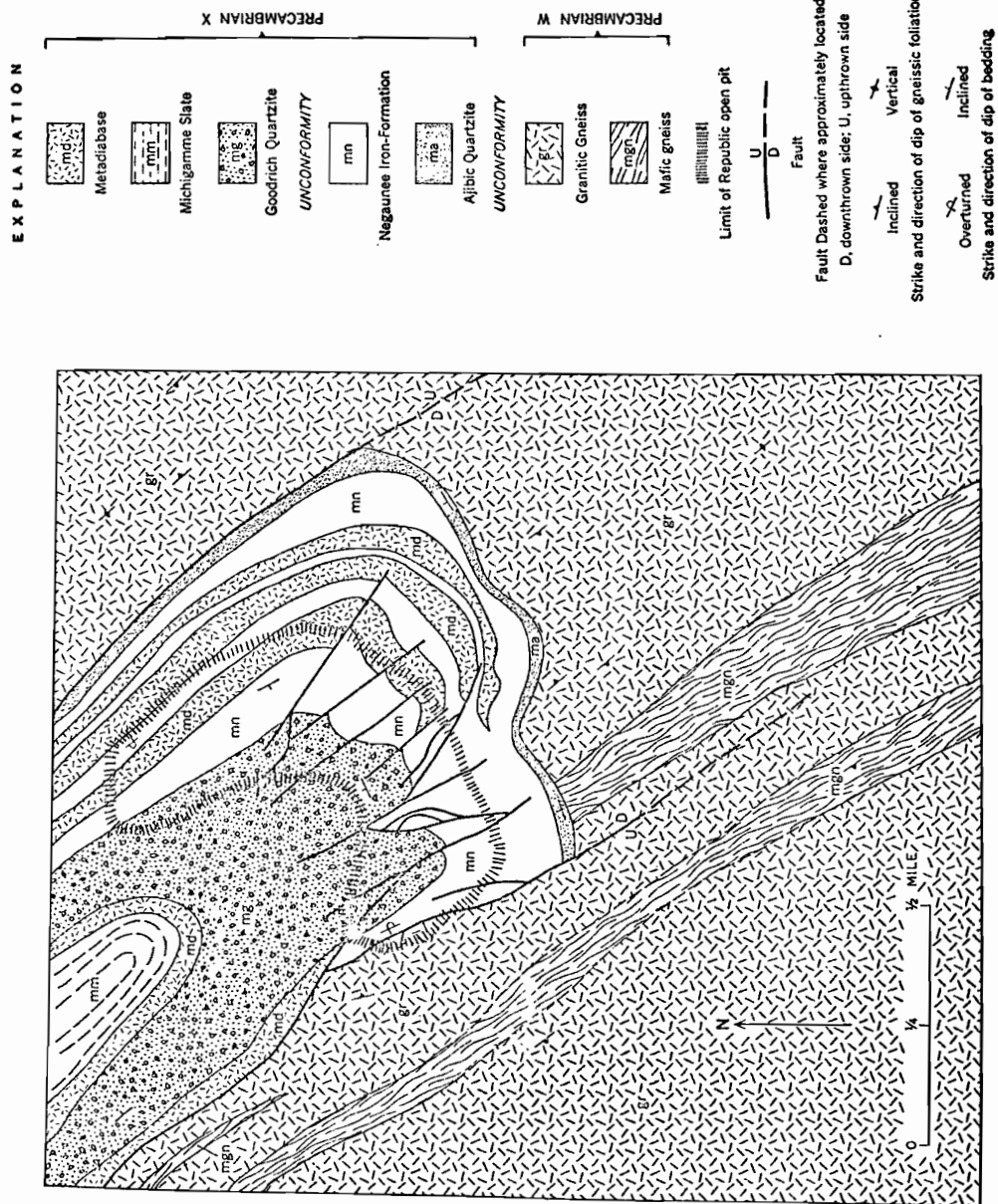


Figure 4.--Geologic map of the Republic area showing the southeastern termination of the Republic trough and the relationship of basement structural trends to trends in the Republic trough.

In the Lake Michigamme area, the Marquette synclinorium opens into a broad synclinal basin. A sketch map (fig. 5) of the fold pattern on an island in the lake near the main synclinal axis shows intensely deformed bedding that has been folded into a series of tight anticlines and synclines having wavelengths of approximately 25 feet. Graded bedding and sedimentary flame structures indicate that the bedding has not been overturned. The north limb of the synclinorium dips 60° south. Minor folds (fig. 8), superimposed on the limbs of the syncline, and gross bedding geometry indicate that the main synclinal axis must be under Lake Michigamme.

The fold geometry at Taylor mine is illustrated by a structural cross section (fig. 9) constructed from surface geology and drill-hole data. The contact between graphitic slate and overlying iron-formation shows that the fold amplitude is approximately 400 feet and that the wavelength is approximately 600 feet. The crests of the folds become progressively deeper toward the south end of the cross section. Minor folds, with wavelengths of approximately 100 feet, are superimposed on the limbs of the larger folds. (See stop 13.).

In contrast to the intensely deformed metasedimentary rocks in the Lake Michigamme and Taylor mine areas, quartzites along the Sturgeon River, at the western end of the northern complex, are essentially flat lying to gently folded and contain fabric elements for only the F_1 phase of Penokean deformation. The reason for their relatively undeformed state (lack of F_2 and F_3 fabric elements) in a region of intense folding, may be that these rocks are near the nose of the west-plunging anticline formed by the uplift of the northern complex. The granitic rocks of the northern complex plunge gently beneath the quartzites, forming a solid floor which protected the quartzites during F_2 and F_3 deformation. During these phases of deformation, the quartzite was simply uplifted as the sedimentary cover on top of the granitic block forming the northern complex. (See stop 12.).

The rationale for the sequence of deformation, as proposed in Table 1, can best be developed by first considering the regional structural picture. Recent regional work suggests that foliation in the northern complex has a concentric structural pattern, and that at least a part of the southern complex has a similar concentric structural pattern (Taylor, 1967). These patterns are not reflected in the mesoscopic tectonite fabric formed within the Precambrian X rocks; the regional structural pattern within these rocks is characterized by a fabric that trends approximately N. 70° W. The mesoscopic fabric elements are slaty cleavage, or schistosity, fold axes where bedding can be recognized, and triaxially deformed calc-silicate concretions. This regional fabric must be due to a regional deformational event (F_1) that affected the Precambrian X but not the Precambrian W rocks.

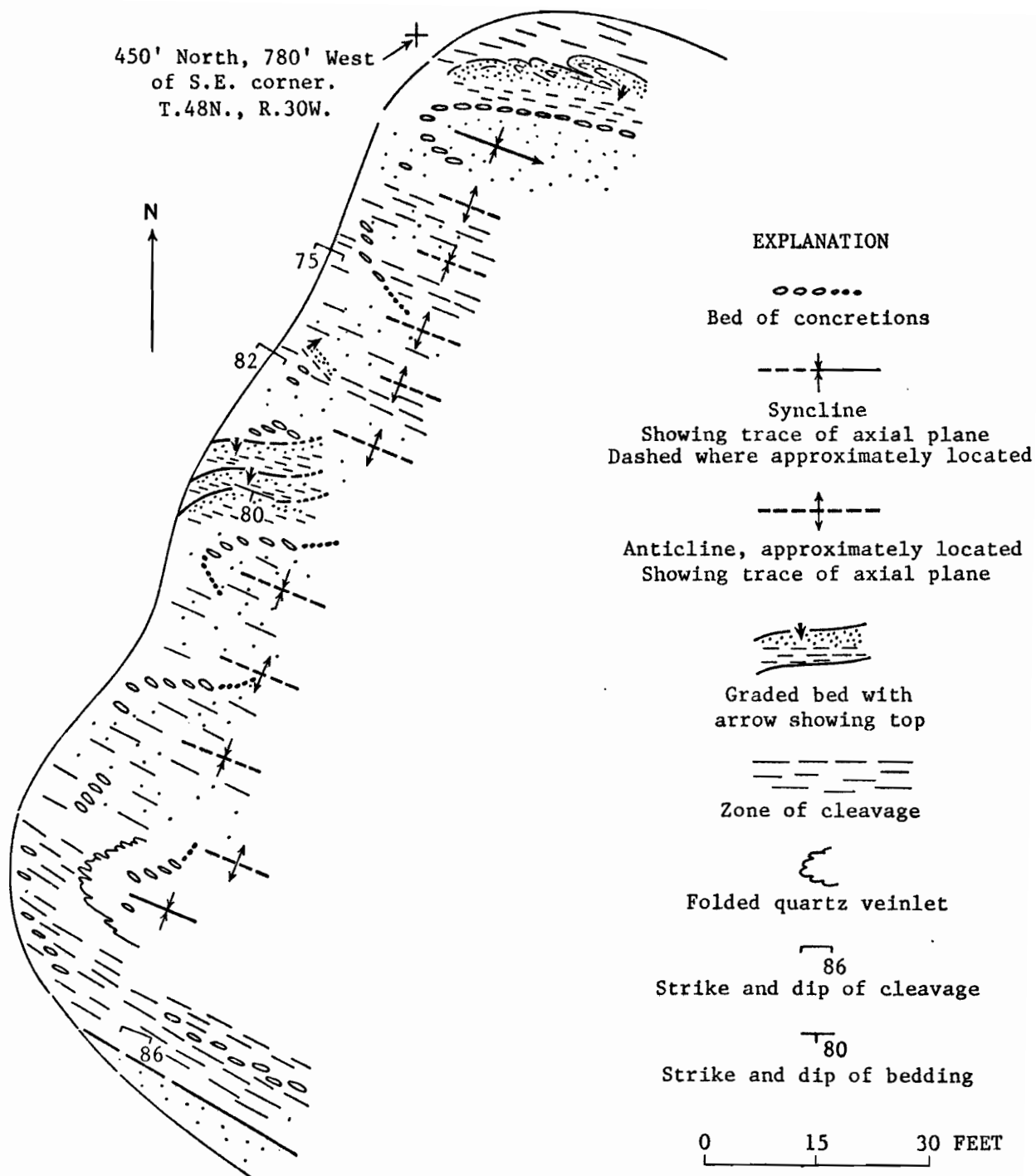


Figure 5.--Sketch map showing fold geometry in the Michigamme Formation on an island in Lake Michigamme sec. 28, T. 48 N., R. 30 W.

Both the Lake Michigamme and Taylor mine areas show a second (F_2) phase of deformation, in that slaty cleavage (S_1), resulting from the F_1 period of deformation, has been crinkle folded on certain outcrops. The attitude and orientation of the F_2 crenulations and associated fracture cleavage suggests that deformation was due to movement of the adjoining granitic complexes. Some minor folds, such as seen at Michigamme mine also relate to this phase of deformation.

A third phase of deformation (F_3) is indicated at both the Taylor mine and Lake Michigamme. Although evidence for this phase is sparse, at Lake Michigamme well-developed kink-banding affects F_1 foliation and fold axes and F_2 foliation and lineations.

It has been postulated above that the source for the second (F_2) phase of Penokean deformation is in the granitic complexes. What evidence is there in the western Marquette Range area to support this hypothesis? As previously noted, Precambrian W rocks in the southern complex have been cut by pre-Penokean mafic dikes, but these dikes were not folded during the Penokean orogenic cycle. Also, no evidence has been found in the northern complex that indicates that the Precambrian W rocks acquired a new structural fabric during Precambrian X time. Therefore it is concluded that Precambrian W granitic complexes behaved as rigid bodies during the Penokean orogeny and that they were not internally deformed by any of the Penokean tectonic events. The occurrence of shear zones between the rigid granitic bodies and the metasedimentary rocks, and abundant shearing in the mafic sills within the metasedimentary rocks, indicate movement between the Precambrian W granitic blocks and the Precambrian X sedimentary rocks. Upward movement of the granitic blocks is interpreted as being the cause of the second (F_2) stage of Penokean deformation.

The cause of the third (F_3) deformational phase is not clear. Evidence for this event is sparse, and it appears that the intensity of deformation was much weaker than the earlier F_1 and F_2 phases. The deformation may be related to continued or recurrent rise of the granitic blocks.

Recent work in the Michigamme area has disclosed a series of north-trending faults that extend from within the granitic complex into the metasedimentary rocks (fig. 2). The presence of these faults is indicated by shear zones within the granitic rocks and by offsets in the contact between the granitic and metasedimentary rocks. Aeromagnetic data north and south of Lake Michigamme support the presence of a fault that trends approximately N. 25° E. To the north, left-lateral offsets of magnetic lows associated with east-trending Keweenaw dikes suggests that faulting was active after the Penokean orogeny. This same fault is extended south along the southern arm of Lake Michigamme on the basis of intensely jointed zones on some of the islands. Also, an abrupt discontinuity in magnetic pattern south of Lake Michigamme indicates that the fault probably extends farther south along the western edge of the southern complex, as shown in figure 2.

Although this fault is in the staurolite zone of metamorphism, samples from the shear zone show metamorphic mineral assemblages no higher than the chlorite zone. Thus movement and shearing must have occurred after Penokean metamorphism.

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FIELD TRIP DESCRIPTIONS

Stops 1 - 13

Stop 1

Republic mine

The open pit at the Republic mine is developed in oxide-facies iron-formation which forms the uppermost stratigraphic horizon of the Negaunee Iron-Formation. The pit exposes a nearly complete cross section of the Republic syncline and is an excellent location at which to examine the stratigraphic relations of part of the Marquette Range Supergroup and the structural geology of the tightly infolded Republic syncline, as well as to see both the presently exploited taconite horizon and the hard ore bodies which were previously mined by underground operations. (See fig. 4 for the location of the pit relative to the syncline.)

The Republic syncline is a northwest-trending second-phase (F_2) fold, and all structures seen in the pit appear to relate to this phase. Earlier east-trending regional folds either never formed here or have been obliterated by the very intense second phase of folding. The pit is near the southeast end of the Republic syncline, and the U-shaped pit configuration reflects the northwest-plunging fold.

The ore zone, which consists of banded hematite and jasper with variable amounts of magnetite, is 400-500 feet thick on the keel of the fold, where it dips about 40° NW. It thins to less than 300 feet at the north end of the pit, where it is vertically dipping on the northeast limb of the syncline, and is only a few tens of feet thick at the west end of the pit, where much of the section has been eliminated by a fault bounding the southwest limb of the syncline.

The smaller scale structures are relatively simple where the rocks lie on the synclinal limbs, but the area under the little mined area near the center of the pit is extremely complex, being in broadest terms, a fault-breached anticline. Minor folds indicate that the syncline plunges about 45° NW.

The jaspilite ore zone is underlain by 50 feet, or less, of banded chert-magnetite iron-formation which is also ore-grade material. This is underlain by an amphibolite sill which forms the high vertical face in the north part of the pit. The rest of the iron-formation consists of cherty silicate-magnetite iron-formation, interlayered with amphibolite sills, and is a potential reserve of magnetic taconite.

The iron-formation is unconformably overlain by the Goodrich Quartzite. In the north half of the pit, the Goodrich is a relatively clean quartzose sediment with discontinuous zones, a few feet thick, of oligomictic iron-formation pebble conglomerate at the base. In the southwest part of the pit, however, it contains a thick lens of polymictic conglomerate at the base, which is as much as 300 feet thick. This material consists of pebble- to cobble-sized, angular to sub-angular clasts of hematitic iron-formation, jasper, and less commonly, quartzose and pelitic sedimentary rocks, and rounded fragments of vein quartz. The matrix is quartz, hematite, and sericite. The iron content is sufficient to make most of the conglomerate concentrating-grade taconite, and about a quarter of the total production comes from this material. The conglomerate grades upward into typical Goodrich Quartzite through a transition zone about 10 feet thick.

Bodies of high-grade hard ore, mostly coarse-grained magnetite and specularite, occur within about 50 feet of the Negaunee-Goodrich contact, especially where the contact has a relatively shallow dip near the keel of the fold. The association of hard ore with areas of low dip, or other potential structural traps, is common throughout the Marquette Range and probably reflects a concentration of hydrothermal fluids beneath the relatively impermeable Goodrich Quartzite.

Stops within the pit cannot be precisely described because of the constantly changing pit configuration. The features that will be examined are:

1. Basement boundary fault at the west end of the pit. Precambrian W granitic rocks are in fault contact with the Negaunee Iron-Formation along a high-angle reverse fault. The fault plane dips about 85° SW., and the Negaunee is overturned, dipping beneath the fault block. The granitic rocks are highly sheared and have a b-lineation with respect to the Republic syncline of 45°, N. 45° W. Sheared and crushed zones in the granitic rocks are mostly recrystallized and annealed, indicating that the faulting predates Penocean metamorphism. Some unannealed zones must be postmetamorphic. Bedding in the Negaunee appears structurally concordant with the fault contact, but 700-800 feet of stratigraphic section are faulted out between this exposure in the pit and the ridge just southeast of the pit.

2. Goodrich conglomerate. The conglomerate at the base of the Goodrich Quartzite occurs as a thick lens in the southwest part of the pit. Many of the fragments of sedimentary rocks appear to be locally derived, but the well-rounded vein quartz pebbles are probably derived from a deeply weathered Precambrian W basement.

The conglomerate is highly deformed and has prominent vertical cleavage (F₂), and the pebbles are elongate parallel to the synclinal axis.

Because of intense deformation, the original geometry of the body is obscure. It may be either a channel-fill deposit, delta, or alluvial fan. A similar conglomerate body in the Humboldt mine, about 7 miles north, clearly rests on little-eroded iron-formation, rather than within an eroded channel, and must be a fan or deltaic deposit.

3. Jaspilite. The major ore zone is composed of banded jasper-hematite iron-formation with variable amounts of magnetite and martite; it forms the upper horizon of the Negaunee Iron-Formation. Bedding is typically $\frac{1}{2}$ to 1 inch thick; most is wavy, the jasper being in lenticular or podiform masses. The hematite is medium- to coarse-grained specularite, generally aligned parallel to bedding. Magnetite is in euhedral grains disseminated in hematite layers and in places is partly or totally converted to martite. The Jasper is maroon to vermillion, and some thicker jasper layers have cores of gray chert. More rarely, the silica-rich beds are dominantly gray chert with thin mantles of jasper along the contact with hematitic layers.

This material yields about 35 percent weight recovery of iron by froth flotation.

4. Hard ore. Bodies of hard ore occur near the Negaunee-Goodrich contact. Although they are strata-bound in gross aspect, they are cross cutting in detail and clearly involve secondary enrichment of the primary oxide iron-formation.

The ore is polygenetic, consisting of 1) primary and (or) diagenetic hematite, which is deformed and metamorphosed, and 2) coarsely granular specularite and magnetite, which is undeformed and, in places, somewhat vuggy and porous. Associated with this material is brecciated iron-formation and ore, which is veined with quartz and dolomite. The ore also contains remnants of jasper layers which are, in part, converted to coarsely crystalline milky quartz, and, in general, bleached to white or gray chert.

Extensive bodies of hard ore occur only near the keel of the syncline, where the dips of the units are at a minimum, and probably reflect a trapping and concentrated flow of hydrothermal fluids beneath the Goodrich Quartzite.

The mineralogy, texture, structural position of the ore, and associated veins all indicate that the hard ore is, at least in part, the result of hydrothermal enrichment of primary iron-formation. The hydrothermal activity must postdate deformation and is probably associated with regional metamorphism.

5. Sheared amphibolite. Three major amphibolite sills occur in the Negaunee Iron-Formation, and several other bodies occur in the Goodrich Quartzite. These, in general, are massive or slightly schistose rocks containing hornblende, plagioclase, garnet, and quartz, with a variety of accessory minerals. In zones of more intense deformation, however, these rocks develop a prominent axial-plane slip cleavage (F_2) and undergo a drastic chemical alteration. This alteration, in which mafic components are lost and the rocks become progressively more siliceous and aluminous, ultimately results in quartz-muscovite-andalusite schist. The progressive nature of the alteration can be seen in continuous exposure over a few feet or a few tens of feet, in which the amphibolite passes into schist, some of which contains blocks of less altered amphibolite. The alteration must have occurred before the peak of metamorphism to allow andalusite to form in the altered rock. The alteration is clearly associated with zones of F_2 shearing and must have occurred either during F_2 deformation or in early stages of metamorphism.

Stop 2 Kloman mine. Outcrops are north of section line road, $\frac{1}{4}$ mile west of Republic and approximately 1,000 feet east, 50-100 feet north of southwest corner of sec. 6, T. 46 N., R. 29 W.

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 6. As a point of reference, the large steel eye bolt set into the outcrop corresponds to the horizon at 42 feet on the section.

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.

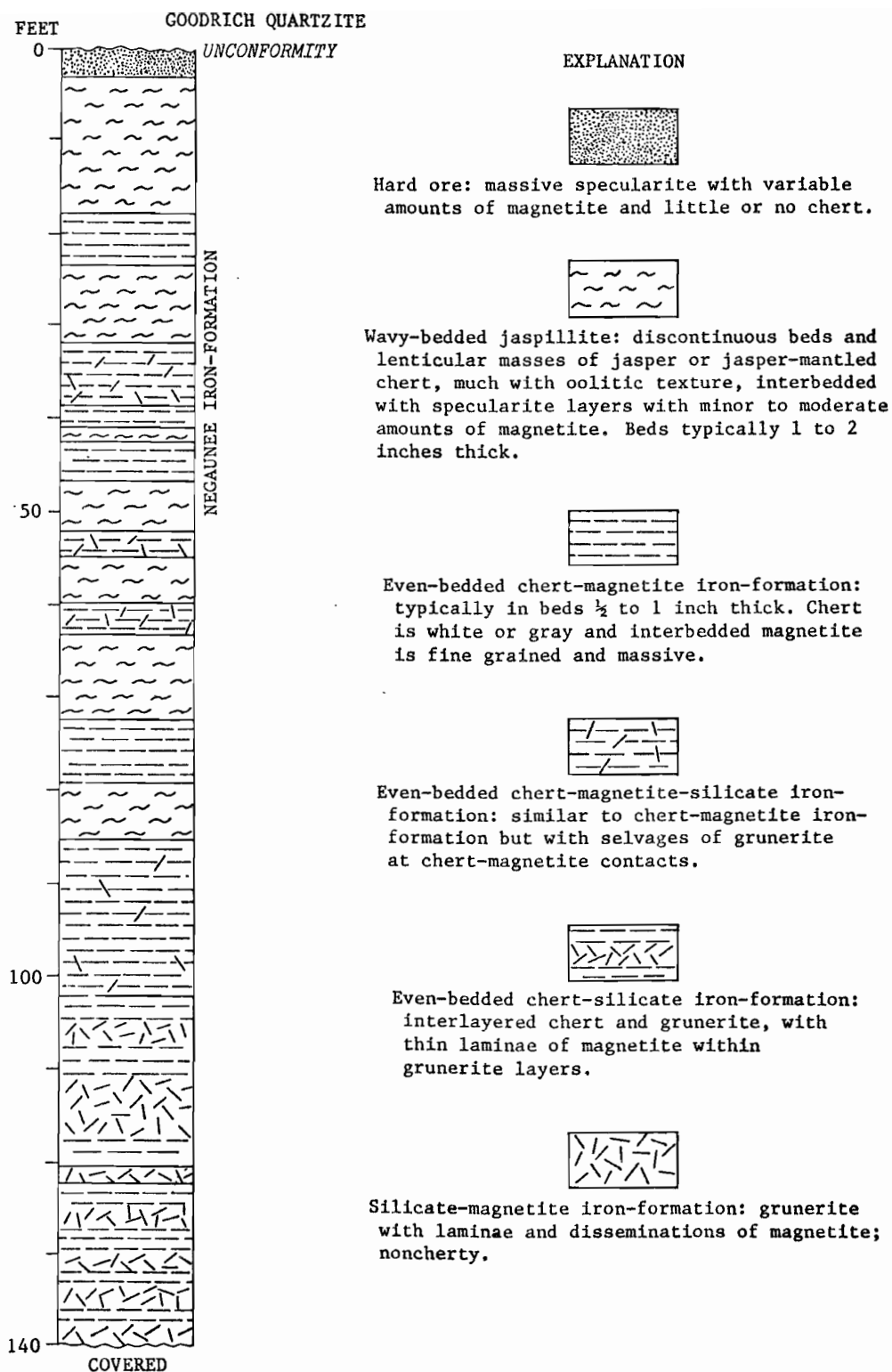


Figure 6 Stratigraphic Section of Negaunee Iron Formation near Kloman Mine, Republic, Michigan.

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 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 unoxxygenated water allowed the accumulation of ferrous iron minerals in uniform layers. If this is so, the rocks here indicate deposition in progressively shallower water with several fluctuations either in depth of water or depth of wave action to produce the inter-layering 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 with 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 buffered by the solid phases during metamorphism.

Stop 3 Michigamme Formation. Outcrop is on east side of Michigan Hwy. 95, approximately 1,000 feet south of bridge over Michigamme River, $\frac{1}{2}$ mile west of Republic.

Tightly folded schist of the Michigamme Formation is exposed near the axis of the Republic syncline. The Michigamme Formation here is mostly iron-rich meta-argillite, now consisting of biotite-garnet-amphibole (grunerite) schist containing a few inch-thick layers of impure quartzite. Although the rocks are in the sillimanite zone of metamorphism, sillimanite is not present because of the lack of appropriate aluminous compositions.

Minor folds with amplitudes much greater than wavelengths and greatly attenuated limbs are common and reflect the gross geometry of the major syncline, which has an amplitude greater than width at this point and achieves even greater amplitude to the northwest. The folding is markedly noncylindrical on outcrop scale, and domains of homogeneous strain are very small, being measurable in a few tens of square feet. Although most minor folds plunge northwest, in accordance with the regional F_2 Republic syncline, the plunge of minor folds varies from about 15° to 65° . The noncylindrical nature of the folding may be a reflection of earlier F_1 folds, but the intense F_2 folding has virtually obliterated any earlier structures.

Stop 4 Southern complex. Outcrops are on west side of Michigan Hwy. 95, just south of turnoff of old Hwy. 95 to Republic, approximately 1,200 feet west and 1,600 feet north of southeast corner of sec. 31, T. 47 N., R. 29 W.

Precambrian W rocks of the southern complex are exposed here, as well as mafic intrusive rocks of two younger ages. The rocks here illustrate some critical structural relationships pertinent to Penokean deformation.

The most abundant rock type in the southern complex is a coarsely porphyroblastic quartz monzonitic gneiss, which is well exposed at the northern and southern ends of the outcrop. The rocks near the center of the outcrop are finer grained and somewhat sheared granitic rocks.

The relations at the south end of the outcrop are sketched in figure 7, and illustrate the two major periods of orogeny which can be defined in the Precambrian of the Marquette Range.

The oldest rock is the granitic gneiss which was foliated and metamorphosed during a late Precambrian W orogeny. The northwest-trending foliation is truncated by the northeast-trending porphyritic metadiabase. The dike trends nearly parallel to the

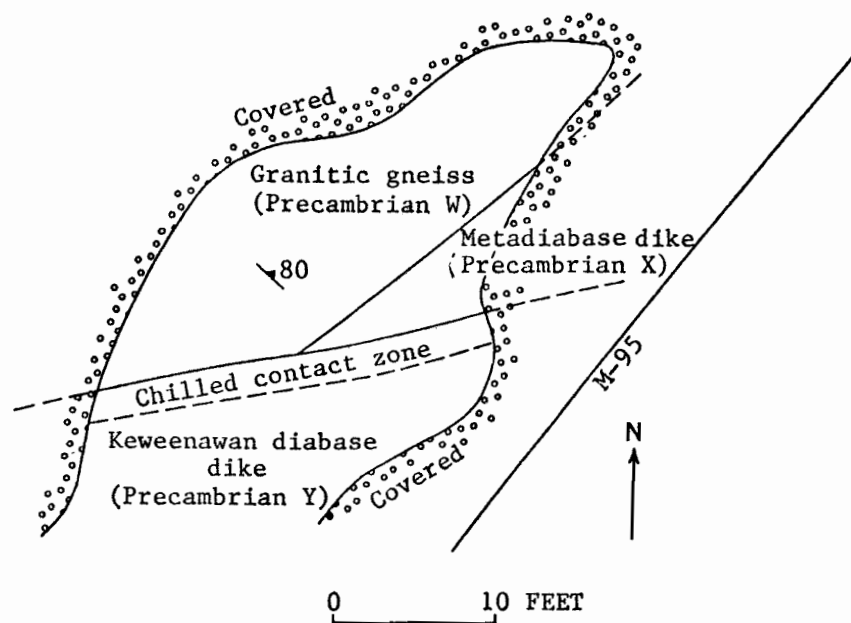


Figure 7.--Sketch map of part of an outcrop of the southern complex showing the relationship between Precambrian W granitic gneiss, a Precambrian X metadiabase dike, and a Keweenawan (Precambrian Y) diabase dike.

roadcut which exaggerates its true size. It is probably no more than a few tens of feet thick. Because this dike truncates the Precambrian W foliation but is massive and is metamorphosed by the Penokean metamorphism, it is of either very late Precambrian W or Precambrian X age. In either case, it predates the Penokean orogeny, but its massive texture and straight outcrop trace indicate that it was not deformed during Penokean deformation. The occurrence of such planar dikes of metadiabase at hundreds of localities throughout the southern complex is the prime evidence that the Precambrian W rocks were not penetratively deformed during the Penokean orogeny.

This northeast-trending dike is, in turn, truncated by an east-trending diabase dike, which has a chilled contact zone against both the metadiabase and granitic gneiss. It is virtually unmetamorphosed and therefore younger than the Penokean orogeny, and presumably of Keweenawan age. Many dikes of this aspect occur throughout the district and have reversed magnetic polarity. They probably correlate with lower Keweenawan volcanic rocks which are also reversely polarized.

Stop 5

Champion mine dump. The Champion mine waste dump is south of main street through Beacon, about 1 mile west of intersection with U.S. 41 at Champion.

The Champion mine (abandoned) recovered hard ore from upper horizons of the Negaunee Iron-Formation in underground operations. Although the rocks cannot be seen in outcrop here, many interesting specimens of ore and associated rocks are available on waste dumps. The mine is in the staurolite zone of metamorphism, and the ore consists of coarse-grained specularite and magnetite. The mineral assemblages and textures clearly indicate that hydrothermal activity was associated with formation of the ore. The fluids were probably of metamorphic origin, and this deposit is a good illustration of the effect of the concentration of such fluids in the iron-formation. The deposit has been studied in detail by L. Babcock who identified more than 80 minerals. A few of the more common and interesting minerals are:

Specularite. Some of the coarsest grained, foliated, and crenulated specularite ore in the Marquette Range occurs here. Specularite also occurs in quartz veins in crystals an inch or more in diameter.

Magnetite. Much of the ore is exceptionally coarse grained and nearly pure masses of magnetite.

Andalusite. Abundant and well-developed prophyroblasts of andalusite occur in micaceous quartzite units of the Goodrich Quartzite and in nearly pure hematite phases of the hard ore.

Garnet. Masses of garnet-rich rock are associated with massive pyrite and quartz. Some garnet is exceptionally manganese rich.

Tourmaline. Good crystals of black tourmaline occur mostly in sheared sericitic rocks which are probably highly altered mafic rocks.

Chloritoid. Exceptionally good crystals of chloritoid occur as plates or rosettes, generally associated with quartz veins.

Siderite. Siderite, with iridescent luster, occurs mostly associated with garnet- and sulfide-bearing quartz veins.

Stop 6 The outcrop is on the north side of U.S. 41, approximately 5.6 miles west of Champion. It is in sec. 21, T. 48N., R30W, approximately 2,300 feet south and 1,000 feet east of the northwest corner of the section.

This stop illustrates the lithology of the upper part of the Ajibik Quartzite which is the basal unit of the Precambrian X section in the western Marquette Range. The Ajibik is in contact with the granitic rocks of the northern complex (exposed in the steep scarp) approximately 150 feet north of this location. In this area the Ajibik is about 80 feet thick.

The presence of a reddish thinly banded ferruginous quartzite-argillite sequence at the east end of the outcrop marks the contact of the Ajibik Quartzite with the overlying Siamo Slate.

Massive Ajibik Quartzite composed of 90-95 percent quartz is found toward the west end of the outcrop. The subrounded grains range in size from 1 mm to approximately 10 mm. Undulatory extinction of the quartz grains indicates straining, possibly the result of Penokean deformation.

A thin fine-grained mafic dike intrudes the Ajibik near the center of the outcrop. It intersects the outcrop face at an acute angle, making it appear thicker than it actually is. Near the dike-quartzite contact, the dike is intensely sheared, and slivers of quartzite have been caught up in the mafic material. This shearing in the mafic material is common in the area and is interpreted as being due to faulting associated with the second (F_2) stage of deformation.

Stop 7 The outcrop is on the north side of U.S. 41, approximately 6.4 miles west of Champion. It is in sec. 20, T. 48 N., R. 30 W., approximately 3,000 feet south and 16,000 feet east of the northwest corner of the section.

This stop illustrates the lithologic character of the Siamo Slate in this area. Throughout the Marquette trough, the Siamo shows a variable lithology, ranging from a slate in the eastern part of the trough to a feldspathic graywacke and dirty quartzite in the western part of the trough. At this outcrop the Siamo is a dark-gray thinly layered graywacke. Angular grains of quartz, minor feldspar, and minor lithic fragments are set in a pelitic matrix. The thin (a few hundredths of an inch to 1 inch) layering is caused by alternation of pelitic layers and more psammitic layers.

At this location the Siamo is tightly folded. The plunge and orientation of the fold axis, based on an estimate from a β diagram, is 20° of plunge toward S. 76° E. Another fold-axis measurement in this area gives 20° plunge toward N. 80° W., indicating noncylindrical folding.

Definite identification of time of folding is not possible. However, these folds are suspected to be F_2 in age because folds found less than 1 mile away at stop 8B, in the same structural position in the Goodrich Quartzite, are clearly F_2 , related to the uplift of the granitic blocks about $\frac{1}{4}$ mile to the north.

Evidence is also found at this outcrop for possible soft-sediment deformation. On the slumped block at the crest of the anticline, slightly west of the center of the outcrop zone, the more pelitic beds are injected into fractures in the psammitic material. These injected zones are at a high angle to bedding and are approximately parallel to the axial-plane cleavage of the fold. This suggests that the pelitic material was still relatively incompetent during folding.

Near the east end of the outcrop zone, a $1\text{--}1\frac{1}{2}$ -inch white calc-silicate bed has numerous randomly oriented amphibole porphyroblasts, indicating that the Penokean thermal metamorphic event occurred after the Penokean deformational events.

Stop 8A Michigamme mine waste dump, 100-200 feet north of U.S. 41, $\frac{1}{2}$ mile east of Michigamme village.

The Michigamme mine was active from 1872-1905 and produced nearly 1 million tons of hard ore from the upper 20 feet of the Negaunee Iron-Formation. The waste dump is well known for exceptionally large specimens of garnet and chloritoid.

The garnet occurs in altered mafic rocks in the iron-formation, which now consist of a quartz-chlorite-magnetite matrix with garnet porphyroblasts as much as about 3 inches in diameter. Most garnets are euhedral but can be extracted from the matrix only with difficulty. In places the garnet has been retrograded

and consists of pseudomorphs of pale-green chlorite. Some of the mafic rocks also contain rosettes and blades of grunerite as much as about an inch long and half-inch octahedra of magnetite. These rocks occur either as thin stringers intercalated with the iron-formation, or as border zones, a foot or two thick on larger mafic bodies. Their rather unusual composition apparently results from chemical interchange between the iron-formation and intrusive rocks either during emplacement or during later regional metamorphism.

Chloritoid occurs in chlorite-rich rocks, which are probably also altered mafic intrusive rocks, and in impure quartzite phases of the Goodrich Quartzite. The chloritoid is present as randomly oriented platy porphyroblasts as much as about 2 inches in diameter.

Stop 8B Negaunee Iron-Formation - Goodrich Quartzite. This outcrop is at the west end of the Michigamme mine on a haul road, cut south from the mine through the lower part of the Goodrich Quartzite. It is in sec. 19, T. 48 N., R. 30 W., approximately 1,300 feet west and 3,800 feet south of the northeast corner of the section.

The purpose of this stop is to show the lithology of the Negaunee Iron-Formation and the Goodrich Quartzite and associated F_2 structures.

The iron-formation in the mine is a banded hematitic jaspilite. Quirke (1953) described the iron-formation in this area as a "hard, hematitic, magnetitic, gruneritic, cherty iron formation, thin to medium banded with regular to brecciated bands." Toward the hanging wall the grunerite disappears. Toward the footwall Siamo contact the iron-formation grades into thinly banded gruneritic unoxidized iron-formation, which, in turn, grades into the underlying graywacke. The ore zone is massive magnetite or specular hematite with thin bands of chert.

Figure 8 is a sketch of the east wall of the cut through the Goodrich. It illustrates the sequence of bedding, some of the lithology and mineralogy of the Goodrich, and the style of folding in the Goodrich. In this exposure there is no evidence for an unconformity between the Goodrich and the Negaunee Iron-Formation.

Minor folds in the Goodrich Quartzite are approximately 5 feet in amplitude, have a wavelength of 10 to 15 feet, and are asymmetrical, the long limb facing south. These are interpreted as being associated with the compression accompanying

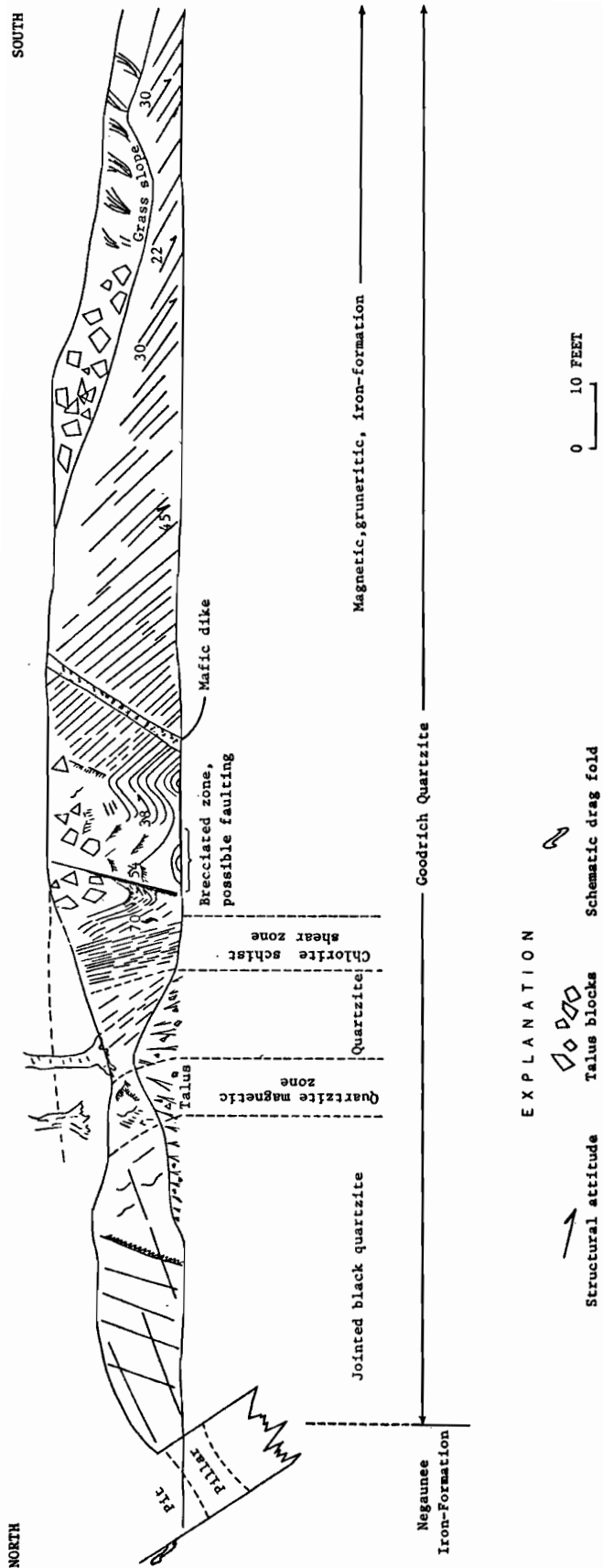


Figure 8.--Sketch of haul road, cut in Negaunee Iron-Formation and Goodrich Quartzite showing lithologic units and structures. West end of Michigamme mine, sec. 19, T. 48 N., R. 30 W.

the uplift of the granitic rocks of the northern complex which are approximately 1,800 feet to the north. The shape and orientation of these folds as well as smaller scale folds in the Negaunee Iron-Formation fit the model for the second-stage (F_2) folding. That is, the meta-sedimentary rocks have been tilted and folded to a steep south-dipping (45° to 60°) orientation during the F_2 deformation. The axis of the regional syncline is to the south under Lake Michigamme, as indicated by the orientation of the minor folds.

Stop 9 Outcrops are about $2\frac{1}{2}$ miles southwest of the village of Michigamme, 200-300 feet east of section line road about 0.1 mile south of northeast corner of sec. 1, T. 47 N., R. 31 W.

The rocks here are part of the Michigamme Formation. They are above the Bijiki Iron-Formation Member, which crops out about 2 miles north. Although there is no gross repetition of the stratigraphy due to folding, the apparent thickness of this unit is much greater than true thickness as the result of small-scale folding, such as seen at this outcrop. These rocks are typical of a thick and monotonous graywacke-shale sequence which underlies hundreds of square miles west and south of here. The stratigraphic thickness of this unit is totally unknown, but it is steeply dipping over most of its extent, and its thickness is probably measurable in miles.

The structure here consists of tight F_1 folds with nearly east-trending axes and prominent F_1 axial-plane schistosity. The folding is clearly shown by a staurolite-rich bed about 6 inches thick, which is repeated by folds several times across the outcrop. This outcrop was several miles from the nearest active basement block during deformation and was, therefore, unaffected by F_2 basement-controlled deformation.

The outcrop is in the staurolite zone and contains abundant porphyroblasts of staurolite as much as about 1 inch long. They coexist with biotite and garnet. The staurolite porphyroblasts are highly poikilitic but are extraordinarily fresh. Most show virtually no alteration, but a few show a thin selvage of white mica in thin section. The random orientation and undeformed nature of these porphyroblasts suggests that the metamorphism culminated under static conditions.

Stop 10 The outcrop is on the north side of the section line road that runs generally east-west, just south of the west end of Lake Michigamme. It is in sec. 30, T. 48 N., R. 30 W., approximately 250 feet east and less than 50 feet north of southwest corner of the section.

This stop illustrates the deformation history of the area, in that evidence for all three phases of folding (F_1 , F_2 , and F_3) can be seen. Table 1 tabulates the deformational history in the Lake Michigamme area. Please refer to this while reading the following comments and while studying the outcrop.

The rock is sericitic, chloritic, quartz-rich phyllite. The dominant foliation is S_1 which strikes approximately N. 70° W. and has nearly vertical dips. Evidence for bedding (S_0) is poor in this outcrop, but good cleavage-bedding relationships can be seen on several similar outcrops in the area. This S_1 foliation is evidence for the first regional (F_1) phase of deformation. On this outcrop, however, the S_1 foliation has been subjected to a second, F_2 , phase of deformation. The S_1 foliation has been crinkle folded, creating S_2 axial-plane fracture cleavage and lineations, L_2 , due to intersection of the axial planes of the crinkle folds with the S_1 foliation surfaces. The L_2 lineations are nearly flat because the strike of S_1 and S_2 are nearly the same. Evidence for the third, F_3 , phase of folding can be seen in the southeast corner of the outcrop. Here a kink band (S_3), approximately 3-5 inches thick has affected all prior structural fabric elements. Changes in orientation of S_1 , S_2 , and L_2 can be seen as they intersect the kink band.

The following explains the alpha-numerical symbols used in the above discussions:

	S_0 - bedding
F_1 - first regional phase of folding	S_1 - foliation plane created by first phase of folding
F_2 - second local phase of folding	S_2 - fracture cleavage due to second phase of folding
	L_2 - lineations due to intersections of second phase
F_3 - third local phase of folding	S_3 - kink-bands or kink-planes associated with the third phase of deformation.

Stop 11 Goodrich Quartzite. This outcrop is on the north side of U.S. 41, approximately 1.2 miles west of the village of Michigamme. It is in sec. 24, T. 48 N., R. 31 W., approximately on the north-south section line between sections 24 and 23.

The purpose of this stop is to study a series of large trough-shaped crossbeds that have the same orientation as the folds in the area.

The Goodrich Quartzite at this location is composed of a polymictic conglomerate containing subrounded to rounded pebbles of black chert, white quartz, and banded iron-formation. Overlying the conglomerate is a dark-gray to black dirty quartzite or metagraywacke.

The troughs or scoops in the conglomerate have been filled in by graywacke, the bedding becoming flatter near the top of the trough. The troughs are approximately 1 to 1½ feet deep and are 2 to 3 feet apart. The fact that the troughs are superposed, lower troughs being truncated by overlying ones, identifies these features as being sedimentary in origin, rather than resulting from folding.

Stop 12

Quartzites at the Sturgeon River. The outcrops are along the Sturgeon River west of U.S. 41, approximately 1.4 miles south of Alberta. Stop at the Sturgeon River bridge on U.S. 41 and follow the trail on the north side of the river approximately ¼ to ½ mile west. The Sturgeon River flows on the bedding of the quartzites and forms a falls in sec. 30, T. 49 N., R. 33 W., approximately 600 feet east of the north-west corner of the section.

This stop illustrates an anomalous structural style in that the rocks are relatively nonfolded as compared with the deformational style in the nearby Precambrian X metasedimentary rocks. Here the quartzites, composed of quartz grains in a clay matrix with chlorite porphyroblasts, show very gentle N. 70° W.-trending monoclinial folds. Ripple marks and "sole marks" are common on bedding surfaces. The more argillaceous layers show the development of N. 70° W.-trending cleavage. The presence of this cleavage plus the presence of porphyroblasts indicate that these rocks are older than the Penokean orogeny and are of Precambrian X age. Their exact correlation with the Precambrian X section is uncertain, but in many respects they bear close resemblance to the graywacke-shale sequence of the upper parts of the Michigamme Formation.

These strata are approximately 2 miles west of the western extremity of the northern complex (fig. 2). Their undeformed condition (lack of S₂ and S₃ fabric elements and gently dipping bedding) may be due to the granitic rocks of the northern complex which may plunge gently beneath the quartzites, forming a solid floor which protected the quartzites from F₂ and F₃ deformation and prevented the formation of S₂ and S₃ fabric elements.

Stop 13 Taylor mine. Taylor mine is approximately 1,700 feet east of the northwest corner of sec. 9, T. 49 N., R. 33 W. The outcrops that will be examined are on a north-south-oriented railroad grade between sections 4 and 9. The area is approximately $2\frac{1}{2}$ miles northeast of Alberta, just off the old U.S. 41.

The purpose of the stop is twofold: 1) to observe the styles of deformation associated with the Penokean orogeny, and 2) to visit a locality that is the source of numerous museum-grade specimens of pyrolusite.

Differing styles of folding in the two predominant rock types, graphitic slate and cherty iron-formation, both a part of the Michigamme Formation, are illustrated in figure 9, and those parts that will be visited are marked on the illustration.

At A (fig. 9), slaty S_1 cleavage has formed in graphitic slate. The slate is relatively homogeneous in composition, and the style of deformation is uniform throughout the stratigraphic unit. Intense folding, accomplished by passive slip along the penetrative planes of cleavage, has transposed the bedding parallel to the cleavage. Bedding-cleavage relationships, rarely found in the graphitic slates in other areas, are illustrated by a small isoclinally folded psammitic layer.

At B (fig. 9) is a fresh, reversely polarized magnetic Keweenaw diabase dike. The dike is approximately 25 feet thick and dips steeply north. Because of their reversed magnetic polarization, the large Keweenaw dikes can be easily traced on aerial magnetic maps. They trend generally east, intrude Precambrian W and X rocks, and show no effects of the Penokean thermal metamorphic event.

At C, a 6-foot-high anticline in the cherty iron-formation shows a style of deformation that differs from that described above in the graphitic slate. The lithology, consisting of alternating layers of chert and minor amounts of iron-rich pelitic and cherty layers cause the cherty iron-formation to deform in quasiflexural manner. Evidence for flow can be seen in the thickening of the cherty layers in the axial region relative to the limbs of the fold. Also, crushed zones along the edges of some of the cherty layers indicate some slip movement between layers. The more pelitic layers possessed much higher ductility than the cherty layers, so, on close examination, the fold shows a disharmonic aspect and fits Donath and Parker's (1964) quasiflexural style of deformation.

At D, a small pit has been blasted in the cherty iron-formation to exposure pyrolusite. This mineral occurs as large (commonly larger than 1 inch in diameter) radiating crystals that are generally coated with a dark-brown stain, possibly psilomelane. The pyrolusite occurs along with botryoidal goethite, manganite, limonite, and drusy quartz in fractures and openings that are generally parallel to bedding.

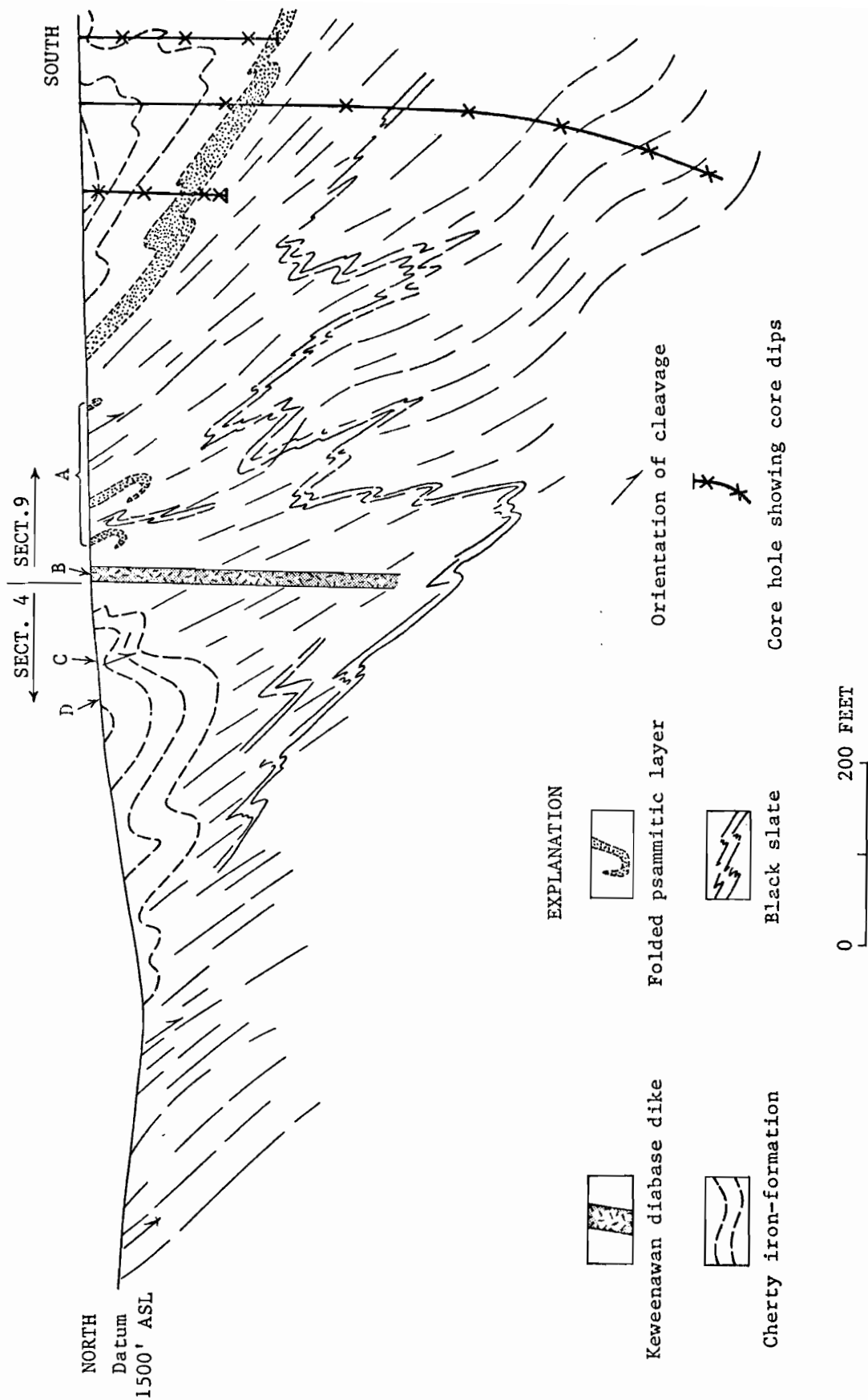


Figure 9.--Cross section of Taylor mine area showing style of folding. Line of section is north-south and 1,800 feet east of west line of secs. 4 and 9, T. 49 N., R. 33 W. Diamond-drill-hole data provided by Ford Motor Company.

Road Log

Mileage

- 0.0 Depart Mather Inn, Ishpeming, and proceed west and north on Euclid St.
- 0.8 0.8 Turn left (west) on U.S. 41
- 11.0 11.8 Abandoned pit and waste dump of Humboldt mine can be seen south of the highway.
- 1.1 12.9 Turn left (south) at blinker light onto Michigan Hwy. 95.
- From 14.4 to 18.8, abundant roadcuts through Precambrian W gneissic rocks of the southern complex. Many metadiabase dikes of Precambrian X age can be seen cutting vertically through the granitic gneiss.
- 5.9 18.8 Turn left onto old Highway 95 toward Republic.
- 1.3 20.1 Turn left at stop sign in Republic village and proceed to entrance of Republic mine.
- 0.9 21.0 Stop 1. Republic mine.
From mine, retrace route to stop sign in Republic.
- 0.9 21.9 Turn left at stop sign, then immediately right. Cross bridge over Michigamme River.
- 1.5 23.4 Stop 2. Kloman mine. Outcrop north of fenced area north of road.
- From Kloman mine, proceed west to intersection of Michigan Highway 95.
- 0.5 23.9 Turn left (south) of Highway 95.
- 0.1 24.0 Stop 3. Michigamme Formation in roadcut on east side of highway.
- U-turn, and head north on Highway 95.
- 1.3 25.3 Stop 4. Rocks of the southern complex exposed in roadcut on west side of highway.
- Continue north on Highway 95.

- 5.9 31.2 Intersection of Highway 95 and U.S. 41. Turn left (west) on U.S. 41, and proceed to Champion.
- 2.8 34.0 Turn left at blinker light in Champion and proceed to Champion mine.
- 1.0 35.0 Stop 5. Champion mine waste dumps south of road. Retrace route to blinker light at intersection with U.S. 41.
- 1.0 36.0 Turn left at blinker light onto U.S. 41.
- 5.5 41.5 Stop 6. Ajibik Quartzite in roadcut north side of U.S. 41.
Continue west on U.S. 41.
- 1.0 42.5 Stop 7. Siamo Slate in roadcut on north side of U.S. 41.
Continue west on U.S. 41
- 0.2 42.7 Stop 8. Michigamme mine on hillside north of U.S. 41.
Continue west on U.S. 41. Stop 8 B is approximately 800 ft west of stop along road and 500 ft north from road.
- 1.9 44.6 Turn left (south) onto County Road.
- 2.0 45.6 Turn left (east) onto gravel road.
- 0.3 46.9 Bear right and continue straight south.
- 0.9 47.8 Stop 9. Outcrops of Michigamme Formation in field east of road.
U-turn and proceed north.
- 0.6 48.4 Turn right.
- 0.2 48.6 Bear left.
- 0.2 48.8 Bear right.
- 0.2 49.0 Turn left.
- 0.3 49.3 Turn right and, with a little luck, stop 10 is 0.5 mile straight ahead.
- 0.5 49.8 Stop 10. Michigamme Formation.
U-turn and retrace route to U.S. 41.
- 4.0 53.8 Turn left (west) on U.S. 41.

0.7 54.5 Stop 11. Goodrich Quartzite in roadcut on north side of U.S. 41.

Continue west and north on U.S. 41

19.4 73.9 Stop 12. Roadside picnic area west of U.S. 41, just north of bridge over Sturgeon River. Walk west, along trail down Sturgeon River, about 0.5 mile to Canyon Falls.

Continue northwest on U.S. 41

1.8 75.7 Turn right onto gravel road.

1.8 77.5 Stop 13. Taylor mine. Walk up trail east from road.
End of field trip.

1.8 79.3 Turn right (north) on U.S. 41 and proceed to Houghton.