This restricted southern limit could be best explained by a thinning towards the source area and a pinch-out at the shoreline which extended through the center of the Northern Peninsula. This would imply a southeastern source and the advancement of the seas from the northwest, as previously adduced.

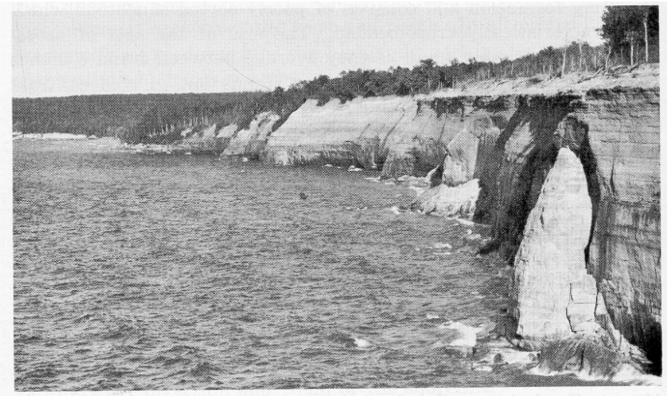

Figure 56. View of the eastern part of the Pictured Rocks cliffs which are composed almost entirely of the Miner's Castle member.

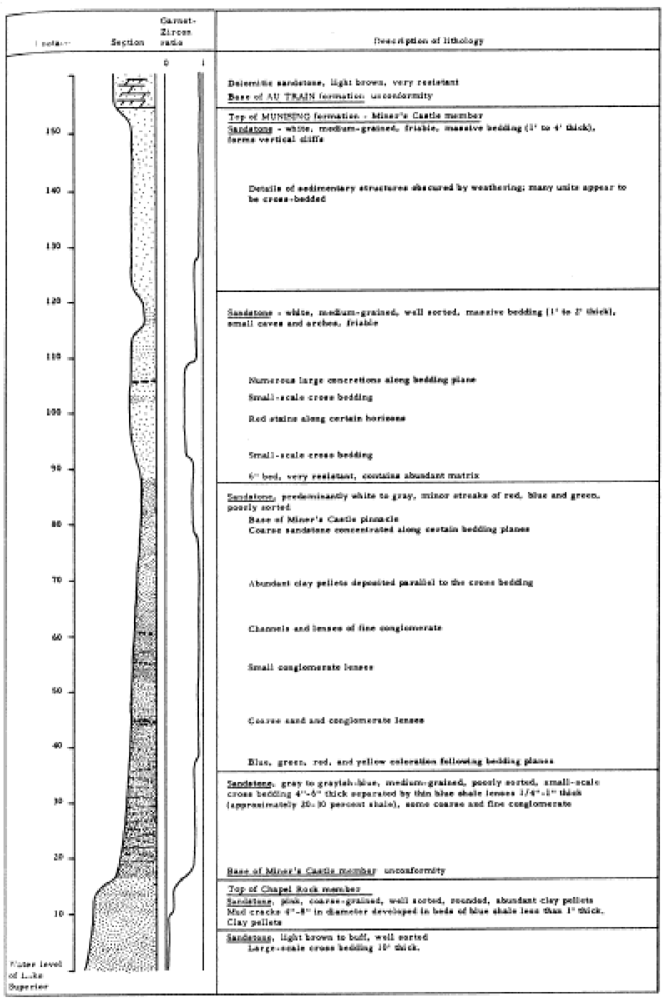

Figure 57. Columnar section of the Munising formation, Miner's Castle, NW ¼, SW ¼ sec. 3, T. 47 N., R. 18 W., Alger County, Michigan.

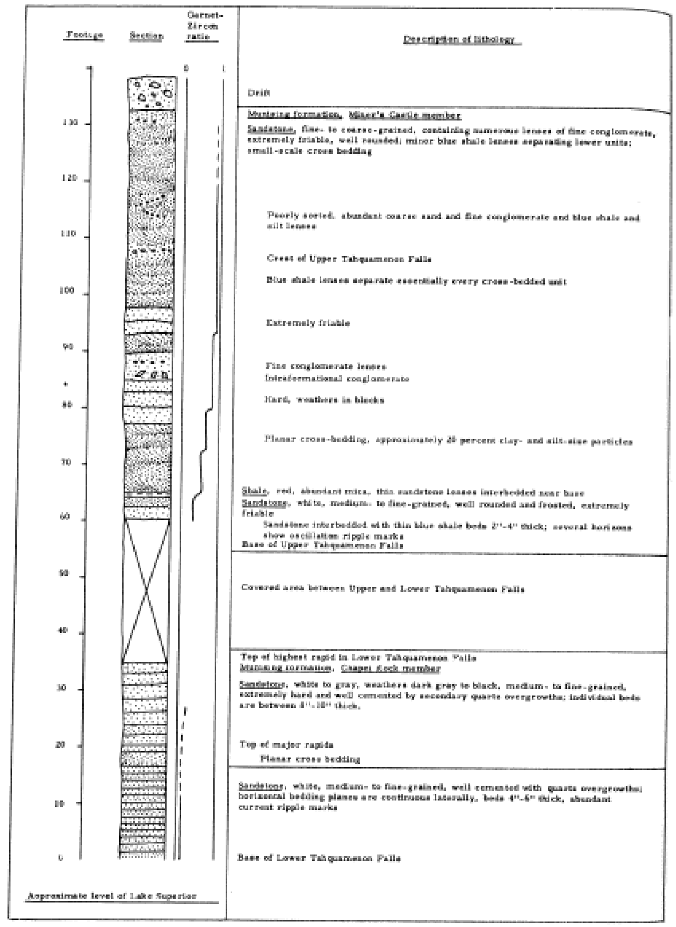

Figure 58. Columnar section of the Munising formation, Upper and Lower Tahquamenon Falls, Chippewa and Luce Counties, Michigan.

Figure 59. Laughing Whitefish Falls, Alger County, Michigan. An excellent example of the numerous waterfalls developed throughout Alger County, where the north-flowing streams across the cuesta developed on the resistant Au Train formation. Except for a thin cap rock of Au Train the entire exposed section is the Miner's Castle member. Note the thin irregular bedding developed by interbedded small-scale cross-laminated units and thin shale lenses.

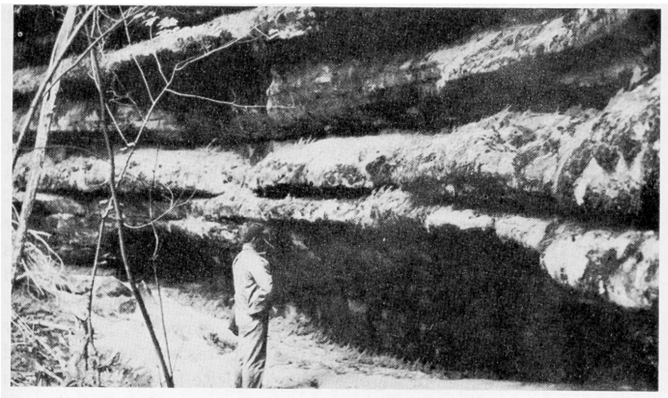

Figure 60. Outcrop of the upper Miner's Castle member in the Silver Creek valley. This outcrop is typical of the type of exposure developed high in the stream valleys just below the protective Au Train formation. Note the small caves developed along the bedding planes by weathering.

MINER'S CASTLE MEMBER

The Miner's Castle member constitutes the upper 140 feet of the Munising formation and consists of poorly sorted sandstone which is characteristically cross-bedded. The size of the sets of cross-strata is remarkably small as they average between 4 and 6 inches thick. This small-scale cross-bedding stands out in bold contrast to the large-scale cross-bedding of the Chapel Rock member and in most outcrops it is sufficient to distinguish the two members. Thin lenses of blue shale nearly everywhere separate the sets of cross-strata in the lower part of the section but most of the upper units are pure sandstone and the sorting is much better. Excellent exposures of the complete section are found at Miner's Castle which is selected as the type locality (figs. 55, 57).

The characteristic lithology of the Miner's Castle member, which can be traced throughout the entire outcrop belt of the Munising formation, shows only minor lateral variations. The entire section is exposed in the vertical walls of the Pictured Rocks between Sand Point and Miner's Castle, a distance of more than 6 miles. East of Miner's Castle is a well-defined western component dip so that the lower Chapel Rock member constitutes most of the section exposed in the Pictured Rocks cliffs and only the lower part of the Miner's Castle member is exposed. Practically all of the Miner's Castle section is exposed at Tahquamenon Falls (fig. 58) and in the bluffs behind Grand Marais. Westward, at least the upper part of this member is exposed in all the major falls in Alger County and in numerous minor falls not shown on the map (figs. 59, 60). The distinctive lithology can also be recognized in all the rock cores drilled in Alger, Dickinson, Delta, and Menominee counties and in most of the outcrops in Dickinson County (Plate 4). Thus the Miner's Castle member is the most widespread unit of the Munising formation.

At the type locality and throughout most of the exposures in the Pictured Rocks, the Miner's Castle member is 140 feet thick. Some slight thinning is indicated to the east and west of Pictured Rocks. Thinning southward over the Northern Michigan Highland (fig. 30) is definite.

COMPOSITION

Quartz grains constitute over 95 percent of the Miner's Castle member, but minor amounts of feldspar were found in most samples studied. Chemical analysis by Bergquist (1937) indicates that thoughout Alger County silica occurs in the Miner's Castle member in amounts exceeding 98 percent. Most of the sand grains are considered to be igneous quartz, but chert fragments and quartzite grains are also common. Differential thermal analysis of the silt and shale lenses indicates that only minor amounts of clay minerals are in those units.

Authigenic quartz surrounding detrital grains is a common feature in the Miner's Castle member but the degree of secondary overgrowths differs considerably from place to place. In most samples only slight secondary enlargement of the detrital grains can be detected. Without much secondary quartz, which is the major cementing agent, the rock remains porous and friable. In a few areas in Dickinson County, however, authigenic quartz constitutes an appreciable amount of the quartz as it fills all the interstices and produces a very hard orthoquartzite. This extreme degree of secondary overgrowths is a local phenomenon, however, since many beds in the same section as the orthoquartzites are as friable and weak as the sandstone in Alger County. Calcite is also abundant in some beds, but is not widespread and is not considered an important cementing material. Authigenic pyrite is common in the middle of the Miner's Castle member and in some strata it is in sufficient amount to be easily recognized in a hand specimen.

HEAVY MINERALS

Heavy minerals constitute between 1 and 2 percent by weight of the Miner's Castle member. The assemblage is very simple but highly characteristic and therefore it can be readily distinguished from the Chapel Rock member or the Jacobsville formation (compare figs. 5, 43, 61). The distinction is due to the abundance of garnet which constitutes 45 percent of the heavies near the base of the section and increases upward to nearly 100 percent near the top. The garnet is colorless to dark pink grains with surface features which resemble crystal faces. Few, if any, of the grains show any rounding or effects of abrasion. Instead numerous rectangular patterns aligned steplike completely cover many grains and give an extremely angular aspect (fig. 62). Many of the smaller grains have only a few large faces which approach a dodechedral pattern. Such angular grains in the samples in which all other minerals are extremely well-rounded indicate that the faces are authigenic.

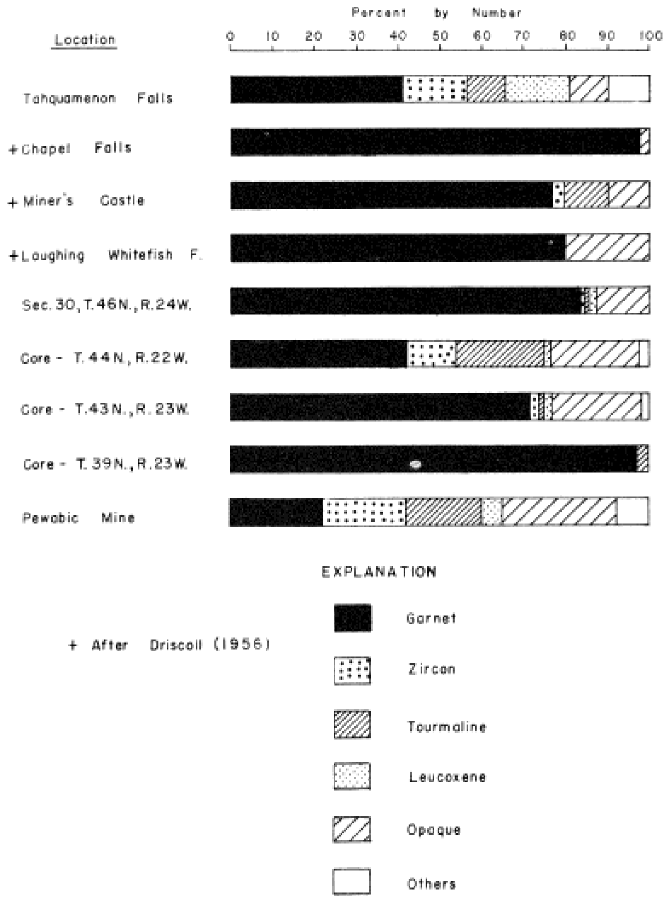

Figure 61. Heavy minerals of the Miner’s Castle member.

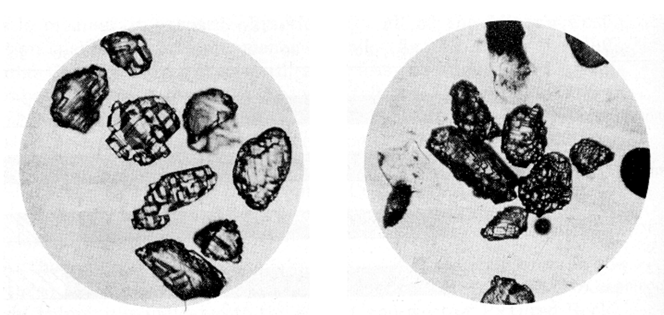

Figure 62, *A*

Garnet grains from the Miner’s Castle member. Sample from drill-hole core from Dickinson County. X65.

Figure 62, *B*

Garnet grains from the Miner’s Castle member. Sample from drill-hole core from Alger County. X63.

Figure 62. Garnet from the Miner’s Castle member.

Bramlette (1929, p. 336-337) describes a similar feature on garnets from Venezuela and attributes it to an etching by alkaline solutions since he found no tendency for development of crystal faces on the samples he studied. From the appearance of several dodechedral faces on many of the garnet grains in the Miner's Castle member, it is quite possible that these faces result from secondary overgrowths, although most of the surface features are probably the result of etching.

In addition to opaque minerals which constitute between 5 and 35 percent of the heavy minerals, zircon, tourmaline, and rutile are generally present in small amounts. The characteristics of these minerals are similar to the same heavy minerals of the Chapel Rock member.

The percentage of garnet in the Miner's Castle member differs but slightly throughout the entire Northern Peninsula of Michigan. The greatest variation is an increase in garnet vertically in the section; consequently, it is possible to estimate with fair certainty the position in the section by the percentage of garnet.

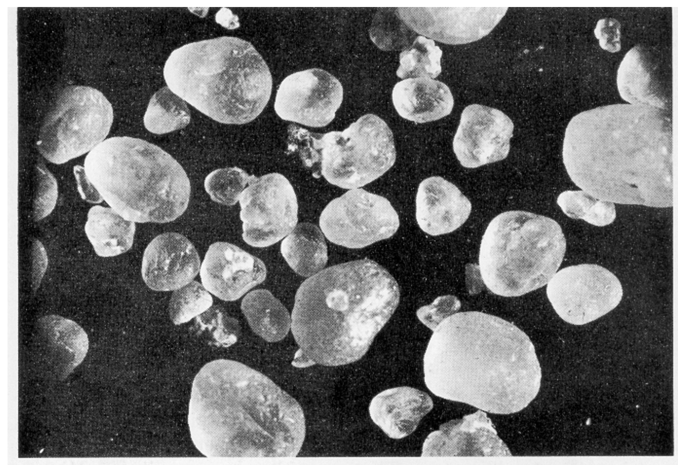

Figure 63. Photomicrograph showing the surface features, size, and sorting of a sample of the Miner's Castle member. Sample taken at Chapel Falls. X10.

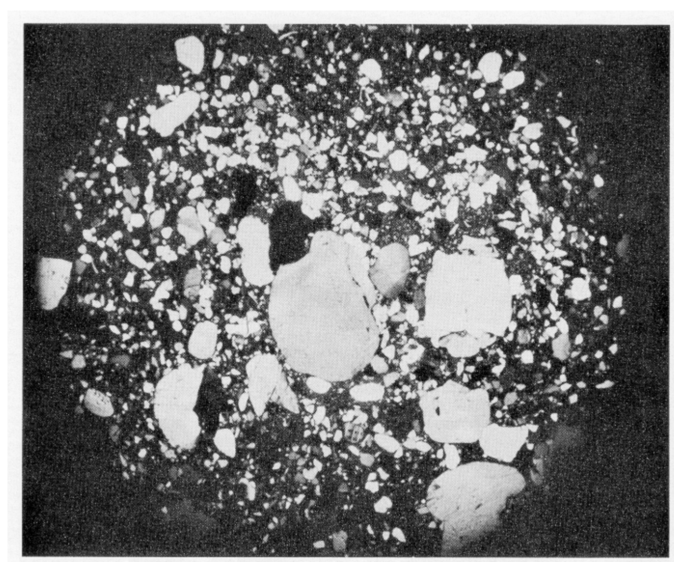

Figure 64. Photomicrograph showing poor sorting and abundance of fine angular grains in the Miner’s Castle member. Sample taken from Miner’s Castle. Crossed nicols. X33.

TEXTURE

The grain size of the Miner's Castle member ranges from that of fine conglomerate to silt and shale (figs. 63, 64). This extreme range in size is primarily between sedimentary units. It is very common to find a medium- to fine-grained cross-bedded unit 4 to 6 inches thick overlain by a shale lens 1 inch thick, which in turn is overlain by a cross-bedded unit 4 inches thick in which coarse sand to fine conglomerate sizes predominate. Many of the individual sedimentary units, however, have a range in grain size from silt to fine conglomerate. Coarse sand and fine conglomerate are concentrated near the base of most cross-laminations and in places even constitute the predominant grain size in several laminae of an otherwise medium- to fine-grained unit. The average grain size of most of the samples analyzed by the writer is from ¼ to ½ millimeter in diameter, which agrees with the measurements obtained by Dnscoll (1956) (fig. 65). Some samples, however have an average grain size of less than ⅛ millimeter and others are greater than 1 millimeter. Thus, considered as a unit, the Miner's Castle member is very poorly sorted. The sorting of the individual sets of cross-strata is somewhat better, but poor sorting is characteristic even within the smaller units.

Sorting is much better in the upper part of the Miner's Castle member which is relatively free from shale and conglomerate. Most of the sand grains are well rounded, but the degree of rounding decreases rapidly with size decrease; therefore the fine sands and silts are characteristically subangular to angular.

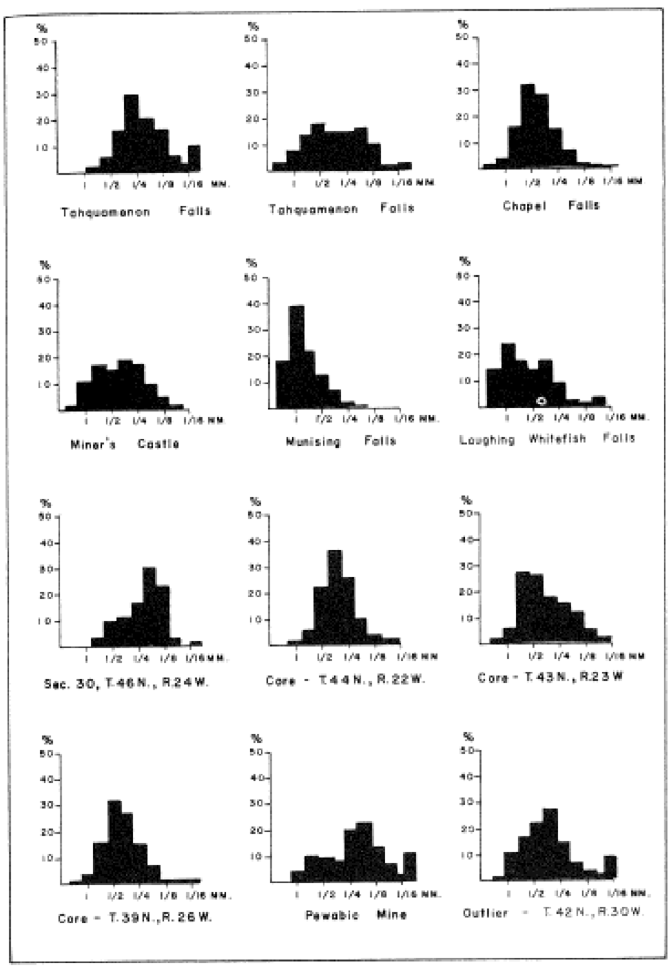

Figure 65. Grain-size distribution in typical samples of the Miner's Castle member.

COLOR

In most outcrops the color of the fresh sandstone of the Miner's Castle member is primarily light-gray to white, but in Dickinson County the sandstone is buff to reddish-brown. A striking deviation from the gray to white color is produced by the abundant greenish-blue shale in the lower units. This gives a greenish-blue hue to that part of the section, whereas the upper units, devoid of shale, are characteristically light gray to white. Like the Chapel Rock member, surficial stains produce various shades of red, brown, yellow, and black in the major outcrops, especially in the Pictured Rocks cliffs.

SEDIMENTARY STRUCTURES

Cross-bedding

Small-scale cross-stratification constitutes the only type of bedding in the lower 90 feet of the Miner's Castle member and is present, but less abundant, in the upper units. This characteristic sedimentary structure is not a local phenomenon but is well exposed in every outcrop extending from Tahquamenon Falls to the outlier in Dickinson County and can even be recognized in drill-core samples. The dominant type of cross-bedding is the trough type of McKee & Wier (1953, p. 387), although planar cross-stratification is present in minor amounts in various localities. The smallest cross-bedded unit observed is only 2 inches deep, but the average size of the troughs is from 15 to 20 inches in width and 4 to 6 inches in depth (fig. 66, 67). The size of these structures is remarkably constant throughout the entire outcrop belt and only slight differences in size are found throughout the section.

In the basal part of the Miner's Castle member, thin shale lenses from ⅛ to 1 inch thick were deposited upon the undulatory erosional surface which separates each set of cross-strata. The section is thus characterized by alternating sets of small-scale cross-bedding and thin lenses of bluish-green shale. In many places small pellets of this shale are included in the cross-bedded units as clay galls in the inclined strata. Coarse sand and even fine conglomerate are commonly concentrated near the base of each set of cross-strata and grade upward into the finer sands. The amount of shale and coarse material decreases upward becoming practically absent in the uppermost units.

Bedding

Extensive horizontal bedding characterizes the upper part of the Miner's Castle member and can be traced laterally for several miles along the Pictured Rocks cliffs. The beds are from 2 to 8 inches thick and although some appear to be massive, close examination reveals that they contain numerous sets of small-scale cross-bedding. Many of the horizontal beds are more resistant than the cross-bedded units and they stand out in relief in the outcrop. Others weather in a vertical face primarily because they are directly overlain by the resistant Au Train formation and not because they are resistant.

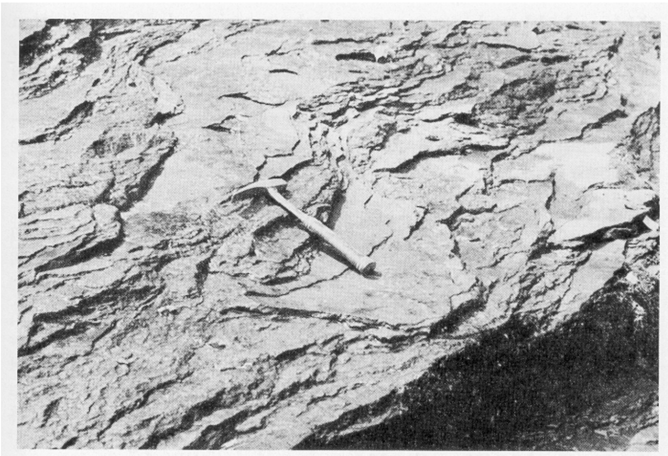

Figure 66. Small-scale trough cross-stratification in the Miner's Castle member, Laughing Whitefish Falls. Hammer handle points in the direction of inferred current flow.

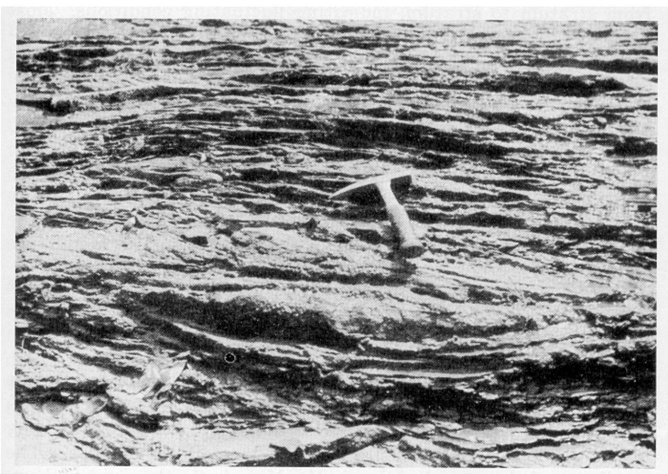

Figure 67. Channel filled with conglomerate in the Miner's Castle member, Laughing Whitefish Falls.

Mud Cracks

Numerous small, thin mud cracks not more than 3 inches in diameter have developed in the shale lenses which separate the small-scale cross-bedding. It is difficult to detect these structures on the vertical cliffs, but they are well exposed in the slopes developed at various waterfalls in Alger County.

Ripple Marks

Forty-four strata containing ripple marks were observed in the lower 50 feet of the outcrop at Laughing Whitefish Falls, but at other outcrops these structures are noticeably lacking. This may be due to the fact that Laughing Whitefish Falls is the only outcrop exposing the horizontal view of numerous bedding planes. The wave length and amplitude of the ripple marks differs considerably from stratum to stratum, indicating fluctuating conditions. Most ripple crests have been flattened by erosion; therefore, it is impossible to determine if the ripple marks are due to currents or to oscillation.

Concretions

Large elliptical concretions are concentrated along several horizons in the upper Miner's Castle member. The size of the concretions ranges from 3 inches in diameter to more than 1½ feet in their largest dimension. No indication of interruption in the bedding planes was observed near the concretions, although the sandstone is better cemented in their immediate vicinity.

PALEOGEOGRAPHY

Analysis of Cross-Bedding

A statistical analysis of the plunge direction of the small-scale trough cross-bedding in the Miner's Castle member was made following the general methods employed in studying the cross-bedding of the Jacobsville formation and the Chapel Rock member. The small size of the cross-bedding in the Miner's Castle member, however, makes sampling possible in much greater detail, and a complete understanding of the paleocurrents of that member.

Figure 68 shows the average direction and standard deviation of the readings taken at each exposure. The average plunge direction is between west-southwest in nearly all localities, indicating that throughout the entire Northern Peninsula the regional slope was remarkably consistent. The direction of this slope remained stable throughout the time required to deposit the Miner's Castle member, as the plunge direction is substantially the same throughout the section at Laughing Whitefish Falls (fig. 69). This marked change in the direction of regional slope during the deposition of the Chapel Rock and Miner's Castle members further indicates that the two members are separated by an unconformity. The Wisconsin arch and the Northern Michigan Highland, which were prominent source areas during Jacobsville and Chapel Rock time, were eroded down and almost completely covered with the Chapel Rock sediments. It is probable that regional tilting caused a regression of the Chapel Rock sea so that by the beginning of Miner's Castle time the regional slope was to the southwest. The transgression of the Miner's Castle sea was from the southwest, across the eroded Wisconsin arch and Northern Michigan Highland, but the major source area lay farther to the northeast in Canada. This change in principal source area clearly explains the change in heavy mineral suite from a high zircon-low garnet in the Jacobsville formation and Chapel Rock member to a high garnet-low zircon in the Miner's Castle member. The irregular Precambrian surface undoubtedly produced many islands in the Cambrian sea, but cross-bedding readings indicate that these islands had little effect upon the regional pattern of sedimentation. The influence of such islands was limited to the formation of conglomerate lenses around their flanks. Such a limited effect of an irregular surface upon local sedimentation suggests a rapid encroachment of the sea.

Ripple Marks

The numerous zones containing ripple marks at Laughing Whitefish Falls clearly indicate that the Miner's Castle member accumulated in a shallow-water environment. The average strike of the ripple marks is north-south, practically perpendicular to the direction of sediment transport (fig. 68) and indicates that the trend of the ancient shoreline was in a general north-south direction.

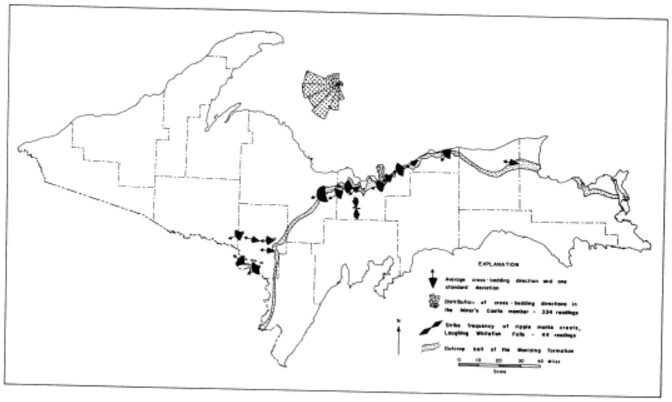

Figure 68. Cross-bedding directions in the Miner's Castle member.

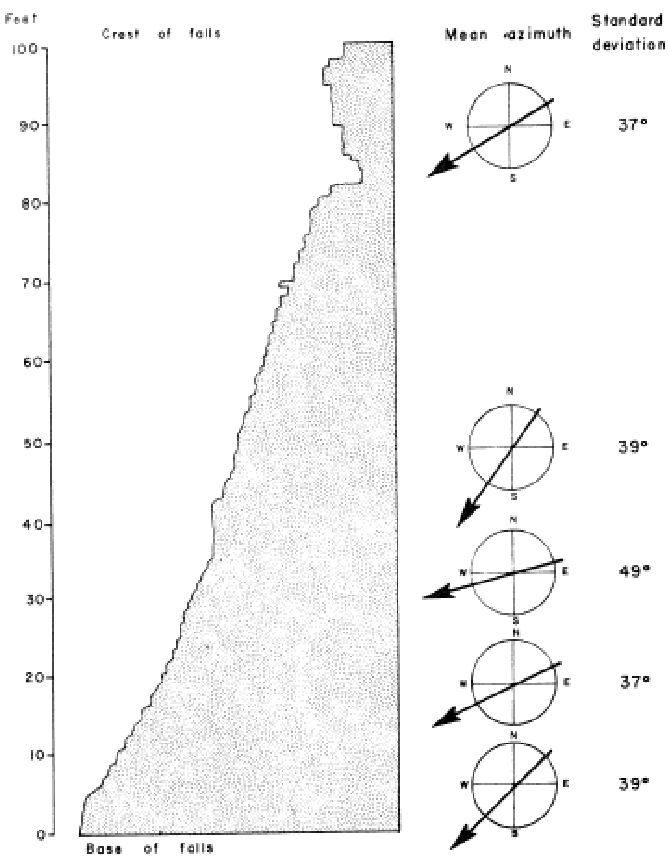

Figure 69. Cross-bedding directions through the section of the Miner's Castle member, exposed at Laughing Whitefish Falls, Alger County, Michigan.

AGE AND CORRELATION

Fossils are extremely rare in the Munising formation, but a few trilobites and brachiopods have been found in the isolated outliers in Dickinson County. Stumm (1956) collected many trilobite fragments from a small roadcut a few hundred feet east of the junction of Highway 2 and the road to Foster City. From this material he was able to identify 4 trilobite genera and 1 species. The species is *Prosaukia curvicostata* and indicates that the zone may be correlated with the *Prosaukia-Ptychaspis* zone of the standard Cambrian section, equivalent to the upper part of the Middle Franconia formation of the type area of the Upper Cambrian St. Croixan series.

The *Prosaukia* zone was recognized by the writer in the north side of the Pewabic mine at Iron Mountain and again in a drill-hole core from sec. 7, T. 39 N., R. 26 W. In both sections the *Prosaukia* zone is 5 feet below the contact with the overlying Au Train formation. The section exposed in the Pewabic mine can be correlated with the Miner's Castle member exposed along the Pictured Rocks. The small-scale cross-bedding and high-garnet heavy mineral suite so distinctive of the Miner's Castle member is readily recognized in all the measured sections and drill-cores between the two areas (fig. 70). The control for such a correlation has been greatly increased by the cores drilled through the Paleozoic section by several iron companies. From Munising to Iron Mountain the distance between an outcrop or core-drill site in which the complete Cambrian section and at least 25 feet of the Au Train formation is available averages 9 miles and does not exceed 25 miles. Inasmuch as the uppermost section of the Cambrian in Dickinson County can be correlated with the upper part of the Middle Franconia, the Miner's Castle member must be equivalent to at least the middle and probably the lower Franconia. The upper Franconia, Trempealeau and lower Ordovician are thus missing in Northern Michigan and are overlapped by the middle Ordovician Au Train formation.

The unconformity which separates the Miner's Castle and Chapel Rock members suggests the equivalence of the Chapel Rock member to the Dresbach formation. This correlation is strongly supported by the remarkable similarities in heavy minerals between the Dresbach and Chapel Rock member. Both are high in zircon and low in garnet. This is strikingly different from the definite high-garnet sands of the Franconia formation and Miner's Castle member.

Au Train Formation

INTRODUCTION

Throughout the Northern Peninsula the Munising formation is overlain by a sequence of thin- to medium-bedded sandy dolomites and dolomitic sands which contain many thin lenses of pure quartzose sandstone. Confusion has existed concerning the age and nomenclature of these rocks because the outcrops which expose them are very small and isolated and only a few poorly preserved fossils have been reported. Even locally these rocks have not been studied in detail. No single outcrop exposes the complete section and very little is known about the upper and lower contacts.

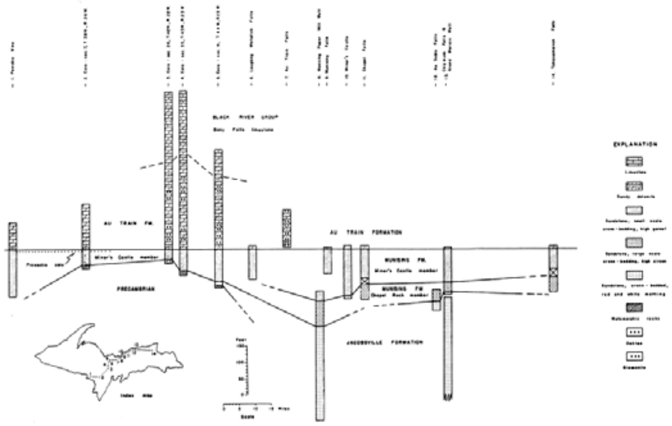

Figure 70. Stratigraphic cross section from Pewabic Mine to Tahquamenon Falls.

Rominger (1873) considered this sequence of rocks to be equivalent to the "Chazy" and "Calciferous" groups of the New York system on the basis of stratigraphic position and lithologic similarities. In 1900, Van Hise and Bayley (1900, p. 11) proposed the term "Hermansville" for the "limestones" which overlie the "Lake Superior Sandstones" in the Menominee district and subsequent workers have used this term for the "Ozarkian" of Northern Michigan. The only description given by Van Hise & Bayley (1900, p. 11) is that "the Hermansville limestone is a coarse grained sandstone with abundant calcareous cement, in alternation with pure dolomite or sometimes oölitic beds." The only descriptions of a type locality is that "the limestone may be seen near the top of the hill east of Iron Mountain, on the bluff north-east of Norway, and at several places on the hills north of Waucedah."

Grabau (1906, p. 583) suggested that the term "Aux Trains" would be a much better name since a considerable section is exposed at Au Train Falls and no type section was given by Van Hise and Bayley. Bergquist (1937), however, used the term "Hermansville" in his studies on the Cambrian-"Ozarkian" contact in Alger County and again in his publication in 1930, but Thwaites (1943, p. 510) and Driscoll (1956, p. 20) favored dropping the term. Inasmuch as no type locality nor type section was presented by Van Hise and Bayley or by any subsequent workers for the term Hermansville, and since the type of lithology and age of the rocks referred to by that term has been so vague and confused, the writer feels that the term is so poorly defined that it should be abandoned.

In recent exploratory drilling by several iron companies, complete cores of the Paleozoic section were obtained from several localities in Alger, Delta, and Menominee counties. The cores and sections measured in the field indicate that a section of rock approximately 300 feet thick separates the Ordovician Black River and Cambrian Munising formations. The writer, following Grabau, proposes that "Au Train" formation be used for these rocks, because the best exposures and thickest sections are at Au Train Falls in Alger County (figs. 71, 72, & 73).

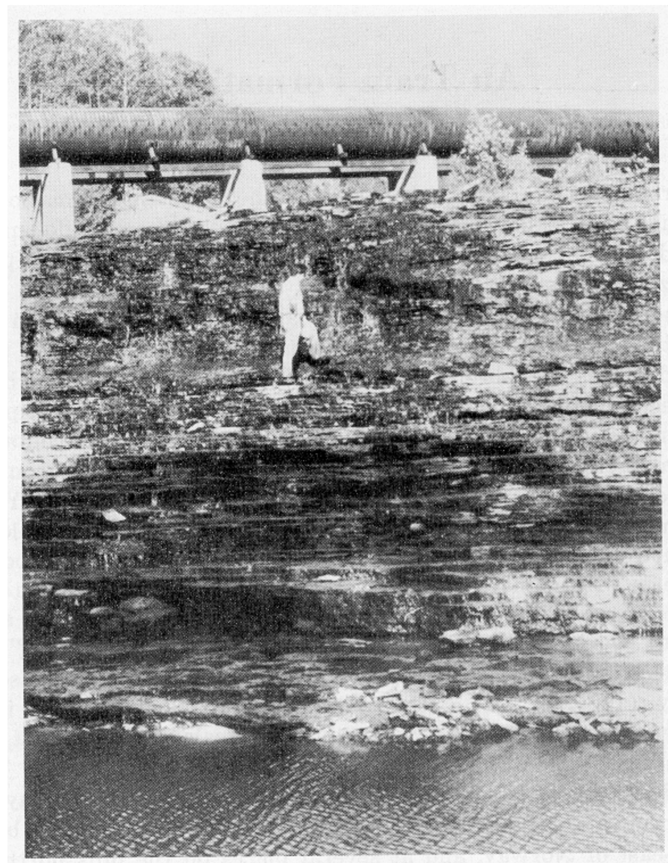

Figure 71. Upper Au Train Falls—upper part of type locality for the Au Train formation.

Figure 72. Lower Au Train Falls—lower part of type locality for the Au Train formation.

GENERAL DESCRIPTION

The Au Train formation is a relatively resistant formation that forms the cap rock of the outermost northern cuesta of the Michigan Basin. The escarpment is prominent in Alger County, but is obscured to the south and west by a thick drift cover. Isolated outcrops are at Sault Point, Tahquamenon River about a quarter of a mile above the upper Falls, and in the bluffs approximately 1 mile south of Grand Marais. The Au Train formation is exposed at the top of Chapel Falls and forms the uppermost units of the Pictured Rocks between Miner's Castle and Sand Point. Isolated patches are also at the highest elevation on Grand Island (Plate 2). West of Munising the escarpment has receded several miles south of the shore, but it maintains its bold character and provides a drop of approximately 100 feet for many of the water falls of Alger County. In Marquette County, the escarpment swings southward and is lost under the greater drift cover in that area. In many places the Au Train formation overlaps the Munising and rests directly upon Precambrian rocks. Numerous isolated outcrops in Marquette and Dickinson counties are either erosional remnants resting on Munising or Precambrian or isolated patches poking through the drift. Subsurface data indicate that the Au Train formation extends throughout most of the Northern Peninsula. However, a definite facies change is noted southwestward with an increase in dolomite.

The basal contact of the Au Train formation is easily recognized by the lithologic break from a hard dolomitic sand to the soft, friable quartzose sand of the Munising formation. The upper contact, however, is much more difficult to recognize. Core samples indicate that the transition from dominant Au Train to typical Black River lithology takes place in an interval of less than 20 feet. The maximum thickness of the Au Train as indicated in core samples is slightly more than 300 feet, but only the lower 125 feet is exposed at Au Train falls. Good thick exposures of the upper part of the section have not been found.

The dominant lithology of the Au Train formation is a medium-to fine-grained dolomitic sandstone. The ratio of sand grains to dolomite throughout the section differs considerably, as some beds are pure dolomite with only an occasional floating sand grain, and other beds are pure sandstone.

Lithologic variation in the Au Train makes it convenient to divide the formation into two members. The lower member is approximately 100 feet thick and is characterized by abundant glauconite. The glauconite occurs as disseminated grains in the dolomitic sand, and in thin dark-green beds in which glauconite constitutes over 35 percent of the mineral composition. The thin beds of concentrated glauconite are more abundant near the base of the section at 3 to 12 foot intervals. Higher in the glauconitic member the beds of concentrated glauconite are less numerous. Locally individual glauconite zones may be used as key beds for correlation (fig. 70). The bedding in the glauconite member is thin and undulatory and accentuated by numerous shale lenses and blebs. The color of the glauconitic member is buff to brownish-gray; but where glauconite is extremely abundant a speckled green or solid dark-green color predominates. Some of the more dolomitic beds are characteristically blue to bluish-gray. Much of the weathered surface of the lowermost beds is a definite brown color which stands out in contrast to the white Munising formation along the Pictured Rock cliffs.

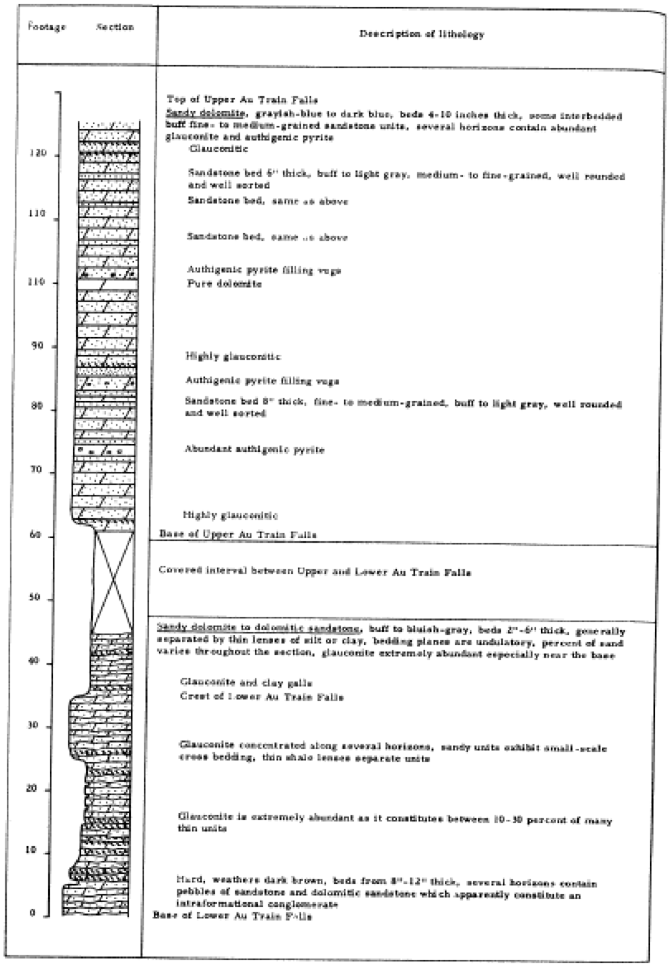

Figure 73. Columnar section of the Au Train formation, Au Train Falls, Alger County, Michigan.

In the upper member of the Au Train formation glauconite is completely absent and thin sandstone lenses are numerous. The thickness of the sandstone lenses measured in drill-cores ranges from ½ to 2 feet. Sandstone beds more than 10 feet thick are present, however, but cannot be traced with any confidence from one core to the next.

The lenticular sandstone is remarkably similar to the sandstone of the upper part of the Miner's Castle member. It is characteristically medium- to fine-grained and contains a few thin lenses of blue to greenish shale along the bounding surfaces of small-scale cross-bedded units. Indeed, exposures of these sandstone beds are easily mistaken for the Miner's Castle member. Numerous thin beds of oölites are also in the upper section. Some oölite beds can be correlated from core to core, but they do not appear to be of value for regional correlation (fig. 70). Authigenic pyrite is very common throughout the section, some large vugs are completely filled by it. Driscoll (1956, p. 39) reports that, like the Miner's Castle member of the Munising formation, the dominant heavy mineral in the Au Train formation is garnet, so it is very possible that the Munising was a part of the source area for the sand.

AGE AND CORRELATION

Oetking (1951, p. 27) reported an impressive suite of Black River fossils from the Au Train formation collected from a road cut exposure less than ½ mile south of Miner's Castle. The writer was unable to find specimens of all the species reported by Oetking, but some well-preserved gastropods and cephalopods of Middle Ordovician age were found (Plate 5) indicating the age of the Au Train formation to be lowermost Black River. Thus lower Ordovician and parts of the upper Cambrian are missing in the area covered by this study.

Structure

GENERAL ATTITUDE OF THE BEDDING

The Jacobsville formation is relatively undisturbed except near the Keweenaw fault where it has been dragged toward a vertical position. In most of the outcrops along the shore the Jacobsville dips from 1 to 6 degrees to the north or northwest. Dips to the south and east were observed in some localities but they are not common.

In addition to the drag folding near the Keweenaw fault, the Jacobsville has undergone considerable deformation in the vicinity of Limestone Mountain. Unfortunately exposures are not sufficient to determine the details of the structure over a broad area. Approximately 1½ miles east of Limestone Mountain, along the road between sections 17 and 20, T. 51 N., R. 35 W., the Jacobsville strikes N. 40° E. and dips 62 degrees to the northwest, but along the same section line ½ mile west of Limestone Mountain the Jacobsville dips 20 degrees to the east. Several other outcrops a mile farther west were reported by Roberts (1940) in which the Jacobsville strikes northeast and dips 20 to 50 degrees west. It therefore seems quite possible that the syncline at Limestone Mountain is a major structural feature and is flanked on the west by an anticline of equal or greater magnitude. An anticline, monocline, or fault may be east of the syncline at Limestone Mountain since the Jacobsville is horizontal in the shore cliff exposures just north of Baraga.

Although both the Jacobsville and Munising formations are relatively undisturbed their regional attitude differs. The Munising formation constitutes the outermost cuesta of the northern Michigan basin and the dip is predominantly to the south and southeast (fig. 74). The southern dip is difficult to detect in the field as it exceeds 2 degrees in a very few places. Numerous elevations established on the top of the Munising formation, however, indicate that the low dip toward the center of the Michigan basin is remarkably constant and averages between 20 and 40 feet per mile (fig. 75). The only area in which the Munising has been subjected to appreciable deformation is at Limestone Mountain where, together with the Jacobsville and sediments as young as Devonian, it has been folded into a tight syncline.

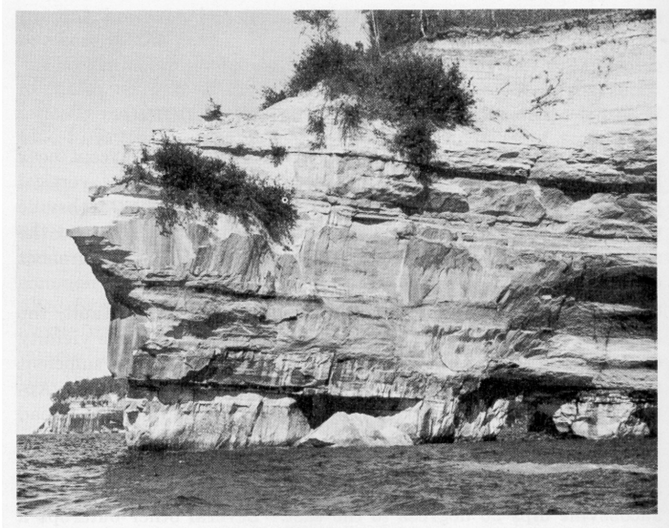

Figure 74. View along the Pictured Rocks showing the Munising formation dipping to the south at a low angle.

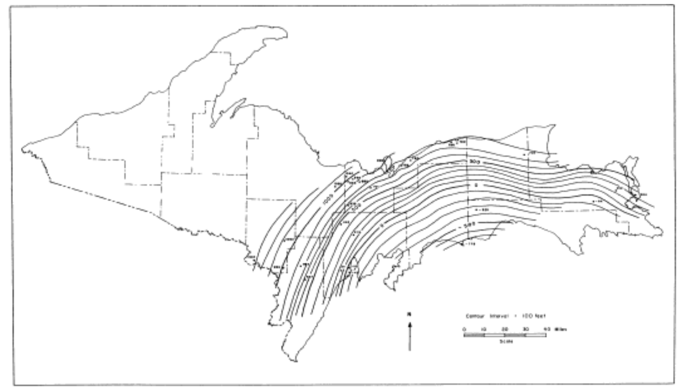

Figure 75. Structure contours on the top of the Munising formation.

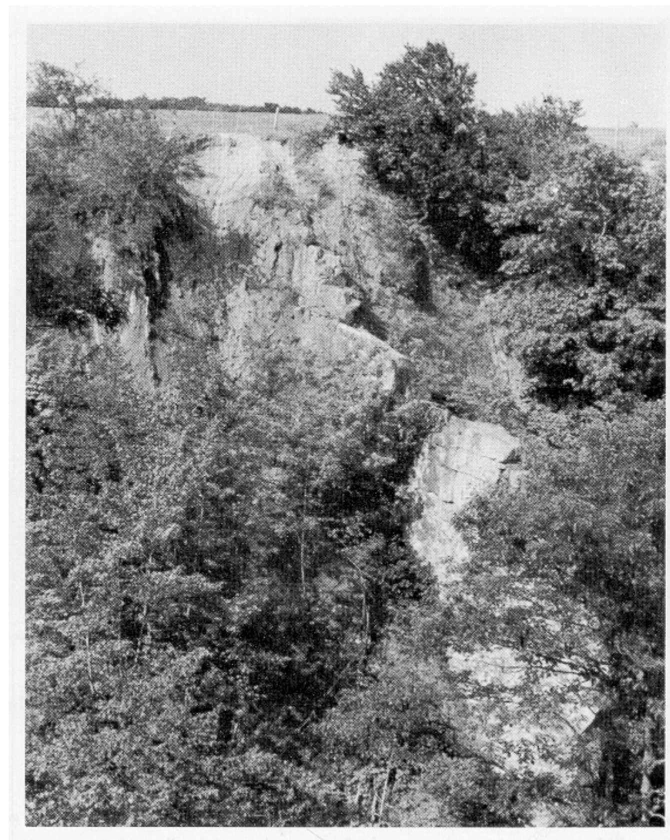

Figure 76. View of the Wall Ravine near Laurium, Houghton County, showing the Jacobsville sandstone in a nearly vertical attitude resulting from drag along the Keweenaw fault. The fault is to the right of the photograph and the younger Jacobsville units are to the left.

KEWEENAW FAULT

The Keweenaw fault can be traced for a distance of more than 100 miles and is considered one of the major structural features in Northern Michigan. It strikes in a general northeast direction and dips 20 to 70 degrees northwest (Butler, Burbank, et al, 1929, p, 48-49). Numerous branches deviate from the general strike, however, and in many places the fault is offset by later cross-faulting. Extensive deformation of the Jacobsville strata, resulting from drag along the Keweenaw fault, can be observed in many of the stream valleys which cut the scarp. At the Wall Ravine the Jacobsville is almost vertical but the dips decrease eastward; within a few hundred yards the formation is almost horizontal and undisturbed (fig. 76). Considerable drag along the Keweenaw fault was observed downstream from Victoria Falls but the Jacobsville is practically undisturbed farther north along the fault contact at Houghton and Hungarian Falls.

The age and amount of displacement of the Keweenaw fault has been a matter of conjecture for many years. The amount of displacement necessary to bring the middle Keweenawan basalts in contact with the Jacobsville is in the order of 3 miles (Butler, Burbank, *et al.*, 1929, p. 50) and has led some geologists to believe that a large amount of displacement took place prior to the deposition of the Jacobsville. It has also been proposed (Irving & Chamberlain, 1885, p. 98-100) that the present fault scarp existed as a shore cliff during Jacobsville sedimentation and that the post-Jacobsville movement was only minor.

In considering the age and movement of the Keweenaw fault three important facts should be kept in mind: (1) the direction of sediment transport during Jacobsville time, as determined by cross-bedding measurements, was to the north and the source of the Jacobsville sediments was to the south. This indicates that the Keweenaw fault scarp did not constitute the shore line and we have no real evidence for pre-Jacobsville movement; (2) the Jacobsville lies unconformably upon tilted Keweenawan basalts as shown in the exposures at Sturgeon River. This suggests that the Keweenawan series was tilted and eroded before the Jacobsville was deposited and that the minimum displacement on the fault is, therefore, not the thickness of the upper Keweenawan rocks but only the thickness of the Jacobsville. This thickness is in the order of magnitude of 2,000 feet; (3) the predominant structural trends of the Jacobsville at Limestone Mountain parallel the Keweenaw fault, suggesting that the folding in the Limestone Mountain area is related to the compressional forces which caused the faulting.

These facts indicate that the age of the Keweenaw fault is post-Jacobsville and probably post-Devonian since Devonian rocks are involved in the folding at Limestone Mountain. The angular unconformity at Sturgeon Falls further indicates that the displacement necessary to bring the Jacobsville in contact with Middle Keweenawan lavas was only a few thousand feet.

NORMAL FAULTING

Thirteen minor normal faults striking between N. 15° E. and N. 20° E. were mapped in the Keweenaw Bay area. These faults have an average displacement of 10 feet and form small horsts and grabens. Their strike, movement, and location near the Keweenaw fault indicate that they probably resulted from the release of the stress which caused the Keweenaw thrust. Minor copper mineralization was found along the fault plane at Pequaming Point and along several points east of Skanee. Normal faults with small displacement were also observed at Au Train Island and at the east end of Pictured Rocks (figs. 77, 78).

MINOR THRUST FAULTS

Small thrust faults are exposed on the east and west sides of Grand Island where clastic dikes are displaced from 1 to 3 feet (fig. 79). The faults strike east-west and dip 4 degrees to the north with the direction of displacement S. 15° W. The fault plane follows a shale bed and is not far below the contact of the Jacobsville and the glacial drift. It is therefore quite probable that these faults are not the result of tectonism, but are drag effects produced by the Pleistocene glacier. Other minor thrust faults were reported by Oetking in the Au Train Bay area and on Laughing Fish Point. Such movement in the Jacobsville could well explain the striations on the Michigamme slate at L'Anse which were considered by Murry (1955) to be evidence for pre-Jacobsville glaciation.

JOINTS

Long straight joints are in most outcrops of the Jacobsville formation, they are very numerous in the shore cliffs just east of Skanee and on the northwest side of Grand Island. In most outcrops the typical red color of the Jacobsville has been leached from the joint walls so that the joint is marked by a straight white band from 2 to 30 inches wide extending along its entire length (figs. 80, 81). This color contrast makes the joints so conspicuous that some can be seen extending out into the lake several hundred feet before being obscured by deep water.

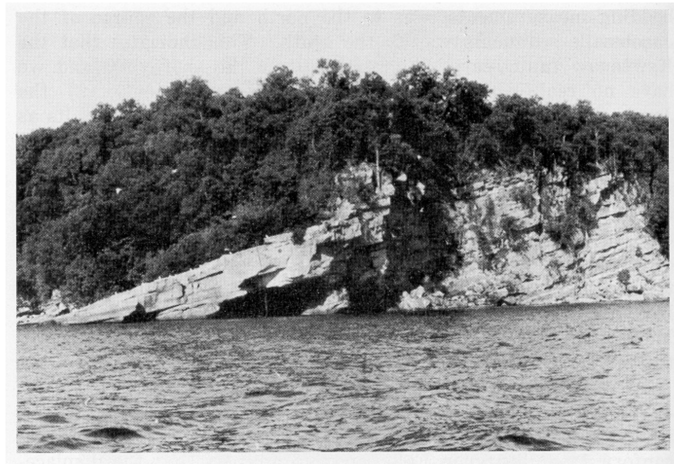

Figure 77. View of the east side of Au Train Island showing the south side of a fault block in which the Jacobsville has been tilted to the south.

Figure 78. High angle normal fault with small displacement. Pequaming Point, Keweenaw Bay.

The joint planes are. remarkably smooth and flat with no warping or irregularities at places where the joints cut contrasting rock types. This is well demonstrated at Wetmore Landing where many moderately well-cemented conglomerate lenses are in a medium- to massive-bedded sandstone. Several joint planes which cut the conglomerate are exposed, but show no deviation of the strike as they pass from the sandstone to the conglomerate. Even the individual pebbles of hard quartzite and soft clay pellets within the conglomerate are cut by an equally smooth joint plane. The writer therefore concludes that these are shear joints since tension fractures would be short, irregular and would not cut contrasting rock types.

Two sets of shear joints intersecting at nearly right angles are recognized in the Jacobsville. In the Keweenaw Bay area one set strikes N. 70° W. and the other N. 10-30° E. Eastward this pattern rotates clockwise so that at Grand Island one set strikes N. 50° W. and the other N. 40° E. (fig. 82). Continued rotation to the east is implied by the joints at Parisian Island in Whitefish Bay, but only one set is present. In the field, the intersection of two joints forms a 70- to 80-degree angle which points in an east-west direction; however, when the measurements are grouped in a frequency diagram, this acute angle is not discernible and the two sets form a rigorously perpendicular system. In all localities the east-west joints have a constant strike but the north-south set varies 10 to 15 degrees. These joints were probably produced by the forces that tilted the Jacobsville to the north and northwest.

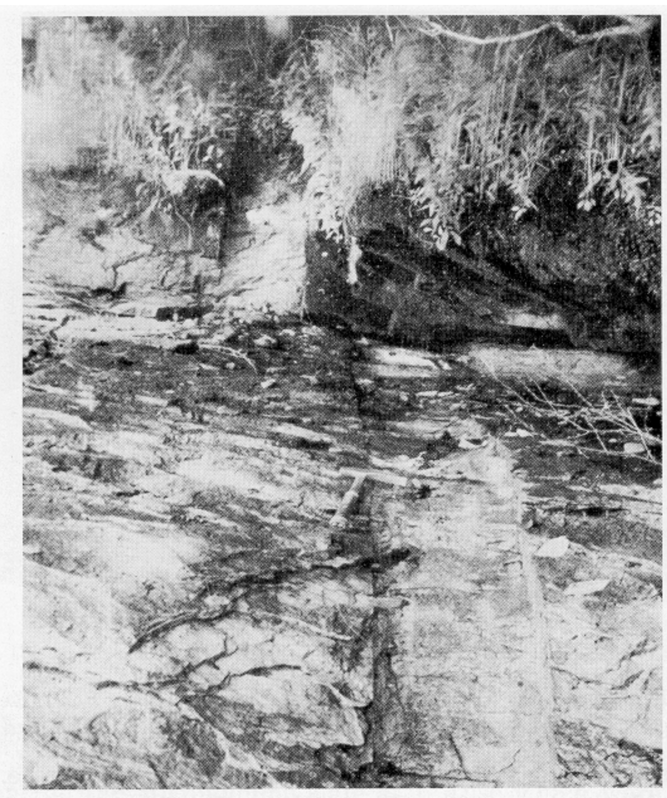

Figure 79. Small low-angle thrust fault on the east side of Grand Island showing clastic dike displaced approximately 2 feet.

Two sets of long straight shear joints are also recognized in the Munising formation but they are not nearly so numerous as in the Jacobsville. In the Pictured Rocks area one set of joints strikes N. 40° E. and the other N. 80° E. Rotation of this pattern occurs along the rim of the Michigan Basin; therefore, the strike of one set remains nearly parallel to the strike of the beds. The jointing in the Munising is one of the main reasons for the preservation of the Pictured Rocks cliffs. One joint set strikes parallel to the shore and causes the cliffs to be eroded back in big blocks instead of a slope. Many of the faces on the vertical cliffs thus expose the joint plane.

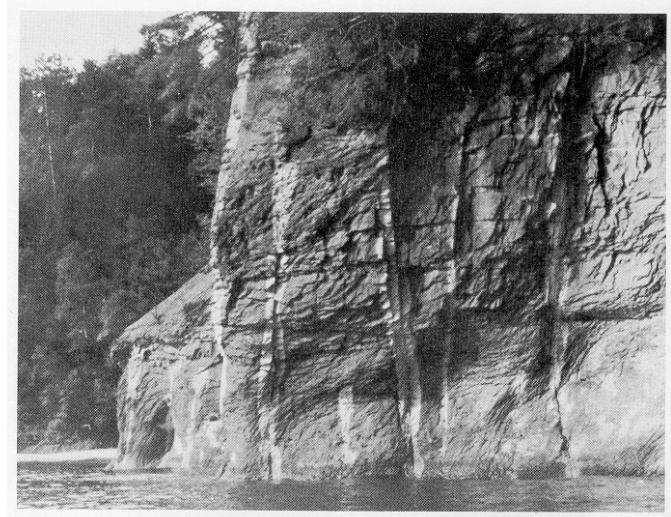

Figure 80. Vertical jointing in the Jacobsville formation showing the white band produced where the red color is leached away from the joint wall. View taken just north of Wetmore Landing.

Many shear joints are in the Au Train formation at Au Train Falls and form a conjugate system parallel to the system in the Munising formation (fig. 82). In places one set of joints truncated the other and a zig-zag pattern resulted. The abundance of joints in the Au Train formation indicates that the number of joints, but not their orientation, is probably dependent on the brittleness of the rock.

The orientation of the joint system in the Jacobsville formation differs from the orientation of joints developed in younger rocks indicating that the joints in each formation resulted from different stresses. Apparently however no relationship exists between jointing in either the Jacobsville or younger formations and the forces which caused the Keweenaw fault. Jointing in the Jacobsville probably developed during the tilting which took place prior to the advancement of the Upper Cambrian seas, whereas jointing in the Munising and younger formations appears to be related to the subsidence of the Michigan Basin.

CLASTIC DIKES

Numerous tabular sandstone dikes in the Jacobsville formation have been briefly described by Oetking (1951, p. 61). They seem to be restricted to the Grand Island area where 30 dikes were mapped on the island itself and 4 on the mainland between Munising and Au Train Bay. Elsewhere along the coast dikes are absent. The outstanding characteristics of the dikes is their constant thickness. They exist as vertical tabular masses 6 to 30 inches wide and can be traced throughout the entire vertical extent of the outcrop, which, in places, is more than 100 feet (fig. 83). Throughout this distance the walls of the dike remain remarkably parallel. The distance in which the dike persists along strike can only be postulated since the only exposures are in vertical cliffs. The position of a number of dikes mapped on the opposite sides of the "thumb" of Grand Island, however, suggests that the dikes may be connected and extend along the strike for over a mile. Fragments of the wall rock are, in places, included in the dikes but the contact between the dike and wall rock is characteristically very straight and sharp.

Figure 81. Conjugate shear system of joints in the Jacobsville formation east of Skanee showing white band resulting from leaching of red color from joint walls. Note the sharp contact between the red and white colors.

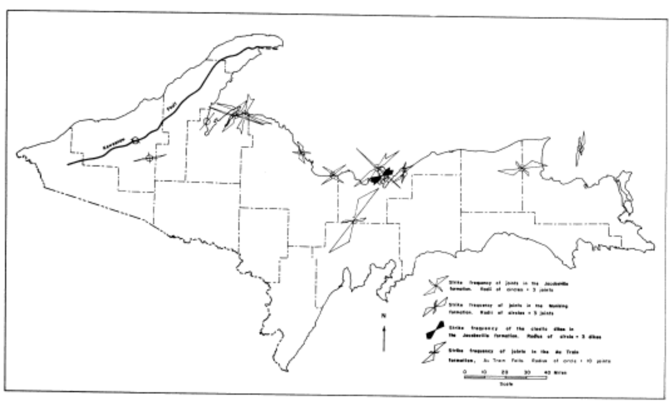

Figure 82. Joint patterns in the Jacobsville, Munising and Au Train formations.

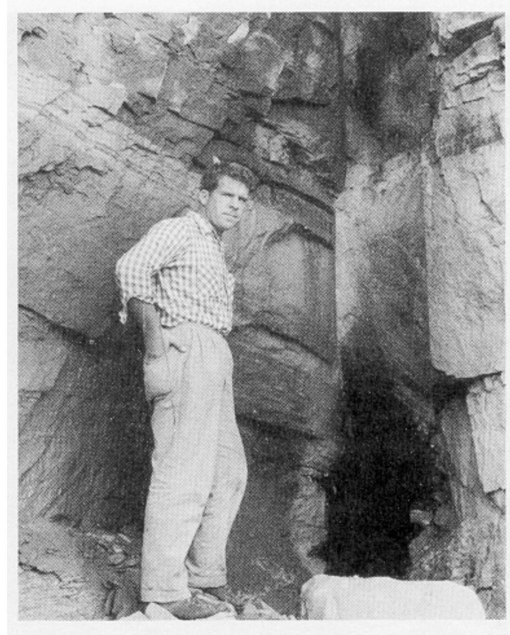

Figure 83. Large clastic dike cutting through the Jacobsville formation on the west side of Grand Island. Note the sharp straight contacts with the wall rock and the cave produced by differential erosion by the waves.

Figure 84. Conglomerate dike on the southward side of the “thumb” of Grand Island. Note the white band produced by leaching of the red coloring near the contacts between the dike and the wall rock.

COMPOSITION

Excepting in a conglomerate dike on the southwest side of the thumb of Grand Island the material filling the dikes is a poorly-sorted sandstone which contains an abundance of silt- to clay-sized particles. The color is typically dark-red to purple, but along the contact with the wall rock the coloring material has been leached white in a manner similar to the leached zones along the joints. Nearly all the narrow dikes are therefore completely white. Quartz grains constitute more than 90 percent of the dike material but feldspar and chert are everywhere present in minor amounts. The grains are typically angular to subrounded and poorly sorted. Overgrowths of quartz, calcite and other cementing materials are noticeably lacking. The dikes are therefore less resistant than the country rock and wave action erodes much dike material away leaving straight narrow caves at the water level. The conglomerate dike is composed predominantly of quartzite and vein quartz pebbles 6 inches in diameter. Rounded pebbles of the Jacobsville, particularly in the smaller size fraction, are also in every sample. The only other rock types are small amounts of granitic pebbles and brown oölitic chert.

The strike of the dikes closely parallels the strike of one joint set in the conjugate system so well exposed on the northwest side of Grand Island (fig. 82). This parallelism and the fact that the dike walls are straight and persist along strike for a considerable distance suggest that the dikes resulted from a widening of one of the joint sets by tension forces younger than the forces which produced the conjugate shear systems. It is quite probable that such tension forces developed during the subsidence of the Lake Superior syncline.

The mechanics by which the fractures became filled is not completely clear. The presence of rounded pebbles of Jacobsville and oölitic chert suggests that the fractures were filled from above and were derived from the basal part of the Munising formation. No stratification within the dikes is indicated, but in several dikes a faint lineation of coarser sand is parallel to the dike walls (fig. 85). This lineation and small apophysis implies forceful injection (fig. 86).

With these facts in mind, the most plausible explanation of the origin of the dikes seems to be the opening of a set of shear joints in the Jacobsville and injection of unconsolidated clastic material from the basal Munising as a slurry under hydrostatic pressure.

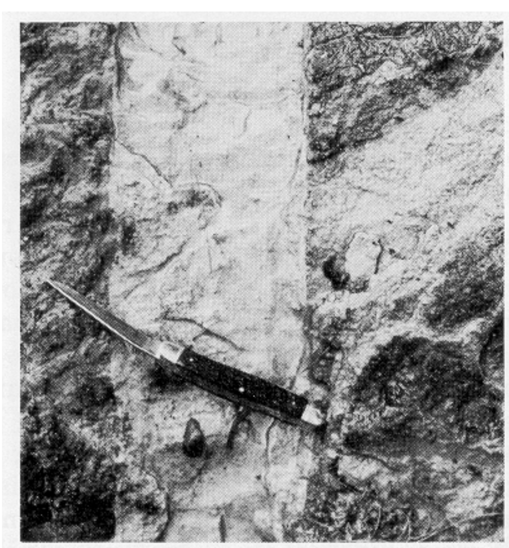

Figure 85. Clastic dike located on the east side of the thumb of Grand Island showing faint lineations parallel with the dike walls. These lineations are produced by difference in grain size and suggest that the dike was filled by forceful injection.

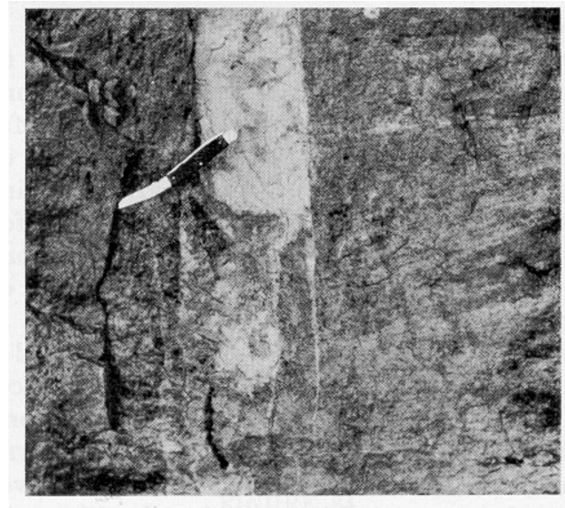

Figure 86. Clastic dike showing apophysis which suggest that the dike was filled by forceful injection. Location same as Fig. 85.

Summary of Geologic History

The angular unconformity between the Jacobsville and middle Keweenawan basalts exposed at Sturgeon Falls and the angular relationship between the Freda and Jacobsville that is implied from the exposures in Whitefish Bay indicate that the Keweenawan series was deformed prior to the deposition of the Jacobsville formation. Following this deformation a period of erosion produced an irregular surface of low relief probably very similar to the present topography of the Huron Mountains area. Deep chemical weathering of this surface is indicated by a regolith containing highly decomposed residual boulders. This erosional interval is considered to include the transition from Precambrian to Paleozoic time.

Jacobsville sedimentation was initiated with the uplift of the Northern Michigan Highland and the deposition of its erosional debris in a basin which developed in approximately the present site of Lake Superior and extended somewhat west of the Keweenaw Peninsula (fig. 87). The regional slope during Jacobsville time was to the north and the principal source area was the Northern Michigan Highland, which connected the Wisconsin Arch with the Precambrian highlands in Ontario. During early Jacobsville time, sedimentation was predominantly fluvial, especially near the upland front. Small lakes undoubtedly were in the center of the basin and as time progressed the lacustrine environment became more widespread. This is indicated by the massive sandstone facies exposed in many of the outcrops in Keweenaw Bay which are considered to be some of the younger units of the Jacobsville formation. With this type of sedimentation the Northern Michigan Highland became buried in its own debris. It is not known if the Northern Michigan Highland was completely covered by the Jacobsville but ample evidence indicates that Jacobsville sediments once covered a greater part of the Huron Mountains than do the formation at the present time.

Uplift tilted the Jacobsville slightly to the north and northwest and probably produced the system of shear joints which is so conspicuous throughout the formation. Prior to, or during, the first advance of the Paleozoic seas the topography developed on the tilted Jacobsville was reduced to a featureless plain, but the hard Precambrian rocks to the south retained their irregular surface which was not unlike the present topography of the Precambrian highlands.

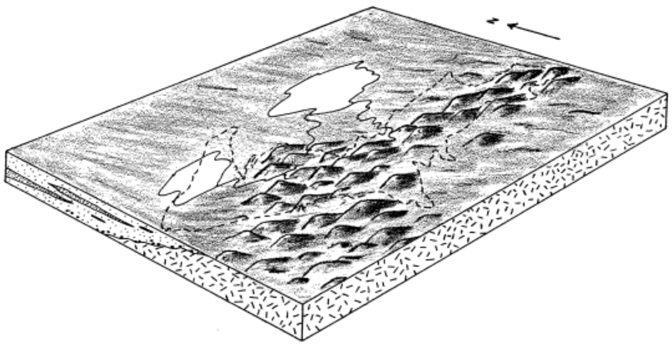

Figure 87. Paleogeography of Northern Michigan during Jacobsville time. The Northern Michigan Highland extended from the Wisconsin Arch through the central part of Northern Michigan and into Canada. Erosional debris from this highland was shed off to the north and accumulated in a fluvial and lacustrine environment.

If the Northern Michigan Highland was completely covered by Jacobsville, it was partly re-exposed by erosion prior to the transgression of the Upper Cambrian seas. During the early part of St. Croixan time this landmass blocked sea invasion onto the Canadian Shield from the south or southeast (fig. 88). The regional slope during lower Munising time as determined by cross-bedding directions, indicates that the first transgression of the Paleozoic seas in Northern Michigan came from the northwest, probably from the Cordilleran geosyncline. The basal conglomerate and Chapel Rock member represent a single transgressive-regressive cycle during which the principal source area was the Northern Michigan Highland. The clean well-sorted characteristic of the Chapel Rock member and its mineralogical similarities to the Jacobsville indicate that the highlands were probably covered in part by the Jacobsville formation, and that the Chapel Rock member represents a second-cycle sand.

Evidence of a regression of the Upper Cambrian seas prior to the deposition of the Miner's Castle member is found in the abundance of large mud cracks which are in a section of interbedded sand and shale layers at the top of the Chapel Rock member. The unconformity is further indicated by (1) changes in heavy mineral suites, (2) significant changes in the regional slope during the deposition of the two members, and (3) changes in composition, sorting, and sedimentary structures.

The Miner's Castle member represents a rapid transgression of the middle Upper Cambrian seas from the southwest over the Precambrian highlands. In many areas the irregular topography of the Precambrian highlands produced islands in the Miner's Castle sea, but they had little effect on regional sedimentation. The major source area was to the northeast in Canada (fig. 89).

Ripple marks, small-scale cross-bedding, and mud cracks indicate that the Miner's Castle member was deposited predominantly in shallow water but was at times exposed to desiccation on tidal flats. Throughout most of Miner's Castle time sea level remained relatively stable and a near balance was maintained between sedimentation and deposition in the area.

A considerable unconformity separates the Miner's Castle member of Middle Cambrian age and the overlying Au Train formation which is Middle Ordovician. The contact is practically a featureless plane with no angular discordance between the Upper Cambrian and Middle Ordovician rocks. However, some evidence of a basal conglomerate is in the lower units of the Au Train formation.

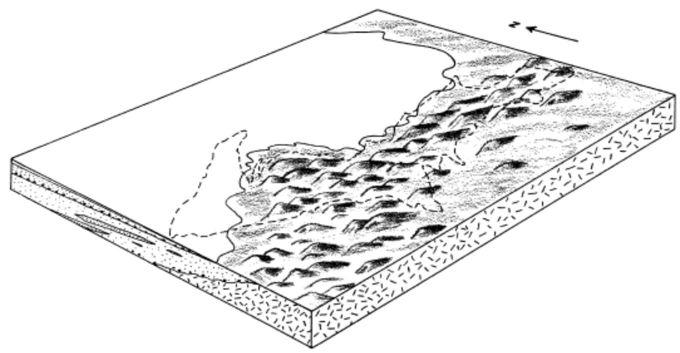

Figure 88. Paleogeography of Northern Michigan during Lower Munising time. The Northern Michigan Highland remained as a positive area although much of it was covered with Jacobsville sediments. The first advancement of the Paleozoic seas came from the northwest, probably from the Cordilleran geosyncline.

Thrusting from the northwest produced the Keweenaw fault sometime after the Jacobsville formation, but the exact age of movement cannot be definitely determined. In the writer's opinion the evidence indicates that the movement was at least post-Devonian. The relax of the stress which produced this great thrust probably produced the small normal faults in the Jacobsville observed along Keweenaw Bay.

The only deformation of the Munising formation is the slight tilting and related joints and minor normal faults, which resulted from subsidence of the Michigan Basin.

Conclusions

The Jacobsville formation extends from the tip of the Keweenaw Peninsula eastward to Sault Ste. Marie and in that area probably constitutes the bedrock over much of the bottom of Lake Superior. It contains four distinct facies, which represent environmental conditions that were local and temporary. The conglomerate facies and the lenticular sandstone facies represent fluvial deposition, but during the later phases of sedimentation a lacustrine environment became more prominent and in it the massive sandstone facies and the red siltstone facies were formed. The source area for the Jacobsville formation was a highland extending eastward through Northern Michigan connecting the Wisconsin arch with a positive area in Canada. The surface upon which the Jacobsville was deposited was highly irregular and had a local relief of at least 400 feet. Prior to the deposition of Jacobsville sediments this surface was subjected to a period of chemical weathering, which produced a regolith at least 6 feet thick.

The angular unconformity between the Munising and Jacobsville formations exposed at Grand Island indicates that the Jacobsville is not part of the St. Croixan series. At Sturgeon Falls the Jacobsville rests unconformably upon tilted and highly weathered Middle Keweenawan basalts; this relationship suggests that the Upper Keweenawan rocks were eroded away before the Jacobsville was deposited. There are also suggestions of an unconformity between the Jacobsville and Freda in the Whitefish Bay area. Cross-bedding directions indicate that the Upper Keweenawan sediments and the Jacobsville formation were derived from different source areas and are not genetically related. The writer therefore concludes that the Jacobsville is not related to the St. Croixan nor to the Keweenawan but represents terrestrial sedimentation in a closed basin during the time when marine sediments of Early and Middle Cambrian age were being deposited in other parts of the continent.

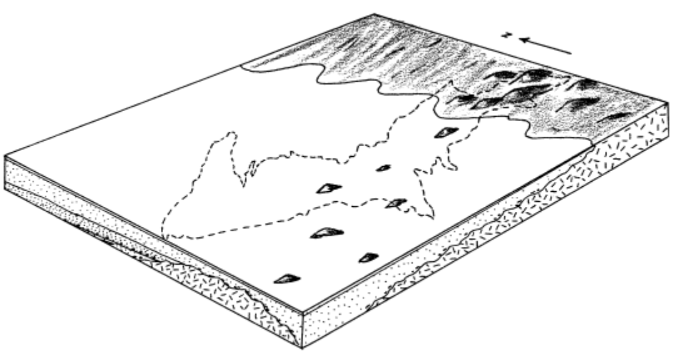

Figure 89. By the beginning of Miner's Castle time the Northern Michigan Highland was eroded down and almost completely buried in its own debris. The Miner's Castle sea advanced from the southwest and received most of its sediments from the Canadian Shield.

The Munising formation represents the first advance of the Paleozoic seas into Northern Michigan. Outcrops are in a narrow band that extends westward from Encampment d'Ours Island to western Marquette County. The outcrop belt then turns southward and can be traced into Wisconsin. Numerous outliers are scattered in Dickinson County, and isolated exposures are as far west as Limestone Mountain.

On the basis of lithology the Munising is divided into three members. The oldest member is an orthoquartzitic conglomerate 3 to 15 feet thick composed of pebbles that are chemically and mechanically very stable. The Chapel Rock member lies conformably upon the basal conglomerate and is characterized by large-scale cross-bedding, good sorting, and a heavy mineral assemblage high in zircon. An unconformity separates the Chapel Rock from the overlying Miner's Castle member and represents a temporary regression of the Munising seas. The basal conglomerate and Chapel Rock members seem to pinch out to the south, but the Miner's Castle member can be recognized throughout the entire outcrop belt by its small-scale cross-bedding, poor sorting, and high garnet content.

The basal conglomerate and Chapel Rock member represent a single transgressive-regressive cycle during which the seas advanced from the northwest and the source area was the Northern Michigan Highland. During Miner's Castle time the seas advanced rapidly from the southwest across the Wisconsin arch and Northern Michigan Highland and the principal source area was located to the northeast in Canada.

The distinctive heavy mineral suites in the Miner's Castle and Chapel Rock members permit a reasonably accurate correlation between the exposures at Pictured Rocks and the outliers in Dickinson County. Fossils found at several localities in the Miner's Castle member indicate that it may be correlated with the Franconia of Wisconsin. On the basis of stratigraphic position and heavy minerals the basal conglomerate and Chapel Rock members are considered to be equivalent to the Dresbach. A major unconformity separates the Munising formation from the overlying Middle Ordovician Au Train formation.

Bibliography

Atwater, G. I. (1935) The Keweenawan-Upper Cambrian unconformity in the upper Mississippi Valley: Kansas Geol. Soc. Guidebook, 9th Ann. Field Conf., pp. 316-319, fig. 214.

Atwater, G. I. & Clement, G. M. (1935) Pre-Cambrian and Cambrian relations in the upper Mississippi Valley: Geol. Soc. Am. Bull., v. 46, no. 11, pp. 1659-1686.

Bacon, L. O. (1957) Personal communication.

Bergquist, S. G. (1930) The occurrence of glauconite in the Hermansville formation of Alger County, Michigan: Mich. Acad. Sci., Arts, & Letters, Papers, v. 12, pp. 231-237.

Bergquist, S. G. (1931) Surface geology of Luce County, Michigan: Mich. Acad. Sci., Arts, & Letters, Papers, v. 14, pp. 437-452.

Bergquist, S. G. (1937) The Cambrian-Ozarkian contact in Alger County, Michigan: Mich. Acad. Sci., Arts, & Letters, Papers, v. 22, pp. 421-435.

Bramlette, M. N. (1929) Natural etching of detrital garnet: Am. Mineralogist, v. 14, no. 9, pp. 336-337.

Butler, B. S. & Burbank, W. S. (1929) Notes from the Copper Deposits of Michigan: U.S.G.S. Prof. Paper 144, 238 pp.

Case, E. C. & Robinson, W. I. (1915) The geology of Limestone Mountain and Sherman Hill in Houghton County, Michigan: Mich. Geol. & Biol. Survey, Pub. 18, pp. 168-181.

Cohee, G. V. (1945) Stratigraphy of Lower Ordovician and Cambrian rocks in the Michigan Basin: U.S.G.S. Oil & Gas Inves. Prelim. Chart no. 9.

Denning, R. M. (1949) The petrology of the Jacobsville sandstone, Lake Superior: Unpub. Master's thesis, Mich. College Min. & Tech., Houghton, Michigan.

Driscoll, E. G., Jr. (1956) An environmental and heavy mineral study of the "Eastern Sandstones" between Marquette and Grand Marais, Michigan: Unpub. Master's thesis, Univ. Nebraska, Lincoln, Nebraska.

Foster, J. W. & Whitney, J. D. (1850) Report on the geology and topography of a portion of the Lake Superior land district in the State of Michigan; Pt. 1, Copper lands: U.S. 31st Congr., 1st Sess. H. Exec. Doc. 69.

Foster, J. W. & Whitney, J. D. (1851) Report on the geology of the Lake Superior land district; Pt. 2, the iron region, together with the general geology: U.S. 32nd Congr., Spec. Sess. S. Exec. Doc. 4.

Fuller, G. N. (1928) Geological Reports of Douglass Houghton: Mich. Hist. Comm.

Grabau, A. W. (1906) Types of sedimentary overlap: Geol. Soc. Am. Bull., v. 17, pp. 567-636 [see p. 583].

Hotchkiss, W. O. (1923) The Lake Superior geosyncline: Geol. Soc. Am. Bull., v. 34, no. 4, pp. 669-678.

Hotchkiss, W. O. (1933a) Lake Superior Region: 16th Internat. Geol. Congr., Guidebook 27, Excursion C-4.

Hotchkiss, W. O. (1933b) Personal communication to F. T. Thwaites, cited in Thwaites (1934).

Hotchkiss, W. O., Rooney, W. J. & Fish, James (1923) Earth resistivity measurements in the Lake Superior copper country: Am. Inst. Min. Met. Eng., Tech Pub. no. 32.

Houghton, Douglass (1841) Fourth annual report of the State geologist: Mich. House of Representatives, Doc. no. 27, pp. 3-89.

Hultman, J. R. (1953) The Cambrian Sandstones, Marquette Quadrangle, Michigan: Unpub. Master's thesis, Univ. Mich., Ann Arbor, Mich.

Irving, R. D. (1874) On the age of the copper-bearing rocks of Lake Superior: Am. Jour. Sci., ser. 3, v. 8, pp. 45-50.

Irving, R. D. (1883) The copper-bearing rocks of Lake Superior: U.S.G.S. Mon. 5, pp. 161-166, 351-352.

Irving, R. D. (1888) On the classification of the early Cambrian and Pre-Cambrian formations: U.S.G.S. 7th Ann. Rept., pp. 365-454.

Irving, R. D. & Chamberlin, T. C. (1885) Observations on the junction between the eastern sandstone and the Keweenawan series on Keweenaw Point, Lake Superior: U.S.G.S. Bull. 23, pp. 385-498.

Knight, S. H. (1929) The Fountain and Casper formations of the Laramie Basin: Univ. Wyo. Pub. Sci. GeoL, v. 1, no. 1, pp. 1-82.

Landes, K. K. (1942) Unpublished report to the Michigan Geological Survey on the geology exposed by new construction at Sault Ste. Marie.

Lane, A. C. & Seaman, A. E. (1907) Notes on the geological section of Michigan, Pt. 1; The pre-Ordovician: Jour. Geol., v. 15, pp. 680-695.

Leith, C. K., Lund, R. J. & Leith, A. (1935) Pre-Cambrian rocks of the Lake Superior region: U.S.G.S. Prof. Paper 184, pp. 1-31.

Leverett, Frank (1910) Surface geology of the Northern Peninsula of Michigan: Mich. Geol. Biol. Survey, pub. 7, geol. ser. 5, pp. 1-86.

Leverett, Frank (1917) Surface geology and agricultural conditions of Michigan; Pt. 1, The surface geology of Michigan: Mich. Geol. Biol. Survey, pub. 25, pp. 47-100.

Leverett, Frank (1929) Moraines and shore lines of the Lake Superior region: U.S.G.S. Prof. Paper 154A, pp. 1-72.

Martin, L. (1911) The geology of the Lake Superior Region: U.S.G.S. Mon. 52, pp. 85-116.

McKee, E. D. (1940) Three types of cross-lamination in Paleozoic rocks of northern Arizona: Am. Jour. Sci., v. 238, no. 11, pp. 811-824.

McKee, E. D. (1953) Report on studies of stratification in modern sediments and in laboratory experiments: U.S. Office of Naval Research Project Nonr. 164(00), NR 081 123, pp. 1-59.

McKee, E. D. & Weir, G. W. (1953) Terminology for stratification and cross-stratification in sedimentary rocks: Geol. Soc. Am. Bull., v. 64, no. 4, pp. 381-389.

Murry, R. C. (1955) Late Keweenawan or Early Cambrian glaciation in upper Michigan: Geol. Soc. Am. Bull., v. 66, pp. 341-344.

Oetking, P. F. (1951) The relation of the Lower Paleozoic to the older rocks in the Northern Peninsula of Michigan: Unpub. Ph.D. thesis, Univ. Wisc., Madison, Wisconsin.

Olson, J. S. & Potter, P. E. (1954) Variance components of cross-bedding direction in some basal Pennsylvania sandstones of the eastern interior basin: statistical methods and geologic application: Jour. Geol., v. 62, no. 1, pp. 26-73.

Pumpelly, Raphael & Brooks, T. B. (1872) On the age of the copper-bearing rocks of Lake Superior: Am. Jour. Sci., ser. 3, v. 3, pp. 428-432.

Raasch, G. O. (1950) Current evaluation of the Cambrian-Keweenawan boundary: Illinois State Acad. Sci., Trans., v. 43, pp. 137-150.

Reiche, Parry (1938) An analysis of cross-lamination; The Coconino sandstone: Jour. Geol., v. 46, no. 7, pp. 905-932.

Roberts, Ellis (1940) Geology of the Alston district, Houghton and Baraga Counties, Michigan: Unpub. Master's thesis, Calif. Inst. Tech., Pasadena, California.

Rominger, C. L. (1873) Paleozoic Rocks: Mich. Geol. Survey, v. 1, pt. 3, 1869-1873, pp. 7-102.

Schoolcraft, H. R. (1821) Narrative journal of travels through the northwestern regions of the United States (Albany, N.Y.), 419 pp.

Smith, R. A. (1916) Mineral resources of Michigan; Pt. 3, Deep well borings: Mich. Geol. Biol. Survey, pub. 24, pp. 210-256.

Spiroff, K. (1956) Personal communication.

Stauffer, C. R. (1927) Age of the Red Clastic series of Minnesota: Geol. Soc. Am. Bull., v. 38, no. 3, pp. 469-477.

Stokes, W. L. (1953) Primary sedimentary trend indicators as applied to ore finding in the Carrizo Mountains, Arizona and New Mexico; Pt. 1, Technical reports for April 1, 1952 to March

31, 1953: U.S. Atomic Energy Comm., RME-3043 (Pt. 1), pp. 1-46.

Stumm, E. C. (1956) Upper Cambrian trilobites from Michigan: Contrib. Mus. Paleont., Univ. Mich., v. 13, no. 4, pp. 95-102.

Thompson, W. O. (1937) Original structures of beaches, bars, and dunes: Geol. Soc. Am. Bull., v. 48, no. 6, pp. 723-752.

Thwaites, F. T. (1912) Sandstones of the Wisconsin coast of Lake Superior: Wisc. Geol. Nat. Hist. Survey, Bull. 25, pp. 1-109.

Thwaites, F. T. (1931) Buried pre-Cambrian of Wisconsin: Geol. Soc. Am. Bull., v. 42, no. 3, pp. 719-750.

Thwaites, F. T. (1934) Well logs in the Northern Peninsula of Michigan, showing the Cambrian section: Mich. Acad, Sci., Arts, & Letters, Papers, v. 19, pp. 413-426.

Thwaites, F. T. (1935) Road log for Monday, September 2. Post-Conference Alternate Trip No. 2: Kansas Geol. Soc. Guidebook, 9th Ann. Field Conf., pp. 221-228.

Thwaites, F. T. (1943) Stratigraphic work in northern Michigan, 1933-1941: Mich. Acad. Sci., Arts, & Letters, Papers, v. 28, pp. 487-502.

Tyler, S. A., Marsden, R. W., et al. (1940) Studies of the Lake Superior pre-Cambrian by accessory-mineral methods: Geol. Soc. Am. Bull., v. 51, no. 10, pp. 1429-1537.

Ulrich, E. O. (1936) Personal communication to Prof. George M. Ehlers, dated March 9, 1936.

Van Hise, C. R. (1893) An historical sketch of the Lake Superior region to Cambrian time: Jour. Geol., v. 1, no. 2, pp. 113-129.

Van Hise, C. R. & Bayley, W. S. (1895) Preliminary report on the Marquette iron-bearing district of Michigan: U.S.G.S. 15th Ann. Rept., pp. 477-650.

Van Hise, C. R. & Bayley, W. S. (1900) Description of the Menominee quadrangle: U.S.G.S. Geol. Atlas, Menominee folio (no. 62).

Van Hise, C. R. & Leith, C. K. (1911) The geology of the Lake Superior region: U.S.G.S. Mon. 52, 641 pp.

Vanlier, K. (1956) Personal communication.

Ver Wiebe, W. A. (1927) Stratigraphy of Chippewa County, Michigan: Mich. Acad. Sci., Arts, & Letters, v. 9, pp. 309-331.

Wadsworth, M. E. (1880) Notes on the geology of the iron and copper districts of Lake Superior: Harvard Coll., Mus. Comp. Zool., Bull. 7, pp. 1-157.

Wadsworth, M. E. (1892) Report of the State Board of Geological Survey for the years 1891 and 1892: Michigan Geol. Survey, Annual Reports of the State Geologist, Chapter 7, pp. 156-167.

Winchell, Alexander (1861) First Biennial report of the progress of the Geological Survey of Michigan (Lansing), 339 pp.

Winchell, N. H. (1895) A rational view of the Keweenawan: Am. Geologist, v. 16, pp. 150-162.

STATE OF MICHIGAN

DEPARTMENT OF CONSERVATION
Gerald E. Eddy, Director

GEOLOGICAL SURVEY DIVISION
William L. Daoust, State Geologist

SPEAKER-HINES AND THOMAS, INC.
PRINTERS - LITHOGRAPHERS - BOOKBINDERS
LANSING - 1958