MASSIVE SANDSTONE FACIES

General Features

The term "massive sandstone facies" is applied to the part of the Jacobsville formation which is distinguished by massive and relatively persistent bedding. Excellent exposures of this facies are found at Victoria Falls, Hungarian Falls, and in many of the shore cliffs in Keweenaw Bay. It is also recognized in several localities along the coast west of Big Bay and in parts of the section on the west and north sides of Grand Island. Exposures of the base and top of the massive sandstone facies were nowhere found in the same area so its maximum thickness is not known. At Victoria Falls a measured section 692 feet thick consists almost entirely of massive sandstone beds more than 10 feet thick. Elsewhere many shore cliffs are composed entirely of massive sandstone indicating that this facies constitutes an appreciable part of the Jacobsville formation.

The color of the massive sandstone facies in most outcrops is light shades of red, reddish-brown, pink or white. Solid colors predominate but the conspicuous white mottling so striking in the lenticular sandstone facies is lacking in many exposures. Some beds are a dark purple with minor irregular white mottling. It is very likely that the predominance of light red, pink and white and very little mottling is due to the more permeable nature of the massive beds which allowed relatively free circulation of ground water solutions which reduced much of the iron.

Sedimentary Structures

BEDDING.—The average thickness of the beds in the massive sandstone facies is approximately 5 feet, although beds more than 18 feet thick were noted in the Victoria Falls section (fig. 20). Most of the bedding planes which separate these massive units are weak and non-resistant so they have been accentuated by weathering and are very conspicuous. Within most of the massive sandstone beds some indication of either horizontal or cross-stratification is shown, especially near their base. This lamination is most commonly expressed by a change in color associated with a slight textural variation. In other massive units lamination is entirely absent and the bed appears to be completely structureless.

The cross-stratification is predominately small scale as the sets of cross-strata range from 8 to 10 inches in thickness. Much of the cross-bedding is very difficult to detect, however, because the laminations have not been accentuated by differential weathering and may be masked by the darker color to which the fresh rock weathers. Exposures of the cross-stratification are almost everywhere limited to vertical cliffs as the sets of small-scale cross-bedded units are incorporated in the massive beds which characteristically maintain a vertical face. Thus, exposures of cross-stratification in three dimensions are uncommon and it is difficult to determine the true form of the lamination. Both planar and trough cross-stratification have been recognized, but the trough type seems to be most abundant.

RIPPLE MARKS.—Oscillation ripple marks are in the massive sandstone facies in several localities. Where the exposures are continuous, a single zone of perfectly symmetrical ripple marks may be traced laterally for several hundred feet. The average ripple has a wave length of 2.5 inches and an amplitude of 0.5 inch. Most of the crests are sharp and the troughs are smooth with no indication of secondary crests. In some areas along the west shore of Keweenaw Bay oscillation ripple marks having the same amplitude and wave length were found at numerous horizons which indicates a relatively constant relationship between water depth and wave energy throughout the period of deposition.

Current and interference ripple marks are also found in the massive sandstone facies but are not nearly so common as the oscillation type.

Interpretation

The massive sandstone facies is believed to have been developed in a lacustrine environment associated with the fluvial deposition of the lenticular sandstone facies. This environment is indicated by the massive and continuous nature of the bedding plus the lateral persistence of oscillation ripple marks. The complete absence of channel and fill structures and fluvial trough cross-stratification also tends to support this conclusion. It appears from the distribution of the massive sandstone facies that the lacustrine environment was more removed from the source area than the lenticular sandstone facies, and existed only intermittently in the central part of the inter-mountain basin in which the Jacobsville formation accumulated.

In the small exposures a detailed study of the stratigraphic relationship of the massive and lenticular sandstone facies cannot be made. They are, in part, time equivalent and they appear to interfinger to a certain extent in some outcrops. In the most extensive exposures, however, such as Victoria Falls and Keweenaw Bay, the massive sandstone facies appears to be higher in the section than the lenticular sandstone facies. The evidence is far from conclusive, but suggests a change during deposition of the Jacobsville formation from a predominantly fluvial to lacustrine environment.

RED SILTSTONE FACIES

At Agate Falls and in the cliffs west of Laughing Fish Point, the Jacobsville formation is composed predominantly of red siltstone and shale. This facies is also in several exposures along the coast north of the town of Jacobsville, but elsewhere it is completely absent or occurs only in minor amounts. The section at Agate Falls is 80 feet thick and is composed of alternating beds of thin platy shale and silty sandstone. The bedding in the shale is horizontal and can be traced laterally throughout the entire exposure. Large mica flakes are abundant and give the red shale a satiny luster where broken along the bedding. A characteristic of the siltstone and shale is that it shows a greater intensity of red coloration and that it lacks the white mottling so common to the coarser sediments in the Jacobsville formation. The interbedded sandstone units contain small-scale trough cross-bedding similar to the type of cross-bedding in the lenticular sandstone facies.

The nature of the environment represented by the red siltstone facies is not clearly understood. The horizontal bedding and the fineness of grain suggest that the deposit accumulated in a lacustrine environment free from strong currents. On the other hand, the sedimentary structures of the interbedded sandstone are identical to structures in the lenticular sandstone facies and suggest a fluvial environment. In several exposures the red siltstone facies is associated with the massive sandstone facies and probably represents alternating fluvial and lacustrine deposition during the later phases of Jacobsville sedimentation.

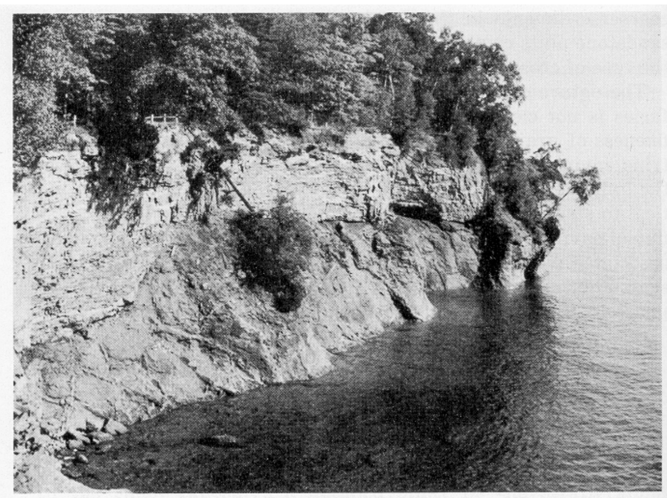


Figure 21. Unconformity between the Jacobsville formation and Precambrian peridotites at Presque Isle.

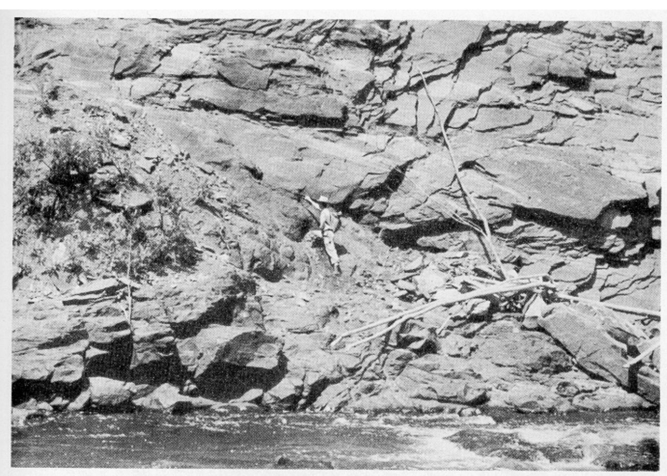


Figure 22. Jacobsville-Keweenawan unconformity at Sturgeon Falls showing the top of a basaltic hill covered with the Jacobsville sandstone. Note the primary dip of the Jacobsville away from the old Precambrian high.

THE PRE-JACOBSVILLE EROSIONAL SURFACE

Exposures of the basal contact of the Jacobsville formation are not widespread but are almost entirely in the area bordering the northern half of the Precambrian highlands. Between Marquette and Big Bay the pre-Jacobsville surface has been developed, for the most part, on massive homogeneous granitic rocks cut by numerous basic dikes. Excellent exposures are at Presque Isle, Partridge Island, Wetmore Landing, Thoney Point, Garlic Island, Granite Point, and on the west side of Big Bay (figs, 9, 21). These outcrops show rounded hills and knobs of granite partly covered with Jacobsville sediments and indicate that the Precambrian surface was highly irregular at the time the Jacobsville was deposited. At Thoney Point the hills are rugged and steep extending almost vertically as high as 120 feet above the lake. Elsewhere only the top 30 to 40 feet of the Precambrian hills are exposed but contours on the lake bottom suggest that the base of many of these hills is over 60 feet below the water level. Erosional remnants of the Jacobsville at an elevation of approximately 1,000 feet indicate that the local relief of the pre-Jacobsville surface was at least 400 feet. The highest exposures were found in the rapids of Chocolay River in the NE ¼, NW ¼, sec. 36, T. 46 N., R. 24 W. Other isolated outcrops found in valleys and around the flanks of hills suggest that much of the present surface in the vicinity of Marquette is an exhumed topography and was developed, for the most part, before the Jacobsville was deposited. West of the Huron Mountains several outcrops show hills and knobs of the pre-Jacobsville erosional surface developed on Middle Keweenawan basalts and Michigamme slates (figs. 22, 23). The form of these hills is very similar to the form of hills developed on the granites in the Marquette area.

From these data the pre-Jacobsville erosional surface appears to be similar in many respects to the present topography in the Precambrian highlands. Martin (1911, p. 90) describes the Precambrian highlands as a peneplain with monadnocks seldom higher than 400 feet, but the relief of the pre-Jacobsville surface was probably somewhat greater since the Precambrian highlands have been subjected to several cycles of erosion. Variations in the thickness of the Jacobsville indicate that the maximum relief of the pre-Jacobsville erosional surface is over 2,000 feet.

In many places a zone of weathered debris as much as 6 feet thick separates the Jacobsville from the underlying Precambrian. This zone appears to be a paleoregolith formed by subaerial weathering on the pre-Jacobsville erosional surface (figs. 24, 25). Its local absence is probably due to stream erosion accompanying Jacobsville deposition. Residual boulders resulting from deep chemical weathering are found near the basal part of the regolith where it passes gradationally downward into the less weathered rock. These boulders are highly altered to residual clay and quartz but some of the larger fragments retain a solid core. The contact between the regolith and the Jacobsville is nearly everywhere sharp and distinct although much of the material from the regolith has been reworked and incorporated into the basal units of the Jacobsville. By and large the regolith is much softer than either the Precambrian or the Jacobsville and is commonly eroded into small lenticular caves by wind and waves. The significance of the regolith containing residual boulders is that it indicates a considerable period of predominantly chemical weathering prior to Jacobsville sedimentation.

Figure 23. Close-up of the contact between the Jacobsville formation and Middle Keweenawan basalts at Sturgeon Falls. Note the weathered nature of the basalt and the small stringers filled with Jacobsville sandstone.

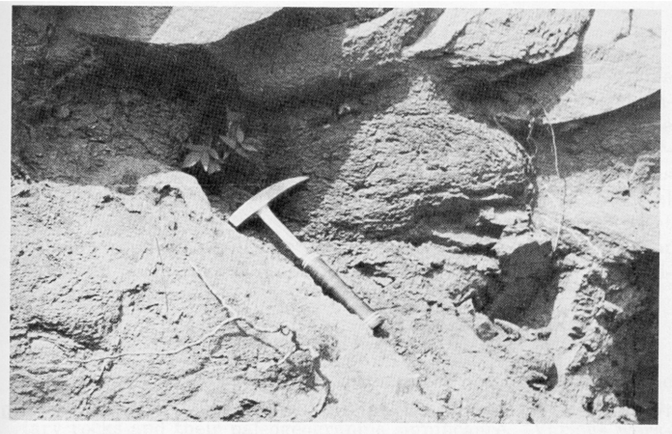


Figure 24. Zone of weathered debris between the Jacobsville formation and Middle Keweenawan basalts at Sturgeon Falls, SW ¼, sec. 16, T. 49 N., R. 35 W. Note the large residual boulder included in the weathered zone.

PALEOGEOGRAPHY

The location and nature of the source area of the Jacobsville formation can be established rather accurately by several independent lines of evidence. Cross-bedding dip directions, the shape of the Jacobsville formation, structural trends of the underlying Precambrian rock, composition of the Jacobsville, variations in thickness of the overlying Munising formation and geophysical data all indicate that the source of the Jacobsville was an east-west trending highland which extended through the central part of Northern Michigan and connected the Wisconsin Arch with a positive area in Canada.

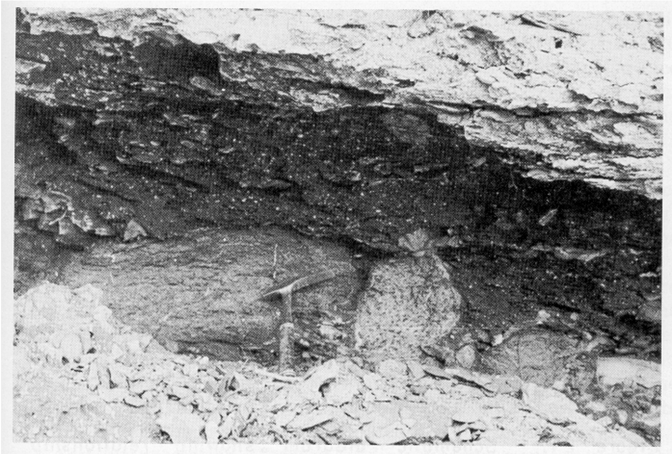


Figure 25. Jacobsville-Precambrian contact showing zone of weathered debris containing large residual boulders of granite. Exposure is located along the coast of Lake Superior two miles north of Thoney Point.

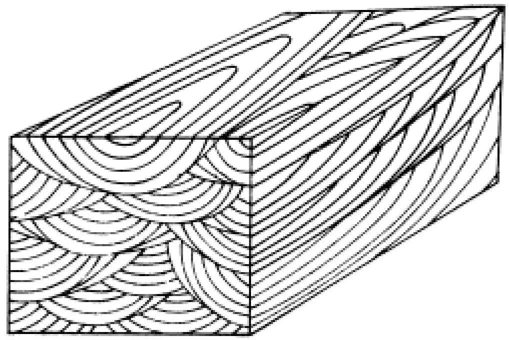


Figure 26. Block diagram showing fluvial trough cross-bedding as it appears on horizontal, transverse and axial sections.

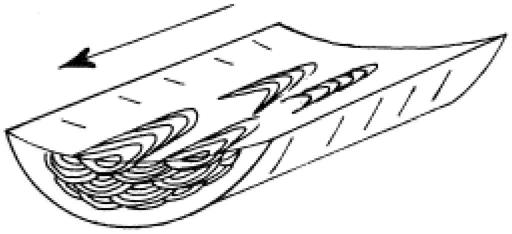


Figure 27. Schematic diagram showing relationship of fluvial trough cross-bedding to stream flow direction and stream channel.

LOCATION OF THE SOURCE AREA

In recent years considerable advancement has been made in the study and understanding of the directional properties of sedimentary rocks and their paleogeographic significance. Various workers have shown that by systematically mapping the attitude of cross-bedding it is possible to determine the regional slope at the time the sediment was deposited and thereby establish the trend of ancient shore lines or the location of probable source areas.

The cross-stratification in the Jacobsville formation is predominantly the trough type (McKee & Wier, 1953, p. 387). Figures 26 and 27 show idealized block diagrams illustrating the appearance of the trough cross-strata on the horizontal, transverse and axial sections and its relationship to the direction of current flow. The horizontal section is by far the best for directional measurements as the direction of stream flow is the direction in which the trough plunges. Accurate directional measurements on the vertical section are difficult and often impossible to make because of the difficulty in distinguishing apparent dip from true dip when the structure is not exposed along the axial plane.

Dip direction measurements were made at every outcrop where trough cross-bedding was exposed sufficiently in three dimensions to permit the determination of the direction of plunge. Measurements made on one stratigraphic unit were analyzed separately and then combined with measurements from other units in the same locality. The mean and standard deviation for all measurements made in each township were calculated and plotted on a map.

Any interpretation of cross-bedding measurements beyond the indication of regional slope is dependent upon a correct interpretation of the environment in which the cross-bedding was formed. In the Jacobsville formation the trough cross-bedding is considered to have developed in stream channels (see section on cross-bedding of lenticular sandstone facies); therefore, a measurement of the direction of plunge is actually a measurement of the direction of stream flow.

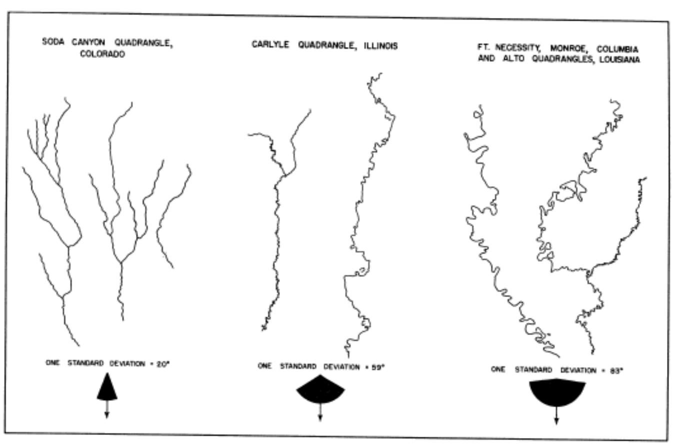


Figure 28. Relationship between stream patterns and the standard deviation of the direction of sediment transport.

Theoretically, therefore, if one could make a large number of measurements on a rock surface of a single age and over a broad area, a skeleton drainage pattern would be developed when the dip directions were plotted on a map. A large number of measurements taken and mapped for each formation of the stratigraphic section would consequently result in a series of drainage patterns superimposed one above another.

In an effort to establish a basis for the interpretation of random measurements of the direction of stream flow, which is in essence what one measures when he measures the dip direction of fluvial trough cross-stratification, random measurements were made on the direction of stream flow on three different types of streams. This was done on selected topographic maps by measuring the stream flow direction at every place a section line crossed the stream. The results are shown in figure 28 and clearly indicate that the size of the standard deviation of the direction of stream flow is directly proportional to the amount of meandering in the stream pattern. One is, therefore, able to interpret certain paleogeologic characteristics from the size of the standard deviation and the nature of any changes in the standard deviation from locality to locality and throughout the stratigraphic section.

If sampling is made in a very restricted stratigraphic zone, it is possible to detect changes in the nature of the stream from place to place. The largest standard deviations would be expected to result from highly meandering streams far removed from the source area and as the sampling approached the source area the standard deviation would be expected to become smaller. Changes in the standard deviation throughout the section at one locality would reflect the development of the physiography of the source area.

The results of cross-stratification studies in the Jacobsville formation are shown in figure 29. It is apparent from the average dip direction that the regional slope in the Lake Superior district during Jacobsville time was northward toward the Canadian Shield and that the source of the Jacobsville sediments was south of the present outcrop belt.

A second and highly significant finding is that very little dispersion in the average direction of sediment transport is in the southern outcrops between Marquette and Parisian Island, whereas appreciable dispersion is noted in the northern outcrops along the Keweenaw Peninsula. At every locality in the southern part of the outcrop belt the direction of stream flow at the time the Jacobsville was deposited was from south to north. This indicates that the source area was an elongated east-west trending highland. The extremely small standard deviation of the cross-bedding direction in the southern exposures suggest steep gradients and straight stream courses indicative of a source area only a few miles south of the present outcrop belt. This conclusion is consistent with the larger standard deviation in the direction of sediment transport and the greater dispersion of the averages for the readings taken at the northern outcrops in the Keweenaw Peninsula. The larger standard deviation indicates greater stream meandering, and a greater dispersion of the average directions for this area suggests a greater diversity in the general direction of the course of each stream. This dispersion likely resulted from a fanning out of the streams into the basin of deposition.

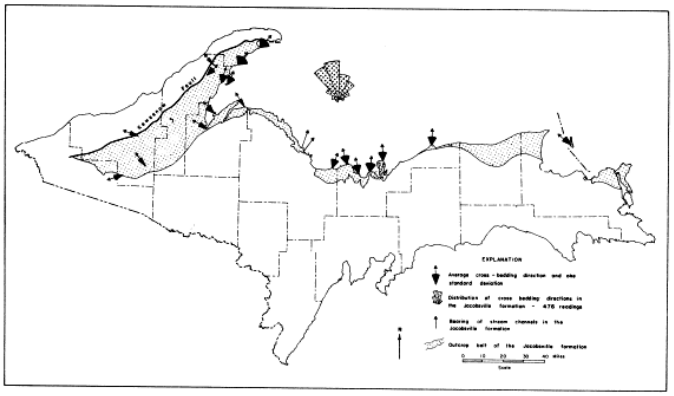


Figure 29. Cross-bedding directions in the Jacobsville formation.

A southern source is also indicated by regional variations in the thickness of the Jacobsville formation. Although data are not sufficient to permit construction of a detailed isopach map, available information indicates that the Jacobsville formation is roughly wedge-shaped and pinches out completely to the south (fig. 2). The thickness of the Jacobsville decreases from over 1,800 feet in the vicinity of Sault Ste. Marie to less than 50 feet at Neebish Island. A similar increase in thickness to the north and pinch out to the south is indicated by well data in Keweenaw Bay area and in the western part of Alger County. Exposures of the basal contact show that the decrease in thickness towards the south is due to progressive overlap. Isopach lines of the Jacobsville formation are therefore parallel to the contour lines of the underlying Precambrian surface and indicate a highland extending through Northern Michigan.

Variations in the thickness of the Munising formation which directly overlies the Jacobsville reflect the position of part of the highland at the time of the first advance of the Paleozoic seas (fig. 30). Although in much of the Northern Peninsula no information concerning the thickness of the Munising formation is available, data from a number of drill-hole cores obtained from several mining companies supplement the data available from well logs and measured sections, so that regional differences in thickness may be estimated. Thinning of the Munising formation from over 200 feet at the northern and southern shore of the Northern Peninsula to less than 50 feet in the center of the Peninsula establishes the approximate position of the east-west trending highland and indicates that parts of it were high during the deposition of the basal part of the Upper Cambrian sequence.

One of the most conclusive evidences that the source area of the Jacobsville formation was very close to the present outcrop belt is the composition of the conglomerate facies. Pebble counts indicate that the differences in composition may be correlated directly with local differences in the lithology of the Precambrian rocks immediately to the south (see section on conglomerate facies). In addition the angularity of pebbles and the inclusion of clay pebbles and blocks, and in places, sandstone pebbles, indicates a local derivation and short transport for the Jacobsville sediments.

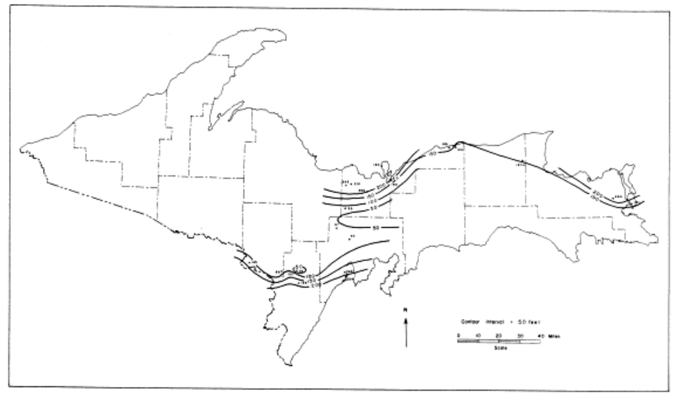


Figure 30. Isopach map of the Munising formation.

Structural trends in the exposed Precambrian rocks and geophysical data are consistent with the pebble data in indicating the position and extent of the source area of the Jacobsville formation. Throughout the Precambrian highlands in Northern Michigan an east-west structural trend in the Huronian rocks is indicated by the Marquette syncline, the Felch trough, and the Menominee trough. The eastward extension of these structural features is concealed by the cover of Paleozoic rocks of the Michigan basin, but similar trends reappear in the Precambrian rock of Canada exposed across the St. Mary's River. This strongly indicates a predominant east-west trend for the structure of the Precambrian rocks beneath the Paleozoic cover and suggests the possibility of a buried east-west mountain range.

Gravity work done by Bacon (1956) and his students indicates an east-west trending gravity high extending from the Precambrian highlands to Canada (fig. 31). The gravity highs could be explained, in part, by a buried Precambrian ridge extending from the Wisconsin Arch to Canada. The gravity low to the north would then result from burial of the dense Precambrian rocks beneath several thousand feet of Jacobsville sediments.

In summary, the position and extent of the source area of the Jacobsville appears to be well established from a large variety of independent evidence. This highland was a major structural feature apparently developed during the Killarney revolution. Inasmuch as the positive area extended through the major part of the Northern Peninsula of Michigan and connected the Wisconsin Arch with Canada, it seems appropriate that it be called the Northern Michigan Highland.

NATURE OF THE SOURCE AREA

The lithology of the Northern Michigan Highland differed considerably from place to place. In some areas granitic rocks predominated as indicated by the abundance of feldspar and vein quartz in the lower part of the

Jacobsville formation. Elsewhere the acidic and basic flows were important rock types in the source area, which accounts for the composition of the conglomerate facies in the area of the Wall Ravine and in several areas near the South Trap Range. The quartzite pebbles in parts of the conglomerate facies and sand grains composed of quartzite fragments in the sandstone facies indicate that meta-sediments were also abundant. Sandstone pebbles having a gross lithology similar to the Freda were found in a number of localities and strongly suggest that parts of the source area were once covered by the Freda sediments. The high quartz content of the Jacobsville supports this theory as one would expect a greater diversity in mineralogy if the source area consisted of granitic and metamorphic rocks exclusively.

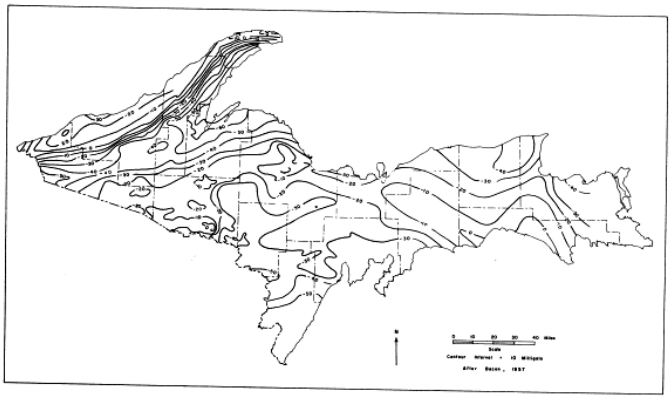


Figure 31. Bouguer gravity anomaly map of Northern Michigan.

From this information it appears that the present Precambrian highlands in Michigan and Canada closely represent the rock types which were eroded to produce the Jacobsville formation.

The source area was apparently technically active during most of Jacobsville time as the direction of sediment transport during the entire period of deposition is remarkably constant. When the cross-bedding dip directions taken on a restricted horizon are combined with other horizons in the same section, the overall standard deviation is only slightly larger than the standard deviation obtained from the individual restricted horizon. If the source area were uplifted and had remained stable during erosion, one would expect a larger standard deviation to result from the increased meandering in the streams during the later phases of deposition. This should be reflected in a larger standard deviation in the cross-bedding directions in the younger strata of the Jacobsville. Since no increase in the standard deviation was detected in the upper part of the section, it is quite probable that the source area was continually being uplifted so that the high regional gradient and the relatively straight courses of the depositing streams were maintained.

AGE AND CORRELATION

The age of the Jacobsville has been a matter of conjecture for many years because of the complete absence of fossils and the limited number of exposures showing its stratigraphic relationship with older and younger rocks. Many of the early geologists considered the Jacobsville to be Upper Cambrian in age because of the apparent gradation between it and the overlying St. Croixan series. Houghton (1841) and Hotchkiss (1933), however, recognized the unconformity at Grand Island between the Upper Cambrian and the Jacobsville. Unfortunately Houghton later reversed his opinion regarding this relationship and Hotchkiss failed to publish his findings so that the tradition of the Upper Cambrian age for the Jacobsville continued. Thwaites (1912, p. 62) questioned the Cambrian age of the Jacobsville and suggested the possibility of its being uppermost Keweenawan. He based his conclusions upon an apparent gradational contact between the Bayfield (considered equivalent to the Jacobsville) and the arkosic sediments of accepted Upper Keweenawan age.

The present study confirms the early reports of an unconformity between the Jacobsville and Upper Cambrian rocks. In the cliffs surrounding Grand Island the Jacobsville dips to the north at an angle between 4 and 6 degrees, whereas the overlying Munising formation dips southward. In addition, a widespread basal conglomerate in the Munising formation truncates numerous clastic dikes in the Jacobsville. This unconformity indicates a major break in sedimentation between the Jacobsville sandstone and the Upper Cambrian sequence. The fundamental problem, therefore, is whether the Jacobsville is genetically, stratigraphically, and structurally associated with the Keweenawan series or is independent of it.

FACTORS FAVORING KEWEENAWAN AGE

In Northern Michigan no evidence was found to indicate that the Jacobsville is Upper Keweenawan in age. The great Keweenaw fault separates the Jacobsville from the Upper Keweenawan sediments so that their stratigraphic relationships cannot be studied in Michigan. The only area where the stratigraphic relationship of the Upper Keweenawan sequence can be studied in outcrops is in Wisconsin; therefore, those favoring a Keweenawan age for the Jacobsville must first accept its equivalence to part of the Bayfield group. This correlation, which seems plausible, is based entirely on lithologic similarities and cannot be proved because of lack of areal continuity and lack of fossils. Even if the correlation of the Bayfield and the Jacobsville is accepted, the evidence presented by Thwaites (1912, p. 62) that the Bayfield is Upper Keweenawan is very scanty. Thwaites (1912, p. 62) states as follows:

> "Outcrops are so scarce that we can at no place trace the two sandstone groups to a point of contact where their relations may be absolutely determined. But it is

possible to find exposures where we should expect to find the contact of the Bayfield and the Oronto (Upper Keweenawan) groups. At all these localities there is a conformable gradation from quartz sandstone of the general type of the Bayfield group downward into red shales and arkose sandstone or conglomerate of the same general type as the main body of the Oronto group."

When it is realized that the Jacobsville (and probably the Bayfield group) is not part of the St. Croixan series, much of the case for favoring their Keweenawan age disappears because the bulk of the argument favoring Keweenawan age indicates only that the Bayfield, Jacobsville, or Red elastics are not Upper Cambrian. Thus, the evidence suggested by Thwaites remains the best reason for assigning the Jacobsville to the Keweenawan series.

EVIDENCE OPPOSING KEWEENAWAN AGE

The Jacobsville and Upper Keweenawan rocks were apparently derived from widely separated source areas and are, therefore, not genetically related. The southern source for the Jacobsville formation is well established by cross-bedding dip directions, regional thinning, composition, and other criteria (see section on paleogeography). The Keweenawan rocks, however, appear to have been derived from a northern source. Hotchkiss (1923, p. 671), from a study of the primary structures in the Keweenawan rocks, concludes that the regional slope during Keweenawan time was from north to south and that the lavas and sediments were derived from a source area north of the present outcrops. This marked change in the regional slope indicates that a period of considerable regional tilting or diastrophism occurred between Upper Keweenawan and Jacobsville time.

Differences in composition between the Jacobsville and Upper Keweenawan sandstones also indicate that they were derived from different sources and are not part of the same sequence. Thwaites (1912, p. 51) describes the Upper Keweenawan sediments as being "mainly composed of angular to subangular fragments derived from igneous rocks without much chemical decomposition." These sandstones are repeatedly referred to as "arkosic" and differ greatly in composition from the Jacobsville sandstones. The only place where the Jacobsville formation has a high feldspar content is near the basal contact with granitic rocks. Throughout the rest of the section the Jacobsville consists primarily of rounded quartz grains. This indicates that the Jacobsville is more mature than the Keweenawan sediments and may be in part a second-cycle sand. With the presence of sandstone pebbles very similar to the Freda imbedded in the Jacobsville, a very likely source for much of the quartz in the Jacobsville formation is the sediments of the Upper Keweenawan series.

In the Sturgeon Falls area horizontal Jacobsville sandstones lie unconformably upon Middle Keweenawan basalts which dip approximately 10 degrees to the northwest. This contact indicates that the Middle Keweenawan rocks were tilted, weathered, and eroded prior to the deposition of the Jacobsville formation. Since the contact between the Upper and Middle Keweenawan rocks shows no angular discordance, it is highly probable that the tilting of the basalts at Sturgeon Falls took place after the deposition of the Upper Keweenawan sediments. The strike and dip of the basalts in the Sturgeon Falls area suggests that tilting was produced by the same forces which folded the Keweenawan series into a syncline. If the Jacobsville is considered part of the Keweenawan series, the relationships at Sturgeon Falls become very difficult to explain.

Suggestions of an angular unconformity between the Freda and Jacobsville formation are also found in several outcrops in Whit-fish Bay. Along the Canadian coast between Goulais Point and Batchawana Bay, sediments which are identical to the Freda in gross lithology, sedimentary structures, and heavy minerals consistently dip 10 to 12 degrees to the north, whereas exposures of the Jacobsville formation found inland and on the west side of Parisian Island are essentially horizontal. The distance between outcrops renders this evidence far from being conclusive but since the Jacobsville is characteristically undisturbed, except near the Keweenaw fault, the unconformable relationship appears quite probable.

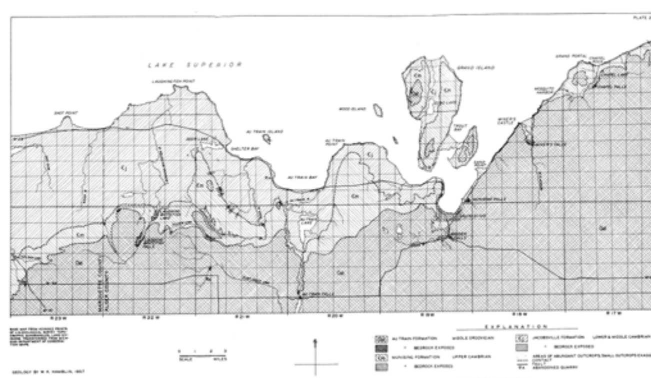


Plate 2. Geologic map of portions of Marquette and Alger counties, Michigan.

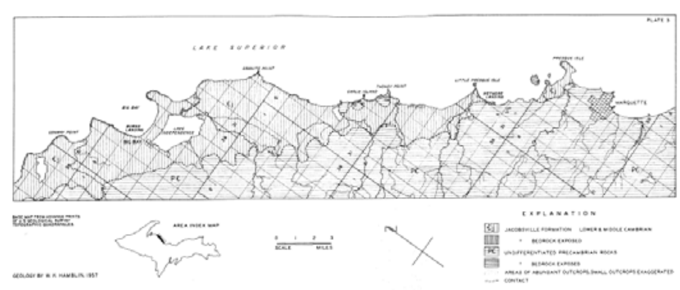


Plate 3. Geologic map of the coast of Lake Superior between Big Bay and Marquette.

CONCLUSION

The unconformity between the Jacobsville and Munising formations exposed at Grand Island proves that the Jacobsville is older than Upper Cambrian. It is impossible, however, to estimate the magnitude of this unconformity and to state whether the Jacobsville is Lower and Middle Cambrian or Upper Keweenawan. The evidence opposing the Keweenawan age for the Jacobsville, however, appears to be quite substantial. The writer, therefore, concludes that the Jacobsville formation represents continental deposition in an enclosed basin during the time marine sediments of Lower and Middle Cambrian age were being deposited in other parts of the continent.

THE PRE-MUNISING EROSIONAL SURFACE

The basal contact of the Munising formation is well exposed in numerous widely separated outcrops in Alger and Dickinson counties. In Alger County the Munising rests upon the Jacobsville formation, but in Dickinson County the Jacobsville is absent and the Munising formation lies directly upon the highly deformed Precambrian rocks.

Evidence that a major unconformity separates the Upper Cambrian from the Huronian (now Animikie) rocks in Dickinson County is so striking that it was one of the first features to be noted by the early geologists. The unconformable relationship of the Upper Cambrian and the Jacobsville formation is not nearly so evident and for many years geologists have considered the contact to be gradational. In the Grand Island area however, ample evidence, indicates that the Jacobsville in Northern Michigan was tilted and eroded prior to the advancement of the Munising seas. A low dip angular unconformity between the Jacobsville and Munising can be seen on the east side of Grand Island where the Jacobsville dips slightly to the north and the Munising dips a few degrees to the south. The unconformable relationship between the two formations is further indicated on the west side of Grand Island where clastic dikes in the Jacobsville sandstone are truncated by the basal conglomerate of the Munising formation (figs. 32, 33).

Inasmuch as the rock type and topographic expression of the pre-Munising erosional surface is distinctly different in the north and southwest, it seems desirable to consider these areas separately in describing the surface upon which the initial Upper Cambrian sediments were deposited.

SURFACE IN ALGER COUNTY

The Jacobsville-Munising contact is exposed in a number of small outcrops from Grand Marais to Skandia, but the most extensive and informative exposures are the shore cliffs which surround Grand Island. On the east and west sides of the island the contact can be traced for several miles without interruption. Although in many places the Jacobsville seems to be practically horizontal, a distinct northerly dip can be seen in the cliffs on the west side of Trout Bay (fig. 34). The erosional surface developed upon the slightly tilted Jacobsville is almost a straight line when seen on the vertical shore cliffs. The only irregularities are a few shallow undulations probably produced by channeling of the Munising sea. The contact of the Jacobsville with the overlying basal conglomerate is sharp and distinct with no evidence of a fossil soil or weathered zone. It is very probable that if a regolith was developed on the Jacobsville it was completely destroyed by wave action of the advancing sea.

A topographic map made from elevations established on the Jacobsville-Munising contact shows that, except for a southerly regional slope which was produced by subsidence of the Michigan Basin, the erosional surface developed on the Jacobsville formation is almost a featureless plane (fig. 35).

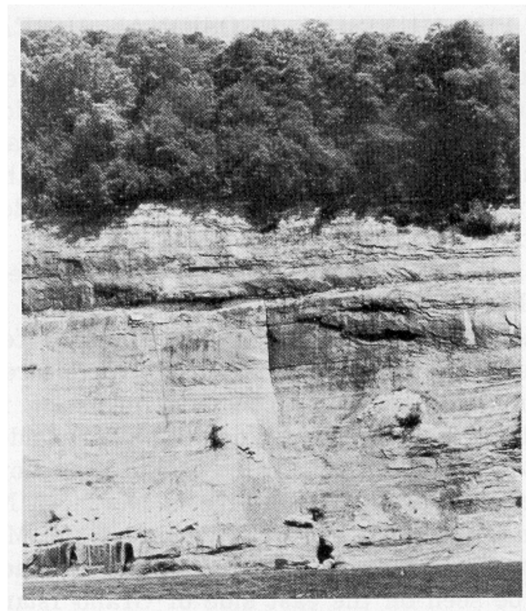


Figure 32. View of the west side of Grand Island showing clastic dikes in the Jacobsville formation (appearing as straight vertical lines in the photograph) truncated by the overlying Munising formation.

SURFACE IN DICKINSON COUNTY

Numerous outliers of the Munising formation have been found throughout most of Dickinson County and are known to extend westward as far as Iron River, Iron County. Many outliers expose the Munising-Precambrian contact and reveal that the pre-Munising erosional surface in this area is in striking contrast to the surface exposed in Alger County (fig. 36). The Precambrian rocks are highly deformed and erosion has developed a topography of considerable relief upon the older and more resistant rocks. In many respects the general features of this topography is very similar to the pre-Jacobsville erosional surface and it is probable that parts of it were formed during pre-Jacobsville time.

The isolated outcrops of the Munising sandstone are most commonly found capping the higher mountains but small patches of the sandstone are also in protected pockets in the valleys. An interesting example of this is at the Breen mine near Waucedah where a patch of sandstone is almost completely surrounded by hills of the iron formation. This suggests that the present topography of the Precambrian rocks is exhumed and only slightly modified by post-Paleozoic erosion.

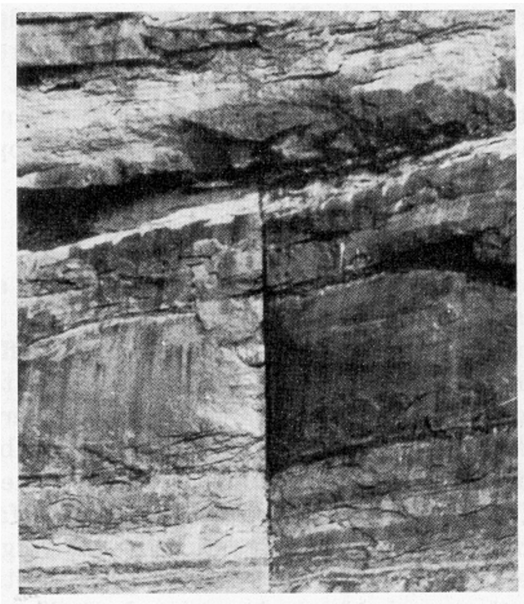


Figure 33. Telescopic picture of clastic dike in the Jacobsville formation which is truncated by the younger Munising formation.

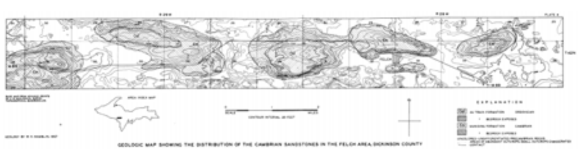


Plate 4. Geologic map showing the distribution of the Cambrian sandstones in the Felch area, Dickinson County.

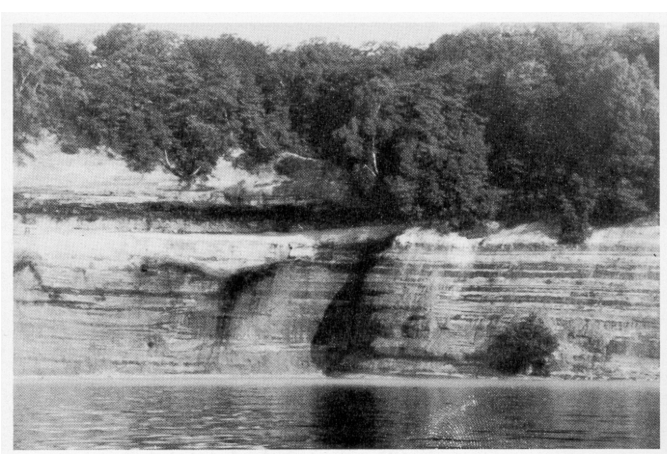


Figure 34. View of a part of the east coast of Grand Island showing the low dip angular unconformity between the Jacobsville and Munising formations. The alternating red and white beds of the Jacobsville show a slight northern dip component (to the right of photograph). The basal conglomerate of the Munising formation appears as the thick dark unit near the top of the picture. The section exposed in the cliffs is parallel to the strike of the Munising formation so the conglomerate appears to be horizontal. Actually the Munising formation dips toward the viewer so that it is at lake level a mile east of this exposure.

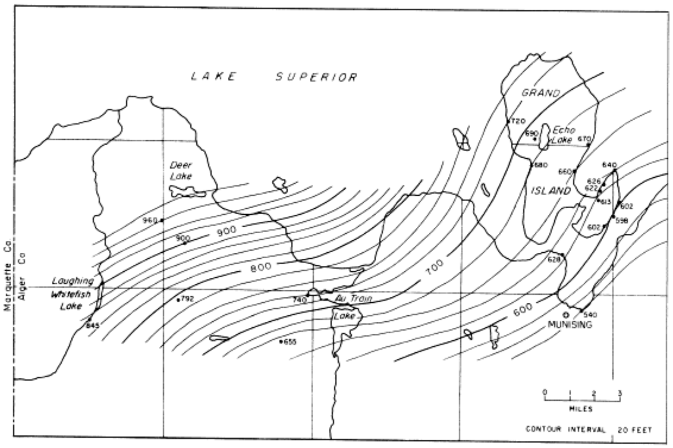


Figure 35. Contours on the pre-Munising surface in western Alger County.

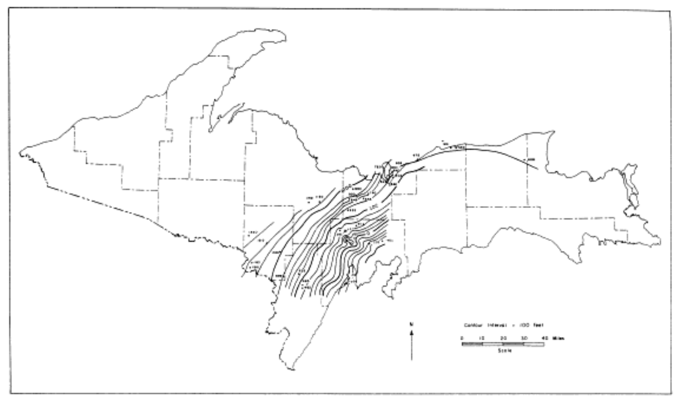


Figure 36. Contours on the pre-Munising surface.

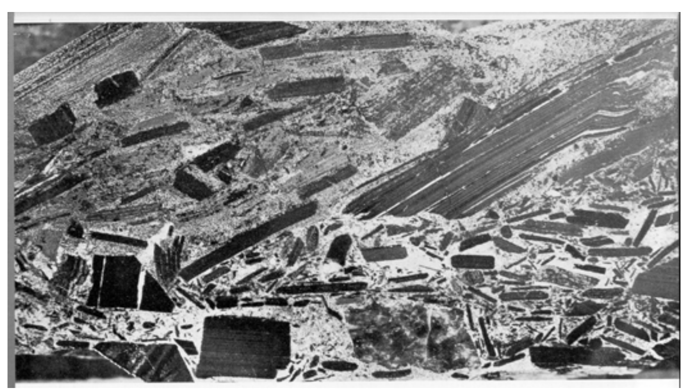
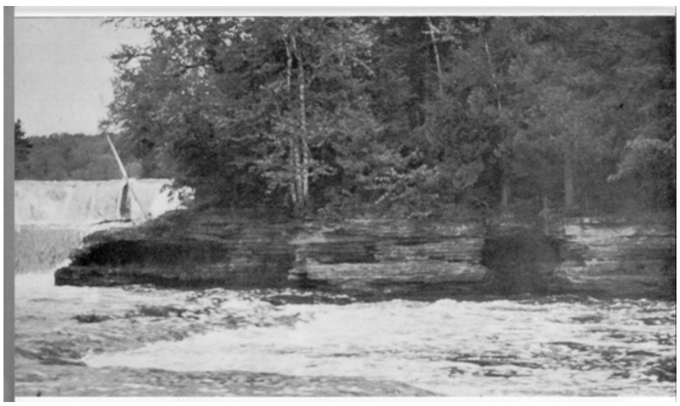


Figure 37. Polished section of conglomerate near the base of the Munising formation in the exposures throughout Dickinson County showing the angular nature of the iron formation pebbles and their imbricate arrangement. Sample taken from Quinnesec Mine. Photograph is X1.

In all but a few exposures of the Munising-Precambrian contact, lenses of highly angular fragments of slate and iron formation flank the Precambrian highs. These conglomerate lenses are as much as 6 feet thick near the margins of the highs, but pinch out within a very short distance. The discrete fragments average 4 to 6 inches in their longest dimension, but few are more than 1 inch thick (fig. 37). In some places large blocks of the iron formation more than 2 feet in diameter are imbedded in the sandstone close to the contact. It is obvious that the angularity of the fragments is due primarily to the slaty nature of the iron formation and to the short distance that these fragments were transported. The maximum local relief of the pre-Munising surface is at least 400 feet, with knobs and hills that average 50 to 75 feet high. The eastern extension of the irregular pre-Munising topography is proved by the records of a number of holes drilled recently by several iron companies.



Lower Tahquamenon Falls. Chapel Rock Member, Munising Formation.

Munising Formation

The upper 250 feet of the "Lake Superior Sandstone" which is characteristically light gray to white in color, was named the Munising formation by Lane & Seaman (1907, p. 692). The early geologists recognized this natural division in the "Lake Superior Sandstones" because of the marked color change from red to white, and various attempts have been made to subdivide the "Upper Gray" or Munising formation into members and correlate it with the Cambrian section of the Upper Mississippi Valley.

Thwaites (1934, p. 426) considered the Munising to be equivalent to the Mazomanie and Dresbach of northeastern Wisconsin, but did not indicate where such a division occurs in the Pictured Rocks section. Later, Thwaites (1943, p. 510) considered the Munising to be only of Franconia age.

Ulrich (1936) believed that the entire Upper Cambrian section, including Dresbach, Franconia, Mazomanie, Upper and Lower Trempealeau and Jordan of the Wisconsin section, was exposed in the vicinity of Munising.

Oetking (1951) probably did more detailed work on the Munising than any of his predecessors and used the terminology "Dresbach" and "Franconia" for lower and upper Munising, but he based his correlation entirely upon heavy minerals and reported no lithologic change throughout the section.

Much of the confusion concerning the division and correlation of the Munising results from the inaccessibility of the vertical Pictured Rocks cliffs which constitute the principal exposure of the formation. These outcrops can be studied in detail only from a small boat or by rappelling over the cliffs with a rope. Most of the isolated outcrops inland are too small to be of value in correlation. Since the section exposed in the Pictured Rocks is unfossiliferous and the lithic units of Wisconsin cannot be traced into the area, the terminology of the Cambrian of Wisconsin should not be used in Northern Michigan.

The present study reveals that the Munising formation consists of three distinct lithic units. They are in ascending order: The basal conglomerate, the Chapel Rock member, and the Miner's Castle member. These units persist with only slight lateral changes throughout the entire outcrop belt and can be distinguished on the basis of grain size, sorting, composition, and sedimentary structures.

Figure 38. Basal conglomerate of the Munising formation exposed near the level of Lake Superior on the east side of Grand Island. Note the sharp contact with both the underlying Jacobsville formation and the overlying Chapel Rock member.

Figure 39. Close-up view of the basal conglomerate of the Musing formation.

BASAL CONGLOMERATE

The basal member of the Munising formation is an orthoquartzitic conglomerate which attains a maximum thickness of 15 feet. Although this member is relatively thin, it is widespread and is present in almost every locality where the contact with the underlying Jacobsville is exposed. The most continuous exposures are in the shore cliffs of Grand Island and in several places along the base of the Pictured Rocks. Smaller isolated outcrops are found at Sable Falls and in several localities in western Alger County. No outcrops of the basal conglomerate were found in the outliers in Dickinson County nor in any of the drill cores taken south of Rock. This suggests that the conglomerate pinches out southward against the flanks of the Northern Michigan Highland and is thus restricted to the northern part of the Northern Peninsula. The basal conglomerate varies from 2 to 15 feet in thickness but is remarkably uniform at each exposure. In several localities of the east side of Grand Island and along the Pictured Rocks the conglomerate is in very sharp contact with both the overlying Chapel Rock member and the underlying Jacobsville formation (fig. 38). In places, however, the upper contact of the conglomerate member is gradational and large pebbles form stringers which follow the cross laminations in the basal part of the overlying Chapel Rock member. Isolated pebbles imbedded in the sandstone of the lower Chapel Rock member are also very common. It thus appears, from the wide distribution of outcrops and relative constant thickness, that the basal conglomerate is a thin blanket deposit somewhat elongated in an east-west direction.

COMPOSITION

Throughout the entire outcrop area the pebbles which make up the basal conglomerate are almost exclusively rock types which are chemically and mechanically stable. Vein quartz, quartzites, and chert invariably constitute over 90 percent of the conglomerate. Only very small amounts of slate, iron formation, basalt, granite and sandstone pebbles are present in any of the samples.

Quartzite pebbles constitute from 25 to 80 percent of the basal conglomerate. In most samples the abundance of quartzite pebbles is independent of pebble size. White, red, purple, black, and brown are the predominant colors, but the percentage of each variety is not constant from one locality to the next. The surface of the quartzite pebbles is characteristically pitted with small holes, some of which are more than 2 millimeters in diameter and 5 millimeters deep. Most of the pebbles show a slight weathered rim which is more granular and less vitreous than the unweathered interior. All pebbles are rounded to well rounded and have a high degree of sphericity.

From 15 to 60 percent of the pebbles in the basal conglomerate are composed of vein quartz. The percentage of vein quartz is greater in the smaller fractions of nearly every sample. The varieties of vein quartz include rose, clear, smoky, and milky. The clear and milky varieties are most abundant. As in the quartzite pebbles, the surface texture of much of the vein quartz is pitted although most of the vein quartz in the smaller size fractions is polished. Rounded to well-rounded pebbles predominate although many pebbles have one or more flat faces with more angular edges.

Small amounts of several types of chert are generally restricted to the finer size fractions. Most of the chert pebbles are flat and disc-shaped, probably the result of original bedding. Otherwise they possess the general characteristics of the quartz and vein quartz pebbles.

In the eastern exposures of the conglomerate member a brown oölitic chert is an important constituent since it comprises as much as 20 percent of the rock types of the conglomerate. East of Chapel Rock, however, oölitic chert is completely absent. The percentage of oölitic chert decreases rapidly in the finer size fractions probably because of its less resistant nature. All degrees of alteration from a solid, hard, polished chert pebble to a soft, white, friable mass having only a few resistant oölites in the center were noted. Most of the brown oölitic chert pebbles are less round than pebbles of other rock types. The surface texture is characterized by numerous large deep pits and holes. These holes appear to result from more rapid decomposition at points where pressure is greater because they are invariably at points of contact with other smaller pebbles.

A few sandstone pebbles of the Jacobsville formation are in every sample of the basal conglomerate examined, but in amounts of less than 1 percent. Most of the Jacobsville pebbles are restricted to the size fractions between 2 and 5 millimeters. In the few larger pebbles, the typical red color of the Jacobsville is preserved with the characteristic white reduction spots.

Since the basal conglomerate member lies directly upon the Jacobsville, one might expect to find more

Jacobsville pebbles included in the conglomerate. It is apparent, however, from the compositional maturity of the basal conglomerate that pebbles as mechanically unstable as the Jacobsville would not be a common constituent.

Minor amounts of slate, iron formation, basalt, clay pellets, and decomposed felsite and granite pebbles were found in the several samples studied showing a complex lithology of the source area.

Pebble counts made at several localities throughout the outcrop belt of the basal conglomerate indicate some significant variations in composition from one locality to the next. The most striking variation in composition is in the percent of brown oölitic chert which is abundant in the eastern end of the outcrop area but is completely absent in all other localities studied. Significant changes in the percentage of black quartzites, vein quartz, and pebbles of the iron formation also are found in an east-west direction. West of Chapel Rock, black quartzite constitutes over 24 percent of the rock types, whereas east of Chapel Rock black quartzite does not exceed 9 percent. Vein quartz, on the other hand, is much more abundant east of Chapel Rock where it is in amounts exceeding 43 percent. In the western end of the outcrop belt the total amount of vein quartz does not exceed 26 percent. Pebbles of cherty iron formation and granite are also restricted almost exclusively to the western end (table 3).

These variations undoubtedly indicate east to west differences in the rock types of the source area.

Type of Pebble	L. W. F. Spur. percent	AuTrain Spur. percent	Grand Island percent	Pictured Rocks percent	Chapel Falls percent	Sable Falls percent
Vein Quartz						
clear	10.3	11.3	9.3	6.8	28.5	54.2
milky	10.3	9.4	3.2	6.2	14.7	4.5
smoky	4.6	0.9	1.2	3.1	0.0	1.0
Total Vein Quartz	25.2	21.6	13.7	16.1	43.2	59.7
Quartzites						
red	20.6	4.2	14.7	26.0	4.6	0.3
brown	4.6	1.4	3.2	13.6	1.5	12.1
white	8.6	7.0	30.0	13.0	20.0	3.4
purple	0.0	2.8	4.2	1.8	0.0	0.0
black	28.0	24.4	28.5	27.8	7.6	8.7
banded	2.3	0.0	1.5	0.0	0.0	0.6
Total Quartzites	64.1	39.8	82.1	82.2	33.7	25.1
Chert	5.5	10.8	0.0	0.6	2.3	2.0
Cherty Iron Fm.	2.3	5.6	0.0	0.6	0.4	0.0
Brown Oölite Chert	0.0	0.0	0.0	0.0	20.0	12.6
Jacobsville	1.5	8.5	4.2	0.5	0.4	0.6
Granite	1.4	4.8	0.0	0.0	0.0	0.0
Slate	0.0	7.0	0.0	0.0	0.0	0.0
Basalt	0.0	1.9	0.0	0.0	0.0	0.0

Table 3. Pebble counts of Basal Conglomerate of Munising Formation.

TEXTURE

Based on estimations made at the outcrops, the average diameter of the pebbles in the basal conglomerate is from 2 to 3 inches. In each exposure the sorting of the particles greater than 2 millimeters in diameter is very good. The largest pebble observed was less than 12 inches in its longest dimension but such large cobbles are rather uncommon. Most of the pebbles are well rounded and exhibit a wide variety of shapes. The present shape of the individual pebbles does not appear to have much significance in indicating the environment of deposition. The shape of the quartzites and vein quartz pebbles is a modification, to a great extent, of the shape of the larger pebbles (from which they were derived) by fracturing prior to deposition. The conchoidal fracture of quartz produces a concave surface which is soon modified by abrasion to a smooth plane. The result is that spherical, elliptical, and disc-shaped pebbles break into smaller pebbles having one flat face. If the pebble is broken several times, the resulting shape approaches a tetrahedron which may later be modified by abrasion to a sphere. All gradations from an angular to well-rounded tetrahedron were observed. The abundance of pebbles broken only a short time prior to deposition indicates exceptionally high current velocities in the encroaching seas.

ORIGIN

A number of features in the basal conglomerate clearly indicate its mode of origin. The composition is very simple as more than 95 percent of the pebbles are either vein quartz, quartzite, or chert, Most of the gravels are well worn and rounded and nearly everywhere well sorted. The conglomerate is a thin blanket deposit having a maximum thickness of only 15 feet and extends laterally a distance of over 60 miles. Exposures of the basal conglomerate at Limestone Mountain indicate that prior to the present cycle of erosion, the conglomerate may have extended an additional 100 miles to the west. The conglomerate is closely associated with the large-scale cross-bedded sandstone of the Chapel Rock member and in places it forms several layers interbedded with sandstone units. In many places the gravels are deposited as lenses and stringers following the cross-laminations of the overlying Chapel Rock member, and "floating pebbles" are very common. All of these features indicate that the basal conglomerate of the Munising formation is a classic example of an orthoquartzitic conglomerate deposited by a transgressive sea over a surface of low relief.

The contact between the basal conglomerate and the Chapel Rock member, in many places, is very sharp indicating rapid transgression of the sea. Elsewhere the contact is gradational, but evidence of a hiatus between the two members was not found. Deposition appears to have been continuous from the basal conglomerate to the Chapel Rock member.

The thinning of the conglomerate to the south and east suggests that the Huronian quartzites of the Northern Michigan Highland were the source for the major part of the basal conglomerate. This supposition is strongly supported by the presence of angular pebbles of the iron formation in the western part of the outcrop belt.

CHAPEL ROCK MEMBER

The Chapel Rock member overlies the basal conglomerate and consists of well-sorted medium-grained sandstone characterized by large-scale cross-bedding. The name, here proposed, is derived from the excellent exposures at Chapel Rock near the eastern end of the Pictured Rocks cliffs (fig. 40).

Excellent exposures of the Chapel Rock member are along the entire extent of the Pictured Rocks. East of Mosquito Harbor this member constitutes virtually the entire section exposed in the cliffs, but because of a southwest component of dip only the upper 10 to 15 feet of the Chapel Rock member is exposed above the lake level from Munising to Miner's Castle. West of Munising the Chapel Rock member is exposed in a number of localities in the drainage basin of the Rock River, but it is structurally too low to be exposed in the numerous waterfalls of Alger County. The southern extent of the Chapel Rock member is poorly defined because of the limited number of good outcrops south of the coast of Lake Superior. The Chapel Rock member is recognized in the drill cores taken at Kiva and Rock, but it has never been recognized in outcrops or wells south of Rock. Westward the Chapel Rock member is exposed on the east and the west flanks of Little Limestone Mountain and at the base of a limestone quarry on the east flank of Limestone Mountain in the NW ¼, sec. 24, T. 51 N., R. 35 W. Eastward, exposures are found in the lower falls of the Tahquamenon River and on Encampement d'Ours Island in the St. Mary's River.

The exact thickness of the Chapel Rock member could be determined in only a few places. Along the Pictured Rocks and apparently throughout most of Alger County it is from 40 to 60 feet thick. Complete sections measured at Grand Marais indicate that the Chapel Rock member, like the basal conglomerate, thins gradually to the east. The southern extent and thickness of the member is uncertain because of insufficient data.

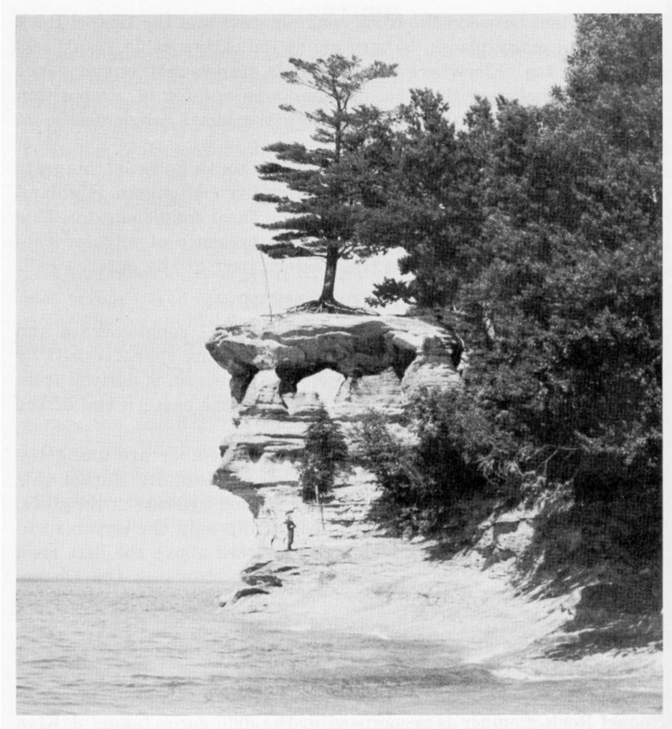


Figure 40. Chapel Rock, the type locality of the Chapel Rock member of the Munising formation. The stratification is a result of large-scale cross-bedding. Note the arches carved by wave action when lake level was higher.

COMPOSITION

The sandstone of the Chapel Rock member is composed almost entirely of quartz, chert and quartzite grains. Most of the quartz grains contain numerous bubble trains and gas bubbles and are therefore considered to have originated from igneous rock. Only minor amounts of feldspar are present. Calcium carbonate is locally abundant but is restricted to zones near fractures and cannot be considered as the predominant cementing material. Many small angular quartz fragments constitute a matrix for larger grains and thus act as a clastic binder. Silica, however, is in most places the predominant cementing material and occurs as secondary overgrowths in crystallographic continuity with the detrital grains. The degree of secondary quartz overgrowths varies considerably throughout the outcrop belt. Generally the Chapel Rock member is friable but at Tahquamenon Falls the degree of secondary quartz overgrowths is so extreme that an orthoquartzite with very little porosity has been produced (fig. 41).

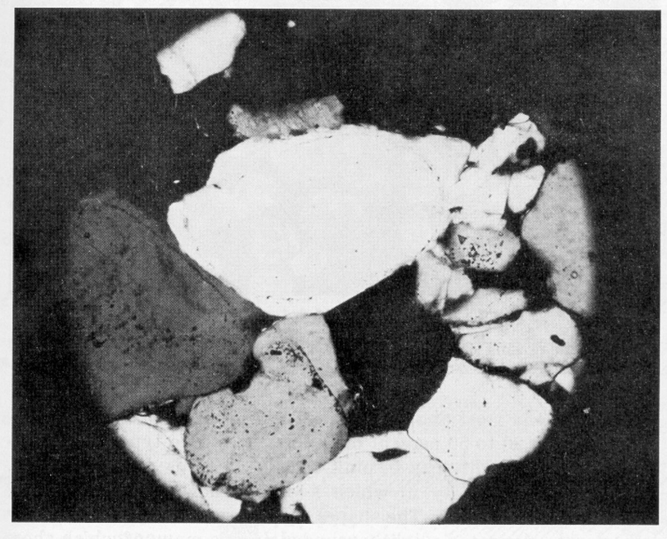


Figure 41. Secondary overgrowths of quartz on well-rounded sand grains of the Chapel Rock member. Crossed nicols. X63.

HEAVY MINERALS

The heavy mineral suite of the Chapel Rock member constitutes between ½ and 2 percent by weight and is not markedly different from the heavy mineral content of the Jacobsville formation. The main differences are a decrease in opaques and an increase in the percentage of zircon and tourmaline. A summary of the heavy minerals from this member and lateral variations are shown in figure 43.

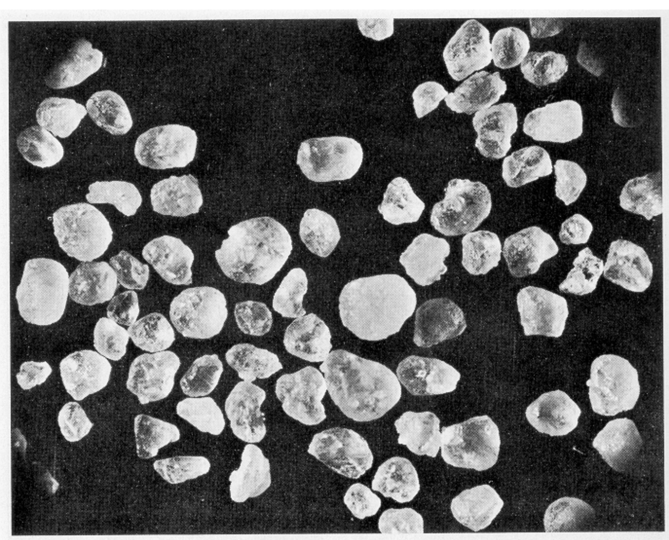


Figure 42. Typical sand grains of the Chapel Rock member illustrating the degree of roundness and sorting and surface texture of the grains. X10.

Zircon is the most abundant mineral because it consistently constitutes from 20 to 50 percent of the heavies. Two types are recognized: a fresh, light-gray to pink variety which is most abundant, and an altered variety in which a dark yellowish-brown coating obscures the true color. The shapes of the grains range from nearly spherical to elongated, slightly rounded prisms many of which show crystal faces. Inclusions are common and zoning is distinguished in most of the altered varieties of grains (fig. 44).

Tourmaline occurs as well-rounded grains, some of which contain inclusions. Brown, black, blue, and green varieties were found, but the brown variety is the most common.

Minor amounts of apatite occur as well-rounded, almost perfectly spherical grains generally free from inclusions and alterations. The mineral is readily distinguished by its spherical shape and low birefringence.

Well-rounded elliptical grains of rutile are nearly opaque, but may be distinguished by their dark reddish-brown color and faint pleochroism.

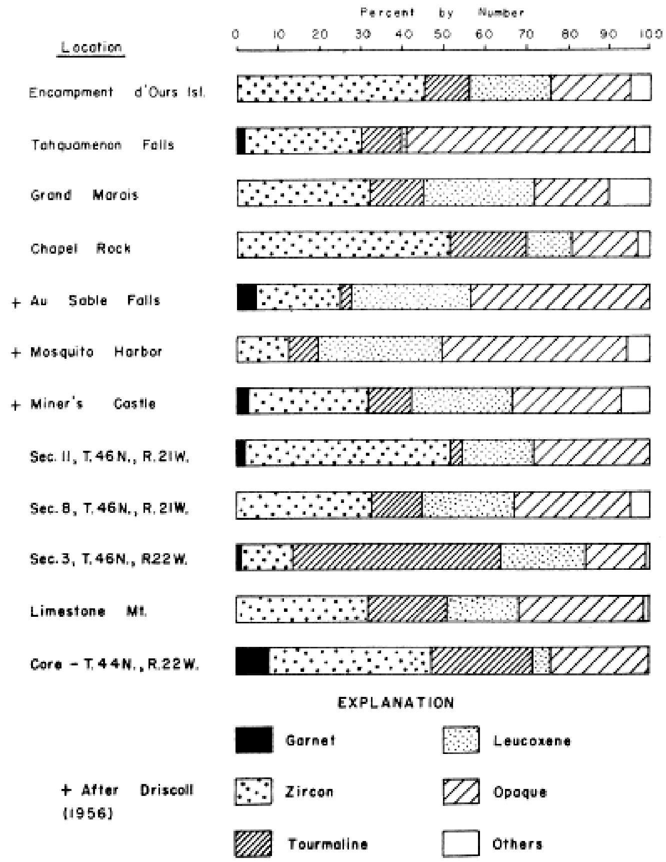


Figure 43. Heavy minerals of the Chapel Rock member.

The small amount of garnet in the Chapel Rock member is similar in most respects to the garnet which characterizes the heavy mineral suite of the Miner's Castle member. However, a few well-rounded grains free from the characteristic surface features were found.

Magnetite, hematite, ilmenite, and minor pyrite comprise the opaque heavy minerals. Magnetite was separated from the remaining heavies and was not studied microscopically. Hematite is generally recognized by its metallic luster but like ilmenite could not always be rapidly distinguished from other opaques. Most of the ilmenite in the samples show some degree of alteration to leucoxene.

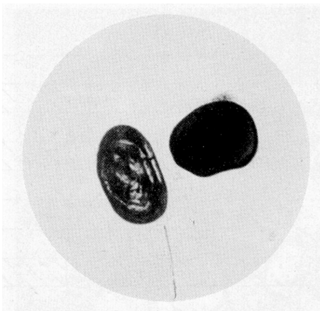


Figure 44, *A*

Tourmaline and altered zircon from the Chapel Rock member. Sample from Chapel Rock. X65.

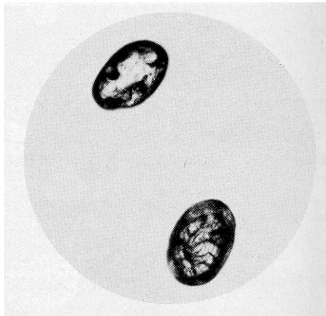


Figure 44, *B*

Altered and unaltered zircon grains from the Chapel Rock member. Sample from bluff south of Grand Marais. X65.

Figure 44. Zircon from the Chapel Rock member.

TEXTURE

The Chapel Rock member is primarily a well-sorted, medium-grained sandstone with varying amounts of scattered pebbles near the base of the section. From 60 to 70 percent of the grains are between ¼ to ½ millimeter in diameter (fig. 45), and most sections are free from shale lenses or partings, which makes the Chapel Rock member a relatively clean sandstone.

COLOR

Excepting surficial stains along the Pictured Rocks, the color of the Chapel Rock member is white, buff, or salmon red. The color differs from place to place but changes are not abrupt. Along the Pictured Rocks, the Chapel Rock member is colored in brilliant shades of red, yellow, green, black, brown, and white. The various colors are in vertical bands where mineral and organic matter is deposited from the effluent seepage of ground water down the face of the cliffs.

SEDIMENTARY STRUCTURES

Cross-bedding

Large-scale trough cross-bedding is the most striking and abundant sedimentary structure in the Chapel Rock member. The size of the troughs ranges from 3 feet to more than 600 feet in width, but the average width is in the magnitude of 30 feet. The larger troughs are most abundant south of Chapel Rock and at Mosquito Harbor. Excepting the section at Lower Tahquamenon Falls, nearly every outcrop of the Chapel Rock member exhibits this typical large-scale cross-bedding and thus it is one of the most useful megascopic features which can be used to distinguish the Chapel Rock member from the Jacobsville formation and from the Miner's Castle member. Good exposures of the complete trough in three dimensions are rather rare, however, because of their tremendous size. Most of the outcrops inland are only large enough to expose a small part of a limb of the troughs and most of the cliffs along the Pictured Rocks expose only a vertical section. At Miner's Castle, Mosquito Harbor, and Chapel Beach, however, good exposures of these structures in three dimensions are numerous (figs. 46, 47). In these localities wave action has produced wide wave-cut terraces which extend out into the lake for a considerable distance. Since the water covering these terraces is only a few feet deep, the horizontal section cutting the troughs can be studied in detail over a large area. Symmetrical and asymmetrical troughs are both common in the Chapel Rock member but it was noted that the number of symmetrical troughs decreased as the size of the troughs increased. The individual lamina which fill the troughs range from ⅛ to ½ inch in thickness and in many outcrops have been etched into relief by weathering. In many places along the Pictured Rocks, however, the cross-bedding is obscured by deposits precipitated by the seepage of ground water down the vertical cliffs. Where the cross-bedding is exposed, each lamina maintains a uniform thickness throughout its entire length and in the larger exposures the individual laminae can be traced without interruption from one limb of the trough to the other. In a horizontal section of the larger troughs, this distance is more than 1,000 feet.

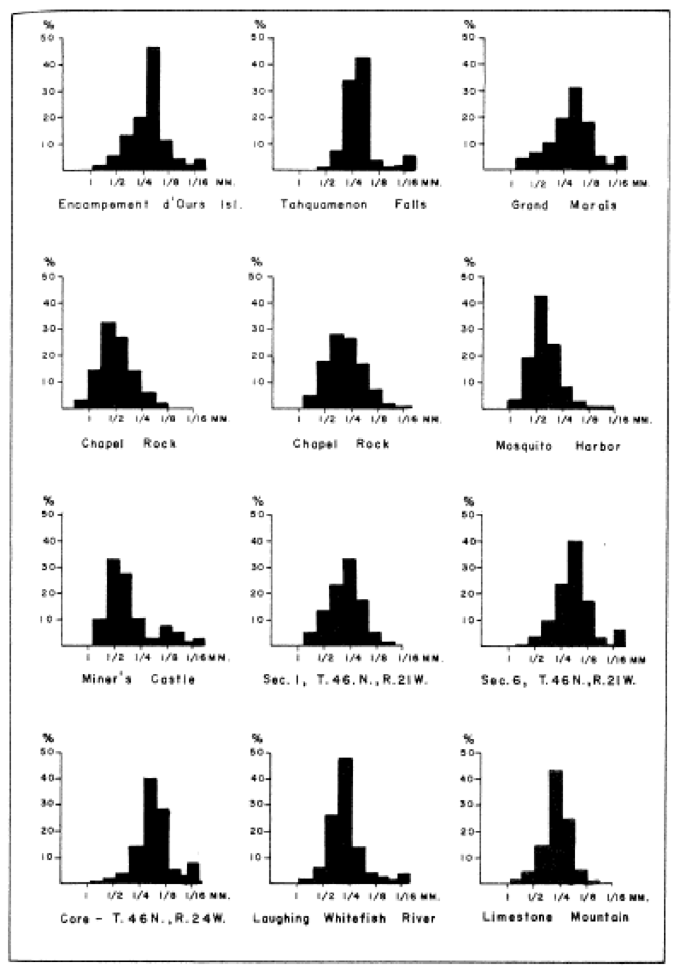


Figure 45. Grain-size distribution in typical samples of the Chapel Rock member.

Figure 46. Horizontal surface of the Chapel Rock member showing the well-developed large-scale trough cross-stratification. Hand is pointing in the direction in which the axes of the trough plunge, which is considered to be the direction of current flow. View taken at Mosquito Harbor.

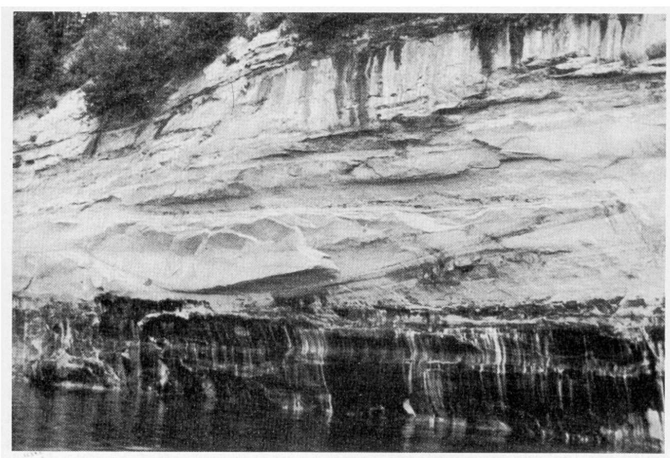


Figure 47. Cliff along the Pictured Rocks showing the appearance of the large-scale trough cross-stratification in a profile perpendicular to the plunge of the trough.

The lower surface of each set of cross-strata show that considerable erosion cut deep channels in the older units prior to the deposition of each succeeding set of cross-strata. The form of the erosional channels generally controls the shape of the set of cross-strata which fills it, but the erosional surface is remarkably smooth and regular; therefore, the shape of the laminae approaches a smooth gentle curve. Most of the lower bounding surfaces are concave upward but in several localities two or more erosional channels were filled simultaneously so that the arches separating the troughs produce cross-bedding that is convex upward (fig. 48). The average angle of plunge of the axis of the trough is very steep near the top of the trough but decreases rapidly in a down-current direction and becomes almost horizontal. Near the base of the Chapel Rock member stringers of pebbles follow the cross-lamination and near the contact with the basal conglomerate pebble-size particles constitute an appreciable part of the cross-bedded material. The close association of the Chapel Rock member with the underlying orthoquartzitic conglomerate leaves little doubt that the large-scale cross-bedding was produced in a marine environment. It appears from the large size and trough-like shape of these structures that they formed in embayments along a cuspate shore.

<u>Mud Cracks</u>

The upper part of the Chapel Rock member is characterized by a 5-foot section of interbedded black shale and buff sandstone (fig. 49). Most of the sandstone and shale beds are only 5 to 10 inches thick but traced laterally many shale lenses are found to coalesce and form a shale bed 3 to 4 feet thick. Locally this unit is absent but in several localities along the Pictured Rocks it marks the uppermost unit of the Chapel Rock member and is directly overlain by the Miner's Castle member. Large mud cracks as much as 3 inches wide form polygonal patterns in essentially every shale lens in this zone. Most of the cracks have been filled with sand which is more resistant to weathering and they stand out in relief, forming a structure which resembles a honeycomb. The polygonal pattern formed by these mud cracks ranges from 4 to 18 inches in diameter. The depth of the crack, however, is restricted by the thickness of the shale bed and in few places exceeds 6 inches. Most of the larger mud cracks have somewhat rounded corners and edges. Many smaller secondary cracks 1 to 1½ inches wide are clearly developed across the areas outlined by the larger crevices and in turn enclose an area which contains short minor incomplete cracks of a third generation. The form of most of the larger cracks is tabular and does not exhibit the characteristic "V"-shaped profile.

It is significant to note that the zone containing the mud cracks is the uppermost unit of the Chapel Rock member and in many places it is in direct contact with basal units of the Miner's Castle member. This indicates that the upper Chapel Rock member was deposited in a shallow-water environment which was repeatedly exposed to subaerial conditions. This might be interpreted as a regressive phase of the Chapel Rock sea.

<u>Ripple Marks</u>

Several strata of the Chapel Rock member exhibit well-developed ripple marks. These structures are especially numerous at Mosquito Harbor and Lower Tahquamenon Falls. Both oscillation and current ripples appear to be present, but many of the crests have been flattened by erosion; therefore, it is impossible to determine in all exposures if currents were responsible for their formation. Only very slight differences were noted in the wave length and amplitude of the current ripple marks exposed, indicating that they were produced by constant current velocities.

<u>Tracks</u>

Two different original structures formed on the ripple marks at Mosquito Harbor may possibly have been formed by organisms. One type trends almost perpendicular to the direction of current flow and consists of a series of parallel grooves. The width of the cluster of grooves is approximately 6 inches and the observable length is more than 10 feet. The grooves are remarkably straight and parallel, deviating from a straight line in broad gentle curves. In all the clusters of grooves observed, the medial groove is the widest and deepest. The straight course and the orientation normal to the strike of the ripple marks indicate that these markings may possibly have been formed by debris pushed along by moving water. The only other explanation is that they represent tracks made by some organism.

The other type of marking found on the ripple marks exposed at Mosquito Harbor is sets of lenticular impressions which show no definite orientation to the ripple marks. The average size of these markings is approximately 4 inches long and 1 to 1½ inches wide, but the size varies to a considerable extent. Where these markings are very numerous they appear at first to be interference ripple marks, but where markings are few, they appear to have a definite systematic orientation (fig. 50).

Concretions

Sand concretions averaging 1 to 2 inches in diameter are common in the Chapel Rock member in some localities where calcite-filled fractures and stringers are abundant. The largest concretions are more than 10 inches in their longest dimension and the smallest are only a fraction of an inch in diameter. The concretions consist of concentric zones of abundant carbonate cement and small amounts of iron oxide. The increase in cementing materials makes them more resistant to weathering and they stand in relief as hard nodules resembling well-rounded pebbles. Bedding planes pass through the concentric structure indicating that they are definitely secondary. Their localized occurrence in the vicinity of fractures, many of which are filled with calcite, suggests that they originated from the diffusion and localization of calcite made available by the increased permeability of fractured zones (fig. 51).

Figure 48. Adjacent troughs in the Chapel Rock member filled simultaneously so that the stratification produced is continuous through a trough, over an arch and into another trough.

Figure 49. Zone of interbedded sandstone and shale showing the extensive development of mud cracks in the upper units of the Chapel Rock member.

Figure 50. Current ripple marks in the Chapel Rock member at Mosquito Harbor. Hammer handle points in the direction of current flow. Note the markings on the surface which are possibly due to organisms.

Figure 51. Large concretions in the Chapel Rock member.

Clastic Dikes

In several localities small irregular sandstone dikes penetrate the Chapel Rock member to a depth of from 3 to 6 feet below its upper contact. Unlike the clastic dikes in the Jacobsville formation, these dikes are only a few inches wide and contain numerous branches or sills which in places connect neighboring dikes. They are entirely restricted to the upper units of the Chapel Rock member and pinch out downward within a few feet. Most of the major dikes are at right angles to the bedding, and they expand upward in such a way that some dikes may be as much as a foot wide at the contact.

The dikes are composed of poorly-sorted sand and blue shale from the overlying Miner's Castle member. These materials are distinctly banded parallel to the walls of the dike. In some localities bedding planes and shale lenses of the Miner's Castle member do not extend across the top of the dike as they would have if the dikes had been truncated at the contact. Instead, they bend down into the dike and thus indicate that the dikes were filled by forceful injection from above.

<u>Clay Pellets</u>

Clay galls or pellets are very common in the upper part of the Chapel Rock member, especially near the zones that contain mud cracks. These pellets range in size from ⅛ of an inch to 4 inches in diameter and are rounded to angular in outline. Most are flattened and discoid but some have upcurled ends. They were undoubtedly derived from the desiccation and breaking of the shale which contains some of the mud cracks.

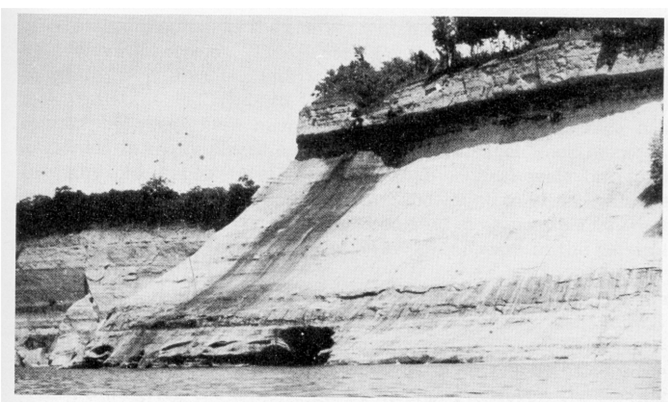


Figure 52. View of the Pictured Rocks showing the contact between the Chapel Rock member (lower, resistant unit protruding 15 to 20 feet above the water level) and the Miner’s Castle member (non-resistant, light-colored, slope-forming unit). Note the resistant cap rock of the Au Train formation.

CONTACT BETWEEN THE CHAPEL ROCK AND MINER'S CASTLE MEMBERS

Along most of the coast of the Pictured Rocks cliffs the contact between the Chapel Rock and Miner's Castle members can be easily recognized. In many places a definite change in color and in the size of cross-bedding marks the contact which also has been accentuated by differential erosion. The Miner's Castle member is a weak, non-resistant, slope-forming unit whereas the Chapel Rock member is more resistant and tends to form a steep cliff (fig. 52). Since the contact between these members is sharp, a narrow terrace has developed in many places on the top of the Chapel Rock member. In many places this terrace is more than 20 feet wide but it is commonly much less (fig. 53). From Sand Point to Miner's Castle the terrace is practically continuous so that it is possible to walk for several miles right on the contact which appears in the vertical section to be a horizontal plane.

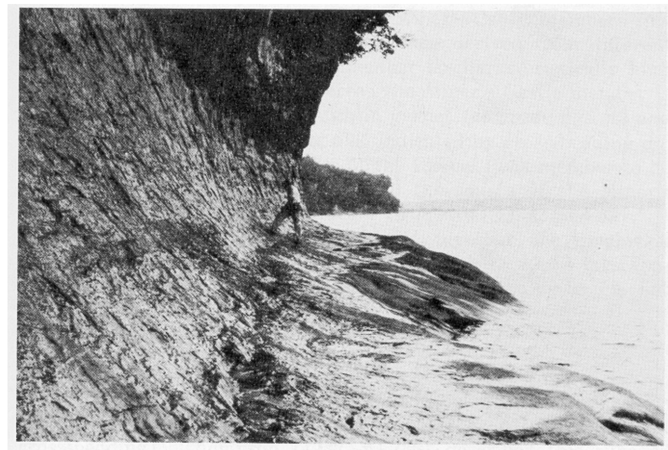


Figure 53. View looking west along the Pictured Rocks cliffs between Miner’s Castle and Munising, showing the terrace developed at the contact between the Chapel Rock and Miner’s Castle members. Note the difference in outcrop texture above and below the contact.

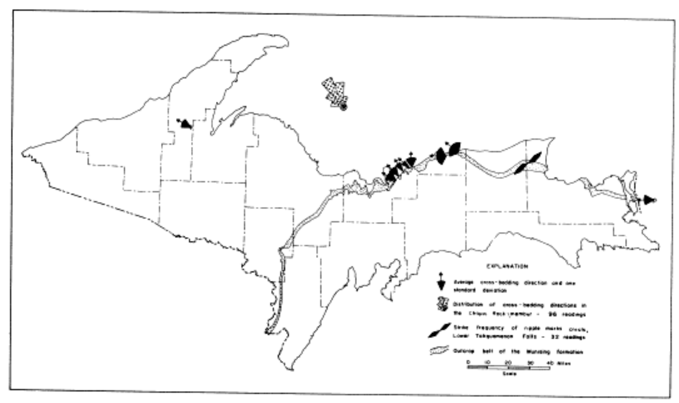


Figure 54. Cross-bedding directions in the Chapel Rock member.

An unconformity separating the Chapel Rock and Miner's Castle members is indicated by significant changes in sorting, sedimentary structures, and heavy mineral assemblages. The Chapel Rock member is a clean, well-sorted sandstone characterized by large-scale cross-bedding. In the Miner's Castle member, however, the sorting is poor and the cross-bedding is distinctively small scale (compare figs. 45 and 65, 46 and 66). The changes in sorting and sedimentary structures are abrupt and occur right at the contact between the two members indicating abrupt changes in environmental conditions. A striking change in the heavy mineral assemblage at the contact between the Chapel Rock and Miner's Castle members further indicates that the two members were derived from different source areas. The Chapel Rock member is characteristically high in zircon and low in garnet, whereas the Miner's Castle member is low in zircon and remarkably high in garnet (compare figs. 43 and 61). Different source areas are also indicated by cross-bedding dip directions which show the source of the Chapel Rock member to be southeast of the present outcrops and the source of the Miner's Castle member to be to the northeast (compare figs. 54 and 68).

When these evidences are considered together the conclusion that an unconformity separates the two members seems inescapable. The size and extent of this unconformity, however, is not known.

PALEOGEOGRAPHY

Analysis of Cross-bedding

The trough cross-bedding in the Chapel Rock member apparently was developed in embayments on a cuspate beach (see section on cross-bedding). Thompson (1937, p. 735) described this type of sedimentary structure of modern beaches and found that the axes of the "scooplike embayments" plunge toward the sea. A statistical analysis of the plunge direction of this type of trough cross-bedding would, therefore, indicate the average seaward direction in the wave zone during the time the sediment was being deposited. The plunge direction of the large-scale trough cross-bedding can be measured accurately only in a horizontal section which exposes the complete trough or in a vertical section containing the axial plane. All other sections expose only an apparent plunge direction or the dip direction of a limb, neither of which is considered to accurately represent the direction of regional slope. Measurements were therefore restricted to exposures showing complete horizontal sections. Such exposures are primarily along the Pictured Rocks, since the outcrops inland in western Alger County are too small to completely expose these large-scale structures. An average of only 12 measurements was obtainable from each locality, but the small variation between measurements indicates that this number is sufficient to present a reliable average.

Figure 54 shows the mean and standard deviation for all the cross-bedding measurements taken at each locality. The average plunge direction of the large-scale trough cross-bedding in the Chapel Rock member is N. 45° W. which indicates that the regional slope and seaward direction in Northern Michigan during the first advancement of the Paleozoic seas was to the northwest. This is undoubtedly due to the fact that the Northern Michigan Highland which provided the sediments for the Jacobsville formation remained a positive area during the beginning of Upper Cambrian time. It formed an obstacle to the advancement of the seas onto the Canadian Shield from the south and southeast permitting an encroachment only from the west and north. In all probability the Jacobsville covered much of the highland and supplied a large part of the sand which was redeposited to form the Chapel Rock member. This theory is strongly supported by the striking similarities between the two units in sorting and in heavy mineral suites. The differences between the two units may be ascribed primarily to the different environments in which they were deposited.

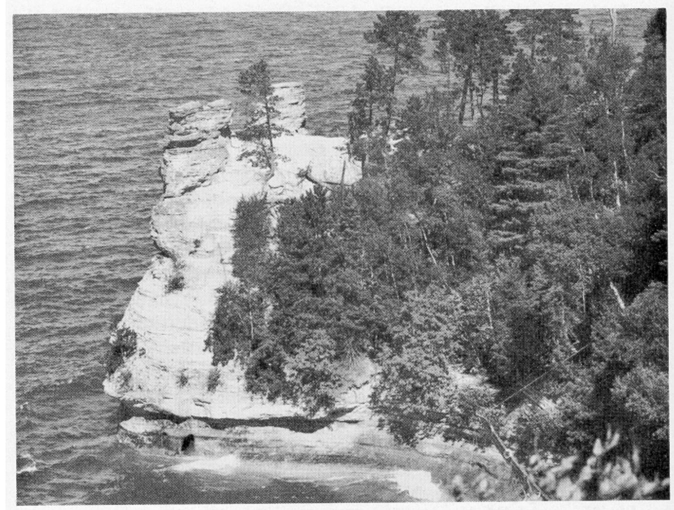


Figure 55. Miner's Castle -- type locality for the Miner's Castle member of the Munising formation. Note the contact with the underlying Chapel Rock member just above the water level.

Ripple Marks

The strike of asymmetrical ripple marks is a highly significant feature because it may be closely correlated with the direction of current flow and is thus a good indicator of the direction of sediment transport. The strike of oscillation ripple marks, however, is not necessarily related to current directions, but is still significant in paleogeographic studies because it is generally related to the prevailing wave direction and trend of the shoreline.

At Lower Tahquamenon Falls ripple marks are exposed in a sufficient number of strata to indicate the general trend of the ancient shoreline. Figure 54 shows that the average strike of the ripple marks is practically perpendicular to the average direction of the plunge of the large-scale trough cross-bedding. The trend of the shoreline, as indicated by the average ripple-mark strike, is northeast-southwest and is in very close agreement with the position of the shoreline which might be inferred from cross-bedding measurements.

Shape of the Chapel Rock Member

Details of the thickness, shape and distribution of the Chapel Rock member are not known, but sufficient data indicate regional trends which are significant. Outcrops indicate that the Chapel Rock member is quite extensive in an east-west direction. The outlier at Limestone Mountain further indicates that at one time the Chapel Rock member extended at least an additional 100 miles to the west of the present outcrop belt. The southern extent, however, is probably quite limited inasmuch as it is not recognized anywhere in the southern half of the peninsula.