# *Middle Proterozoic to Cambrian Rifting, Central North America*

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# Petrography and sedimentation of the Middle Proterozoic (Keweenawan) Nonesuch Formation, western Lake Superior region, Midcontinent Rift System

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## ABSTRACT

**Detailed sedimentological descriptions and petrographic analysis of the upper Keweenawan Nonesuch Formation were accomplished for selected Bear Creek drill cores from Ashland, Bayfield, and Douglas Counties, Wisconsin. These data, coupled with the information from outcrops in northwestern Wisconsin and Upper Michigan, provide evidence on source rocks, environment of deposition, and the tectonic framework of the Nonesuch Formation in the Midcontinent Rift System.**

**Lower Keweenawan felsic, intermediate, and mafic volcanic units were the major contributors of detritus to the formation. Younger Keweenawan volcanic and granitic intrusive rocks were minor sources. Detritus from Early Proterozoic and Archean crystalline rocks increases in abundance upsection as older source rocks outside the rift were unroofed.**

**Sedimentary structures and stratigraphic facies relationships suggest that deltaic processes, sheetfloods, density and turbidity currents, and suspension settling were the primary mechanisms of deposition in a thermally stratified perennial lake. Rapid fluctuations in water levels were brought on by changes in tectonism or climate. The gradational contacts of the Nonesuch Formation with the underlying Copper Harbor Formation and the overlying Freda Formation, along with outcrop and drill core facies data, suggest that the site of Nonesuch deposition was adjacent to, and sometimes upon, a prograding alluvial fan complex.**

**The Nonesuch Formation in the Bear Creek drill cores was divided into six sedimentational intervals (1, 2, 3, 3a, 4, and 5, lowest to highest) based on textures, sedimentary structures, and color. Light gray to black rocks predominate in all of the intervals and indicate that deposition of Nonesuch sediments was in a predominantly euxinic environment. The facies assemblages represented in these sedimentational intervals record clastic deposition that occurred during the initial transgressive and final regressive stages of the Nonesuch Lake over the contemporaneous alluvial fan complex of the upper Copper Harbor Formation and the subaerial fluvial plain environment of the lower Freda Formation.**

**Examination of the genetic relationship of the Nonesuch sedimentational intervals, the textures within each facies type, petrographic data, paleocurrent analyses, and the regional interpretation of the western Lake Superior rift structure, suggest that most sediment was transported northward into the rift zone from the southern**

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**flank of the basin. Less important sources were present within the rift zone but on the northern side of the Nonesuch basin. These data also suggest that the Nonesuch Formation in the Bear Creek cores was deposited in a basin that was partially restricted, or perhaps completely isolated, from areas containing Nonesuch Formation farther east in Wisconsin and Upper Michigan.**

## INTRODUCTION

The 1.1-Ga Midcontinent Rift in the Lake Superior region contains a thick sequence of sedimentary rocks that overlies a thick sequence of flood basalts and associated volcanic rocks. The sedimentary rocks are as thick as 9 km and the volcanic flows as thick as 18,000 m (Allen et al., 1993). The sedimentary rocks are comprised of the Oronto Group and the overlying Bayfield Group.

The Oronto Group consists of, in ascending order, the Copper Harbor Conglomerate, the Nonesuch Formation, and the Freda Formation. The Copper Harbor and Freda are red bed units, whereas the Nonesuch is a gray to black unit. This paper is concerned with the Nonesuch Formation, and is a condensation of a Masters of Science thesis (Suszek, 1991).

From 1958 through 1961, Bear Creek Mining and Exploration Company conducted an exploration program in northwestern Wisconsin in search of sedimentary-hosted copper deposits similar to those found in the Middle Proterozoic (Keweenawan) Nonesuch and Copper Harbor Formations at the White Pine Mine approximately 145 km (90 mi) to the east of the study area in Upper Michigan. The project failed to discover any economic mineral potential, but did partially define the extent of the Oronto Group.

The purpose of this study was to examine the sedimentary rocks in selected Bear Creek drill cores (Fig. 1), with emphasis on the petrography and sedimentology of the Nonesuch Formation. Ten holes were measured, described, and sampled from the bottom of each hole in the Copper Harbor Formation to a short distance above the Nonesuch Formation–Freda Formation contact. To the best of my knowledge, this is the first comprehensive detailed sedimentologic and petrographic analysis of the Nonesuch Formation in the Bear Creek drill cores from northwestern Wisconsin. For the purpose of comparison with drill cores, six Nonesuch outcrops between Silver City, Michigan, and Mellen, Wisconsin (Fig. 1), were measured, described, and sampled.

## SEDIMENTOLOGY

### *Outcrops*

Sedimentary rocks of the Nonesuch Formation are dominantly light gray to black sandstones, siltstones, mudstones, and shales, with minor conglomeratic sandstones in the lower part of the section. The Nonesuch has a greater compositional and textural maturity than the underlying Copper Harbor red bed sequence. Grain sizes generally range from clay-sized material to medium-grained sand, with an average grain size of coarse silt (0.04 mm). Reddish brown rocks decrease in abundance upsection from the contact with the underlying Copper Harbor Formation. Conversely, there is a slight increase in reddish brown rocks as the contact with the overlying Freda Formation is approached. The Copper Harbor–Nonesuch contact was defined as the horizon where dark gray to black rocks dominate the section. The Nonesuch-Freda contact was defined as the horizon where red-brown beds again become dominant. The metamorphic grade in all three formations is zeolite to lower greenschist facies.

The Nonesuch Formation thins and coarsens to the west from 244 m (800 ft) at the Big Iron River to approximately 75 m (250 ft) at the Bad River (Copper Falls State Park). These two exposures are approximately 96 km (60 mi) apart. A typical section of Nonesuch Formation outcrop is illustrated in Figure 2.

The pattern of sedimentation, based on the outcrops examined, is dominated by numerous graded beds (Fig. 3) and fining-upward sequences (Fig. 4). Note that thin graded beds occur within the fining-upward sequences.

### *Paleocurrents*

A total of 102 paleocurrent indicators were measured in the Nonesuch Formation at the Big Iron River, Presque Isle Park, and Parker Creek (Fig. 5). Each measurement was rotated to horizontal by rotation on an axis parallel to the strike of the bed. The data at the Big Iron River appear to support a general flow regime to the north-northeast, towards the rift zone axis, but to the west at the Presque Isle River the flow appears to be to the southwest parallel to the rift zone axis.

### *Drill Cores*

The Nonesuch Formation in cores is similar to that in outcrops and is composed of unoxidized grayish black to brown sandstone, siltstone, and shale. Macroscopically, the coarse to fine-grained grayish black to brown sandstones are generally composed of quartz, feldspar, and lithic fragments in a micaceous or calcareous matrix/cement. The siltstones and shales are darker grayish green to black and are chloritic and micaceous. Calcium carbonate cement is generally confined to the sandstone and sandy siltstone beds. Minor reddish brown oxidized siltstone, mudstone, and shale are randomly distributed throughout the typically gray-black Nonesuch Formation, but increase markedly in abundance at the Copper Harbor–Nonesuch and Nonesuch-Freda contacts. Siltstone comprises the majority of the formation in these cores. Overall, the Nonesuch exhibits a general fining-upward trend.

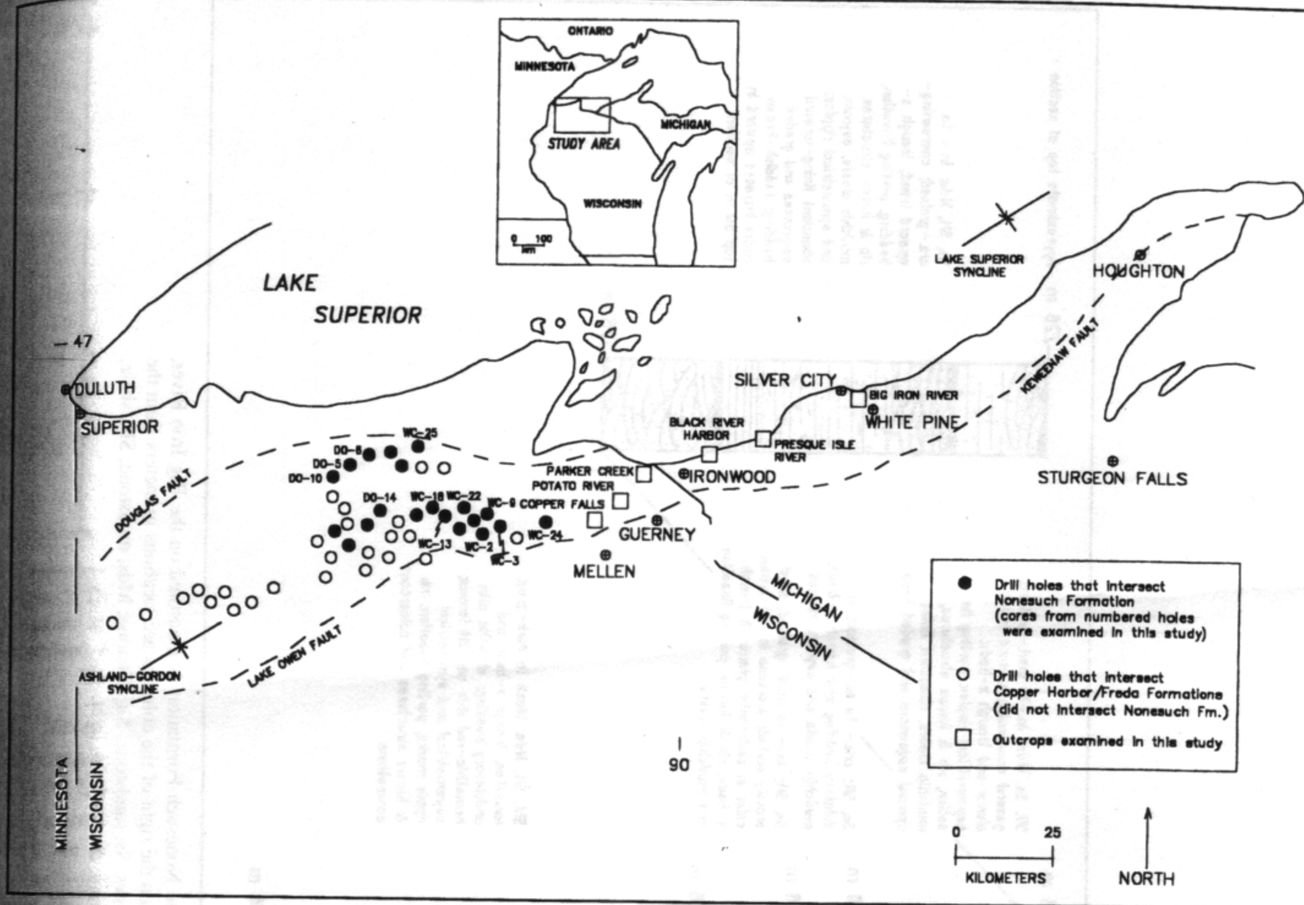


Figure 1. Location of Bear Creek drill holes and outcrops examined during this study.

The Nonesuch Formation cores were divided into six sedimentary intervals based on the occurrence of similar sedimentary structures and textural elements. The criteria used to develop these intervals were (1) significant changes in the percentages of coarse-grained and/or fine-grained sedimentary rocks; and (2) the occurrence of similar sedimentary structures, with particular emphasis on parallel-laminated beds, massive and graded beds, micro-trough cross-bedding, and carbonate laminite. All intervals are gradational and generally indicate gradual fluctuations in sedimentary processes. Figure 6 illustrates the sedimentational intervals in drill core WC-2.

## PETROGRAPHY

Petrographic analysis of 27 thin sections from Nonesuch outcrop and drill core samples indicates that the average composition of the major framework clasts in the sandy and sandy-silt facies is: 36% volcanic rock fragments; 11.7% metamorphic, plutonic, and sedimentary rock fragments; 24% unit quartz grains; and 26.8% feldspar grains (predominantly plagioclase). Mafic volcanic rock fragments dominate in all of the outcrop samples. Mafic volcanic rock fragments dominate in the cores examined from the southern and southeastern regions of the study area, whereas felsic volcanic fragments dominate in cores from the western and northwestern areas.

The Nonesuch is well indurated, but contains considerably less cement than the underlying Copper Harbor Formation. Cementing agents are, in order of abundance: calcite, quartz, and laumontite. Matrix materials are, in order of abundance: chlorite, epidote, sericitic clay, and silt-sized feldspar and quartz.

The sandstone samples from drill cores and outcrops indicate a general but subtle increase in mineralogical maturity from the upper Copper Harbor Formation (6 m thickness) through the Nonesuch to the lower Freda (25 m thickness). The majority of Nonesuch sandstone samples in drill cores and outcrops are lithic arenites, after Dott (1964; Fig. 7). Six samples, not included on the plot in Figure 7, contain greater than 15% micaceous matrix and are classified as lithic graywackes.

Mafic and intermediate volcanic rock fragments are most abundant in the cores along the southern part of the study area (cores WC-3, WC-2, WC-9, WC-13, WC-18, and WC-22) and decrease westward and northward. Felsic volcanic rock fragments increase to the west-northwest, as indicated by cores WC-25, DO-5, DO-6, DO-10 and DO-14 (see Fig. 1).

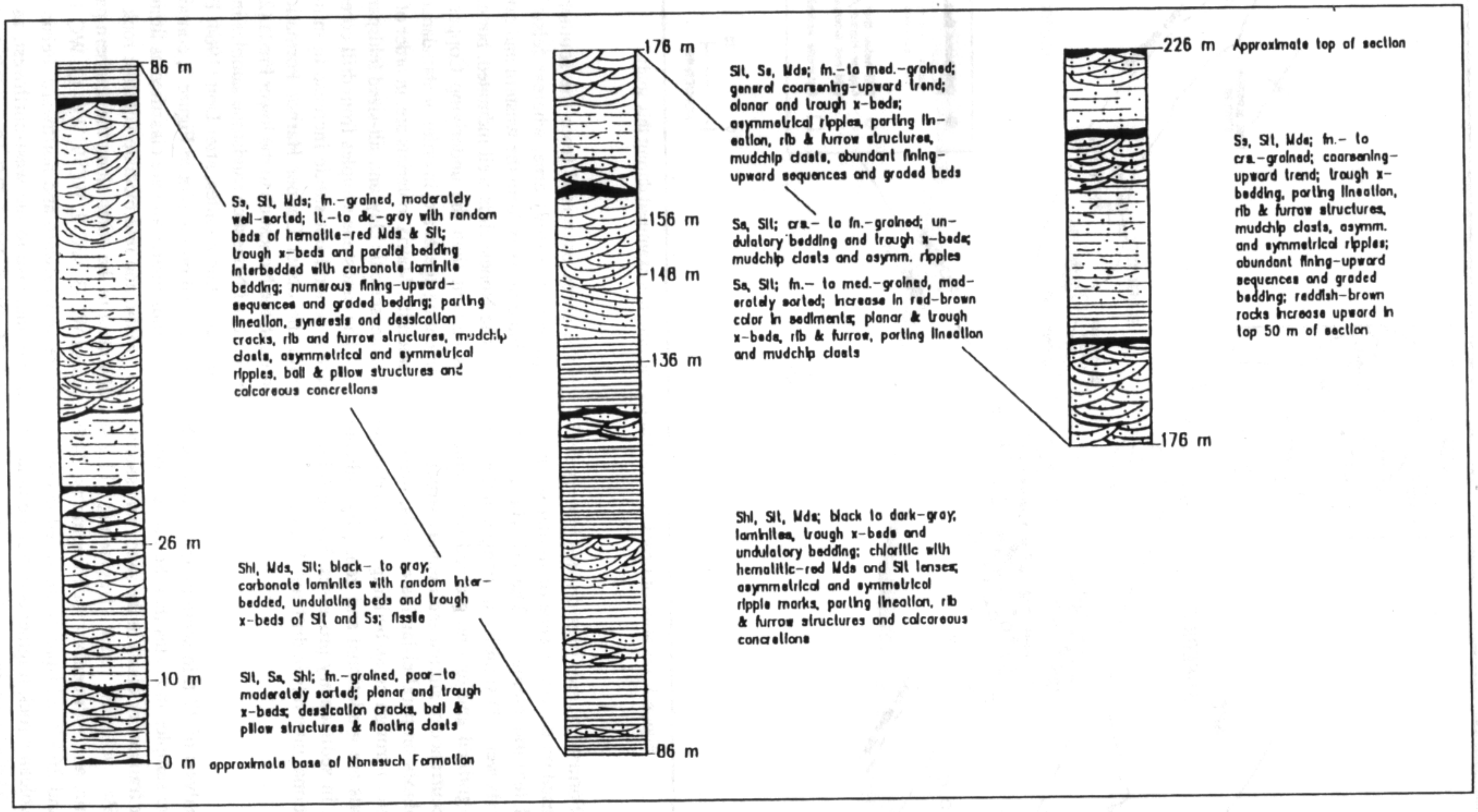


Figure 2. Diagrammatic illustration of the Nonesuch Formation as measured on the Big Iron River, Ontonagon County, Michigan. Numbers on the right of the columns are locations in meters from the base of the section. Abbreviations as follows: Ss, sandstone; Slt, siltstone; Mds, mudstone; Shl, shale; x, cross; fn., fine; crs., coarse; med., medium; dk., dark; lt., light.

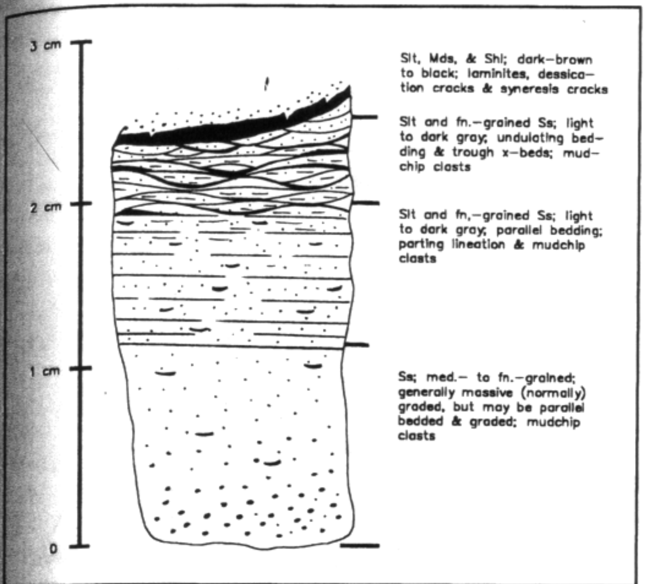


Figure 3. Diagrammatic illustration of a graded bed, Big Iron River measured section. This bed is 79 m above the base of the Nonesuch Formation. Abbreviations used are the same as in Figure 2.

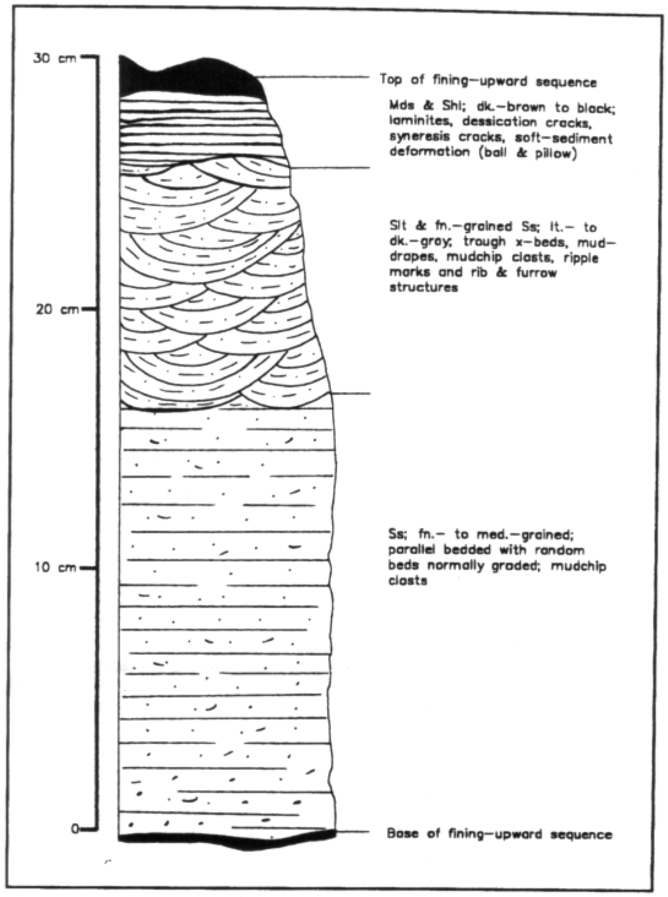


Figure 4. Diagrammatic illustration of a fining-upward-sequence, Big Iron River measured section. This sequence is 132 m above the base of the Nonesuch Formation. Abbreviations used are the same as in Figure 2.

Metasedimentary and plutonic rock fragments decrease to the north-northwest as indicated by cores WC-25, DO-6, and DO-10. Unstrained volcanic quartz shows a sharp increase to the northwest from WC-18 to WC-25 and appears to correlate with the felsic volcanic fragments that predominate in drill cores from this part of the study area. In the southern part of the core area, the highest percentages of strained quartz are in the cores that contain slate, schist, quartzite, iron-formation, and

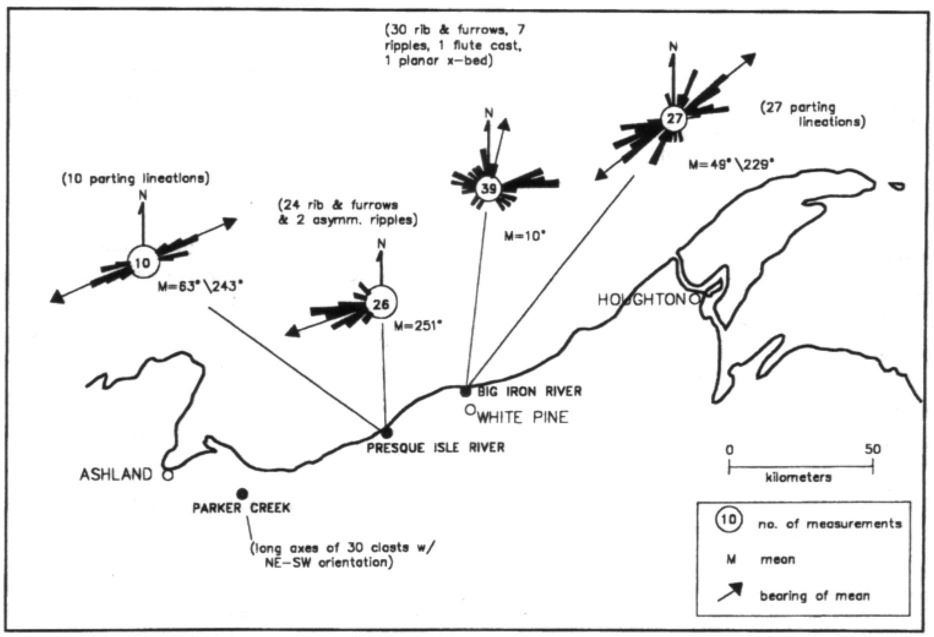


Figure 5. Paleocurrent indicators for the Nonesuch Formation at the Big Iron River measured section and the Presque Isle River exposure.

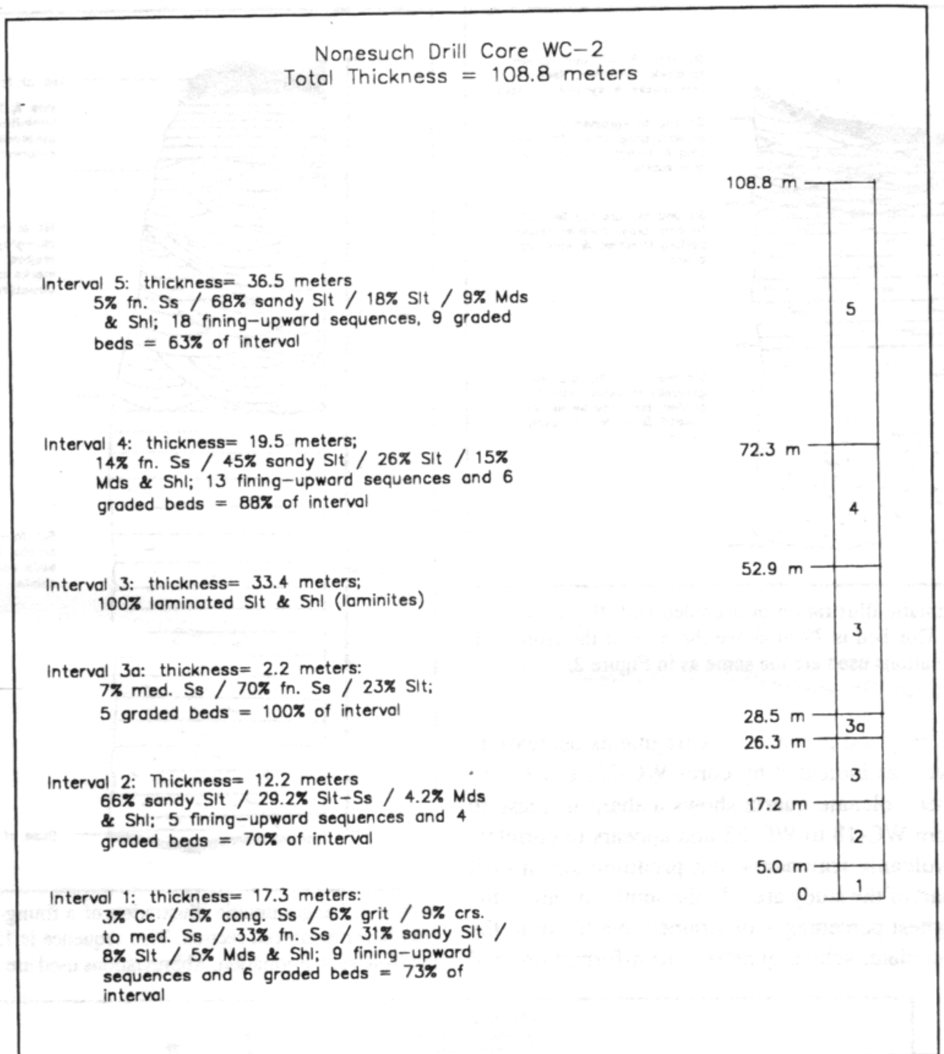


Figure 6. Diagrammatic illustration showing stratigraphic position and data for Nonesuch Formation sedimentational intervals in drill core WC-2. WC-2 is representative of cores exhibiting intervals 1 through 5. Abbreviations used are the same as in Figure 2.

plutonic rock fragments (WC-3, WC-2, WC-22, and WC-13). Multicycle calcite grains (reworked Copper Harbor Formation) and multicycle quartz grains occur in trace amounts in all cores.

Plagioclase shows a general decrease from east to west and from south to north, except in cores WC-3 and WC-13 where the highest percentages of plagioclase coincide with the highest percentages of intermediate volcanic rock fragments, suggesting derivation of the plagioclase was also from the intermediate volcanics. Potassium feldspar shows a slight decrease from east to west through the study area. The lateral variations in compositions of Nonesuch sandstones are illustrated in Figure 8.

An overall comparison of the lateral and vertical variations in composition in the Oronto Group in Bear Creek cores shows a general northward trend (WC-3 to WC-25) toward increased compositional maturity with an increase in felsic volcanic fragments, unit strained quartz, and unit unstrained quartz, and a decrease in all other constituents. Compositional maturity increases upsection from a lithic (volcanic) arenite to a quartzofeldspathic arenite. The same trend is observed in outcrops. Quartz, feldspars, and pre-Keweenawan metasedimentary and plutonic rock fragments generally increase upsection while volcanic rock fragments generally decrease.

## ENVIRONMENT OF DEPOSITION

Recent investigations (Daniels, 1982; Elmore et al., 1988; Imbus et al., 1990; this study) suggest that the Nonesuch Formation represents deposition in a perennial lake located at the toe of a transgressing-regressing alluvial fan complex, within

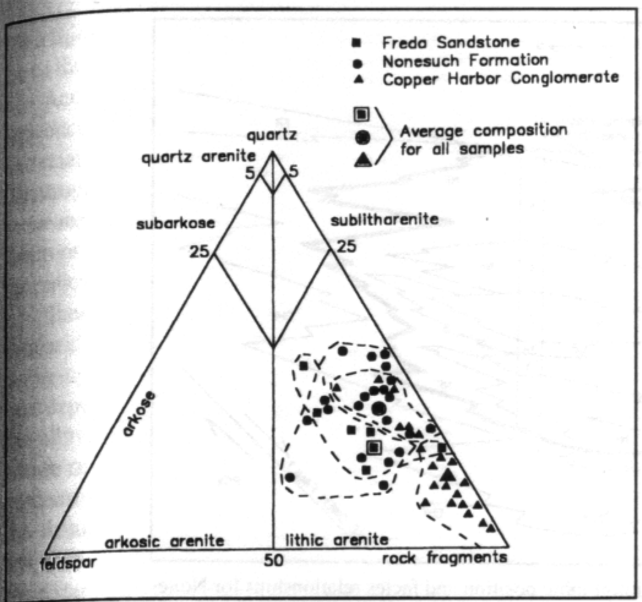


Figure 7. Compositions of Oronto Group rocks in Bear Creek drill cores of this study. A total of 47 thin sections provided the data; each symbol on the plot indicates the average of all samples from an individual core. Arenite classification after Dott (1964).

the Midcontinent Rift System. The sedimentational intervals observed in the Nonesuch drill cores contain vertical facies assemblages that record clastic deposition in a transgressing-regressing lacustrine environment. The principal evidence suggesting that the Nonesuch Formation was deposited in a lake as opposed to a marine environment is the close association of Nonesuch rocks with continental facies, especially the predominantly red oxidized fluvial rocks of the Copper Harbor and Freda Formations, which have long been regarded as continental facies. The Copper Harbor and Freda Formations are gradational with and completely enclose the Nonesuch Formation (Elmore and Daniels, 1980; Daniels, 1982; Elmore and others, 1988; this study). It can also be demonstrated that the Nonesuch Formation is coeval in part with the upper Copper Harbor and the lower Freda Formations (Daniels, 1982; this study).

Figure 9 depicts the drill core study area as a local basin that is bounded on the north by the Douglas fault and on the south by the Lake Owen fault. The five sedimentational intervals observed in drill cores were stratigraphically superimposed in a model illustrating the progressive development of the upper Copper Harbor, Nonesuch, and lower Freda Formations as perceived from the integration of facies relationships observed in outcrops and drill cores.

Figure 9 illustrates the Copper Harbor Formation as a generally northward-prograding succession of middle to distal alluvial fan facies deposited in a subsiding basin. From south to north (basinward) the alluvial facies of the Copper Harbor consist of: (1) mid-fan facies, consisting of poorly sorted and crudely bedded clast-supported conglomerate and minor matrix-supported conglomerate interbedded with trough and planar cross-bedded pebbly sandstone; (2) distal-fan facies (sandflat facies), consisting of trough and planar cross-bedded pebbly sandstone to siltstone; and (3) distal-fan facies, central basin (mud-flat facies), consisting of small-scale trough cross-bedded and parallel laminated sandy siltstone, siltstone, and mudstone. The outcrops and drill cores record a gradual down-fan transition from deposition of poorly sorted, coarse alluvium, to deposition of finer-grained clastics by braided and meandering stream processes. Daniels and Elmore (1980) and Elmore

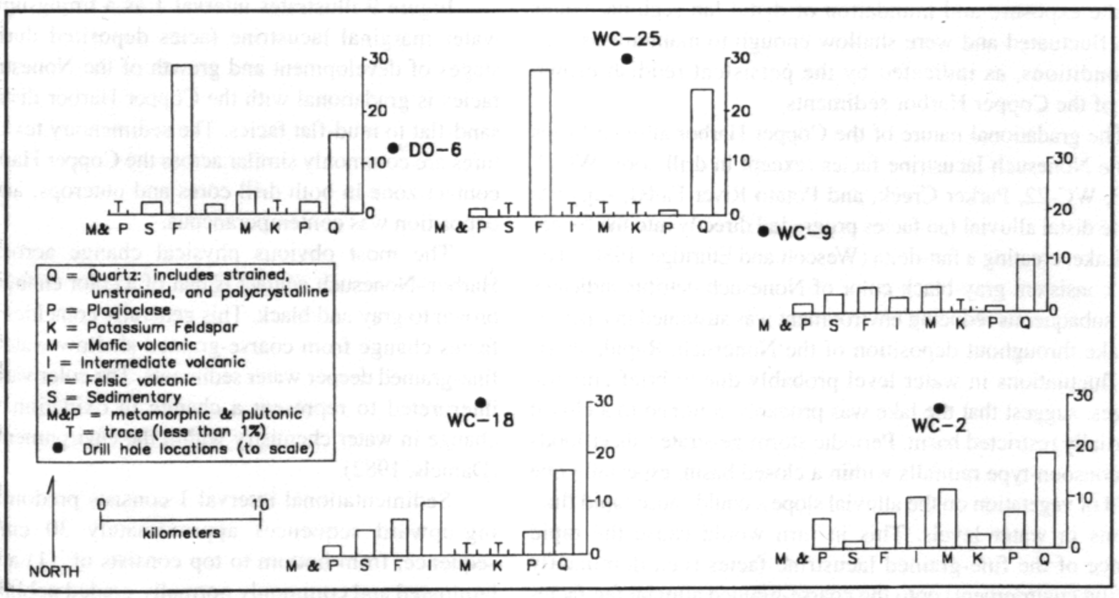


Figure 8. Lateral variations in the compositions of Nonesuch Formation sandstones from representative Bear Creek drill cores. (Units on the vertical axes indicate percent composition).

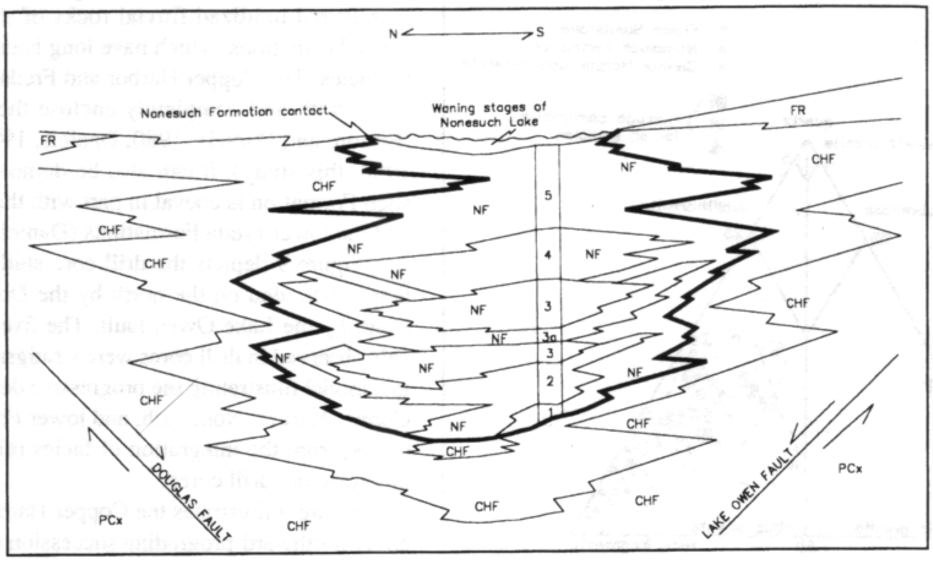


Figure 9. Diagrammatic illustration showing stratigraphic position and facies relationships for Nonesuch Formation sedimentational intervals as inferred from drill hole WC-13. Similar inferences were made from drill cores WC-2, WC-18, WC-22, DO-6, and DO-14, which contain all six sedimentational intervals. FR, Freda Formation; NF, Nonesuch Formation; CHF, Copper Harbor Formation; PCx, Lower Proterozoic and Archean crystalline rocks. Not to scale.

(1984) interpreted these rocks, where exposed in outcrops in northwestern Wisconsin and Upper Michigan, to indicate a facies assemblage that represents deposition on a prograding alluvial fan.

The distal regions of the fan (sand flat to mud flat), contain abundant asymmetrical and symmetrical ripple marks and mud cracks, indicating active stream and beach processes, and periodic exposure and inundation of distal fan regions. Water levels fluctuated and were shallow enough to maintain oxidizing conditions, as indicated by the persistent reddish brown color of the Copper Harbor sediments.

The gradational nature of the Copper Harbor alluvial facies and the Nonesuch lacustrine facies (except in drill cores WC-2, WC-3, WC-22, Parker Creek, and Potato River Falls), suggests that the distal alluvial fan facies prograded directly into the Nonesuch Lake, creating a fan-delta (Wescott and Ethridge, 1980). The fairly consistent gray-black color of Nonesuch detritus indicates that a subaqueous reducing environment was sustained in a perennial lake throughout deposition of the Nonesuch. Rapid, short-term fluctuations in water level probably due to brief climatic changes, suggest that the lake was probably confined to a closed or partially restricted basin. Periodic storm-generated sheetfloods and monsoon-type rainfalls within a closed basin, especially one devoid of vegetation on the alluvial slopes, could cause rapid fluctuations in water levels. This in turn would cause the rapid advance of the fine-grained lacustrine facies (i.e., dominantly reducing environment) onto the coarse-grained alluvial fan facies (i.e., subaerial oxidizing environment) as observed in cores WC-2, WC-3, WC-22, Parker Creek and Potato River Falls.

### *Drill core sedimentational interval 1*

Sedimentational interval 1 consists of light gray massive, trough cross-bedded, and parallel laminated conglomeratic sandstones and coarse-grained sandstones (Fig. 6). The interval gradually fines upward to dark gray medium- to fine-grained sandstones, siltstones, and mudstones.

Figure 9 illustrates interval 1 as a fining-upward, shallow water marginal lacustrine facies deposited during the initial stages of development and growth of the Nonesuch Lake. This facies is gradational with the Copper Harbor distal alluvial fan, sand-flat to mud-flat facies. The sedimentary textures and structures are commonly similar across the Copper Harbor–Nonesuch contact zone in both drill cores and outcrops, and suggest that deposition was contemporaneous.

The most obvious physical change across the Copper Harbor–Nonesuch contact is that of a color change from reddish brown to gray and black. This generally coincides with a vertical facies change from coarse-grained shallow water sediments to fine-grained deeper water sediments. The color variation has been interpreted to represent a change in oxidation state due to a change in water chemistry within the environment of deposition (Daniels, 1982).

Sedimentational interval 1 consists predominantly of fining-upward sequences approximately 30 cm thick. Each sequence, from bottom to top consists of: (1) a basal, parallel laminated and commonly normally graded pebbly-sandstone to sandy-siltstone bed with mudchip rip-up clasts; (2) micro-trough cross-bedded fine-grained sandstones and siltstones; and

(3) a thin mudstone drape. Note that these sequences are similar to those in outcrops as illustrated in Figure 4.

According to Reading (1986, p. 11) "Where fining-upward sequences dominate an alluvial succession, interpretation is extremely difficult because both environmental switching and catastrophic flows can occur, each producing similar sedimentary sequences." The fining-upward sequences in the drill cores and in outcrops suggest that clastic deposition was predominantly by sporadic sheetfloods or by subaqueous fan-delta streams.

Sheetflood deposits are typically found on alluvial fans in semiarid climates (Bull, 1964; Denny, 1965; Hooke, 1967). The fining-upward sequences in interval 1 are interpreted to represent deposition by waning sheetfloods that originated high on the alluvial fan as short-lived storm events. Deposits of this nature occur where sediment carried both as bedload and in suspension in a high velocity channel flow, spreads out below the channel (Bull, 1964). The shallow sheet flows seldom persist far onto the alluvial sand flat, largely due to infiltration of the water (Rahn, 1967). This suggests that flooding events that deposited detritus as fining-upward sequences well beyond the toe of the alluvial fan into the Nonesuch depositional basin were probably of considerable magnitude and lateral extent. On an alluvial fan surface devoid of vegetation, even a moderate rainfall would probably have resulted in a sediment-laden sheetflood of considerable depth and velocity. This appears to be the case as indicated by the frequency and lateral extent of fining-upward intervals throughout all the Nonesuch Formation in drill cores and outcrops.

A sediment-laden sheet of water, upon entering the lake at the toe of the alluvial fan (i.e., fan-delta), would become a density current. The initial deposit from this current would be the basal parallel laminated sand and silt (±mica) with reddish brown mudchip clasts, from detritus that was transported as bedload (Collinson, 1978). Where the basal parallel laminations of each sequence are composed of fine-grained sand and reasonably free of mica, high-velocity currents and shallow water depth are indicated; where very micaceous sands occur, lower flow conditions may have applied (Collinson and Thompson, 1982, p. 97). With further velocity decrease, fine sand and silt would be deposited as small-scale cross-beds (rib-and-furrow structures) as current ripples migrated across the surface (Collinson and Thompson, 1982, p. 98). Asymmetrical ripple marks are present on numerous bedding surfaces. The current-generated ripples that were measured in the lower Nonesuch Formation at the Big Iron River and Presque Isle River sections have an average ripple index of 9, indicating that the micro-trough cross-beds were deposited by medium- to low-velocity currents (Reinick and Singh, 1980, p. 29). The mud drapes that top fining-upward sequences were deposited by suspension settling of mud dispersed in the water column.

Sharp contacts are common between the mudstone top of one fining-upward sequence and the overlying sandstone base of another. This indicates that deposition was sporadic, yet quite common, as might be expected with sheetflooding. The lack of gradation at sequence contacts suggests that extrinsic factors such as climate may have partially controlled the rate and style of deposition.

Randomly interbedded with the fining-upward sequences are ≤1-m-thick sandstone beds that are massive, ungraded, or normally graded, and very coarse to fine grained. The occurrence of these sandstone beds suggest deposition by turbidity currents that carried an abundance of coarse-grained detritus; they may well be coarse-grained channel sands deposited by turbidity currents in subaqueous channels that represent a lakeward extension of fan-delta fluvial processes.

Reddish brown oxidized sediments are interbedded with gray-black sediments throughout interval 1 and decrease in abundance upsection. The occurrence of red, oxidized sediments interbedded with gray to black sediments that were deposited in a reducing environment (Elmore et al., 1988) is interpreted as an interfingering relationship of the Copper Harbor and Nonesuch Formations. Oxidized sediments, when introduced into a reducing environment, can be preserved as such if they are rapidly deposited and buried (Ehrlich and Vogel, 1971).

Asymmetrical and symmetrical ripple marks, mud cracks, and syneresis cracks indicate fluctuating water levels, variations in flow velocity and direction, and periodic subaerial exposure.

### *Drill core sedimentational interval 2*

Sedimentational interval 2 consists of gray, massive, micro-trough cross-bedded and parallel-laminated, medium- to fine-grained sandstone, sandy siltstone, siltstone, and mudstone that record the continued expansion and deepening of the Nonesuch Lake. The vertical facies assemblage shows a gradual transition from shallow-water marginal lacustrine to deep-water marginal lacustrine, and represents a continuation of the fining-upward, basinward-fining trend observed in interval 1. An upsection increase in the percentage of fine-grained sandstone, siltstone, and mudstone, and the absence of pebbly sandstone and coarse-grained sandstone in drill cores, were the main criteria for separating out interval 2.

Fining-upward sequences continue to dominate the sedimentary pattern, but are not as frequent (Fig. 6). The number of massive and normally graded, medium-grained sandstone to sandy-siltstone beds increase upsection and basinward from interval 1. This suggests that as the lake became deeper, turbidity currents played a greater role in the depositional processes.

Interbedded reddish brown sandstones, siltstones, and mudstones decrease upsection. Near the top of the interval, carbonate laminite beds are sparsely interbedded with massive, normally graded, and micro-trough cross-bedded sandstones and siltstones. This is interpreted to represent a gradual basinward shift from current-generated deposits (sheetflood and turbidity currents), to deposition by suspension settling of mud and $CaCo_3$ from the water column in deeper and quieter areas of the basin.

The carbonate laminite consists of thin (≤1 mm), light gray, carbonate-rich fine-grained sandstones and siltstones and thinner (<1 mm), black to green, organic-rich mudstone/shale beds. Thicker sandstone-siltstone laminae commonly display normal grading or microtrough cross-bedding. Individual laminae commonly show evidence of loading and mixing. Sand and silt detritus was often rapidly deposited on top of soft mud laminae, as indicated by the occurrence of flame structures, load casts (ball and pillow variety), and the swirled appearance of mixed sandstone, siltstone, and mudstone. The black, organic-rich shale laminae were deposited by suspension settling of mud-sized detritus that was dispersed in the water column by the turbidity currents, and by the normal suspension settling of very fine grained detritus and organic material from higher up in the water column where density overflows and interflows may have occurred (Fig. 10).

### *Drill core sedimentational intervals 3 and 3a*

Sedimentational interval 3 consists of gray micro-trough cross-bedded fine-grained sandstone, siltstone, mudstone, and carbonate laminite (Fig. 6). The Nonesuch facies in this interval records a transition from deep marginal lacustrine facies to central lake basin facies, and is interpreted to represent clastic deposition when the lake reached its highest water level. The facies transition from interval 2 to interval 3 is gradational. Percentages of siltstone and mudstone increase and become progressively darker and more organic-rich upsection (Elmore et al., 1988).

The dominant lithology is carbonate laminite. Interbedded with the laminite beds are what appear to be turbidity current deposits consisting of massive, graded, parallel-laminated, convolute bedded, and microtrough cross-bedded, medium- to fine-grained sandstone and siltstone beds. Turbidity currents generated by storms or initiated by gravity slumping along the steeper slopes flanking the central lake basin, continued to deposit medium-to fine-grained sandstone beds well into the lake basin. The turbidites in interval 3 are thinner and less frequent than the turbidites observed in interval 2.

The laminite is correlative in all drill cores. The question is posed as to what conditions were responsible for the widespread and fairly even distribution of carbonate silt and clayey mud detritus to form extensive carbonate laminite. A thermally stratified lake (Fig. 10) would have provided an effective means of sorting and distributing fine-grained detritus in the water column throughout the basin. Elmore (1983, 1984) and Elmore et al. (1988) suggested that the production and preservation of organics could have been best accomplished by the presence of a fluctuating thermocline in a stratified Nonesuch Lake. The thermocline is the layer of water characterized by a rapid decrease in temperature and an increase in density with depth that separates the overlying epilimnion from the underlying hypolimnion (Sturm and Matter, 1978). A thermocline, when encountered by turbidity currents, could have diverted a large amount of the finer-grained detritus to surface currents. A portion of the heavier detritus probably continued to move along the lake bottom whereas more of the lighter detritus was removed and distributed to interflows in the epilimnion. The epilimnion is the uppermost layer of water in a stratified lake, characterized by an essentially uniform temperature that is generally warmer than anywhere else in the lake (Sturm and Matter, 1978). Once in the epilimnion, pelagic sediments could have been distributed over a large area of the basin, and deposited over the deeper and quieter areas of the central lake bottom by suspension settling.

Mud-size detritus may have settled out of the epilimnion continually during the course of the year as dictated by climate

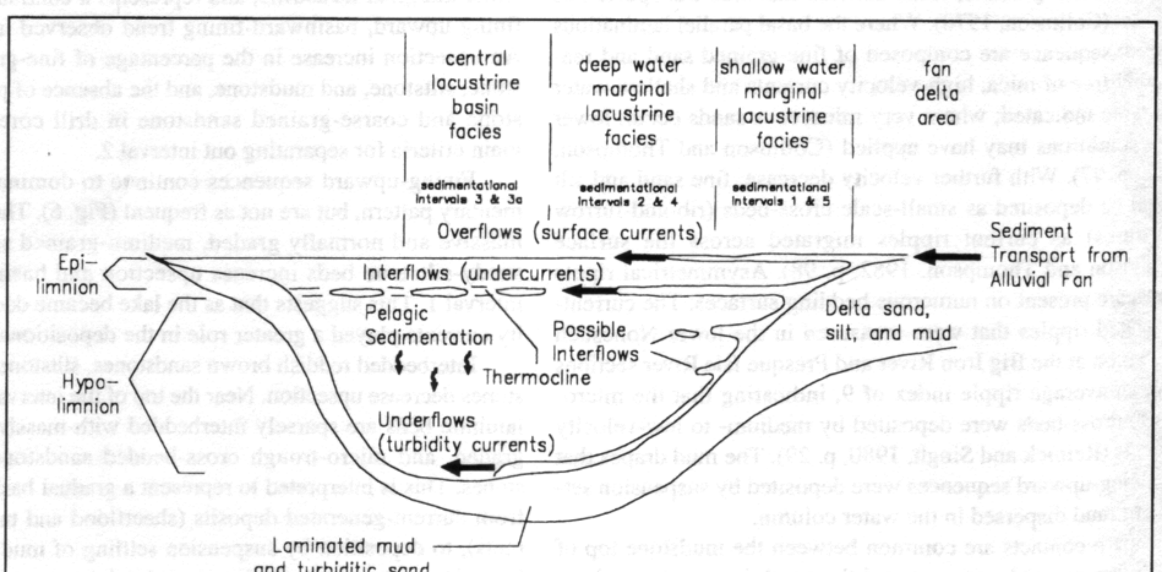


Figure 10. Thermally stratified lake model and distribution mechanisms proposed for the Nonesuch Formation in the Bear Creek drill cores (modified after Sturm and Matter, 1978).

and seasonal lake turnover. A nonseasonal lake turnover could have occurred if the epilimnion periodically became saturated with detritus due to an increase in the rate of sediment influx. The result would have been a decrease in the density variation between epilimnion and hypolimnion (the layer of cold, dense water at the bottom of the lake below the thermocline), which could have caused the lake to turn over and dump more mud and silt than normal into lower depths of the lake. Evidence for this is weak, but is suggested by the variation in thickness of mudstone laminae (0.1 to 0.75 mm) and siltstone laminae (0.5 to 1.0 mm).

The heavier, coarse-grained sediment may have been carried below the thermocline and distributed to interflow currents in the hypolimnion or deposited directly on the basin floor as turbidity flow deposits (Fig. 10). Microscopic trough cross-bedding randomly occurs in the coarser-grained carbonate-rich laminae, as seen in drill core WC-9 at 72 m (235 ft) above the base of the Nonesuch Formation. This suggests that low-velocity bottom currents were depositing and perhaps reworking detritus in the deepest areas of the lake basin.

The settling out of mud put into suspension by density currents and turbidity current flows along the lake bottom, and organic detritus derived from the algae that were produced during the warmer seasons (Elmore et al., 1988), accounts for most of the constituents in the black mud-rich laminae.

The origin of the carbonate in the light gray siltstone laminae is partially due to biogenic processes as suggested by the presence of algal-like filaments and an amorphous organic groundmass within the clastic laminae (Kelts and Hsu, 1978; Elmore et al., 1988; Imbus et al., 1990). In addition to biogenic carbonate, numerous well-rounded silt-sized limestone grains, consisting of fine-grained sparry calcite, were observed within the carbonate-rich laminae. The presence of these grains suggests that they may have been derived from subaerial evaporites or caliche, eroded by sheetfloods from nearby (Copper Harbor) alluvial fan sand-flat and mud-flat areas, reworked, and redeposited with silt-sized grains of quartz and feldspar by turbidity flows and by suspension settling. However, the presence of stromatolites in the Copper Harbor on the Keweenaw Peninsula (Daniels and Elmore, 1980; Elmore, 1983), and the presence of oncolites in the Copper Harbor (Suszek, 1991) shows that these are another possible source of carbonate.

Sedimentational interval 3a (Fig. 6) consists of massive, normally graded, and small-scale trough cross-bedded, coarse- to fine-grained sandstone and siltstone with only minor interbedded carbonate laminite near the bottom and top of the interval. Interval 3a occurs as a distinctly different facies stratigraphically enclosed by interval 3 (Fig. 9).

The facies assemblage in interval 3a records a temporary lake regression from deep-water, central lake facies to deep-water, marginal lake facies. Coarse-grained sandstones and siltstones increase near the top of interval 3, and prevail throughout most of interval 3a. The abundance of coarse-grained detritus rapidly decreases near the top of interval 3a as contact with upper portion of interval 3 is approached.

The sedimentary structures in interval 3a suggest that deposition was predominantly by turbidity and density flows. Graded beds range from 2 cm to 0.5 m in thickness. Fining-upward sequences deposited by sheetfloods are rare. This suggests that interval 3a represents a facies transition between deep-water marginal lacustrine and deep-water central lake, even though the texture of the rocks suggests deposition in areas of the lake basin close to the alluvial fan complex. The change in facies from 3 to 3a appears to have been short lived but widespread, and can be correlated in drill cores throughout the entire basin. Such a rapid facies change was probably brought on by a sudden, but brief, change in tectonics or climate. If the change was regional, one would expect to see a more gradual and stratigraphically thicker facies transition as was observed in intervals 1, 2 and 3.

Interval 3a fines upward where it is in gradational contact with the upper part of interval 3. The segment of interval 3 above interval 3a is again dominated by deep-water, central lake carbonate laminite that gradually coarsens upward to deep-water, marginal lacustrine facies.

### *Drill core sedimentational intervals 4 and 5*

Sedimentational intervals 4 and 5 consist of gray, small-scale trough cross-bedded, massive and graded, coarse- to fine-grained pebbly sandstone, siltstone, and mudstone (Fig 6). These intervals record a gradational, coarsening-upward, and shallowing-upward facies trend as the Nonesuch drill core basin began to fill with detritus and the lake regressed (Fig. 9).

Interval 4 shows a decrease in carbonate laminite upsection. Medium- to fine-grained sandstones, siltstones, and mudstones occur as fining-upward sequences and turbidity flow deposits. Sheetflood deposits (fining-upward sequences) become more frequent upsection. Interbedded red oxidized sediments begin to occur again, and increase in abundance upsection.

Interval 5 records the final stages of lake regression. Gray, pebbly, coarse-grained, trough cross-bedded sandstones and fining-upward sequences increase upsection. The upper facies of interval 5 indicates a gradational transition from shallow-water marginal lacustrine to fluvial flood-plain deposits of the lower Freda Formation. The upper contact of interval 5 establishes the Nonesuch Formation–Freda Formation contact in drill cores WC-2, WC-3, WC-9, WC-13, WC-18, WC-22, and DO-14. Intervals 4 and 5 are missing in drill core WC-25, and interval 5 is missing in cores DO-5 and DO-6.

## PROVENANCE AND BASIN ANALYSIS

Based on petrographic analysis, the most likely major source for Oronto Group sediments would have been Keweenawan igneous rocks within the Midcontinent Rift System. Heavy mineral suites show a relative increase in contributions from older Proterozoic and Archean rocks (i.e., extrabasinal rocks) at stratigraphically higher intervals in the

Oronto Group. These older metamorphic and plutonic rocks became important sources as streams reached farther afield as the rift was becoming filled, and as the Keweenawan volcanic rocks were reduced in quantity on the sides of the rift.

Hubbard (1972) suggested that lower Keweenawan and older rocks provided much, if not all, of the detritus for the Keweenawan sedimentary rocks in the Upper Peninsula of Michigan and in Wisconsin. He demonstrated structurally and petrographically that lower Keweenawan rocks were metamorphosed, uplifted, and eroded during later Keweenawan time. During that time, middle Keweenawan volcanic and sedimentary rocks were largely protected from erosion. Hubbard's (1972) conclusions are based on (1) the general lack of volcanic rock fragments with ophitic textures that are indicative of mafic rock types in the middle Keweenawan Portage Lake Volcanics, and (2) the predominance of volcanic rock fragments that have been metamorphosed to upper greenschist facies and are indicative of sedimentary and igneous rocks that occur in the lower Keweenawan Powder Mill Group, the oldest of the Keweenawan volcanic units.

The conglomerate and sandstone facies in drill cores contain minor fragments of granophyre and granite, which suggests that the Keweenawan Mellen Intrusive Complex and related intrusives to the southeast of the drill core locations were being unroofed during that time. Minor iron-formation, jasper, slate, and quartz-mica schist rock fragments indicate that Early Proterozoic Animikie Group and Archean rocks to the south were also being eroded.

The mafic, intermediate, and felsic volcanic rock fragments bear a strong resemblance to basalt, andesite, rhyolite, and quartz latite flows described by Hubbard (1975). The groundmass in the majority of the mafic and intermediate fragments has been extensively altered to epidote and chlorite, and feldspar phenocrysts are seriticized; these fragments are probably from the lower Keweenawan Siemens Creek Formation.

The felsic volcanic fragments exhibit distinctive snowflake textures and platy quartz textures that are commonly observed in the quartz latites and rhyolites of the lower Keweenawan Kallander Creek Formation (Hubbard, 1975), and the North Shore Volcanic Group (John C. Green, personal communication, 1992). Ophitic textures in basaltic fragments that would suggest the middle Keweenawan Portage Lake Volcanics as a possible source terrane were not observed.

Higher percentages of mafic to intermediate volcanic rock fragments in cores from the eastern and southern areas of the drill core study area suggest the presence of a mafic to intermediate volcanic source to the south and southeast (Fig. 11). Recent field investigations by Cannon et al. (1993), suggest that a lower Keweenawan broad central volcano centered near Mellen, Wisconsin (see Kallander Creek Volcanic Center, Fig. 11), affected the distribution and lithology of younger rocks.

The general increase in unit strained and unstrained volcanic quartz and a sharp increase in felsic volcanic rock fragments to the north and northwest (cores WC-25, DO-14, DO-10, and DO-6), indicate that a felsic volcanic source probably existed in the area with the same composition as the felsic volcanic detritus observed directly below the lower Nonesuch Formation contact in core WC-25. The upsection increase in detritus from Early Proterozoic and Archean quartz-bearing crystalline rocks on the flanks of the rift was probably the major cause of the upsection increase in mineralogical maturity.

Analysis of paleocurrent structures in the Oronto Group from the Big Iron and Presque Isle Rivers obtained during this study (see Fig. 5), and from the work of previous investigators (White and Wright, 1960; Hamblin and Horner, 1961; Hite, 1968; Daniels, 1982), confirms that the transportation of detritus was generally towards the north, northeast, and northwest. However, paleocurrent structures show a change in current direction, from northeastward near the base of the Nonesuch Formation to southwestward near the top of the formation, at the Big Iron River and the Presque Isle River exposures.

Hite (1968) also noted that in the lower Freda Formation at the Bad River exposure (Copper Falls on Fig. 1), paleocurrent directions were to the southwest. Northeast of the Bad River, at the Potato River, the paleocurrents in the lower Freda Formation are toward the south and northeast (Hite, 1968). This suggests that an elevated highland existed between the Potato River and the Bad River sections, and diverted currents to the west and east. Local reversals in paleocurrent direction, according to Daniels (1982), may also be due to stream meandering, diversion by lava flows or alluvial fan lobes, or reversal of the slope of the basin floor.

Hite (1968) recorded an upsection increase in basaltic fragments in the upper Copper Harbor Formation exposed along the Bad River. Basaltic fragments also account for the largest detrital constituent in upper Copper Harbor Formation in cores WC-24, WC-2, and WC-3, which are the Bear Creek drill holes closest to the Keweenawan (Kallander Creek) central volcano of Cannon et al. (1993), and what Hite (1968) suggested was an elevated mafic volcanic highland in the vicinity of the Bad River. Note that the presence of a highland in this area is also indicated by paleocurrent data.

Drill hole WC-24, located at the far eastern edge of the drill core study area, intersected approximately 30 m (100 ft) of predominantly clast-supported basalt-rich conglomerate of the Copper Harbor Formation, directly below the Pleistocene glacial overburden. The absence of Nonesuch and Freda sedimentary rocks in this core could be the result of faulting and erosion. However, the proximity of WC-24 to the proposed volcanic center/highland of Hite (1968) and Cannon et al. (1993), suggests that these conglomerates were located on the upper slopes of a highland that was topographically high enough to be isolated from the Nonesuch and Freda sedimentary environments.

The Nonesuch Formation thins westward from the Big Iron River to the Bad River at Copper Falls State Park, and becomes thicker again westward from drill hole WC-24 along the southern part of the Nonesuch drill core basin in cores WC-3, WC-2, WC-9, WC-22, WC-13, and WC-18 (Fig. 11). These data also suggest

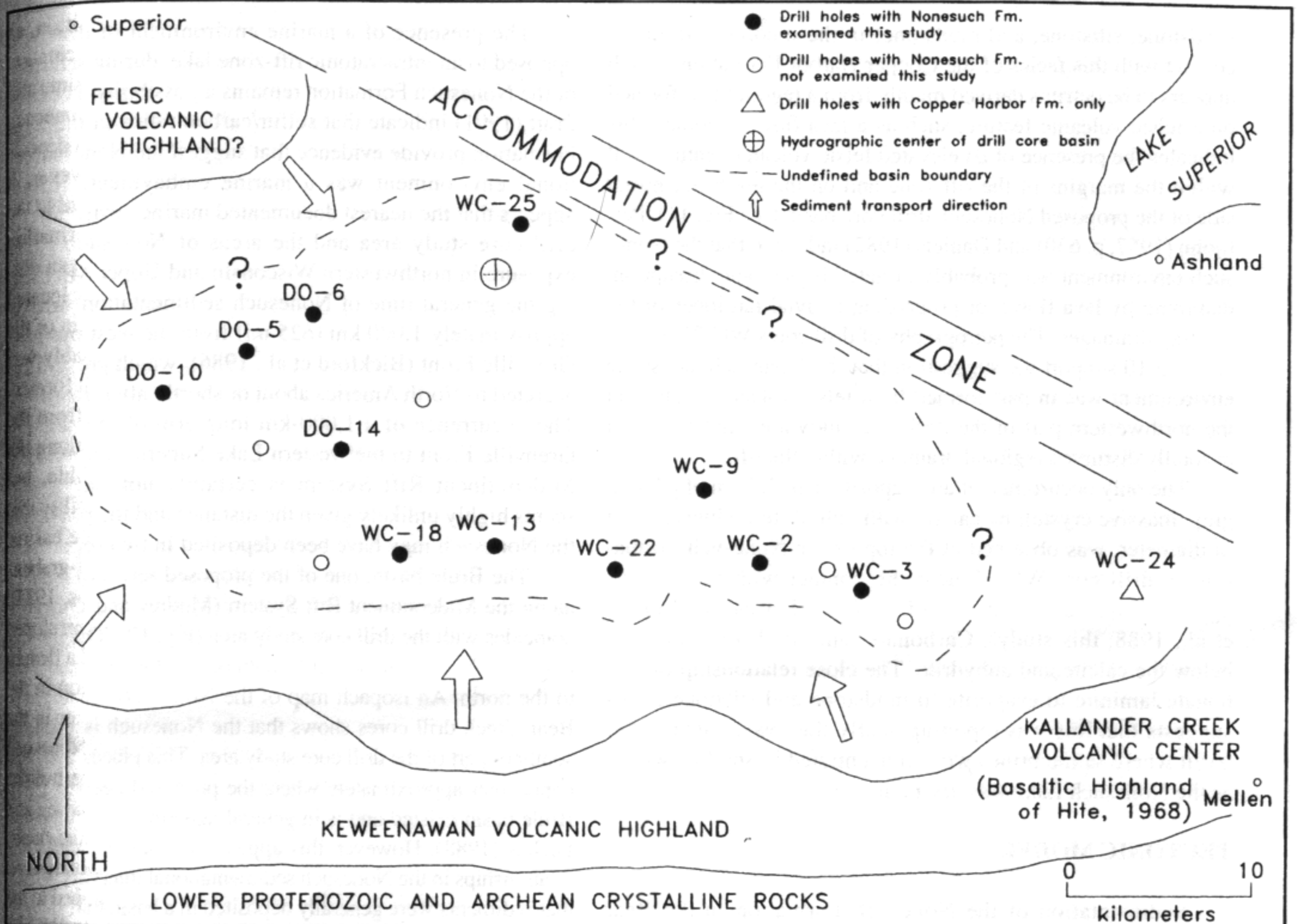


Figure 11. Generalized map of the drill core study area showing the Nonesuch depositional basin and source areas. (Proposed accommodation zone from Mudrey and Dickas, 1988).

that an elevated highland in the eastern part of the drill core study area may have separated or partially separated the study basin from a basin or basins containing Oronto Group sediments farther east in northwestern Wisconsin and Upper Michigan.

Drill holes WC-2, WC-9, and WC-22, along the southern perimeter of the Nonesuch drill core basin, indicate that the red-brown conglomeratic facies of the Copper Harbor Formation directly underlies gray-brown sandstones, siltstones, and mudstones of the overlying Nonesuch Formation. The Copper Harbor–Nonesuch contacts in these drill cores are similar to those observed in exposures to the east of the core study area at Parker Creek and Potato River Falls (see Fig. 1). Elmore et al. (1988) suggested that the abrupt transition from red-brown clast-supported conglomerates to fine-grained sandstones and siltstones is due to the rapid encroachment of the Nonesuch sediments onto a steeply dipping alluvial fan surface, which prohibited the development of a gradual proximal to distal subaerial fan facies–subaqueous fan-delta transition.

The facies changes at the Copper Harbor–Nonesuch contacts become texturally less abrupt northward and westward from drill holes WC-2, WC-3, and WC-22. This indicates a gradual northward and westward (basinward) facies transition from conglomerate to sandstone to siltstone and mudstone.

Drill core sedimentological intervals 4 and 5 (dark gray, coarse- to fine-grained sandstones, siltstones, and mudstones as fining-upward sequences, and massive and graded beds), which overlie interval 3 (dark gray to black carbonate laminite), are stratigraphically thicker in the cores to the south (WC-3, WC-2, WC-9, WC-22, WC-13, WC-18, and DO-14), and totally absent or total less than 1 m thick in the northernmost cores WC-25 and DO-6 (see Fig. 1). This suggests that the sediments in intervals 4 and 5 were deposited in a deep- to shallow-water euxinic marginal lacustrine environment basinward (northward) of a prograding fluvial-deltaic environment.

The upper Copper Harbor Formation in drill cores WC-25, DO-6, and DO-10 contains grit and coarse-grained sandstones consisting predominantly of felsic volcanic rock fragments and volcanic quartz. Sedimentational interval 2 (gray fine-grained sandstone, siltstone, and mudstone) in these cores is in direct contact with this facies of the Copper Harbor Formation, which appears to be detritus derived mainly from a regolith that formed on a felsic volcanic feature, such as a lava flow or dome. This indicates the presence of an elevated felsic volcanic feature well within the margins of the rift zone and on the north-northwest side of the proposed Nonesuch drill core basin (see Fig. 11). Pettijohn (1957, p. 630) and Daniels (1982) indicated that the Nonesuch environment was probably initiated by tectonic disruption, damming by lava flows, or prograding alluvial fan lobes of the existing drainages. The petrography of drill cores WC-25, DO-6, and DO-10 support the suggestion that the Nonesuch lacustrine environment was in part formed by a felsic volcanic feature in the northwestern part of the drill core study area that restricted or totally disrupted regional drainage within the rift.

The only occurrence of an evaporite bed, 2.75 m of pinkish gray, massive crystalline calcite with anhydrite nodules ≤2 cm in diameter, was observed at the top of the Nonesuch Formation in drill core WC-25 near the contact with the reddish brown siltstone and mudstone of the Freda Formation (Elmore et al., 1988; this study). Carbonate laminite beds occur just below the calcite and anhydrite. The close relationship of carbonate laminite to evaporite to mudstone and siltstone facies suggests that this was topographically the lowest area in the basin where saline brines were concentrated in shallow waters as the Nonesuch Lake was drying up.

## TECTONIC MODEL

Sedimentation of the Nonesuch Formation in the Bear Creek drill hole study area appears to have occurred in an east-west-trending, fault-bounded basin (see Fig. 9). The Douglas fault on the north and the Lake Owen fault on the south bounded the depositional basin in the study area within the Ashland syncline. Reverse movement along these faults sometime after Oronto Group deposition created the St. Croix Horst.

Recent geologic mapping southeast of the drill core study area near Mellen, Wisconsin (Cannon et al., 1993), data compiled on the Oronto Group exposures in northwestern Wisconsin (Hite, 1968), and the data examined during this study place an elevated volcanic highland south and east of drill hole WC-24 (see Fig. 11). The recent interpretation of seismic reflection and three-dimensional gravity data of the Lake Superior syncline (Allen et al., 1993), and the interpretation of gravity, magnetic, and geologic data by White (1966), indicate the presence of a prominent pre-Keweenawan ridge (White's Ridge) that crosses northern Wisconsin and southwest tip of Lake Superior north-northeast of the drill core study area. These data, along with information compiled from the Bear Creek drill cores, indicate that the Nonesuch drill core study area in northwestern Wisconsin (see Figs. 1 and 11) was bounded by uplands on the south, east, and north, and was either completely separate or partially isolated from the basin containing Oronto Group sedimentary rocks to the east in Wisconsin and Upper Michigan.

The presence of a marine environment of deposition, as opposed to an intracratonic rift-zone lake, during sedimentation of the Nonesuch Formation remains a possibility. Hieshima and Pratt (1991) indicate that sulfur/carbon ratios in the Nonesuch Formation provide evidence that suggest the Nonesuch depositional environment was a marine embayment. However, it appears that the nearest documented marine environment to the drill core study area and the areas of Nonesuch Formation exposure in northwestern Wisconsin and Upper Michigan during the general time of Nonesuch sedimentation, was located approximately 1,000 km (625 mi) from the west margin of the Grenville Front (Bickford et al., 1986), which presumably was accreted to North America about or shortly after the rift formed. The occurrence of a 1,000-km-long arm of the sea from the Grenville Front to the western Lake Superior region along the Midcontinent Rift System is certainly not impossible, but seems highly unlikely given the distance and the possibility that the Nonesuch may have been deposited in two separate basins.

The Brule basin, one of the proposed series of half-grabens along the Midcontinent Rift System (Mudrey and Dickas, 1988), coincides with the drill core study area (Fig. 12). The basin sloped to the south with a major fault south of the study area and a flexure to the north. An isopach map of the Nonesuch Formation in the Bear Creek drill cores shows that the Nonesuch is thicker in the southern part of the drill core study area. This places the Nonesuch depocenter approximately where the proposed deepest part of the Brule basin existed and is in general agreement with Mudrey and Dickas (1988). However, this appears to disagree with the facies relationships in the Nonesuch sedimentational intervals which show that sediments were generally deposited in a basin that sloped to the north toward a basin center in the vicinity of drill hole WC-25 where minor evaporites were deposited (Fig. 11). This contradiction can be explained if the rate of sediment influx exceeded the rate of basin subsidence along the southern boundary of the drill core study area during the time that Oronto Group sediments were being deposited. This places the deepest areas of the basin (not the thickest sequence) to the north and west of the drill holes that define the southern part of the basin (WC-3, WC-2, WC-9, WC-13, WC-18, WC-22). Thick accumulations of poorly sorted and crudely bedded Copper Harbor conglomerates derived from a source terrane south-southeast of the core study area indicate that deposition was rapid along what were probably steep, fault-bounded, southern and eastern boundaries of the Nonesuch drill core basin.

## SUMMARY AND CONCLUSIONS

In general, the Nonesuch Formation in drill cores from northwestern Wisconsin is lithologically and petrographically similar to the Nonesuch in outcrops to the east in Wisconsin and Upper Michigan. Deposition occurred in a subaqueous environment. Although the marine versus lacustrine enigma may not be resolved, the close spatial and temporal relationship of the Nonesuch to the Copper Harbor Formation alluvial fan complex and the Freda Formation fluvial flood plain suggests that the Nonesuch was deposited in a lacustrine environment within the rift

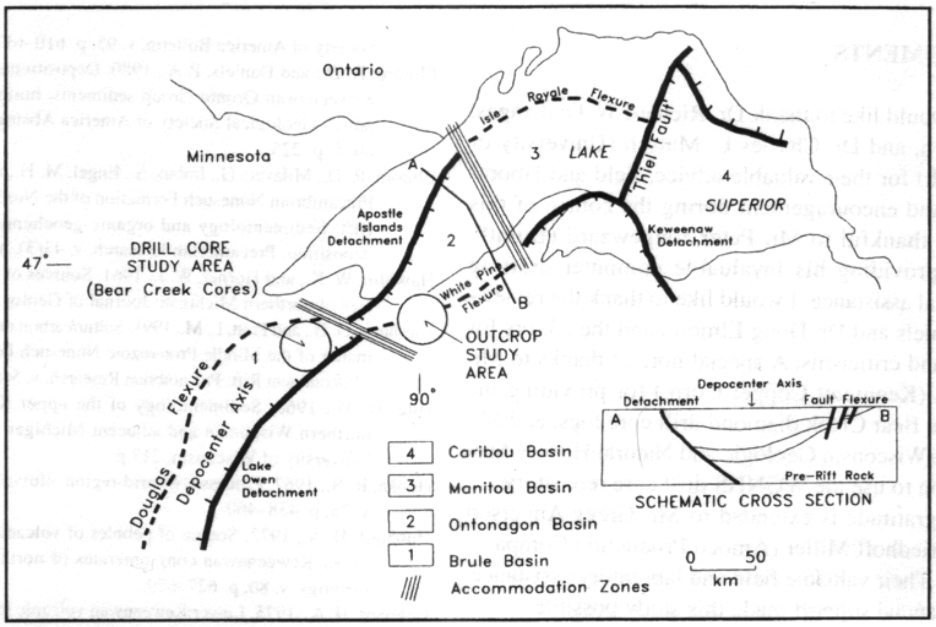


**Figure 12. Interpretation of the western Lake Superior structure along the Midcontinent Rift System (modified from Mudrey and Dickas, 1988).**

zone. Nonesuch deposition was gradational and diachronous with the upper Copper Harbor and lower Freda Formations.

The Bear Creek drill cores from northwestern Wisconsin contain a variety of lithologies and textures. Detailed sedimentologic and petrographic analysis of the cores determined that:

1. Provenance for the majority of Nonesuch detritus was the lower Keweenawan Powder Mill Group to the southeast of the drill core study area in northwestern Wisconsin. Pre-Keweenawan crystalline rocks and reworked upper Copper Harbor Formation (i.e., clasts of brown mudstone, multicycle calcite grains, and oncolites) were minor sources of detritus. Volcanic rock fragments constitute about 42% of framework grains in the coarse sandstones. The remaining framework components consist of grains of plagioclase, potassium feldspar, unit strained quartz, unstrained volcanic quartz, multicycle calcite grains, and multicycle quartz grains, granophyre and granite from lower Keweenawan sedimentary, volcanic and intrusive rocks, and slate, schist, quartzite, and iron-formation from Early Proterozoic and Archean crystalline rocks.

2. The lateral changes in the composition of Nonesuch detrital fragments in the core study area varies from predominantly mafic volcanic in the east to felsic volcanic in the west. Plagioclase and potassium-feldspars show no significant lateral variations. Metamorphic and intrusive fragments and unit quartz grains increase slightly upsection. The majority of the core samples are mineralogically immature and are classified as lithic arenites (<10% matrix).

3. Sediment transport was predominantly from south to north from an elevated highland south of the drill hole locations along the southern margin of the Midcontinent Rift System, and along a northeast-southwest trend approximately parallel to the rift zone axis. Some detritus was also derived from an elevated Keweenawan felsic volcanic terrane within the rift zone, north and west of drill hole WC-25. Sediment from this source area was probably transported to the south and east within the core study area.

4. Six sedimentational intervals in the Nonesuch Formation in the Bear Creek drill cores were established as follows: interval 1, dominantly shallow-water marginal lacustrine facies; interval 2, dominantly deep-water marginal lacustrine facies; interval 3, dominantly deep-water central lake basin facies; interval 3a, dominantly deep-water central lake basin or deep-water marginal lacustrine facies; interval 4, dominantly deep-water marginal lacustrine facies; and interval 5, dominantly shallow-water marginal lacustrine facies.

5. Deposits of the Nonesuch sedimentational intervals probably originated as ephemeral sheetfloods and subaerial fluvial-deltaic streams on Copper Harbor fans that developed into underflow turbidity currents, interflow density currents, and bottom currents in the Nonesuch basin. Finer-grained sediment was a product of suspension settling.

6. The environment of deposition for the Nonesuch Formation in cores was a fluctuating, thermally stratified, perennial lake located on the prograding Copper Harbor alluvial fan complex in a fault-bounded, subsiding basin within the Midcontinent Rift zone. Sedimentological data suggest that the Nonesuch in the core study area may have been deposited in a basin that was separate or partially restricted from Nonesuch depositional basins farther east in northwestern Wisconsin and Upper Michigan.

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