PETROGRAPHY AND SEDIMENTATION OF
THE MIDDLE PROTEROZOIC (KEWEENAWAN) NONESUCH FORMATION,
WESTERN LAKE SUPERIOR REGION,
MIDCONTINENT RIFT SYSTEM

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

THOMAS JOHN SUSZEK

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

JUNE, 1991

DEDICATED TO MY WIFE THERESE, AND MY DAUGHTERS
ANDREA AND STEPHANIE...THEY MADE
IT ALL WORTHWHILE

ABSTRACT

Detailed sedimentological descriptions and petrographic analysis of the upper Keweenawan Nonesuch Formation was accomplished for selected Bear Creek drill cores (drilled in 1958, 1959 and 1960) from Ashland, Bayfield, and Douglas Counties, Wisconsin. These data, coupled with the information from outcrops in northwest 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. Middle 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 and/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 the occurrence of similar textures, sedimentary structures and color. Light-gray to black rocks predominate in all of the intervals and indicates that deposition of Nonesuch sediments was in a reducing environment. This is in contrast to the reddish-brown rocks of the underlying Copper Harbor and overlying Freda Formations, which were deposited in oxidizing environments.

Sedimentational intervals 1 and 2 indicate a fining-upward and basinward fining trend consisting of conglomeratic sandstones to mudstones that occur as fining-upward sequences, and massive and normally graded beds deposited by turbidity and density currents in a shallow to deep water marginal lacustrine environment. The facies assemblages in intervals 1 and 2 record clastic deposition that occurred during the initial stages of development and transgression of the Nonesuch lake over the contemporaneous alluvial fan complex of the upper Copper Harbor Formation.

Interval 3 of the Nonesuch consists predominantly of alternating varve-like beds of organic-rich mudstones and

carbonate-rich siltstones deposited by suspension settling and bottom currents during periods of high water level in deep/quiet water areas of the central lake basin. Interval 3a consists of massive and normally graded turbidity and density current deposits and is completely enclosed by the carbonate laminite of interval 3. Interval 3a facies record a rapid and brief climatic and/or tectonic change, with either large-scale turbidity currents reaching the deeper areas of the basin, or a shift in environment of deposition from deep water central lake basin to shallower water marginal lacustrine.

Sedimentational intervals 4 and 5 indicate a general coarsening-upward trend from deep water central lake siltstone and carbonate laminite mudstone, to shallow water marginal lacustrine facies with massive and normally graded beds and fining-upward sequences consisting of conglomeratic sandstone, siltstone and mudstone. Parallel beds, lenticular beds, small-scale trough cross-beds, and mud drapes with dessication cracks increase in abundance upsection. The facies in intervals 4 and 5 record clastic deposition during the final regressive stages of the Nonesuch lake and are contemporaneous with the lower Freda Formation, which records a subaerial fluvial plain environment to the south.

Examination of the genetic relationship of the Nonesuch sedimentational intervals, combined with percentages of the

various compositions and textures within each facies type, petrographic data, 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 flank of the basin. Less important sources occurred 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.

TABLE OF CONTENTS

ABSTRACT.....	i
TABLE OF CONTENTS.....	v
APPENDICES.....	vii
FIGURES.....	viii
TABLES.....	xiv
ACKNOWLEDGEMENTS.....	xv
INTRODUCTION.....	1
Purpose and Scope of Study.....	3
Method of Study.....	6
Previous Work.....	8
REGIONAL GEOLOGY.....	12
General Setting.....	12
Archean.....	14
Early Proterozoic.....	14
Middle and Late Proterozoic.....	15
Lower Keweenawan.....	19
Middle Keweenawan.....	20
Upper Keweenawan.....	21
Structure.....	23
FIELD DESCRIPTIONS.....	29
Introduction.....	29
Sedimentology of Outcrops.....	30
Big Iron River Measured Section.....	31
Presque Isle River.....	51
Black River Harbor.....	53
Parker Creek Measured Section.....	56
Potato River Falls.....	64
Copper Falls State Park.....	67
Paleocurrents.....	69
DRILL CORE DESCRIPTIONS.....	75
Introduction.....	75
Sedimentology of Drill Cores.....	76
Copper Harbor Formation.....	76
Nonesuch Formation.....	78
Freda Formation.....	82
Nonesuch Sedimentational Intervals.....	85

Interval 1.....	85
Interval 2.....	86
Interval 3.....	86
Interval 3a.....	87
Interval 4.....	88
Interval 5.....	88
PETROGRAPHY.....	99
General Statement.....	99
Operational Definitions.....	102
Upper Copper Harbor Formation.....	107
Nonesuch Formation.....	113
Lower Freda Formation.....	116
Classification.....	118
Upper Copper Harbor Formation.....	120
Nonesuch Formation.....	120
Lower Freda Formation.....	121
Diagenesis.....	121
Outcrops.....	121
Bear Creek Drill Cores.....	123
COMPOSITIONAL VARIATION AND PROVENANCE.....	127
Lateral and Vertical Variations in Compositions of Sandstones in Outcrops.....	127
Upper Copper Harbor Formation.....	127
Nonesuch Formation.....	128
Lower Freda Formation.....	128
Lateral and Vertical Variations in Compositions of Sandstones in Drill Cores.....	129
Upper Copper Harbor Formation.....	129
Nonesuch Formation.....	131
Lower Freda Formation.....	133
Summary.....	133
Provenance.....	136
SEDIMENTOLOGICAL MODEL.....	142
Source and Basin Analysis.....	143
Environment of Deposition.....	148
Interpretation of Nonesuch Formation Sedimentological Intervals.....	150
Introduction.....	150
Interval 1.....	154
Interval 2.....	160
Interval 3 and 3a.....	163
Interval 4 and 5.....	170
TECTONIC MODEL.....	174
SUMMARY AND CONCLUSIONS.....	181

APPENDICES

I	Bear Creek Drill Hole Locations And Core Thicknesses	A1
II	Corrected Thicknesses For Nonesuch Formation In Bear Creek Drill Cores.....	A6
III	Formations, Lithologies and Stratigraphic Locations of Drill Core and Outcrop Samples Used In Petrographic Analysis.....	A7
REFERENCES		185

Figure	FIGURES	Page
1.	CORRELATION CHART FOR MIDDLE PROTEROZOIC ROCKS IN THE LAKE SUPERIOR REGION.....	2
2.	LOCATIONS OF OUTCROP AND DRILL HOLE STUDY AREAS.....	4
3.	LOCATIONS OF BEAR CREEK DRILL HOLES AND OUTCROPS.....	5
4.	PROGRESS OF THOUGHT IN GEOLOGIC NOMENCLATURE FOR KEWEENAWAN SERIES ROCKS.....	9
5.	GEOLOGIC MAP OF LAKE SUPERIOR REGION.....	13
6.	CORRELATION CHART FOR THE MARQUETTE RANGE SUPERGROUP IN MICHIGAN AND WISCONSIN...	16
7.	GENERAL LOCATION OF THE MIDCONTINENT RIFT SYSTEM.....	18
8.	ISOPACH MAP OF NONESUCH FORMATION IN BEAR CREEK DRILL CORES.....	25
9.	STRUCTURAL CROSS-SECTION OF NONESUCH FORMATION IN STUDY AREA.....	26
10.	STRUCTURAL CONTOUR MAP OF BASE OF NONESUCH FORMATION IN DRILL CORES.....	27
11.	STRUCTURAL CONTOUR MAP OF TOP OF NONESUCH FORMATION IN DRILL CORES.....	28
12.	LOCATION MAP FOR BIG IRON RIVER SECTION.....	32
13.	KEY TO GEOLOGIC SYMBOLS AND LITHOFACIES CODE FOR FIGURES 14, 16, 32 & 45 thru 54.....	34
14.	DIAGRAMMATIC ILLUSTRATION OF THE MEASURED SECTION AT THE BIG IRON RIVER.....	37
15.	DIAGRAMMATIC ILLUSTRATION OF A GRADED BED FROM PARKER CREEK.....	40
16.	DIAGRAMMATIC ILLUSTRATION OF A FINING-UPWARD SEQUENCE, BIG IRON RIVER.....	41
17.	PHOTOGRAPH OF FINING-UPWARD SEQUENCES, BIG IRON RIVER.....	43

18.	PHOTOGRAPH OF CARBONATE LAMINITE, BIG IRON RIVER.....	43
19.	PHOTOGRAPH OF SYNERESIS CRACKS, BIG IRON RIVER.....	45
20.	PHOTOGRAPH OF BALL AND PILLOW STRUCTURES, BIG IRON RIVER.....	45
21.	PHOTOGRAPH OF SOFT SEDIMENT DEFORMATION, BIG IRON RIVER.....	46
22.	PHOTOGRAPH OF CALCAREOUS CONCRETIONS, THE BIG IRON RIVER.....	46
23.	PHOTOGRAPH OF LARGE-SCALE TROUGH CROSS- BEDDING, BIG IRON RIVER.....	47
24.	PHOTOGRAPH OF SLUMPED SANDSTONE BED, BIG IRON RIVER.....	47
25.	PHOTOGRAPH OF ASYMMETRICAL RIPPLE MARKS, BIG IRON RIVER.....	49
26.	PHOTOGRAPH OF PARTING LINEATION, BIG IRON RIVER.....	49
27.	PHOTOGRAPH OF RIB AND FURROW STRUCTURES, BIG IRON RIVER.....	50
28.	PHOTOGRAPH OF SUBAERIAL MUDCRACKS, BIG IRON RIVER.....	50
29.	LOCATION MAP FOR THE PRESQUE ISLE RIVER EXPOSURE.....	52
30.	PHOTOGRAPH OF FINING-UPWARD SEQUENCES, PRESQUE ISLE RIVER.....	53
31.	LOCATION MAP FOR THE BLACK RIVER HARBOR EXPOSURE.....	54
32.	LOCATION MAP FOR THE PARKER CREEK MEASURED SECTION.....	57
33.	DIAGRAMMATIC ILLUSTRATION OF MEASURED STRATIGRAPHIC SECTION AT PARKER CREEK.....	58
34.	LOCATION MAP FOR THE POTATO RIVER FALLS EXPOSURE.....	65

35.	PHOTOGRAPH OF GRADED BEDS AND INTERBEDDED CARBONATE LAMINITE, POTATO RIVER FALLS.....	68
36.	PHOTOGRAPH OF NORMALLY GRADED BEDS, POTATO RIVER FALLS.....	68
37.	LOCATION MAP FOR THE BAD RIVER EXPOSURE.....	70
38.	PLOT OF PALEOCURRENT INDICATORS FOR THE NONESUCH FORMATION AT THE BIG IRON RIVER AND PRESQUE ISLE RIVER.....	72
39.	DIAGRAMMATIC ILLUSTRATION OF STRATIGRAPHIC VARIATION IN PALEOCURRENT INDICATORS AT THE BIG IRON RIVER.....	73
40.	PHOTOGRAPH OF MICRO-TROUGH CROSS-BEDDING IN DRILL CORE WC#2.....	79
41.	PHOTOGRAPH OF SYNERESIS CRACKS IN DRILL CORE WC#25.....	79
42.	PHOTOGRAPH OF LOADING IN DRILL CORE WC#3.....	80
43.	PHOTOGRAPH OF CARBONATE LAMINITE IN DRILL CORE WC#2.....	80
44.	PHOTOGRAPH OF ANHYDRITE NODULE IN CALCITE IN DRILL CORE WC#25.....	81
45.	DIAGRAMMATIC ILLUSTRATION OF STRATIGRAPHIC SECTION IN DRILL CORE WC#2.....	84
46.	DIAGRAMMATIC ILLUSTRATION AND DATA FOR NONESUCH SEDIMENTATIONAL INTERVALS IN DRILL CORE WC#2.....	90
47.	DIAGRAMMATIC ILLUSTRATION AND DATA FOR NONESUCH SEDIMENTATIONAL INTERVALS IN DRILL CORE WC#3.....	91
48.	DIAGRAMMATIC ILLUSTRATION AND DATA FOR NONESUCH SEDIMENTATIONAL INTERVALS IN DRILL CORE WC#9.....	92
49.	DIAGRAMMATIC ILLUSTRATION AND DATA FOR NONESUCH SEDIMENTATIONAL INTERVALS IN DRILL CORE WC#13.....	93

50.	DIAGRAMMATIC ILLUSTRATION AND DATA FOR NONESUCH SEDIMENTATIONAL INTERVALS IN DRILL CORE WC#18.....	94
51.	DIAGRAMMATIC ILLUSTRATION AND DATA FOR NONESUCH SEDIMENTATIONAL INTERVALS IN DRILL CORE WC#22.....	95
52.	DIAGRAMMATIC ILLUSTRATION AND DATA FOR NONESUCH SEDIMENTATIONAL INTERVALS IN DRILL CORE WC#25.....	96
53.	DIAGRAMMATIC ILLUSTRATION AND DATA FOR NONESUCH SEDIMENTATIONAL INTERVALS IN DRILL CORE DO#6.....	97
54.	DIAGRAMMATIC ILLUSTRATION AND DATA FOR NONESUCH SEDIMENTATIONAL INTERVALS IN DRILL CORE DO#14.....	98
55.	PHOTOMICROGRAPH OF MAFIC VOLCANIC ROCK FRAGMENT FROM DRILL CORE WC#3.....	109
56.	PHOTOMICROGRAPH OF SNOWFLAKE TEXTURE IN A QUARTZ PHENOCRYST IN A FELSIC VOLCANIC ROCK FRAGMENT FROM DRILL CORE DO#6.....	109
57.	PHOTOMICROGRAPH OF POIKILITIC TEXTURE IN VOLCANIC QUARTZ FROM DRILL CORE WC#25.....	110
58.	PHOTOMICROGRAPH OF A GRANOPHYRIC ROCK FRAGMENT FROM DRILL CORE WC#18.....	111
59.	PHOTOMICROGRAPH OF AN ONCOLITE FROM DRILL CORE WC#3.....	111
60.	PHOTOMICROGRAPH SHOWING SECONDARY ENLARGEMENT OF A QUARTZ GRAIN FROM DRILL CORE WC#2.....	113
61.	PHOTOGRAPH OF CRUDE OIL IN CORE SAMPLE FROM DRILL CORE WC#13.....	115
62.	PHOTOMICROGRAPH OF CRUDE OIL IN THIN SECTION FROM DRILL CORE WC#13.....	116
63.	QFL CLASSIFICATION OF ORONTO GROUP ROCKS IN BEAR CREEK DRILL CORES.....	119
64.	QFL CLASSIFICATION OF ORONTO GROUP ROCKS IN OUTCROPS.....	119

65.	PHOTOMICROGRAPH SHOWING PARAGENESIS OF CEMENTS IN DRILL CORE DO#14.....	125
66.	GRAPH SHOWING LATERAL VARIATIONS IN COMPOSITIONS IN NONESUCH FORMATION IN DRILL CORES.....	134
67.	GENERALIZED SKETCH MAP OF NONESUCH FORMATION DEPOSITIONAL BASIN AND SOURCE TERRANES IN THE DRILL CORE STUDY AREA.....	143
68.	ILLUSTRATION OF CROSS-SECTION SHOWING LAKE SUPERIOR BASIN ALONG GLIMPSE SEISMIC LINE C.....	151
69.	DIAGRAMMATIC ILLUSTRATION SHOWING CROSS- SECTION OF COPPER HARBOR FORMATION AS AN ALLUVIAL FAN COMPLEX IN THE DRILL CORE BASIN.....	152
70.	DIAGRAMMATIC ILLUSTRATION SHOWING STRATI- GRAPHIC POSITION AND FACIES RELATION- SHIPS FOR NONESUCH SEDIMENTATIONAL INTERVAL 1.....	155
71.	DIAGRAMMATIC ILLUSTRATION SHOWING STRATI- GRAPHIC POSITION AND FACIES RELATION- SHIPS FOR NONESUCH SEDIMENTATIONAL INTERVAL 2.....	161
72.	DIAGRAMMATIC ILLUSTRATION SHOWING STRATI- GRAPHIC POSITION AND FACIES RELATION- SHIPS FOR NONESUCH SEDIMENTATIONAL INTERVALS 3 AND 3A.....	164
73.	DIAGRAMMATIC ILLUSTRATION OF A THERMALLY STRATIFIED LAKE MODEL.....	166
74.	DIAGRAMMATIC ILLUSTRATION SHOWING STRATI- GRAPHIC POSITION AND FACIES RELATION- SHIPS FOR NONESUCH SEDIMENTATIONAL INTERVALS 4 AND 5.....	171
75.	DIAGRAMMATIC ILLUSTRATION SHOWING CORRELATION OF NONESUCH SEDIMENTATIONAL INTERVALS IN DRILL CORES.....	173
76.	A GRAVITY INTERPRETATION OF THE STRUCTURE OF WESTERN LAKE SUPERIOR.....	175

77.	MAP SHOWING LOCATION OF GRENVILLE FRONT..... IN RELATION TO THE MIDCONTINENT..... RIFT SYSTEM.....	177
78.	A SEISMIC AND SEDIMENTOLOGIC INTERPRETATION OF WESTERN LAKE SUPERIOR STRUCTURE.....	179

TABLES

Table		Page
1.	PETROGRAPHIC SUMMARY OF ORONTO GROUP SEDIMENTS IN DRILL CORES AND OUTCROPS...	100
2.	X-RAY ANALYSIS OF MUDSTONE SAMPLES IN DRILL CORE WC#2.....	124
3.	LATERAL VARIATION IN COMPOSITION OF LOWER COPPER HARBOR SANDSTONES IN DRILL CORES.	130
4.	LATERAL VARIATION IN COMPOSITION OF NONESUCH SANDSTONES IN DRILL CORES.....	132
5.	LATERAL VARIATION IN COMPOSITION OF LOWER FREDA SANDSTONES IN DRILL CORES.....	135
6.	A COMPARISON OF LATERAL AND VERTICAL VARIATION IN COMPOSITION OF ORONTO GROUP ROCKS IN DRILL CORES.....	137

ACKNOWLEDGEMENTS

I would like to thank my principal advisor Dr. Richard W. Ojakangas (University of Minnesota-Duluth) for his guidance, advice and encouragement during the course of this study. My sincere thanks and gratitude Dick, for being instrumental in obtaining the research assistantship that made this thesis possible. I thank my committee members Dr. John C. Green and Dr. Paul Siders (UMD) for their advise and critical readings of this thesis. I also thank Dr. Charles Matsch (UMD) for his advice and encouragement.

My gratitude is extended to Amoco Production Company of Houston, Texas, and especially to Gregg Anderson and Diana Friedhoff Miller, for providing me with the research assistantship and laboratory assistance that made this study possible. Additional funding, supplied by a scholarship from the American Federation of Mineralogical Societies, is also greatly appreciated.

A word of thanks to a couple of good friends, Gene and Sally LaBerge. Their encouragement and moral support have helped me through. I'll be sure to pass it on.

Finally, my sincerest thanks and gratitude are extended to my wife Therese, my daughters Andrea and Stephanie, and my mother Joanne. I thank them for their love, patience and support.

INTRODUCTION

The cessation of volcanic activity along the Keweenaw Midcontinent Rift System in the Lake Superior region ushered in a period when sedimentary processes dominated within the rift zone.

The Oronto Group (Fig. 1) consists of three formations; the Copper Harbor ("Conglomerate") Formation, 1830m (6000 ft); the Nonesuch ("Shale") Formation, 75 m (250 ft); and the Freda ("Sandstone") Formation, 3660 m (12,000ft). These three formations comprise a (+/- 5,500 m) rift-fill sequence whose sediments have been ascribed to dominantly fluvial and lacustrine processes (Daniels, 1982). Collectively these formations represent part of a thermotectonic volcanic-clastic sequence created in response to rifting and subsidence (Fowler and Kuenzi, 1978).

The Copper Harbor and Nonesuch Formations in Upper Michigan are host rocks for economic copper deposits. In 1958, 1959 and 1960, the Bear Creek Mining Company conducted an exploration program in northwestern Wisconsin in search of copper deposits similar to those found in Nonesuch and Copper Harbor sediments at the White Pine Mine approximately 145 km (90 mi) to the east in Upper Michigan. The project failed to discover any economic mineral potential, but did detect trace amounts of crude oil in Nonesuch sediments from three diamond drill holes. This study focuses on the nature of the Nonesuch sedimentary rocks recovered during that

program.

The occurrence of small amounts of crude oil in the Nonesuch Formation in Wisconsin and Michigan raises the possibility that perhaps economic petroleum deposits may exist in the Lake Superior region, as well as in other areas along the Midcontinent Rift System. This has prompted the petroleum industry to examine the Upper Keweenawan sedimentary rocks along the rift system for their economic potential.

Purpose and Scope

The purpose of this study was to examine the sedimentary rocks of the Oronto Group in select Bear Creek drill cores from northwestern Wisconsin (Figs. 2 & 3), with emphasis on the sedimentology and petrography 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.

For the purpose of comparison with drill cores, six outcrops between Silver City, Michigan, and Mellen, Wisconsin (Fig. 3) were measured, described and sampled.

The objectives of this study were to:

- 1) Analyze the lateral and vertical variations in composition of the upper Copper Harbor, the Nonesuch, and lower Freda Formations;

Figure 2. General location of outcrop and drill hole study areas.

Figure 3. Approximate location of Bear Creek drill holes and outcrops examined during this study.

- 2) Interpret the sedimentary environments and the general modes of deposition;
- 3) Determine the provenance of detritus;
- 4) Interpret the post-depositional history of the sediments;
- 5) Determine the relationship of the Nonesuch Formation in Bear Creek drill cores from northwestern Wisconsin to outcrops farther east in Wisconsin and Upper Michigan; and
- 6) Propose a depositional model for the Nonesuch Formation in northwestern Wisconsin.

Method of Study

Field work for this study was conducted during the spring, summer and fall of 1988. Outcrop locations were found in the literature (Daniels, 1982; Schmidt and Hubbard, 1972; White, 1971), and by personal communication and field assistance from Ray Leone, White Pine, Michigan; Richard W. Ojakangas, Geology Department, University of Minnesota-Duluth; and Bob Seabor, Copper Range Company, White Pine, Michigan.

Examination of the Bear Creek drill cores took place at the Wisconsin Geological and Natural History Survey Drill Core Repository in Milwaukee, Wisconsin. Diamond drill hole logs were provided by R.C. Babcock Jr. of B.P. Minerals America. Assistance at the repository was provided by

Richard W. Ojakangas, Geology Department, University of Minnesota-Duluth, and B. Brown, T. Evans and M. Mudrey of the Wisconsin Geological and Natural History Survey.

Outcrops were chosen because of their accessibility and because they represent a diversity of the lithologies and sedimentary structures present in the Oronto Group. Stratigraphic sections at Bonanza Falls (Big Iron River, Silver City, Michigan) and at Parker Creek (approximately 12 miles northwest of Hurley, Wisconsin) (Fig. 3), were measured with a Jacob Staff and Brunton compass. Where present, paleocurrent indicators such as rib and furrow structures, asymmetrical ripple marks, symmetrical ripple marks, planar cross-bedding, and parting lineation, were measured.

Approximately 400 samples were collected from outcrops and drill cores; from these, 105 thin sections were prepared representing a full range of compositions and textures. Thin section heels were stained for plagioclase and potassium feldspar.

Samples were examined with petrographic and binocular microscopes. A total of 50 thin sections, 45 from drill cores and 5 from outcrops, were point-counted along traverses perpendicular to bedding, with approximately 600 points per section. The rocks were then classified after Dott (1964).

Eighteen clay-rich samples representing the full length

of one drill core (WC#2), were analyzed by x-ray diffraction methods (courtesy of Amoco Production Company of Houston, Texas) to determine the clay mineralogy, and to identify various zeolites.

Previous Work

The clastic sedimentary rocks from the southern shore of Lake Superior have been the object of considerable research and debate since about 1840 when they were first described by Houghton (1841). In Michigan he named these rocks "The Lake Superior Sandstones", and believed them to be Lower Paleozoic strata. The major changes in thought, which have occurred since these rocks were first examined, are indicated on Figure 4.

The Upper Keweenawan Oronto Group was named by Thwaites (1912). Originally composed of five formations, it was reduced to three, the Copper Harbor Conglomerate, Nonesuch Shale and Freda Sandstone, by Tyler and others (1940).

The Nonesuch Shale was named by Irving (1883) for exposures near the Nonesuch Mine, which was located approximately 3 km west of the White Pine Mine, Ontonagon County, Michigan. The formation was renamed the "Nonesuch Formation" by Lane and Seaman (1907). This latter designation is preferable, as shale is only a subordinate lithology to fine and very-fine-grained sandstone and siltstone (Daniels, 1982).

		1883 Irving	1907 Lane & Seaman	1911 VanHise & Leith	1911 Lane	1943 Thwaites	1951 Oelking	1953 White, Cornwall, & Swanson	1972 Craddock	1972 White	1973 Wolff & Huber	1975 Hubbard	1976 Sims 1978 Fowler & Kuenzi
Series	Division	Red Sandstone	Freda Sandstone		Freda	Jacobsville (Bayfield) Freda	Jacobsville (Bayfield)	Freda	Freda Sandstone	Freda Fm.	Freda Sandstone	Freda Fm.	Freda Sandstone
		Nonesuch Shale	Nonesuch Fm.	Keweenaw Upper	Nonesuch		Freda	Nonesuch	Nonesuch Fm.	Nonesuch Shale	Nonesuch Shale	Nonesuch Fm.	Nonesuch Fm.
Series	Division	Outer Conglomerate	Outer Conglomerate		Outer Copper Harbor Conglomerate			Copper Harbor Cong. Outer Conglomerate Lake Shore Traps Great Conglomerate	Copper Harbor Conglomerate				Copper Harbor Conglomerate
		Diabase, diabase amygdaloid and melaphyr Lake Shore Traps	Lake Shore Traps	Lake Shore Traps									
Series	Division	Great Conglomerate	Great Conglomerate	Great Copper Harbor Conglomerate and Sandstone									
		Copper Harbor	Copper Harbor	Copper Harbor									
Precambrian													

Figure 4. Progress of thought in geologic nomenclature for Keweenaw Series rocks in the southern Lake Superior district (from Daniels and others, 1982).

According to Hite (1968), White (1972), and Hubbard (1975c), the Nonesuch is generally conformable with, and at least in part is transgressive over, the Copper Harbor Formation. It is also conformable with the overlying Freda Formation (White and others, 1953; White, 1972).

White and Wright (1954) were the first to recognize the Nonesuch Formation as representing a distinctly different depositional environment, relative to the alluvial-fluvial conditions that prevailed before and after Nonesuch deposition. Ensign and others (1968), White (1972), and Hubbard (1975b), concluded that the Nonesuch was formed in some type of standing body of water.

Nonesuch depositional environments proposed by earlier workers have included estuarine (White and Wright, 1954; Moore and others, 1969), deltaic (Ehrlich and Vogel, 1971), marine (Jost, 1968), lacustrine (Pettijohn, 1957), and fluvial-lacustrine (Elmore, 1981; Daniels, 1982; Elmore and others, 1988).

Moerlein (1963), concluded that the Bear Creek drill cores from Ashland, Bayfield, Burnett, Douglas and Washburn Counties, Wisconsin (this study) (Fig. 3), consisted of the normal sequence of Oronto Group sediments. He suggested that perhaps the drill cores from these counties all lie near the western tip of the Lake Superior Syncline.

Although much has been written about Late Keweenawan age sedimentary rocks in Michigan and Wisconsin, very little

has been said about the Bear Creek drill cores from Wisconsin. To the best of this author's knowledge, the only sedimentologic studies conducted on the Nonesuch Formation in these cores were by Moerlein (1963), Elmore (1981) and Elmore and others (1988). Elmore and others (1988) concluded that the Nonesuch Formation is composed of facies assemblages that record deposition in marginal lacustrine, perennial lacustrine, and fluvial-lacustrine settings within the Keweenawan trough.

Recent interpretation of geophysical data, along with information obtained from Bear Creek drill hole logs and outcrops (Dickas, 1986; Mudrey and Dickas, 1988), portray the Midcontinent Rift System in the Lake Superior region as a series of sub-basins separated by "accommodation zones". Their interpretations suggest the presence of structurally independent depositional basins within the Keweenawan Rift.

REGIONAL GEOLOGY

General Setting

The study area in northwest Wisconsin and adjacent Upper Michigan is in the southern portion of the Superior Province of the Precambrian Canadian Shield. This region of the province is characterized by metamorphosed sedimentary and volcanic rocks and granitic intrusions of Archean age, metamorphosed sedimentary and volcanic sequences of Early Proterozoic age, and vast accumulations of only slightly metamorphosed (zeolite to lower greenschist facies), volcanic and sedimentary rocks with gabbroic and granitic intrusions of Middle and Late Proterozoic age, belonging to the Midcontinent Rift System. The distribution of rocks in the western Lake Superior district is shown in Figure 5.

Traversing from south to north through the study area, the first rocks encountered (e.g., south of Mellen, Wi.) are Archean. These rocks are unconformably overlain by Early Proterozoic sedimentary rocks, which are in turn unconformably overlain by the volcanic and sedimentary rocks of the Midcontinent Rift System. The Proterozoic sequences have a fairly consistent northeast strike, with a variable northwest dip. Structurally the rocks form a monocline, defining the southern limb of the Lake Superior Syncline.

Figure 5. Generalized geologic map of northwestern Wisconsin and adjacent areas. The abbreviation KW is used for Keweenaw, and the throw of major faults is indicated by U (up) and D (down) (from Paull, 1986).

Archean

The Archean rocks in the southern Lake Superior region consist of: 1) a gneiss terrane composed of amphibolite to granulite grade basement gneisses ($>3,000$ Ma), and younger migmatitic gneisses (2,800-3,000 Ma) (Morey and Van Schmus, 1988) and; 2) a granite-greenstone terrane composed of predominantly mafic volcanic rocks, felsic volcanics, and related intrusives and sediments that have been subjected to greenschist and lower amphibolite grade metamorphism (Sims, 1976; Morey and Van Schmus, 1988). The study area in northwest Wisconsin and adjacent Upper Michigan lies within the granite-greenstone terrane.

Early Proterozoic

The following discussion on the regional Proterozoic rocks in the study area will be presented with more detail than were the Archean rocks because they may have been major contributors of detritus to the Oronto Group.

Early Proterozoic rocks in the region consist of a thick succession of sedimentary rocks composed of dolostones, quartzites, iron-formations, graywackes, slates, and some volcanic (basaltic) units. Early Proterozoic deposition is thought to have begun approximately 2100 Ma (Sims, 1976), and ceased with the Penokean Orogeny and igneous activity approximately 1850 Ma (Morey, 1972).

The oldest rocks in the region belong to the Chocolay

Group (Cannon and Gair, 1970) (Fig. 6). This group consists of the basal Bad River Dolomite in Wisconsin, which is underlain by the Sunday Quartzite in Michigan. Both formations unconformably overlie the Archean basement.

The Menominee Group unconformably overlies the Chocoday Group and consists of, in ascending order; the Palms Formation, which is composed of conglomerate, slate and quartzite, and the Ironwood-Iron Formation (Aldrich, 1929; Ojakangas and Morey, 1982a).

Conformably overlying the Ironwood Iron Formation is the Baraga Group. This group contains the Tyler Formation, which is unconformably overlain by Keweenaw age rocks in the study area. The Tyler Formation is composed predominantly of interbedded sandstone, siltstone and mudstone (Alwin, 1976). The majority of these rocks have been classified as graywackes (Alwin, 1976).

Middle and Late Proterozoic

Late Proterozoic time marks the last episode of major crustal evolution in the Lake Superior region. The Keweenaw event is dominated by extensional and compressional tectonics (King and Zietz, 1971; White, 1972; Chase and Gilmer, 1973; Fowler and Kuenzi, 1978; Hinze and Wold, 1982; Van Schmus and Hinze, 1985), and vast accumulations of associated plateau lavas and clastic sedimentary rocks (Green, 1982; Ojakangas and Morey, 1982b).

Northwest segment					Southeast segment				
Gunflint range, Minnesota-Ontario	Mesabi Range, Minnesota	Cuyuna range, Minnesota	Western part Gogebic range, Wisconsin	Eastern part Gogebic range, Michigan	Western Marquette range, Michigan	Eastern Marquette range, Michigan	Amasa uplift, Michigan	Iron River-Crystal Falls range, Michigan	Menominee range, Wisconsin
Goodwin, 1956	White, 1954	Morey, 1978a	Aldrich, 1929	Sims and others, 1984	Cannon, 1986	Gair and Thaden, 1968	Cannon, 1986	Cannon, 1986	Bayley and others, 1968
								Fortune Lakes Slate Stambaugh Formation Hiawatha Graywacke Riverton Iron-formation Dunn Creek Slate	
				Michigamme Formation	Michigamme Formation		Badwater Greenstone	Badwater Greenstone	Badwater Greenstone
Rove Formation	Virginia Formation	Rabbit Lake Formation	Tyler Formation	Copps Formation	Goodrich Quartzite	Goodrich Quartzite	Michigamme Slate	Michigamme Formation	Michigamme Slate
Gunflint Iron-formation	Biwabik Iron-formation	Trommald Formation	Ironwood Iron-formation	Emperor Volcanic Complex Blair Creek Formation	Negaunee Iron-formation	Negaunee Iron-formation	Amasa and Fence River Formations	Amasa and Fence River Formations	Vulcan Iron-formation
Basal conglomerate member	Pokegama Quartzite	Mahnomen Formation	Palms Formation	Palms Formation	Siamo Slate Ayibik Quartzite	Siamo Slate Ayibik Quartzite	Hemlock Formation	Hemlock Formation	Felch Formation
						Weve Slate			
						Kona Dolomite	Saunders Formation		Randville Dolomite
						Mesnard Quartzite			Sturgeon Quartzite
						Enchantment Lake Formation ? ? Reany Creek Formation			Fern Creek Formation

Annick Group

Paint River Group

Baraga Group

Menominee Group

Chocoma Group

Mille Lacs Group

Chocoma Group

Archean rocks, undivided

Figure 6. Correlation chart for the Marquette Range Supergroup of Michigan and Wisconsin (modified from Morey, 1983b).

Keweenawan rocks occur along the margins of Lake Superior and occupy a large syncline in which Lake Superior is located. In the western portions of the lake, the syncline has a southwesterly trend and is asymmetrical with the steep limb to the south and a gently dipping north limb (Halls, 1966; Craddock, 1972). In eastern Lake Superior, the axis of the syncline bends around to trend south.

The Lake Superior Syncline narrows toward the west and structural contours show closure of the syncline to the south of Duluth, Minnesota (Smith and others, 1966). Gravity, aeromagnetic and borehole data (Lyons, 1959; Thiel, 1956; Zietz 1965), show that Keweenawan rocks continue southwestward in a narrow trough for some 1600 km (1000 mi) into Kansas (Fig. 7).

The entire Keweenawan volcanic-sedimentational episode is thought to have occurred from approximately 1370 Ma to 1000 Ma (Roy and Robertson, 1978; Halls and Pesonen, 1982; Morey and Van Schmus, 1988) during the onset of rifting and sedimentation (Franklin and others, 1980; Van Schmus and others, 1982), to approximately 900 Ma, culminating with further clastic sedimentation (Ojakangas and Morey, 1982b). Keweenawan igneous activity is thought to have occurred in the interval from 1120 Ma to 1140 Ma based on U/Pb isotope dating (Van Schmus et. al., 1982; Paces and Davis, 1988).

The Keweenawan column has been lithologically divided into Lower Keweenawan sedimentary and igneous rocks, Middle

Figure 7. Map showing general location of the Midcontinent Rift System (stippled area) (modified from Craddock, 1972).

Keweenawan igneous rocks and Upper Keweenawan sedimentary rocks (Van Hise and Leith, 1911; Books, 1968; Craddock, 1972; White, 1972; Hubbard, 1975c; Green, 1972 and 1977; Morey and Van Schmus, 1988). The distribution of Keweenawan rocks in the southern Lake Superior region is shown in Figure 5.

Lower Keweenawan

The lower Keweenawan sequence of rocks in the southern Lake Superior region consists of, in ascending order, the Bessemer (Quartzite) Formation, Siemens Creek Formation, and the Kallander Creek Formation.

The Bessemer Quartzite consists of a well-cemented, red-to white, cross-bedded to laminated quartzose sandstone, with a basal conglomeratic layer containing fragments of vein quartz, chert, iron formation, slate and graywacke (Van Hise and Leith, 1911; Dott and Mattis, 1972; Ojakangas and Morey, 1982a; Ojakangas and Morey, 1982b). The Bessemer is exposed in small sparse outcrops scattered from Mellen, Wisconsin, to east of Lake Gogebic, Upper Michigan (Aldrich, 1929; Fritts, 1969). Average thickness of the Bessemer is approximately 90 m (300 ft) (Hubbard, 1975c), and it lies with unconformity on the Tyler Formation.

The Powder Mill Group includes the Siemens Creek Formation and the Kallander Creek Formation. Together they have a thickness of approximately 6,100 m (20,000 ft) (Hubbard, 1975c). In Wisconsin, Powder Mill rocks are

intruded by gabbro, anorthosite and related rocks of the Mellen Intrusive Complex (Aldrich, 1929; Olmstead, 1969; Mangham, 1974). In Upper Michigan, a sill of pyroxene-bearing diorite possibly related to the Mellen Complex, intrudes Powder Mill rocks (Felmlee, 1970; Hubbard, 1975c). The Siemens Creek Formation is approximately 1,340 m (4,300 ft) thick and is composed predominantly of thin basalt flows with subordinate andesite flows (Hubbard, 1975a and 1975c). The Siemens Creek is conformable with the underlying Bessemer Quartzite, and contains rare interbeds of Bessemer-type sandstone in the lower 30 m (98 ft). Rocks of the Siemens Creek crop out between Sturgeon Falls, Upper Michigan and Mellen, Wisconsin (Fig. 5).

The Kallander Creek Formation consists of approximately 4,500 m (15,000 ft) of predominantly intermediate lava flows, and interbedded sedimentary rocks. The relationship to the underlying Siemens Creek is not certain. Kallander Creek rocks crop out from the Black River in western Upper Michigan, to just south of Grandview, Wisconsin (Hubbard, 1975c) (Fig. 3).

Middle Keweenawan

In the western part of the Upper Peninsula of Michigan and in northwestern Wisconsin, the Middle Keweenawan is composed of the Portage Lake Lava Series, which includes a younger unnamed formation (White, 1972; Hubbard, 1975c; Daniels, 1982). This series unconformably overlies the

Lower Keweenaw Powder Mill Group (Hubbard, 1975c).

The Portage Lake Lava Series consists of approximately 4,700 m (15,000 ft) of basalt and andesite flows with interflow sedimentary beds (Lane, 1911; Aldrich, 1929; White, 1952 & 1957; Huber, 1973). The series crops out intermittently as a narrow band from the tip of the Keweenaw Peninsula, to Ironwood, Michigan, and across Lake Superior on Isle Royale, Michigan (Fig. 5). In northwestern Wisconsin, the Portage Lake Volcanics are confined to the St. Croix Horst (Craddock, 1972; Morey, 1972).

Upper Keweenaw

Upper Keweenaw rocks indicate a time when Keweenaw volcanism was in its waning stages and clastic sedimentation predominated. These vast accumulations of clastic sedimentary rocks in Michigan and northwest Wisconsin are represented by the Oronto Group (White, 1972; Daniels, 1982), and the younger Bayfield Group (Wisconsin), and equivalent Jacobsville Sandstone (Upper Michigan) (Hamblin, 1961; Ostrom, 1967) (Fig. 1).

The Oronto Group of Upper Michigan and northwest Wisconsin, of particular interest to this study, includes the Copper Harbor Formation, the Nonesuch Formation, and the Freda Formation (Tyler and others, 1940; Hite, 1968). The Oronto Group has an outcrop extent of about 300 km (188 mi), from northwest Wisconsin to the eastern tip of the Keweenaw Peninsula, Upper Michigan and on Isle Royale, Michigan

(Daniels, 1982) (Fig. 5). Oronto Group sedimentary rocks are also known to occur under glacial drift to the southwest of Ashland, Wisconsin for approximately 50 km (30 mi).

The Copper Harbor Formation consists of reddish-brown, lithic conglomerate and sandstone with a maximum thickness of approximately 1830 m (6000 ft) (Hubbard, 1972; Daniels, 1982; Wolff and Huber, 1973). The Copper Harbor comprises the basal formation in the Oronto Group and is conformable over, and interbedded with, the Portage Lake Volcanics and the "unnamed formation" (White and Wright, 1960; White, 1972).

The Nonesuch Formation consists of gray to black lithic sandstone, siltstone and shale that conformably overlies the Copper Harbor Formation. The thickness of the Nonesuch varies from about 30 m (98 ft) in northwest Wisconsin, to approximately 215 m (700 ft) on the Keweenaw Peninsula, Upper Michigan.

The Freda Sandstone consists of a thick sequence of red-brown ferruginous sandstone, siltstone and shale with minor conglomerate in the lower one-third of the formation (Hite, 1968). The contact with the Nonesuch Formation is conformable. The Freda crops out in a belt extending southwestward from the Keweenaw Peninsula to northwestern Wisconsin (White, 1971; Hubbard, 1975a; Daniels, 1982). Thicknesses range from 1,525 m (5,000 ft) in the Keweenaw Peninsula, to 3660 m (12,000 ft) along the Upper Michigan-

Wisconsin boundary (Irving, 1883; Hubbard, 1975a; Hite, 1968).

The Bayfield Group (Wisconsin) and the Jacobsville Sandstone (Michigan) represent the last stages of clastic sedimentation during the Keweenawan event in Michigan and Wisconsin. The Bayfield Group consists of arkosic, quartzose and feldspathic sandstones with an approximate thickness of 1250 m (4013 ft), (Craddock, 1972; Ojakangas and Morey, 1982b). The correlative Jacobsville Sandstone is a +900 m (2890 ft) thick sequence of feldspathic and quartzose sandstones, conglomerates, siltstones and shales (Kalliokoski, 1982). The unexposed contact between these units and the underlying Freda Sandstone was thought to be conformable by Tyler and others (1940), Hamblin (1958), and Ostrom (1967), and unconformable by others (Thwaites, 1912; Hite, 1968; Morey and Ojakangas, 1982).

Structure

The majority of the Keweenawan sequence is located in the Lake Superior Syncline, the dominant structure in the region. The Proterozoic formations in Upper Michigan and northwestern Wisconsin all have a regional northeasterly strike and variable north to northwest dips along the steep southern limb of the syncline.

Two major high angle reverse faults occur in the region. The Douglas and Lake Owen Faults (Aldrich, 1929),

trend roughly parallel to the northeasterly strike of Keweenaw volcanic and sedimentary rocks in the southern Lake Superior region. The Lake Owen Fault dips north-northwest toward the Lake Superior Syncline and the Douglas Fault dips to the south-southeast. Both faults serve to create a horst structure in northwest Wisconsin and adjacent Minnesota.

The St. Croix horst (Craddock, 1972) is bounded on the northwest by the Douglas Fault and on the southeast by the Lake Owen Fault. The Portage Lake Volcanics and Oronto Group sedimentary rocks in northwest Wisconsin lie within basins along the horst axis. The Ashland Syncline (Dutton and Bradley, 1970), one of these basins, serves as the location for the Bear Creek drill cores examined during this study. Figures 8 thru 11 illustrate structural attitude, variation in sediment thicknesses and structural contours of the upper and lower contacts of the Nonesuch Formation in select Bear Creek drill cores from the Ashland Syncline.

Numerous smaller faults perpendicular to the axial trend of the Lake Superior Syncline and Ashland Syncline also exist. These smaller cross faults have perhaps served to create a number of small localized grabens and half-grabens within the larger synclinal structures along the Midcontinent Rift System (Dickas, 1986; Mudrey and Dickas, 1988).

Figure 8. Isopach map of the Nonesuch Formation in the Bear Creek drill cores from northwestern Wisconsin. Nonesuch thins from south to north.

Figure 9. Structural cross-section of the Nonesuch Formation (stipled area) from A to A' on isopach map (Fig. 8).

Figure 10. Structural contour map of the base of the Nonesuch Formation in Bear Creek drill holes.

Figure 11. Structural contour map of the top of the Nonesuch Formation in Bear Creek drill holes.

FIELD DESCRIPTIONS

Introduction

In order to gain a thorough understanding of the sedimentary structures, textures and contacts of the Nonesuch Formation in the Bear Creek drill cores, it was necessary to observe field relationships at selected outcrop locations in Upper Michigan and northwest Wisconsin (Fig. 3).

Nonesuch exposures are generally confined to river valleys and the Lake Superior shoreline. The exposures at the Big Iron River (Michigan) and Parker Creek (Wisconsin) were measured, sampled and described in detail. Outcrops at Black River Harbor, Michigan, the Presque Isle River (Presque Isle Park, Michigan), the Potato River (Potato River Falls Park, Wisconsin), and the Bad River (Copper Falls State Park, Wisconsin) were only observed and sampled. Contacts of the Nonesuch Formation with the underlying Copper Harbor Formation and overlying Freda Formation are exposed along the Big Iron River, Presque Isle River, Parker Creek, Potato River, and Bad River. Only those contacts at Parker Creek, Potato River Falls, Presque Isle Park, and Copper Falls State Park were observed during this study.

Sedimentology of Outcrops

Nonesuch Formation sedimentary rocks consist of light-gray to black, sandstones, siltstones, mudstones and shales, with minor conglomeratic sandstones that are generally confined to the lower parts of the section.

Macroscopically, the Nonesuch has a greater compositional and textural maturity than the Copper Harbor redbed sequence below. Grain sizes generally range from clay-sized material to medium-grained sand, with an overall average grain size of coarse silt (0.04 mm), (Daniels 1982). The finer-grained rocks are typically dark-gray to black and are present in greater percentages than are the red-brown and green siltstones, mudstones and shales. 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 position of the Copper Harbor-Nonesuch contact was defined at the horizon where dark-gray to black rocks dominate the section. The Nonesuch-Freda contact was defined at the horizon where red-brown beds again become dominant. The metamorphic grade is zeolite facies.

Several types of sedimentary structures were observed. These included asymmetrical and symmetrical ripple marks, climbing ripples, parting lineation, rib and furrow structures, trough and planar cross-bedding, graded beds,

varve-like parallel-laminated bedding that will be referred to as carbonate laminite in this study, mud cracks, syneresis cracks, soft sediment deformation features such as ball and pillow structures, flame structures and distorted (slumped) beds, and diagenetic calcareous concretions.

The Nonesuch Formation thins and coarsens to the west from 244m (800 ft) at the Big Iron River to approximately 75 m (250 ft) at Copper Falls State Park. These two exposures are about 96 km (60 mi) apart. Accompanying the thinning to the southwest is an increase in medium-and coarse-grained lithic sandstone and a decrease in fine-grained siltstone, mudstone and shale.

Big Iron River Measured Section

The Nonesuch Formation along the Big Iron River at Bonanza Falls (Fig. 12) is approximately 244 m (800 ft) thick. Neither lower nor upper contacts were observed. Measurements began at a point approximately one-quarter of a mile south of Silver City, Michigan where the rocks change attitude from N60°W, 18°NE, to N30°E, 20°SE. Approximately one-half mile upriver, the measured section ends where the attitude returns to N55°W, 20°NE. It appears that the nose of the eastward-plunging Porcupine Mountain anticline transects the river at this location, with the measurements taken along the southern limb of the anticline.

Figure 12. Location of the measured section on the Big Iron River, SE 1/4, NE 1/4, Sec.13, T.51N., R.42W., White Pine, Michigan (U.S.G.S. 7.5' topographic quadrangle map, 1956).

The section at the Big Iron River (Figs. 13 & 14), generally consists of fine-grained sandstone, siltstone, mudstone and shale. Several felsic volcanic clasts were recognized at the base of the section along with several thin lenses of coarse-grained, planar cross-bedded, calcareous, arkosic sandstone. Dark-gray to black siltstone and shale in the lowest 10 m of the section show signs of minor copper mineralization along bedding planes in the form of chalcocite, bornite and malachite, along with subhedral grains of stratiform pyrite and numerous, thin (<1 cm), calcite-filled fractures.

The pattern of sedimentation throughout the entire section is dominated by numerous graded beds (Fig. 15) and fining-upward sequences (Fig. 16). The normally-graded beds commonly consist of, from bottom to top, a basal, massive, graded or parallel-bedded and graded, medium- to fine-grained sandstone or conglomeratic sandstone with mudchip clasts; a parallel-bedded, very fine-grained sandstone and siltstone with mudchip clasts; an undulatory and/or small-scale trough cross-bedded unit of sandy siltstone and siltstone interbedded with mudchip clasts and thin lenses of mudstone; and an overlying interval of massive or parallel-laminated mudstone and shale. Each distinctive lithologic interval within a graded bed, fines upward. The graded beds range from 1 cm to 1 m in thickness.

- Gm: Clast-supported conglomerate; massive or crudely bedded, horizontal bedding and commonly imbricate.
- Gms: Matrix-supported conglomerate; muddy matrix, lacks imbrication and internal stratification.
- Gt: Clast-supported conglomerate; stratified, trough cross-bedded
- Gp: Planar cross-bedded conglomerate; transitional from clast-supported through matrix-supported
- Sh: Sand; very fine to very coarse, horizontal lamination, parting lineation
- St: Sand; medium to very coarse, may be pebbly; trough cross-stratified
- Sp: Sand; medium to very coarse, may be pebbly, planar cross-stratified
- Sr: Sand; very fine to coarse, ripple marks of all types
- Fl: Sand, silt, mud: fine lamination (laminites), very small ripples
- Fm: Mud, silt: massive, desiccation cracks
- * Note: Lithofacies code from Miall (1977), used in Copper Harbor Formation and Freda Formation descriptions only.

Figure 13. Key to geologic symbols (AGI Data Sheets, 1984); and lithofacies code, (modified from Miall, 1977), for Figures 14, 15, 16, 32 and 45 thru 54.

Figure 13. (continued)

Nonesuch Formation lithofacies code:

Ss = sandstone
Slt = siltstone (0.031 to 0.008 mm diameter)
Shl = shale
Mds = mudstone (< .004 mm diameter)
Cm = conglomerate, matrix-supported
Cc = conglomerate, clast-supported

Grain sizes:

fn. = fine-grained (0.125 to 0.25 mm diameter)
med. = medium-grained (0.25 to 0.5 mm diameter)
crs. = coarse-grained (0.5 to 1.0 mm diameter)
grit = 1.0 to 5.0 mm diameter
cong = conglomeratic (pebbles and cobbles, 0.5
cm to 7.0 cm diameter)

f-u-s & gb = fining-upward sequence and graded
beds; expressed as number of sequences per
sedimentary interval, range of thicknesses, and
percent of total interval consisting of f-u-s and
gb.

Figure 13. (continued)

Figure 14. Diagrammatic illustration of the Nonesuch Formation measured section on the Big Iron River, Ontonagon County, Michigan. (Numbers on the right of the column are locations in meters from the base of the section).

Figure 14. (continued)

Figure 14. (continued)

Figure 15. Diagrammatic illustration of a graded bed, Big Iron River measured section (location is 79 m (253 ft) stratigraphically above the approximate base of the Nonesuch Formation).

Figure 16. Diagrammatic illustration of a fining-upward sequence, Big Iron River measured section (location is 132 m (435 ft) stratigraphically above the approximate base of the Nonesuch Formation).

Each fining-upward sequence consists of, from bottom to top, a basal unit of massive and/or parallel-laminated, fine-grained sandstone with random units containing mudchip clasts; small-scale trough cross-bedded siltstone commonly containing numerous mudchip clasts and calcareous concretions; and parallel-laminated shale and silty-mudstone that commonly has a mudcracked surface. Good exposures indicate sharp contacts between the uppermost shale bed of each sequence and the basal sandstone bed of the overlying sequence, as well as sharp contacts between the trough-cross bedded siltstone, and overlying mudstone and shale within each sequence. Random beds of fine-grained sandstone and siltstone within each sequence display normal grading as well as a general thinning of beds upwards. The best exposure of fining-upward sequences is beneath Bonanza Falls, at the end of the footpath leading to the Big Iron River, approximately one-half mile south of Silver City, Michigan on Hwy M64 (Fig. 17). Here, complete sequences range from approximately 20 cm to 53 cm in thickness.

Interbedded with the fining-upward sequences and graded beds from the base of the measured section to 123 m (403 ft) stratigraphically above the base of the section, are thin, varve-like laminated carbonate beds (laminite) of siltstone and mudstone (Fig. 18). Laminations are generally less than 1 mm thick and are alternations of light gray, 0.5 mm to 2 mm thick calcareous siltstone and black, 0.1 mm to 0.5 mm

Figure 17. Fining-upward sequences at Bonanza Falls on the Big Iron River approximately 130 m (420 ft) stratigraphically above the base of the Nonesuch Fm. (Bracket marks one complete sequence).

Figure 18: Polished slab of carbonate laminite beds, Big Iron River measured section, approximately 123 m (403 ft) stratigraphically above the base of the Nonesuch Formation (scale in cm).

mudstone. Bedding generally occurs as well-defined laminations, but they are occasionally disrupted and offset by vertical, calcite-filled fractures resembling syneresis cracks, or by soft-sediment deformation features such as ball and pillow structures and minor loading (Figs. 19, 20 and 21). Thin lenses of fine-grained, micro-trough cross-bedded, calcareous sandstone are commonly interbedded with the laminite beds, along with some diagenetic calcareous concretions (Fig. 22).

The remainder of the section, from a point 121 m (388 ft) stratigraphically above the base to the top at 244 m (783 ft), exhibits a general coarsening-upward trend. Asymmetrical and symmetrical ripple marks increase in abundance in the top 20 m of the section. Also observed were large-scale trough cross-beds (Fig. 23). One 8 m (26 ft) thick reddish-brown, normally graded, medium-grained sand to silt bed (Fig. 24), is located 156 m (500 ft) stratigraphically above the base of the section. It contains undulating upper and lower bedding surfaces and numerous 1 cm to 10 cm diameter mudchip clasts.

Throughout the entire section, and especially in the upper half, there are numerous thin 1 cm to 3 cm thick micaceous and chloritic, light grayish-green to brown, graded sandstone and siltstone beds. These beds tend to separate along surfaces containing either parting lineation, rib and furrow structures, ripple marks or an occasional

Figure 19. Syneresis cracks, Big Iron River section approximately 9.3 m (30 ft) stratigraphically above the base of the Nonesuch Formation.

Figure 20. Ball and pillow structures, Big Iron River measured section approximately 37 m (120 ft) stratigraphically above the base of the Nonesuch Formation.

Figure 21. Minor loading, Big Iron River measured section approximately 3 m (9 ft) stratigraphically above the base of the Nonesuch Formation.

Figure 22. Calcareous concretions in siltstone, Big Iron River measured section approximately 5 m (16 ft) stratigraphically above the base of the Nonesuch Formation.

Figure 23. Large-scale trough cross-bedding, Big Iron River measured section approximately 132 m (425 ft) stratigraphically above the base of the Nonesuch Formation.

Figure 24. Eight meter thick red-brown (slumped) sandstone bed with numerous mudchip intraclasts, Big Iron River section approximately 152 m (500 ft) stratigraphically above the base of the Nonesuch Formation.

mud-cracked surface (Figs. 25, 26, 27, 28).

Ripple marks include current and wave types with straight, sinuous, or bifurcating crests. Wavelengths vary from 9 cm to 45 cm, with amplitudes from 3 cm to 5 cm. Ripple indices (wavelength/amplitude) range from 5 to 16 with an average of 9 for 12 measurements. Ripple marks and mudcracks are commonly associated with the uppermost siltstones and mudstones of fining-upward sequences.

Beds containing parting lineation surfaces consist of very fine-grained sandstone and micaceous siltstone. These surfaces commonly contain angular-to subrounded mudchips. In cross-section, these laminae are usually only a few grain diameters thick and are defined by the concentration of mica or slight grain size differences. Beds containing surfaces with parting lineation are commonly, but not necessarily, the basal sandstones of fining-upward sequences.

Rib and furrow structures consist of a series of micaceous and chloritic, small-scale trough cross-bedded sandy-siltstone and siltstone beds. The bedding surfaces exhibiting rib and furrow structures consist of small troughs 1 cm to 2 cm deep and 5 cm to 15 cm long. The coarser-grained silt beds optically show a preferred alignment of grains parallel to the axes of the furrows. Rib and furrow structures are the small-scale troughs within the cross-bedded sandstones and siltstones overlying the basal parallel laminated and massive sandstones of

Figure 25. Asymmetrical ripple marks, Big Iron River section approximately 1.5 m (5 ft) stratigraphically above the base of the Nonesuch Formation. (Lee side of ripples to top of photo).

Figure 26. Parting lineation surfaces, Big Iron River section, approximately 131 m (430 ft) stratigraphically above the base of the Nonesuch Formation.

Figure 27. Rib and furrow structures (micro-trough cross-bedding), Big Iron River section approximately 137 m (450 ft) stratigraphically above the base of the Nonesuch Formation. (Current direction from left to right).

Figure 28. Subaerial mudcracks, Big Iron River section approximately 4.5 m (15 ft) stratigraphically above the base of the Nonesuch Formation.

fining-upwards sequences.

Presque Isle River

In the section at Presque Isle State Park, Michigan, at the mouth of the Presque Isle River, approximately 12.5 km (20 mi) west-southwest of the Big Iron River section (Fig. 29), the upper part of the Nonesuch Formation as well as the contact with the Freda Formation is exposed. Exposures here are located along the east limb of the northwest-plunging Presque Isle syncline with rocks striking at N.40°W and dipping 7°S.W.

The Nonesuch Formation here has textures and sedimentary structures similar to those observed at the Big Iron River section. Fining-upward sequences and laminites, interbedded with massive graded sandstones and siltstones, dominate the sedimentary column (Fig. 30).

The pattern of sedimentation indicates a coarsening-upward trend to the Freda Formation contact. The contact is gradational and consists of medium-to coarse-grained, reddish-brown, large-scale planar and trough cross-bedded lithic sandstone, interbedded with dark-gray, small-scale trough cross-bedded siltstone and laminated sandy-mudstone. The approximate position of the Freda Formation contact was established where oxidized reddish-brown sediments became dominant.

Figure 29. Location of exposure at Presque Isle State Park, Michigan; at the mouth of the Presque Isle River, SE1/4, SE1/4, Sec. 19 and E1/2, NE1/4, Sec. 30, T.50N., R.45W., Gogebic County, Michigan (Thomason U.S.G.S. 15' topographic quadrangle map, 1956).

Figure 30. Fining-upward sequences, Presque Isle State Park, Michigan, (approximate stratigraphic location is in upper Nonesuch Formation near Freda Formation contact). (Bracket marks one complete sequence).

Black River Harbor

The Black River Harbor exposure is located approximately 27 km (17 mi) north of Bessemer, Michigan at the mouth of the Black River on the Lake Superior shoreline (Fig. 31). The exposure consists of a few meters of Nonesuch Formation that crop out along the boardwalk on the west side of the harbor. The Nonesuch lies within 10 meters

stratigraphically of the lowermost contact with the Copper Harbor Formation. The contact is not exposed. Strike of the bedding is 80° N.E. and the dip is 17° N.W.

The Nonesuch here consists of 5 cm to 10 cm thick beds of massive to micro-trough cross-bedded, calcareous, fine-grained sandstones and siltstones. These are overlain by dark-gray to-black, fissile laminites of mudstone and shale. The sandstone and siltstone beds show irregularity in thickness within individual beds and contain undulating bedding contacts with the shale beds. Flame structures were also observed in the sandstones and siltstones. This exposure bears a strong resemblance to the Nonesuch at the base of the Big Iron River measured section.

Copper Harbor Formation crops out a few hundred meters upriver and down section, along the harbor boardwalk. Here it consists of grayish-brown to reddish-brown conglomeratic sandstone with a lithic sandstone matrix. Several 1 cm to 10 cm diameter, well-rounded clasts of rhyolite, basalt and iron-formation were observed.

The exposure of upper Copper Harbor Formation at Black River Harbor consists of approximately 1525 m (5000 ft) of rippled, trough cross-stratified and horizontally laminated fine-to medium-grained sandstone that represents a fining-upward trend (Elmore and Daniels, 1980). Although the contact is not exposed, the Nonesuch is presumably in conformable contact with this facies of the Copper Harbor.

Parker Creek Measured Section

The section along Parker Creek is located approximately 12.5 km (20 mi), southwest of Black River Harbor and 7.5 km (12 mi) northwest of Ironwood, Wisconsin (Fig. 32).

In sharp contrast to the attitude of Nonesuch outcrops to the northeast in Michigan, the Parker Creek section strikes approximately N60°E with dips varying from 75°NW to nearly vertical. Sedimentary structures were less obvious here due to the vertical attitude of the bedding cross-cut by the narrow creek valley with near-vertical walls. The total thickness of Nonesuch Formation along the creek was measured at 131 m (430 ft) (Fig. 33).

Approximately 65 m (212 ft) of Copper Harbor Formation was measured and observed directly below the Nonesuch-Copper Harbor contact; approximately another 135 m (433 ft) thickness of Copper Harbor Formation crops out below that, but was not studied. The Copper Harbor here consists largely of poorly sorted and crudely bedded clast-supported conglomerate with minor matrix-supported conglomerate, and large-scale trough and planar cross-bedded, pebbly sandstone interbeds. Several clasts in the conglomerate were observed and consist of sub-rounded to well-rounded amygdaloidal basalt, rhyolite, pink and gray granite, gabbro, banded iron-formation, jasper, quartzite and chert. Clast diameters range from 2 cm to 40 cm. Granitic clasts are among the least abundant, but largest in diameter. The

Figure 32. Location of measured section on Parker Creek, Wisconsin; NW1/4, Sec. 30, T.47N., R.1E., Iron County, Wisconsin, (Oronto Bay U.S.G.S. 7.5' topographic quadrangle map, 1980).

Figure 33. Diagrammatic illustration of the measured stratigraphic section of Oronto Group rocks at Parker Creek, Iron County, Wisconsin. (Numbers to the right of the column right are stratigraphic locations in meters from the base of the section.)

Figure 33. (continued)

Figure 33. (continued)

total stratigraphic thickness of the Copper Harbor Formation exposed along Parker Creek is approximately 200 m (642 ft) (Rosenberry, 1924).

The general lithologic trend within the Copper Harbor is fining-upward with a decrease in clast sizes within the interbedded conglomeratic sandstones, upsection to the contact with the Nonesuch Formation. Several pebbly lithic sandstone interbeds appear as planar and trough cross-bedded lenses, with the range in thickness of single beds from 5 cm to 60 cm. Several beds were observed to pinch out along strike within the confines of the creek ravine which is approximately 50 m (160 ft) wide.

The Nonesuch contact with the Copper Harbor is gradational and is noticeably marked by a change in color and texture. The contact zone consists of a one-meter-thick, fining-upward bed of red-brown, trough cross-bedded, lithic sandstone that grades upward into gray-brown, micro-trough cross-bedded, calcareous sandy siltstone and siltstone. Thin layers of malachite were observed along bedding planes in the siltstones. A clast-supported conglomeratic bed of the Copper Harbor Formation directly underlies the one meter thick contact zone. The exact Nonesuch-Copper Harbor contact was placed where gray-brown sandstones and siltstones are in direct contact with red-brown clast-supported conglomerate.

Sedimentary structures in the Nonesuch include

asymmetrical and symmetrical ripple marks, parting lineation, mudchip intraclasts, mud cracks, sole marks, micro-trough cross-bedding, large-scale trough and planar cross-bedding, laminites, soft-sediment loading and calcareous concretions. Thinly bedded, parallel-laminated siltstones and shales (laminite) appear to be less abundant in this section than in Nonesuch exposures to the east in Michigan. Laminite beds generally occur as sequences less than 0.5 m in thickness, and are commonly interbedded with 10 cm to 60 cm thick, massive graded sandstone and siltstone beds.

The general sedimentary trend within the Nonesuch Formation is coarsening upward, with the pattern of sedimentation dominated by fining-upward sequences and graded beds ranging in thickness from 2 cm to 7.5 m. These features are similar in detail to those described at the Big Iron River section and are generally confined to the unoxidized, grayish-brown to-black, medium to fine-grained lithic sandstones, siltstones, shales and mudstones.

In addition to the commonly occurring unoxidized, fining-upward sequences and graded beds, there are at least four distinctive, reddish-brown, normally-graded beds that range from 3.7 m to 7.5 m in thickness. These beds, which strongly resemble turbidites (Bouma a-b-c-e beds), occur from approximately 53 m (170 ft) to 97 m (311 ft) stratigraphically above the Nonesuch-Copper Harbor contact.

Each graded bed consists of a basal large-scale trough or planar cross-bedded conglomeratic sandstone or coarse-grained lithic sandstone that grades upward to a convoluted and micro-trough cross-bedded, dark-brown to gray, micaceous and chloritic, fine-grained sandstone and siltstone. The uppermost trough cross-bedded siltstones are commonly interbedded with thin lenses of mudstone. Mudstone commonly occurs as a drape over the entire bed. The coarse-grained, reddish-brown oxidized lithic sandstones within each of these massive-graded beds, resemble Copper Harbor Formation rocks, and are in strong contrast to the overlying and underlying dark-brown-to black finer-grained sedimentary rocks. Each sequence contains dark-brown-to black mudchip intraclasts up to 10 cm in diameter, and in order of decreasing abundance, 2 cm to 18 cm diameter clasts of basalt, rhyolite, milky quartz, quartzite, chert, banded iron-formation, jasper, gabbro and granite. Many clasts show a preferred alignment of their long axes.

The Nonesuch Formation contact with the Freda Formation is also gradational over approximately 18 m (59 ft), from 182 m (583 ft) to 200 m (642 ft) stratigraphically above the base of the Nonesuch. The Nonesuch-Freda contact was placed at 131 m (430 ft) stratigraphically above the Nonesuch-Copper Harbor contact. The exact contact was established where reddish-brown oxidized coarse-to medium-grained sandstone beds prevailed and gray-to black

unoxidized fine-grained sandstone, siltstone and shale beds ceased.

The Nonesuch Formation exposure in Parker Creek contains a substantial percentage of coarse-grained oxidized (reddish-brown) conglomeratic sandstone interbedded with unoxidized (gray), fine-grained sandstone, siltstone and shale. Overall, the exposure here contains significantly more coarse-to fine-grained lithic sandstone than Nonesuch exposures observed to the east of Parker Creek.

Potato River Falls

The exposure of Nonesuch Formation at the Potato River Falls, Wisconsin was not measured. This outcrop was briefly described and observed for similarities and/or differences to observations made at the Big Iron River and Parker Creek measured sections.

The Falls of the Potato River are located 2.4 km (1.5 mi) southwest of Gurney, Wisconsin, and approximately 11 km (7 mi) southwest of the Nonesuch exposure at Parker Creek (Fig. 34). The outcrop is along the banks of the Potato River and exposes Nonesuch Formation contacts with both the underlying Copper Harbor and the overlying Freda Formations. The bedding strikes northeast with near vertical dips to the northwest. The total thickness of Nonesuch exposed here is approximately 107 m (350 ft) (Myers, 1971).

The Nonesuch Formation contact with the Copper Harbor

Figure 34. Location of Potato River Falls exposure; NE1/4, NE1/4, Sec. 18, T.46N., R.1W., Iron County, Wisconsin, (Mellen U.S.G.S. 15' topographic quadrangle map, 1967).

Formation appears gradational. Myers (1971) stated that the contact may be a minor diastem. Within the 2 m contact zone, the rocks grade upward from poorly sorted and crudely bedded clast-supported conglomerate of the Copper Harbor Formation, to dark-brown to black, micro-trough cross-bedded, fine-grained sandstones, siltstones and mudstones of the Nonesuch. The exact location of the contact was placed where oxidized, reddish-brown clast-supported conglomerates below are directly overlain by dark-brown-to dark-gray, small-scale trough cross-bedded and parallel-bedded sandstones and siltstones.

The Nonesuch at this exposure, although not measured and described in detail by this author (Myers, 1971), generally appears to consist of the previously described fining-upward sequences and graded beds composed of unoxidized fine-grained sandstone with mudchip intraclasts and parallel-laminated and small-scale trough cross-bedded siltstone. Interbedded with these sequences and graded beds are reddish-brown, large-scale trough or planar cross-bedded conglomeratic sandstone beds that fine upward to green-gray, micro-trough cross-bedded and thinly laminated, micaceous and chloritic siltstone with mudstone drapes.

Interbedded with laminite beds, as described at previous exposures, are 0.5 m to 1 m, light-gray to dark-brown, normally-graded, medium-to fine-grained sandstone and siltstone beds resembling turbidites (Fig.

35). In each sandstone bed, a massive part grades upward into a laminated part and then upward to a micro-trough cross-bedded siltstone that is commonly interbedded with mudstone, and overlain by a thin mud drape; these strongly resemble Bouma a-b-c-e beds (Fig. 36).

Fine- to coarse-grained sandstone and sandy siltstone beds predominate at this exposure. Several 0.5 m to 2 m thick beds of oxidized conglomeratic sandstone were observed grading upward to fine-grained sandstones, siltstones and mudstones.

In general, the Nonesuch exposure at the Potato River is a coarsening upward sequence and appears to contain fewer fine-grained sandstone, siltstone, mudstone and shale beds than exposures further east in Wisconsin and Michigan.

The Freda-Nonesuch contact is also gradational, and was placed where the oxidized reddish-brown to purple sedimentary rocks coarsened to the point of containing at least 50% medium-to coarse-grained sandstone. Sedimentary structures include large-scale trough and planar cross-beds, micro-trough cross beds, parting lineation and asymmetrical ripple marks.

Copper Falls State Park (Bad River)

The exposure of Nonesuch Formation At Copper Falls State Park, Wisconsin was not measured, but was studied for similarities with other Nonesuch exposures. Copper Falls

Figure 35. Graded sandstone beds interbedded with carbonate laminite, Potato River Falls approximately 30 m (98 ft) to 40 m (131 ft) stratigraphically above the base of the Nonesuch Formation (tops to left).

Figure 36. Normally graded sandstones & siltstones with interbedded mudstone, Potato River Falls, Wisconsin, approximately 30 m (98 ft) to 40 m (131 ft) stratigraphically above the base of the Nonesuch Fm.

State Park is approximately 14.5 km (9 mi) southwest of the last observed section at the Potato River Falls and approximately 6.5 km (4 mi) north of Mellen, Wisconsin (Fig. 37). The Oronto Group is exposed along the banks of the Bad River, and strikes northeast with a near vertical northwesterly dip. Approximately 30 m (98 ft) of Nonesuch Formation are exposed, as are the contacts with both the Copper Harbor and Freda Formations.

In general, the Nonesuch appears to be considerably sandier throughout the entire section here than at previously described exposures to the east. Thin, parallel-laminated and micro-trough cross-bedded siltstone and shale beds are minor and are commonly interbedded with coarse-to fine-grained large-scale trough cross-bedded sandstone. Contacts appear to be gradational and very similar to those observed at Parker Creek and Potato River Falls, with unoxidized, interbedded fine-grained sandstones and siltstones of the Nonesuch Formation within 1 m or 2 m stratigraphically of clast-supported conglomeratic facies of the Copper Harbor Formation.

Paleocurrents

A total of 128 sedimentary features were measured for the purpose of determining paleocurrents in the Nonesuch Formation at the Big Iron River measured section, the Presque Isle River exposure and the Parker Creek measured

Figure 37. Location of exposure on the Bad River at Copper Falls State Park; SE1/4, Sec. 17, T.45N., R.2E., Ashland County, Wisconsin, (Mellen U.S.G.S. 15' topographic quadrangle map, 1967).

section (Fig. 38). They can be divided into two groups; (1) those structures that indicate the current sense as being from one direction towards another, as for example, from east towards the west, and consist of rib and furrow structures (small-scale trough cross-beds), asymmetrical ripple marks, planar cross-bedding and flute casts and; (2) structures that indicate two possible current directions 180° apart, as for example, to the east or to the west. These consist of parting lineations and can be used in conjunction with those in group (1) to establish a general current direction.

A total of 39 current sense measurements were recorded at the Big Iron River measured section. Rib and furrow structures were the most common with 30 measurements giving a vectorial mean of 45° . Asymmetrical ripples yielded a vectorial mean of 11° for seven measurements, planar cross-beds gave a 350° azimuth for one reading and one flute cast gave an azimuth of 275° . These data appear to support a general flow regime to the north-northeast. Figure 39 illustrates the variation in paleocurrent indicators within the Nonesuch Formation at the Big Iron River section and indicates a shift in general paleocurrent directions from the west at the base of the section, to the east nearer the top of the section.

A total of 26 current sense measurements were taken at the Presque Isle River exposure. Twenty-four rib and furrow

Figure 38. Paleocurrent indicators for the Nonesuch Formation at the Big Iron River measured section and Presque Isle River exposure.

Figure 39. Diagrammatic illustration of the variation in paleocurrent indicators in the Nonesuch Formation at the Big Iron River measured section.

structures gave a vectorial mean of 250° , while two asymmetrical ripple marks gave a vectorial mean of 289° .

Twenty-seven parting lineation surfaces were measured at the Big Iron River section and gave a vectorial mean of $49/229^{\circ}$. Ten parting lineation surfaces were measured at the Presque Isle River exposure and gave a vectorial mean of $63/243^{\circ}$.

These data support a general flow regime to the west-southwest in the upper parts of the Nonesuch Formation near the Freda Sandstone contact at the Presque Isle River exposure. This is opposite the flow direction which prevailed during deposition of Nonesuch Formation sediments at the Big Iron River section (to the east-northeast) and is consistent with the paleocurrent data presented by Hite (1968).

At Parker Creek, 300 ft (93 m) stratigraphically above the base of the Nonesuch Formation, the long axes of 30 clasts were measured and indicated a general northeast-southwest orientation. These clasts were located at the base of one 6.2 m (20 ft) thick, reddish-brown-to dark-brown, massive-graded, coarse-to fine-grained sandstone bed, which is probably a turbidite bed. This information is used in conjunction with paleocurrent data from exposures to the east and appears to support a general current flow to the northeast.

DRILL CORE DESCRIPTIONS

Introduction

Bear Creek Mining Company drilled a total of 47 holes in Ashland, Bayfield, Burnett, Douglas and Washburn counties, Wisconsin (Fig. 3). Sixteen of these drill holes, in Bayfield and Douglas Counties, Wisconsin, intersected all three formations of the Oronto Group, but in most holes only the top several meters of Copper Harbor Formation are intersected. Of these 16 drill cores, ten were measured, examined in detail and/or sampled. These 10 cores provide a good representation of the Nonesuch Formation in the Bear Creek drill core study area. The cores from Douglas county are DO#6, DO#10 and DO#14, and those from Bayfield county are WC#2, WC#3, WC#9, WC#13, WC#18, WC#22 and WC#25. Douglas County drill core DO#5 was neither sampled or described at the core repository, but sedimentologic data from the original Bear Creek diamond drill hole log were analyzed and used for facies correlation and construction of a fence diagram. Drill core DO#10 was sampled and used for petrographic and basin analysis only. Drill core WC#24, from Ashland county, was briefly observed and sampled for use in petrographic and basin analysis. See Appendix I and II for drill hole locations and formation thicknesses.

The cores selected for this study are from an area approximately 48 km (30 mi) from WC#3 west-northwest to DO#6, and approximately 24 km (15 mi) from WC#13

north-northeast to WC#25 (Fig. 3). These dimensions define an area of approximately 1150 km.² (450 mi.²), and partially define the Nonesuch depositional basin in the drill core study area in northwestern Wisconsin (referred to in this paper as the Nonesuch drill core basin). The drill core study area lies approximately 48 km (30 mi) to the west from the Nonesuch outcrop at Copper Falls State Park, Wisconsin, and 128 km (80 mi) to the west-southwest from the Big Iron River, Michigan, measured section.

Sedimentology of Drill Cores

Copper Harbor Formation: Each drill core was logged starting at the bottom of each hole in the Copper Harbor Formation. The Copper Harbor consists of oxidized reddish-brown, poorly sorted and crudely bedded, clast-or matrix-supported conglomerate, mudchip conglomerate, and planar and trough cross-bedded conglomeratic sandstone, sandstone and siltstone with mudstone interbeds. The sedimentary trend is fining upward to the Nonesuch Formation contact. Clasts are composed of well-rounded pebbles and cobbles (0.5 cm to 8 cm diameter) of basalt, rhyolite, quartzite, chert, iron-formation, pink granite and gabbro. The matrix consists of compositionally and texturally immature sandstone of quartz and lithic fragments with abundant calcium carbonate cement. Fining-upward sequences, generally from pebbly sandstone to siltstone or mudstone,

dominate the sedimentary pattern, with thicknesses ranging from 22 cm to 4.5 m.

The only significant difference at the base of the drill holes occurs in drill core WC#25. The base of this core is composed of a felsic volcanic rock resembling rhyolite porphyry. Approximately 1 m of this rock type is in the core box and this is overlain by 5.5 m (17.7 ft) of coarse-to fine-grained sandstone facies of the Copper Harbor Formation. This sandstone is composed entirely of detritus which strongly resembles the felsic volcanic rock that it overlies. This places a felsic volcanic source rock approximately 5.5 m (17.7 ft) below the Nonesuch Formation on the northern edge of the drill core study area.

The Copper Harbor-Nonesuch contact is gradational in all cores. In drill cores WC#2, WC#3, WC#9 and WC#22, the contact zone contains a significant textural change as well as a color change, with gray-brown sandstone, siltstone and mudstone of the Nonesuch Formation in contact with or within 1 m of reddish-brown, clast-supported conglomerate of the Copper Harbor Formation. The same observation was made at Parker Creek, Potato River Falls and Copper Falls State Park. In cores WC#13, WC#18, WC#25, DO#6 and DO#14, the sedimentary texture is fairly consistent above, below and through the contact zone, with sandy-silty Nonesuch facies in contact with sandy-silty Copper Harbor facies; in these cores, the contact was established where the color changes

from reddish-brown Copper Harbor to gray-brown Nonesuch.

Nonesuch Formation: The Nonesuch Formation in cores is similar to outcrops in appearance: typically unoxidized grayish-black-to brown sandstone, siltstone and shale. Macroscopically, the coarse- to fine-grained sandstones are light gray and are generally composed of quartz and lithic fragments in a micaceous and/or calcareous matrix. 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. 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.

Sedimentary structures observed within the Nonesuch were micro-trough cross-bedding, syneresis cracks, rip-up mudchip intraclasts, soft sediment deformation features (load casts, distorted bedding, flame structures), laminated siltstone and mudstone beds (laminite), massive and normally-graded sandstone and sandy-siltstone beds resembling Bouma abce beds, and calcareous concretions (Figs. 40, 41, 42 and 43).

Figure 40. Micro-trough cross-bedding in Nonesuch Formation (core WC#2), 15 m (50 ft) stratigraphically above the lower Nonesuch contact (scale in cm). (Top of core to left).

Figure 41. Syneresis cracks in Nonesuch Formation (core WC#13), 21 m (69 ft) stratigraphically below the upper Nonesuch contact (scale in cm). (Top of core to left).

Figure 42. Minor loading in Nonesuch Formation (core WC#3), 88 m (287 ft) stratigraphically above the lower Nonesuch contact (scale in cm). (Top of core to left).

Figure 43. Carbonate laminite in Nonesuch Formation (core WC#2), 32 m (104 ft) stratigraphically above the lower Nonesuch contact.

Figure 44. Anhydrite nodule in crystalline calcite in Nonesuch Formation (Core WC#25), 2.1 m (7 ft) stratigraphically below the upper Nonesuch contact (scale in cm). (Top of core to left).

Several 1 to 2 cm diameter anhydrite nodules occur within approximately 2.0 m of crystalline calcite in what appears to be an isolated occurrence at the top of the Nonesuch Formation in drill core WC#25 (Fig. 44). This observation and confirmation of the mineralogy were also made by Elmore and others (1988), by means of x-ray analysis.

The pattern of sedimentation in the Nonesuch is dominated by fining-upward sequences and graded beds that bear a strong resemblance to the same features observed in outcrops. An entire fining-upward sequence, from bottom to top, consists of a basal massive and/or parallel bedded,

medium-to fine-grained sandstone with mudchip clasts; micro-trough cross-bedded, chloritic and micaceous sandy siltstone interbedded with thin (<2 mm) undulating beds (wisps) of calcareous sandstone and mudstone; and an undulating mudstone-shale bed which appears draped over the underlying trough cross-bedded siltstone. Sharp boundaries exist between the shaley-muddy top of each sequence and the sandy base of the overlying sequence, making their distinction and occurrence more obvious. Sharp boundaries separating the different lithofacies within each individual sequence were also commonly recognized. In each sequence, the finer-grained beds generally thin upward, but in a few cases there are thicker (1 to 5 cm) mudstone beds overlying the sandstone and siltstone beds. Sequences range in thickness from 20 cm to 2 m with the thicker sequences containing massive and/or normally-graded medium-to fine-grained sandstone beds overlain by micro-trough cross-bedded, very fine-grained sandstone and siltstone.

The graded beds commonly consist of, from bottom to top, a normally-graded, medium-to fine-grained sandstone; convoluted-undulatory beds and/or small-scale trough cross-beds of sandy siltstone and siltstone with interbedded, thin lenses of mudstone; and a top layer of mudstone that quite commonly contains thin lenses (wisps) of fine-grained sandstone and siltstone.

Freda Formation: The Nonesuch-Freda contact is

gradational in all cores. The contact zones range from less than one meter to a few meters thick. The contact with the Freda Formation was generally not as texturally abrupt as the contact with the Copper Harbor. In most cases, changes in texture within the contact zone were not evident, and contacts were established where oxidized reddish-brown sedimentary rocks began to prevail. Reddish-brown oxidized sedimentary rocks occur randomly throughout the Nonesuch in all the drill cores, but an increasing percentage is observed as the Freda contact is approached.

A general increase in planar and small-scale trough cross-bedded, coarse-to fine-grained sandstone is evident upsection in the Freda Formation. With the exception of drill core WC#2, which was logged to the top of the hole, the cores were logged to include from 15 m (48 ft) to 25 m (80 ft) of the Freda Formation.

Drill core WC#2 was the only core logged from the bottom of the hole in Copper Harbor Formation to the Freda Formation-Pleistocene glacial drift contact, a total of 359 m (1177 ft) (Fig. 45). The entire length of core was logged and sampled in order to gain a greater understanding of the sedimentary processes and diagenetic changes that have occurred throughout the Oronto Group represented in core. It was established that fining-upward sequences and graded beds are the dominant sedimentary patterns in all three formations from the upper Copper Harbor into the lower Freda

Figure 45. Diagrammatic illustration of Oronto Group rocks from Bear Creek drill core WC#2.

Formation. The only significant break in this pattern is where the laminated siltstone and shale beds (laminite) occur in the Nonesuch Formation.

Nonesuch Formation Sedimentational Intervals

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 going upsection 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.

Intervals 1 and 2: Intervals 1 and 2 represent a general fining-upward trend from the Copper Harbor-Nonesuch contact to the occurrence of laminite beds in interval 3.

Interval 1: A fining-upward interval composed of light gray, black, green and dark brown, calcareous conglomeratic sandstone with pebble and cobble size clasts of rhyolite, amygdaloidal basalt, quartzite, chert and agate. Other detrital constituents include grit, coarse-to fine-grained sandstone, siltstone and mudstone. This interval was defined largely on the occurrence of conglomeratic sandstone

to medium-grained sandstone, both of which decrease in abundance upward. Sedimentary structures include planar and micro-trough cross-bedding with mudchips and numerous fining-upward sequences that dominate the sedimentary pattern. Interval 1 is stratigraphically located at the base the Nonesuch above the Copper Harbor contact in drill cores WC#2, WC#13, WC#18 and DO#14.

Interval 2: A fining-upward interval composed of dark gray, green and black, fine-grained sandstone, micaceous and chloritic siltstone, shale and mudstone. This interval was defined largely on the significant increase in fine-grained sandstone and siltstone and a decrease in the coarser-grained rocks. Sedimentary structures include micro-trough cross-beds with mudchip clasts and mud drapes, massive and graded beds, laminite, distorted bedding and numerous fining-upward sequences. Near the top of the interval, laminite beds increase in abundance and fining-upward sequences and graded beds decrease and become thinner. Normally-graded fine-grained sandstone beds resembling turbidites are commonly observed intercalated with sequences of laminite beds. This interval is gradational with interval 3. In cores WC#3, WC#9, WC#22, WC#25, DO#5 and DO#6, interval 1 is missing and interval 2 represents the base of the Nonesuch Formation and is in gradational contact with the Copper Harbor Formation. Interval 2 was recognized in all of the drill cores.

Intervals 3 and 3a: Interval 3 consists predominantly of light gray and black laminite beds. The 0.5 mm to 2 mm thick light gray beds are composed of calcareous siltstone that alternates with thin 0.1 mm to 0.5 mm black, carbonaceous and pyritic mudstone beds. Laminae are subparallel to undulating and commonly broken up or distorted by syneresis cracks, load casts, flame structures and rip-ups. Interbedded with the laminite beds are minor very fine-grained sandstone, siltstone and mudstone as fining-upward sequences, and massive and normally-graded medium-to fine-grained sandstone and siltstone beds less than 1 m thick. The interbedded fining-upward sequences are gradational with the laminites at the base and top of interval 3. The massive and graded beds are randomly distributed throughout those areas of the interval dominated by laminite beds. Interval 3 was recognized in all of the drill cores.

Interval 3a: This is a 3 m to 9 m thick interval composed predominantly of graded beds made of coarse-to fine-grained sandstone, siltstone, and minor mudstone and shale. Stratigraphically it is located within interval 3 and is completely enveloped by, and gradational with, the laminite beds that typify interval 3. This interval is generally in sharp contrast with the finer-grained interval 3 rocks stratigraphically above and below it. The abrupt appearance of coarser-grained rocks in interval 3a appears

to represent a sudden shift in sedimentary processes.

Interval 3a was recognized in drill cores WC#2, WC#13, WC#18, WC#22, WC#25, DO#5, DO#6 and DO#14.

Intervals 4 and 5: These intervals represent a coarsening-upward trend. With the exception of drill core WC#25, all Nonesuch cores end in either interval 4 or 5, which are in gradational contact with the Freda Formation.

Interval 4: A coarsening-upward interval composed of light-gray to black, green and reddish-brown, medium- to fine-grained sandstone, chloritic and micaceous siltstone, mudstone, and shale. This interval was established largely because of a significant increase in siltstone and sandy siltstone which occurs in fining-upward sequences and graded beds.

Sedimentary structures consist of micro-trough cross-beds with mud drapes, massive and graded sandstone and sandstone beds 10 cm to 1 m thick, laminites, and micaceous and chloritic parallel-laminated sandy siltstone to muddy siltstone beds with mudchip clasts. Fining-upward sequences dominate the pattern of deposition. Reddish-brown oxidized sediments and thin (<1 cm), green shale interbeds increase upsection. The top of interval 4 marks the Nonesuch-Freda contact in cores DO#5 and DO#6. Interval 4 is gradational with the Freda Formation and/or with interval 5, and was recognized in all drill cores except WC#25.

Interval 5: This is a continued coarsening-upward

interval composed of light-gray, green and reddish-brown coarse-to fine-grained sandstone, siltstone, mudstone and shale. Interval 5 represents a substantial increase in coarse-to medium-grained lithic sandstone. There is a progressive increase in the abundance of reddish-brown oxidized sedimentary rocks and in the thickness of massive and normally graded, and trough and planar cross-stratified coarse-grained to fine-grained sandstone beds upsection to the Freda Formation contact.

Sedimentary structures include micro-trough cross-bedded sandstone and siltstone with muddy interbeds and mud drapes, parallel-laminated micaceous and chloritic sandy siltstone, and muddy siltstone beds with numerous mudchips, mudcracks, and as best as can be perceived from the cores, large-scale planar and trough cross-bedding with numerous mudchips clasts. Interval 5 was recognized in cores WC#2, WC#3, WC#9, WC#13, WC#18, WC#22 and DO#14 where it is in gradational contact with the Freda Formation.

Figures 46 through 54 diagrammatically illustrate the stratigraphic position and thickness of each sedimentational interval, and the data used to distinguish between them.

Nonesuch Drill Core WC#2
Total Thickness = 108.8 meters

Figure 46. Diagrammatic illustration showing stratigraphic position and data for Nonesuch Formation sedimentational intervals in core WC#2 (Scale: 1 cm = 9 m).

Nonesuch Drill Core WC#3
Total Thickness = 116.7 meters

Figure 47 Diagrammatic illustration showing stratigraphic position and data for Nonesuch Formation sedimentational intervals in core WC#3 (Scale: 1 cm = 9 m).

Nonesuch Drill Core WC#9
Total Thickness = 144.5 meters

Figure 48. Diagrammatic illustration showing stratigraphic position, and data that defines Nonesuch Formation sedimentational intervals in drill core WC#9 (Scale: 1 cm = 9 m).

Nonesuch Drill Core WC#13
Total Thickness = 119.8 meters

Figure 49. Diagrammatic illustration showing stratigraphic position and data for Nonesuch sedimentational intervals in drill core WC#13 (Scale: 1 cm = 9 m).

Nonesuch Drill Core WC#18
Total Thickness = 136.8 meters

Interval 5: thickness = 32.5 meters
60% fn. Ss / 14% sandy Slt / 24% Slt /
2% Mds. & Shl; 82 f-u-s & gb, 2cm to
3.80m thick, = 80% of interval

Interval 4: thickness = 38.1 meters
2% med. Ss / 7% fn. Ss / 40% sandy
Slt / 47% Slt / 4% Mds. & Shl;
81 f-u-s & gb, 1cm to 75cm thick,
= 37% of interval

Interval 3a: thickness = 4.6 meters
60% fn. Ss / 8% sandy Slt / 18%
Slt / 14% Mds. & Shl;
37 gb, 1cm to 97cm thick, = 80%
of interval

Interval 3: thickness = 30.6 meters
30% sandy Slt / 70% Slt & Mds., (laminite);
96% of interval as laminites. No f-u-s, gb
statistics.

Interval 2: thickness = 23.4 meters
30% fn. Ss / 20% sandy Slt / 44% Slt / 6%
Mds. & Shl;
60 f-u-s & gb, 1cm to 30cm thick, = 70%
of interval

Interval 1: thickness = 7.5 meters
3% cong. Ss / 1% grit / 7% crs. Ss / 28% med.
Ss / 32% fn. Ss / 18% sandy Slt / 7% Slt / 4%
Mds. & Shl;
15 f-u-s & gb, 2cm to 1.2m thick, = 40%
of interval

Figure 50. Diagrammatic illustration showing stratigraphic position and data for Nonesuch sedimentational intervals in drill core WC#18 (Scale: 1 cm = 9 m).

Nonesuch Drill Core WC#22
Total Thickness = 133.0 meters

Figure 51. Diagrammatic illustration showing stratigraphic position and data for Nonesuch sedimentational intervals in drill core WC#22 (Scale: 1 cm = 9 m).

Nonesuch Drill Core WC#25
Total Thickness = 60.0 meters

Interval 3a: thickness = 3.7 meters
76% Slt / 24% Mds. & Shl;
60 gb, 2cm to 15cm thick, = 17%
of interval

Interval 3: thickness = 43.9 meters
2% fn. Ss / 12% sandy Slt / 86%
Slt & Mds., (laminite);
12 gb, 2cm to 66cm thick, = 17%
of interval

Interval 2: thickness = 12.5 meters
7% crs. Ss / 4% med. Ss / 8% fn. Ss /
16% sandy Slt / 61% Slt / 4% Mds. & Shl;
41 f-u-s & gb, 2cm to 1.20m thick, = 65%
of interval

Figure 52. Diagrammatic illustration showing stratigraphic position and data for Nonesuch sedimentational intervals in drill core WC#25 (Scale: 1 cm = 9 m).

Nonesuch Drill Core DO#6
Total Thickness = 67.0 Meters

Interval 4: thickness = .9 meters
100% Slt and Shl; No % statistics.
Core badly broken in box.

Interval 3a: thickness = 4.6 meters
65% fn. Ss / 29% Slt / 6% Mds. & Shl;
6 gb, 66cm to 1.90m thick, = 50%
of interval

Interval 3: thickness = 30.7 meters
100% Slt & Mds., (laminite);

Interval 2: thickness = 30.9 meters
7% fn. Ss / 53% sandy Slt / 40% Slt;
No statistics on f-u-s or gb

Figure 53. Diagrammatic illustration showing stratigraphic position and data for Nonesuch sedimentational intervals in drill core DO#6 (Scale: 1 cm = 9 m).

Nonesuch Drill Core DO#14
Total Thickness = 94.5 Meters

Interval 5: thickness = 15.0 meters
73% fn. Ss / 12% sandy Slt / 14% Slt /
2% Mds. & Shl;
237 f-u-s & gb, 2cm to 38cm thick,
= 92% of interval

Interval 4: thickness = 10.8 meters
44% fn. Ss / 20% sandy Slt / 31% Slt
/ 5% Mds. & Shl;
158 f-u-s & gb, 1cm to 40cm thick,
= 89% of interval

Interval 3a: thickness = 12.0 meters
1% med. Ss / 58% fn. Ss / 28% sandy Slt /
11% Slt/ 2% Mds. & Shl;
113 gb, 2cm to 76cm thick, = 86%
of interval

Interval 3: thickness = 28.8 meters
38% fn. Ss / 7% sandy Slt / 55% Slt
& Mds., (laminite);
2 gb, 97cm & 1.80m thick, = 11%
of interval

Interval 2: thickness = 21.0 meters
1% crs. Ss / 58% fn. Ss / 17% sandy Slt
/ 22% Slt/ 2% Mds. & Shl;
70 f-u-s & gb, 2cm to 75cm thick, = 64%
of interval

Interval 1: thickness = 6.9 meters
28% crs. Ss / 33% med. Ss / 26% fn. Ss /
9% sandy St / 4% St;
26 f-u-s & gb, 1cm to 51cm thick, = 71%
of interval

Figure 54. Diagrammatic illustration showing stratigraphic position and data for Nonesuch sedimentational intervals in drill core DO#14 (Scale: 1 cm = 9 m).

PETROGRAPHY

General Statement

Siltstone and mudstone are the most abundant rock types in the Nonesuch Formation. Due to the difficulty in point-counting these fine-grained samples, only samples containing fine sand and larger grain sizes were counted.

Fifty thin sections cut perpendicular to bedding, 45 from drill core samples and 5 from outcrops, were counted, with an average of 600 points per section (Table 1). Appendix III indicates the lithology and stratigraphic location of each sample used in the petrographic analysis. All thin sections were prepared with blue epoxy in order to easily identify the pore spaces. Staining for plagioclase (using the "Laniz" stain developed by Ruperto Laniz of Stanford University), and for potassium feldspar (using sodium cobaltinitrite) (Chayes, 1952; Rosenblum, 1956; Bailey and Stevens, 1960) was done on all 50 thin section heels, which were then examined with a hand lens.

The petrology of the Oronto Group has been well documented by previous workers. A comparison of the upper Copper Harbor, Nonesuch and lower Freda Formations was conducted largely from outcrop data compiled by previous workers, and with Bear Creek drill core data compiled during this study. The majority of the statistical information used for petrographic comparison was taken from Hite's

TABLE 1. PETROGRAPHIC SUMMARY OF ORONTO GROUP
SANDSTONES IN SELECT BEAR CREEK
DRILL CORES AND OUTCROPS

FORMATION	SAMPLE NUMBER	QUARTZ							FELDSPAR					ROCK		FRAGMENTS			
		UNIT UNSTRAINED	VOLCANIC	UNIT STRAINED	MULTICYCLE	ANGULAR & VEIN QUARTZ	POLYCRYSTALLINE	TOTAL QUARTZ	ALTERED PLAGIOCLASE	FRESH PLAGIOCLASE	ALTERED K-SPAR	FRESH K-SPAR	TOTAL FELDSPAR	MAFIC VOLCANIC	INTERMEDIATE VOLCANIC	FELSIC VOLCANIC	PLUTONIC	SEDIMENTARY	
FF	MC82-235	T		19.5		T	2.8	22.8	12.5	T	1.7	T	15.0	6.9	3.1	3.5	1.0	T	
FF	MC82-276		T	16.0		T	1.3	3.6	20.8		1.0	1.9	13.0	2.6	18.9	5.9	2.3	1.3	
FF	MC82-378			10.1			1.5	1.1	13.6		T	1.6	14.0	5.1	21.3	T	2.8	4.3	
NF	MC82-798		T	11.6				T	13.7		1.7	3.0	13.7	13.3	11.0	4.0	3.0	1.3	
NF	MC82-843	T	T	7.6		T	T	9.6	10.1		4.8	6.0	21.1	12.0	4.8	1.3	2.3	T	
NF	MC82-876		T	12.8		T	T	5.6	17.3			3.9	7.8	13.6	8.6	5.7	11.9	3.1	
NF	MC82-899	1.3		15.3				5.1	21.6		T	T	7.1	8.5	14.8	17.3	1.2	3.0	
CHF	MC82-931			9.8		T		4.6	14.3		T		4.2	12.1	19.0	22.9	T	3.2	
CHF	MC82-1239	T	T	4.8			T	1.2	6.4			T	3.2	11.2	20.0	16.4	T	6.4	
CHF	MC82-1355	T				T		17.2	17.4				T	11.8	22.0	22.4	T	2.5	
FF	MC83-885	2.2		14.9		T	T	17.4	7.4			T	8.1	2.8	10.2	T	1.8	12.9	
NF	MC83-1303			14.7		T	2.8	17.5	10.8	T	T	2.3	14.1	2.2	7.7	T	2.5	4.9	
NF	MC83-1313		T	6.0			1.6	T	10.2		T	T	9.9	6.4	13.4	1.6	1.2	3.0	
CHF	MC83-1379			4.1				4.5	2.1		T	T	2.5	24.5	10.3	15.2		5.3	
CHF	MC83-1385	T	T	5.2		T	1.4	6.8	3.2				3.2	10.8	16.4	4.0	T	14.0	
FF	MC89-1046	T		4.9		T	1.5	6.7	3.9		T		4.2	12.7	10.3	10.3		4.4	
NF	MC89-1574		T	6.0		T	3.2	9.2	1.4		T	T	2.8	4.2	2.8	4.2	T	3.8	
CHF	MC89-1723	T		16.9		T	2.1	19.9	2.6		T	1.3	4.1	13.7	6.0	23.6	T	2.6	
CHF	MC89-1741		T	23.2		T	T	23.6	1.4		T	T	2.8	7.6	6.3	13.4	T	3.9	
NF	MC813-3142	T		15.4			1.9	1.7	18.7		T	T	13.4	1.0	13.7	5.8	T	2.6	
NF	MC813-3188	1.2		19.0		T	2.4	22.8	9.2			3.6	12.8	T	11.0	4.9	T	5.4	
NF	MC813-3282	3.5	T	22.5			1.2	29.0	7.0		T		7.3	3.8	15.4	6.4	1.2	1.8	
CHF	MC813-3292	3.8	T	11.1			2.1	1.6	17.6		T		3.9	6.7	17.5	6.5	1.3	6.9	
NF	MC818-1777	T		15.4			1.0	1.4	18.3			T	6.1	T	14.7	T	1.0	3.2	
NF	MC818-1863	4.0	T	10.7		T	T	1.0	15.7			T	3.8	T	5.8	13.0	T	6.3	
CHF	MC818-1885	2.4	1.4	24.3		1.2	T	1.8	29.9			T	6.9	4.7	15.8	5.4	1.5	3.9	
CHF	MC818-1893	2.3	2.4	12.3			2.0	2.1	21.1			T	5.0	5.2	17.3	8.9	T	5.5	
NF	MC822-2029			27.5				1.9	29.4		4.8	1.9	10.3	5.2	3.3	9.9		3.7	
NF	MC822-2050	1.4		21.4		T	T	4.5	27.3		T	1.4	5.1	6.8	15.0	10.7	1.5	5.5	
CHF	MC822-2053	2.4		7.6		T		1.6	11.6		T		1.3	9.3	6.6	32.6	9.7	1.6	
CHF	MC824-547			1.3				3.8	5.2		T			15.0	28.4	22.9	1.0	3.5	
CHF	MC824-582			4.5			1.4	T	6.5		1.0		1.0	12.5	11.1	31.9		5.1	
NF	MC825-2317	4.5	11.7	13.5				T	30.6		1.2	T	1.5	3.0	T	26.1	3.0	T	
NF	MC825-2340	14.2		12.5		T	1.6	29.1	1.6		T		2.0	T	T	30.4	T	T	
CHF	MC825-2376	5.0	3.0	12.0				T	21.4		T		4.9	1.0	1.3	36.3	T	1.7	
CHF	MC825-2378	5.5	T	20.0		T	T	1.7	27.2		T	T	11.0	2.0	9.0	7.6	1.7	2.8	
FF	DO86-1224	T	2.3	5.2		T	T	8.9			T	T	T		3.0	14.6		T	
NF	DO86-1394	1.2		14.1			1.8	17.3	1.2				1.2	4.3	2.4	29.0	T	2.6	
CHF	DO86-1517	4.3		5.5				2.0	10.2					8.2	12.2	5.9		4.9	
CHF	DO86-1576	3.8		2.5					6.3							70.7		1.4	
NF	DO810-309	T		17.5				1.0	19.3		T	T	3.7	T	5.7	14.8	T	1.0	
CHF	DO810-381	T	T	5.5		T	T	1.4	7.3					T	13.7	31.0	T	2.1	
NF	DO814-3073	5.1	18.3					T	25.4		1.9	2.9	4.8	T		27.7		1.8	
NF	DO814-3204	2.9	T	24.5			1.5	2.5	31.4		3.8	T	1.3	10.0	5.2	10.2	T	5.4	
NF	DO814-3217	1.6	1.4	7.8			T	T	11.6		4.0		4.8	9.5	10.5	23.7	T	4.5	
NF	PI87	5.7	4.8	22.0					32.5		1.0	4.0	2.0	6.0	T	1.3	20.0	T	T
CHF	BR86			5.2		T		T	6.0		6.0	T	T	6.6	12.5	6.8	16.9	T	T
CHF	PC80			4.2		T	T	1.9	6.1		2.8		3.0	20.8	8.1	3.9	T	3.1	
NF	PC8518			13.5			1.1	4.0	18.6		5.2	T	1.3	7.1	15.6	7.7	4.1	T	7.1
NF	PRF81			8.1		T	T	9.0	17.1		9.5	1.7	1.5	12.7	21.4	11.1	7.2	T	4.8

FF = Frada Formation / NF = Norwich Formation / CHF = Copper Harbor Formation
PI = Presque Isle River / BR = Black River / PC = Parker Creek / PRF = Potato River Falls

(Sample numbers give core numbers & footage
in the core - see Appendix III)

TABLE 1. (Continued)

ROCK FRAGMENTS					CEMENT & MATRIX										Q-F-L INDEX						
CHERT	SCHIST	IRON-FORMATION	QUARTZITE	OTHER R.F.	TOTAL ROCK FRAGMENTS	ZEOLITE	QUARTZ	CARBONATE	IRON OXIDES	EPIDOTE & CHLORITE	CLAY	HEMATITIC CLAY	QUARTZ & FELDSPAR	TOTAL C & M	OPAQUES	TOTAL PORE SPACE	POINTS COUNTED PER THIN SECTION	QUARTZ	FELDSPAR	LITHIC FRAGMENTS	CLASSIFICATION
T	T	1.0	T		28.3		5.2	9.0	3.8	2.4	T	2.4	1.0	29.3	4.6	T	574	36	23	41	LA
T	1.0	1.7	1.0		36.7		5.2	9.4	4.6			7.8		27.7	1.8		614	30	19	51	LA
1.2	3.5	1.5	T		43.3	6.3	T	4.0	6.6	2.2		6.3		23.9	2.9		785	20	20	60	LA
1.6	2.7	T	1.0		35.7			12.7		14.5	2.0		3.3	33.0	3.8		600	23	20	57	LA
T	1.0	T			24.2	T	T	10.1		25.8	4.0		1.6	42.2	2.1		750	18	38	44	LA
T	1.4	T	T		48.7	1.2	T	15.6		5.1	1.4		T	23.5	2.3		403	25	11	64	LA
	2.3	2.3	1.6		42.8	1.4		8.5		15.7	17.0		1.3	27.0	T		705	29	7	64	LM
3.6	1.3	3.6			67.0	1.6	T	8.5			2.3			13.1	1.6		612	22	5	73	LA
2.0	1.0	6.2	T		67.0	4.0	19.5			T	T		T	24.8	T		818	9	4	87	LA
T	T	3.2	3.0		67.1	T		13.3			T			14.1	T		633	22	1	77	LA
T	T	1.8	T		34.5		T	27.4	1.8		3.7	6.1		40.5		T	644	30	13	57	LA
2.1		2.2	T		22.5			6.8		25.7	5.2		T	38.6	T		651	36	26	38	LM
2.5	T	2.2	T		35.2		40.1			5.4				45.5	T		624	16	19	65	LA
	T	4.7			62.9	6.5	T	16.0		5.2	T		T	28.5	1.1		611	10	4	86	LA
T	T	4.4	2.0		53.0	T	T	18.4		3.0	7.0	T	6.0	32.6	2.0	1.3	994	13	5	82	LA
1.9	2.0	2.5	2.5		44.6	8.8	T	20.0	6.8		2.4		4.4	43.0	1.5	T	614	17	8	75	LA
2.3	T	2.3			19.2			62.1		2.3	4.0			68.8			214	40	9	51	LA
2.6	1.6	1.6			52.5	1.9	1.6	1.4		7.6	2.1	T	T	16.0	2.1	5.5	831	30	5	65	LA
1.6	1.3	3.2	T		40.9	17.2	1.6	8.1		1.2	T			28.9	1.0	2.8	602	41	4	55	LA
1.7	1.7	1.0	T	T	28.3		2.0	2.4		31.9	2.0		T	38.9	1.4		582	35	23	42	LM
			1.8		25.5			24.6		7.4	1.8		1.2	35.0	3.9		325	38	20	42	LA
1.2	1.2	2.2	1.9	1.2	36.3			12.9		7.7	1.2		T	22.1	1.5	3.8	620	45	10	45	LA
1.0	T	5.3	2.9	5.6	53.9		T	14.1	T	1.2	3.4	T	T	22.6	1.0		736	26	5	69	LA
T	1.8	1.0	T		23.9			35.6		1.8	7.1		2.1	46.6	5.1		555	38	12	50	LA
1.1	T	2.2	T	1.1	30.4			41.1		1.4	4.7		1.6	48.8	1.3		668	34	7	59	LA
1.2	T	4.8	T	1.5	41.2			1.8		6.9			T	9.0	1.0	12.0	629	41	8	51	LA
1.7	2.4	4.7	T		46.7		T	21.6			T		1.2	24.0	2.4	T	802	31	7	62	LA
	T	1.4	T		24.9			20.7		7.2	5.3			33.2	2.2		621	37	13	50	LA
T	3.0	1.4	T	2.2	44.4	3.1	7.1			7.3	1.2			19.5	1.0	2.7	630	38	7	55	LA
1.0	T	10.7	T	T	71.0		T	1.3	7.3		T			9.3	2.8		666	15	2	83	LA
	T				76.3			T		1.5	5.3	T	6.3	14.0	4.0		598	6	1	93	LA
T	2.0		2.7		66.3			18.3		3.8		1.2	T	23.7	2.2		814	10	1	89	LA
			T		31.9			26.1		4.2	2.7			33.1	1.6		665	48	5	47	LA
T	T	1.7	T		32.7	16.1		11.2		4.2	T	T	T	32.9	T	2.7	605	46	3	51	LA
T	2.6	2.3	1.1	T	31.0	2.7		13.6		1.3	2.0	4.8	2.4	26.8	1.6	T	572	31	7	62	LA
T		T	T		19.6		T	9.6		10.3	2.6		T	26.6	2.7	T	683	41	16	43	LA
T	T				39.4			40.4		T	7.2	6.9	11.5	66.7	3.4		763	25	1	74	LM
T	T			1.2	39.4			8.0		20.9	6.1			35.2	4.5		486	30	2	68	LM
T	1.0				32.5			39.8		12.6		T	2.0	53.7	3.3	T	767	25	7	75	LA
		T			72.4		2.6			14.6		T	1.9	20.0	1.3		616	8		92	LM
T	1.0	T	T	2.0	26.5			35.4		5.5	1.4		T	43.1	7.4		592	39	7	54	LA
T		1.0			48.9			17.3		17.4			3.9	39.2	3.1	T	714	15		85	LM
	T				30.7		T	19.7		2.8	7.5		5.6	36.5	2.6		637	42	8	50	LM
T	4.6	2.4	1.6	1.2	41.4		T	T		10.8	1.8		T	14.3	T	6.3	648	42	8	50	LM
	3.7	3.1	T		56.3	T		14.2		6.8	2.5		T	24.9	2.4		700	17	7	76	LA
					22.0	20.4	6.1		1.5	2.3	1.5			32.8	3.9	2.8	609	53	11	36	LA
	T	T	T		37.3			21.8	6.2	7.0	8.3	6.5		49.8	T		733	12	13	75	LM
	T	5.0	T	T	43.7	24.7		18.2		1.3				44.1	3.1		639	15	6	79	LA
5.1	T	3.3	T		45.1	3.8		T		20.3	1.2		1.2	26.7	1.2	1.4	652	33	10	57	LM
2.2	1.4	5.9	T		58.0	1.4	1.4	T		4.2	1.9		T	10.0	2.2		718	23	15	62	LA

T = Trace amount (less than 1%) / Average points per thin section = 646
 LA = Lithic Arenite, LM = Lithic Graywacke (Dott, 1964)

(1968) data, which were compiled from Oronto Group exposures on the Presque Isle River and in the Porcupine Mountains in the western Upper Peninsula of Michigan, and from exposures on the Bad, Potato and Montreal Rivers and Parker Creek in northwestern Wisconsin.

Operational definitions:

1) Quartz

a) Unit unstrained: Single crystal with crystal outlines; angular to sub-rounded; few inclusions; sharp extinction.

b) Volcanic quartz: Single crystal with sharp extinction; angular to sub-rounded; embayments with and without fine-grained volcanic groundmass material.

c) Reworked quartz: Single crystal with abraded, well-rounded, quartz overgrowths; undulatory extinction ($<15^\circ$ of rotation).

d) Unit strained: Single crystal, angular to sub-rounded; numerous inclusions; undulatory extinction ($>20^\circ$ of rotation).

e) Amygdule and vein quartz: Sub-angular to sub-rounded; undulatory extinction; gray-to red-brown; irregular crystal boundaries; cockscomb structures and concentric crystal growth; amygdule (agate) quartz is chalcedony.

f) Polycrystalline:

Stretched polycrystalline: Angular to rounded; sutured boundaries between different crystals in the same grain; undulose extinction.

Recrystallized polycrystalline: Angular to sub-rounded; polygonal crystal boundaries; sharp extinction within individual crystals.

2) Feldspar:

a) Plagioclase: Subhedral crystals; twinned and untwinned; varying degrees of sericite alteration, and zeolite and calcium carbonate replacement; utilizing the Michel-Levy statistical method of identification (Heinrich, 1965), the range of plagioclase is from An_5 to An_{50} ; fresh grains rare.

b) Potassium feldspar: Subhedral crystals; cross-hatched twinning (microcline), Carlsbad twinning alone (orthoclase, sanidine); commonly altered to sericite and replaced by calcite and/or zeolite along grain boundaries; fresh grains are common.

3) Rock fragments:

a) Mafic Volcanic: Subangular to rounded; varying degrees of epidote, sericite and chlorite alteration; commonly dark-brown from iron-oxide staining; porphyritic with subhedral plagioclase crystals in a microcrystalline groundmass; pilotaxitic, intergranular, glomeroporphyritic and

amygdular; amygdules of chalcedony, calcite, epidote, chlorite and zeolite.

b) Intermediate volcanic: Subangular to subrounded, trachytic and sub-trachytic; plagioclase phenocrysts in dark aphanitic groundmass that is largely altered to epidote and chlorite; plagioclase phenocrysts commonly altered to sericite; plagioclase compositions range from An_{20} to An_{50} as determined by the Michel-Levy method.

c) Felsic volcanic: Subangular to subrounded, light-brown to dark-brown; staining indicates 3% to 15% potassium feldspar in an aphanitic groundmass; porphyritic with embayed quartz phenocrysts and randomly oriented subhedral orthoclase crystals; quartz crystals <1 mm in diameter poikilitically enclose or partially enclose subhedral potassium feldspar crystals; snowflake and platy quartz textures common; partially altered to sericite and replaced by calcite and/or zeolite.

d) Plutonic: Subangular to subrounded; contain plagioclase, microcline and/or perthite and strained quartz; commonly as a micrographic intergrowth of quartz and feldspar (granophyre).

e) Metamorphic:

Iron-formation: angular to subrounded coarse-to fine-grained sand-size fragments; banded and oolitic with magnetite and/or hematite, chert, and jasper.

Quartzite: subrounded to well-rounded coarse-to fine-grained sand-size fragments; sutured and polygonal crystal boundaries commonly containing mica along crystal boundaries.

Schist: quartz-mica; medium-to fine-grained sand-size fragments showing varying degrees of carbonate replacement.

Chert: subrounded to well-rounded medium-to fine-grained sand-size fragments; microcrystalline texture with pinpoint extinction.

f) Sedimentary siliciclastic: Angular to well-rounded fragments of mudstone, siltstone, quartz sandstone, lithic sandstone, and mudchip intraclasts; commonly reddish-brown with iron oxide stain and light-green to gray with chlorite alteration.

g) Sedimentary carbonate: well-rounded, fine-grained sand to silt-sized grains; commonly coated with iron oxide along grain boundaries; mosaic-like arrangement of sparry calcite crystals. Note: This grain type was observed only in the carbonate laminite lithology which was not point-counted.

h) Other: Includes those fragments that have been

extensively or entirely altered to epidote, chlorite and sericite, replaced by carbonate or zeolite, or obscured by iron-oxide stain so as to mask their original compositions.

i) Opakes and miscellaneous grains: Actinolite, biotite, hornblende, garnet, muscovite, prehnite, pyrite, zircon, magnetite, hematite and sphene.

4) Cement:

a) Zeolite: Clear to light brown to light gray laumontite with two cleavages at nearly right angles; low refractive index; optically continuous crystals 1 mm to 4 mm in size; partially replaces volcanic rock fragments and feldspar crystals; X-ray confirmation in drill core WC#2.

b) Quartz: Optically continuous rims on quartz grains.

c) Carbonate: Calcium carbonate (sparry variety); generally displays good rhomboid cleavages with high order interference colors; replaces zeolite and quartz cements and all other detrital constituents and matrix.

d) Iron oxide: Hematite-red color in reflected light, optically opaque.

5) Matrix:

a) Clay: Optically unidentifiable felted aggregates with moderate interference colors; in discontinuous patches (such patches could represent feldspar crystals

and volcanic rock fragments that have been totally altered).

b) Chlorite: Light-green to brown to purple microcrystalline grains with weak pleochroism (pale yellow to green); occurs as an alteration mineral in the interstices around mafic to intermediate rock fragments; chlorite matrix may be confused with fragments that have been totally altered to lower greenschist facies.

c) Epidote: Fine-grained crystal aggregates in the interstices between mafic to intermediate volcanic rock fragments; aggregates are too small for unambiguous optical identification, but a combination of high birefringence, weak pleochroism (colorless to gray to yellow), color, and mottled extinction serve to make an identification.

d) Quartz and feldspar: Minor matrix constituents; occur as angular to subangular coarse-to fine silt-size grains; feldspar is optically unidentifiable; staining indicates the presence of both potassium feldspar and plagioclase in the silt and clay matrix in 45 of the 50 thin sections analyzed.

Upper Copper Harbor Formation

Framework Grains: The average composition of the major framework constituents in the sandstone facies of the upper

Copper Harbor in drill cores (recalculated to 100%) is 57.6% volcanic rock fragments, 11.9% plutonic, metamorphic and sedimentary rock fragments, 5.7% feldspar grains, and 24.8% unit quartz grains and volcanic quartz grains.

In outcrops, mafic volcanic rock fragments are the most abundant constituent followed by intermediate and felsic volcanics. In cores, felsic volcanics are the most abundant followed by intermediate and mafic volcanics. Mafic, intermediate and felsic volcanic fragments were observed in all core samples except in DO#6-1576, which contains only felsic volcanics.

The mafic to intermediate volcanics in cores are either fine-grained or porphyritic with randomly oriented or sub-parallel aligned plagioclase laths in an aphanitic groundmass (Fig. 55). All of the felsic volcanics are microcrystalline and they commonly exhibit snowflake and platy quartz textures (Fig. 56); most of the quartz contains optically unidentifiable anhedral crystals of potassium feldspar (Fig. 57).

There appears to be a direct relationship between the occurrence of metamorphic clasts and the amount of strained, stretched polycrystalline and recrystallized polycrystalline quartz. Unstrained quartz ranges from <1% to 5.5% in 13 thin sections and is probably largely of volcanic origin.

Metamorphic fragments occur in all thin sections, with

Figure 55. Photomicrograph of a mafic to intermediate volcanic fragment in the Copper Harbor (core WC#3), 3 m (10 ft) stratigraphically below Nonesuch Formation contact (X-Nicols, field = 5.1 mm wide).

Figure 56. Photomicrograph of snowflake texture in microcrystalline quartz in a felsic volcanic fragment from Copper Harbor core DO#6, 18.9 m (62 ft) stratigraphically below the Copper Harbor-Nonesuch Formation contact (X-Nicols, field = 1.3 mm wide).

Figure 57. Photomicrograph of a quartz enclosing altered k-feldspar crystals in a felsic volcanic fragment from Nonesuch core WC#25, 1 m (3.2 ft) stratigraphically above the lower Nonesuch Formation contact, (X-Nicols, field = 1.3 mm wide).

the largest contribution from iron-formation, followed by slate, schist, chert and quartzite with mica. Plutonic rock fragments consist mainly of granophyre (Fig. 58), granite with quartz and microcline and/or perthite, and several diorite fragments consisting of andesine, quartz and hornblende.

Sedimentary fragments constitute from <1% to 14.0% of clasts in all thin sections and consist of lithic sandstone, siltstone and mudstone with varying degrees of sericite, chlorite and epidote alteration. Oncolites (Fig. 59) were observed in drill core WC#13, 7.9 m stratigraphically below the Copper Harbor contact with the Nonesuch Formation.

Figure 58. Photomicrograph of granophyric rock fragment from Copper Harbor in core WC#18, 0.9 m (3 ft) stratigraphically below the Nonesuch Formation contact (X-Nicols, field = 1.3 mm wide).

Figure 59. Photomicrograph of an Oncolite in Copper Harbor core WC#3, 7.9 m (26 ft) stratigraphically below the Nonesuch Formation contact, (PPL, field = 1.3 mm wide).

Concentric layers of calcium carbonate around the nucleus are highlighted by thin films of iron oxide between each successive layer.

Cement: Calcite is the most abundant cement. In order of abundance after calcite are zeolite, quartz and iron oxide. Zeolite cement (laumontite) occurs in 10 samples. The presence of laumontite was confirmed by optical properties and by x-ray analysis (courtesy of Amoco Production Company, Houston, Texas) of drill core WC#2. Hite (1968), Noble (1965) and Taylor (1989) also confirmed the presence of laumontite as a cement in the Copper Harbor Formation. Quartz cement occurs as optically continuous overgrowths on quartz grains (Fig. 60).

Matrix: Matrix materials consist, in order of abundance, of chlorite and epidote, micaceous clay, silt-sized grains of quartz and feldspar (the majority identified as potassium feldspar), and hematitic clay. Chlorite and epidote are common alteration products of the original mud and silt matrix and although they generally appear to be acting as cementing agents, they are treated as matrix in this study.

Figure 60. Photomicrograph showing secondary enlargement of quartz grains in Nonesuch core WC#2, 9.1 m (30 ft) stratigraphically above the Nonesuch contact (X-Nicols, field = 5.1 mm wide).

Nonesuch Formation

Framework grains: The average composition of the major framework clasts in the sandy and sandy-silt facies of the Nonesuch in cores (recalculated to 100%) is: 36.6% volcanic rock fragments; 11.7% metamorphic, plutonic and sedimentary rock fragments; 24.9% unit quartz grains; and 26.8% feldspar grains. As in the Copper Harbor, mafic volcanic rock fragments dominate in the outcrops examined, and felsic volcanic fragments dominate in the cores.

Metamorphic and plutonic rock fragments occur in all samples; in order of abundance they are iron-formation,

chert, schist, granophyre, quartzite and granite. The average percentage of metamorphics is lower (3.3%) than the amount in Copper Harbor cores.

Samples with the greatest amount of unstrained quartz grains occur in those cores with the largest percentage of felsic volcanic rock fragments (WC#25, DO#6 and DO#14), suggesting derivation from felsic volcanics.

There is approximately a 100% increase in plagioclase in Nonesuch cores and outcrops over Copper Harbor cores and outcrops.

Cement: The Nonesuch is well indurated but contains considerably less cement than the Copper Harbor cores and outcrops. Cementing agents in cores consist of, in order of abundance, calcite, quartz and laumontite.

Matrix: Matrix materials in Nonesuch cores consist, in order of abundance, of chlorite and epidote, sericitic clay, and silt-sized feldspar and quartz.

Opaque minerals occur as thin, <1 mm thick lag deposits, in trough cross-beds, and in ripple cross-laminated sandy-siltstones and fine-grained sandstones. Stratiform subhedral pyrite was observed in siltstone in core WC#18 approximately 27.4 m stratigraphically above the Copper Harbor-Nonesuch contact. X-ray analysis also indicates the presence of pyrite (1% to 5%) in mudstone and shale samples from core WC#2.

In several drill cores, (WC#9, WC#13, WC#25 and DO#6),

traces of crude oil were observed in hand samples and in thin section. In hand samples (Fig. 61), the oil is concentrated along calcite-filled cross-cutting fractures in dark-gray, sandy siltstones and mudstones. In thin section the oil appears as small <0.25 mm blotches in fine-grained sandstone and sandy siltstone (Fig. 62). All traces of crude oil in the cores were located from 25.2 m to 74.2 m stratigraphically above the Copper Harbor-Nonesuch contact. Further studies on the origin of organic material and the development of hydrocarbons in the Nonesuch Formation can be found in Nishio (1919), Fritts (1931), Eglinton and others (1964), Meinschein and others (1964), Barghoorn and others

Figure 61. Photograph of crude oil in siltstone along a calcite-filled fracture in Nonesuch Fm. in core WC#13, 50 m (165 ft) stratigraphically above the lower Nonesuch Formation contact.

Figure 62. Photomicrograph of crude oil in siltstone in Nonesuch Fm. in core WC#13, 50 m (165 ft) stratigraphically above the Nonesuch Formation contact (PPL, field = 5.1 mm wide).

(1965), Ensign and others (1968), Moore and others (1969), Hoering (1976), and Elmore and others (1988).

Lower Freda Formation

Framework grains: The average composition of the major detrital constituents of the sandstone facies in the lower Freda Formation (recalculated to 100%) is: 34.6% volcanic rock fragments; 12.0% sedimentary, metamorphic and plutonic fragments; 25.5% unit quartz grains; and 27.8% feldspar grains. Intermediate volcanics predominate in the cores examined, whereas Hite (1968) found that felsic volcanics dominate as clasts in outcrops.

An inverse relationship between the percentage of volcanic fragments and unit quartz grains is especially evident in outcrops; volcanic fragments have decreased by 13.8% relative to Nonesuch outcrops, whereas strained and unstrained quartz grains increased by 9.7% (Hite, 1968).

Metamorphic and plutonic fragments increase by approximately 2.5% from Nonesuch to Freda cores. In both cores and outcrops (Hite, 1968), there is a general increase in metamorphic and plutonic fragments upsection in the Freda.

Several sedimentary reworked (multicycle) grains with at least one abraded quartz overgrowth occur in the Freda Formation, 82 m (268 ft) stratigraphically above the Nonesuch Formation contact in core WC#2. Unstrained quartz is the largest detrital constituent in Freda outcrops and surpasses volcanic fragments as the most abundant clast type. In outcrops, unit quartz grains increased by 14.5% from the Nonesuch to the lower Freda (Hite, 1968). A 9.2% increase in total quartz from the base to the top of the Freda in drill core WC#2, is consistent with the increase shown by Hite's (1968) outcrop data.

Cement: Cementing agents in drill cores consist, in order of abundance, of calcite, iron oxide, quartz, and laumontite. Sparry calcite and laumontite generally occupy the interstices in the fine- to coarse-grained sandstones in cores and outcrops; rock fragments and grains commonly

appear to be floating in cement. Calcite commonly encloses the pebbles and cobbles in the intraformational conglomerate beds near the base of the lower Freda in outcrops at Parker Creek and the Potato River. Hite (1968) and Noble (1965) noted the presence of calcite, quartz, laumontite, and hematite, in order of decreasing abundance, as cementing agents in outcrops.

Matrix: Matrix constituents in cores consist, in order of decreasing abundance, of hematitic clay, sericitic clay, silt-sized quartz and feldspar, and chlorite and epidote.

Classification

The sandstones from drill cores and outcrops indicate an increase in mineralogical maturity from the upper Copper Harbor through the Nonesuch to the lower Freda. The same observation of Oronto Group sandstones was made by Tyler and others (1940), Noble (1965), (Hite (1968), Wolff and Huber (1973) and Hubbard (1972 and 1975c). The progressive unroofing of quartz-bearing lower Proterozoic and Archean crystalline rocks on the flanks of the rift was probably the major factor for the upsection increase in mineralogical maturity, in addition to an increase in transport distances and reworking of lithic fragments. Figures 63 and 64 compare the Oronto Group as classified by others to the Oronto Group rocks in the Bear Creek drill cores.

Figure 63. Compositions of Oronto Group rocks in Bear Creek drill cores (this study); arenite classification after Dott 1964).

Figure 64. Comparative compositions of Oronto Group rocks from outcrops (from Daniels 1982).

Upper Copper Harbor Formation

The overwhelming majority of the sandstone samples in drill cores and outcrops are lithic arenites, after Dott (1964). Only 2 out of 18 samples from drill cores DO#6 and DO#10 and 1 from outcrop (BR#6, Black River Harbor), contain >10% matrix and are classified as lithic graywackes. Hite (1968) indicated that 26 out of 30 Copper Harbor sandstone samples contain less than 10% matrix and are classified as arenites. Only those samples from the Presque Isle River, Michigan, approach the composition of feldspathic or quartz wackes (Hite, 1968).

Nonesuch Formation

As in the Copper Harbor Formation, the majority of Nonesuch sandstone samples (15 of 21) are classified as lithic arenites and 6 samples are lithic graywackes (>10% matrix) after Dott (1964). The average Q-F-L index (maturity index) for the Nonesuch cores is 32-11-57 compared with 23-5-73 for the Copper Harbor cores. Thus the Nonesuch drill core samples are compositionally immature, but more mature than the Copper Harbor core samples.

Hite (1968) determined that 28 outcrop samples are lithic arenites (volcanic arenites) and 5 are lithic wackes (volcanic wackes) according to Gilbert's (1954) classification. Daniels (1982) also showed that the overall average composition of Nonesuch outcrop samples from several localities is lithic arenite.

Lower Freda Formation

Five sandstone samples from drill cores are lithic arenites and one is a lithic wacke. Hite (1968) classified 35 outcrop samples as lithic arenites and 9 as lithic wackes.

Hite (1968) noted a very slight increase in roundness of framework grains in Freda sandstones, compared to those in the Nonesuch. No significant variation in texture was observed in the sandstones and siltstones from the Nonesuch to the lower Freda in cores (this study), though no quantitative measurements were made.

Diagenesis

Outcrops

The effects of diagenesis in Oronto Group outcrops of Wisconsin and in outcrops and drill cores from the Upper Peninsula of Michigan have been studied by numerous workers. Only recent work will be cited in this study. Additional information on diagenesis in the Oronto Group can be found in White and Wright (1954), Hite (1968), Jost (1968), Vogel and others (1976), Autra (1977), Daniels (1982), and Taylor (1989).

A brief synopsis of previous work indicates that the Oronto Group sedimentary rocks are generally well indurated with very little pore space. The highest metamorphic grade is lower greenschist facies, and the grade decreases to

zeolite facies upsection (Hubbard, 1975a).

Many of the original constituents and textures of grains and clasts are well preserved. Hubbard, (1975c) concluded that the majority of the chlorite-and epidote-rich volcanic rock fragments in the Copper Harbor, Nonesuch and Freda formations were altered prior to deposition in the Oronto Group. Several of the secondary minerals that occur within framework grains (smectite, epidote, chlorite, laumontite) also occur in alteration assemblages in the Keweenaw North Shore Volcanic Group, and were used to determine the alteration conditions during burial metamorphism (Jirsa, 1980; Merk and Jirsa, 1982; Schmidt and Green, 1989).

The bulk of the cement in the Copper Harbor, Nonesuch and Freda Formations is sparry calcite, followed by quartz, laumontite, feldspar, hematite, and clays. Calcite is observed in virtually every outcrop sample of Copper Harbor and Freda. X-ray spectra indicate that the calcite is of the iron-poor variety (Taylor, 1989). The source of the calcite remains enigmatic. The iron oxide (largely hematite) in the Copper Harbor and Freda Formations is diagenetic in origin and is possibly the result of alteration of basic volcanic clasts and iron-bearing minerals (Elmore 1981; Noble 1965; Taylor 1989;).

Taylor (1989) indicated that the diagenetic history is strongly influenced by the rock composition. Rocks with

high proportions of opaques and mafic volcanic rock fragments contain large amounts of epidote and chlorite cement. Chlorite was precipitated early in diagenesis, followed by feldspar, quartz and calcite (Taylor, 1989). Feldspar cement was probably derived from altered and dissolved volcanic fragments (Elmore, 1981; Taylor, 1989).

Bear Creek drill cores:

The effects of diagenesis in cores were observed with a petrographic microscope and by X-ray analysis of clay samples at approximately 60 m (100 ft) intervals in core WC#2 (Table 2).

The sedimentary rocks of the Oronto Group cores are generally well cemented and well compacted, and are commonly composed of the same diagenetic constituents found in outcrops. This suggests similar diagenetic histories. Diagenetic minerals noted in this study include laumontite, calcite, gypsum, anhydrite, chalcedony, quartz, chlorite, epidote, sericite, kaolinite, illite, smectite, prehnite, hematite, dolomite, siderite, pyrite, barite, malachite and azurite.

Authigenic cements in cores consist, in order of abundance, of calcite, laumontite, quartz and iron oxide. Iron oxide (hematite) is present as a coating on grains and fragments where sufficient color contrast exists to allow for its recognition at grain contacts. The post-iron oxide

X-RAY MINERAL PERCENTAGES

[illegible]

F = Freda Formation / N = Nonesuch Formation / C = Copper Harbor Formation

Table 2. X-ray analysis of Oronto Group Mudstones from Bear Creek drill core WC#2 (analysis courtesy of Amoco Production Company, Houston, Texas)

paragenesis of cements is as follows: quartz is replaced by laumontite, and the two of these are replaced by calcite (Fig. 65).

Figure 65. Photomicrograph showing paragenesis of cementing agents (quartz (Q), replaced by zeolite (Z), and zeolite replaced by calcite (C)), in Nonesuch core DO#14, 44 m (145 ft) stratigraphically above the lower Nonesuch Formation contact (X-Nicols, field = 5.1mm wide).

X-ray analysis shows the major clay constituents in the mudstones consist of chlorite and illite, with <1% kaolinite and smectite. Boles and Franks (1979) suggested that smectite is often converted to illite early in diagenesis and later may react to form chlorite. This suggests that the same alteration sequence may have occurred during the diagenesis of Oronto Group sediments. X-ray data correlate with petrographic observations and show that the majority of the chlorite in the Bear Creek drill cores is in the Nonesuch Formation.

Porosity values for the Oronto Group in drill cores (calculated from Table 1) range from <1.0% to 12.0% for the Copper Harbor, and are <1% for both the Nonesuch and the Freda. Average total pore space for the 45 drill core thin-sections is 0.9%.

COMPOSITIONAL VARIATION AND PROVENANCE

Lateral and vertical variations in compositions of sandstones in outcrops

Upper Copper Harbor Formation: Daniels (1982)

indicated that there are no readily discernible vertical or lateral trends in the conglomerate and sandstone facies of the Copper Harbor Formation. Hite (1968) showed that there is a gradual increase in volcanic detritus from the Presque Isle River westward to Parker Creek, and eastward across the Keweenaw Peninsula. The volcanic contribution is greatest in the Parker Creek and Potato River sections, with mafic volcanics dominating. Lateral changes in composition do occur, but are largely a function of grain size rather than a change in source area (Hite, 1968). The upper Copper Harbor Formation shows an upsection reduction in volcanic rock fragments and an increase in plutonic and metasedimentary rock fragments and quartz. Hite (1968) indicated that where volcanic detritus is most abundant, there is a decrease in the amount of unstrained quartz and feldspar. He attributes this inverse relationship to the release of individual quartz and feldspar grains by break down of the volcanics. This relationship also exists in the drill cores.

Nonesuch Formation: The lateral variation in the Nonesuch sandstones is similar to the Copper Harbor sandstones. The contribution from volcanic rock fragments increases eastward and westward from the Presque Isle River. Felsic volcanics predominate in the Parker Creek and Potato River sections, but are scarce at the Bad River where mafic fragments dominate (Hite, 1968).

The vertical variation in composition in Nonesuch outcrops shows a general decrease in volcanic rock fragments upsection. Furthermore, felsic volcanic fragments increase upward as basalt decreases. Metasedimentary and plutonic rock fragments, quartz, chert, schist and iron-formation increase upsection, but are absent at the Bad River where basaltic rock fragments predominate.

As in the Copper Harbor outcrops, the abundance of volcanic rock fragments in the Nonesuch is inversely related to the amount of quartz (especially unstrained quartz).

Lower Freda Formation: Laterally, there is a general decrease in volcanic rock fragments southwest from Parker Creek to the Potato River. The Bad River is the exception, with 98% basaltic rock fragments as framework grains (Hite, 1968). Metasedimentary and plutonic rock fragments, chert, slate, schist, iron-formation and unit quartz increase, from the Presque Isle River west to the Bad River, but are absent in the Bad River section (Hite, 1968).

The lower Freda Formation shows an overall upsection decrease in volcanic rock fragments and an increase in metasedimentary and plutonic clasts, quartz, iron-formation and chert.

Lateral and vertical variations in compositions of sandstones in drill cores

Upper Copper Harbor Formation: The lateral variation in composition of sandstones in the Copper Harbor (Fig. 3, Table 3), shows a decrease in mafic volcanic rock fragments and an increase in felsic volcanics westward from WC#3 to DO#6. The cores in the eastern part of the basin (WC#24, WC#2 and WC#3) contain the largest percentages of mafic volcanics and are closest to the predominantly mafic volcanic Bad River exposure of Copper Harbor Formation described by Hite (1968). Intermediate volcanics show no apparent lateral change in comparison to mafic and felsic volcanics, except in cores WC#13 and WC#18 where there is a marked decline in felsic volcanic fragments, accompanied by a marked increase in intermediate volcanic fragments. The cores in the north and northwest areas (WC#25, DO#6 & DO#10) show a predominance of felsic volcanic fragments.

There is very little east-west variation in metamorphic, plutonic and sedimentary rock fragments. However, the south-to-north trend shows a decrease in

Clast Type	Drill Core Number									
	DO#10	DO#6	WC#25	WC#18	WC#13	WC#22	WC#9	WC#2	WC#3	WC#24
Unstrained Qtz.	T	5.5	8.2	3.7	6.4	3.0	T	T	T	-
Strained Qtz.	10.1	5.5	25.4	28.3	11.5	9.5	31.2	9.5	7.3	3.3
Polycrystal. Qtz.	2.4	2.6	1.7	3.1	2.7	2.0	3.2	10.0	2.0	2.8
Plagioclase	-	-	10.8	7.7	6.1	2.5	3.1	2.9	4.2	1.7
K-Feldspar	-	-	T	T	T	T	T	T	T	-
Mafic Vol. Rock Fragments	T	11.3	2.3	7.7	11.6	12.0	16.3	15.0	28.3	18.8
Intermediate Vol. Rock Fragments	25.3	16.9	8.2	25.7	30.5	8.4	9.4	26.4	21.4	27.0
Felsic Vol. Rock Fragments	57.0	53.1	35.0	11.0	11.3	42.0	28.5	26.1	15.5	37.6
Plutonic Rock Fragments	T	-	1.6	1.5	2.2	12.5	T	T	T	1.3
Sedimentary Rock Fragments	3.5	4.4	3.5	7.2	12.0	2.0	4.9	5.0	15.4	5.9
Metamorphic Rock Fragments	T	T	2.5	3.5	5.0	5.2	2.3	2.9	4.0	1.6

T = Trace (less than 1%)

(Note: All percentages are recalculated to 100% from total constituents in Table 1.)

Table 3. Lateral variations in compositions of major detrital constituents in the upper Copper Harbor Formation sandstones in Bear Creek drill cores. Cores are arranged from NW (left side) to SE (right side) (see Figure 3 for drill hole locations).

metamorphic and plutonic fragments from WC#22 to WC#25.

Sedimentary rock fragments also show a slight decrease to the north and northwest from WC#3 to DO#10.

Strained quartz shows a general decrease from south to north except in WC#25. Unstrained quartz increases to the west and northwest from WC#3 to WC#25 and is accompanied by a substantial increase in felsic volcanic fragments in the same direction.

Plagioclase grains increase dramatically westward from WC#24 to WC#18; the largest increase in plagioclase is northwestward from WC#24-WC#22 to WC#25.

Nonesuch Formation: Nonesuch sandstones in cores generally show the same trends in composition as the Copper Harbor cores (Table 4). Mafic and intermediate volcanic rock fragments are most abundant in the cores along the southern part of the study area and decrease northward (Fig. 3). Felsic volcanics increase to the north and northwest.

Metasedimentary and plutonic rock fragments decrease to the north-northwest in WC#25, DO#6 and DO#10. Unstrained 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. Along the southern boundary of the core area, the highest percentages of strained quartz are in the cores that contain the highest percentage of plutonic rock

Clast Type	Drill Core Number									
	DO#10	DO#6	DO#14	WC#25	WC#18	WC#13	WC#22	WC#9	WC#2	WC#3
Unstrained Qtz.	T	2.0	8.2	18.0	5.3	2.8	2.1	T	2.0	T
Strained Qtz.	40.0	25.5	23.2	23.1	13.1	30.9	36.2	22.0	18.1	22.2
Polycrystal. Qtz.	2.2	-	1.6	1.8	2.2	3.2	4.7	11.6	8.2	3.6
Plagioclase	4.5	2.0	4.4	2.4	10.0	15.7	5.3	5.1	10.6	20.7
K-Feldspar	T	-	1.7	T	T	4.1	3.1	T	5.0	4.0
Mafic Vol. Rock Fragments	T	7.6	9.6	T	T	2.9	8.9	15.4	18.1	9.1
Intermediate Vol. Rock Fragments	13.1	4.3	11.1	T	24.5	21.7	13.5	10.3	15.0	22.6
Felsic Vol. Rock Fragments	34.1	52.8	29.6	50.4	16.1	9.3	15.2	15.4	10.7	2.3
Plutonic Rock Fragments	2.2	T	T	3.0	T	1.6	2.2	T	7.1	4.0
Sedimentary Rock Fragments	2.2	4.5	5.5	T	11.5	5.2	6.8	14.0	2.9	8.5
Metamorphic Rock Fragments	T	T	3.0	T	2.6	2.6	2.0	5.0	2.3	2.5

T = Trace (less than 1%)

(Note: All percentages are recalculated to 100% from total constituents in Table 1.)

Table 4. Lateral variations in compositions of Nonesuch Formation sandstones in Bear Creek drill cores. Cores are arranged from NW (left side) to SE (right side), (see Figure 3 for drill hole locations).

fragments (WC#3, WC#2 and WC#22, WC#13).

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 two cores that contain the highest percentage of intermediate volcanic rock fragments, suggesting derivation from the intermediate volcanics. Potassium feldspar content shows a decrease from south to north-northwest. The lateral variations in compositions of Nonesuch sandstones is illustrated in Figure 66 with mineralogical information from representative cores within the Nonesuch drill core basin.

Lower Freda Formation: The lateral variations in Freda compositions (Table 5), are similar to those that occur in the Nonesuch and Copper Harbor Formations. Mafic and intermediate volcanic rock fragments predominate in cores to the south and east, and felsic volcanics show a marked increase to the northwest (Fig. 3). Metamorphic, plutonic and sedimentary rock fragments are most abundant in the south and decrease to the west and northwest. Unstrained, strained polycrystalline and recrystallized quartz, plagioclase, and potassium feldspar all decrease to the west and north.

Summary:

An overall comparison of the lateral and vertical

Figure 66. Lateral variations in compositions of Nonesuch Formation sandstones from representative Bear Creek drill cores.

Clast Type	Drill Hole Number			
	DO#6	WC#9	WC#22	WC#3
Unstrained Qtz.	T	T	T	5.0
Strained Qtz.	22.8	9.7	27.0	34.4
Polycrystal. Qtz.	T	3.0	4.3	T
Plagioclase	T	7.7	20.4	17.0
K-Feldspar	T	T	2.1	T
Mafic Vol. Rock Fragments	-	25.2	8.4	6.3
Intermediate Vol. Rock Fragments	13.2	20.0	25.6	23.4
Felsic Vol. Rock Fragments	62.0	20.0	5.8	T
Plutonic Rock Fragments	-	-	3.4	4.0
Sedimentary Rock Fragments	T	8.7	T	29.7
Metamorphic Rock Fragments	T	4.5	1.7	2.1

T = Trace (less than 1%)

(Note: All percentages are recalculated to 100% from total constituents in Table 1.)

Table 5. Lateral variations in compositions of lower Freda Formation sandstones in Bear Creek drill cores. Cores are arranged NW (left side) to SE (right side), (see Figure 3 for drill hole locations).

variations in composition in the Oronto Group in Bear Creek cores (Table 6) shows a general northward trend (WC# 3 to WC#25) (Fig.3) 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 and, an upsection increase in compositional maturity from a lithic (volcanic) arenite to a quartzo-feldspathic arenite. The same trend is observed in outcrops.

Quartz, feldspars and pre-Keweenawan metasedimentary and plutonic rock fragments increase upsection and volcanic rock fragments decrease. An exception to this is the vertical change in drill core WC#9, which shows a 23% decrease in quartz and a 24% increase in volcanic rock fragments, from the Nonesuch to the lower Freda (percentages are based on the vertical change in framework constituents from the Copper Harbor to the Nonesuch to the Freda).

Provenance

Hite (1968), Hubbard (1972 and 1975), and Daniels (1982) concluded that the most likely provenance for Oronto Group sediments would be Keweenawan igneous rocks within the Midcontinent Rift System. Heavy mineral suites showed a relative increase in contributions from older Proterozoic rocks (i.e, extrabasinal rocks) at stratigraphically higher intervals in the Oronto Group, as underlying metamorphic and

Drill Core #	Formation	Quartz	Feldspar	Volcanic R.F.	Other R.F.	Q-F-L
WC#2	FF	27	21	37	15	27-21-52
WC#2	NF	24	19	42	15	24-19-57
WC#2	CHF	18	3	64	15	18- 3-79
WC#3	FF	30	13	23	34	30-13-57
WC#3	NF	26	23	30	21	26-23-51
WC#3	CHF	12	5	61	22	12- 5-83
WC#9	FF	17	8	60	15	17- 8-75
WC#9	NF	40	9	36	15	40- 9-51
WC#9	CHF	36	5	49	12	36- 5-61
WC#13	NF	39	18	31	12	39-18-43
WC#13	CHF	26	5	40	29	26- 5-69
WC#18	NF	36	10	35	19	38-10-54
WC#18	CHF	36	8	38	18	36- 8-56
WC#22	NF	38	10	34	18	38-10-52
WC#22	CHF	15	2	55	28	15- 2-83
WC#24	CHF	8	1	78	13	8- 1-91
WC#25	NF	47	4	45	4	47- 4-49
WC#25	CHF	36	12	41	11	36-12-52
DO#6	FF	25	1	44	30	25- 1-74
DO#6	NF	30	2	59	9	30- 2-68
DO#6	CHF	17	-	76	7	17- 0-83
DO#10	NF	39	7	44	10	39- 7-54
DO#10	CHF	15	-	79	6	15- 0-85
DO#14	NF	34	8	46	12	34- 8-58
FF = Freda Formation / NF = Nonesuch Formation / CHF = Copper Harbor Formation (numbers expressed as % of total grains and fragments)						

Table 6. A comparison of lateral and vertical variations in compositions of Oronto Group sandstones in Bear Creek drill cores.

plutonic rocks were progressively unroofed (Tyler and others, 1940).

Hubbard (1972) suggested that lower Keweenawan and older rocks provided much, if not all, of the detritus for the middle and upper 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 were being eroded during middle and late Keweenawan time. During this 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 which are indicative of sedimentary and igneous rocks that occur in the lower Keweenawan Powder Mill Group, the oldest of the Keweenawan volcanic units.

Samples collected from the Presque Isle River, Parker Creek, Potato River Falls and Bad River during this study contain fragments of granophyre and granite, which indicate that the Keweenawan age Mellen Intrusive Complex and related intrusives to the southwest of the outcrop locations were being unroofed during this 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 during sedimentation of the Oronto Group.

The detritus in the conglomerate and sandstone facies in drill cores suggests derivation from similar, if not the same, lower Keweenawan igneous and sedimentary, and pre-Keweenawan metamorphic and plutonic rocks that crop out in Wisconsin and Upper Michigan. The mafic, intermediate, and felsic volcanic rock fragments bear a strong resemblance to basalt, andesite, rhyolite and quartz latite flows described by Hubbard (1975c). The groundmass in the majority of the mafic and intermediate fragments has been extensively altered by epidote and chlorite, and feldspar phenocrysts are sericitized; these fragments are probably from the lower Keweenawan Siemens Creek Formation.

The felsic volcanic fragments exhibit distinctive snowflake and platy quartz textures that are commonly observed in the quartz latites and rhyolites of the lower Keweenawan Kallander Creek Formation (Hubbard 1975c, and the North Shore Volcanic Group (personal communication, John C. Green). 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 part of the drill core study area suggest the presence of a mafic volcanic

source to the south or southeast. This is the study area nearest the Bad River exposure where Hite (1968) recorded an increase in the percentage of mafic volcanic clasts in the upper Copper Harbor, Nonesuch and lower Freda Formations. The general increase in unit strained and unstrained 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 below, and in lower contact with, the Nonesuch Formation in core WC#25.

Granophyre, granite, iron-formation, jasper, chert, slate, schist and quartzite rock fragments and quartz and feldspar, are most abundant in all three Oronto Group formations along the southern boundary of the drill core study area, in cores WC#3, WC#2, WC#22 and WC#13. This suggests that the Mellen Intrusive Complex, lower Keweenawan sedimentary, and early Proterozoic Animikie Group and Archean rocks, all located to the south and east of the drill core study area in northwest Wisconsin, were also source terranes for drill core detritus. This is in general agreement with White and Wright (1960), Hamblin and Horner (1961), Hite (1968), Hubbard (1972), and Daniels (1982), that the primary source terrane for the upper Keweenawan sedimentary rocks in Wisconsin and Upper Michigan was an elevated highland along the margins of the Midcontinent Rift

System, generally to the south of Oronto Group exposures in northwest Wisconsin and Upper Michigan.

SEDIMENTOLOGICAL MODEL

Source and basin analysis

Analysis of paleocurrent structures in the Oronto Group from the Big Iron and Presque Isle Rivers obtained during this study, and from the work of previous investigators (White and Wright, 1960; Hamblin and Horner, 1961; Hite, 1968; and Daniels, 1982), confirms that the transportation of detritus was generally towards the north, northeast and northwest. However, paleocurrent structures show a vertical 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. Figure 67 illustrates the location of the Bear Creek drill holes with respect to the proposed Nonesuch drill core basin and source areas.

Hite (1968) also noted that in the lower Freda Formation at the Bad River exposure, paleocurrent directions were to the southwest. Northeast of the Bad River, at the Potato and Montreal Rivers, the paleocurrents in the lower Freda Formation were toward the south and northeast, respectively (Hite, 1968). This suggests that an elevated highland existed between the Potato River and the Bad River that diverted currents to the west and east.

The paleogeography of the Bad River area does not, however, account for the paleocurrent reversals at the Big

Figure 67. Generalized map of the drill core study area showing the Nonesuch depositional basin and source areas. (Proposed accommodation zone from Mudrey and Dickas, 1988).

Iron and Presque Isle Rivers. Such reversals are not uncommon and are known to occur in the fine-grained red sandstones, siltstones and mudstones of the upper Copper Harbor Formation. Local reversals in paleocurrent direction, according to Daniels (1982), may 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 in cores WC#24, WC#2 and WC#3, which are the Bear Creek drill holes closest to the Bad River exposure (21 km or 13 mi to the southeast). At least two possibilities, according to Hite (1968), explain the situation: 1) an unusual thickness of basaltic lavas in this area resulted in a long-lasting volcanic source; or 2) elevation of the lava sequence as a result of forceful intrusion of the Mellen Intrusive Complex. Either possibility places an elevated highland in the area around, and to the east, of drill hole WC#24, a highland that may have acted as an eastern barrier or restriction for sediment transport in the drill core basin. Note that the presence of this highland 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 overburden. The absence of Nonesuch and Freda sedimentary rocks in this core, could be the result of faulting. However, the close proximity of WC#24 to the proposed elevated basaltic highland of Hite (1968), suggests that these conglomerates were located on the upper slopes of a highland that was topographically high enough to be isolated from Nonesuch and Freda sedimentation.

The Nonesuch Formation thins westward from the Big Iron River to the Bad River, and becomes thicker again westward from drill hole WC#24 along the southern part of the Nonesuch drill core basin in cores WC#2, WC#3, WC#9, WC#22, WC#13 and WC#18 (Fig. 8). These data also suggest 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 or is within one meter of, 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 at the Parker Creek and Potato River Falls sections. Elmore and others (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 fan facies transition.

The facies changes at the Copper Harbor-Nonesuch contacts become less abrupt texturally, 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 (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 varve-like 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 less than one meter thick in the northernmost cores WC#25 and DO#6. This suggests that the sediments in intervals 4 and 5 were deposited in a northward (basinward) prograding alluvial fan 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. Nonesuch drill core 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 (Fig. 67). Pettijohn (1957, p.630) and Daniels (1982) indicated that the Nonesuch environment was probably initiated by tectonic disruption, and/or damming by lava flows and/or prograding alluvial fan lobes of the existing drainages. The petrography of the above drill cores supports this suggestion.

The only occurrence of an evaporite bed, 2.75 m of pinkish-gray, massive crystalline calcite with anhydrite nodules $\leq$ 2cm 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. 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.

Environment of Deposition

Investigations conducted on the Oronto Group during the last several decades have concluded that the Nonesuch Formation was deposited in a standing body of water. One of the most persistent questions asked regarding the nature of this body of water is whether it was marine or lacustrine. Recent investigations (Daniels 1982; Elmore and others 1988; and 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 the Midcontinent Rift System.

In addition to being recognized from their association with continental facies, particularly fluvial deposits, ancient lake deposits are directly identified with the help of faunal, chemical and physical criteria (Feth 1964; Picard and High 1973). The lack of paleontologic evidence eliminates the use of fauna. Sulfur isotope $\delta^{34}\text{S}$ studies by Burnie and others (1972) on Nonesuch sediments indicated that a clear distinction between sea water and saline lake water could not be confirmed because of the uncertainties of the content of sulfate in Precambrian fresh and marine waters. They concluded with uncertainty that the Nonesuch Formation was most likely deposited in a lake, or an estuary that was periodically cut off from seawater. Recent oxygen

isotope studies aimed at resolving the marine versus lacustrine problem are being conducted on Nonesuch Formation sedimentary rocks from the same Bear Creek drill cores from northwestern Wisconsin; this research is in progress at the University of Indiana, and will not be published in time for this study (personal communication, Richard W. Ojakangas).

The sedimentational intervals observed in the Nonesuch drill cores (Figs. 46-54) 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 upper Copper Harbor and Freda Formations. Picard and High (1973) indicated that ancient lake sediments can best be recognized from their association with other demonstrably continental facies. The Copper Harbor and Freda Formations are gradational with and completely enclose the Nonesuch Formation (Thwaites, 1912; Hite, 1968; White, 1971; Wolff and Huber, 1973; 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).

Interpretation of Nonesuch Formation sedimentational intervals

Introduction: The basic outline for a two-dimensional genetic sedimentary model that would satisfy the sedimentary facies relationships observed in the Nonesuch sedimentational intervals in the Bear Creek drill cores was modeled in part after the GLIMPCE (Great Lakes International Multidisciplinary Program on Crustal Evolution) seismic profile across seismic line C in the western Lake Superior region (Cannon and others, 1989) (Fig. 68).

The drill core study area is depicted as a local basin within the Midcontinent Rift System that is bounded on the north by the Douglas Fault and on the south by the Lake Owen Fault (Fig. 69). The five sedimentational intervals observed in drill cores were stratigraphically superimposed (not to scale), into 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 69 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 consist of: 1) mid-fan facies consisting of poorly sorted and

Figure 68. Interpreted reflection profile along seismic line C showing the subsurface beneath western Lake Superior. Inferred subsurface units are projected updip to their exposed extensions on land in northern Michigan and Wisconsin (from Cannon and others, 1989).

Figure 69. Diagrammatic illustration showing cross-section of Copper Harbor Formation as an alluvial fan complex in the drill core basin. CHF-Copper Harbor Formation; PLV-Portage Lake Volcanics; PMV-Powder Mill Volcanics; PEx-lower Proterozoic and Archean crystalline rocks.

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 (mudflat 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) 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 (sandflat to mudflat), contain abundant asymmetrical and symmetrical ripple marks and mud cracks, indicating active stream and beach processes and periodic 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 intergradational 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 Nonesuch time. 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. Abrupt facies changes from red conglomerate to gray siltstone and mudstone, as previously described in outcrop and drill core, seems to be more common than gradual facies transitions. This is suggestive of a 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).

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. The interval gradually fines upward to dark-gray medium-to fine-grained sandstones, siltstones and mudstones.

Figure 70 illustrates interval 1 as a fining-upward,

Figure 70. Diagrammatic illustration showing stratigraphic position and facies relationships for Nonesuch Formation sedimentational interval 2. NF-Nonesuch Formation; CHF-Copper Harbor Formation; PLV-Portage Lake Volcanics; PMV-Powder Mill Volcanics; PEx-lower Proterozoic and Archean crystalline rocks.

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, sandflat-mudflat facies. The sedimentary textures and structures are commonly similar across the Copper Harbor-Nonesuch contact zone in both drill cores and outcrops, and suggests 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 (Fig. 16). 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.

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, and by subaqueous fan-delta streams.

Sheetflood deposits are typically found on alluvial fans in semi-arid 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 sandflat, largely due to infiltration of the water (Rahn 1967; Rachocki 1981). 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 drape which tops a fining-upward sequence was deposited by suspension settling of mud that was 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 <1m thick sandstone beds that are massive, ungraded and normally graded, conglomeratic, and coarse-to fine-grained. The occurrence of these sandstone beds suggests 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 one and decrease in abundance upsection. The occurrence of red, oxidized sediments interbedded with gray to black sediments formed in a reducing environment (Elmore and others, 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).

Aysmmetrical 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 records the continued expansion and deepening of the Nonesuch lake (Fig. 71). 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. The number of massive and normally-graded, medium-grained sandstone to sandy-siltstone beds resembling Bouma abc 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. Sheet flooding still occurred, but only the largest floods deposited sediment as fining-upward sequences, massive, and graded

Figure 71. Diagrammatic illustration showing stratigraphic position and facies relationships for Nonesuch Formation sedimentational intervals 2 and 3. NF-Nonesuch Formation; CHF-Copper Harbor Formation; PMV-Powder Mill Volcanics; PEx-lower Proterozoic and Archean crystalline rocks.

beds (not necessarily in succession) at greater distances from the shoreline.

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 (sheet flood and turbidity currents), to deposition by suspension settling of mud from the water column in deeper and quieter areas of the basin.

The carbonate laminite consist of thin (≤ 1 mm), light-gray, carbonate-rich fine-grained sandstones and siltstones and thinner < 1 mm, black-to green, organic-rich mudstone beds (Elmore and others, 1988). Thicker sandstone-siltstone laminae commonly display normal grading or trough 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 mudstone 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.

Drill core sedimentational interval 3 and 3a:

Sedimentational interval 3 consists of gray micro-trough cross-bedded fine-grained sandstone, siltstone, mudstone and carbonate laminite. The Nonesuch facies in this interval (Fig. 72) 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 and others, 1988).

The dominant lithology is carbonate laminite. Interbedded with the laminite beds are what appear to be turbidity current deposits consisting of massive and normally graded, and micro-trough cross-bedded, fine-grained sandstone and siltstone beds. Turbidity currents continued to deposit medium-to fine-grained sandstone beds well into the lake basin, but these beds are thinner and less frequent than in interval 2. These deposits appear to represent combinations of massive, graded, parallel-laminated, and convoluted and micro-trough cross-bedded, Bouma abcd beds. Turbidity currents were generated by storms or were initiated by gravity slumping along the steeper slopes of the central lake basin.

Figure 72. Diagrammatic illustration showing stratigraphic position and facies relationships for Nonesuch Formation sedimentational intervals 3 and 3a. NF-Nonesuch Formation; CHF-Copper Harbor Formation; PCx-lower Proterozoic and Archean crystalline rocks.

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 silt and mud detritus to form extensive carbonate laminite. A thermally stratified lake (Fig. 73) 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 and others (1988), suggested that the production and preservation of organics could best have been 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 epilimnion from the 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 where 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 (Hutchinson and Loffler, 1956; Beadle, 1974; Sturm and Matter, 1978). Once in the epilimnion, pelagic sediments could have been distributed over a large area of the basin, and deposited

Figure 73. Thermally stratified lake model and distribution mechanisms proposed for Nonesuch Formation in the Bear Creek drill cores (after Sturm and Matter, 1978).

over the deeper and/or 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 and seasonal lake turnover (Allen and Collinson, 1986). 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 and siltstone laminae.

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. 73). Microscopic trough cross-bedding randomly occurs in the coarser-grained carbonate-rich laminae, as in drill core WC#9 at 72 m (235 ft) above the base of the Nonesuch Formation. This indicates that low-velocity bottom currents were depositing and perhaps reworking detritus in the deepest areas of the 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 and others, 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; Donovan, 1975 and 1980; Elmore and others, 1988). In addition to biogenic carbonate, numerous well-rounded silts-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 alluvial fan sandflat and mudflat 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), and the presence of oncolites in the Copper Harbor (Fig. 59) shows that these are another possible source of carbonate.

Sedimentational interval 3a consists of massive, normally graded and small-scale trough cross-bedded, coarse- to fine-grained sandstone and siltstone with 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 (Figs. 46-54).

The facies assemblage in interval 3a (Fig. 72) 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 suggest that deposition was predominantly by turbidity and density flows. Graded beds range from 2 cm to <1 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 throughout the entire drill core 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 longer

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. 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. 74).

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-initiated 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

Figure 74. Diagrammatic illustration showing stratigraphic position and facies relationships for Nonesuch Formation sedimentational intervals 4 and 5. FR-Freda Formation; NF-Nonesuch Formation; CHF-Copper Harbor Formation; PEx-lower Proterozoic and Archean crystalline rocks.

shallow water marginal lacustrine to fluvial flood plain deposits of the lower Freda Formation (Daniels, 1982). 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. Figure 75 shows the stratigraphic correlation of each Nonesuch sedimentational interval.

Figure 75. Stratigraphic correlation of Nonesuch Formation sedimentational intervals from Bear Creek drill cores. (Note core WC#18 for interval numbers)

TECTONIC MODEL

Sedimentation of the Nonesuch Formation in the Bear Creek drill hole study area in northwestern Wisconsin appears to have occurred in an east-west trending fault bounded basin. 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.

White (1966b), on the basis of gravity surveys, interpreted the structure in the western Lake Superior region. He proposed the existence of two basins with thick accumulations of Keweenaw lavas, separated by a gravity low, under western Lake Superior (Fig. 76). The gravity low, interpreted to exist where the lavas are thin or absent, extends to the south-southwest from the Tofte, Minnesota area to northeast Bayfield County, Wisconsin, where it bends to the southeast through Ashland County, Wisconsin. The southeast projection of the gravity low places the ridge approximately where Hite (1968), and data generated during this study, place an elevated mafic volcanic highland east of drill hole WC#24 and in the vicinity of the Bad River (see Fig. 67). Figure 76 indicates that the basin located to the west-northwest of the gravity low ("Middle Keweenaw Trough"), becomes deeper

Figure 76. Gravity interpretation of the structure in the western Lake Superior district (hachures close on gravity highs) (modified from White, 1966b).

to the west-northwest of the study area. This is in general agreement with the sedimentology of the drill cores which show the Nonesuch drill core basin deepening to the west-northwest (Fig. 67).

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. 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 approximately 1000 km (625 mi) away along the west margin of the Grenville Front (Bickford and others, 1986) (Fig. 77), which presumably was accreted to North America about or shortly after the rift formed. The occurrence of a 1000 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.

Dickas (1986) and Mudrey and Dickas (1988) presented the East African Rift System as a modern day analogy to the Midcontinent Rift System in the Lake Superior region. They cite similarities in sedimentary geometries and geophysical data that suggest the presence of a series of opposed half-

Figure 77. Generalized map showing approximate location of the Grenville Front to the drill core study area in the Midcontinent Rift System (stippled area) (modified from Bickford and others, 1986).

grabens separated by accomodation zones along the Midcontinent Rift System.

The Brule Basin, one of the proposed half-grabens of Mudrey and Dickas (1988), coincides with the drill core study area. The basin sloped to the south with a major fault south of the study area and a flexure to the north (Fig. 78). An isopach map of the Nonesuch Formation in drill cores (Fig. 8) 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 (Fig. 67). 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 to the north and west of the drill holes that define the southern part of the basin (WC#2, WC#3, WC#9, WC#13, WC#18, WC#22). Thick accumulations of poorly sorted and crudely bedded Copper Harbor conglomerates derived from a primary source terrane south of the core study area, indicate that

Figure 78. Interpretation of the western Lake Superior structure along the Midcontinent Rift System (modified from Mudrey and Dickas, 1988).

deposition was rapid along what was probably a steep fault-bounded southern boundary of the Nonesuch drill core basin.

SUMMARY AND CONCLUSIONS

Summary

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 floodplain, suggests that the Nonesuch was deposited in a lacustrine environment within the rift 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 Keweenaw Powder Mill Group, or equivalent lower Keweenaw volcanic rocks, in northwestern Wisconsin. Pre-Keweenaw crystalline rocks and reworked upper Copper Harbor Formation 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 and fragments of plagioclase, potassium

feldspar, unit strained and unstrained quartz, volcanic quartz, reworked calcite and quartz grains, granophyre, granite and quartzite from lower and middle Keweenawan sedimentary and intrusive rocks, and slate, schist and iron-formation from Early Proterozoic and Archean crystalline rocks.

2) The lateral 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 K-feldspar 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) after Dott (1964).

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. Some detritus was also derived from an elevated lower to middle Keweenawan 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 consisting of fining-upward, light-to dark-gray, small-scale trough cross-bedded and parallel-bedded, coarse-to medium-grained pebbly sandstones, and minor siltstones and mudstones occurring as fining-upward sequences, massive, and normally graded beds; Interval 2) dominantly deep-water marginal lacustrine facies consisting of fining-upward, light-to dark gray, micro-trough cross-bedded and parallel-bedded, fine-grained sandstones, siltstones and mudstones occurring as fining-upward sequences, massive and normally graded beds; Interval 3) dominantly deep-water central lake basin facies consisting of dark-gray to black, alternating varve-like beds (laminite) of organic-rich mudstone and carbonate-rich siltstone; Interval 3a) dominantly deep-water central lake basin and/or deep-water marginal lacustrine facies consisting of dark-gray, small-scale trough cross-bedded and parallel-bedded coarse- to fine-grained sandstones, siltstones and minor mudstones occurring as massive and normally graded beds; Interval 4) dominantly deep-water marginal lacustrine facies consisting of coarsening-upward dark-to light-gray, micro-trough cross-bedded and parallel-bedded, fine-grained sandstones, siltstones and mudstones occurring as fining-upward sequences, massive and normally graded beds; and Interval 5) dominantly shallow-water marginal lacustrine facies consisting of coarsening-upward light-gray, small-scale trough cross-bedded and parallel-

bedded, coarse-to fine-grained pebbly sandstones, siltstones, and mudstones occurring as fining-upward sequences, massive and normally graded beds.

5) Deposition as recorded in the Nonesuch sedimentational intervals probably was from ephemeral sheetfloods and fluvial-deltaic streams, underflow turbidity currents, interflow density currents, bottom currents, and 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.

REFERENCES CITED

- Aldrich, H. R., 1929, The geology of the Gogebic Iron Range of Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 71, 279 p.
- Allen, P.A., and Collinson, J.D., 1986, Lakes, in: Reading, H.G. ed., Sedimentary Environments and Facies, 615 p.
- Alwin, B. W., 1976, Sedimentation of the Middle Precambrian Tyler Formation of northcentral Wisconsin and northwestern Michigan: M.S. thesis, University of Minnesota, Duluth, 175 p.
- Autra, K.B., 1977, Syngenetic model for the origin of copper mineralization in the Precambrian Nonesuch Shale, White Pine, Michigan [M.S. thesis]: Michigan State University, East Lansing, Michigan, 45 p.
- Bailey, E.H., and Stevens, R.E., 1960, Selective staining of K-feldspar and plagioclase on rock slabs and thin sections: Am. Mineral., v. 45, pp. 1020-1025.
- Barghoorn, E.S., Meinschein, W.G., and Schopf, J.W., 1965, Paleobiology of a Precambrian shale: Science, v. 148, p. 461-472.
- Beadle, L.C., 1974, The Inland Waters of Tropical Africa, in Longman, London, 4.2; 4.4; 4.5; pp.365.
- Bickford, M.E., Van Schmus, W.R., and Zietz, I., 1986, Proterozoic history of the midcontinent region of North America: Geology, v. 14, p. 492-496.
- Boles, J.R. and Franks, S.G., 1979. Clay diagenesis in the Wilcox Formation sandstones of southwest Texas: implications of smectite diagenesis on sandstone cementation. Journal of Sedimentary Petrology, v. 49, pp. 55-70.
- Books, K. G., 1968, Magnetization of the lowermost Keweenawan lava flows in the Lake Superior area: United States Geological Survey Professional Paper 600-D, p. D248-D254.
- Books, K.G., 1972, Paleomagnetism of some Lake Superior Keweenawan rocks: U.S. Geological Survey Professional Paper 760, 42 p.

- Bouma, A.H., 1962, Sedimentology of some flych deposits; A graphic approach to facies interpretation, pp. 168, Elsevier, Amsterdam.
- Bouma, A.H. and Brouwer, A., 1964, Turbidites, pp. 264, Elsevier, Amsterdam.
- Breemen, O.V., and Davidson, A., 1988, Northeast extension of Proterozoic terranes of mid-continental North America: Geological Society of America Bulletin, v. 100, p.630-638.
- Brown, A.C., 1971, Zoning in the White Pine copper deposit, Ontonagon County, Michigan: Economic Geology, v. 66, p. 543-573.
- Bull, W.B., 1964, Geomorphology of segmented alluvial fans in western Fresno County, California: U. S. Geologic Survey Professional Paper 352-E, p. 89-129.
- Burnie, S.W., Schwarcz, H.P. and Crocket, J.H., 1972, A sulfur isotopic study of the White Pine Mine, Michigan: Economic Geology, v. 67, p. 895-914.
- Cambray, F.W., 1979, The Precambrian basement of Michigan [abs.], in The Hydrocarbon Potential-The Michigan Basin-The Way Ahead, a symposium: Michigan Basin Geological Society, Lansing, Michigan, p. 5.
- Cannon, W.F., Green, A.G., Hutchinson, D.R., Lee, M., Milkereit, B., Behrendt, J.C., Halls, H.C., Green, J.C., Dickas, A.B., Morey, G.B., Sutcliffe, R. and Spencer, C., 1989, The North American Midcontinent Rift Beneath Lake Superior From Glimpce Seismic Reflection Profiling: Tectonics, v. 8, no. 2, pp. 305-332.
- Cannon, W. F., and Gair, J. E., 1970, A revision of stratigraphic nomenclature of middle Precambrian rocks of northern Michigan: Geological Society of America Bulletin, v. 81, p. 2843-2846.
- Chase, C. G., and Gilmer, T. H., 1973, Precambrian plate tectonics: The midcontinent gravity high: Earth and Planetary Science Letters, v. 21, p.70-78.
- Chayes, F., 1952, Notes on the staining of potassium feldspar with sodium cobaltinitrite in thin section: Am. Mineral., v. 37, pp. 337-340.
- Collinson, J.D., 1978, Vertical sequence and sand body shape in alluvial sequences. in: Fluvial Sedimentology (Ed. by A.D. Miall), Mem. Can. Soc. Petrol. Geol., v. 5, p.

577-586.

- Collinson, J.D., and Thompson, D.B., 1982, Sedimentary Structures: Allen and Unwin, London, 194 p.
- Cooper, R. W., 1973, Middle Precambrian and Keweenaw rocks north of the Gogebic Range in Wisconsin: [M.S. Thesis], University of Wisconsin, Madison, 83 p.
- Cornwall, H. R., and Wright, J. C., 1954, Bedrock geology of the Eagle Harbor quadrangle, Michigan: United States Geological Survey Geological Quadrangle Map GQ-36.
- Craddock, C., 1972, Late Precambrian regional geologic setting, in Sims, P. K., and Morey, G. B., eds., Geology of Minnesota: centennial volume: Minnesota Geological Survey, p. 281-291.
- Daniels, P. A., Jr., 1982, Upper Precambrian sedimentary rocks: Oronto Group, Michigan-Wisconsin: in Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior Basin: Geological Society of America, Memoir 156, p. 107-133.
- Daniels, P.A., and Elmore, R.D., 1980, Depositional setting of stromatolite-oolite facies on a Keweenaw alluvial fan [abs.]: 26th Annual Institute on Lake Superior Geology, Eau Claire, Wisconsin, p.27.
- Davidson, D. M., Jr., 1982, Geological evidence relating to interpretation of the Lake Superior Basin structure, in Wold, R. J., and Hinze, W. J., eds., Geology and Tectonics of the Lake Superior Basin: Geological Society of America Memoir 156.
- Denny, C.S., 1965, Alluvial fans in the Death Valley Region, California and Nevada: U.S. Geological Survey Professional Paper 466, 62 p.
- Dickas, A. B., 1986, Comparative Precambrian stratigraphy and structure along the Mid-continent rift: American Association of Petroleum Geologists Bulletin, v. 70, p. 225-238.
- Donovan, R.N., 1975, Devonian lacustrine limestones at the margin of the Orcadian Basin, Scotland. Jour. Geol. Soc. London, 131: p. 489-510.
- Donovan, R.N., 1980, Lacustrine cycles, fish ecology and stratigraphic zonation in the Middle Devonian of Caithness. Scot. Jour. Geo., 16; p. 35-50.

- Dott, R.H., 1964, Wacke, graywacke and matrix - What approach to immature sandstone classification?: Jour. Sed. Petrology, v.34, no.3, p.625-632.
- Dott, R. H., Jr., and Mattis, A. F., 1972, A post-Animikean pre-Keweenawan transgressive sand blanket over the Lake Superior region [abs.]: Geological Society of America Abstracts with programs, v. 4, p. 490.
- DuBois, P.M., 1962, Paleomagnetism and correlation of Keweenawan rocks; Geological Society of Canada Bulletin 71, 75 p.
- Dutton, C.E., and Bradley, R.E., 1970, Lithologic, geophysical and mineral commodity maps of Precambrian rocks in Wisconsin: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-631.
- Eglington, G., Scott, P.M., Belsky, T., Burlingame, A.L., and Calvin, M., 1964, Hydrocarbons of biological origin from a 1 billion year old sediment: Science, v. 145, p. 263- 264.
- Ehrlich, R., and Vogel, T. A., 1971, Depositional and diagenetic models for the lower Nonesuch Shale based on lithologic variation: Unpublished technical report, White Pine Copper Company, White Pine, Michigan, 121 p.
- Elmore, R.D. and Daniels, P.A., 1980, Depositional system model for upper Keweenawan Oronto Group sediments, northern Peninsula, Michigan [abs]: Geological Society of America Abstracts with Programs, v. 12, no.5, p.225.
- Elmore, R. D., 1981, The Copper Harbor Conglomerate and Nonesuch Shale: sedimentation in a Precambrian intracontinental rift, upper Michigan. Dissertation, University of Michigan, 200 p.
- Elmore, R.D., 1983, Precambrian non-marine stromatolites in alluvial fan deposits, Copper Harbor Conglomerate, upper Michigan. Sedimentology, 30; p. 829-842.
- Elmore, R.D., 1984, The Copper Harbor Conglomerate: a late Precambrian fining-upward alluvial fan sequence in northern Michigan. Geol. Soc. Am. Bull., 95; p. 610-617.
- Elmore, R. D., Milavec, G., Imbus, S., Engel, M. H., Daniels, P., 1988, The Precambrian Nonesuch Formation of the North American Midcontinent Rift: Sedimentology and organic geochemical aspects of lacustrine deposition: Precambrian Research, 43(3), p.191-213.

- Ensign, C. O., Jr., White, W. S., Wright, J. C., Patrick, J. L., Leone, R. J., Hathaway, D. J., Trammel, J. W., Fritts, J. J., and Wright, T. L., 1968, Copper deposits in the Nonesuch Shale, White Pine, Michigan: American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 1, p. 459-488.
- Felmlee, J. K., 1970, Geologic structure along the Huronian-Keweenaw contact near Mellen, Wisconsin: Madison, Wisconsin, University of Wisconsin, unpublished M. A. Thesis.
- Feth, J. H., 1964, Review and annotated bibliography of ancient lake deposits (Precambrian to Pleistocene) in Western States. Bull U.S. Geol. Surv., 1080, 119pp. 4.8.1.
- Fowler, J. H., and Kuenzi, W. D., 1978, Keweenaw turbidites in Michigan (deep borehole red beds): A founded basin sequence developed during evolution of a protoceanic rift system: Journal of Geophysical Research, v. 83, p. 5833-5843.
- Franklin, J. M., McIlwaine, W. H., Poulsen, K. H., and Wanless, R. K., 1980, Stratigraphy and depositional setting of the Sibley Group, Thunder Bay district, Ontario, Canada: Canadian Journal of Earth Sciences, v. 17, p. 633-651.
- Fritts, C.C., 1931, Carbonaceous matter in the Nonesuch Shale (northeastern Wisconsin) [M.S. thesis]: University of Wisconsin, Madison, Wisconsin, 20p.
- Fritts, C. C., 1969, Bedrock geologic map of the Marenisco-Watersmeet area, Gogebic and Ontonagan Counties, Michigan: United States Geological Survey Miscellaneous Geologic Investigations Map I-576, scale 1:48,000.
- Gilbert, C.M., 1954, Sedimentary rocks: in Williams, H., Turner, F.J., and Gilbert, C.M., eds., Petrography, an Introduction to the Study of Rocks in Thin Sections, 406 p.
- Goldrich, S. S., 1972, Geochronology in Minnesota: in Sims, P.K., and Morey, G. B., eds., Geology of Minnesota: A centennial volume: Minnesota Geology Survey, P. 27-37.
- Green, J. C., 1972, North Shore Volcanic Group, in Sims, P. K., and Morey, G. B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p.294-332.

- 1977, Keweenawan plateau volcanism in the Lake Superior region, in Barager, W. R. A., Coleman, L. C., and Hall, J. M., eds., Volcanic Regimes in Canada: Geological Association of Canada Special Paper 16, p.407-422.
- 1981, Pre-Tertiary plateau basalts, in Basaltic Volcanism Study Project, Basaltic Volcanism on the Terrestrial Planets: New York, Pergamon, p. 30-77.
- 1982, Geology of Keweenawan extrusive rocks, in Wold, R. J., and Hinze, W. J., eds., Geology and tectonics of the Lake Superior Basin: Geological Society of America, Memoir 156, p. 47-55.
- Halls, H. C., 1966, A review of the Keweenawan geology of the Lake Superior region, in Steinhart, J. S., and Smith, T. J., eds., The Earth Beneath the Continents: American Geophysical Union Geophysical Monograph 10. p. 3-27.
- Halls, H. C., and Pesonen, L. J., 1982, Paleomagnetism of Keweenawan rocks, in Wold, R.J., and Hinze, W. J., eds., Geology and tectonics of the Lake Superior Basin: Geological Society of America Memoir 156.
- Hamblin, W. K., 1958, Cambrian sandstones of northern Michigan: State of Michigan, Department of Conservation, Geological Survey Division, Publication 51, 146 p.
- Hamblin, W. K., 1961, Paleogeographic evolution of the Lake Superior region from late Keweenawan to Late Cambrian time: Geological Society of America Bulletin, v. 72, p. 1-18.
- Hamblin, W.K., and Horner, W.J., 1961, Sources of Keweenawan conglomerates of northern Michigan: Journal of Geology, v. 69, p.204-211.
- Henry, S.G., Mauk, F.J., and Van der Voo, R., 1977, Paleomagnetism of the upper Keweenawan sediments: The Nonesuch Shale and the Freda Sandstone: Canadian Journal of Earth Sciences, v. 14, p. 1128-1138.
- Hinze, W. J., and Wold, R. J., 1982, Lake Superior geology and tectonics -- overview and major unsolved problems: Geological Society of America, Memoir 156, p. 273-280.
- Hite, D. M., 1968, Sedimentology of the upper Keweenawan sequence of northern Wisconsin and adjacent Michigan: Ph.D. Thesis, University of Wisconsin, Madison, 217 p.

- Hoering, T.C., 1976, Molecular fossils from the Precambrian Nonesuch Shale: Carnegie Institution of Washington Yearbook, no. 75, p. 806-813.
- Hooke, R. B., 1967, Processes on arid-region alluvial fans: Journal of Geology, v. 75, p. 438-460.
- Horner, W. J., 1958, Paleocurrent studies of the middle and upper Keweenaw conglomerates of Michigan: M.S. Thesis, University of Kansas, Lawrence, 38 p.
- Hornstein, O. M., 1950, A field and petrographic study of some extrusive and metasedimentary rocks along the Carp and Little Carp rivers in Ontonagon and Gogebic counties, Michigan, M.S. Thesis: Michigan State University, East Lansing, Michigan, 55 p.
- Houghton, D., 1841, Fourth annual report of the state geologists: Michigan House of Representatives Document 27, p. 3-89.
- Hubbard, H. A., 1972, Source of Pebbles of volcanic rocks in the middle and upper Keweenaw conglomerates of northern Michigan: Journal of Geology, v. 80, p. 627-629.
- 1975a, Keweenaw geology of the North Ironwood, Ironwood and Little Girls Point quadrangles, Gogebic County, Michigan: United States Geological Survey Open File Report of 75-152, 23 p.
- 1975b, Geology of Porcupine Mountains in Carp River and White Pine quadrangles, Michigan: United States Geological Survey Journal of Research, v. 3, p. 519-528.
- 1975c, Lower Keweenaw volcanic rocks of Michigan and Wisconsin: United States Geological Survey Journal of Research, v. 3, p. 529-541.
- Huber, N.K., 1971, Keweenaw geology of Isle Royale, Michigan [abs.]: 17th Annual Institute on Lake Superior Geology, Duluth, Minnesota, p. 31.
- Huber, N. K., 1973, The Portage Lake Volcanics (middle Keweenaw) on Isle Royale, Michigan: United States Geological Survey Professional Paper 754-C, 32 p.
- Hutchinson, G.E. and Loffler, H., 1956, The Thermal Stratification of Lakes. Proc. Nat. Acad. Sci., Wash., v. 42, p. 84-86.

- Irving, R. D., 1883, The Copper-Bearing Rocks of Lake Superior, Monographs of the United States Geological Survey, v. 5, 464 p.
- Jirsa, M. A., 1980, The Petrology and tectonic significance of interflow sediments in the Keweenaw North Shore volcanic group of northwestern Minnesota, M.S. Thesis, University of Minnesota, Duluth, 125 p.
- Jost, M., 1968, The White Pine copper deposit, Michigan, United States of America, mineralogical investigation and genetic interpretation (Ph.D. Thesis): Johannes Gutenberg University, Mainz, Germany, 78 p.
- Kalliokoski, J., 1982, Jacobsville Sandstone, in Wold, R. J., and Hinze, W. J., eds., Geology and tectonics of the Lake Superior Basin: Geological Society of America Memior 156, p. 147-156.
- Kelts, K., and Hsu, K.J., 1978, Freshwater carbonate sedimentation. in: A. Lerman, ed., Lakes: Chemistry, Geology, Physics. Springer-Verlag, New York, pp. 295-323.
- King, E. R., and Zietz, I., 1971, Aeromagnetic study of the Midcontinent gravity high of the central United States: Geological Society of America Bulletin, v. 82, p. 2187-2208.
- Lane, A. C., 1911, The Keweenaw series of Michigan: Michigan Geological Survey Publication 6, 983 p.
- Lane, A. C., and Seaman, A. E., 1907, Notes on the geological section of Michigan, Part 1. The Pre-Ordovician: Journal of Geology, v. 15, no. 7, p.680-695.
- Leith, C. K., Lund, F. J. and Leith, A., 1935, Precambrian rocks of the Lake Superior region: United States Geological Survey Professional Paper 184, 34 p.
- Lyons, P. L., 1959, The Greenleaf Anomaly, A significant Gravity Feature, in Symposium on Geophysics in Kansas, Kansas Geological Survey Bulletin 137, p. 105-120.
- Mangham, J. R., 1974, The petrology and structure of the Mellen Gabbro Complex near Hurley, Wisconsin: M. S. Thesis, University of Wisconsin, Madison, Wisconsin.
- Meinschein, W.G., Barghoorn, E.S., and Schopf, J.W., 1964, Biological remnants in a Precambrian sediment: Science, v. 145, p. 262-263.

- Merk, G. P., and Jirsa, M. A., 1982, Provenance and tectonic significance of the Keweenaw interflow sedimentary rocks: in Wold, R. J., and Hinze, W. J., eds., Geology and tectonics of the Lake Superior Basin: Geologic Society of America Memoir 156, p.97-106.
- Miall, A.D., 1977, A review of the braided-river depositional environment: Earth Science Reviews, v. 13, p. 1-62.
- Moerlein, G. A., 1963, Structure and stratigraphy of the upper Keweenaw rocks in northwestern Wisconsin [abs.]: 9th Annual Institute on Lake Superior Geology, Duluth, Minnesota, p. 7.
- Moore, L. R., Moore, J. R., and Spinner, E., 1969, A geo-microbiological study of the Precambrian Nonesuch Shale: Proceedings of Yorkshire Geological Society, v. 37, part 3, no. 17, p.351-394.
- Morey, G. B., 1972, Petrology of Keweenaw sandstones in the subsurface of southeastern Minnesota, in Sims, P. K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 463-449.
- Morey, G. B., and Ojakangas, R. W., 1982, Keweenaw sedimentary rocks of eastern Minnesota and northwestern Wisconsin, in Wold, R.J., and Hinze, W. J., eds., Geology and Tectonics of the Lake Superior Basin: Geological Society of America Memoir 156.
- Morey, G.B. and Van Schmus, W.R., 1988, Correlation of Precambrian Rocks of the Lake Superior Region, United States: U.S. Geological Survey Professional Paper 1241-F, 31 p.
- Mudrey, M. G., Jr., and Dickas, A. B., 1988, Midcontinent rift model based upon Gregory Rift tectonic and sedimentation geometries [abs.]: 34th Annual Institute on Lake Superior Geology, Marquette, Michigan, v. 34, p. 73-75.
- Myers, W.D., II, 1971, The sedimentology and tectonic significance of the Bayfield Group (Upper Keweenaw?), Wisconsin and Minnesota: University of Wisconsin, Madison, unpublished Ph.D. thesis, 269 p.
- Nishio, K., 1919, Native copper and silver in the Nonesuch Formation, Michigan: Economic Geology, v. 14, p. 324-334.

- Noble, J.H., 1965, The petrology of the conglomeratic zone of the Freda Formation of northern Michigan [M.S. thesis]: Miami University, Miami, Ohio, 125 p.
- Nordeng, S.C., 1963, Precambrian stromatolites as indicators of polar shift, in Munyan, A.C., ed., Polar Wandering and Continental Drift: Society of Economic Paleontologists and Mineralogists Special Publication 10. p. 131-139.
- Ojakangas, R. W., and Morey, G. B., 1982a, Proterozoic sedimentary rocks: Geological Society of America, Memoir 156, p. 83.
- Ojakangas, R. W., and Morey, G. B., 1982b, Keweenawan sedimentary rocks of the Lake Superior region: A summary: Geological Society of America, Memoir 156, p. 157-164.
- Olmstead, J. R., 1969, Petrology of the Mineral Lake intrusion, northwestern Wisconsin, in Isachsen, Y. W., ed., Origin of Anorthosites and Related Rocks: New York State Museum and Science Service Memoir 18, p.149-161.
- Ostrom, M.E., 1967, Paleozoic stratigraphic nomenclature for Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 8, 1 sheet.
- Paces, J.B., and Davis, D.W., 1988, Implications of high precision U-Pb age dates on zircons from Portage Lake volcanic basalts on midcontinent rift subsidence rates, lava flow repose periods and magma production rates [abs.]: 34th annual Institute on Lake Superior Geology, Marquette, Michigan, v. 34, p. 85-86.
- Pettijohn, F.J., 1957, Sedimentary rocks [2nd ed.]: New York, Harper and Row, 718 p.
- Pettijohn, F.J., Potter, P.E., and Siever, R., 1973, Sand and Sandstone: New York, Springer-Verlag, 618 p.
- Picard, M.D. and High, L.R., 1973, Criteria for recognizing lacustrine rocks in: Recognition of Ancient Sedimentary Environments [ed. by J.K. Rigby and W.K. Hamblin], pp 108-145.
- Rachocki, A., 1981, Alluvial fans: [An attempt at an empirical approach]; Chichester; New York: J. Wiley, 161 p.

- Rahn, P.H., 1967, Sheetfloods, streamfloods and the formation of sediments: Annual Association of American Geographic., v. 57, p. 593-604.
- Reading, H. G., 1986, Facies, in: Reading, H.G. ed., Sedimentary Environments and Facies, 2nd edition, 615 p.
- Reinick, H. E., and Singh, I. B., 1980, Depositional sedimentary environments: Springer-Verlag, New York, 440 p.
- Rosenberry, S.C., 1924, General geology, in: Wisconsin Geological and Natural History Survey Township Report T. 47 N., R. 1 E., (1924), p. 17-28.
- Rosenblum, S., 1956, Improved technique for staining potash feldspars: Am. Mineral., v. 41, pp. 662-664.
- Roy, J. L., and Robertson, W. A., 1978, Paleomagnetism of the Jacobsville Formation and the apparent polar path for the interval - 1,000 to -670 m.y. for North America [abs.]: EOS (American Geophysical Union Transactions), v. 59, p. 54.
- Schmidt, R. G. and Hubbard, H. A., 1972, Penokean orogeny in the central and western Gogebic region, Michigan and Wisconsin [field guidebook]: 18th Annual Institute on Lake Superior Geology, Houghton, Michigan., p. A-1 to A-27.
- Schmidt, S. T., and Green, J. C., 1989, Metamorphic Zonation in the North Shore Volcanic Group, Minnesota [abs.]: 35th Annual Institute on Lake Superior Geology, Duluth, Minnesota, p. 78-79.
- Silver, L. T., and Green, J. C., 1963, Zircon ages for middle Keweenawan rocks of Lake Superior region [abs.]: American Geological Union Transactions, v. 44, p. 107.
- Sims, P.K., 1976, Precambrian tectonics and mineral deposits, Lake Superior region: Economic Geology, v. 71, p. 1092-1118.
- Smith, T. J., Steinhart, J. S., and Aldrich, L. T., 1966, Lake Superior crustal structure: Journal Geophysics Research, v. 71, p.1114-1172.
- Sturm, M., and Matter, A., 1978, Turbidites and varves in Lake Brienz (Switzerland): deposition of clastic detritus by density currents. in: Modern and Ancient Lake Sediments (Ed. by A. Matter and M.E. Tucker), pp.

145-166.

- Taylor, I.E., 1989, Middle and upper Keweenawan siliclastics of the Lake Superior Basin: Doctorial, November, 1987, McMaster Univ., Hamilton, On., Canada, 319 p.
- Thiel, E. C., 1956, Correlation of gravity anomalies with the Keweenawan geology of Wisconsin and Minnesota: Geological Society of America Bulletin, v. 67, p. 1079-1100.
- Thwaites, F. T., 1912, Sandstones of the Wisconsin coast of Lake Superior: Wisconsin Geological and Natural History Survey Bulletin 25, 117 p.
- Tyler, S. A., Marsden, R. W., Grout, F. F. and Thiel, G. A., 1940, Studies of the Lake Superior Precambrian by accessory mineral methods: Geological Society of America Bulletin, v. 51, p. 1429-1538.
- Van Hise, C. R. and Leith, C. K., 1911, The Geology of the Lake Superior Region, United States Geological Survey Monograph 52, 641p.
- Van Schmus, W. T., Green, J. C., and Halls, H. C., 1982, Geochronology of Keweenawan rocks in the Lake Superior region, in Wold, R. J., and Hinze, W. J., eds., Geology and tectonics of the Lake Superior Basin: Geological Society of America Memoir 156.
- Van Schmus, W. T. and Hinze, W. J., 1985, The Midcontinent Rift System: Am. Rev. Earth Planet. Sci., v. 13, p. 345-383.
- Vincent, S. A., and Yaskawa, K., 1968, Phenomenon of partial self-reversal in Keweenawan rocks; Part 2, Magnetization of upper Keweenawan lavas and sediments and of lower Keweenawan dikes; Journal of Geophysical Research, v. 73, p. 2753-2767.
- Vogel, T. A., McBride, M. B., and Ehrlich, R., 1976, Syngenetic model for the origin of the White Pine copper deposit [abs.]: 22nd Annual Institute on Lake Superior Geology, St Paul, Minnesota, p. 65-66.
- Walker, R.G., 1976, Facies models; 2, Turbidites and associated coarse clastic deposits: Geoscience Canada, v. 3, p. 25-36.
- Walker, R. G., 1983, Facies models: Geoscience Canada Reprint Series 1, p. 1-9.

- Wescott, W.A. and Ethridge, F.G., 1980, Fan-delta sedimentology and tectonic setting - Yallahs fan-delta, southeast, Jamaica. Bull. Am. Ass. petrol. Geol., 64, 374-399. 3.3, 12.4.3, 14.8.1.
- White, W. S., 1952, Imbrication and Dip in a Keweenaw Bed, Journal of Sedimentary Petrology, v. 22, p.189-199.
- 1957, Regional structural settings of the Michigan native copper district, in Snelgrove, A. K., ed., Geological Exploration: Institute on Lake Superior Geology, Michigan Technological University Press, Houghton, Michigan, p. 3-16.
- 1966, Geologic evidence for crustal structure in the western Lake Superior basin, in Steinhart, J. S., and Smith, T.J., eds., The earth beneath the continents: American Geophysical Union Geophysical Monograph 10, p.28-41.
- 1966b, Tectonics of the Keweenaw basin, western Lake Superior region: United States Geological Survey Professional Paper 524-E, p. E1-E23.
- 1971, Geologic setting of the Michigan Copper District, in Guidebook for field conference, Michigan Copper District, Sept. 30- Oct. 2, 1971: Houghton, Michigan, Michigan Technological University Press p. 3-17.
- 1972, The base of the upper Keweenaw, Michigan and Wisconsin: United States Geological Survey Bulletin 1354-F, p. F1-F23.
- White, W. S., Cornwall, H. T., and Swanson, R. W., 1953, Bedrock geology of the Ahmeek quadrangle, Michigan: United States Geological Survey Geologic Quadrangle Map GQ27, scale 1:24,000.
- White, W. S., and Wright, J. C., 1954, The White Pine copper deposit, Ontonagon County, Michigan: Economic Geology, v. 49, p. 675-716.
- White, W. S., and Wright, J. C., 1960, Lithofacies of the Copper Harbor Conglomerate, northern Michigan: United States Geological Survey Professional Paper 400-B, p. B5-B8.
- Wolff, R. G., and Huber, N. K., 1973, The Copper Harbor Conglomerate (middle Keweenaw) on Isle Royal Michigan, and its regional implications: U. S. Geological Survey Professional Paper 754-b, p. B1-B15.

Zietz, I., 1965, Aeromagnetic study of the mid-continent gravity anomaly [abs.]: United States Progr. Report Intern., Upper Mantle Project.

APPENDIX I

BEAR CREEK DRILL HOLE LOCATIONS AND CORE THICKNESSES

Explanation and Abbreviations

All thicknesses listed are as indicated on the Bear Creek diamond drill hole logs (uncorrected for dip). Copper Harbor sections are incomplete except for cores DO#10 and BU#2.

Formations and Rock Types

OB = Glacial Overburden
 FF = Freda Formation
 NF = Nonesuch Formation
 CHF = Copper Harbor Formation
 KL = Keweenaw Lava Flows

DDH#	Location	FM.	Uncorrected (Feet)	Thickness (Meters)
BAYFIELD COUNTY, WI. DRILL HOLES				
WC#2	SW1/4, SW1/4, SW1/4, Sec.6, T45N, R6W	OB	180.0	54.8
		FF	327.0	99.7
		NF	384.0	117.0
		CHF	476.0	145.1
WC#3	SE1/4, NE1/4, SW1/4, Sec.15, T45N, R6W	OB	284.0	86.6
		FF	642.0	195.7
		NF	445.0	135.6
		CHF	15.0	4.6
WC#4	SW1/4, SW1/4, SW1/4, Sec.33, T47N, R6W	OB	280.0	85.4
		FF	2,316.0	706.0
WC#5	NE1/4, SW1/4, NW1/4 Sec.14, T45N, R8W	OB	363.0	110.7
		CHF	274.0	83.5
WC#6	NE1/4, NW1/4, NE1/4, Sec.34, T45N, R9W	OB	311.0	94.8
		CHF	1,685.0	513.7
WC#7	SW1/4, SW1/4, NE1/4, Sec.5, T45N, R6W	OB	525.0	160.1
		FF	1,614.0	492.1
WC#8	SW1/4, SW1/4, SW1/4, Sec.31, T46N, R6W	OB	225.0	68.6
		FF	2,715.0	827.7

APPENDIX I (continued)

WC#9	SW1/4, SW1/4, SW1/4, Sec.31, T46N, R7W	OB	596.0	181.7
		FF	629.0	191.7
		NF	500.0	152.4
		CHF	16.0	4.9
WC#10	NE1/4, SE1/4, NW1/4, Sec.11, T47N, R9W	OB	470.0	143.3
		FF	1,095.0	333.8
WC#11	NW1/4, NW1/4, NW1/4, Sec.13, T45N, R9W	OB	535.0	163.1
		CHF	281.0	85.7
WC#12	NE1/4, SW1/4, NE1/4, Sec.3, T47N, R9W	OB	653.0	199.1
		FF	2,022.0	616.5
WC#13	SW1/4, SW1/4, NW1/4, Sec.36, T46N, R9W	OB	979.0	298.5
		FF	1,852.0	564.6
		NF	434.0	132.3
		CHF	32.0	9.8
WC#14	SE1/4, SE1/4, SE1/4, Sec.32, T48N, R9W	OB	435.0	132.6
		FF	1,082.0	329.9
		NF	240.0	73.2
		CHF	14.0	4.3
WC#15	NW1/4, NW1/4, NW1/4, Sec.33, T48N, R8W	OB	330.0	100.6
		FF	2,656.0	809.8
WC#16	SE1/4, SE1/4, NE1/4, Sec.8, T45N, R6W	OB	320.0	97.6
		FF	913.0	278.4
		NF	328.0	100.0
		CHF	11.0	3.3
WC#17	SW1/4, NW1/4, Sec3., T45N, R7W	OB	250.0	76.2
		FF	696.0	212.2
		NF	388.0	118.3
		CHF	77.0	23.5
WC#18	SE1/4, SE1/4, NE1/4, Sec.6, T45N, R9W	OB	680.0	207.3
		FF	725.0	221.0
		NF	462.0	140.9
		CHF	34.0	10.4
WC#19	NW1/4, NE1/4, NW1/4, Sec.9, T45N, R8W	OB	500.0	152.4
		CHF	166.0	50.6
WC#20	NW1/4, SW1/4, SW1/4, Sec.25, T45N, R9W	OB	287.0	87.5
		CHF	559.0	170.4

APPENDIX I (continued)

WC#21	SW1/4, SW1/4, SW1/4, Sec.39, T45N, R9W	OB CHF	252.0 268.0	76.8 81.7
WC#22	NW1/4, NW1/4, NW1/4, Sec.3, T45N, R8W	OB FF NF CHF	746.0 867.0 439.0 24.0	227.4 264.3 133.8 7.3
WC#23	NE1/4, SE1/4, NE1/4, Sec.28, T45N, R5W	OB CHF	266.0 534.0	81.1 162.8
WC#25	SE1/4, SW1/4, SW1/4 Sec.30, T48N, R8W	OB FF NF CHF	330.0 1,848.0 214.0 8.0	100.6 563.4 65.2 2.4

ASHLAND COUNTY, WI. DRILL HOLE

WC#24	NW1/4, NW1/4, NE1/4, Sec.18, T45N, R4W	OB CHF	535.0 101.0	163.1 30.8
-------	---	-----------	----------------	---------------

DOUGLAS COUNTY, WI. DRILL HOLES

DO#1	NW1/4, NW1/4, Sec.10, T44N, R11W	OB CHF	254.0 868.0	77.4 264.6
DO#2	NE1/4, NE1/4, Sec.34, T45N, R10W	OB CHF	299.0 147.0	91.2 44.8
DO#3	SW1/4, SW1/4, SW1/4, Sec.34, T44N, R10W	OB CHF	202.0 74.0	61.6 22.6
DO#4	NE1/4, SE1/4, NE1/4, Sec.27, T45N, R10W	OB CHF	482.0 114.0	147.0 34.8
DO#5	SE1/4, SE1/4, SE1/4, Sec.19, T47N, R10W	OB FF NF CHF	232.0 557.0 247.0 23.0	70.7 169.8 75.3 7.0
DO#6	SW1/4, SW1/4, NW1/4, Sec.15, T47N, R10W	OB FF NF CHF	190.0 1,092.0 236.0 72.0	57.9 332.9 71.9 21.9

APPENDIX I (continued)

DO#7	NW1/4, Sec.10, T45N, R10W	OB CHF	687.0 178.0	209.5 54.3
DO#8	NW1/4, NE1/4, NE1/4, Sec3., T45N, R10W	OB FF NF CHF	666.0 326.0 420.0 61.0	203.0 99.4 128.0 18.6
DO#9	NE1/4, SE1/4, Sec.25, T46N, R11W	OB CHF	307.0 154.0	93.6 46.9
DO#10	NW1/4, SW1/4, NE1/4, Sec.34, T47N, R11W	OB NF CHF KL	240.0 140.0 605.0 110.0	73.2 42.7 184.5 33.5
DO#11	SE1/4, SW1/4, SW1/4, Sec.16, T45N, R11W	OB CHF	263.0 33.0	80.2 10.1
DO#12	SE1/4, SE1/4, SE1/4, Sec.10, T46N, R11W	OB CHF	205.0 41.0	62.5 12.5
DO#13	SW1/4, SW1/4, SW1/4, Sec.8, T46N, R10W	OB FF NF CHF	410.0 215.0 293.0 18.0	125.0 65.5 89.3 5.5
DO#14	SW1/4, NW1/4, SW1/4, Sec.11, T46N, R10W	OB FF NF CHF	560.0 2,340.0 320.0 6.0	170.7 713.4 97.6 1.8

BURNETT COUNTY, WI. DRILL HOLES

BU#1	NW1/4, NW1/4, NE1/4, Sec.1, T41N, R14W	OB CHF	195.0 2,805.0	59.5 855.2
BU#2	SE1/4, SE1/4, SE1/4, Sec.3, T41N, R15W	OB CHF KL	270.0 2,340.0 127.0	82.3 713.4 38.7

WASHBURN COUNTY, WI. DRILL HOLES

WA#1	SE1/4, NW1/4, Sec.17, T42N, R11W	OB CHF	111.0 2,662.0	38.8 811.6
------	-------------------------------------	-----------	------------------	---------------

APPENDIX I (continued)

WA#2	NE1/4, NW1/4, Sec.13, T42N, R12W	OB CHF	110.0 496.0	33.5 151.2
WA#3	SE1/4, NE1/4, SE1/4, Sec.2, T42N, R12W	OB CHF	130.0 504.0	39.6 153.7
WA#4	SE1/4, SW1/4, Sec.4, T42N, R12W	OB CHF	180.0 388.0	54.9 118.3
WA#5	SE1/4, NE1/4, NE1/4, Sec.6, T42N, R12W	OB CHF	242.0 154.0	73.8 47.0
WA#6	NW1/4, NE1/4, NE1/4, Sec.2, T42N, R13W	OB CHF	260.0 140.0	79.5 42.7
WA#7	SE1/4, SE1/4, SE1/4, Sec.1, T42N, R11W	OB KL	67.0 177.0	20.4 54.0

APPENDIX II

CORRECTED THICKNESSES FOR NONESUCH FORMATION IN BEAR CREEK DRILL CORES

DDH#	Corrected Thickness	
	(Feet)	(Meters)
WC#2	357.5	109.0
WC#3	383.8	117.0
WC#9	482.0	147.0
WC#13	393.6	120.0
WC#14	207.0	63.0
WC#16	253.0	77.0
WC#17	325.0	99.1
WC#18	449.0	136.9
WC#22	436.0	132.9
WC#25	211.9	64.6
DO#5	236.2	72.0
DO#6	220.0	67.0
DO#8	420.0	128.0
DO#10	137.8	42.0
DO#13	288.6	88.0
DO#14	315.0	96.0

(Thicknesses corrected for dip)

APPENDIX III

FORMATIONS, LITHOLOGIES AND STRATIGRAPHIC LOCATIONS OF DRILL CORE AND OUTCROP SAMPLES USED IN PETROGRAPHIC ANALYSIS

EXPLANATION AND ABBREVIATIONS

The sample numbers in Table 1 and Fig. 33 indicate the following:

WC#2 - 235 / \	Bear Creek drill hole number or outcrop abbreviation.	Where the sample was collected (in feet) below the drill hole collar elevation, or in the measured section (Parker Creek only).
-------------------	---	---

FF = Freda Formation
 NF = Nonesuch Formation
 CHF = Copper Harbor Formation
 BR = Black River Harbor
 PC = Parker Creek
 PI = Presque Isle River
 PRF = Potato River Falls

Drill core samples

Sample No.	Fm.	Collar Elev. (feet)	Lithology & Stratigraphic Location
WC#2-235	FF	1050	Med.-grained SS, xbedded; 274 ft (83.5m) above the NF contact
WC#2-276	FF	"	Med.-grained SS-SLT, xbedded w/ mudchips; 233 ft (71.0m) above the NF contact
WC#2-378	FF	"	Med. to Fn.-grained SS, lenticular bedding, xbedded w/ mudchips; 131ft (39.9m) above the NF contact
WC#2-798	NF	"	Silty-SS, lenticular bedding, xbedded; 108ft (32.9m) above the CHF contact

APPENDIX III (continued)

WC#2-843	NF	1050	Silty-SS, parallel bedded; 63ft (19.2m) above the CHF contact
WC#2-876	NF	"	Med. to Fn.-grained SS, xbedded; 30ft (9.1m) above the CHF contact
WC#2-899	NF	"	Med. to Fn.-grained SS, xbedded; 7ft (2.4m) above the CHF contact
WC#2-931	CHF	"	Crs. to med.-grained pebbly SS; 25ft (7.6m) below the NF contact
WC#2-1239	CHF	"	Crs.-grained SS; 333ft (101.5m) below the NF contact
WC#2-1355	CHF	"	Crs. to med.-grained pebbly SS; 449ft (136.8m) below the NF contact
WC#3-885	FF	916	Med.-grained SS; 40ft (12.2m) above the NF contact
WC#3-1303	NF	"	Crs. to med.-grained SS, xbedded w/ mudchips; 66ft (20.1m) above the CHF contact
WC#3-1313	NF	"	Med.-grained SS, xbedded, mudchips; 56ft (17.1m) above the CHF contact
WC#3-1379	CHF	"	Crs.-grained pebbly SS; 10ft (3.1m) below the NF contact
WC#3-1385	CHF	"	Crs.-grained pebbly SS; 16ft (4.9m) below the NF contact
WC#9-1046	FF	1100	Crs. to med.-grained SS, xbedded, mudchips; 187.5ft (57.2m) above the NF contact

APPENDIX III (continued)

WC#9-1574	NF	1100	Sandy Slt w/crude oil blotches; 151ft (46m) above the CHF contact
WC#9-1723	CHF	"	Crs.-grained SS; 2ft (.6m) below the NF contact
WC#9-1741	CHF	"	Crs. to med.-grained SS; 16ft (4.9m) below the NF contact
WC#13-3142	NF	1260	Silty SS, soft sediment deformation (loading); 143ft (43.6m) above the CHF contact
WC#13-3188	NF	"	Fn.-grained SS, xbedded; 97ft (29.6m) above the CHF contact
WC#13-3282	NF	"	Crs. to med.-grained SS, xbedded, mudchips; 10ft (3.0m) above the CHF contact
WC#13-3292	CHF	"	Fn.-grained SS, xbedded, mudchips; 7ft (2.1m) below the NF contact
WC#18-1777	NF	1170	Med. to Fn.-grained SS; 105ft (32m) above the CHF contact
WC#18-1863	NF	"	Crs.-grained pebbly SS; 19ft (5.8m) above the CHF contact
WC#18-1885	CHF	"	Med. to fn.-grained SS; 3ft (.9m) below the NF contact
WC#18-1893	CHF	"	Silty SS, xbedded, mudchips; 11ft (3.4m) below the NF contact
WC#22-2029	NF	1285	Fn.-grained SS, xbedded, mudchips; 23ft (7m) above the CHF contact

APPENDIX III (continued)

WC#22-2050	NF	1285	Med.-grained SS, xbedded, mudchips; 2ft (.6m) above the CHF contact
WC#22-2053	CHF	"	Clast-supported conglomerate w/ crs.-grained SS matrix; 1ft (.3m) below the NF contact
WC#24-547	CHF	1060	Clast-supported conglomerate w/ crs. to med.-grained SS matrix; 12ft (3.7m) below the glacial overburden contact
WC#24-582	CHF	"	Crs.-grained pebbly SS; 47ft (14.3m) below the glacial overburden contact
WC#25-2317	NF	1000	Silty SS; 57ft (17.3m) above the CHF contact
WC#25-2340	NF	"	Med.-grained SS, mudchips; 34ft (10.3m) above the CHF contact
WC#25-2376	CHF	"	Crs.-grained SS, xbedded; 2ft (.6m) below the NF contact
WC#25-2378	CHF	"	Crs. to med.-grained SS w/ mudstone lenses, xbedded; 4ft (1.2m) below the NF contact
DO#6-1224	FF	1078	Fn.-grained SS, xbedded; 58ft (17.6m) above the NF contact
DO#6-1394	NF	"	Fn.-grained SS, xbedded; 120ft (36.5m) above the CHF contact
DO#6-1517	CHF	"	Crs.-grained SS; 3ft (.9m) below the NF contact

APPENDIX III (continued)

DO#6-1576	CHF	1078	Crs.-grained SS; 62ft (18.9m) below the NF contact
DO#10-309	NF	1160	Fn.-grained SS, xbedded, mudchips; 71ft (21.6m) above the CHF contact
DO#10-381	CHF	"	Crs. to med.-grained SS, mudchips; 1ft (.3m) below the NF contact
DO#14-3073	NF	1120	Med.-grained SS, xbedded; 145ft (44.2m) above the CHF contact
DO#14-3204	NF	"	Med.-grained SS, xbedded; 14ft (4.3m) above the CHF contact
DO#14-3217	NF	"	Crs.-grained SS, mudchips; 1ft (.3m) above the CHF contact

Outcrop Samples

Sample#	Formation	Lithology and Stratigraphic Location
PI#7	NF	Fn.-grained SS, xbedded, mudchips; approximate location is near the FF contact
BR#6	CHF	Med.-grained SS, xbedded; approximate location is near the NF contact
PC#0	CHF	Crs. to med.-grained SS, xbedded, mudchips; 212ft (64.6m) below the NF contact
PC#518	NF	Fn.-grained SS w/ SLT lenses, xbedded; 306ft (93.3m) above the CHF contact
PRF#1	NF	Crs. to med.-grained conglomeratic SS; CHF-NF contact zone