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THE PROVENANCE OF THE JACOBsville FORMATION  
OF THE UPPER PENINSULA OF MICHIGAN  
THROUGH A PETROGRAPHIC STUDY

by

David Walter Lindsay

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Geology

Western Michigan University
Kalamazoo, Michigan
April 1986
THE PROVENANCE OF THE JACOBsville FORMATION
OF THE UPPER PENINSULA OF MICHIGAN
THROUGH A PETROGRAPHIC STUDY

David Walter Lindsay, M.S.
Western Michigan University, 1986

The Upper Keweenawan Jacobsville Formation source areas were mixed source terranes with dominant terrane types changing regionally in relative abundances of sediment contribution. Dominant source terranes were older sediments, including a weathered soil zone, Upper Keweenawan Freda Sandstone and other recycled sandstones; plutonic Precambrian basement rocks; Middle Keweenawan Portage Lake Volcanics; and the chlorite to staurolite grade metamorphic rocks and iron ranges of Michigan's upper peninsula.

Depositional environments of the formation's four facies types range from fluvial to deltaic/lacustrine. Sediments were in transport for a short distance, resulting in grain freshness and angularity, moderate sorting and preservation of unstable sediments. Rapid erosion and deposition caused rock immaturity, an abundance of fresh, coarse feldspars and a wide range of alteration in a single species of feldspar. Two major basins of deposition were partially separated by a plutonic to metamorphic terrane highland. Major source areas were to the southeast of the western end of the outcrop belt and to the south of the eastern two-thirds of the outcrop belt.
ACKNOWLEDGEMENTS

I am very grateful to Dr. William B. Harrison, III for his guidance and useful criticism as my thesis advisor. Thanks go to Robert Havira (Western Michigan University) for help in technical areas and with photography. I would also like to thank The Graduate College for their financial support. The Huron Mountain Club is deeply appreciated for allowing me access to, and lodging on, their beautiful tract of land. Special thanks to Tim and Lee Flaherty for their warm hospitality during my stay with them.

My deepest appreciation goes to Karen, my wife, for her patience, moral support and love. Heartfelt thanks go to Lisa, our daughter, for all of the joy she provided us during this project.

David Walter Lindsay
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# Table of Contents

**Acknowledgements** ........................................ ii

**List of Tables** ........................................ iv

**List of Figures** ........................................ v

**Introduction** ........................................ 1

**Previous Work** ........................................ 4

**Regional Setting** ........................................ 7

**Description of Facies** .................................... 14
  - Red Siltstone Facies ..................................... 15
  - Conglomerate Facies ..................................... 16
  - Massive Sandstone Facies ................................ 22
  - Lenticular Sandstone Facies .............................. 25

**Depositional Regions of the Jacobsville** .................. 28

**Petrographic Analysis** .................................... 32
  - Region I ................................................ 32
  - Region II ............................................... 40
  - Region III ............................................... 51
  - Region IV ............................................... 60
  - Region V ............................................... 70
  - Region VI ............................................... 80
  - Region VII ............................................. 89

**Conclusion** .............................................. 102

**Bibliography** ............................................ 110
LIST OF TABLES

1. Modal Analysis of Sandstone Samples From Outcrops 1 and 2 of Region I ........... 37
2. Modal Analysis of Sandstone Samples From Outcrops 3, 4, 5, 6 and 7 of Region II .... 47
3. Modal Analysis of Sandstone Samples From Outcrops 8, 10, 11 and 12 of Region III ... 57
4. Modal Analysis of Sandstone Samples From Outcrops 13, 14 and 16 of Region IV ...... 66
5. Modal Analysis of Sandstone Samples From Outcrops 17, 18, 19, 20 and 21 of Region V .. 77
6. Modal Analysis of Sandstone Samples From Outcrops 22 and 23 of Region VI .......... 86
7. Modal Analysis of Sandstone Samples From Outcrops 24, 25, 26, 27, 28 and 29 of Region VIII .......... 97
8. The Averaged Modal Analysis Results for Each of the Depositional Regions ........... 107
LIST OF FIGURES

1. Map of Michigan's Upper Peninsula Showing the Jacobsville Outcrop Belt .................. 2
2. General Map of the Lake Superior Area Showing the Lake Superior Syncline and the Distribution of the Jacobsville—Bayfield Group Outcrop Belts .................. 8
3. Map Showing the Outcrop Distribution of Keweenawan Rocks and Positive Bouguer Gravity Anomalies .................. 10
4. General Stratigraphic Column of Upper Precambrian Rocks in the Lake Superior Region .................. 12
5. Closeup View of Red Siltstone Facies at Agate Falls on the Ontonagon River ................. 17
6. Typical Appearance of Channel-fill Conglomerates Collected Between Marquette and Big Bay, in Thin Section .................. 18
7. Typical Appearance of Alluvial Conglomerates Collected at Locations Near the Keweenaw Fault, in Thin Section .................. 21
8. Conglomerate Facies Outcrops .................. 23
9. Massive Sandstone Unconformably Overlying Older Precambrian Basalts at Sturgeon River Falls .................. 25
10. Lenticular Sandstone Outcrop Located Near the Village of Jacobsville on the Lake Superior Shoreline .................. 27
11. Map of Michigan's Upper Peninsula Showing the Jacobsville Outcrop Belt and the Locations of Sampled Outcrops .................. 29
12. General Map of Upper Peninsula Area Showing the Seven Regions of Jacobsville Deposition .................. 31
LIST OF FIGURES - CONTINUED

13. Mineralogic Classification for Sandstone Samples Collected at Outcrops 1 and 2 of Region I ................. 34

14. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σₚ) of Sandstone Samples Collected at Outcrops 1 and 2 of Region I ..................... 36

15. Mineralogic Classification for Sandstone Samples Collected at Outcrops 3, 4, 5, 6 and 7 of Region II ...................... 43

16. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σₚ) of Sandstone Samples Collected at Outcrops 3, 4 and 5 of Region II ..................... 45

17. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σₚ) of Sandstone Samples Collected at Outcrops 6 and 7 of Region II ..................... 46

18. Mineralogic Classification for Sandstone Samples Collected at Outcrops 8, 10, 11 and 12 of Region III ...................... 53

19. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σₚ) of Sandstone Samples Collected at Outcrops 8 and 10 of Region III ..................... 55

20. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σₚ) of Sandstone Samples Collected at Outcrops 11 and 12 of Region III ..................... 56
LIST OF FIGURES - CONTINUED

21. Mineralogic Classification for Sandstone Samples Collected at Outcrops 13, 14 and 16 of Region IV ............................... 63

22. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σ) of Sandstone Samples Collected at Outcrops 13, 14 and 16 of Region IV ................. 65

23. Mineralogic Classification for Sandstone Samples Collected at Outcrops 17, 18, 19, 20 and 21 of Region V ..................... 72

24. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σ) of Sandstone Samples Collected at Outcrops 17, 18, and 19 of Region V ..................... 75

25. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σ) of Sandstone Samples Collected at Outcrops 20 and 21 of Region V ..................... 76

26. Mineralogic Classification for Sandstone Samples Collected at Outcrops 22 and 23 of Region VI ................................. 83

27. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σ) of Sandstone Samples Collected at Outcrops 22 and 23 of Region VI ................................. 85

28. Mineralogic Classification for Sandstone Samples Collected at Outcrops 24, 25, 26, 27, 28 and 29 of Region VII ................. 92
LIST OF FIGURES - CONTINUED

29. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σr) of Sandstone Samples Collected at Outcrops 24, 25 and 26 of Region VII ........................................ 95

30. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σr) of Sandstone Samples Collected at Outcrops 27, 28 and 29 of Region VII ........................................ 96

31. General Map of Upper Peninsula Area Showing the Iron Formation Ranges and Zones of Regional Metamorphism in the Precambrian Rocks .................................................... 105

32. General Map of Upper Peninsula Area Showing Paleocurrent Directions in the Jacobsville Sandstone ................................................................. 106
INTRODUCTION

A thermal tectonic event affecting the proto-North American Continent occurred approximately 1,100 million years ago forming the Midcontinent Rift System (Hinze and Wold, 1982). The Lake Superior Basin represents a portion of the rift; the Keweenawan rocks within the basin being the only exposed portion of the Midcontinental Rift (Hinze and Wold, 1982). The Jacobsville, Believed by most geologists to be of Upper Keweenawan age, is a thick fluvial and lacustrine formation, within the Lake Superior Basin, outcropping in Michigan's upper peninsula. It consists of four facies: the Lenticular sandstone, massive sandstone, conglomerate, and red siltstone facies (Hamblin, 1958). Previous studies of the formation have neglected petrographic details that would help to make a more complete interpretation of the source material from which these deposits were derived. The project which led to this paper, involves the collection of samples from all four of the formation's facies and a subsequent petrographic and statistical analysis of those samples.

Six weeks were spent in the field during the summer of 1982. The Michigan Geological Survey publication, Cambrian Sandstones of Northern Michigan
(Hamblin, 1958), was used extensively in locating outcrops. Rock samples were taken from outcrops located throughout almost the entire length and width of the outcrop belt (Figure 1). Every facies present at an outcrop was sampled when physically possible. Field data were taken with a compass having a dip meter to determine orientations, amounts of dip, and paleocurrent directions of sedimentary structures. Data and observation were used to find relations of sedimentary structures to specific facies and their geographic distribution.

Fifty-one thin sections were produced from selected rock samples. Using several of the guidelines and methods of Robert Folk's *Petrology of Sedimentary Rocks* (1974) and a petrographic microscope, Modal analysis of the thin sections was performed. The point count method (Folk, 1974) was used to determine grain size, roundness, grain alteration, compaction, porosity and composition of the sandstone samples. The eleven thin sections of siltstone and conglomerate rocks were looked at in detail to determine textures and compositions.
Figure 1. Map of Michigan's Upper Peninsula Showing the Jacobsville Outcrop Belt (After Hamblin, 1958).
PREVIOUS WORK

The age of the Jacobsville has been a controversial matter for nearly 150 years. Most ages given for the formation range from a Lower-Middle Keweenawan age to a Middle Cambrian age. A lower age limit is based on the Jacobsville's position below the Late Cambrian Munising Sandstone (Kalliokoski, 1982). The close proximity, lithologic and structural similarities of the Upper Precambrian Bayfield Group of Wisconsin and Minnesota to the Jacobsville, both formations being within the Lake Superior syncline, have led many geologist to suggest that a late phase of Keweenawan sedimentation is represented by the Jacobsville (Kalliokoski, 1982). Roy and Robertson (1978) suggest that the Jacobsville Formation on Keweenaw Bay has an Upper Keweenawan pole position based on their paleomagnetic data, assigning the formation an age of about 1,100 million years. The writer will consider the Jacobsville to be of Upper Keweenawan age based on the previous work presented.

Douglas Houghton was the first to study the Jacobsville Formation. In his Fourth Annual Report of the State Geologist (1841), he briefly identifies the conglomerate, red sandstone and shales noting general locations, relative proportions and direction and amount of bedding dip. Irving and Chamberlin (1885) completed some extensive
work on the general geology of the sandstone in the area of the Keweenaw fault on the Keweenaw Peninsula. The formation was named by Lane and Seaman (1907) after the quarry town of Jacobsville (Figure 1). Lane and Seaman give a general description of some outcrop locations and briefly summerize lithologies. In 1949 Denning did a petrographic study on the heavy mineral suites on samples collected in the Keweenaw Bay area. Driscoll (1956) made the same type of study on samples located in the Munising area. Both studies showed that the heavy mineral assemblage of the Jacobsville Formation remains fairly constant over a large area and throughout the stratigraphic section.

Hamblin (1958) was the first to extensively study all major aspects of the formation. He describes the characteristic lithologies of each facies and the sedimentary structures contained within. Hamblin also determined paleocurrent directions through field measurements and hypothesized a general source and source location for the Jacobsville. He gives a Lower and/or Middle Cambrian age for the formation.

Tolunay's (1970) sedimentological study used grain size analysis and morphometric tests to come up with a warm-humid fluviatile paleoenvironment of deposition. Aho (1971) did a reflection seismic investigation to determine the thickness of the Jacobsville and it's structures at depth. French and VanderVoo (1975) and Roy and
Robertson (1978) conducted paleomagnetic studies to determine the age of the Jacobsville. The direction of magnetization gave French and VanderVoo a Lower Cambrian age. Roy and Robertson show the Jacobsville as Upper Keweenawan by chemical isolation in early phase remanence. Babcock's report (1975) on a four year study of the Jacobsville gives criteria to distinguish between different strata and establishes an environmental model for the Jacobsville in the Keweenaw Bay Peninsula area. Kalliokoski (1982) summarizes present knowledge of the Jacobsville and presents new information on stratigraphy, mineralogy and alteration in the area southwest of the Keweenaw Bay.
REGIONAL SETTING

The Jacobsville Formation is known to be exposed only in Michigan's upper peninsula along the southern shore of Lake Superior (Figure 1). Lake Superior occupies a large (approximately 600 km long, 250 km wide) topographic depression underlain entirely by a regional geologic structure named the Lake Superior Basin. The Jacobsville Formation is a wedge shaped red-bed sequence contained completely within the basin; the basin being developed during Middle and Late Proterozoic time (Hinze and Wold, 1982). The formation greatly thickens northward as it dips gently north under Lake Superior (Kalliokoski, 1982). The Jacobsville is considered the time equivalent of the Bayfield Group of Minnesota and Wisconsin, both formations being a portion of the Lake Superior Syncline (Figure 2). The western half of the Lake Superior Basin is dominated by the syncline, an asymmetrical structure having a steeply dipping north limb (Davidson, 1982). Both structures are tectonic features resulting from active plate processes that created an intraplate continental rift during Keweenawan time.

The Lake Superior Basin represents a portion of the Midcontinental Rift. The basin was interpreted geophysically by signatures of mafic intrusive and extrusive rock and
Figure 2. General Map of the Lake Superior Area Showing the Lake Superior Syncline and the Distribution of the Jacobsville - Bayfield Group Outcrop Belts (After Davidson, 1962).
widely distributed drill hole samples. These mapped signatures show that the basin is connected with the midcontinent and mid-Michigan gravity anomalies (Hinze and Wold, 1982). Highly deformed, anomalously thick, dense rock give the midcontinental gravity high values where the rifting took place (Figure 3). Chase (1973) concluded that the midcontinental gravity high anomaly defines the width of the rift. Lava filled the gap between the edges of the spreading continental plates during Keweenawan time.

Two geologic terranes dominate the basement in the Lake Superior Basin; a gneissic terrane and a volcano-sedimentary-plutonic (greenstone to granite) terrane. The gneissic basement is older and has undergone complex deformation. These terranes are spatially distinct with the boundaries and structural grain generally trending east-west (Davidson, 1982). The general axis of the present basin is subparallel to the structural trend of the Archean basement terranes in western Lake Superior. Intrusion of lava into the rift created a lava plateau that probably subsided with sediment load and thermal decay. The subsidence along with faulting on subbasin margins created the Lake Superior Basin (Davidson, 1982). Later folding of Keweenawan sediments, unconformably overlaying Keweenawan volcanics extruded into the basin, created the Lake Superior Syncline (Hamblin, 1965).
Figure 3. Map Showing the Outcrop Distribution of Keweenawan Rocks and Positive Bouguer Gravity Anomalies (After Fowler and Kuenzi, 1978).
Archean age rocks (>2.5 b.y. old) are exposed throughout the Superior province of the Canadian shield (Davidson, 1982). These rocks surround the Superior structural basin and make up the basement complex. The Keweenawan rocks overlay Middle Precambrian metasedimentary rocks intruded during the Penokian orogeny (Fowler and Kuenzi, 1978). The thin sequence of Lower Keweenawan rocks are dominated by quartzarenites and record tectonic stability. The thick sequence (19,000 feet) of Middle and Upper Keweenawan rocks, however, record a period of tectonic instability (Fowler and Kuenzi, 1978). Mantle-derived intrusion and extrusion of igneous rocks into long structural troughs gives a sequence of deformed volcanics (Portage Lake Volcanics) and subordinate intra-stratified conglomerates and arkosic sandstones that transect pre-existing structural patterns (Hinze and Wold, 1982). These rocks were deformed contemporaneously with their accumulation during plate separation. Subsidence continued while the undeformed Jacobsville was deposited as a cap onto conglomerates, arkosic sandstones (Freda Sandstone) and subordinate intrastratified volcanics and shales (Fowler and Kuenzi, 1978). The combined thickness of the Keweenawan rocks is over 30,000 feet (Figure 4). This accumulation of interbedded sediments and basaltic flows underlies most of the Lake Superior Basin and most likely extends a considerable distance to the southwest under the cover of Paleozoic sediments (Hamblin, 1965).
Figure 4. General Stratigraphic Column of Upper Precambrian Rocks in the Lake Superior Region (After Fowler and Kuenzi, 1978).
The Jacobsville Formation was deposited into a basin located in a large region where sedimentation has been structurally controlled by the basement complex beneath the basin. The Keweenaw fault that truncates the Jacobsville outcrop belt in the west (Figure 1) put the Jacobsville Formation in fault contact with older Precambrian rocks after Keweenawan sedimentation was completed.
DESCRIPTION OF FACIES

Four distinct lithologic units make up the Jacobsville Formation. Outcrops are generally widely scattered, mostly two dimensional, and sometimes virtually inaccessible. Few outcrops have exposures of more than one lithic unit and those few are not continuous enough for a detailed understanding of their relationships. Each unit represents a facies and local, temporary environmental conditions (Hamblin, 1958). These facies make up a thick red-bed sequence comprised of upper, middle and lower members. This sequence is similar to the Bayfield and Freda Sandstone in that the lower member is thicker and more sedimentologically immature than the upper member with the thin middle member being the most mature (Babcock, 1975).

The Jacobsville ranges in color from a deep red to white; variations of brown are common. The red color is a primary feature resulting from iron oxide staining (Hamblin, 1958). Leaching at bedding planes, joints, and lamination boundaries leaves the sandstone white. This leaching occurs when permeability allows water to reduce the iron oxide. White mottling is common and occurs when pebbles or organic matter reduce the iron surrounding them.
The two most abundant facies are the lenticular and massive sandstone facies. The lenticular facies can be found in outcrops over the entire extent of the outcrop belt. Massive sandstone is most commonly found in the Keweenaw Bay area. Both facies are very similar in composition and texture but differ in sedimentary structure due to differing environments of deposition. The cross-stratification and channel structures of the lenticular facies indicate a fluvial environment of deposition whereas the structures of the massive units indicate a lacustrine environment. The conglomerate facies is present as either channel-fill deposits or as alluvial fan-type deposits. The red siltstone facies is a shaley, thin-bedded unit which sometimes interfingers with the massive facies, but is more generally at the top of the formation.

Red Siltstone Facies

The red siltstone facies is present in only a few widely scattered outcrops and interfingers with massive sandstone when present in other outcrops. It is almost entirely composed of red, silty sandstone interbedded with red, thin, platey shale. Mica flakes are abundant in the shale giving it a satiny luster on wet, broken surfaces. The unit is an intense red color and only occasionally has a minor amount of white mottling.
The red siltstone has horizontal bedding except where interfingering with beds of slightly dipping massive sandstone. Bedding is thin and can usually be traced laterally throughout the entire exposure. Small-scale trough crossbedding is common in the silty sandstone. The presence of small-scale crossbedding in a fine material indicates fluxes of higher energy in a predominantly low-energy environment (Hamblin, 1958). This facies represents later phases of Jacobsville deposition when environments of deposition changed from a fluvial to a deltaic/lacustrine environment allowing red siltstone to interfinger with massive sandstone near the top of the section (Figure 5).

Conglomerate Facies

The conglomerate facies is found as alluvial fan-type deposits or as channel-fill deposits located in either bedrock valleys or lenses scattered throughout the lenticular sandstone. Most of the conglomerates are found at or near the base of the sampled outcrop exposures. The conglomerates east of the Keweenaw Bay are typically channel fillings while alluvial fan-type deposits increase to the west of Keweenaw Bay. This westward increase in alluvial fans reflects a greater tilting of the basin floor during sedimentation (Kalliokoski, 1982).
The conglomerates from Marquette to Big Bay are typically channel-fill deposits. Pebble size material, in the samples analyzed by the writer, is the most common while the few boulders found are almost exclusively in deep bedrock valleys. Vein quartz is the most abundant pebble type found in the samples. It is typically fresh, subangular and has iron stained rims. Potash feldspar is the next most abundant. It is angular, fresh and becomes more abundant as the average pebble size decreases. Quartz-staurolite, chert and strained iron oxide pebbles are also abundant (Figure 6). Large, angular hunks of soft nonresistant shale is fairly common.
Figure 6. Typical Appearance of Channel-fill Conglomerates Collected Between Marquette and Big Bay, in Thin Section; crossed nicols, X 43.75
Many shale hunks are completely weathered out. Calcite is the major cement making up as much as 30% of the material. Large calcite crystals surround the pebbles and constitute the entire matrix in a few samples. Large, dark brown, rounded, older sandstone pebbles almost identical to sandstone pebbles found in the Freda are somewhat common (Hamblin, 1961). The older sandstone pebbles generally have well sorted, tightly-cemented angular grains. Minor amounts of chalcedonic quartz are found in several channel-fill conglomerate samples.

Conglomerates were deposited in a deep bedrock valley on the Carp River near Marquette. Hultman (1953) found the main constituents to be angular to rounded cobbles and boulders of quartzite, dolomite and iron formation. The composition of the bedrock outcrops on either side of the valley suggest that the hills on the sides of Carp River are the source (Hamblin 1958). At L'Anse, in the Keweenaw Bay Area, the conglomerates are heterogeneous. Besides the typical vein quartz and feldspars, Spiroff (1956) found pebbles of quartzite, ferrugineous chert, amygdaloidal basalt, graywacke and slate. This is an area with a fairly large variety of exposed Precambrian rocks that were the likely source of the conglomerate.
Most outcrops of the conglomerate facies found near the Keweenaw fault in the Keweenaw Peninsula are thick exposures of alluvial fan-type deposits. Irving and Chamberlin (1885) found pebbles of felsite and granite porphyries to be the main constituents of an alluvial conglomerate located near the Keweenaw fault. The Alluvial conglomerate rock samples collected by the writer commonly have a considerable amount of basalt pebbles and minor amounts of chalcedonic quartz besides quartz and feldspar (Figure 7). The matrix of the sampled alluvial conglomerate rocks typically consist of poorly cemented sand and decomposed particles. Calcite is lacking. The composition of most pebble to boulder size clasts indicate a dominantly volcanic source terrane.

Most conglomerates are fluvially deposited basal channel-fillings while others are alluvial deposits. Channel-fill in the deep bedrock valleys had a nearby source of material as large amounts of angular feldspar and angular blocks of soft shale would indicate. Alluvial fan-type deposits are also in close proximity to their source. Based on maximum clast size-slope-distance from source data on alluvial fans by Blissenbach (1962), Jacobsville-type conglomerates were probably deposited between 6 and 16 km from their source (Babcock, 1975). Alluvial fans developed at deep basin margins where block faulting and rapid subsidence were taking place.
Figure 7. Typical Appearance of Alluvial Conglomerates Collected at Locations Near the Keweenaw Fault, in Thin Section; crossed nicols, X 43.75.
Strong currents carried the conglomerates deposited in lenticular sandstone channel structures a further distance from source areas than conglomerate material deposited as alluvium or deep bedrock fillings (Figure 8).

Massive Sandstone Facies

The massive sandstone facies is known for its massive, continuous bedding. It is mainly found in the keweenaw Bay lowland area but is found as far east as Grand Island and as far inland as Victoria Falls. The sandstone is medium grained with average grain size being slightly less that the medium-grained lenticular sandstone. The colors in outcrop range from a reddish-brown to white with minor amounts of white mottling occurring in a few of the exposures. Solid, light-tan colors predominate. This predominance of light colors and lack of persistent white mottling is due to a free circulation of ground water (Hamblin, 1958). Leaching gives the massive sandstone a lighter color than the less permeable lenticular sandstone.

Bedding thickness in the massive sandstone ranges from a few inches to over 15 feet. The average thickness is approximately 4 feet. Bedding is almost always horizontal with weak bedding planes being easily recognized by the effects of weathering. Several of the beds have either horizontal or cross-stratification. Trough and planar cross-stratification are mainly found near the
Figure 8. Conglomerate Facies Outcrops. Top: Closeup view of alluvial conglomerate located east of Laurium. Bottom: Channel-fill conglomerate occurring as channel deposits in lenticular sandstone located west of Marquette on the Lake Superior shoreline.
base of the beds and range from 6 to 10 inches in thickness. Slight tectural variations cause color differences that accentuate the lamination, however, the vertical, two dimensional nature of the massive sandstone exposures make a detailed understanding of the laminations difficult.

Oscillation ripple marks are found in a few scattered locations. The average ripple has a wavelength of 2.3 inches and an amplitude of 0.4 inches. Oscillation ripple marks having the same amplitude and wavelength were found at different levels of stratification indicating a fairly constant relationship between water depth and wave energy (Hamblin, 1958).

The massive sandstone facies was deposited in a dominantly lacustrine environment with finer deltaic/lacustrine-deposited red siltstone interfingering at some upper horizons. Though the massive sandstone also interfingers with the lenticular sandstone, it appears to be higher in the section than the lenticular facies. The environment changed from a fluvial to predominantly lacustrine environment during Jacobsville sedimentation as the regional relief decreased and the depositional basin transgressed, covering previously deposited sediments with shallow lakes (Figure 9).
Lenticular Sandstone Facies

The lenticular facies is the most abundant and widespread unit of the Jacobsville Formation. The only area where it is lacking in outcrop is the Keweenaw Bay lowland area. It is dark red to light brown in color and is medium-grained. Discontinuous, lenticular-bedding characterizes this facies. The beds range from under an inch to over 10 feet in thickness, with almost all the beds pinching-out before the lateral extent of the exposures. Thick beds sometimes pinch-out as quickly as thinner beds, while in the same outcrop, thin beds sometimes
pinch-out as gradually as thicker beds. The lenticular nature of the beds resulted from some of the same fluvial processes that formed the channel structures found throughout the unit.

Channel-fill structures are numerous and usually concentrated toward the base of the outcrops. Channel sizes range widely. There is usually a large variety of channel sizes occurring together in the same outcrop. The most common channel-filling is pebble-conglomerate material, making the channels easily distinguishable from the medium-grained lenticular sandstone.

Crossbedding is the most abundant sedimentary structure in the facies and can be seen in every outcrop. Because of textural differences, lamination is accentuated by color change and relief due to leaching and weathering. Modern wave action has carved three dimensional exposures in some locations. Direction of plunge was measured on three dimensional exposures in order to determine paleo-current directions. The crossbedding is of two different types: (1) planar, in which bounding surfaces of erosion are horizontal; and (2) trough, in which the bounding surfaces of erosion are curved. Both types are fluvial in origin. Trough crossbedding is the most abundant type and was measured for direction of plunge. Trough sizes range from 1 to 10 feet in width and from 4 inches to 3 feet in depth.

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Shale pebbles can be found throughout the facies. They are usually disc-shaped and are between $\frac{1}{2}$ to 5 inches in diameter. They are identical to pebbles found in the conglomerate and may be from penecontemporaneous erosion and redeposition of finer sediments within the Jacobsville (Hamblin, 1958). Current ripple marks are well developed in some of the finer-grained lenticular sandstone.

The discontinuous bedding, prominent crossbedding, presence of shale pebbles, and current ripple marks indicate that this facies was deposited in a fluvial environment (Figure 10).

Figure 10. Lenticular Sandstone Outcrop Located Near the Village of Jacobsville on the Lake Superior Shoreline.
DEPOSITIONAL REGIONS OF THE JACOBsville

Samples were taken from 29 outcrops located throughout the western 3/4 of the Jacobsville outcrop belt (Figure 11). The point-count method was used to do a modal analysis of the thin sections made from the sandstone samples and to determine composition and texture of the red siltstone and conglomerate thin section samples. Mean grain diameter, sorting, mean grain roundness, mean grain alteration, compaction, porosity and composition of the sandstone thin section samples were determined. Parameters, given somewhat exclusive range limits, were chosen as criteria to group together samples from different outcrops. The parameters, chosen as the rock properties that would help most to distinguish depositional regions, are listed with their range limits:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean grain diameter</td>
<td>± 0.1 mm</td>
</tr>
<tr>
<td>sorting</td>
<td>± 0.1 phi</td>
</tr>
<tr>
<td>mean grain roundness</td>
<td>± 0.5 ρ</td>
</tr>
<tr>
<td>mean grain alteration</td>
<td>± 0.5</td>
</tr>
<tr>
<td>contacts/grain</td>
<td>± 0.25</td>
</tr>
<tr>
<td>% mono quartz</td>
<td>± 5.0%</td>
</tr>
<tr>
<td>% poly quartz</td>
<td>± 2.5%</td>
</tr>
<tr>
<td>% feldspar</td>
<td>± 2.5%</td>
</tr>
<tr>
<td>% rock fragments</td>
<td>± 2.5%</td>
</tr>
</tbody>
</table>
Figure 11. Map of Michigan's Upper Peninsula Showing the Jacobsville Outcrop Belt and the Locations of Sampled Outcrops.
Samples from regionally proximal outcrops having point-count results that were within the listed range limits for at least six out of the nine parameters were grouped together. By grouping the outcrops, represented by the samples, together, the writer was able to determine seven regions of Jacobsville deposition (Figure 12). The detailed petrographic analysis done for each of the seven depositional regions was completed in petrographic report form (Folk, 1974).
Figure 12. General Map of Upper Peninsula Area Showing the Seven Regions of Jacobsville Deposition.
PETROGRAPHIC ANALYSIS

Region I

Sample Identification

Region I includes outcrops 1 and 2. The description is based on a composite from samples collected at Au Sable Falls (outcrop 1) and Au Sable Point (outcrop 2).

Field Relations

Outcrop 1 is a stream-cut exposure approximately 150 feet thick. Lenticular sandstone is the only unit present. The sandstone exposure is part of a large channel structure. Planar and trough crossbedding is prominent throughout. Very minor amounts of disc-shaped shale pebbles are found at a few different horizons.

Outcrop 2 is a beach-cliff exposure of lenticular sandstone that averages approximately 11 feet thick. Wave action has cut three-dimensional terraces that accentuate the ubiquitous crossbedding and laminations. The plunge of the trough crossbedding indicates a northerly direction of transport. The sandstone at both outcrops has a slight northerly dip and was deposited in a fluviatile environment of deposition.
**Hands specimen Description**

The sandstone, in outcrop, has deep red to light tan laminations with moderate amounts of white mottling in the deeper-colored sandstone. It is medium-grained and very-well sorted. It is identified as a lithic arkose by the relative abundances of essential constituents (quartz, feldspars and rock fragments) (Figure 13).

Cementation is lacking at outcrop 1 where the sandstone is easily disaggregated. Outcrop 2 is moderately cemented. Grains appear subrounded in minor to moderate amounts of iron oxide-stained clay matrix. Moderate amounts of weathering and alteration are evident. There are some small-scale cross bedding and abundant laminations present.

**Thin section Description**

**Thin section Abstract**

The sandstone is typically a well-sorted lithic arkose. Monocrystalline and polycrystalline quartz grains are moderately fresh, subrounded and comprise an average 57.1% of the rock. Feldspars are generally coarser than quartz and comprise 12.9% of the rock. Rock fragments are dominated by older sediments and comprise 13.9% of the rock. Iron oxide, sericite, chert, magnetite, mica and clay make up the rest of the rock. The framework is bound by clay and
Figure 13. Mineralogic Classification for Sandstone Samples Collected at Outcrops 1 and 2 of Region I (After Folk, 1974). Abbreviations used are described as follows: Q - all types of quartz including chert; F - all single feldspar grains including granite and gneiss fragments; RF - all other rock fragments.

secondary quartz. Compaction has been moderate. The sandstone was derived from a mixed-source terrane dominated by older sediments. The outcrops are parts of channel structures.
Texture

1. The rock is supported by a partially to mostly iron-stained clay matrix (average 3.2%) and secondary quartz cement within the framework grains. Grain contacts are an average 2.2 contacts/grain, indicating a moderate amount of compaction.

The rock is mainly bound by the clay matrix. The sandstone is easily disaggregated where clay has been weathered out. Secondary quartz cement makes up an average 1.9% of the rock. The moderate compaction, due to burial, and precipitation of secondary quartz, due to diagenesis, have reduced original porosities to an average 5.1%

2. Grain size distribution is that of a very-well-sorted, pebbly, medium-grained sand (Figure 14). Size distribution of the sandstone samples are skewed to fine sizes because of the clay content.

3. The average visual roundness of the medium-sized quartz grains is 3.23 (subrounded). Coarser grains tend to be more rounded.

4. The sandstone is texturally mature at outcrop 1 where the clay has been weathered out. The sandstone at outcrop 2 is immature because the clay was not weathered out.
Mineralogy - Terrigenous Detritus (Table 1)

1. Quartz is separable into monocrystalline and polycrystalline grains, secondary quartz cement and chert. Most of the quartz is common plutonic variety. The grains are mainly subrounded, moderately fresh and contain numerous gas bubbles. A considerable percentage of the grains have abraded overgrowths which indicates they are from older sediments. Clear, straight-edged volcanic-type
Table 1
Modal Analysis of Sandstone Samples From Outcrops 1 and 2 of Region I.

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Outcrop 1</th>
<th>Outcrop 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Point Ind. counts</td>
<td>%</td>
</tr>
<tr>
<td>Quartz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mono-</td>
<td>157</td>
<td>52.3</td>
</tr>
<tr>
<td>poly-</td>
<td>15</td>
<td>5.0</td>
</tr>
<tr>
<td>Feldspar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-spar</td>
<td>18</td>
<td>6.0</td>
</tr>
<tr>
<td>Plag.</td>
<td>20</td>
<td>6.7</td>
</tr>
<tr>
<td>Rock frag.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sed.</td>
<td>20</td>
<td>6.7</td>
</tr>
<tr>
<td>granitic</td>
<td>13</td>
<td>4.3</td>
</tr>
<tr>
<td>met.</td>
<td>7</td>
<td>2.3</td>
</tr>
<tr>
<td>volc.</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Iron Oxide</td>
<td>7</td>
<td>2.3</td>
</tr>
<tr>
<td>Magnetite</td>
<td>3</td>
<td>1.0</td>
</tr>
<tr>
<td>Secondary qtz.</td>
<td>6</td>
<td>2.0</td>
</tr>
<tr>
<td>Chert</td>
<td>9</td>
<td>3.0</td>
</tr>
<tr>
<td>Chalcedony</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Chert</td>
<td>8</td>
<td>2.7</td>
</tr>
<tr>
<td>Mica</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Calcite</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Pore space</td>
<td>16</td>
<td>5.3</td>
</tr>
<tr>
<td>Total</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

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quartz is present only in very minor amounts. A small percentage of quartz grains are undulose and strained due to metamorphic effects. An average 4.9% of the quartz is polycrystalline. The majority of polycrystalline grains are undulose and have sheared boundaries between grains. Most of the polycrystalline quartz is from a metamorphic source, while the remaining 35% is plutonic in origin. Chert is abundant, comprising an average 2.8% of the rock. The chert indicates a significant sediment contribution from a carbonate-rich older sediment terrane.

2. Feldspars comprise an average 12.9% of the rock. They are present as varieties of potassium feldspar and plagioclase. K-spar is more abundant, with microcline being the dominant variety. Most microcline is albite-twinned; some grains are pericline-twinned. The feldspars are mostly fresh to moderately fresh and range from unaltered to moderately altered in the same species; with the plagioclase having a wider range of alteration than the K-spar. The feldspars are generally larger than the quartz grains.

3. Rock fragments comprise 13.9% of the rock and are mainly older sediments. Moderate amounts of both metamorphic and granitic fragments are present in approximately equal amounts. Sedimentary fragments are dominantly older carbonate sands and older sandstones. Metamorphic fragments are dominantly quartzite.
4. Mica, mainly in the form of muscovite, is present in minor amounts. Sericite is fairly abundant and usually occurs as shards bent around framework grains.

5. Heavy minerals comprise 2.9% of the rock. Hematite is the most abundant variety. Magnetite is present in minor amounts. Other heavy minerals are rare and unidentified.

Chemical Constituents

The only authigenic material present is secondary quartz. The abraded quartz overgrowths were precipitated in previously-existing older sedimentary rock.

Interpretation

Region I is almost exclusively lenticular sandstone deposited fluvially as channel structures. The source area for the sandstone was a mixed-source terrane covered by an iron oxide-rich soil. The mixed terrane consisted of older sedimentary, plutonic, metamorphic and volcanic rock. The abundance of sedimentary fragments and chert, subroundness of the quartz, and presence of abraded quartz overgrowths indicate that the major source was reworked preexisting sedimentary rocks.

At least mild tectonic instability existed at the time of deposition. The immature nature of the rocks at outcrop 2, the abundance of feldspar, the general coarseness of
the feldspar grains, and the wide range of alteration in a single species of feldspar fit into Krynine's (1948) definition of a tectonic arkose. Rapid erosion of rugged topography in a warm, seasonally-humid climate produces the feldspar found in a tectonic arkose (Folk, 1974). The large channel structures of region I are indicative of a semi-arid environment that caused rapid erosion in an area of at least moderate relief. The preservation of fresh feldspar and clay pebbles indicate that the eroded material was not exposed to a highly-weathering medium for an extended length of time. The subroundness and the very-well-sorted nature of most grains are indicative of a transport distance that was probably on the order of tens of miles or greater.

Region II

Sample Indentification

Region II includes outcrops 3 through 7. The description is based on a composite from samples collected at the five outcrops located along Lake Superior between Au Train Bay and Marquette.
Field Relations

Outcrops 3, 5 and 6 are small beach-cliffs composed dominantly of lenticular sandstone. The lenticular sandstone of outcrop 5 dips north under a 14 foot beach-cliff exposure of red siltstone located 200 yards north-east of outcrop 5. Massive sandstone and red siltstone interfinger at a 22 foot thick roadcut exposure at outcrop 4. Outcrop 4 sandstone and siltstone are essentially flat-lying and up-section of outcrop 5 lenticular sandstone. Outcrop 7 is a deep, river-valley exposure where lenses of sandstone interfinger with channel-fill conglomerate.

The lenticular sandstone of Region II has prominent planar and trough crossbedding throughout. The plunge of the trough crossbedding gives an average N9°E transport direction. The red siltstone of outcrop 4 occurs as deep red, 2.5 to 3.0 foot thick lenses in the middle section of the massive sandstone. Siltstone beds range from .25 inches thick to fine laminations and are flat-lying. The conglomerate of outcrop 7 is mainly cobbles, boulders and shale blocks deposited in a deep bedrock valley during massive erosion.

The lenticular sandstone was deposited fluvially as parts of large-scale channel structures. The red siltstone and massive sandstone were deposited later in a lower-energy deltaic/lacustrine environment after basin water transgression.
**Handspecimen Description**

The sandstone ranges in color from pinkish-red to tan with minor amounts of white mottling in the darker-colored lenticular sandstone. It is well-sorted and medium-grained. It ranges from a lithic arkose at outcrop 5 to feldspathic litharenite at the other outcrops (Figure 15).

The sandstone is moderately cemented at all of the outcrops as indicated by the effort it takes to disaggregate it. Grains appear subangular in moderate amounts of iron oxide-stained clay matrix. Minor amounts of weathering and moderate alteration are evident. Small-scale crossbedding and abundant laminations are present in the lenticular sandstone.

**Thin Section Description**

**Thin Section Abstract**

The sandstone is typically a well-sorted feldspathic litharenite. Monocrystalline and polycrystalline quartz are subangular to subrounded and comprise an average 50.6% of the rock. Feldspars are generally coarser than quartz and comprise 10.1% of the rock. Rock fragments are dominated by metamorphic fragments and comprise an average 13.0% of the rock. Iron oxide, magnetite, secondary quartz, chert, chalcedony, sericite, mica, calcite and clay
Figure 15. Mineralogic Classification for Sandstone Samples Collected at Outcrops 3, 4, 5, 6 and 7 of Region II. (After Folk, 1974).

make up the rest of the rock. The framework is bound by clay, secondary quartz and minor amounts of chalcedony and calcite. Compaction has been moderate. The sandstone was derived from a mixed-source terrane dominated by metamorphic rock. The outcrops are channel structures, deep valley fillings and deltaic/lacustrine deposits.
Texture

1. The rock is supported by a partially to mostly iron-stained clay matrix (average 3.6%). Secondary quartz cement, chalcedony and calcite occur as minor cements in some of the samples. Grain contacts are an average 2.7 contact/grain indicating a moderate to moderately-high amount of compaction.

The rock is mainly bound by the clay matrix. Authigenic cements make up an average 3.4% of the rock in region II. Outcrop 3 sandstone is 5.6% authigenic cement. The moderately-high compaction and precipitation of authigenic cement have reduced original porosities to an average 11.3%.

2. Grain size distribution is that of a well-sorted, medium sand (Figure 16 and 17). Size distribution is skewed to fine sizes because of the clay content.

3. The average visual roundness of the medium-sized quartz grains is 2.7 (subangular). Coarser grains tend to be more rounded.

4. The sandstone is either immature due to clay content or submature as indicated by the moderate sorting.
Figure 16. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σi) of sandstone Samples Collected at Outcrops 3, 4 and 5 of Region II.
Figure 17. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σı) of Sandstone Samples Collected at Outcrops 6 and 7 of Region II.

Mineralogy - Terrigenous Detritus (Table 2)

1. Quartz is separable into monocrystalline and polycrystalline grains, secondary quartz cement, quartz overgrowth, chert and chalcedony. Bubbly, subangular, medium-grained plutonic quartz is the most abundant type. Most samples have a small percentage of abraded quartz overgrowths indicating an older sediment origin. A moderate amount of monocrystalline quartz is slightly
Table 2

Modal Analysis of Sandstone Samples From Outcrops 3, 4, 5, 6 and 7 of Region II.

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Outcrop 3 Point Ind. %</th>
<th>Outcrop 4 Point Ind. %</th>
<th>Outcrop 5 Point Ind. %</th>
<th>Outcrop 6 Point Ind. %</th>
<th>Outcrop 7 Point Ind. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>267 42.5</td>
<td>127 42.3</td>
<td>159 39.8</td>
<td>167 47.7</td>
<td>122 40.7</td>
</tr>
<tr>
<td>mono-poly-</td>
<td>59 9.4</td>
<td>26 8.7</td>
<td>30 7.5</td>
<td>24 6.8</td>
<td>20 6.7</td>
</tr>
<tr>
<td>Feldspar</td>
<td>27 4.3</td>
<td>16 5.3</td>
<td>43 10.8</td>
<td>28 8.0</td>
<td>14 4.7</td>
</tr>
<tr>
<td>K-spar</td>
<td>16 2.5</td>
<td>13 4.3</td>
<td>21 5.3</td>
<td>12 3.4</td>
<td>9 3.0</td>
</tr>
<tr>
<td>plag.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock frag.</td>
<td>31 4.9</td>
<td>14 4.7</td>
<td>12 3.0</td>
<td>21 6.0</td>
<td>10 3.3</td>
</tr>
<tr>
<td>sed.</td>
<td>18 2.4</td>
<td>8 2.7</td>
<td>6 1.5</td>
<td>7 2.0</td>
<td>5 1.7</td>
</tr>
<tr>
<td>granitic</td>
<td>55 8.8</td>
<td>22 7.3</td>
<td>16 4.0</td>
<td>19 5.4</td>
<td>13 4.3</td>
</tr>
<tr>
<td>met.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vol.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron Oxide</td>
<td>23 3.7</td>
<td>8 2.7</td>
<td>17 4.3</td>
<td>14 4.0</td>
<td>18 6.0</td>
</tr>
<tr>
<td>Magnetite</td>
<td>13 2.1</td>
<td>3 1.0</td>
<td>3 0.7</td>
<td>1 0.3</td>
<td>7 2.3</td>
</tr>
<tr>
<td>Secondary qtz.</td>
<td>23 3.7</td>
<td>--</td>
<td>10 2.5</td>
<td>4 1.1</td>
<td>--</td>
</tr>
<tr>
<td>Chert</td>
<td>19 3.0</td>
<td>3 1.0</td>
<td>6 1.5</td>
<td>7 2.0</td>
<td>5 1.7</td>
</tr>
<tr>
<td>Chalcedony</td>
<td>13 2.1</td>
<td>--</td>
<td>--</td>
<td>6 1.7</td>
<td>4 1.3</td>
</tr>
<tr>
<td>Sericite</td>
<td>7 1.1</td>
<td>4 1.3</td>
<td>3 0.7</td>
<td>9 2.6</td>
<td>4 1.3</td>
</tr>
<tr>
<td>Mica</td>
<td>3 0.5</td>
<td>9 3.0</td>
<td>4 1.0</td>
<td>10 2.8</td>
<td>3 1.0</td>
</tr>
<tr>
<td>Calcite</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>3 0.7</td>
<td>--</td>
</tr>
<tr>
<td>Pore space</td>
<td>52 8.3</td>
<td>47 15.7</td>
<td>66 16.5</td>
<td>23 6.5</td>
<td>36 12.0</td>
</tr>
<tr>
<td>Total</td>
<td>628</td>
<td>300</td>
<td>399</td>
<td>352</td>
<td>300</td>
</tr>
</tbody>
</table>
undulose to undulose and shows straining effects due to metamorphism. There is a minor amount of clear, fairly straight-sided volcanic quartz. An abundance of polycrystalline quartz is in the samples, comprising an average 8.0% of the rock. Almost all of the polycrystalline quartz is undulose and has either sutured grain boundaries, elongated oriented grains, or grains of varying sizes within the same grain, indicating a source or sources that underwent various degrees of metamorphism. There is a moderate amount of chert, comprising an average 2.0% of the rock. The chert is indicative of an older carbonate-rich sediment terrane.

2. Feldspars comprise an average 10.1% of the rock. They are present as varieties of potassium feldspar and plagioclase. K-spar is more abundant, with microcline being the dominant variety; most microcline is albite-twinned; some grains are pericline-twinned. Grains range from moderately altered to unaltered in the same species, but most grains are moderately fresh. The feldspars are generally more rounded and larger than the quartz grains.

3. Rock fragments comprise an average 13.0% of the rock and are mainly metamorphic fragments. Sedimentary fragments are common and follow metamorphic fragments in abundance. Granitic fragments are present in minor amounts. Metamorphic fragments are dominantly quartzite. Sedimentary fragments are siltstone, carbonate sand and older sandstone.
4. Mica is abundant, comprising an average 1.5% of the rock. The mica is nearly all muscovite with small amounts of biotite. It occurs in shreds and plates, many being deformed around the edges of framework grains. Sericite is also abundant.

5. Heavy minerals present are iron oxide, mainly in the form of hematite and magnetite. Iron oxide is fairly abundant, comprising an average 4.0% of the rock. Other heavy minerals are rare and unidentified.

Chemical Constituents

Secondary quartz cement and chalcedony occur in minor amounts in most of the samples. Outcrop 3 sandstone has an abundance of both secondary quartz and chalcedony. Calcite cement only occurs in minor amounts in two samples. Minor amounts of abraded quartz overgrowths occur in several of the samples, but were precipitated in older sediments.

Interpretation

Region II has rock types from all four facies of the Jacobsville. This depositional region has seen the depositional environmental conditions change from a high-energy fluvial environment, depositing lenticular sandstone and valley-fill conglomerate, to a lower-energy deltaic/lacustrine environment when red siltstone and red siltstone
interfingering with massive sandstone were deposited. The source area for the sandstone was an iron oxide-rich, soil-covered, mixed-source terrane located to the south of the depositional sites. The mixed terrane consisted of various degrees of metamorphosed rock, older sediments, plutonic and volcanic rock. The abundance of strained-undulose quartz, polycrystalline grains, and variously-altered quartzite indicate that the major source was metamorphic rock.

The immature to submature nature of the sandstone and the wide range of alteration in a single species of feldspar indicate at least moderate tectonic instability at the time of deposition. Lenticular sandstone and conglomerate were deposited early after basin subsidence created the relief needed, in a semi-arid environment, for rapid erosion and transport of material by high-energy drainage streams. When the relief was reduced enough from erosion and basin transgression, the energy regime decreased, allowing for the existence of intra-basin lakes. The massive sandstone and redsiltstone were deposited over the lenticular sandstone and conglomerate in the lake that covered depositional sites. The well-sorted, subrounded grains and preservation of fresh feldspar and polycrystalline grains are indicative of a transport distance on the order of tens of miles or greater.
Region III

Sample Identification

Region III includes outcrops 8 through 12. The description is based on a composite from samples collected at the five outcrops located along the Lake Superior shoreline between Marquette and Big Bay.

Field Relations

All of the outcrops of region III are beach-cliff exposures that range in thickness from 8 feet to 90 feet of exposure. Lenticular sandstone is the dominant unit at every outcrop. Conglomerate channel-fill deposits within the lenticular sandstone are found in most of the outcrops. The conglomerate channel structures range greatly in size and can usually be found at several horizons within the outcrops. Outcrop 8 lenticular sandstone unconformably overlies intrusive Precambrian peridotite. Planar and trough crossbedding and numerous laminae are prominent throughout the outcrops. The plunges of measured trough crossbedding are N25°W at outcrop 8 and N18°W at outcrop 11, indicating a transport direction of northwest and a source area to the southeast. Beds dip from 0° to 12° to the north and northeast.
The lenticular sandstone was deposited in a high-energy fluviatile environment of deposition. The conglomerate was deposited as channel-fill within the lenticular channel structures.

**Hand specimen Description**

The sandstone is red to tan with abundant white mottling in several locations. Channel-fill samples are usually a different color than the host rock and range in color from light tan to pinkish-red. Reddish-orange, disc-shaped clay pebbles are abundant in some of the lenticular sandstone samples. The grains are moderately sorted and medium-to-coarse sand-sized. The sandstone ranges from a feldspathic litharenite at outcrop 12 to lithic arkose at the other outcrops (Figure 18).

The samples are almost all moderately-well cemented. Grains appear subangular in a moderate amount of iron oxide-stained clay matrix. Very little alteration and moderate weathering at some locations are evident. Bedding is lenticular, and small-scale crossbedding and laminations are found throughout.
Figure 18. Mineralogic Classification for Sandstone Samples Collected at Outcrops 8, 10, 11 and 12 of Region III (After Folk, 1974).

**Thin Section Description**

**Thin Section Abstract**

The sandstone is typically a moderately-sorted, pebbly feldspathic litharenite to lithic arkose. Monocrystalline and polycrystalline quartz grains are subangular and comprise and average 41.4% of the rock. Feldspars are generally coarser than quartz and comprise
an average 12.2% of the rock. Rock fragments are dominantly older sediment and plutonic fragments and comprise an average 12.2% of the rock. Mica, sericite, calcite, chert, chalcedony, secondary quartz, magnetite, clay and iron oxide make up the rest of the rock. The framework is bound by clay, calcite and minor amounts of secondary quartz and chalcedony cement. Compaction has been minor. The sandstone was derived from a mixed-source terrane dominated by older sediments and plutonic rock. The outcrops are channel structures with conglomerate channel fillings.

Texture

1. The rock is supported by a partially iron-stained clay matrix (average 4.3%). Calcite, minor amounts of secondary quartz and chalcedony occur as cements in most of the samples. Grain contacts are an average 1.6 contacts/grain indicating a minor amount of compaction.

The rock is mainly bound by the clay and calcite matrix. Authigenic cements comprise an average 5.2% of the rock. The minor compaction and precipitation of cement have reduced original porosities to an average 18.0%.

2. Grain size distribution is that of a moderately-sorted, pebbly, medium-to-coarse-grained sand (Figure 19 and 20). Size distribution is skew to fine sizes because of the clay content.
3. The average visual roundness of the medium-sized quartz grains is 2.3 (subrounded). Coarser grains tend to be more rounded.

4. The sandstone in region III is either immature due to clay content or, more often, submature as indicated by the moderate sorting.
Figure 20. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σt) of Sandstone Samples Collected at Outcrops 11 and 12 of Region III.

Mineralogy - Terrigenous Detritus (Table 3)

1. Quartz is separable into monocrystalline and polycrystalline grains, secondary quartz cement, chert and chalcedony. Monocrystalline quartz with some vacuoles and straight extinction are the dominant type. A few of the more altered grains have abraded overgrowths. There is minor to moderate amounts of clear, generally coarser, volcanic grains. The amount of undulose and/or
Table 3
Modal Analysis of Sandstone Samples From Outcrops 8, 10, 11 and 12 of Region III.

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Outcrop 8 Point Ind. counts %</th>
<th>Outcrop 10 Point Ind. counts %</th>
<th>Outcrop 11 Point Ind. counts %</th>
<th>Outcrop 12 Point Ind. counts %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mono</td>
<td>150 40.5</td>
<td>108 34.7</td>
<td>122 34.5</td>
<td>103 34.2</td>
</tr>
<tr>
<td>poly</td>
<td>19 5.1</td>
<td>21 6.8</td>
<td>14 3.9</td>
<td>16 5.3</td>
</tr>
<tr>
<td>Feldspar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-spar</td>
<td>30 8.1</td>
<td>26 8.4</td>
<td>30 8.5</td>
<td>21 7.0</td>
</tr>
<tr>
<td>plag.</td>
<td>15 4.1</td>
<td>19 6.1</td>
<td>13 3.7</td>
<td>9 3.0</td>
</tr>
<tr>
<td>Rock frag.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sed.</td>
<td>14 3.8</td>
<td>14 4.5</td>
<td>20 5.6</td>
<td>19 6.3</td>
</tr>
<tr>
<td>granitic</td>
<td>9 2.4</td>
<td>11 3.5</td>
<td>19 5.4</td>
<td>15 5.0</td>
</tr>
<tr>
<td>met.</td>
<td>11 3.0</td>
<td>8 2.6</td>
<td>10 2.8</td>
<td>8 2.7</td>
</tr>
<tr>
<td>vol.</td>
<td>2 0.5</td>
<td>3 1.0</td>
<td>--</td>
<td>6 2.0</td>
</tr>
<tr>
<td>Iron Oxide</td>
<td>11 3.0</td>
<td>9 4.2</td>
<td>19 7.1</td>
<td>14 4.6</td>
</tr>
<tr>
<td>Magnetite</td>
<td>2 0.5</td>
<td>5 1.6</td>
<td>6 1.7</td>
<td>4 1.3</td>
</tr>
<tr>
<td>Secondary qtz.</td>
<td>2 0.5</td>
<td>--</td>
<td>3 0.8</td>
<td>4 1.3</td>
</tr>
<tr>
<td>Chert</td>
<td>12 3.2</td>
<td>16 5.1</td>
<td>13 3.7</td>
<td>9 3.0</td>
</tr>
<tr>
<td>Chalcedony</td>
<td>9 2.4</td>
<td>11 3.5</td>
<td>4 1.1</td>
<td>5 1.7</td>
</tr>
<tr>
<td>Sericite</td>
<td>--</td>
<td>--</td>
<td>5 1.4</td>
<td>6 2.0</td>
</tr>
<tr>
<td>Mica</td>
<td>--</td>
<td>--</td>
<td>5 1.4</td>
<td>14 4.6</td>
</tr>
<tr>
<td>Calcite</td>
<td>12 3.2</td>
<td>13 4.2</td>
<td>--</td>
<td>7 2.3</td>
</tr>
<tr>
<td>Pore space</td>
<td>72 19.5</td>
<td>47 15.1</td>
<td>71 20.1</td>
<td>51 16.9</td>
</tr>
<tr>
<td>Total</td>
<td>370</td>
<td>311</td>
<td>354</td>
<td>301</td>
</tr>
</tbody>
</table>
strained monocrystalline quartz is minor. Polycrystalline quartz comprises an average 5.2% of the rock and is mostly metamorphic in origin as indicated by its undulose extinction and sutured grain boundaries. Most of the quartz is fresh and of plutonic origin. Chert is indicative of a significant contribution from a carbonate-rich, older sediment terrane.

2. Feldspars comprise an average 12.2% of the rock. They are present as varieties of potassium feldspar and plagioclase. K-spar is more abundant, with microcline being the dominant variety. Most microcline is albite-twinned; some grains are pericline-twinned. Grains range from fresh to altered in the same species, but most grains are moderately fresh. The feldspars are generally more angular and coarser than the quartz grains.

3. Rock fragments comprise an average 12.2% of the rock and are dominantly older sediments and granitic fragments. There is a moderate amount of metamorphic fragments and a minor amount of volcanic fragments. Sedimentary fragments are mainly shales and carbonate sands. Metamorphic fragments are mainly quartzite. The few volcanic fragments are mostly fragments of diabase.

4. Mica and sercite are only present in two samples. Mica is abundant in outcrop 12, where it comprise over 4.0% of the sample. It is mainly muscovite occurring as plates floating in the matrix.
5. Heavy minerals are abundant. Hematite and magnetite are found in all of the samples. Iron oxide comprises an average 4.0% of the rock. Other heavy minerals are rare and unidentified.

Chemical Constituents

Calcite is in every sample but one. It comprises an average 2.4% of the rock. Chalcedony and secondary quartz occur as minor cements in most of the samples.

Interpretation

Region III outcrops are dominantly lenticular sandstone and channel-fill conglomerate deposited in a fluvial environment of deposition. The source area for the sandstone was an iron oxide-rich, soil-covered, mixed-source terrane located to the south and southeast of the depositional sites. The mixed terrane consisted of older sediments, plutonic, metamorphic and volcanic rock. The abundance of older sedimentary fragments and chert indicate a major source was carbonate-rich, older sediment terrane. Abundant plutonic quartz, granitic fragments and heavy minerals suggest that plutonic rock was also a major contributor of source material. Metamorphic and volcanic terranes were less significant.
The maturity of the rock and range of alteration in a single species of feldspar indicate at least moderate tectonic instability at the time of deposition. The lenticular sandstone and conglomerate channel-fill were deposited in a high-energy, fluvial environment, during tectonic instability, in a semi-arid climate. The abundance of subangular, medium-to-coarse, sand-sized, fresh grains and heavy minerals are indicative of a transport distance on the order of tens of miles. Distance of transport must have been relatively short, as indicated by the lack of significant alteration of almost all the grains.

Region IV

Sample Identification

Region IV includes outcrops 13 through 16. The description is based on a composite from samples collected at the four outcrops located along Lake Superior between Big Bay and the Huron River, and outcrop 15 located on Mountain Lake Stream in the Huron Mountains.

Field Relations

Outcrops 13, 14 and 16 are vertical beach-cliff exposures that range in thickness from 8 feet just west of the Huron River Point to 120 feet northwest of Big Bay Harbor. Outcrop 15 is a stream-cut exposure of over
100 feet. The beach cliffs are lenticular sandstone with abundant clay clasts; conglomerate channel-fill structures are lacking. The stream-cut exposure of outcrop 15 is up-section of the beach-cliff outcrops and is composed of flat-lying red siltstone with some interfingering massive sandstone beds up to 3 feet thick. The massive sandstone lenses are mainly found toward the top third of the exposure. The lenticular sandstone, once again, has prominent planar and trough crossbedding and numerous laminae throughout. Trough crossbedding is dominant and measures up to 40 feet across. Plunge directions range from N60°W at outcrop 13 to N35°E at outcrop 16. Lenticular sandstone dips gently north.

The lenticular sandstone was deposited in a high-energy fluvial environment of deposition. The red siltstone and massive sandstone were later deposited in a lower-energy deltaic/lacustrine environment. The source area was to the southeast and southwest.

**Handspecimen Description**

The sandstone is deep red to light tan with moderate amounts of white mottling. Reduction spots up to 9 inches in diameter occasionally occur in the lenticular sandstone. Angular clay clasts of pebble size are fairly abundant
in the lenticular sandstone. The clay clasts are a rusty-orange color. The grains are moderately sorted and medium sand-sized. The sandstone is identified as a lithic arkose (Figure 21).

The samples are almost all moderately cemented. Grains appear mainly angular in a moderate amount of iron-stained clay matrix. Very little alteration or weathering is evident. Bedding is lenticular, except for the massive bedding found at outcrop 15. The lenticular sandstone, silty sand of the red siltstone and massive sandstone all have at least minor amounts of small-scale crossbedding. The lenticular sandstone and red siltstone have abundant lamination.

Thin Section Description

Thin Section Abstract

The sandstone is typically a moderately-sorted, pebbly, lithic arkose. Monocrystalline and polycrystalline grains are angular and comprise an average 51.5% of the rock. Feldspars are generally coarser than quartz and comprise an average 11.9% of the rock. Rock fragments are dominantly older sediment and comprise an average 8.5% of the rock. Mica, sericite, calcite, chert, chalcedony, magnetite, clay and iron oxide make up the rest of
the rock. The framework is bound by clay and calcite. Compaction has been relatively minor. The sandstone was derived from a mixed-source terrane dominated by carbonate-rich older sediments. The outcrops are channel structures and deltaic/lacustrine deposits.
Texture

1. The rock is supported by a partially to mostly iron-stained clay matrix (average 4.0%). Moderate amounts of calcite occur in all of the samples. Grain contacts are an average 1.8 contacts/grain, indicating a relatively minor amount of compaction.

The sandstone is mainly bound by the clay and calcite matrix. Authigenic cements comprise an average 2.7% of the rock. The minor compaction and precipitation of cement have reduced original porosities to an average 13.4%.

2. Grain size distribution is that of a moderately-sorted, pebbly, medium-grained sand (Figure 22). Size distribution is skewed to fine sizes because of clay content.

3. The average visual roundness of the medium-sand sized grains is 1.8 (angular). Coarser grains tend to be more angular.

4. The sandstone in region IV is either immature due to clay content or, more often, submature as indicated by the moderate sorting.

Mineralogy - Terrigenous Detritus (Table 4)

1. Quartz is separable into monocrystalline and polycrystalline grains, chert and chalcedony. Monocrystalline quartz is dominantly the common plutonic
Figure 22. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation ($\sigma_t$) of Sandstone Samples Collected at Outcrops 13, 14 and 16 of Region IV.
Table 4
Modal Analysis of Sandstone Samples From Outcrops 13, 14 and 16 of Region IV.

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Outcrop 13</th>
<th>Outcrop 14</th>
<th>Outcrop 16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Point Ind.</td>
<td>Point Ind.</td>
<td>Point Ind.</td>
</tr>
<tr>
<td></td>
<td>counts %</td>
<td>counts %</td>
<td>counts %</td>
</tr>
<tr>
<td>Quartz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mono-</td>
<td>149</td>
<td>139</td>
<td>127</td>
</tr>
<tr>
<td>poly-</td>
<td>16</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>48.2%</td>
<td>48.8%</td>
<td>42.3%</td>
</tr>
<tr>
<td></td>
<td>5.2%</td>
<td>4.9%</td>
<td>5.0%</td>
</tr>
<tr>
<td>Feldspar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-spar</td>
<td>23</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>plag.</td>
<td>20</td>
<td>11</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>7.4%</td>
<td>5.6%</td>
<td>5.7%</td>
</tr>
<tr>
<td></td>
<td>6.5%</td>
<td>3.9%</td>
<td>6.3%</td>
</tr>
<tr>
<td>Rock Frag.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sed.</td>
<td>10</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>granitic</td>
<td>8</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>met.</td>
<td>5</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>vol.</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3.2%</td>
<td>3.2%</td>
<td>4.3%</td>
</tr>
<tr>
<td></td>
<td>2.6%</td>
<td>1.8%</td>
<td>2.3%</td>
</tr>
<tr>
<td></td>
<td>1.6%</td>
<td>0.7%</td>
<td>2.0%</td>
</tr>
<tr>
<td></td>
<td>1.0%</td>
<td>1.4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Iron Oxide</td>
<td>9</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2.9%</td>
<td>2.8%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Magnetite</td>
<td>2</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>0.6%</td>
<td>2.1%</td>
<td>2.3%</td>
</tr>
<tr>
<td>Secondary qtz.</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Chert</td>
<td>5</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>1.6%</td>
<td>6.7%</td>
<td>4.7%</td>
</tr>
<tr>
<td>Chalcedony</td>
<td>3</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>1.0%</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Sercite</td>
<td>6</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>1.9%</td>
<td>2.8%</td>
<td>2.3%</td>
</tr>
<tr>
<td>Mica</td>
<td>3</td>
<td>4</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>1.0%</td>
<td>1.4%</td>
<td>--</td>
</tr>
<tr>
<td>Calcite</td>
<td>9</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2.9%</td>
<td>2.1%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Pore space</td>
<td>38</td>
<td>34</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>12.3%</td>
<td>11.9%</td>
<td>16.0%</td>
</tr>
<tr>
<td>Total</td>
<td>309</td>
<td>285</td>
<td>300</td>
</tr>
</tbody>
</table>

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type. Most grains have straight extinction and few-to-several vacuoles. The grains are typically medium sand-sized, fresh and more rounded than other grains. There are a few semicomposite grains which are mainly sightly undulose. Minor to moderate amounts of clear, usually straight-sided volcanic quartz are found in all of the samples. The volcanic quartz is generally larger than other quartz grains. A few of the monocrystalline grains have abraded overgrowths. Some of the moderately-altered grains have inclusions. There is a relatively minor amount of polycrystalline quartz (average 5.0%). Most of the polycrystalline quartz is of metamorphic origin. Chert is abundant, comprising an average 4.3% of the rock. This indicates a significant contribution from a carbonate-rich, older sediment terrane.

2. Feldspars comprise an average 11.9% of the rock. They are present as varieties of potassium feldspar and plagioclase. K-spar is more abundant, with microcline being the dominant variety. Most microcline is albite-twinned; some grains are pericline-twinned. Grains range from unaltered to moderately altered in a single species. The majority of grains are fresh and coarser than the quartz grains.

3. Rock fragments comprise an average 8.5% of the rock and are dominantly older sediments. Minor to moderate amounts of granitic, metamorphic and volcanic fragments
are found in all of the samples. Sedimentary fragments are mainly older sandstone, carbonate sands and some shales. Metamorphic fragments are mainly quartzite and mica shists.

4. Mica comprises an average 0.8% of the rock. Muscovite is the dominant type of mica and usually occurs as plates floating in the matrix. Sericite is present as relatively-large shards.

5. Heavy minerals are present in moderate amounts. Iron oxide comprises an average 3.0% of the rock and is usually in the form of hematite. Magnetite is present in minor amounts in all of the samples.

Chemical Constituents

Calcite is an important cement. It is found in every sample and comprises an average 2.1% of the rock. Chalcedony is a minor constituent of one sample. Secondary quartz is not present.

Interpretation

Region IV is dominated by beach-cliff exposures of lenticular sandstone deposited as channel structures in a fluvial environment of deposition. A stream-cut exposure of red siltstone and interfingering massive sandstone, deposited in a deltaic/lacustrine environment of deposition, is up-section of the channel structures.
The source area for the sandstone was an iron oxide-rich, soil-covered, mixed-source terrane located to the southeast and southwest of the depositional sites. The mixed terrane consisted of older sediments, plutonic, metamorphic and volcanic rock. The abundance of chert and older sediment fragments and subroundness of several quartz grains indicate that the source terranes were dominated by a carbonate-rich, older sediment terrane.

The maturity of the rock and the range of alteration in a single species of feldspar indicate at least moderate tectonic instability at the time of deposition. The lenticular sandstone was deposited in a high-energy fluvial environment during tectonic instability. The red siltstone and massive sandstone were later deposited in a lower-energy deltaic/lacustrine environment after the relief between source area and basin of deposition decreased. The abundance of angular, fresh, medium sand-sized grains and preservation of clay clasts indicate a transport distance on the order of tens of miles. Time in transport was relatively short.

The source material was rapidly eroded in a semi-arid environment of at least moderate relief and fluvially deposited as channel structures. The source material continued to be rapidly eroded and was later deposited as deltaic/lacustrine deposits in a lake covering the previously-deposited lenticular sandstone.
Region V

Sample Identification

Region V includes outcrops 17 through 21. The description is based on a composite from samples collected at the four outcrops located on the shore of Lake Superior between the Huron River and the town of Keweenaw Bay, and outcrop 21 located at Sturgeon Falls on the Sturgeon River.

Field Relations

Outcrop 21 is a thick stream-cut exposure of flat-lying massive sandstone unconformably overlaying Precambrian basalts. Outcrop 20 is an approximately 60 foot vertical beach-cliff exposure of massive sandstone. Massive bedding thickness generally ranges from 2 to 8 feet. Lenticular sandstone comprises the channel structures exposed as beach cliffs at outcrops 17 and 18 and the road-cut exposure at outcrop 19. Lenticular channel structures are up to 300 feet wide at outcrop 17 and over 40 feet thick at outcrop 19. Outcrop 19 has channel-fill conglomerate located near the base of the exposure. The channel structure at outcrop 19 unconformably overlies Michigamme Slate.
Trough crossbedding is the dominant type of cross-bedding in the lenticular sandstone. Plunge directions at outcrop 18 are N17°W and N6°W, indicating northwest transport directions. The massive sandstone at outcrop 20 has oscillation ripple marks located at different horizons, and yet they all trend in a general northeast direction. The massive sandstone is flat-lying, while lenticular sandstone is either flat-lying or dipping slightly to the north.

The lenticular sandstone and conglomerate channel-fill were deposited in a high-energy fluvial environment of deposition. The massive sandstone was deposited in a shallow lake where the flow direction remained relatively constant over a long period of time, as indicated by the existence and similar trends of oscillation ripple marks located at different horizons in the same exposure. The source areas were to the southeast.

**Handspecimen Description**

The sandstone is a weathered dark red to bright pinkish-red to light tan color, with moderate amounts of white mottling in the lenticular sandstone. The minor to moderate amounts of clay pebbles in the lenticular sandstone are usually a deep rusty-red color. The grains are typically medium sand-sized and moderately sorted. The sandstone is identified as a lithic arkose (Figure 23).
Figure 23. Mineralogic Classification for Sandstone Samples Collected at Outcrops 17, 18, 19, 20 and 21 of Region V (After Folk, 1974).

The samples are typically moderately-cemented, though some highly-weathered parts of a few outcrops have easily-disaggregated rock. Grains appear mainly subangular in a moderate amount of iron-stained clay matrix. Moderate to minor amounts of weathering and minor alteration are evident. Both the lenticular sandstone and massive sandstone have at least some small-scale crossbedding. Laminations in the lenticular sandstone are abundant.
Thin Section Description

Thin Section Abstract

The sandstone is typically a moderately-sorted, pebbly, lithic arkose. Monocrystalline and polycrystalline quartz grains are subangular and comprise an average 49.2% of the rock. Feldspars are generally coarser than quartz and comprise an average 14.2% of the rock. Rock fragments are mainly metamorphic, sedimentary and granitic and comprise an average 10.4% of the rock. Mica, sericite, calcite, chert, chalcedony, magnetite, clay and iron oxide make up the rest of the rock. The framework is bound by clay and minor amounts of cement. Compaction has been minor. The sandstone was derived from a mixed-source area dominated by a metamorphic terrane. The outcrops are channel structures and lacustrine deposits.

Texture

1. The rock is supported by a partially to totally iron oxide-stained clay matrix (average 3.9%) with minor amounts of calcite, chalcedony and secondary quartz cement occasionally present within the framework grains. Grain contacts are an average 1.7 contacts/grain indicating a minor amount of compaction.
The sandstone is mainly cemented by the binding-clay matrix. Authigenic cements are minor. Only outcrop 21 has a significant amount of authigenic cement, with calcite comprising 7.3% of the sample. The minor compaction and precipitation of cements have reduced original porosities to an average 13.8%.

2. Grain size distribution is that of a moderately-sorted, medium-grained sand (Figure 24 and 25). Size distribution is skewed to fine sizes because of clay content.

3. The average visual roundness of the medium-sized quartz grains is 2.2 (subangular). Coarser grains tend to be more rounded.

4. The sandstone in region V is either immature due to clay content or, more often, submature as indicated by moderate sorting.

Mineralogy - Terrigenous Detritus (Table 5)

1. Quartz is separable into monocrystalline and polycrystalline grains, secondary quartz, chert and chalcedony. Most monocrystalline grains have several vacuoles and are subangular. A moderate amount of the grains show the effects of strain and are slightly undulose to undulose. There is a considerable amount of volcanic type quartz having large clear quartz grains with straight sides and rounded corners. A few grains have embayments.
Figure 24. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size ($M_z$) and Sorting or Standard Deviation ($\sigma_i$) of Sandstone Samples Collected at Outcrops 17, 18 and 19 of Region V.
Polycrystalline quartz is abundant, comprising an average 8.7% of the rock. Polycrystalline grains are dominantly of metamorphic origin. Approximately 18.0% of the monocrystalline and polycrystalline grains have slightly undulose to undulose extinction. Most of the quartz is either fresh or moderately altered. Chert comprises 2.1% of the rock and is indicative of a carbonate-rich, older sediment terrane contribution.
Table 5
Modal Analysis of Sandstone Samples From Outcrops 17, 18, 19, 20 and 21 of Region V.

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Outcrop 17</th>
<th></th>
<th>Outcrop 18</th>
<th></th>
<th>Outcrop 19</th>
<th></th>
<th>Outcrop 20</th>
<th></th>
<th>Outcrop 21</th>
<th></th>
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<tr>
<td></td>
<td>Point Ind.</td>
<td>Point Ind.</td>
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<td>Point Ind.</td>
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<tr>
<td></td>
<td>counts %</td>
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<td>counts %</td>
<td>counts %</td>
<td>counts %</td>
<td>counts %</td>
<td>counts %</td>
<td>counts %</td>
<td>counts %</td>
<td>counts %</td>
</tr>
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<tr>
<td>mono-</td>
<td>113</td>
<td>37.7</td>
<td>170</td>
<td>45.2</td>
<td>93</td>
<td>32.7</td>
<td>128</td>
<td>44.1</td>
<td>124</td>
<td>41.2</td>
</tr>
<tr>
<td>poly-</td>
<td>29</td>
<td>9.7</td>
<td>33</td>
<td>8.8</td>
<td>26</td>
<td>9.1</td>
<td>25</td>
<td>8.6</td>
<td>22</td>
<td>7.3</td>
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<tr>
<td>Feldspar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-spar</td>
<td>25</td>
<td>8.3</td>
<td>29</td>
<td>7.7</td>
<td>16</td>
<td>5.6</td>
<td>21</td>
<td>7.2</td>
<td>29</td>
<td>9.6</td>
</tr>
<tr>
<td>plag.</td>
<td>19</td>
<td>6.3</td>
<td>26</td>
<td>6.9</td>
<td>12</td>
<td>4.3</td>
<td>18</td>
<td>6.2</td>
<td>25</td>
<td>8.3</td>
</tr>
<tr>
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<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>sed.</td>
<td>12</td>
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<td>2.3</td>
</tr>
<tr>
<td>granitic</td>
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<td>6</td>
<td>2.1</td>
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</tr>
<tr>
<td>met.</td>
<td>12</td>
<td>4.0</td>
<td>11</td>
<td>2.9</td>
<td>9</td>
<td>3.2</td>
<td>8</td>
<td>2.8</td>
<td>7</td>
<td>2.3</td>
</tr>
<tr>
<td>vol.</td>
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<td>5</td>
<td>1.3</td>
<td>4</td>
<td>1.4</td>
<td>5</td>
<td>1.7</td>
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<td>0.9</td>
</tr>
<tr>
<td>Iron Oxide</td>
<td>12</td>
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<td>15</td>
<td>4.0</td>
<td>11</td>
<td>3.9</td>
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<td>2.4</td>
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<td>3.0</td>
</tr>
<tr>
<td>Magnetite</td>
<td>10</td>
<td>3.0</td>
<td>5</td>
<td>1.3</td>
<td>7</td>
<td>2.5</td>
<td>2</td>
<td>0.7</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Secondary qtz.</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>11</td>
<td>3.8</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Chert</td>
<td>7</td>
<td>2.3</td>
<td>9</td>
<td>2.4</td>
<td>7</td>
<td>2.5</td>
<td>6</td>
<td>2.1</td>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>Chaledony</td>
<td>3</td>
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<td>--</td>
<td>--</td>
<td>3</td>
<td>1.1</td>
<td>3</td>
<td>1.0</td>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>Sericite</td>
<td>5</td>
<td>1.7</td>
<td>2</td>
<td>0.5</td>
<td>6</td>
<td>2.1</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Mica</td>
<td>8</td>
<td>2.7</td>
<td>2</td>
<td>0.5</td>
<td>5</td>
<td>1.8</td>
<td>3</td>
<td>1.0</td>
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<td>0.9</td>
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<tr>
<td>Calcite</td>
<td>--</td>
<td>--</td>
<td>4</td>
<td>1.1</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>22</td>
<td>7.3</td>
</tr>
<tr>
<td>Pore space</td>
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<td>41</td>
<td>10.9</td>
<td>64</td>
<td>22.5</td>
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<td>12.6</td>
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<tr>
<td>Total</td>
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<td>376</td>
<td></td>
<td>284</td>
<td></td>
<td>290</td>
<td></td>
<td>301</td>
<td></td>
</tr>
</tbody>
</table>
2. Feldspars comprise an average 14.2% of the rock. They are present as varieties of plagioclase and potassium feldspar. K-spar is more abundant, with microcline being the dominant variety. Most microcline is albite-twinned; some grains are pericline-twinned. The feldspars range from unaltered to altered, with most grains being fresh. Plagioclase grains have the widest range of alteration. The feldspars are generally coarser than the quartz grains.

3. Rock fragments comprise an average 10.4% of the rock with metamorphic, granitic and older sediment fragments occurring in almost equal amounts. Volcanic fragments are significant, comprising an average 12.4% of the total amount of fragments. Metamorphic fragments are mainly basalt.

4. Mica is relatively abundant, comprising an average 1.4% of the rock. Muscovite is the dominant variety and is either floating in the matrix or bent around framework grains.

5. Iron oxide and magnetite are the dominant varieties of heavy minerals present in region V. Iron oxide comprises an average 3.5% of the rock and is usually in the form of hemitite. Magnetite is present as a minor constituent of all but one sample. Other heavy minerals are unidentified.
Chemical Constituents

Calcite is only present in two samples. It is a significant cement at outcrop 21. Minor amounts of chalcedony are present in most samples. Secondary quartz is only present at outcrop 20, where it comprises 0.8% of the sample.

Interpretation

Region V is dominated by lenticular and massive sandstone. Channel-fill conglomerate is present near the base of outcrop 19. The conglomerate is characterized by pebbles of quartz, quartzite, iron oxide, chert and slate. The lenticular sandstone channel structures were deposited in a high-energy fluvial environment of deposition while massive sandstone was deposited later in a shallow lake under a lower-energy regime. The source area for the sandstone was an iron oxide-rich, soil-covered, mixed-source terrane located approximately southeast of the depositional sites. The mixed terrane consisted of older sediments, plutonic, metamorphic and volcanic rock. The abundance of undulose grains, polycrystalline grains, quartzite, slate and mica indicate that the major source terrane was metamorphic. The abundance of quartzite and slate pebbles in the channel-fill are also indicative of a dominant metamorphic source
terrane. The increased abundance of volcanic quartz and basaltic rock fragments are evidence of a westward increase of volcanic source material when going from region I to region V.

The submaturity of the sandstone, the range of feldspar alteration and abundance of fresh feldspar indicate at least moderate tectonic instability at the time of deposition. The subangular, fresh appearance of grains and preservation of shale pebbles and abundant polycrystalline grains indicate a transport distance on the order of tens of miles. Rapid erosion and a relatively short transport distance allowed for very little alteration.

The source material was rapidly eroded in a semi-arid environment of at least moderate relief and, at first, deposited as channel structures. Massive sandstone was deposited later in a shallow-basin lake that transgressed over previous depositional sites.

Region VI

Sample Identification

Region VI includes outcrops 22 and 23. The description is based on a composite from samples collected at outcrop 23 located near Traverse Point and outcrop 22 located near the village of Jacobsville.
Field Relations

Outcrop 23 is a 16 foot beach-cliff exposure of massive sandstone. The beds range in thickness from 0.8 feet to 5 feet. There is some small-scale cross-bedding brought out by alternate red and tan laminations. Measurement of plunge gives an average northeast transport direction. Oscillation ripple marks located at two different horizons all trend in a general northwest direction. Amplitudes were between 0.1 to 0.3 inches, and wavelengths ranged from 1.5 to 4.0 inches. Outcrop 22 is a 25 foot beach-cliff exposure of massive sandstone. Bed thickness ranges from 4 feet to 12 feet. Moderate amounts of lamination are brought out by alternating pink and light tan coloring. Small-scale cross-bedding is present toward the base of some beds.

The massive sandstone was deposited by lower-energy currents in a shallow intra-basin lake. Oscillation ripple marks indicate flow direction was relatively constant for a long period of time. Transport directions for the material became northeast after entering the intra-basin lake.
Handspecimen Description

The sandstone is pinkish-red to light tan and lacks white mottling. Minor amounts of alternately-colored laminations occur at different horizons. The sandstone is fine-sand grained and moderately sorted. It is identified as a subarkose (Figure 26).

There is a moderate amount of cementation. Grains appear subangular in a moderately abundant iron-stained clay matrix. Only minor weathering and alteration is evident. Bedding is continuous and generally thick. There are small-scale planar and trough crossbedding and oscillation ripple marks present.

Thin Section Description

Thin Section Abstract

The sandstone is typically a moderately-sorted subarkose. Monocrystalline and polycrystalline quartz grains are subangular and comprise an average 65.8% of the rock. Feldspars are generally larger than quartz and comprise an average 7.6% of the rock. Rock fragments are mainly older sediment and also comprise an average 7.6% of the rock. The framework is bound by clay and secondary quartz cement. Compaction has been minor. The sandstone was derived from a mixed-source area dominated by an older sedimentary terrane. The outcrops are lacustrine deposits.
Figure 26. Mineralogic Classification for Sandstone Samples Collected at Outcrops 22 and 23 of Region VI (After Folk, 1974).

Texture

1. The rock is supported by a partially to mostly iron oxide-stained clay matrix (average 5.8%) and a moderate amount of secondary quartz cement within the framework grains. Grain contacts are an average 1.2 contacts/grain indicating a minor amount of compaction.

The sandstone is cemented by the binding clay and the secondary quartz cement.
comprises an average 2.5% of the rock. The minor compaction and precipitation of cement have reduced original porosities to an average 8.0%.

2. Grain size distribution is that of a moderately-sorted, fine-grained sand (Figure 27). Size distribution is skewed to fine sizes because of clay content.

3. The average visual roundness of the medium-sized quartz grains is 2.1 (subangular). Coarser grains tend to be more rounded.

4. The sandstone in region VI is immature due to the abundant clay content.

Mineralogy - Terrigenous Detritus (Table 6)

1. Quartz is separable into monocrystalline and polycrystalline grains, chert and secondary quartz cement. Volcanic and plutonic type quartz are present in nearly equal amounts. A moderate amount of plutonic-type quartz shows slight undulosity. Almost all of the semicomposite and polycrystalline grains show at least slightly undulose extinction. Polycrystalline quartz only comprises an average 4.7% of the rock. Nearly all of it shows the effects of metamorphism. Most of the quartz is subrounded, fine sand-sized grains and is fresh or moderately altered. Chert comprises an average 3.0% of the rock indicating a significant contribution from a carbonate-rich older sediment terrane.
Figure 27. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σ₁) of Sandstone Samples Collected at Outcrops 22 and 23 of Region VI.

2. Feldspars comprise an average 7.6% of the rock. They are present as varieties of plagioclase and potassium feldspar. K-spar is more abundant with microcline being the dominant variety. Most microcline is albite-twinned; some grains are pericline-twinned. The feldspars range from fresh to moderately altered in a single species. The microcline in region VI samples has a narrower range of alteration than the microcline in other regions.
Table 6
Modal Analysis of Sandstone Samples
From Outcrops 22 and 23 of Region VI.

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Outcrop 22</th>
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<th>Outcrop 23</th>
<th></th>
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</thead>
<tbody>
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<td></td>
<td>Point Ind. counts</td>
<td>%</td>
<td>Point Ind. counts</td>
<td>%</td>
</tr>
<tr>
<td>Quartz</td>
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<td>278</td>
<td>62.5</td>
</tr>
<tr>
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<td>15</td>
<td>5.4</td>
<td>19</td>
<td>4.3</td>
</tr>
<tr>
<td>Feldspar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-spar</td>
<td>11</td>
<td>4.0</td>
<td>20</td>
<td>4.5</td>
</tr>
<tr>
<td>plag.</td>
<td>8</td>
<td>2.9</td>
<td>16</td>
<td>3.6</td>
</tr>
<tr>
<td>Rock frag.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sed.</td>
<td>8</td>
<td>2.9</td>
<td>16</td>
<td>3.6</td>
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<td>granitic</td>
<td>3</td>
<td>1.1</td>
<td>7</td>
<td>1.6</td>
</tr>
<tr>
<td>met.</td>
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<td>1.1</td>
<td>8</td>
<td>1.8</td>
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<tr>
<td>vol.</td>
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<td>0.7</td>
<td>4</td>
<td>0.9</td>
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<tr>
<td>Iron Oxide</td>
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</tr>
<tr>
<td>Secondary qtz.</td>
<td>5</td>
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<td>13</td>
<td>2.9</td>
</tr>
<tr>
<td>Chert</td>
<td>10</td>
<td>3.6</td>
<td>12</td>
<td>3.6</td>
</tr>
<tr>
<td>Chalcedony</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Sericite</td>
<td>3</td>
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<tr>
<td>Total</td>
<td>227</td>
<td></td>
<td>445</td>
<td></td>
</tr>
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</table>

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3. Rock fragments comprise an average 7.0% of the rock. Older sedimentary fragments are by far the most abundant type. Most of the older sediments are older sandstones and siltstone. Shale and carbonate-sand fragments are also present. There are approximately equal amounts of metamorphic and granitic fragments. Volcanic fragments are present in minor amounts.

4. Mica comprises an average 0.9% of the rock. It is present in the form of muscovite and biotite. Most of the mica is oriented and floating in the matrix. Sericite is present in nearly equal amounts and is generally coarser than the mica.

5. Heavy minerals consist of iron oxide and magnetite. Iron oxide, mainly in the form of hematite, comprises an average 2.1% of the rock. Magnetite is relatively abundant. Other heavy minerals are rare and unidentified.

Chemical Constituents

Secondary quartz cement is the only chemical constituent present. It comprises an average 2.5% of the rock in region VI.

Interpretation

Region VI is dominated by massive sandstone deposited in a lacustrine environment where lower-energy, shallow-lake currents flowed in a relatively constant direction.
The source area for the sandstone was a mixed terrane covered by an iron oxide-rich soil. The mixed terrane consisted of older sediments, plutonic, volcanic and metamorphic rock. Older sediments were by far the most abundant fragment type. The abundance of older sedimentary fragments, red-clay matrix and chert, and subroundness of the quartz, indicate that the major source terrane was older sediments. The abundance of volcanic quartz indicates a significant volcanic terrane contribution of sediment even though very few volcanic fragments were preserved during erosion and transport. The abundance of feldspar, plutonic quartz, hemitite and magnetite is indicative of a considerable plutonic terrane contribution.

The immature nature of the sandstone and the moderately-wide range of alteration in the microcline indicates at least mild tectonic instability at the time of deposition. The subangular, moderately sorted, fine sand-sized grains were transported on the order of tens of miles or greater. The lack of less resistant volcanic fragments and polycrystalline grains may be due to a slightly longer transport distance for region VI material as compared to material deposited in region III through V. After rapid erosion the material was transported by drainage streams toward the intra-basin lake where the lower-energy currents only had the competence to carry the finer sand-sized grains
and smaller material to depositional sites well within the shallow-basin lake.

Region VII

Sample Identification

Region VII encompasses more area and outcrops than any other region. It includes outcrops 24 through 29. The description is based on a composite from region VII samples collected at the four northern most outcrops in the Keweenaw Peninsula and outcrops 28 and 29 located near Victoria Falls and at Agate Falls respectively.

Field Relations

Outcrop 25 is a thick stream-cut exposure of an alluvial fan-type conglomerate with interbedded massive sandstone and some mudstone. The sedimentary units here are located just southeast of the Keweenaw fault and have been folded into an asymmetrical antiformal structure. Beds in this area were folded by local faulting prior to induration (Babcock, 1975). Ripple mark casts are on the base of a resistant massive sandstone bed. Felsite and rhyolite pebbles are abundant in the easily dis-aggregated conglomerate. Outcrop 26 is a thick stream-cut exposure, at Houghton Falls, of an alluvial fan-type conglomerate with interbedded sandstone and shale. The
conglomerate here dips W16° and contains numerous, angular shale blocks. Outcrop 27, located at Hungarian Falls, is a cross section through the distal portion of an alluvial fan (Babcock, 1975). Lenticular sandstone channel structures, with various thicknesses of friable mudstone and conglomerate located at various horizons, dominate the exposure. Crossbedding plunge in the sandstone gives an average northeast transport direction. Outcrop 24 is an 11 foot thick Lake Superior beach-cliff exposure of massive sandstone. Beds are 2 to 5 feet thick and have moderate amounts of small-scale cross-bedding and laminations. Crossbedding plunge indicates an average northeast transport direction. Outcrop 28 is a stream-cut exposure just down river from Victoria Falls. The vertical 80 foot exposure is entirely composed of massive sandstone with beds up to 15 feet thick. Crossbedding and laminations are rare in the section of the exposure accessible to the writer. The only measured crossbedding plunge gives a N38°W transport direction. Outcrop 29 is a stream cut exposure of red siltstone at Agate Falls. The exposure is approximately 65 feet thick and consists of alternating thin beds of platey shale and silty sandstone. The siltstone is very friable.
The lenticular sandstone was deposited fluvially as channel structures. The conglomerates were deposited as portions of alluvial fans. Massive sandstone was deposited within intra-basin lakes. Red siltstone was deposited at and near intra-basin lake boundaries as deltaic deposits. Source area for the lenticular sandstones and outcrop 24 massive sandstone is to the southwest of the outcrops. The outcrop 28 sandstone source area is to the southeast of the outcrop.

**Handspecimen Description**

The sandstone ranges in color from deep red to light tan with moderate white mottling in the lenticular sandstone. Rusty-red, disc-shaped clay pebbles are moderately abundant in the lenticular sandstone. The sandstone is medium to coarse grained and moderately sorted. It is identified as a subarkose (Figure 28).

There is a moderate amount of cementation in the sandstones while siltstone and conglomerates are generally poorly cemented. Grains appear mainly subangular in moderate amounts of iron-stained clay matrix. Moderate weathering and minor amounts of alteration are evident. Sandstone bedding is either lenticular or massive. The lenticular sandstone has some small-scale crossbedding.
Figure 28. Mineralologic Classification for Sandstone Samples Collected at Outcrops 24, 25, 26, 27, 28 and 29 of Region VII (After Folk, 1974).

and abundant laminations. The massive sandstone has abundant small-scale crossbedding at one outcrop and moderate to minor laminations.

Thin Section Description

Thin Section Abstract

The sandstone is typically a moderately-sorted, pebbly subarkose. Monocrystalline and polycrystalline grains
are subangular and comprise an average 63.0% of the rock. Feldspars are generally coarser than quartz and comprise an average 8.8% of the rock. Rock fragments are mainly granitic, metamorphic and older sediment and comprise an average 5.4% of the rock. Mica, sericite, chert, chalcedony, magnetite, clay and iron oxide make up the rest of the rock. The framework is bound by clay and secondary quartz cement. Compaction has been moderate. The sandstone was derived from a mixed-source area dominated by a plutonic terrane. Outcrops are lacustrine and deltaic deposits, and parts of alluvial fans and channel structures.

**Texture**

1. The rock is supported by a partially to totally iron oxide-stained clay matrix (average 3.4%) with moderate to abundant amounts of secondary quartz cement within the framework grains. Grain contacts are an average 2.5 contacts/grain indicating a moderate amount of compaction.

   The sandstone is mainly cemented by the binding clay and secondary quartz cement. Secondary quartz cement comprises an average 3.1% of the rock and is present in all but one sample. The moderate compaction and precipitation of cement have reduced original porosities to an average 12.6%.
2. Grain size distribution is that of a moderately sorted, medium-to-coarse-grained sand (Figure 29 and 30). Size distributions are skewed to fine size because of the clay content.

3. The average visual roundness of the medium-sized quartz grains is 2.3% (subangular). Coarser grains tend to be more rounded.

4. The sandstone in region VII is submature based on the moderate sorting.

Mineralogy - Terrigenous Detritus (Table 7)

1. Quartz is separable into monocrystalline and polycrystalline grains, secondary quartz cement, chert and chalcedony. Large, clear volcanic quartz and smaller, more angular, bubbly, plutonic quartz comprise the vast majority of monocrystalline grains. Most of the grains show straight extinction. There is a minor amount of semicomposite grains, most of which are slightly undulose. The moderately abundant (average 6.4%) polycrystalline grains show straight to undulose extinction. Most polycrystalline grains are metamorphic in origin though a considerable amount appear to be plutonic in origin based on the unoriented equal-sized grains. The quartz grains range from unaltered to altered but are
Figure 29. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size ($M_z$) and Sorting or Standard Deviation ($\sigma'$) of Sandstone Samples Collected at Outcrops 24, 25 and 26 of Region VII.
Figure 30. Cumulative Curves (probability ordinate) for Sand-size Particles and Calculated Sediment Parameters of Mean Grain Size (Mz) and Sorting or Standard Deviation (σ1) of Sandstone Samples Collected at Outcrops 27, 28 and 29 of Region VII.
Table 7
Modal Analysis of Sandstone Samples From Outcrops 24, 25, 26, 27, 28 and 29 of Region VII.

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Outcrop 24 Point Ind. counts %</th>
<th>Outcrop 25 Point Ind. counts %</th>
<th>Outcrop 26 Point Ind. counts %</th>
<th>Outcrop 27 Point Ind. counts %</th>
<th>Outcrop 28 Point Ind. counts %</th>
<th>Outcrop 29 Point Ind. counts %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mono</td>
<td>198 50.5</td>
<td>161 57.3</td>
<td>157 58.1</td>
<td>211 55.1</td>
<td>243 62.0</td>
<td>181 57.1</td>
</tr>
<tr>
<td>poly</td>
<td>41 10.5</td>
<td>19 6.8</td>
<td>17 6.3</td>
<td>26 6.8</td>
<td>15 3.8</td>
<td>13 4.1</td>
</tr>
<tr>
<td>Feldspar</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-spar</td>
<td>16 4.1</td>
<td>12 4.3</td>
<td>13 4.8</td>
<td>19 5.0</td>
<td>24 6.1</td>
<td>14 4.4</td>
</tr>
<tr>
<td>plag.</td>
<td>22 5.6</td>
<td>9 3.2</td>
<td>12 4.4</td>
<td>13 3.4</td>
<td>14 3.6</td>
<td>11 3.5</td>
</tr>
<tr>
<td>Rock frag.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sed.</td>
<td>6 1.5</td>
<td>2 0.7</td>
<td>6 2.2</td>
<td>5 1.3</td>
<td>9 2.3</td>
<td>5 1.6</td>
</tr>
<tr>
<td>granitic</td>
<td>6 1.3</td>
<td>4 1.4</td>
<td>2 0.7</td>
<td>1 0.3</td>
<td>3 0.8</td>
<td>3 0.9</td>
</tr>
<tr>
<td>met.</td>
<td>5 1.3</td>
<td>2 0.7</td>
<td>1 0.3</td>
<td>3 0.8</td>
<td>3 0.9</td>
<td></td>
</tr>
<tr>
<td>vol.</td>
<td>5 1.3</td>
<td>2 0.7</td>
<td>1 0.3</td>
<td>3 0.8</td>
<td>3 0.9</td>
<td></td>
</tr>
<tr>
<td>Iron Oxide</td>
<td>6 1.5</td>
<td>7 2.5</td>
<td>11 4.1</td>
<td>13 3.4</td>
<td>9 2.3</td>
<td>7 2.2</td>
</tr>
<tr>
<td>Magnetite</td>
<td>2 0.5</td>
<td>2 0.7</td>
<td>--</td>
<td>--</td>
<td>3 0.8</td>
<td>--</td>
</tr>
<tr>
<td>Secondary qtz.</td>
<td>14 3.6</td>
<td>23 8.2</td>
<td>2 0.7</td>
<td>16 4.2</td>
<td>--</td>
<td>9 2.8</td>
</tr>
<tr>
<td>Chert</td>
<td>7 1.8</td>
<td>6 2.1</td>
<td>--</td>
<td>--</td>
<td>10 2.6</td>
<td>8 2.0</td>
</tr>
<tr>
<td>Chaledony</td>
<td>2 0.5</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Sericite</td>
<td>4 1.0</td>
<td>--</td>
<td>5 1.9</td>
<td>2 0.5</td>
<td>4 1.0</td>
<td>7 2.2</td>
</tr>
<tr>
<td>Mica</td>
<td>1 0.3</td>
<td>--</td>
<td>3 1.1</td>
<td>--</td>
<td>4 1.0</td>
<td>7 2.2</td>
</tr>
<tr>
<td>Calcite</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Pore space</td>
<td>55 14.0</td>
<td>31 11.0</td>
<td>35 13.0</td>
<td>50 13.1</td>
<td>48 12.2</td>
<td>41 12.9</td>
</tr>
<tr>
<td>Total</td>
<td>392</td>
<td>281</td>
<td>270</td>
<td>383</td>
<td>392</td>
<td>317</td>
</tr>
</tbody>
</table>
mainly fresh. Chert comprises an average 1.8% of the rock indicating a carbonate-rich older sediment terrane contribution.

2. Feldspars comprise an average 8.8% of the rock. They are present as varieties of plagioclase and potassium feldspar. K-spar is more abundant with microcline being the dominant variety. Most of the microcline is albite-twinned. Pericline twins are present in minor amounts. The feldspar ranges from moderately altered to unaltered in a single species. Most feldspars are either fresh or moderately fresh. Grains are generally coarser and more rounded than the typical quartz grains of region VII.

3. Rock fragments comprise an average 5.4% of the rock with granitic, older sediment and metamorphic fragments present in nearly equal amounts. Volcanic fragments comprise 14.4% of the total amount of fragments. Sedimentary fragments are mainly shale and older sandstone. Metamorphic fragments are mainly quartzite.

4. Mica is present in most samples and comprises an average 0.7% of the rock. Muscovite and biotite are the varieties of mica present. The mica is typically bent around framework grains.

5. Heavy minerals are fairly abundant comprising an average 3.2% of the rock. Hematite and magnetite are the most abundant heavy minerals. Other heavy minerals are unidentified.
Chemical Constituents

Secondary quartz cement is found in moderately abundant amounts throughout the region. Chalcedony is present in only one sample as a minor constituent. Calcite is not present in region VII samples.

Interpretation

In the central part of the Keweenaw Peninsula, region VII is dominated by alluvial fan-type conglomerates with interbedded sandstone, shales and mudstones. North trending lenticular sandstone structures cut into the alluvium at outcrop 27. Massive sandstone dominates two of the outcrops and red siltstone is the only unit present at outcrop 29.

The conglomerates and interbedded sediments were deposited with mud flows as portions of alluvial fans formed at basin margins where rapid subsidence and local faulting controlled sedimentation. The conglomerate was derived from a nearby source area. The transport direction for the alluvium was locally controlled by the trends of the sub-basin faults. Lenticular channel structures were fluvially deposited by northeast flowing currents that cut into the alluvium at some locations. The depositional environment changed from fluvitile to
lacustrine allowing outcrop 24 sandstone to be deposited by northeast-flowing, low-energy currents well within a sub-basin shallow lake.

The massive sandstone and red siltstone of outcrops 28 and 29 appear to be deposited in a different sub-basin than other outcrops in region VII. Transport direction for the massive sandstone is N38°W indicating a source area to the southeast. The red siltstone was deposited in a deltaic environment located in the area of a lake margin. The red siltstone is located to the southeast of the massive sandstone and could mark the edge of the lake that the massive sandstone was deposited in.

The source areas for the sandstones were mixed terranes covered by iron oxide-rich soil. The abundance of granitic rock fragments, plutonic quartz grains, and feldspar indicate that the major source terrane was plutonic. The presence of alluvium in fault zone areas, the submaturity of the sandstone and the wide range of alteration in a single feldspar species indicates tectonic instability at the time of deposition. The subangular, fresh, moderately sorted, medium to coarse sand-sized grains, preservation of clay clasts and abundant feldspar indicate a transport distance on the order of tens of miles. Rapid erosion and deposition allowed only slight weathering and alteration.
Rapid subsidence and faulting resulted in the formation of sub-basins of deposition. Alluvial fan deposits occurred along the trend of faults where basin tilting was the greatest. The semi-arid environment and moderate to high relief caused rapid erosion of source areas. Source areas for the alluvium were the terranes on the uplifted sides of the basin margin faults. Lenticular sandstone was then deposited fluvially in the basins. The source area for the lenticular sandstone and massive sandstone of outcrop 24 was to the southwest. Outcrop 24 massive sandstone was later deposited away from the basin margin within a shallow lake. The massive sandstone and red siltstone of outcrops 28 and 29 were probably deposited in a separate sub-basin lake. The source area was located to the southeast. The red siltstone was a deltaic deposit on the edge of the lake while the massive sandstone was transported further away from the source to well within the lake.
CONCLUSION

The results of the petrographic analysis for each region show that the Jacobsville Formation changes regionally in the relative abundance of sediment contribution from the different types of source terrane. Also, the range of constituents present from region to region remains relatively constant across the sampled area. Constituents not being common to most regions are rare.

The material comprising the Jacobsville Formation was derived from a mixed-source terrane with different terrane types being the dominant material contributor in different depositional regions. The dominant source terranes were older sediment, plutonic, metamorphic and volcanic. The source areas were covered by a weathered soil zone as indicated by the amount of resistant debris and the simple heavy mineral assemblage that remains fairly constant over a large area and throughout the stratigraphic section (Denning, 1949 and Driscoll, 1956). Jacobsville deposition was preceded by tectonic stability, allowing the soil to accumulate and become weathered. As the soil eroded away, more of the basement rocks became exposed and eroded, allowing feldspar to increase in abundance above the base of the sandstone (Kalliokoski, 1982).
Major sources of the older sediment, which is the dominant type of material in three of the seven regions of deposition, was the weathered soil zone and the Freda Sandstone Formation. The Freda is an Upper Keweenawan formation occurring unconformably below the Jacobsville Formation (Figure 4). The Freda Sandstone consists of arkoses, feldspathic sandstones and micaceous shale. Quartz with abraded overgrowths and significant amounts of subrounded quartz present in the Jacobsville are from recycled sandstone. Several of the older sandstone pebbles in the Jacobsville are identical to pebbles in the Freda. The Jacobsville represents, at least in part, second cycle Freda Sandstone (Hamblin, 1961).

Previously-deposited Keweenawan rocks also comprise at least some of the volcanic source terranes which contributed more sediment in the western regions of deposition. Basalt boulders and pebbles in the alluvial conglomerate, volcanic quartz and volcanic rock fragments were, at least in part, derived from the Middle Keweenawan Portage Lake Volcanics which are concentrated at and beyond the western half of the outcrop belt.

The abundance of undulose quartz and quartzite, found throughout the outcrop belt, and the presence of quartz-staurolite and somewhat-altered iron oxide pebbles in the channel-fill conglomerates, suggest a source in
the chlorite-to-staurolite grade metamorphic zones and iron ranges in Michigan's upper peninsula (Figure 31). This area was probably a basement highland at the time of Jacobsville deposition where streams diverged radially away from the highland to join major, basin-influenced, depositional streams which carried the eroded material to widespread depositional sites.

The paleocurrent directions of the Jacobsville Formation, as determined by the plunge of trough cross-bedding, are shown in Figure 32. There are three major directions of transport: north, northeast and northwest. This may indicate that there were two major basins of deposition partially separated by a source highland, with the chlorite-to-staurolite metamorphic zones possibly being a portion of the highland. One basin was located to the north of the eastern two-thirds of the outcrop belt, and the other basin was located to the west and northwest of the Keweenaw Peninsula. The major source areas were located to the southeast of the western end of the outcrop belt and to the south of the eastern two-thirds of the outcrop belt.

By looking at the average modal analysis results for each of the regions (Table 8), one can see that the material in regions I and II is better sorted, more rounded and more altered than the material deposited
Figure 31. General Map of Upper Peninsula Area Showing the Iron Formation Ranges and the Staurolite and Chlorite Zones of Regional Metamorphism in the Precambrian Rocks (After James, 1955).
Figure 32. General Map of Upper Peninsula Area Showing Paleocurrent Directions in the Jacobsville Sandstone.
Table 8
The Averaged Modal Analysis Results for Each of the Depositional Regions.

<table>
<thead>
<tr>
<th></th>
<th>Region I</th>
<th>Region II</th>
<th>Region III</th>
<th>Region IV</th>
<th>Region V</th>
<th>Region VI</th>
<th>Region VII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorting (σ)</td>
<td>.31 vws</td>
<td>.43 ws</td>
<td>.68 ms</td>
<td>.62 ms</td>
<td>.60 ms</td>
<td>.85 ms</td>
<td>.57 ms</td>
</tr>
<tr>
<td>Roundness (ρ)</td>
<td>3.3 sr</td>
<td>2.7 sr</td>
<td>2.2 sa</td>
<td>1.8 a</td>
<td>2.2 sa</td>
<td>2.3 sa</td>
<td>2.3 sa</td>
</tr>
<tr>
<td>Alteration</td>
<td>2.2 mf</td>
<td>2.3 mf</td>
<td>1.6 f</td>
<td>1.7 f</td>
<td>1.6 f</td>
<td>1.8 f</td>
<td>1.6 f</td>
</tr>
<tr>
<td>Grain diam. (mm)</td>
<td>.33 ms</td>
<td>.32 ms</td>
<td>.47 ms</td>
<td>.31 ms</td>
<td>.35 ms</td>
<td>.18 fs</td>
<td>.31 ms</td>
</tr>
<tr>
<td>Mono. quartz (%)</td>
<td>52.2</td>
<td>42.5</td>
<td>36.2</td>
<td>46.4</td>
<td>40.5</td>
<td>61.1</td>
<td>56.6</td>
</tr>
<tr>
<td>Poly. quartz (%)</td>
<td>4.9</td>
<td>8.0</td>
<td>5.2</td>
<td>5.0</td>
<td>8.7</td>
<td>4.7</td>
<td>6.4</td>
</tr>
<tr>
<td>Feldspars (%)</td>
<td>12.4</td>
<td>10.1</td>
<td>12.2</td>
<td>11.9</td>
<td>14.2</td>
<td>7.6</td>
<td>8.8</td>
</tr>
<tr>
<td>Rock frags. (%)</td>
<td>13.9</td>
<td>13.0</td>
<td>12.2</td>
<td>8.5</td>
<td>10.4</td>
<td>7.0</td>
<td>5.4</td>
</tr>
<tr>
<td>Contacts/grain</td>
<td>2.2</td>
<td>2.7</td>
<td>1.6</td>
<td>1.8</td>
<td>1.7</td>
<td>1.2</td>
<td>2.5</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>5.1</td>
<td>11.3</td>
<td>18.0</td>
<td>13.4</td>
<td>13.8</td>
<td>8.0</td>
<td>12.6</td>
</tr>
</tbody>
</table>
in regions I and II and was in a highly-weathering medium for a longer period of time than material deposited in other regions. The greater amount of weathering was due to a longer time in transport because of lower relief and longer distance between source and basin in the east. The occurrence of alluvial fans and abundant faulting in the west indicate that the basin was tilted more there. The ratio of feldspar to rock fragments increases when going from east to west and indicates that the higher relief in the west eroded the soil cover faster, allowing more basement rock to be eroded. Overall, the distance of transport for Jacobsville sediments was relatively short, as indicated by the general grain freshness, angularity and moderate sorting found in most samples.

Though relief was greatest in the west, tectonic instability existed across the entire depositional area. According to the properties of a tectonic arkose (Krynine, 1948), the immature-to-submature nature of the rocks, the abundance of dominantly fresh, coarse feldspars and the wide range of alteration in a single species of feldspar are evidence of the tectonic instability that existed.

The climate at the time of deposition was semi-arid as indicated by the fluvial-to-lacustrine environments of deposition for the formation's four facies types. Tolunay's (1970) sedimentological study of the Jacobsville
concluded that the environment was semi-arid based on grain size distribution analysis, CM diagram, and a morphometric study based on roundness and elongation of individual pebbles. Roy and Robertson (1978) did a paleomagnetic study that gives an equatorial location for the area during Jacobsville sedimentation, so the climate may also have been warm.

Jacobsville deposition occurred in a semi-arid environment after the axis of the Midcontinental Rift sank with respect to source areas. Rapid erosion was initiated at fault-bounded basin margins in the west where alluvial conglomerates and mudflows were originally deposited. The soil zone cover was eroded first, followed by the erosion of basement highlands. Streams carried material radially away from existing highlands to major drainage streams that eventually deposited the material in the basins to the north and northwest after a relatively short distance of high-energy transport. Eventual transgression of the basin waters allowed lacustrine and deltaic/lacustrine deposition to occur in shallow lakes, covering previously-deposited alluvial fans and channel structures in later phases of Jacobsville deposition.
BIBLIOGRAPHY


