the Precambrian is well illustrated on the east side of the Precambrian area of the Upper Peninsula of Michigan and northern Wisconsin." In the absence of the Freda Formation, the Jacobsville overlies basement rock.

The feldspar content of the Jacobsville is similar to the whole of the Freda and the Orienta. Analyses of outcrop samples collected from the Jacobsville Formation between Marquette and Munising in the Upper Peninsula of Michigan indicate feldspar contents of from 20 to 40 percent, although some beds may contain less than 5 percent.

The lithologic, mineralogic, and textural character of the Jacobsville, plus paleomagnetism and other characteristics, is interpreted to indicate that the Jacobsville may be equivalent to either or both the Freda and the Orienta.

Rock units in southern Wisconsin and southeastern Minnesota that are tentatively correlated with the Devils Island Formation include the Hinckley Formation of northeastern Minnesota, the "Hinckley-Mt. Simon" of southeastern Minnesota, and the Mt. Simon Sandstone of Wisconsin. The bases for correlation are (1) similar stratigraphic position, namely above either Precambrian crystalline rock or rock of the Oronto Group and below the Eau Claire Formation; (2) lithologic and mineralogic similarity; (3) contact relationships that show conformity and unconformity at the base and conformity and transition at the top; and (4) occurrence within the same geological and structural province, namely the structural feature manifest as the Midcontinent Gravity High.

RESERVOIR CHARACTERISTICS OF THE KEWEENAWAN SUPERGROUP, LAKE SUPERIOR REGION

Richard W. Ojakangas

INTRODUCTION

This is a brief review of the stratigraphic, sedimentologic, and petrographic characteristics of the several thousand meter thick, post-volcanic, siliciclastic Keweenawan Supergroup in the Lake Superior region with an emphasis on petroleum reservoir potential. It has been known for several decades that the black Nonesuch Shale, low in the post-volcanic rock column, is rich in organic material and even exudes petroleum in the Copper Range Mine, White Pine, Michigan. During late Precambrian time, many sedimentary and volcanic rock units were deposited in the Lake Superior region. The upper Precambrian rock column can be thought of as consisting of three sequences: pre-volcanic quartz sandstone (Ojakangas and Morey, 1982a), Keweenawan volcanic rock (Green, 1982b), and the post-volcanic sedimentary rock units that are the subject of this paper.

Keweenawan Supergroup rock, a red bed sequence that includes the Oronto Group and the overlying Bayfield Group, and their correlative rock units, are dominated by coarse clastic units that have potential as reservoir rock for petroleum that may have been generated within the Nonesuch Shale during deep burial. Few published data are available on porosity and permeability of these units. Petrography has focused on the framework composition of the sandstone and conglomerate, rather than on diagenesis.

STRATIGRAPHY AND SEDIMENTOLOGY

The post-volcanic sedimentary rock units were deposited in and adjacent to the Midcontinent Rift all along its 1,400 km length, but are exposed only in the

Lake Superior region. Following the first rather thorough field study by Thwaites (1912), several geologists studied the post-volcanic sedimentary rock in the Lake Superior region. A recent review has been provided by Dickas (1986) and more detailed data on the Oronto and Bayfield Groups, respectively, can be found in Daniels (1982) and Morey and Ojakangas (1982). A summary of Keweenawan sedimentation is also available (Ojakangas and Morey, 1982b). A generalized rock column is presented as figure 1.

Paleocurrent studies for each of the units show that the depositing currents moved from the edges toward the center of the basin that existed during late Keweenawan time in the Lake Superior region (fig. 2).

The lowest and coarsest formation, the Copper Harbor Conglomerate, exhibits characteristics typical of alluvial fan-braided stream deposition, and fines both upward and basinward (Daniels, 1982). Mudstone and limestone, including stromatolitic beds, represent less than 1 percent of the formation.

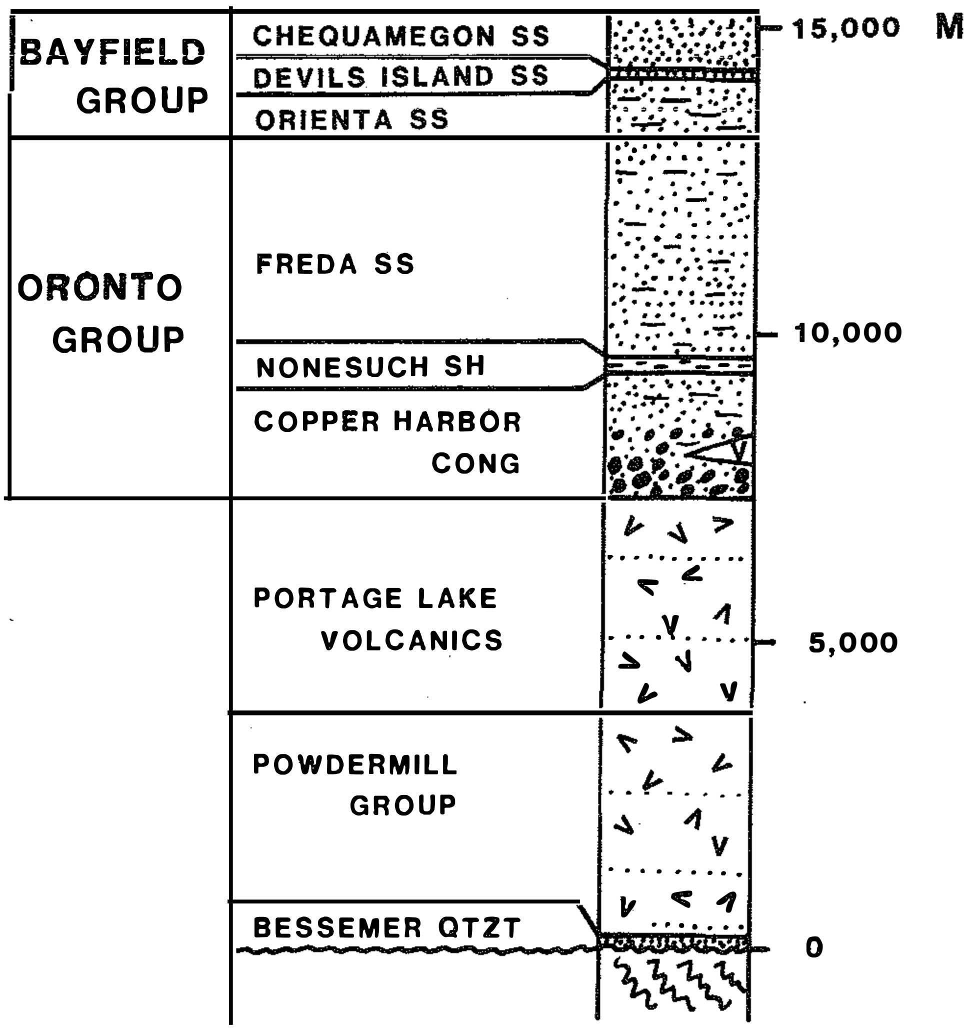

Figure 1. Generalized column of the Keweenawan Supergroup.

Conglomerate composed of volcanic rock is dominant in the lower half of the formation, and sandstone in the upper half.

The Nonesuch Shale is a dominantly black, organic-rich, shale-mudstone that exudes thick, black petroleum from joints in the Copper Range Copper Mine at White Pine, Michigan. The 180 m of black shale probably accumulated in a lacustrine environment, with the lower part equivalent in age to the upper part of the Copper Harbor Conglomerate, as summarized by Daniels (1982). The contact with the Copper Harbor is gradational, and some conglomerate is present. For example, one 3-m thick bed in the valley of Parker Creek, Wisconsin, near the Wisconsin-Michigan border is graded from 20 cm boulders at the base to fine sand at the top, and may be the product of a large turbidity current. The sandstone in the lower part of the formation, as seen in the Copper Range Mine, is abundantly trough cross-bedded with sets on the order of 25- to 50-cm thick. Various tool and scour marks are present on the sole of the "upper sandstone" (a bed as thick as 1.2 m) that forms the roof in many areas of the mine. The formation in general displays a myriad of primary bedding plane and internal sedimentary structures, including mudcracks and mudchip layers.

The Freda Sandstone has been studied by numerous workers, including Hamblin (1961), Hite (1968), and Daniels (1982). The formation, consisting largely of sandstone but including 10 percent siltstone and some conglomerate, is generally interpreted as a fining-upward fluvial sequence.

The Orienta Sandstone (Myers, 1971) is also fluvial. The correlative Fond du Lac Formation to the west in Minnesota is probably continuous with the

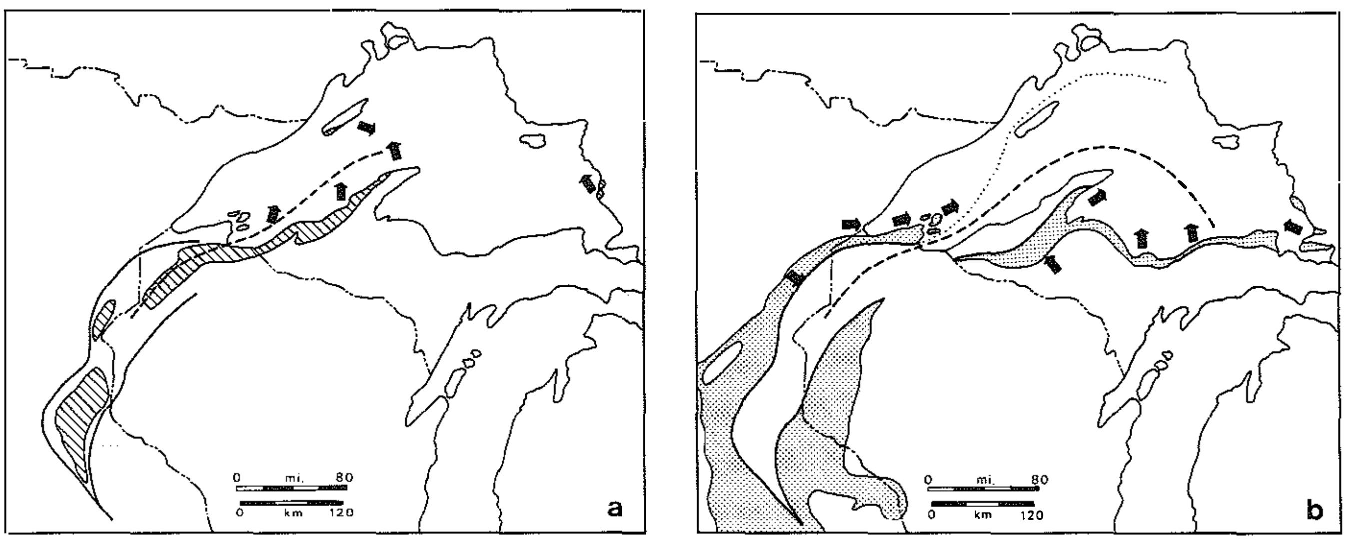

Figure 2. Paleocurrent trends in the Oronto and Bayfield Groups and equivalent units (from Ojakangas and Morey, 1982b). In (a), the arrow on the east end of Lake Superior represents the "Mica Bay Sandstone"; the cross-hatched areas in southeastern Minnesota are subsurface occurrences, the dashed line is the axis of the Lake Superior Syncline, and the solid heavy lines are major faults. In (b), the two westernmost arrows represent the Fond du Lac Formation and the Hinckley Sandstone, and those in Michigan and Ontario represent the Jacobsville Sandstone. The strippled areas in southeastern Minnesota and adjacent Wisconsin are subsurface occurrences.

Orienta in the subsurface and has a similar history (Morey, 1967; Morey and Ojakangas, 1982).

The orthoquartzitic Devils Island Sandstone (Myers, 1971) and the correlative and perhaps continuous Hinckley Sandstone to the west in Minnesota (Tryhorn and Ojakangas, 1972) may be products of the reworking of Fond du Lac feldspathic and lithic detritus in a lacustrine environment. However, it seems likely that eolian action on the vegetationless Fond du Lac and Orienta alluvial plains was a major factor in the maturation of the sediment, perhaps prior to final deposition in a lake or lakes.

The Chequamegon Sandstone (Myers, 1971) is similar to the Orienta and appears to be fluvial.

The Jacobsville Sandstone is as thick as 300 m and is the youngest unit from the Keweenaw Peninsula on eastward. It is variable in texture and composition, ranging from feldspathic and orthoquartzitic sandstone to shale, siltstone, and conglomerate (Kalliokoski, 1982). I observed places where the conglomerate consists largely of resistant pebbles and cobbles, including iron-formation, jasper, chert, quartzite, and vein quartz. Kalliokoski (1982) has described palesols from beneath the formation; the mineralogical maturity of the conglomerate is compatible with this finding.

A dominant alluvial fan-fluvial environment is indicated (Kalliokoski, 1982). Further evidence of fluvial processes is provided by the variance (the square of the standard deviation) calculation on cross-bedding measurements. Groups of cross-beds measured at three Jacobsville localities near Sault St. Marie, Ontario, at the east end of Lake Superior (N = 10); on Cisco River northeast of Marenisco, Michigan (N = 10); and in railroad and river cuts northwest of Wakefield, Michigan (N = 32), have calculated variances of 3,723, 2,284, and 1,903, respectively. Variances of less than 4,000 (Long and Young, 1978) or 6,000 (Potter and Pettijohn, 1977) are thought to be typical of fluvial environments.

PETROGRAPHY

The sandstone of the Keweenawan Supergroup (fig. 1) in general becomes more mature mineralogically and texturally upward in the column (fig. 3). An exception is the Chequamegon, which presumably is younger than the Devils Island but which has about the same composition as the Orienta and Fond du Lac Sandstones. It has been suggested (Mudrey, 1979) that the Chequamegon does not overlie the Devils Island, but is instead the Orienta; this is a problem that may be resolvable with detailed field study. On figure 3 the lithic pole consists largely of volcanic rock fragments derived from the underlying Keweenawan flows, whereas most of the feldspar and the quartz probably had an extra-basinal source.

There is nearly a total lack of porosity data. Original porosity in some Copper Harbor sandstones has been estimated at 20-25 percent by White and Wright (1954) and Wolff and Huber (1973), and Daniels (1982) listed the present average porosity of the Copper Harbor at 3 percent. To crudely estimate porosity, I point-counted two random thin sections of sandstone from each formation (300 points on each), delineating only sand-sized grains, matrix-cement, and pores. The results (table 1) indicate as expected, low porosity in the lower formations and a higher porosity in the upper formations. Low in the sequence, most primary pore space has been filled by various cements, including calcite,

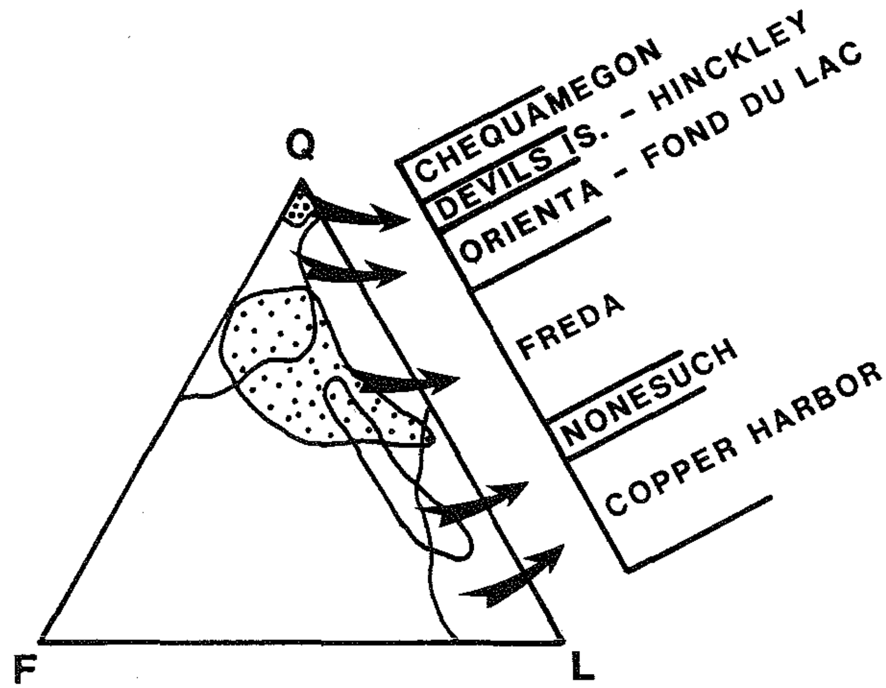

Figure 3. QFL triangle with fields of five sandstone units. Based on data from Daniels (1982), Morey (1967; 1974), Myers (1971), and Tryhorn and Ojakangas (1972). The Chequamegon Sandstone is not shown, but its plot is nearly identical to that of the Orienta Sandstone.

Table 1. Crude estimate of porosity of Lake Superior sandstones, based on averages of only two thin sections of sandstone per formation with 300 points counted on each. Some porosity estimates may be high due to grains lost during thin-section preparation.

	Framework matrix		
	Grains	Cement	Pores
Chequamegon Sandstone	70%	16%	14%
Hinckley Sandstone	66	14	20
Jacobsville Sandstone	76	18	6
Fond du Lac Formation	77	16	7
Freda Sandstone	72	26	2
Nonesuch Shale	70	25	5
Copper Harbor Conglomerate	77	20	3

silica, zeolite (laumontite), hematite, chlorite, other clay minerals, and feldspar. The highest grade of metamorphism, lower greenschist facies, occurs low in the sequence, and zeolite facies is prevalent (Hubbard, 1975). Therefore, both diagenesis and metamorphism contributed to the elimination of original porosity. In the upper mature quartzose sandstone units, original porosity should have been higher than in the more poorly sorted sandstone of the lower formations, most of which contained some original clayey matrix. However, cementation by silica, kaolinite, and feldspar has eliminated much of the original porosity.

Secondary porosity may exist, especially at depth, but has not been documented in the Keweenawan Supergroup. Obviously much needs to be done on both primary and secondary porosity studies before reservoir potential can be given a valid appraisal.

PETROLEUM TRAPS

Several types of traps are likely to be present within the sequence, including anticlinal, fault, unconformity, and varieties of stratigraphic traps.

An anticline has been interpreted from seismic data beneath Lake Superior off the Bayfield Peninsula (fig. 4); this anticline can be projected onshore. Others, large and small also exist, especially in the Oronto Group, as summarized by Craddock (1972a).

Numerous faults are present and the movement of reservoir beds into contact with impermeable shale or lava is possible. The most detailed information

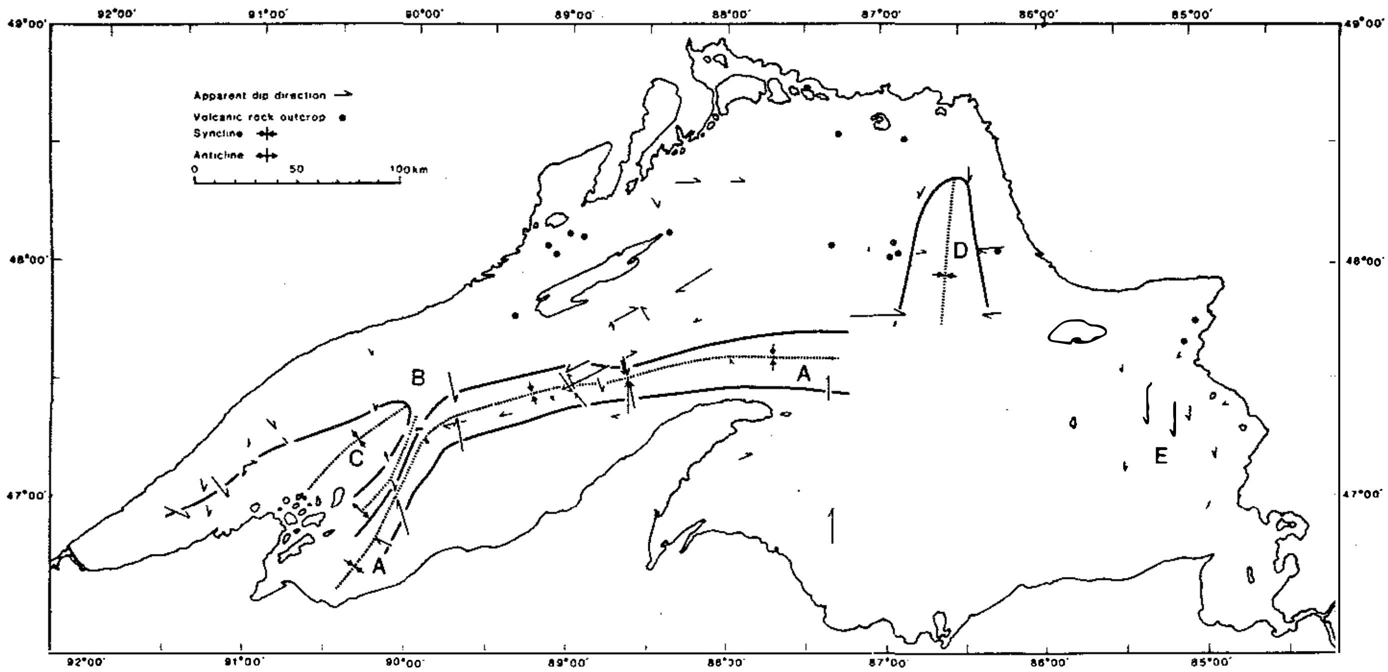

Figure 4. Apparent dip directions to subcrops observed on seismic-reflection profiles. A = Lake Superior depositional syncline; B = Anticline; C = southwest-plunging syncline; D = south-plunging syncline; E = south apparent dips. (from Wold and others, 1982).

relevant to fault traps is a subsurface geological study by Morey (1974) in the vicinity of the St. Croix Horst in east-central Minnesota. His cross section indicates that such traps are likely.

A major unconformity may exist between the Oronto Group and the overlying Bayfield Group. This speculation is based on the fact that the Oronto Group rock commonly has steep dips (some beds are vertical or overturned); the Bayfield Group rocks are subhorizontal. For example, south of Ashland, Wisconsin, steeply-dipping Freda rock form the flanks of the Ashland syncline; a few kilometers to the north, Bayfield Group rock is subhorizontal. However, the importance of drag along faults (such as the Douglas Fault) is difficult to evaluate. If there is indeed an unconformity at this stratigraphic horizon, a regolith may be required as an impermeable seal over the Oronto Group. Paleosols could form cap rock at other unconformities, as between the Solor Church and the Hinckley where the Fond du Lac is missing, and below the Upper Cambrian units, where they rest unconformably upon the Precambrian sedimentary units.

Stratigraphic traps of various types could be present. The fining-upward sequences so common in fluvial rock commonly contain shale units in their upper parts and these would serve as a local impermeable cap on the lower sandy part of the cycle. Such traps should be common, for the Copper Harbor, Freda, Orienta, Fond du Lac, Chequamegon, and Jacobsville appear to be fluvial deposits. For example, Morey (1974) described microcycles and megacycles in the subsurface Solor Church Formation. I have logged a 656-m thick drill core of Fond du Lac Formation about 65 km southwest of Duluth and counted 171 fining-upward fluvial cycles that composed 88 percent of the core (see Morey and Ojakangas, 1982, p. 142). Some of the thicker cycles are 18 m thick and the average thickness is 3.4 m; thus, some could constitute sizeable traps for petroleum (and uranium), perhaps in a stacked sequence. Such fluvial traps have been reviewed by Galloway and Hobson (1983).

Other miscellaneous sand lenses could be present in all the fluvial formations, including miscellaneous sand beds and lenses in the Nonesuch Shale itself. With the steep attitudes of the formations of the Oronto Group, it is even possible that stratigraphically lower Copper Harbor sandstones updip from Nonesuch source rocks could be a reservoir. The quartzose units of the Bayfield Group and their equivalents may be the best reservoirs from a textural point of view, but cap rock is lacking unless the regolith at the Upper Cambrian-Precambrian unconformity constitutes an impermeable cap.

CONCLUSIONS

The thick Keweenawan Supergroup, despite its age of about 1,100 to 1,000 Ma, possesses characteristics favorable to petroleum accumulation. These characteristics include source beds, reservoir beds, structural and stratigraphic traps, and cap rock. However, much work needs to be done to properly evaluate the potential.

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