OIL AND GAS POTENTIAL OF KEWEENAWAN MIDCONTINENT RIFT SYSTEM IN NORTHWESTERN WISCONSIN

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ABSTRACT

Extensive leasing and seismic exploration along the Keweenawan Midcontinent Rift System from Upper Michigan into Kansas centered in northwestern Wisconsin during 1983 - 1985. Detailed geochemical and geophysical justification for this petroleum play remains confidential, but regional geological knowledge encourages speculation.

Continental rifting with extrusion and intrusion of igneous rocks caused subsidence in northwestern Wisconsin, and 6,100 m of Upper Keweenawan conglomerate, shale, and sandstone accumulated to form the Oronto Group (Copper Harbor Conglomerate, Nonesuch Shale, and Freda Sandstone). The slightly metamorphosed rock is dominantly red beds deposited as alluvial fans grading upward into finer, texturally and mineralogically more mature lacustrine and fluvial deposits. After 50 to 90 km of separation the rift failed and axial uplift created the St. Croix Horst with subsiding flank basins. Up to 1,500 m of sandstone with minor shale (Bayfield Group) accumulated in basins adjacent to the eroding horst.

Shale and siltstone of the Nonesuch contain sufficient organic matter that oil seeps occur within the formation in Upper Michigan. As the only source rock and the most continuous seal, the persistence of the Nonesuch is critical to the petroleum potential of northwestern Wisconsin. A flawed analogy with giant oil and gas fields in Siberia, U.S.S.R., provides additional support. Possible traps include anticlines, reverse faults with upthrown basalt seals, depositional truncation against basement highs, porous lenses, and an angular unconformity.

Keweenawan petroleum potential is heightened by inexpensive leases for large tracts of public land, relatively cheap drilling in a politically stable area, and the potential for discovering gas storage. Wisconsin, however, has high taxes and strong environmental laws, and drilling in Lake Superior would be prohibited even if a lakeside field were discovered.

Exploration activity has waned due to current economics in the petroleum industry, and Amoco cancelled a 1985 wildcat in Bayfield County that would have evaluated the St. Croix Horst. A significant upturn in hydrocarbon prices will be required to rekindle interest in northwestern Wisconsin.

INTRODUCTION

Interest in the petroleum potential of the Keweenawan Midcontinent Rift System in northwestern Wisconsin was initially stimulated by oil seeps from the Upper Keweenawan Nonesuch Formation in the Copper Range Mine, White Pine, Ontonagon County, Michigan (fig. 1). This occurrence was described by Eglinton and others (1964), Barghoorn and others (1965), and Johns and others (1966). Subsequently, the oil was sampled and studied by several major oil companies in the early 1970s. Industry interest in the Keweenawan oil occurrence undoubtedly was stimulated by the 1962 discovery of significant gas and oil reserves within Upper Precambrian rocks in Siberia, U.S.S.R. (Meyerhoff, 1980). More recent hydrocarbon occurrences in Upper Precambrian rock in Australia, China, and Montana helped to sustain the enthusiasm for the potential of the Midcontinent Rift System.

The presence of oil at White Pine established source and generation, and surface studies indicated potential reservoirs and traps were present. This information, coupled with the belief that oil prices would exceed $50/barrel and natural gas would reach at least $8.00/Mcf in the late 1980s, resulted in extensive geophysical activity, intensive leasing, and some recent drilling along the Keweenawan Rift System from upper Michigan to Kansas during the early 1980s (fig. 1).

Leasing for oil and gas exploration in northwestern Wisconsin started in 1983, and more than 690,000 acres were under contract to at least 7 oil companies by 1986. Standard terms per acre were $1.00 bonus and $1.00 rental/year. Royalty interest was 1/8, and the terms of most leases were 3 years. In addition to leasing activity, more than 500 miles of contract and speculative seismic lines were run in Ashland and Bayfield Counties, Wisconsin.

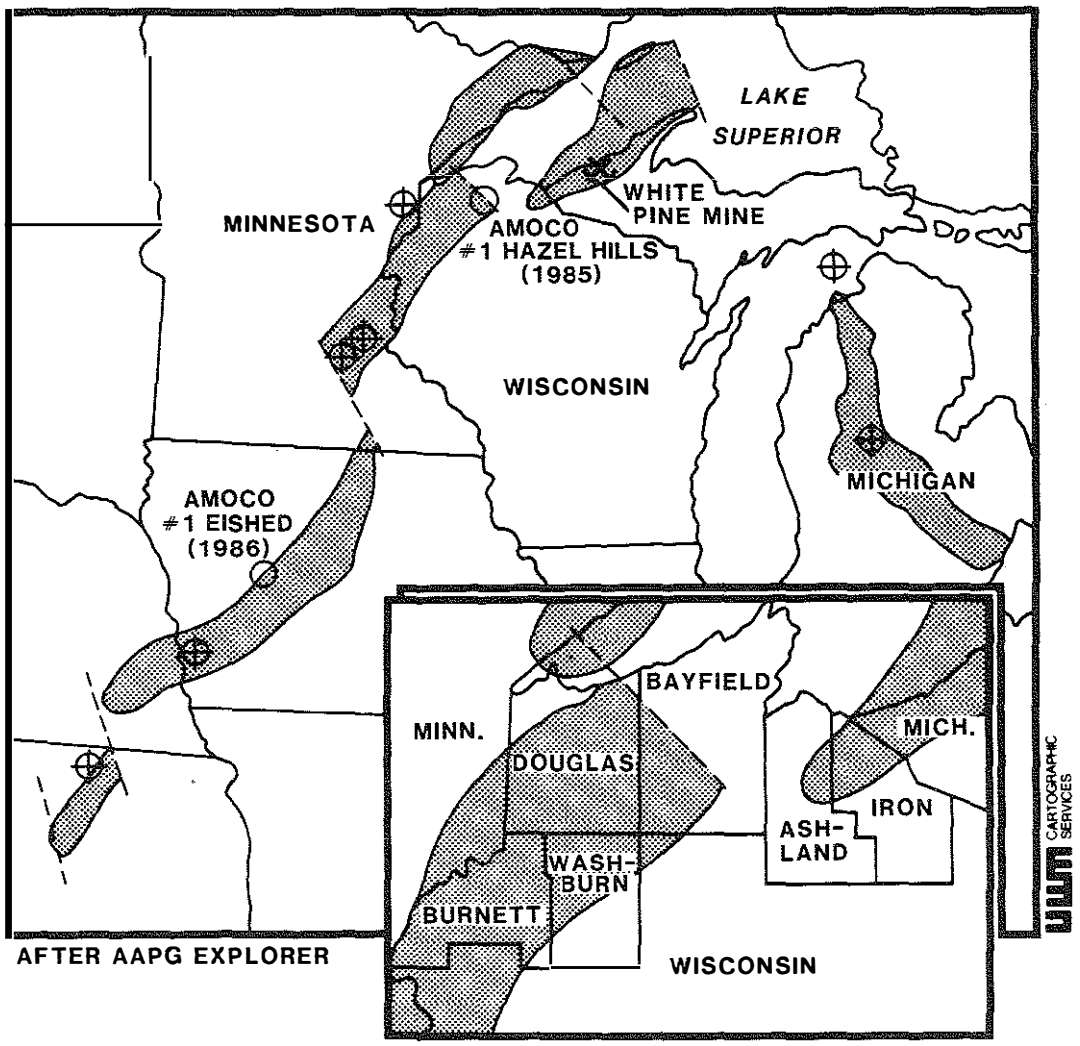

Figure 1. The Keweenawan Midcontinent Rift System is delineated by the stippled pattern. Selected dry holes are shown by crossed circles, and the location of the Copper Range Mine is indicated. Open circles are two suspended test wells announced by Amoco in 1985 (No. 1 Hazel Hills) and 1986 (No. 1 Eished).

GEOLOGIC SETTING

The Keweenawan Midcontinent Rift System is defined in the subsurface by the Midcontinent Gravity High, which cross-cuts older Precambrian structural patterns (Lyons and O'Hara, 1982). This feature may also extend southeastward from Upper Michigan through Lower Michigan, and possibly farther southward (fig. 1). The geologic evolution of the entire Midcontinent Rift System was systematically reviewed by Dickas (1986).

Surface exposures of the Keweenawan Rift System are limited to Upper Michigan and northwestern Wisconsin, where the veneer of Paleozoic rocks was removed by erosion. A brief summary of the geologic history of this region follows.

Continental rifting of 50 to 90 km due to crustal attenuation associated with extensive extrusion and intrusion of Lower and Middle Keweenawan rocks formed a subsiding sedimentary basin about 1.1 Ga (table 1). This basin was filled in by up to 6,100 m of the Oronto Group (basal Copper Harbor Conglomerate with associated volcanic, medial Nonesuch Shale, and uppermost Freda

Table 1. Comparison of Siberian and Midcontinent petroleum basins.

E. SIBERIA, U.S.S.R. PROTEROZOIC ANALOGY

	SIBERIA	WISCONSIN
TECTONICS:	Craton-Platform Deposits Little Deformation C Evaporite Seals	Craton-Failed Rift Uplift and Erosion No Paleozoics Remain
SOURCE:	Max. Burial 600m Generation Established Marine Sh. Interbeds Proterozoic <925 Ma Gas, Condensate, Oil	Max. Burial 600m? Generation Established Lacustrine Sh. Unit Proterozoic <1040 Ma Gas?, Condensate?, Oil??
RESERVOIR:	Marine Ss. Intergranular - Low	Fluvial Ss. Intergranular - Low
TRAP:	Interbedded Sh. Seals Pinchout on Highs Lenses Major Folds 2000+m Depth	Nonesuch & Freda Ss. w/Sh Pinchout on Highs? Lenses? Anticlines Reverse Faults 2000+m Depth
POTENTIAL:	Huge Area 200 Tcf Gas 100 Bill. Bbls. Oil	Small Area Potential Unknown

Note: Siberian information is from Meyerhoff (1980).

Sandstone) (fig. 2). This group is dominated by a fining upward, texturally and mineralogically immature sequence of red beds deposited as alluvial fans and fluvial sediments. The exception is the Nonesuch Formation, which is an anoxic lacustrine deposit.

The rift failed after deposition of the Oronto Group, and compression resulted in the uplift of a central horst block (St. Croix Horst) flanked by sub-

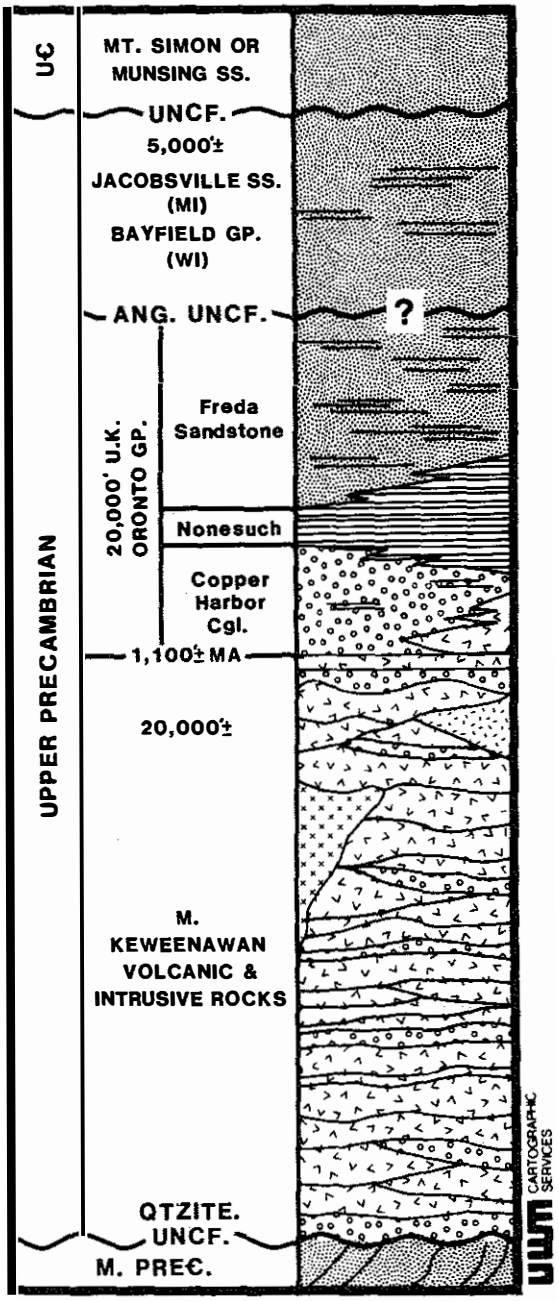

Figure 2. Summary of upper Precambrian (Keweenawan) stratigraphy in Upper Michigan and northwestern Wisconsin.

siding basins (fig. 3). Up to 1,500 m of uppermost Precambrian Bayfield Sandstone accumulated in angular discordance on the Freda Sandstone in the flank basins (fig. 2). The Bayfield is a texturally and mineralogically upward-maturing succession of nonmarine sandstone that was derived, at least in part, from erosion of the Oronto Group on the St. Croix Horst.

An erosional interval in northwestern Wisconsin preceded Paleozoic deposition during the Late Cambrian, Ordovician, and Silurian. It is also possible that Devonian and Upper Cretaceous rocks were deposited in this area. In all, some 650 m of post-Precambrian sedimentary rocks were deposited and subsequently removed prior to deposition of Pleistocene glacial deposits, which mantle much of the countryside and obscure bedrock relations.

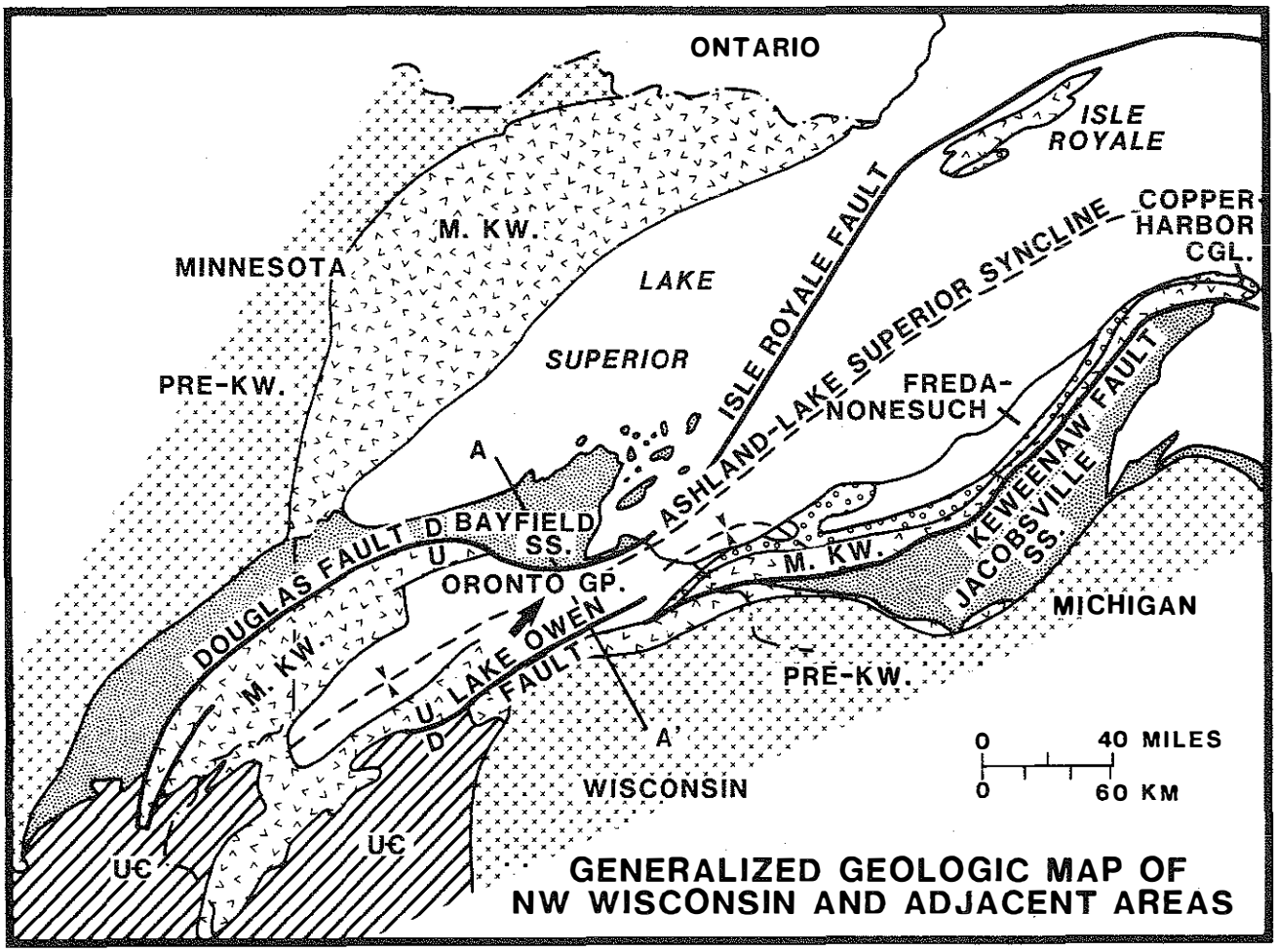

Figure 3. Generalized geologic map of northwestern Wisconsin and adjacent areas. The St. Croix Horst is defined by the Douglas and Lake Owen Faults. The location of the suspended Amoco test well in the Ashland-Lake Superior Syncline is indicated by the arrow near the center of the map. The abbreviation KW is used for Keweenawan, and the throw of major faults is indicated by U (up) and D (down).

PETROLEUM POTENTIAL

The petroleum potential of a frontier area like the Midcontinent Rift System is dependent upon the fortuitous association in time and space of source, reservoir, and trap. Each of those aspects is considered below.

Source

As previously described, the shale of the Nonesuch Formation is the only potential source rock in the dominantly red bed sequence of Upper Precambrian rock in northwestern Wisconsin (figs. 4 and 5). The organic content of samples associated with oil seepage at White Pine is about 0.5 perent C (Dickas, 1986, p. 232). The origin of the oil is attributed to fungi, algae-like "sporomorphs", and bacteria deposited in a lacustrine environment (Moore and others, 1969).

Rock in Minnesota (Solar Church Formation) correlative with the Nonesuch Formation is lower in organic content, and well past the stability stage for oil (Hatch and Morey, 1985). The paleogeothermal history of Upper Keweenawan rock in northwestern Wisconsin is unknown, but the presence of low-grade metamorphic minerals suggests the possibility of high heat flow. Maximum burial of about 6,000 m in the basins flanking the St. Croix Horst seems feasible. If we assume that this depth estimate is correct and the geothermal gradient was "normal" (1° F/50 ft), an extrapolation back 1.1 Ga would suggest that no hydrocarbons remain in the deeper part of the flanking basins. Although temperature was less severe on the St. Croix Horst and oil is stable at White Pine, I would expect only methane gas in this block in northwest Wisconsin.

The Nonesuch Formation is up to 200 m thick in Michigan, and it thins southwestward. It may, however, thicken basinward (northwestward) (Daniels, 1982). The thickness, eastward extent, and organic character of this formation in the subsurface of Bayfield and Douglas Counties, Wisconsin is the most important consideration in assessing the petroleum potential of northwestern Wisconsin.

Reservoir

Potential reservoir rocks within the Upper Keweenawan sequence are conglomerate and sandstone. As previously described, textural and mineralogical maturity increase upward, and these changes result in improved reservoir characteristics in younger rock. Unfortunately, the best reservoirs are farther from the Nonesuch Formation.

Carbonate cement, which is ubiquitous within Upper Keweenawan clastic rock, severely limits the porosity and permeability of many potential reservoir rocks. In spite of this general concern, surface samples indicate porosities up to 15 percent are locally present in all units except the Nonesuch. Some of this porosity may result from the leaching of carbonate cement at outcrops.

Traps

Both stratigraphic and structural traps can be expected in the Midcontinent Rift System within northwestern Wisconsin. Stratigraphic traps include lenticular sand and conglomerate bodies deposited as bars, beaches, alluvial fans, and turbidites in the subsiding Lake Superior Basin during deposition of the lacustrine Nonesuch Formation (fig. 4).

Although small stratigraphic plays are not a primary objective in frontier exploration, petroleum accumulations in such traps are favored in areas of high heat flow. Furthermore, these types of traps are important producers in the Precambrian of eastern Siberia.

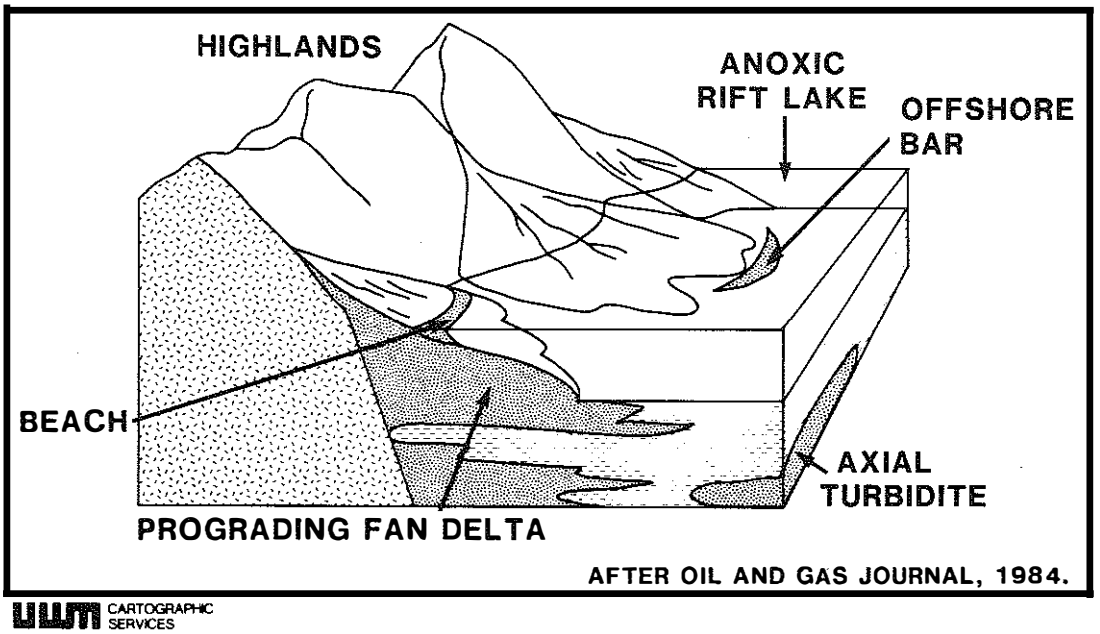

Figure 4. Hypothetical depositional setting for potential reservoir rock associated with accumulation of the Nonesuch Formation in an anoxic rift lake.

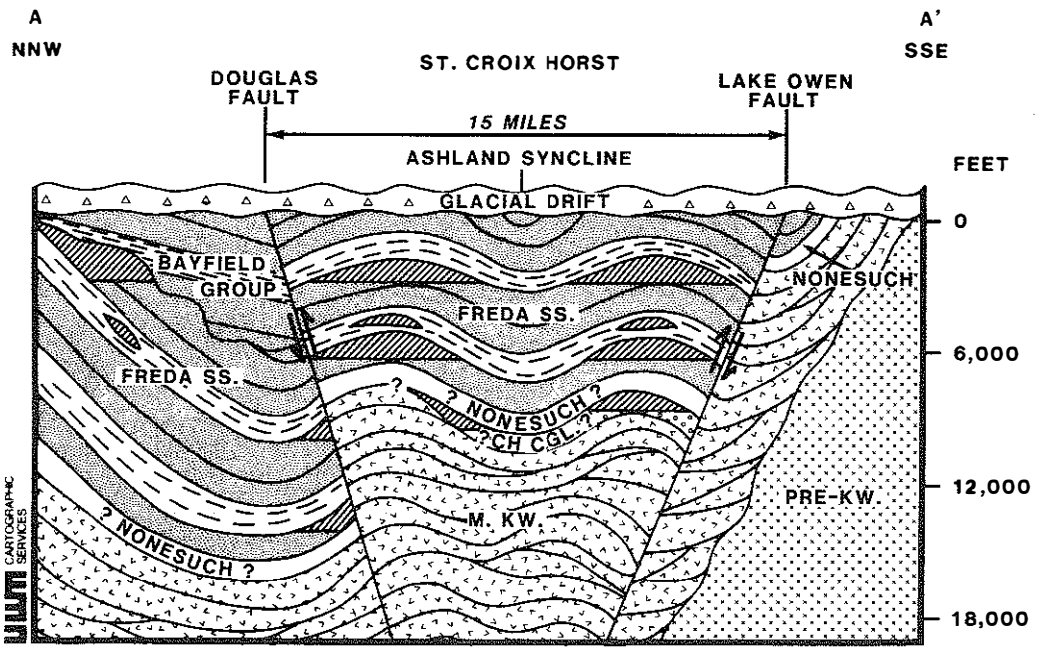

Figure 5. Hypothetical cross section A-A' (fig. 3) across the St. Croix Horst illustrating a veriety of entrapment possibilities within Upper Keweenawan rock in northwestern Wisconsin. Possible oil and gas accumulations are indicated by steep diagonal lines, and include depostional pinchouts against basement highs, lenticular sand bodies, anticlines, an angular unconformity, and the placement of impervious lavas against porous sediment along the Douglas Fault. The approximate position of the suspended Amoco location is near the probable axis of the Ashland-Lake Superior Syncline.

Other possibilities for stratigraphic entrapment include sedimentary pinchouts of the Copper Harbor Conglomerate against impervious highs on the Middle Keweenawan volcanic basement, and along the angular unconformity between the Freda Formation and the overlying Bayfield Group (fig. 5). In both instances seals of impervious shale are required.

Structural traps include anticlines formed during the compressional episode that created the St. Croix Horst (fig. 5) The reverse Douglas Fault brings impervious Middle Keweenawan lavas over porous Upper Keweenawan sedimentary rock to provide another potential structural trap (fig. 5). The existence of both types of structures is supported by surface observations.

The structures described above formed during development of the St. Croix Horst. If the geothermal gradient was high, hydrocarbon migration may have occurred prior to the formation of these traps. If so, the petroleum potential of the area is minimal. A similar concern for the Minnesota segment of the Midcontinent Rift System was described by Hatch and Morey (1985).

One of the primary concerns with most of the entrapment possibilities described above involves the general paucity of shale to form effective seals. The Nonesuch is the thickest and most extensive impervious horizon within the Upper Keweenawan succession. Interbedded shales make up 60 percent of the Oronto Group, but less than 1 percent of the Bayfield Group (Dickas, 1986). The vertical distribution, sealing effectiveness, and lateral persistance of shale interbeds in both units is a critical unknown.

SIBERIAN ANALOGY

The early publicity on the Keweenawan Midcontinent Rift System by trade journals, industry newsletters, and local newspapers repeatedly referenced the significant occurrences of gas and oil in upper Precambrian rock in eastern Siberia, U.S.S.R. (Lee and Kerr, 1983; Dickas, 1984). Analysis of this comparison discloses significant differences in the geologic history of the two areas (table 1).

The most important flaws with the Siberian analogy include major differences in the general tectonic setting and depositional environment. The hydrocarbon-rich, Precambrian rocks in Siberia are marine cratonic sedimentary rock, whereas those of the U.S. midcontinent Keweenawan are nonmarine sedimentary rock that accumulated within a failed rift. Another significant difference involves the high percentage of interbedded shale within the Precambrian sequence and the evaporites within the Cambrian in Siberia. These provide a series of very effective seals, which are probably lacking in the Keweenawan of northwestern Wisconsin. Finally, there is a major size discrepancy involved in the comparison between the productive Precambrian area in eastern Siberia and the entire Midcontinent Rift System (fig. 6).

RECENT DEVELOPMENTS

In 1985 Amoco announced and subsequently suspended a 12,000-foot test well about 15 miles southwest of Ashland, Wisconsin, in Bayfield County (figs. 1, 3, and 5). Another rift test was announced by Amoco late in 1985 for Carroll County, Iowa. As oil and gas prices plunged in early 1986, this well was also suspended.

During the summer of 1985, Grant-Norpac, Inc., conducted an extensive speculative seismic survey on several of the Great Lakes, including Lake Superior. This action infuriated the governors of the eight Great Lakes states, and re-

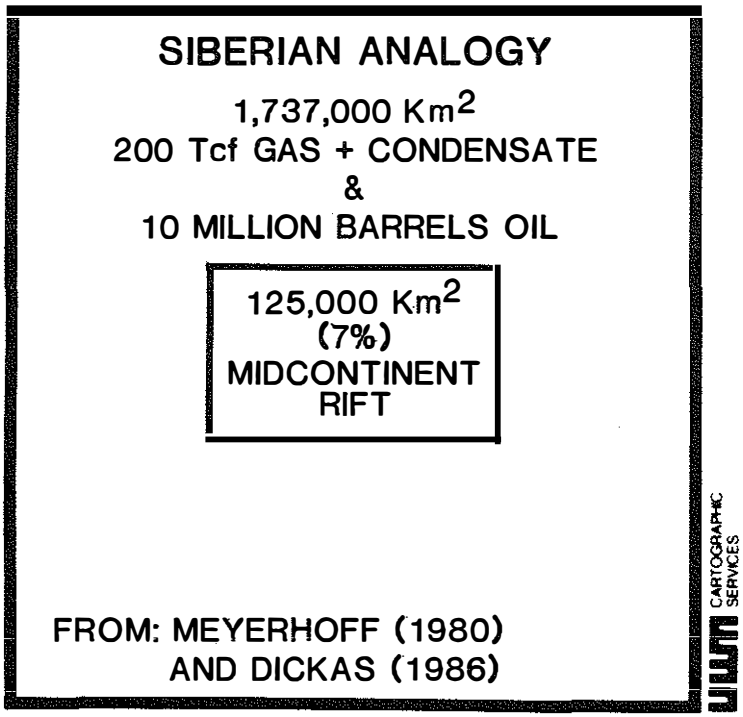

Figure 6. Diagrammatic areal comparison of the productive Precambrian region in eastern Siberia with the Midcontinent Rift System from Kansas through Lower Michigan. As shown, the Rift is only 7 percent of the Siberian area.

sulted in a proclamation in February 1986, opposing petroleum exploration and drilling in the lakes.

A significant indication of continuing industry interest in the petroleum potential of northwestern Wisconsin will be forthcoming in the fall of 1986 when many early leases are due to expire. The ultimate test, however, will require a wildcat.

CONCLUSIONS

The petroleum potential of the Midcontinent Rift System in northwestern Wisconsin is marginal. Although significant production from Proterozoic rock in eastern Siberia establishes the hydrocarbon potential of older rock, failed rifts are high risk prospects throughout the world (Kingston and others, 1983). In the rare cases when failed rifts are productive, the favored setting is central horst blocks (Kingston and others, 1983).

Volumetrically modest amounts of source rock with relatively low carbon content (Nonesuch Formation) and of uncertain lateral extent are also bothersome. The probable lack of sufficient shales to serve as trap seals is another concern.

On the positive side, the Wisconsin part of the Midcontinent Rift System is a frontier area with large, inexpensive tracts of public acreage available. This situation allows major companies the opportunity to control large acreage

blocks so they may employ technology (seismic and organic geochemistry) to minimize risk. Drilling will be comparatively shallow, and relatively low cost.

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Robert Seasor and Timothy Rohrbacher made it possible for me to examine the Nonesuch oil seepages in the Copper Range Mine, White Pine, Michigan, in 1972. Rachel K. Paull contributed on numerous field excursions to examine Keweenawan rock in Upper Michigan and Wisconsin during the past 15 years. Recent conversation with Albert B. Dickas and M.G. Mudrey, Jr. helped to refine my understanding of the petroleum potential of northwestern Wisconsin. In spite of all this help, I accept responsibility for any speculation that proves erroneous when the first well tests my theories.

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