SUPERIOR PROVINCE (051)

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INTRODUCTION

The Superior Province includes all of the State of Minnesota, except for 14 counties in the southeastern corner, the western counties of Wisconsin, and the western Upper Peninsula of Michigan. The 14 southeastern Minnesota counties are included in the Iowa shelf Province. The Superior Province comprises approximately 132,000 sq mi. In northern and central Minnesota, surface bedrock is Precambrian rocks of the Canadian shield, whereas in southern Minnesota, surface bedrock consists of younger (<570 MYBP) Paleozoic and Cretaceous age sedimentary rocks. In northern Wisconsin, Precambrian rocks of the Wisconsin Dome are the surface rocks, whereas in the southwestern part of the State, Cambrian and Ordovician rocks make up the bedrock. Essentially most of the bedrock in the Superior Province is now covered by unconsolidated glacial and postglacial debris. One notable exception is in the Driftless Area in the southwestern part of Wisconsin.

No commercial oil has been found in the Superior Province. However, one hypothetical conventional play was identified and individually assessed—the Precambrian Midcontinent Rift System Play (5101). Although parts of the play extend southwest into six other provinces, the play is discussed here (including assessment of its undiscovered resources) because a significant portion of the play lies within the Superior Province.

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CONVENTIONAL PLAY

5101. PRECAMBRIAN MIDCONTINENT RIFT SYSTEM PLAY (HYPOTHETICAL)

This hypothetical conventional play consists of possible oil and gas accumulations in structural and stratigraphic traps associated with the 800 mi long Midcontinent Rift System (MRS). This system, a failed continental rift of middle Proterozoic age (1.1 billion yrs) delineated by gravity and magnetic anomalies, extends from the central Lake Superior region to central Kansas. A related arm of the rift, which extends from eastern Lake Superior southeastward to the southern boundary of Michigan, is evaluated in the Michigan Basin Province (063) as Play 6315. Besides the Superior Province, the MRS also occupies portions of the Iowa Shelf, Forest City Basin, Nemaha Uplift, Salina Basin, Sedgewick Basin, and Cambridge Arch-Central Kansas Uplift Provinces. The play covers about 57,000 sq mi.

In general, the MRS is characterized by broad medial horsts, composed mostly of layered basaltic volcanic rock, bounded by high-angle normal or reverse faults and flanked by asymmetric half-grabenlike basins filled primarily with sedimentary clastic rock, as much as 30,000 ft thick (Wold and Hinze, 1982; Hatch and Morey, 1985; Dickas, 1986; Mudrey, 1986; Anderson, 1990; and references listed therein). Sedimentary basins have also developed in places atop the horsts filled with 6,500-3,000 ft of clastic material (Chandler and others, 1989). Throughout portions of the rift, the horst/graben structures have been separated by transverse, scissor-like fault systems or accommodation zones (Chandler and others, 1989; Mudrey and Dickas, 1989). Most of the rift is concealed by Phanerozoic strata or waters of Lake Superior. Volcanic and sedimentary rocks of the rift system are exposed only in the Lake Superior region where the sedimentary rocks have been assigned to the upper Keweenawan Supergroup, comprised of the Bayfield Group above and Oronto Group below. The Nonesuch Formation, middle member of the Oronto Group, is the only identified petroleum source rock within the Keweenawan Supergroup. Besides being relatively organic rich, containing as much as 3.0 weight percent total organic carbon (TOC) (Imbus and others, 1990), the Nonesuch is especially noted for its capability to generate liquid hydrocarbons as attested to by live oil seeps from subsurface fractures within Nonesuch shales in the White Pine Copper Mine, Keweenaw Peninsula, Mich. (Robert W. Seasor, White Pine Copper Company, oral commun.).

Structural and stratigraphic traps associated with the rift were formed initially by crustal extension and sedimentary facies distribution. In late rift development near the

end of the Proterozoic, tectonic inversion was superimposed resulting in compressional and wrench structures in different segments of the rift.

Petroleum exploration interest in the MRS began in the early 1980's resulting in the drilling of several key wildcat wells: the Texaco No. 1 Poersch well, Washington Co., Kans. (1985) (Berendsen and others, 1988); the Producers Engineering 1-4 Finn well, Marshall Co., Kans. (1986) (Newell and others, 1993); the Amoco No. 1 M. G. Eischeid well, Carroll Co., Iowa (1987) (Anderson, 1990; Palacas and others, 1990); and the Terra 7-22 Patrick well, Bayfield Co., Wis. (1992) (Palacas and Burruss, 1994). Although not a result of petroleum exploration, another key well, the Lonsdale 65-1, drilled in the mid-1960's in Rice County, Minn., is included herein because of its strategic importance in assessing a portion of the Minnesota segment of the MRS. It penetrated 1898 ft of the Solor Church Formation which correlates with the Oronto Group (Hatch and Morey, 1985).

The impetus for the search of oil and gas in this Precambrian rift setting was spurred on not only by the identification of an organic-rich source rock (Nonesuch Fm.) and its associated indigenous live crude oil seeps (Pratt and others, 1991) but also by the attraction of large petroleum reserves in other rift basins of the world (for example, North Sea, Gulf of Suez, and Pripyat Basin) and the proven production of giant petroleum reserves in other Precambrian terranes, such as Lena-Tunguska Petroleum Province, Eastern Siberia; Sichuan Basin, southern China; and the Upper Proterozoic Huqf Group, Oman.

In the following discussion of various attributes of the MRS Play, most of the information, unless stated otherwise, has been gleaned from reports focusing on the Lake Superior segment of the rift.

Reservoirs: Primary targets are fluvial, deltaic and (or) shoreline sandstones, as much as 30 ft thick, that occur (1) within the Nonesuch Formation, particularly in the lower part, where porosities are as much as 13 percent (avg. ~8.0 percent) and (2) in the underlying upper Copper Harbor Conglomerate where porosities are as much as 13 percent and average about 7 percent. Other potential reservoirs include fractured shales within the Nonesuch Formation and sandstones in the overlying Freda Sandstone in which porosities have been measured as high as 18 percent. In the deep portion of the flanking Defiance Basin of western Iowa, sandstones that are probably equivalent to the Copper Harbor Conglomerate of the Lake Superior region (cumulative thickness 127 ft) have generally low porosities averaging 4.4 percent (max 6.0 percent)

(Schmoker and Palacas, 1990). In Kansas, in the Texaco Poersch No. 1 well, upper Keweenawan arkose and arkosic sandstone are generally tight (porosities ~2 percent) but one 22-ft sandstone unit, at 11,054 ft exhibited a porosity of 15 percent (Berendsen and others, 1988).

Source Rocks: The Nonesuch Formation ranges from 250 to 700 ft in thickness (avg almost 600 ft) and consists of interbedded dark-gray to black siltstone, silty shale, and sandstone. It is the finely laminated silty to calcareous shale that contains the highest proportion of organic matter, as high as nearly 3.0 percent TOC (avg. ~0.6 percent) (Imbus and others, 1990; Pratt and others, 1991). The source rock is characterized chiefly by type II and type I kerogens and is moderately mature (T_{max}, 435-440¡C). Based primarily on stratigraphic relationships, many geoscientists have suggested a lacustrine depositional environment for the Nonesuch, but based on compositional traits of the organic matter, a marine or estuarine environment cannot be ruled out. In the Minnesota segment of the rift, at the Lonsdale 65-1 well, dark-gray mudstone of the Solor Church Formation has TOC contents ranging from 0.13 to 1.77 percent (avg. 0.4 percent) and is overmature with respect to oil generation (T_{max} 494¡C). In the deep portion of the flanking basin in the Iowa segment, the silty shales of the Nonesuch Formation equivalent contain as much as 1.4 percent TOC (avg 0.6 percent) and are also overmature (avg T_{max} 503¡C). In the Kansas portion of the rift, in the upper section of the Rice Formation (1-4 Finn well), dark-gray siltstone averages about 0.7 percent TOC and is well into the oil generation window (T_{max} 445-451¡C). Although the organic matter is oil prone, the type of hydrocarbons generated, oil or gas, would depend largely on the degree of maturation of the source rock. For example, in the overmature settings in the areas of the Lonsdale No. 1-4 and the Eischeid No. 1 wells, Minnesota and Iowa segments of the rift, respectively, the choice hydrocarbons would be natural gas.

Timing and migration of hydrocarbons: During the extensional phase of tectonism, the Nonesuch Formation and its equivalents generated oil and gas especially in the deeper portions of the basins before the second phase of compressional tectonics took place. In the shallower portion of the flanking basins, a second phase of oil and gas generation probably occurred after the deposition of Paleozoic sediments. Also, hydrocarbons that might have accumulated in structural and stratigraphic traps in the initial phases of rifting might have remigrated into structures formed during the compressional episode.

Traps: A dual stage of tectonism has provided a multiplicity of trapping conditions. However, different styles of fault-related structures are to be expected in different segments of the rift: in Kansas, rotated, half graben structures; in Iowa, overthrust and normal faults; and along the southern Lake Superior region, high-angle reverse faults. Tectonic inversion has also created large as well as small structural features which could contain giant accumulations of hydrocarbons. In south-central Minnesota, seismic reflection has documented large anticlinal features that resemble flower structures which could be associated with wrench-type motion or foreland compression generated during inversion (S. M. Landon, Denver, CO, 1993, written commun.). Drag folds against reverse faulting offer multiple reservoir possibilities. Stratigraphic traps are also possible. Changing depositional environments forming offshore bars and alluvial-fan deposits offer potential entrapment structures. The most prominent seal would be shales within the Nonesuch Formation itself. Other seals may be found in tight horizons in the overlying Freda Sandstone and in the Bayfield Group. Faulting producing gouging may also account for some seals. Drilling depths would vary from 3,000 ft to perhaps as much as 25,000 ft.

Exploration status: Throughout the areal extent of the MRS (about 57,000 sq mi), only 5 wells have penetrated the lower Keweenawan Supergroup rocks which have the highest potential for hydrocarbon reserves. To date, no commercial oil or gas accumulations exist. It is a purely hypothetical play.

Resource potential: This is a high risk play. Because of the very few wells that have been drilled in the area, it is safe to say that the entire MRS has not been adequately tested. For example, in the Defiance Basin, western Iowa, only the deepest portion of the flanking basin has been tested where potential source rocks are overmature and reservoir porosities poor. However, we speculate that equivalent source rock facies might have fair to good source rock potential if present at shallower depths of burial, under lower levels of thermal maturity, along the basin flanks, away from the frontal fault zone of the medial horst.

UNCONVENTIONAL PLAYS

There are no unconventional plays described in this province report. However, unconventional plays listed in the surrounding provinces may include parts of this province. Individual unconventional plays are usually discussed under the province in which the play is principally located.

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