I. OVERVIEW

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INTRODUCTION

Recognition that economically recoverable oil and gas occur in the Proterozoic Sinian in China, in the Markovo field in Siberia, possibly in the Amadeus basin of Australia, and in the Gibbs No. 1 of northwestern Montana is causing industry to reexamine North American Precambrian petroleum potential. Indigenous petroleum is known from the Nonesuch Shale in the Lake Superior area. This occurrence has attracted about half a dozen companies into the area at some level of exploration. Nearly 700,000 acres of land have been leased for the purpose of petroleum exploration in Wisconsin, and several million more acres have been leased along the Midcontinent trend in Minnesota, Iowa, and Kansas. Several thousand line-miles of seismic surveys have been undertaken, including speculative surveys such as that by Geosource, and proprietary surveys by Grant Geophysical and others. Grant-Norpac, Inc., conducted a marine survey in Lake Superior for about a dozen clients in 1985.

The papers in this volume represent a summary of much of the historic information that has led to petroleum evaluation of the Midcontinent trend, and new evaluation of tectonics based on known geology and preliminary analysis of seismic data. In addition, the interested user is referred to a recent summary article on the Midcontinent trend by Dickas (1986) and a sedimentologic and stratigraphic analysis of possible source and reservoir rock by Daniels (1982).

PROTEROZOIC PETROLEUM

Seven factors are normally examined when the petroleum potential of an area is evaluated. These include source bed characteristics, nature of hydrocarbons, thermal maturation, petroleum migration possibilities, reservoir characteristics, reservoir seals, and structural style of tectonic evolution. Information to evaluate these factors and to understand the evolution of the Keweenawan and its petroleum potential is presented in separate papers.

Conventional petroleum wisdom indicates that "commercial [original emphasis] petroleum and natural gas are almost exclusively products of sedimentary rocks deposited during only the last one-eighth to one-fourth of the earth's history, that part during which an atmosphere rich in oxygen prevailed and during which complex multicellular organisms developed" (McCulloh, 1973, p. 480). Murray and others (1980) most recently reviewed evidence of Precambrian biologic activity and petroleum potential.

Halbouty and others (1970) concluded that among factors affecting formation of giant oil and gas fields "there is no magic in geologic age per se. Each basin went through its own cycle...." At the time of Halbouty's article (1970), the Amadeus Basin of Australia and the Markovo field of Siberia were conjectured to host Proterozoic petroleum. Recent work in the Amadeus Basin tends to discount a Proterozoic origin; however, Soviet work strongly supports a Proterozoic source for the Markovo field (Balashova and others, 1983), and production from the Sinian of China is generally ascribed to Proterozoic sources (Shicong and others, 1980).

Barghoorn and others (1965) detected metalloporphyrins from an extract of the 1,100 Ma Nonesuch Shale in Michigan. Furthermore, the recovery of alkanes from petroleum seepage in the Copper Range Mine in White Pine, Michigan (White

and Wright, 1954), lends strong emphasis to the fact that petroleum, at least as a possible source bed, occurs in the Precambrian of North America (Kelly and Nishioka, 1985). Four events have been proposed as leading to the creation of the Midcontinent Rift System: graben development about 1,100 Ma, and the outpouring of basaltic plateau lava flows; isostatic sinking of the volcanic rock and associated gabbroic complexes that led to erosion and clastic sedimentation; reactivation and uplift of graben and erosion of material on the horst and deposition of clastics in horst flanking basins; and erosion of the horst into Phanerozoic time, perhaps with minor tectonic adjustments continuing as late as Middle Ordovician.

Lee and Kerr (1984) summarized the industry perspective for Proterozic petroleum favorability along the Midcontinent trend. Salient features include the existence of petroleum seeps of proper hydrocarbon affinity (source bed), accumulation of sediments in alluvial fans, prograding fluvial plains and deep organic-rich anoxic lakes in a rift setting, overlying reservoir bed-type sediments (Oronto and Bayfield Group sandstones), structural tectonic history and known faults and folds for traps, and sufficient thermal maturity to suggest generation and migration of petroleum. Hatch and Morey (1985) reported that the organic geochemistry of a weakly organic Keweenawan sandstone from drillcore in southern Minnesota (Lonsdale 65-1) is thermally mature, but that this occurred prior to horst development and possible reservoir beds may well have been eroded. Proprietary data available to M.G. Mudrey, Jr. suggests that the Nonesuch Formation near White Pine is thermally immature (see also Barghoorn and others, 1965). Thus, the petroleum potential may exist in the area between Lonsdale and White Pine (eastern Minnesota and northwestern Wisconsin), and in the basins flanking the uplifted horsts.

MIDDLE PROTEROZOIC GEOLOGY OF THE LAKE SUPERIOR AREA

The final event in the formation of the Precambrian crust in this region was the development of the Midcontinent Rift System (Wold and Hinze, 1982). Rifting was accompanied by the massive upwelling of mantle-derived magma with solidification of mafic plutonic rock at depth and widespread volcanism and clastic sedimentation at the surface in a series of coalesced basins (Morey, 1978; Weiblen and Morey, 1980; Green, 1977).

Rock within the rift system can be divided into three lithotectonic assemblages that partially overlap in space and time. The oldest assemblage consists of predominantly sedimentary rock and possible coeval low-alumina tholeiitic sills, which did not significantly deform or metamorphose their country rock. The main stage of tectonic activity consisted of predominantly igneous rock in at least two separate successions of lava flows and associated plutonic rock that were emplaced over a relatively short time span, about 1,100 to 1,000 Ma. These were emplaced into an evolving rift system that extended from Lake Superior to at least as far as southern Kansas. The uppermost lithotectonic assemblage consists of two suites of clastic sedimentary rock of alluvial to fluvial origin. The older suite, which locally is intercalated with the uppermost lava flows, consists of lithic sandstone and shale that were deposited in a number of fault-bounded basins along the axis of the rift. The younger suite consists of arkosic and quartzose sandstone deposited in a large half-graben-like basin along the flanks of the rift. These predominantly sedimentary assemblages mark the gradual cessation of crustal separation and magmatism.

Dominantly vertical faulting continued intermittently throughout the time of active sedimentation and into the Paleozoic Era. This most recent tectonic

event is characterized by the development of an axial horst along the main rift trend and subsequent subsidence of the rifted region to form the major embayments that existed during the Paleozoic Era.

Recent geologic studies in the Lake Superior region have focused on petrochemical relationships of the magmatic rock (P.W. Weiblen, J.C. Green, L.A Haskin), a small number of sedimentological studies (P. Daniels, W. Kelley, G.B. Morey, R.W. Ojakangas), and regional geophysics (W. Hinze, V. Chandler, H. Mooney, R.P. Meyer). Some new studies have started in the past year include magnetotelluric sounding by R. Wunderman and C.T. Young to determine the deep electrical conductivity structure of the area to help define basin configuration, and coupled reflection seismology, gravity profiling, and ground magnetic modeling by H. Wang and J. Nyquist to constrain thermal-mechanical models of rift formation.

Correlation of units in the uppermost lithotectonic assemblage is controversial because of lack of exposures and key beds between areas that have been well studied. The Nonesuch Formation, the presumed source bed, is generally conceded to pinch out to the southwest of its type locality in Michigan, and is recognized as only a few meters thick in northwestern Wisconsin. Some feel that the stratigraphic interval represented by the Nonesuch is replaced by unknown, but correlative petroleum source beds to the southwest in Minnesota and Iowa (Lee and Kerr, 1984). Others, notably Hatch and Morey (1985), feel that this correlation is unwarranted. Ostrom (in Ostrom and Slaughter, 1967) has proposed that the Devils Island Formation and overlying Chequamegon Formation, the uppermost units of the Bayfield Group, are in fact Paleozoic and correlate, at least in part, with the Jacobsville Sandstone. He would assign an early Cambrian age to these units. Others, notably Morey and Ojakangas (1982), assign these same units to the Middle Proterozoic.

Structures, including folds and faults, are recognized in the uppermost Keweenawan; however, there is some question as to the age of deformation. Studies by Sloan (1965) and Mudrey (in progress) in Paleozoic rock overlying the Keweenawan sequence in the Twin Cities Basin and River Falls Syncline suggest that at least some of the structures are as young as Middle Ordovician. How much of the deformation along the Midcontinent Rift System is Proterozoic in age, and how much represents minor isostatic adjustment of the rift remains to be resolved.

Davidson and Mudrey (1986) evaluated principal factors in petroleum formation and preservation, and concluded that the petroleum potential for the marginal and axial basins was a possible 5 billion barrels TOC (total organic carbon content) resource; source volume constraints led them to curtail that estimate to 70 million barrels of oil or 420 billion cubic feet of gas.

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