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REVIEW OF THE GEOLOGY OF THE SIOUX UPLIFT AND IOWA SHELF PROVINCES AS A BASIS FOR ESTIMATES OF UNDISCOVERED HYDROCARBON RESOURCES

By

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INTRODUCTION

The purpose of this report is to review the geology of the Sioux uplift and Iowa shelf provinces as an aid in estimating the amounts of undiscovered hydrocarbons that may be present. The Sioux uplift province (fig. 1) includes all of the state of Minnesota except 14 counties in the southeastern corner. These 14 southeastern Minnesota counties and all of Iowa except 12 counties in the southwest corner of the state are included in the Iowa shelf province (fig. 1).

An geologic province is an area that contains one or more geologic features, the most common of which is a sedimentary basin. The method used to estimate the amounts of undiscovered hydrocarbons is based on play analysis. A play is one or more hypothetical hydrocarbon accumulations that are similar because they share certain characteristics, which may include source rocks, reservoir type or trap type. Present estimates of undiscovered hydrocarbons are limited to accumulations with expected ultimate recovery volumes greater than one million barrels of oil (MMBO) or six billion cubic feet of gas (BCFG). Geologic data used to assess the hydrocarbon potential of the Sioux uplift and the Iowa shelf province were collected from the literature.

GEOLOGIC SETTING

The Sioux uplift province straddles the boundary between Precambrian rocks of the Canadian Shield and the younger (<570 m.y.) cover of Paleozoic and Cretaceous sedimentary rocks (Morey, 1984) (fig. 2). Surface bedrock in the Iowa shelf province (fig. 3) is primarily of Paleozoic age, with Cretaceous rocks restricted to an area in western and northwestern Iowa (Howell, 1922; Iowa Geological Survey, 1969; Anderson 1983). Near 90 percent of the bedrock on the Sioux uplift and Iowa shelf is now covered by unconsolidated glacial and postglacial debris (Howell, 1922; Morey, 1984). The following summary of the geology of the Sioux uplift is modified slightly from Morey (1984); for the Iowa shelf, Howell (1922) and Anderson (1983).

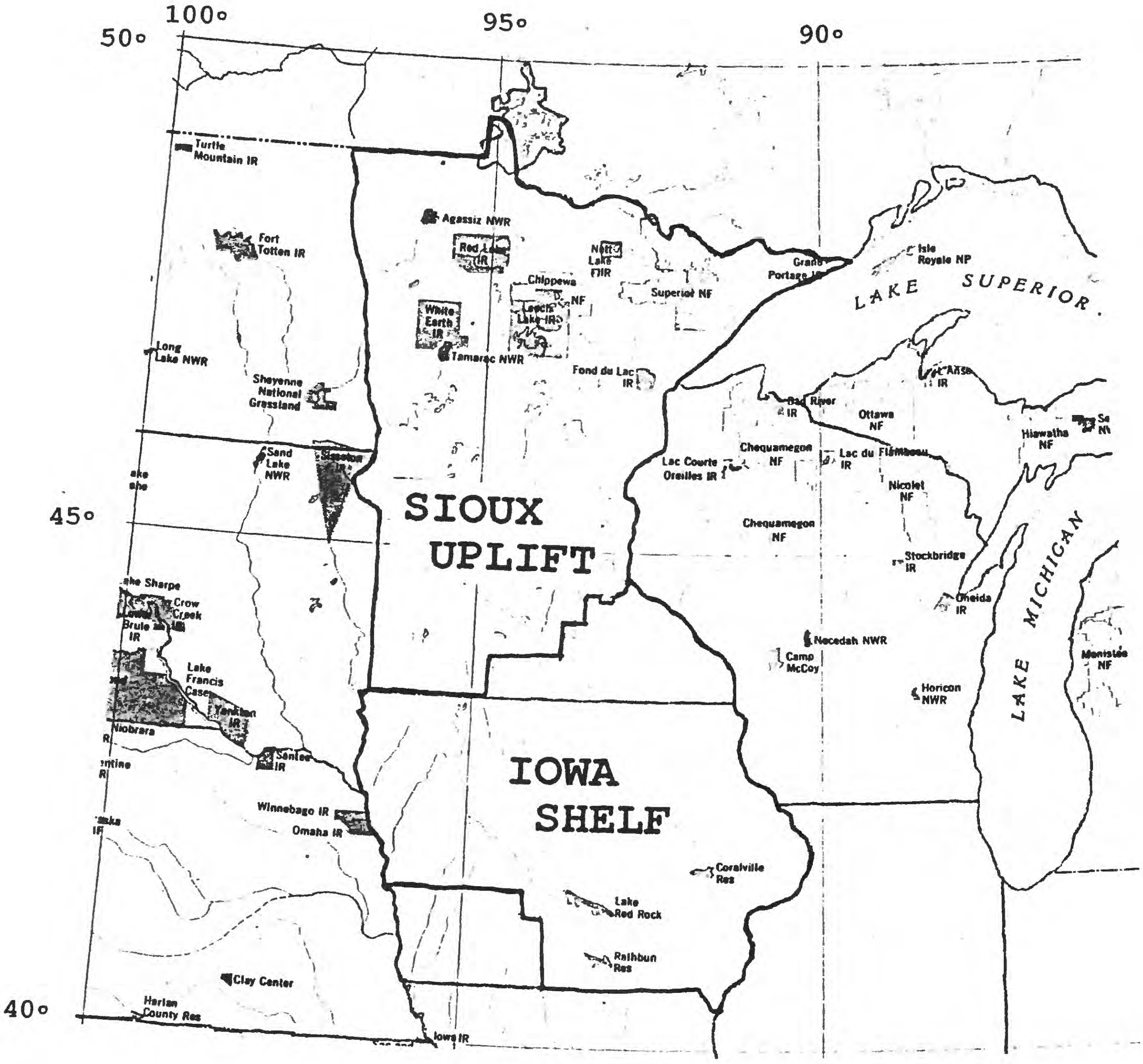

Figure 1.--Index map showing the location of the Sioux uplift and Iowa shelf assessment areas (modified from U.S. Geological Survey, 1970)

Precambrian Rocks

The Precambrian succession in the Sioux uplift area is divided into five terranes (fig. 2). Of these terranes, I and II are fundamental crustal segments older than 2,500 m.y. Terrane I was formed, in part, about 3,600 m.y. ago and consists of varieties of gneiss. It was intruded and metamorphosed by

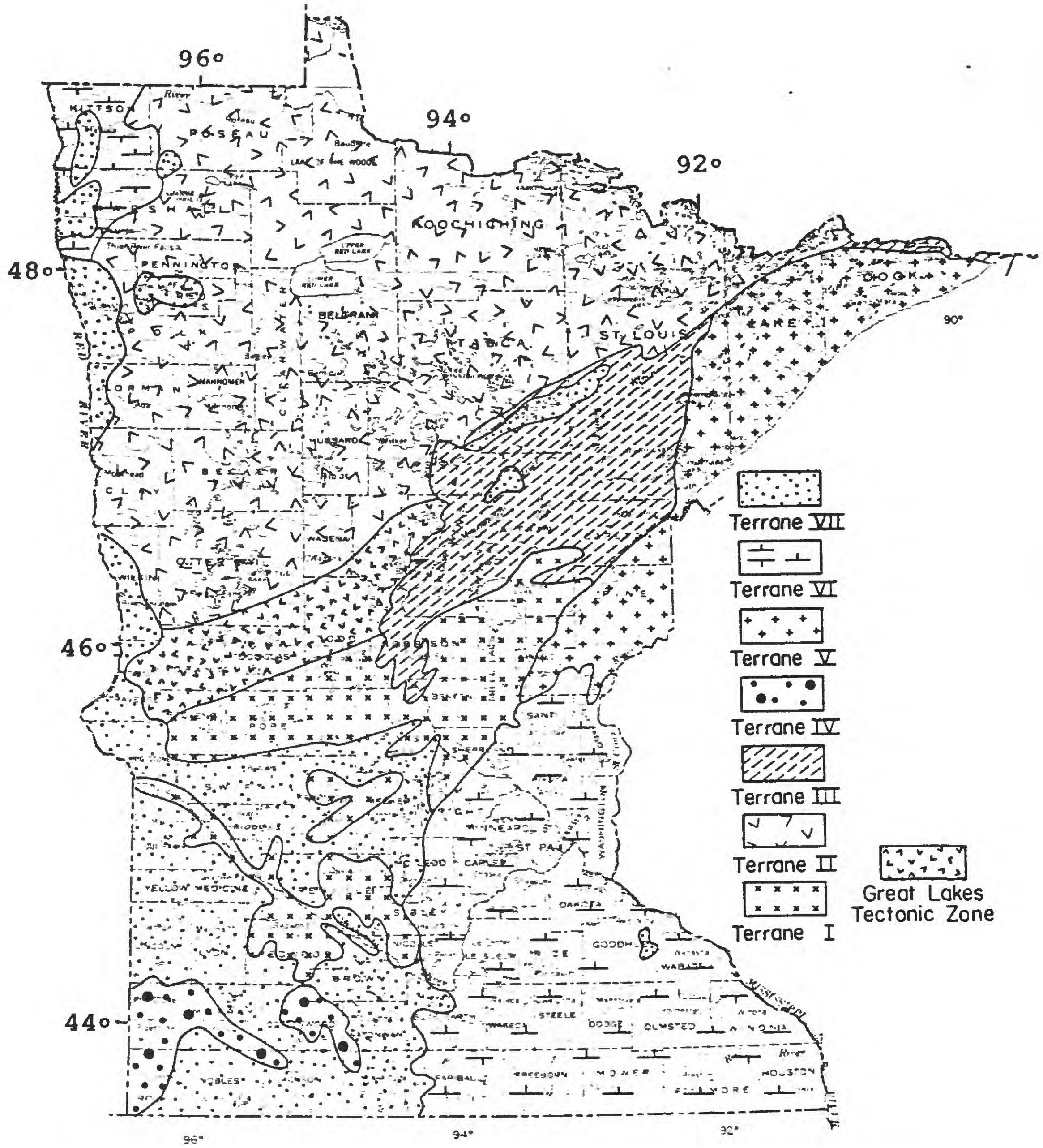

Figure 2.--Inferred distribution of bedrock terranes in Minnesota (see text for discussion). Terrane I, Precambrian gneiss terrane; terrane II, Precambrian greenstone-granite; terrane III, Precambrian intracratonic stratified rocks; terrane IV, Precambrian platform-type supracrustal rocks; terrane V, Precambrian Midcontinent rift system rocks; terrane VI, Paleozoic rocks; terrane VII, Mesozoic rocks (Morey, 1984, his fig. 9)

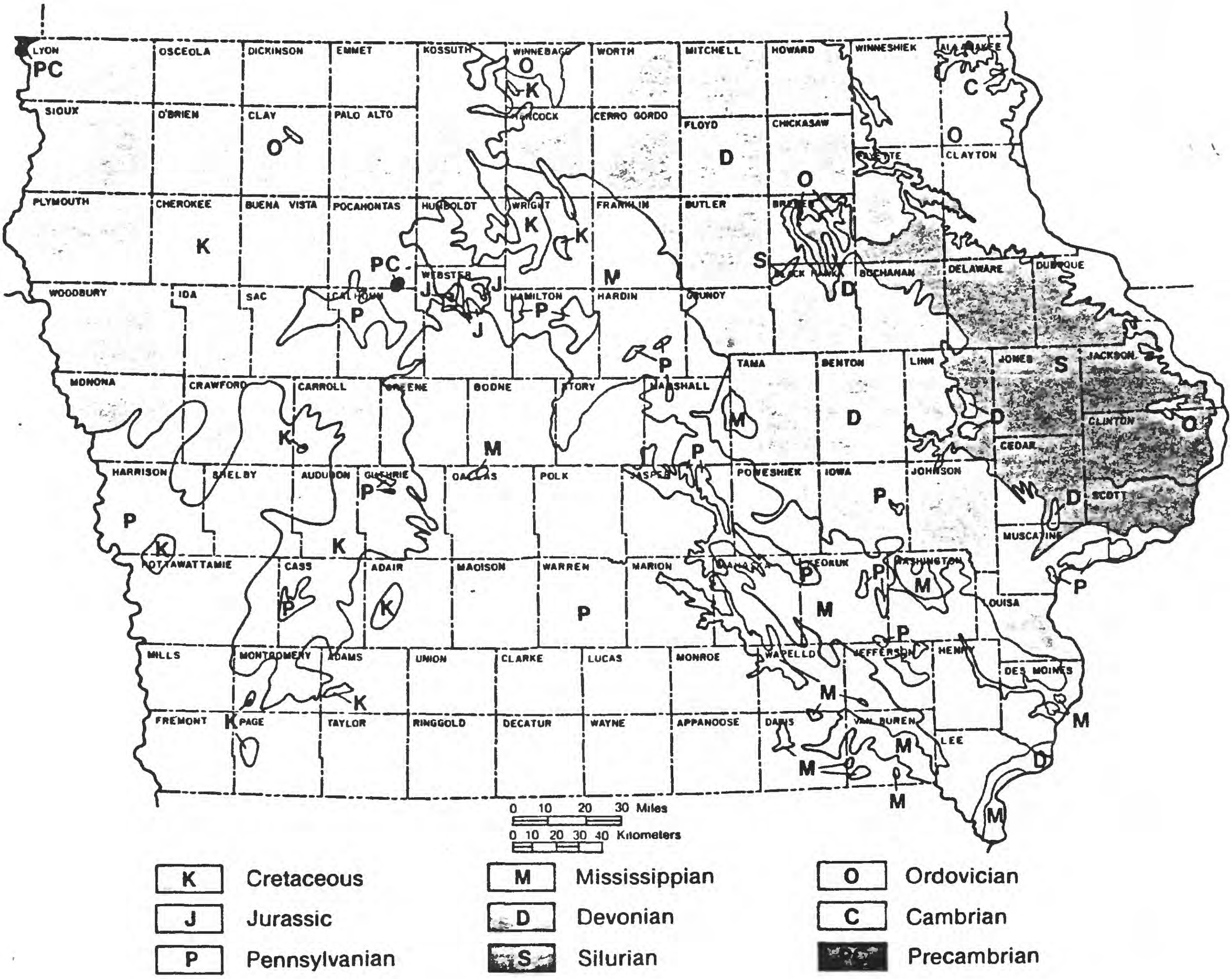

Figure 3.--Bedrock distribution map of Iowa (Iowa Geological Survey, 1969).

igneous rocks several times prior to 2,500 m.y. ago. Terrane II consists of layered and plutonic rocks (greenstones-granites) formed about 2,650 m.y. ago. The layered components include several kinds of volcanic and sedimentary rocks that were extensively folded, faulted, and metamorphosed when the plutonic rocks were emplaced.

Rocks of terrane II are separated from those of terrane I by the Great Lakes tectonic zone, a major structure about 30 miles wide that trends northeastward across central Minnesota. In east-central Minnesota, this tectonic zone was the locus of a large sedimentary basin that filled with layered volcanic and sedimentary rocks (terrane III) around 2,000 m.y. ago. These layered rocks were folded and metamorphosed about 1,870 m.y. ago when several large granite batholiths were emplaced.

Terrane IV consists chiefly of red quartzite and shale and was deposited between 1,725 and 1,600 m.y. ago in several small basins on the gneissic rocks of terrane I in southwestern Minnesota.

Terrane V consists of mafic plutonic and volcanic rocks and derivative red-colored nonmarine sedimentary rocks that accumulated in a major rift (Midcontinent rift) that broke the older terranes in northeastern, east-central, and southeastern Minnesota, north-central, central, and southwestern Iowa, and northeastern Kansas between 1,200 and 950 m.y. ago.

Phanerozoic Rocks

In southeastern Minnesota, (part Sioux uplift, part Iowa shelf) Paleozoic sedimentary rocks (terrane VI, fig. 2) accumulated in the Hollandale embayment, a broad southward-plunging extension of the Forest City basin in southwestern Iowa (fig. 4). These rocks are of Cambrian, Ordovician and Devonian age. In northwestern Minnesota, terrane VI rocks of Ordovician age define the eastern edge of the Williston basin. On the Sioux uplift, Cretaceous rocks (terrane VII) occur along the Red River to the north, and in southwestern Minnesota as an erosionally dissected blanket. In Iowa, Cambrian age rocks outcrop in the northeast corner, with younger Paleozoic age rocks (Ordovician to Upper Pennsylvanian) outcropping successively to the southwest (fig. 3) (Howell, 1922; Anderson 1983). Only small structural modifications have occurred in these provinces during the last 570 m.y.

IDENTIFIED PLAYS

Based on all available published data, two potential hydrocarbon plays were identified within the Sioux uplift and Iowa shelf provinces: The Middle Proterozoic Midcontinent rift play and the Champlainian (Middle Ordovician) play.

Middle Proterozoic Midcontinent Rift Play

The Midcontinent rift play is in Middle Proterozoic Keweenawan Supergroup clastics deposited in basins associated with the Midcontinent rift system. This system, a failed rift that developed approximately one billion years ago, extends

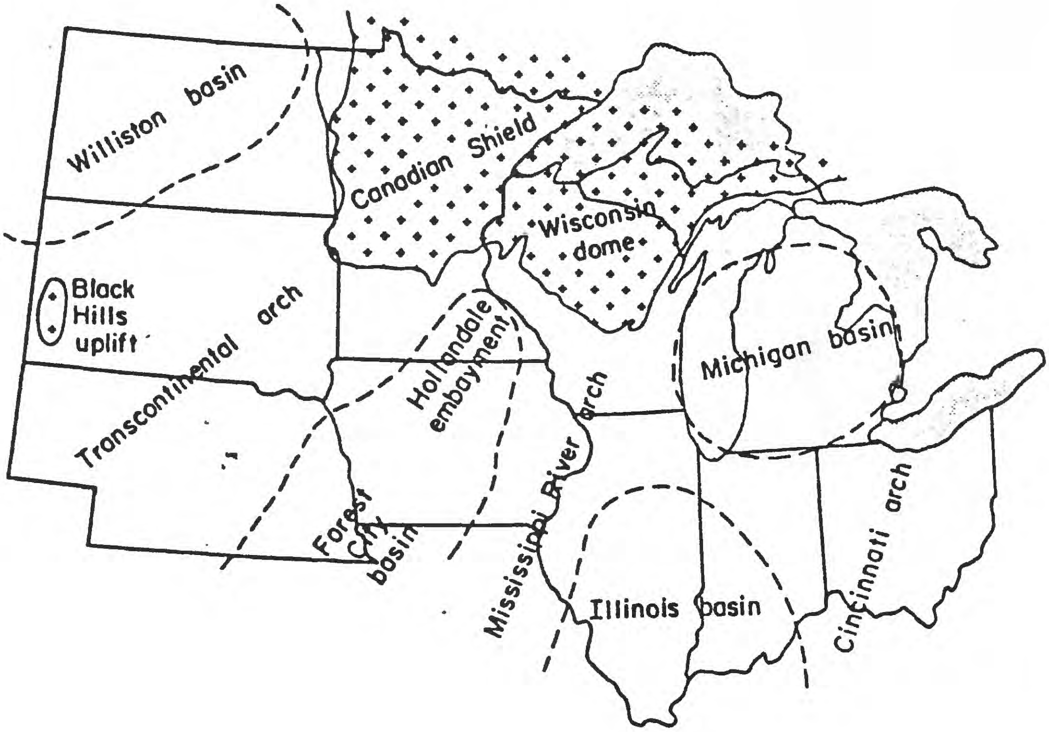

Figure 4.--Canadian Shield, and domes, arches and sedimentary basins of the Upper Midwest (Morey, 1984, his fig. 7).

from the central Lake Superior region to east-central Kansas (fig. 5). Rocks of the Midcontinent rift system outcrop in northeastern Minnesota, northern Wisconsin, and northern Michigan. Elsewhere, the Midcontinent rift system is defined by a continuous linear gravity anomaly. The positive part of the anomaly originates from dense mafic volcanic rocks, whereas, the flanking negative anomalies result from contrasting low-density sedimentary rocks (Chase and Gilmer, 1973). At present there is no production of oil or gas from rocks of the Midcontinent rift.

Hydrocarbon Source-Rock Characterization

Gustavson (1983), Lee and Kerr (1983 and 1984), and Petroleum Information, Inc. (1984) speculate that Keweenawan Supergroup sedimentary rocks associated with the Midcontinent rift have potential to produce hydrocarbons. They base their speculations on comparisons with hydrocarbon potential of other

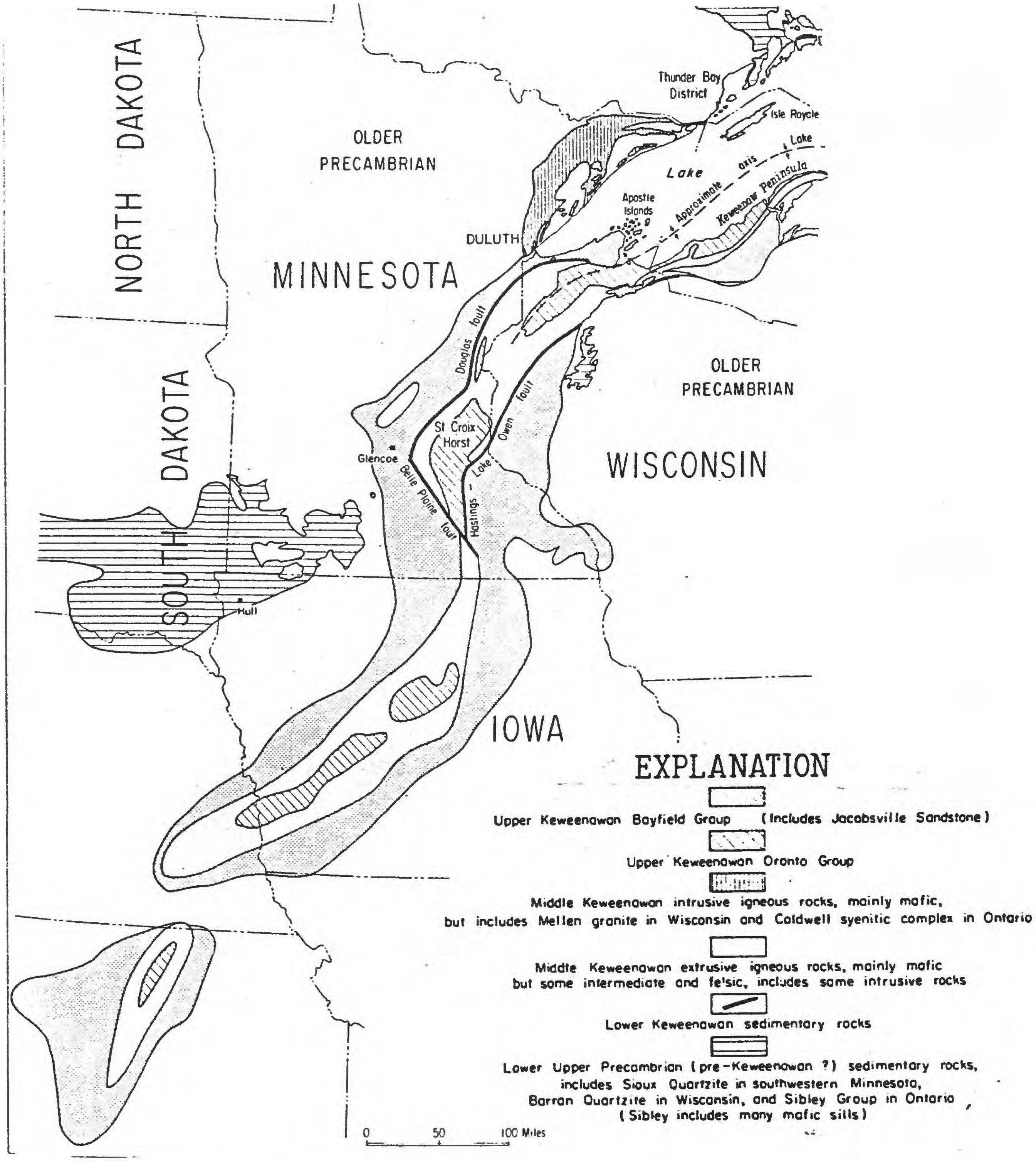

Figure 5.--Map showing the distribution of terrane V (Upper Keweenawan rocks) and the Midcontinent play area in the Midcontinent region (after Craddock, 1972a, his fig. V-2). The Midcontinent rift play includes areas underlain by sedimentary rocks of the Oronto and Bayfield Groups, or equivalents).

rift basins (e.g., Rhine Graben) and on the occurrences of organic-matter-rich lithologies and oil seeps in the Middle Proterozoic Nonesuch Formation (Keweenawan Supergroup) in northern Wisconsin and the Upper Peninsula of Michigan.

Since these initial speculations were published, hydrocarbon source-rock evaluations of core and (or) cuttings of Midcontinent rift sedimentary rocks from four areas have been completed. These sample sets are from: 1) the Nonesuch Formation in northern Wisconsin and the Upper Peninsula of Michigan (Pratt and others, 1989), 2) the Lonsdale 65-1 well, Rice County, Minnesota (Hatch and Morey, 1985), 3) the Eischeid #1 well, Carroll County, Iowa (Palacas and others, 1990 and "in press"), and 4) the Texaco Poersch #1 well, Washington County, Kansas (Berendsen and others, 1988).

Nonesuch Formation

Keweenawan Supergroup clastic sedimentary rocks outcrop on the Upper Peninsula of Michigan, northern Wisconsin, and northeastern Minnesota. Stratigraphic subdivisions for these rocks are shown in figure 6. In northern Wisconsin and the Upper Peninsula of Michigan, the Nonesuch Formation of the Oronto Group consists of about 590 ft of interbedded dark-grayish to greenish sandstone, siltstone, and silty shale, and most likely represents a lacustrine depositional environment (Imbus and others, 1988; Pratt and others, 1989). Based on analyses of 200 samples collected from outcrops, cores, and subsurface mines, Pratt and others (1989) conclude that: 1) organic carbon contents of the Nonesuch Formation are generally less than 0.3 percent, but that in some thin intervals of finely laminated silty or calcareous shale collected from cores, organic carbon contents may range from 0.5 to 2.2 percent; 2) samples of the Nonesuch Formation collected from the vicinity of mineralized areas (e.g., Copper Range Mine near White Pine, Wisconsin) have no potential to generate significant amounts of hydrocarbons as indicated by genetic potential (S_1 + S_2 peaks, Rock-Eval pyrolysis) values less than 0.2 mg HC/g rock; 3) samples collected from cores away from mineralized areas may have significant hydrocarbon generating potential with genetic potentials ranging up to 7.5 mg HC/g sample (samples with >6 mg HC/g rock have good to excellent hydrocarbon source rock potential (Tissot and Welte, 1978 and 1984)). This organic matter, however, is generally marginally mature with respect to petroleum generation; and 4) if thicker sections of the finely laminated organic-matter rich shales are present down-dip from the outcrop belt, they may have good hydrocarbon generation potential.

Lonsdale 65-1 Well

Hatch and Morey (1985) studied the hydrocarbon source-rock potential of the Middle Proterozoic Solor Church Formation

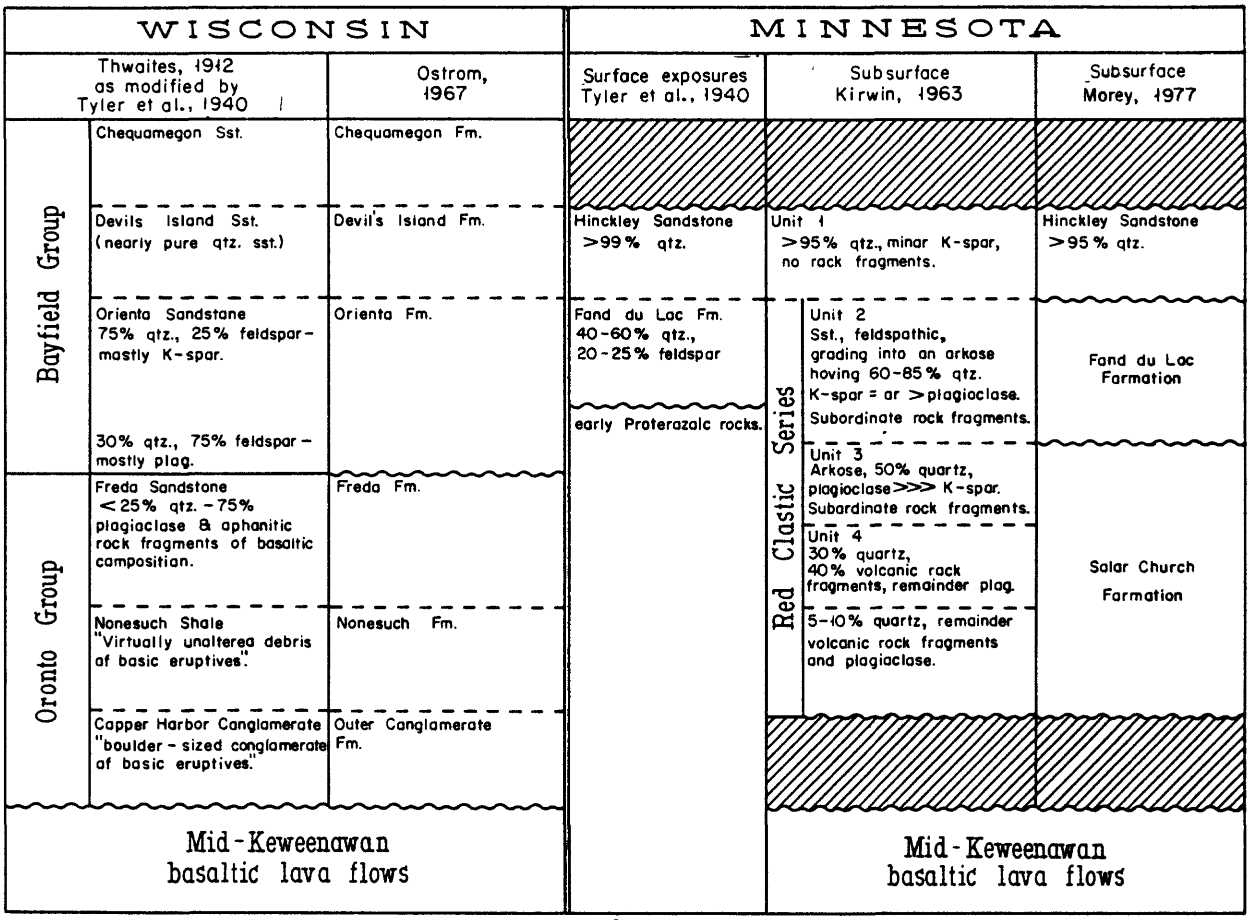

Figure 6.--Stratigraphic terminology for Proterozoic sedimentary rocks in Minnesota, Wisconsin and northern Michigan (Modified from Morey, 1977, his table 2).

(Oronto Group equivalent, see fig. 6) in the Lonsdale 65-1 well, Rice County, Minnesota. They collected 25 samples of gray to grayish-black mudstones and siltstones from a 740-ft interval of the 1,898 ft of Solor Church Formation encountered in this core. At this locality, seismic geophysical evidence (Mooney and others, 1970) indicates that the formation is at least 3,200 ft thick. Analyses of these samples show that: 1) the rocks are organic-matter lean (24 of 25 samples have less than 0.8 percent organic carbon); 2) the organic matter is thermally post mature, probably near the transition between the wet gas phase of catagenesis and metagenesis (dry gas zone); 3) the rocks have minimal potential for producing additional hydrocarbons (genetic potential, <0.3 mg HC/g rock); and 4) the thermal maturation of the organic matter in the Solor Church Formation probably took place relatively early (about 900 m.y. ago) and any hydrocarbons that might have been generated were probably lost due to uplift and erosion.

M. G. Eischeid #1 Well

Palacas and others (1990 and "in press") studied the hydrocarbon source-rock potential of the Middle Proterozoic rocks encountered in the Amoco M. G. Eischeid #1 well, Carroll County, Iowa. They collected 40 core and cuttings samples from depths between 4,150 and 17,550 ft. Rocks encountered in this well consist of a 6,900-ft thick upper "red clastic" sequence that resembles rocks of the Middle Proterozoic Bayfield Group in the outcrop area of northern Wisconsin and the Upper Peninsula of Michigan (see fig. 6) and a 7,200-ft thick lower "red clastic" sequence that is broadly correlative with the Middle Proterozoic Oronto Group in the outcrop area. All rocks in the upper "red clastic" sequence and 80 percent of the rocks in the lower "red clastic" sequence have organic carbon contents less than 0.1 percent and genetic potentials of less than 0.1 mg HC/g rock, indicating no additional potential to generate hydrocarbons.

Thin interbeds of medium-gray to dark-gray, pyrite-bearing, laminated shales, which may be equivalent to the Nonesuch Formation, are found at depths between 15,000 and 16,425 ft in the lower "red clastic" section of this well. Cumulative thickness of these shales within this interval may be 200-300 ft. Organic carbon contents of the shales range from 0.04 to 1.4 percent (average value, 0.6 percent) and genetic potentials are all less than 0.4 mg HC/g rock, indicating minimal hydrocarbon generation potential. The thermal maturity of organic matter in these shales is at least in the wet-gas zone of hydrocarbon generation and possibly in the dry-gas zone. Time-temperature-index calculations by Palacas and others (1990, and "in press") suggest that these rocks passed through the oil window approximately 800 m.y. ago. They further speculate that if the shale facies is present at shallower depths along the flanks of the basin, where organic-matter thermal maturity would be lower, the hydrocarbon generation potential may be higher.

Poersch #1 Well

In the Texaco Poersch #1 well in Washington County, Kansas, Midcontinent rift rocks were encountered between 2,846 ft and the total depth of 11,300 ft. As described by Berendsen and others (1988), the rocks penetrated by the well can be roughly divided into two distinct parts or successions of almost equal thickness. Ninety percent of the upper succession (2,846-7,429 ft) is characterized by mafic volcanics and subordinate mafic and acidic intrusives. The remaining ten percent of the section is made up of oxidized siltstone and arkose. Ninety percent of the lower succession (7,429 to TD 11,300 ft) is characterized by arkose and subarkose, with minor amounts of oxidized siltstone and shale. The remaining ten percent of the lower succession consists of two mafic units (at 8,678-8,806 ft and 10,622-10,840 ft) and some minor volcanic flows. No organic-matter rich intervals were encountered in the Poersch #1 well (Berendsen and others, 1988, Appendix 3).

Reservoir Rocks

Since oil and gas have not been produced from sedimentary rocks associated with the Midcontinent rift, information on reservoir lithologies or on the nature of traps is speculative. If hydrocarbons are to be found in these rocks, however, the most likely reservoirs are the more porous/permeable sandstone intervals. Other Keweenawan lithologies (arkose/subarkose/ feldspathic sandstone) are compositionally immature and likely to have unfavorable porosity and permeability.

Sandstones in Oronto Group equivalent rocks in the Eischeid #1 well, Carroll County, Iowa, constitute 29 percent of the interval between 11,450 and 17,340 ft. Porosity of these sandstones, as determined from compensated density and neutron logs (Palacas and others, 1990) ranges between 1 and 6 percent and averages only 2.3 percent. "Better" porosities (3.5-6.0 percent) are distributed throughout this interval and appear to correlate with higher percentages of plagioclase feldspar.

Arkosic sediments present in the Texaco Poersch #1 well, Washington County, Kansas, have low porosities, averaging 2 percent. The notable exception to this occurs at depths between 11,055-11,077 ft where both neutron and density logs indicate a zone with porosities ranging up to 15 percent (Berendsen and others, 1988).

In east-central Minnesota, the Hinckley Sandstone (fig. 6) is medium to coarse grained, poorly to moderately sorted, contains >95 percent quartz, and weakly to strongly cemented by silica (Tryhorn and Ojakangas, 1972). Near the type section, in Pine County, Minnesota, this unit is more than 500 ft thick. It thins progressively southward and on the average is about 150 ft thick near Minneapolis and St. Paul (Grout and others, 1951). In the Twin Cities area, the Hinckley Sandstone is an important fresh-water aquifer (Craddock, 1972).

Traps

Throughout the Midcontinent rift, regional structures in the basins flanking the central horst appear gently homoclinal, but local flexures and fault structures possibly exist. Upward bending of strata adjacent to the major faults may have produced suitable structural traps (Craddock, 1972).

Champlainian (Middle Ordovician) Play

The Champlainian (Middle Ordovician) play in the Iowa shelf province is based on: 1) current hydrocarbon production from age equivalent rocks in adjacent provinces; 2) prior minor petroleum production from Champlainian rocks on the Iowa shelf; 3) the presence of good to excellent hydrocarbon source rocks within the Champlainian section; and 4) the presence of potential sandstone and porous dolomite reservoirs. The area of the Champlainian play in the Iowa shelf province is the area underlain by Champlainian rocks, which includes all the province except for small areas in northwestern Iowa, and southeastern Minnesota (fig. 7). On the Iowa shelf, Champlainian rocks are divided into the Ancel, Platteville and Galena Groups (fig. 8) (Willman and others, 1967; Willman and Buschbach, 1975).

In provinces adjacent to the Iowa shelf (fig. 4) oil is produced from Champlainian rocks. In the Forest City basin province to the southwest, oil is produced from fields associated with small faulted and folded structures. Production is from porous sandstones in the Simpson Group (Ancel Group equivalent) and(or) from intercrystalline and vugular porosity in the Viola Limestone (Galena Group equivalent)(Adler and others, 1971). In the Michigan basin to the northeast, oil is produced from stratigraphic traps caused by porosity and permeability variations in dolomitized limestones of the Trenton Group (Galena Group equivalent) (Charpentier, 1987); in the Illinois basin to the southeast, oil is produced from fields associated with structural highs in the limestone/dolomite of the Galena Group ("Trenton")(Bristol and Buschbach, 1973).

Oil and Hydrocarbon Source Rock Characterization

Oil has been produced from Champlainian rocks on the Iowa shelf. In 1963, the Natural Gas Pipeline Co. of America drilled the W. F. Flynn P-1 well in Washington County, Iowa, in exploration for a natural gas storage site, and found the Keota Dome field. Slightly more than 400 barrels of oil were produced from vugular porosity in the Pecatonica Dolomite and from fractures in the Mifflin Limestone (Adler and others, 1971). Hatch and others (1985, 1987, and "in press") and Jacobson and others (1988) identified this oil as a typical "Ordovician" oil, characterized by an abundance of *n*-alkanes with carbon numbers less than 20, a predominance of odd-numbered *n*-alkanes between C_{10} and C_{20}, and small amounts of branched and cyclic alkanes (including the isoprenoids). Source rock for this oil is the underlying Glenwood Formation (Hatch and others, 1985 and "in press").

Potential hydrocarbon source rocks occur at several horizons within the Champlainian section (Hatch and others, 1985, 1986, 1987 and "in press"; and Jacobson and others, 1988). Organic-rich shale interbeds occur in the St. Peter Sandstone (Ancel Group), Glenwood Formation (Ancel Group), Quimbys Mill Formation (Platteville Group), and Guttenburg Formation (Galena Group).

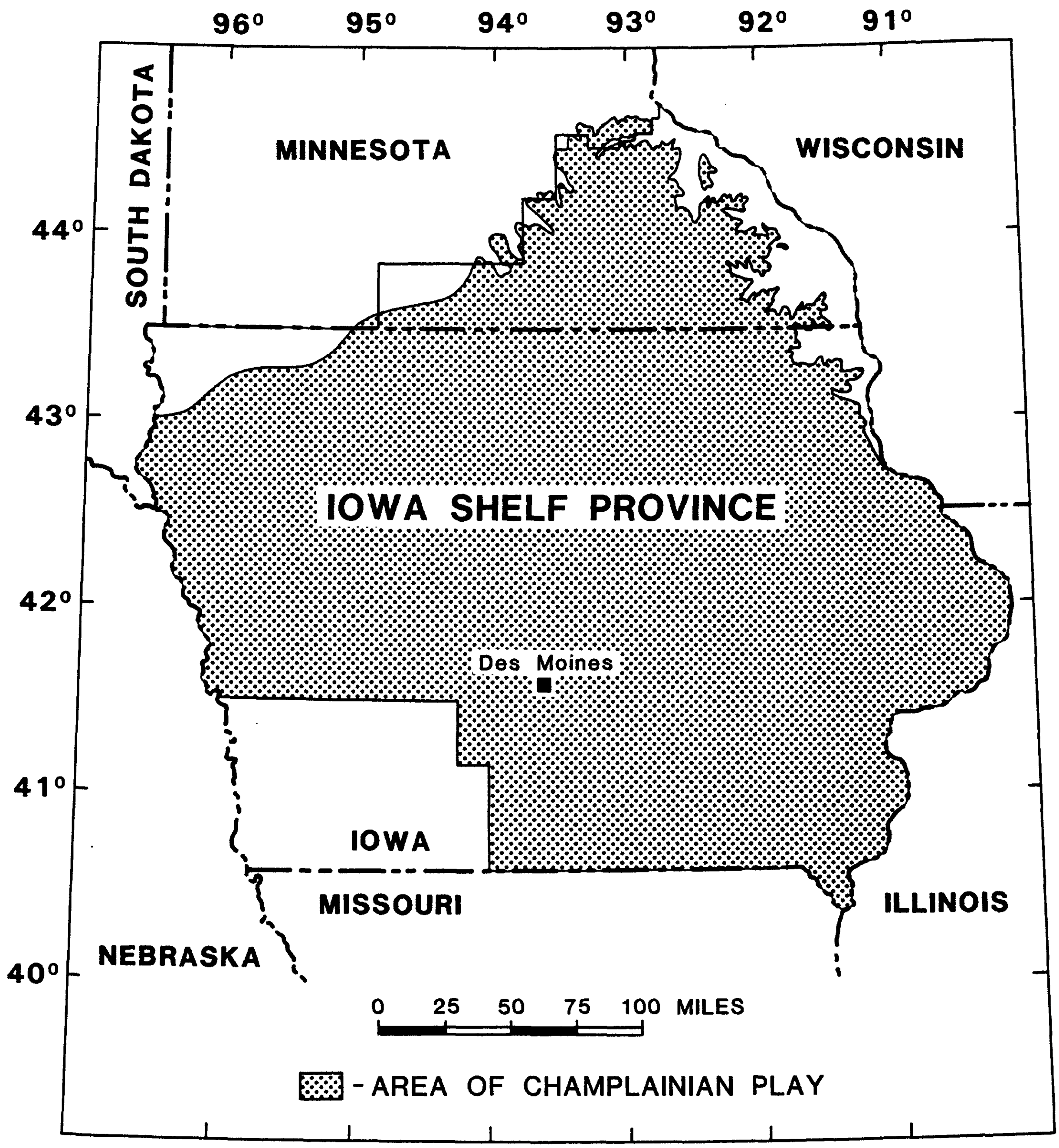

Figure 7.--Extent of Champlainian play on the Iowa Shelf (Modified from King and Beikman, 1974; and Adler et al, 1971).

Hatch et al. (1987 and "in press") collected 32 samples of Champlainian rocks from cores in Washington and Jackson Counties, Iowa. Organic carbon contents for these samples range from 0.13 to 43.3 percent with a median value of 7.9 percent; genetic potentials range from <0.2 to 470 mg HC/g rock with a median value of 49 mg HC/g rock. Thermal maturity of organic matter in

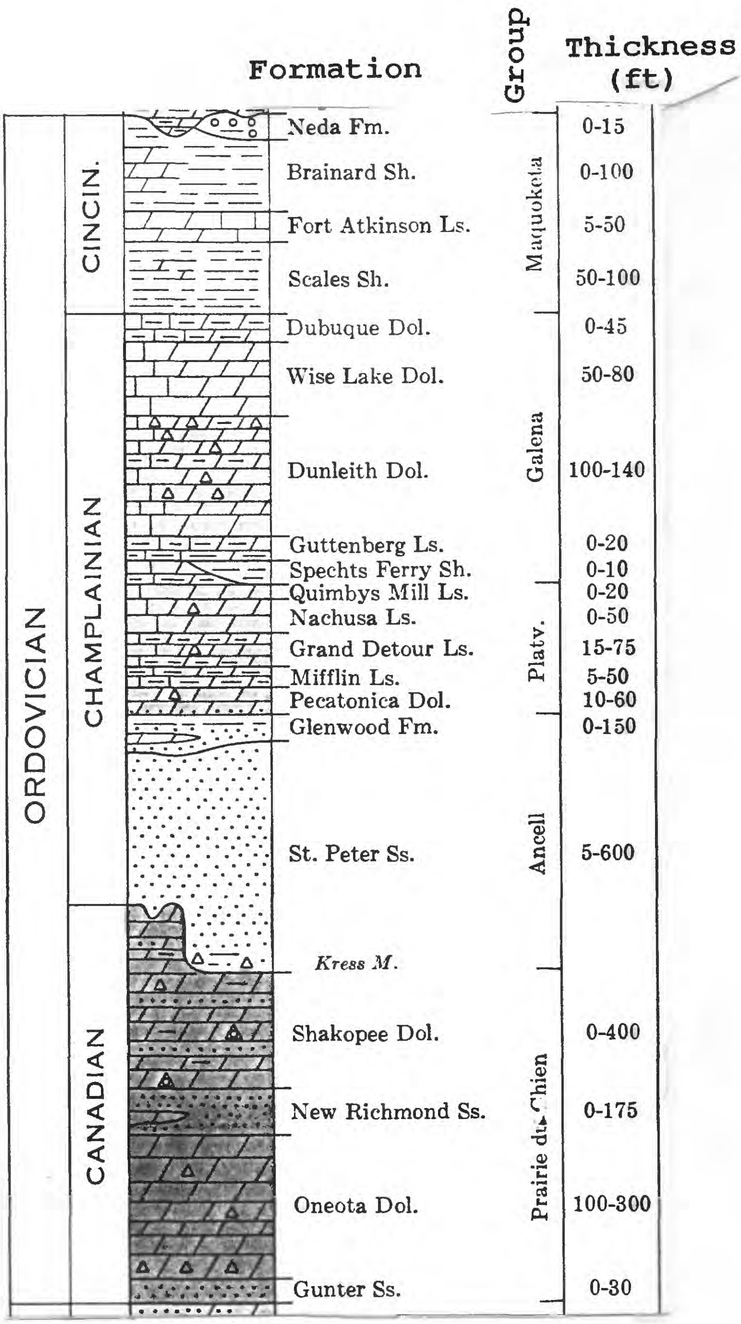

Figure 8.--Stratigraphic terminology for Champlainian rocks in Iowa (from Willman and others, 1967).

Champlainian rocks on the Iowa shelf ranges from immature to marginally mature (Hatch and others, 1987 and "in press"; Jacobson and others, 1988).

Reservoir Rocks

Almost 70 years ago, Howell (1922) recognized that the Champlainian St. Peter Sandstone and Galena Group rocks in Iowa have potential to be hydrocarbon reservoir rocks. Howell (1922) stated: "The St. Peter is a massive, uniform, generally rather loosely cemented sandstone. . . . Owing to its high porosity and the presence of the impervious Platteville above, the St. Peter would be an ideal reservoir." Howell (1922) also stated that "In most places the Galena is a thick bedded, massive dolomite, buff in color and highly porous." On a more negative note, Howell (1922) noted that "throughout the northern and eastern parts of Iowa, the St. Peter is an aquifer, and its water is notably pure and of low mineral content."

Traps

Both structural and stratigraphic traps are possible on the Iowa shelf. The most prominent structural features are the series of domes and anticlines termed the Thurman-Redfield structural zone (Hershey and others, 1961) which extends from Fremont County (southwestern corner of Iowa) northeast to Hardin County (central Iowa). All of this structural zone coincides with or parallels the eastern boundary of the Midcontinent rift. Numerous other structural features (anticlines, domes, and synclines) of smaller areal extent have been mapped. These features were formed during the folding which began in the Mississippian and continued into the Pennsylvanian (Adler and others, 1971).

The only documented example of a stratigraphic trap on the Iowa shelf is in the Keota Dome field, where facies in the Pecatonica Dolomite changes from pure carbonate to sandy carbonate (Adler and others, 1971).

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