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Source-Rock Potential of Precambrian Rocks in Selected Basins of the United States

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GEOLOGIC CONTROLS OF DEEP NATURAL GAS RESOURCES IN THE UNITED STATES

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ABSTRACT

Assessment of gas source potential, based mostly on organic matter richness and thermal maturity, was conducted on Precambrian (Proterozoic) rocks of four segments of the Midcontinent Rift system and in the Grand Canyon area, Arizona. In the Lake Superior segment of the Midcontinent Rift system, at shallow depths, indigenous oil seeps are present in thin intervals of silty shales of the Nonesuch Formation. These shales contain as much as 3.0 percent total organic carbon (average 0.6 percent) and are marginally mature to mature with respect to the principal zone of oil generation. Should thicker sections of organic-rich shales of the Nonesuch Formation be present at greater depths of burial where higher maturity levels have been attained, the gas source potential could be fair to good.

In the Minnesota segment of the Midcontinent Rift system, as evaluated in the Lonsdale 65–1 borehole, St. Croix horst, Rice County, Minnesota, darker gray mudstones of the Solor Church Formation have organic carbon contents of commonly less than 0.4 percent and genetic potentials (S_1+S_2) of less than 0.1 milligrams of hydrocarbon per gram of rock. The rocks are thermally overmature (T_{max}=494˚C) and most likely have a poor remaining source potential, at least in the vicinity of the Lonsdale well. Other parts of the Minnesota segment have not been appraised.

The Iowa segment of the Midcontinent Rift system was evaluated from drill samples from the Amoco 1 Eischeid well, immediately west of the Iowa (medial) horst, Carroll County, Iowa. Analyses of 200–300 ft (61–91 m) of dark-gray to black shale, at depths of 15,000–16,425 ft (4,570–5,006 m), indicate that the rocks are overmature (T_{max}=503˚C), contain as much as 1.4 percent organic carbon (average 0.6 percent), and have a genetic potential as high as 0.4 milligrams of hydrocarbon per gram of rock. Although potential for commercial gas production is poor at the Eischeid locality, good source potential cannot be precluded from other areas. One such area may be where equivalent shales are present at lower maturity levels, along the basin flanks, away from the frontal fault zone of the medial horst.

Evaluation of the Kansas segment of the Midcontinent Rift was confined to two boreholes that penetrated only two of a series of small, structurally and stratigraphically complex subbasins. In the first subbasin, penetrated by the Texaco 1 Poersche well, sedimentary rocks of the Rice Formation have no petroleum source potential. In the second subbasin, penetrated by the Producers Engineering 1–4 Finn well, a 296-foot- (90 m)-thick unit of the Rice Formation composed of gray siltstone has some hydrocarbon source potential. The much richer, upper half of this unit is characterized by a total organic carbon content of as much as 0.95 percent (average 0.66 percent) and a genetic potential of as much as 0.75 milligrams of hydrocarbon per gram of rock. A more conclusive evaluation of the Kansas segment requires study of some of the adjoining subbasins.

The 5,370-foot (1,636 m)-thick Late Proterozoic Chuar Group, exposed in the eastern Grand Canyon, Arizona, contains abundant gray to black mudstone and siltstone that have good petroleum source potential. The Walcott Member, the uppermost unit of the Chuar Group, is the richest unit in terms of hydrocarbon-generating material. Source rocks of the lower half of the Walcott Member are thermally mature and have organic carbon contents as high as 10.0 percent (average 3.0 percent), genetic potential as high as 16.0 milligrams of hydrocarbon per gram of rock (average 6.0) and extractable organic matter contents as high as 4,000 ppm. Strata of the Chuar Group may be sources for economic accumulations of gas and oil in Late Proterozoic or lower Paleozoic reservoirs in northern Arizona and southern Utah.

INTRODUCTION

Although Precambrian rocks are distributed throughout the United States and commonly are present in the deeper parts of sedimentary basins, their petroleum source-rock potential is poorly known. These rocks may have generated and expelled petroleum that was subsequently trapped in Precambrian and (or) younger overlying Phanerozoic rocks.

In this report, I discuss the source-rock potential of Precambrian (Proterozoic) unmetamorphosed sedimentary rocks in selected basins of the United States.

The impetus for ascribing a viable petroleum potential to Precambrian rocks in the United States is provided by the production of commercial oil and gas derived from Precambrian rocks in other parts of the world. For example, in Oman, carbonate-evaporite rocks of the Late Proterozoic Huqf Group are believed to be the source of about 12 BBO and an undetermined amount of gas accumulated in Proterozoic and overlying Paleozoic and Mesozoic reservoirs (Grantham and others, 1987; Brett Mattes, as reported in Fritz, 1989; Edgell, 1991). In the Lena-Tunguska petroleum province of eastern Siberia, major and giant fields produce gas, gas condensate, and oil from Proterozoic (Riphean and Vendian age) and Lower Cambrian strata (Meyerhoff, 1980; Clarke, 1985). One of the largest fields discovered, the Verkhnevilyuy field, has proven plus probable reserves of 10.5 TCFG and about 260 million barrels of condensate (Meyerhoff, 1980). The predominant source beds are of Proterozoic age (Meyerhoff, 1980; Clarke, 1985). Undiscovered petroleum resources of the Lena-Tunguska basin may be as high as 189 TCFG and about 11 BBO (Clarke, 1985). Interestingly, in an earlier assessment, Meyerhoff (1980, p. 225) estimated an ultimate recovery of “200 TCFG together with condensate.”

In the Sichuan basin of southwest China, giant accumulations of natural gas were derived from Late Proterozoic (Sinian) carbonate rocks (Korsch and others, 1991). One of the gas fields in the basin, the Weiyuan gas field, is estimated to have a total reserve of as much as 1.41 TCFG (Korsch and others, 1991).

In this report, I focus on the source-rock potential of Proterozoic rocks in two regions of the United States, the Midcontinent Rift system and the Grand Canyon area in northern Arizona and vicinity. Other promising areas exhibiting Precambrian petroleum potential are in the Uinta Mountains and vicinity, where the relatively organic rich Late Proterozoic Red Pine Shale and equivalent rocks are widely distributed both in the surface and subsurface (M.W. Reynolds, oral commun., 1990; R. Raynolds, Amoco Production Company, written commun., 1990), and in the Rocky Mountain overthrust belt of northwestern Montana, where gas shows were encountered in 1.43-Ga rocks to depths of 17,774 ft (5,418 m) in the Atlantic-Richfield No. 1 Gibbs well (Shirley, 1985).

MIDCONTINENT RIFT SYSTEM

Rocks of the Midcontinent Rift system, which is delineated by strong gravimetric and magnetic anomalies, are exposed in the Lake Superior region of Michigan, northern Wisconsin, and Minnesota and extend in the subsurface through Minnesota, Iowa, Nebraska, and into northeastern Kansas (fig. 1). Based on gravity measurements, a related arm of the rift system can also be traced in the subsurface from the Lake Superior region southeastward into the lower peninsula of Michigan (fig. 1) (Dickas, 1986). This easterly extension of the rift is not discussed in this report. The 940-mile (1,500 km)-long Midcontinent Rift system is a failed rift characterized by a series of asymmetric basins filled with clastic rocks in places as thick as 32,000 ft (9,754 m) (Anderson, 1989). The rocks belong to the Middle Proterozoic Keweenawan Supergroup, comprising the Bayfield Group above and the Oronto Group below. The Midcontinent Rift system can be divided into four geographically identifiable segments (Lake Superior, Minnesota, Iowa, and Kansas), and the petroleum potential of each segment is assessed separately, based mostly on geologic and (or) geochemical data derived from examination of Middle Proterozoic rocks from specific localities within each segment.

LAKE SUPERIOR SEGMENT

The potential for petroleum reserves in the Midcontinent Rift system has long been recognized because of active crude oil seeps emanating from shales within the ≈1.1-Ga Nonesuch Formation at the White Pine mine in the Lake Superior region (fig. 1) (Dickas, 1986). In this region, the Nonesuch Formation, the middle unit of the Oronto Group, ranging in thickness from about 250 to 700 ft (76–213 m) and averaging 600 ft (183 m), consists of interbedded dark-grayish to -greenish sandstone, siltstone, and silty shale. Analyses of almost 400 outcrop and shallow core samples (Imbus and others, 1987; Pratt and others, 1989) indicate that the total organic carbon content for Nonesuch rocks is generally less than 0.3 percent; however, the total organic content of finely laminated calcareous and noncalcareous silty shales, which are in thin intervals, ranges from 0.25 to 2.8 percent and averages 0.6 percent (table 1) (Hieshima and others, 1989). It is these finely laminated silty shales that show promise of being hydrocarbon source beds. Surprisingly, these 1.1-Ga shales along the outcrop belt have never experienced severe thermal stress. Rock-Eval T_{max} data (table 1) and biological marker distributions suggest that these fine-grained source rocks are marginally mature to mature with respect to the principal zone of oil generation (Hieshima and others, 1989; Pratt and others, 1989).

If thicker sections of these finely laminated, hydrocarbon-generating shales are downdip from the outcrop belt and if these shales were subjected to higher levels of thermal maturation in the geologic past, the gas source potential for the Lake Superior and the adjoining area in northern Wisconsin should be fair to good. This evaluation is, of course, contingent also on the presence of adequate reservoir rocks and seals.

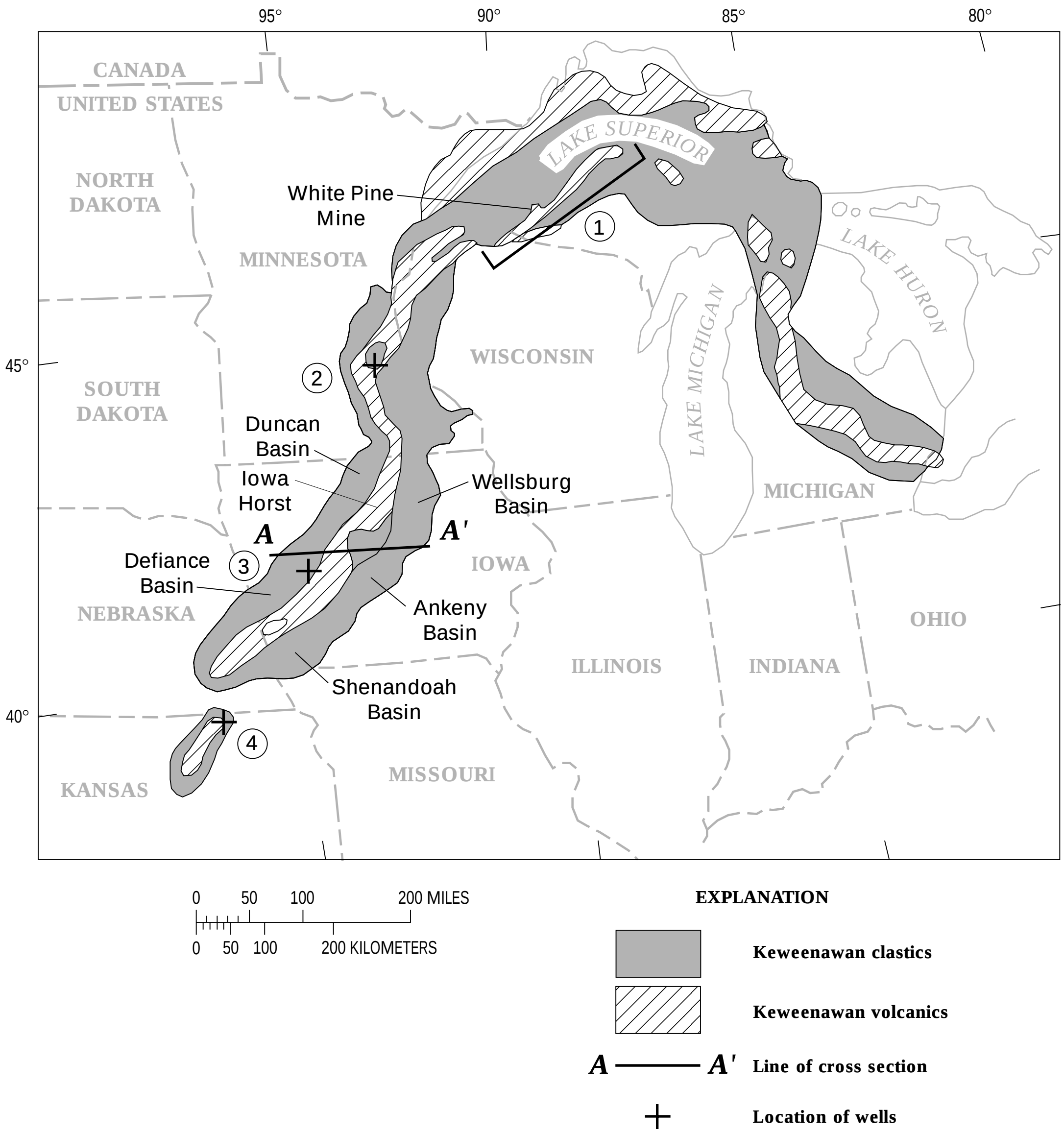

Figure 1. Map showing the general location of major rock types of the Midcontinent Rift system and the four localities at which Precambrian sedimentary rocks were studied. (1) Lake Superior segment outcrop belt; (2) Minnesota segment, Lonsdale 65–1 well, Rice County; (3) Iowa segment, Amoco Eischeid No. 1 well, Carroll County; (4) Kansas segment, Texaco 1 Poersche well, Washington County, and the Producers 1–4 Finn well, Marshall County, which is 21 miles northeast of the 1 Poersche well. Line of section *A–A'* (fig. 2) is also shown. Modified from Palacas and others (1990).

MINNESOTA SEGMENT

The source-rock potential of the Minnesota segment of the Midcontinent Rift system was evaluated from examination of Keweenawan Solor Church Formation rocks as sampled in the Lonsdale 65–1 borehole, in the Saint Croix horst, Rice County, Minnesota (Hatch and Morey, 1985). The Lonsdale borehole penetrated 1,898 ft (579 m) of the Solor Church Formation, but seismic evidence indicates that at least a 3,200-foot (975 m)-thick sequence of the formation is present at this location. The formation consists principally of interbedded conglomerate, sandstone, siltstone, and shale or mudstone similar in lithology and hence broadly correlative to the Oronto Group of Michigan and Wisconsin.

Analyses of 25 core samples, mainly from the lower 20 percent of the 1,898-foot (578 m)-thick core, indicate total organic carbon contents ranging from 0.01 to 1.77 percent and averaging 0.24 percent, suggesting an overall poor source-rock potential for oil or gas for the entire formation. Darker gray mudstone that makes up about half of the samples analyzed is characterized, however, by slightly higher total organic carbon content ranging from 0.13 to

Table 1. Geochemical data from possible Precambrian source rocks, Midcontinent Rift system and Grand Canyon, northern Arizona.
[Locations are shown in figures 1 and 3]

Location	Stratigraphic unit and lithology	Total organic carbon content (weight percent) Range	Average	T_{max} (°C)	Level of maturity
Midcontinent Rift system					
Lake Superior segment	Nonesuch Formation (dark shale)	0.25–2.8	0.6	418–427	Marginally mature to mature.
Minnesota segment	Solor Church Formation (mudstone)	0.13–1.77	0.4	494	Overmature.
Iowa segment	Nonesuch Formation equivalent (dark shale)	0.1–1.4	0.6	497–508	Overmature.
Kansas segment (Producers Finn No. 1 well)	Keweenawan (undifferentiated) (siltstone)	0.1–0.8	0.6	445–450	Mature.
Grand Canyon area, northern Arizona					
Eastern Grand Canyon	Walcott Member[1] (dark mudstone)	1.0–10.0	~3.0	424–452	Mature.

1.77 percent and averaging 0.4 percent. Under certain circumstances, average total organic carbon contents of 0.4 percent and even 0.3 percent have been considered by some geochemists as the minimum necessary to form a hydrocarbon source rock (Dow, 1977; Palacas, 1978; Tissot and Welte, 1984, p. 497). Thus, from the standpoint of total organic carbon alone, the shale could be considered to have some petroleum source-rock potential. The average genetic potential (S_1+S_2) of less than 0.1 milligrams of hydrocarbon per gram of rock strongly indicates, however, that these rocks are now poor in hydrocarbon-generating organic matter both for oil and gas. The very low average genetic potential is mostly attributed to the advanced level of thermal maturation. This level of thermal maturation is corroborated by the only realistic T_{max} value (494˚C), obtained from the richest mudstone sample analyzed (total organic carbon content, 1.77 percent). Based on previous maturity evaluations of basins worldwide, the T_{max} value of 494˚C suggests that the Solor Church organic matter at the Lonsdale 65–1 locality has advanced to the transition stage between the wet-gas and dry-gas generating zones (Hatch and Morey, 1985).

From the above considerations, it is clear that at the present time the gas source potential of the Middle Proterozoic Solor Church Formation rocks is poor in the region of the Saint Croix horst and particularly at the Lonsdale well locality. Perhaps in the geologic past economic quantities of gas were generated; however, Hatch and Morey (1985) suggested that, if hydrocarbons were generated when the Solor Church Formation experienced maximum burial depth and high geothermal gradients, the generated hydrocarbons were lost as a consequence of subsequent uplift and erosion that produced clastic sediments included in the overlying Fond du Lac Formation (Bayfield Group correlative).

IOWA SEGMENT

The Iowa segment of the Midcontinent Rift system is unique in that the hydrocarbon source-rock assessment was made of the thickest section (14,898 ft, 4,540 m) of Precambrian sedimentary rock sampled by drilling from anywhere in the 940-mile (1,500 km)-long structure. Assessment of this segment is based on analysis of 40 core and cuttings samples from the 17,851-foot (5,440 m)-deep Amoco M.G. Eischeid No. 1 well drilled in 1987 in an asymmetric half-graben-like basin northwest of the medial horst (Iowa horst), Carroll County, Iowa (figs. 1, 2) (Palacas and others, 1990). The Eischeid well penetrated 2,802 ft (854 m) of Phanerozoic (mostly Paleozoic) strata, 14,898 ft (4,541 m) of Middle Proterozoic (Keweenawan) unmetamorphosed sedimentary rocks, and 151 ft (46 m) of Middle Proterozoic gabbroic intrusive rocks. The Keweenawan rocks comprise 7,708 ft (2,349 m) of an upper "Red Clastic" sequence, resembling the Bayfield Group of Wisconsin, and 7,190 ft (2,191 m) of a lower "Red Clastic" sequence, generally correlative to the Oronto Group of Wisconsin.

Most of the Keweenawan sedimentary rocks, composed of red and red-brown sandstone, siltstone, and silty shale, are oxidized and have no source-rock potential. These oxidized rocks have total organic carbon contents of less than 0.1 percent and genetic potentials of less than 0.1 milligrams of hydrocarbon per gram of rock. In the lower "Red Clastic" sequence, at depths between 15,000 and 16,425 ft (4,572–5,006 m), a conspicuous darker colored section of rock, possibly equivalent to the Nonesuch Formation of the Lake Superior region, contains a cumulative thickness of 200–300 ft (61–91 m) of gray to black, pyrite-bearing, laminated shale. Total organic carbon content of this shale averages 0.6 percent and is as high as 1.4 percent (table 1), and genetic potential ranges from 0.1 to 0.4 milligrams of hydrocarbon per gram of rock. An average T_{max} value of 503˚C

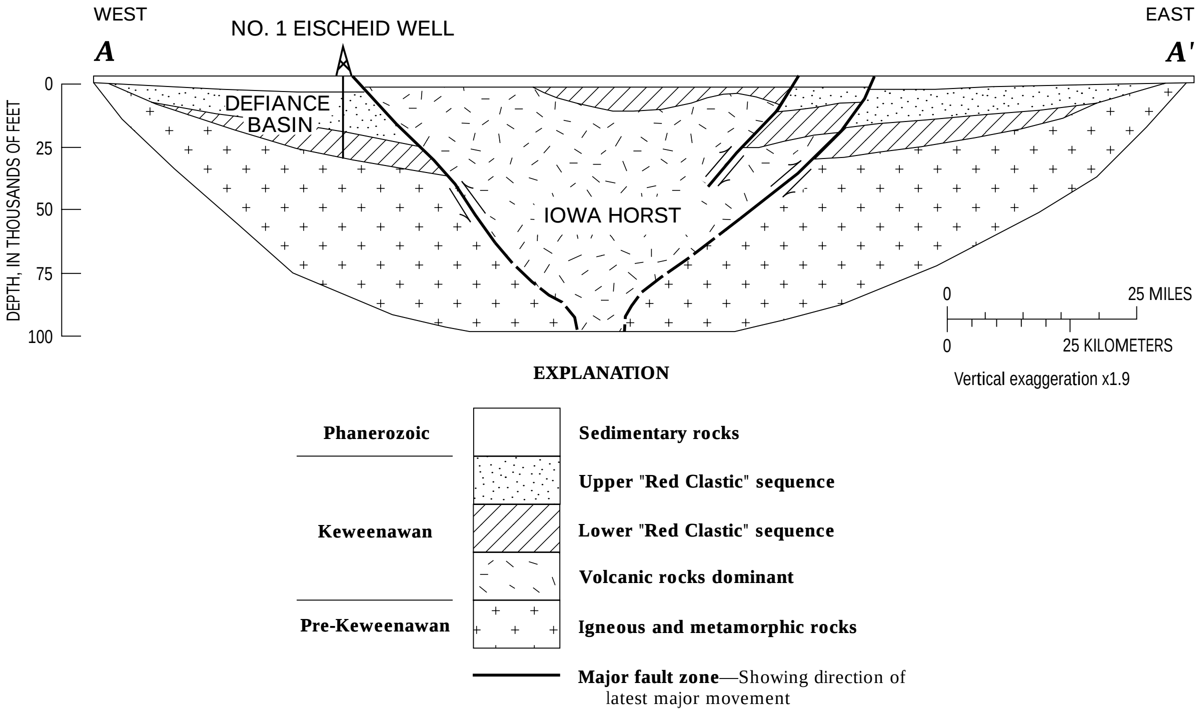

Figure 2. Schematic geologic cross section of Midcontinent Rift system, central Iowa. Note approximate location of Amoco M.G. Eischeid No. 1 well with respect to Iowa horst. Line of section is shown in figure 1. Modified from Palacas and others (1990).

strongly indicates that the shale is thermally overmature and in the transitional zone between wet gas and dry gas, similar to the findings for the Solor Church Formation in southeastern Minnesota.

These data suggest that the dark-colored, laminated shale between 15,000 and 16,425 ft (4,572–5,006 m) has little remaining capacity for hydrocarbon generation but may have generated significant amounts of gas in the geologic past, most likely during Proterozoic time. Support for this conclusion is provided by the on-site chromatographic detection of minor amounts of methane and ethane throughout most of the darker colored shaley interval. If indeed commercial volumes of gas were generated and expelled, I speculate that the most plausible pathway of migration would not have been vertical because of constraints imposed by very low porosities (average 2.3 percent) and permeabilities (Schmoker and Palacas, 1990) but rather would have been updip along bedding structures toward the shallower parts of the basin. This direction of movement is in harmony with the probable hydrodynamic flow from the deeper, central parts of the basin toward the updip margins of the basin (Ludvigson and Spry, 1990). I further speculate that an equivalent laminated shale facies, such as that observed in the Eischeid well, might have fair to good hydrocarbon source potential if present at shallower depths of burial, under lower levels of thermal stress, along basin flanks, away from the frontal fault zone of the medial horst.

KANSAS SEGMENT

The Kansas segment of the Midcontinent Rift system was tentatively evaluated on the basis of examination of cuttings samples from two boreholes in northeastern Kansas: the Texaco 1 Noel Poersche well, sec. 31, T. 5 S., R. 5 E., Washington County, and the Producers Engineering 1–4 Finn well, sec. 4, T. 4 S., R. 7 E., Marshall County (Berendsen and others, 1988; Newell and others, 1993). The 1–4 Finn well is 21 mi (34 km) northeast of the 1 Poersche well. The two wells exhibit remarkably different lithologies, probably reflecting different structural, stratigraphic, and (or) depositional regimes, and the two sections of rock may have been deposited in two different subbasins. This conclusion is commensurate with the findings provided by geophysical and borehole data that the segment of the Midcontinent Rift system in northeastern Kansas is divided into small subbasins that probably are only a few tens of square miles in areal extent (K.D. Newell, written commun., 1991).

The Poersche well, drilled to total depth of 11,300 ft (3,444 m), penetrated 2,846 ft (867 m) of Phanerozoic rock and 8,454 ft (2,576 m) of Precambrian (Keweenawan) rock, the latter of which comprises almost equal successions of highly oxidized arkosic sandstone and siltstone and mafic volcanic and intrusive rocks. The lack of organic matter in any of the oxidized sedimentary rocks unequivocally indicates no source-rock potential.

On the other hand, the Producers Engineering 1–4 Finn well, which encountered 1,848 ft (563 m) of Precambrian rock, consisting mostly of arkosic sandstone, siltstone, and shale, showed some minor gas source potential in a 396-foot (90 m)-thick unit of gray siltstone directly beneath the Paleozoic-Precambrian unconformity. The upper half of this unit is the richer, characterized by total organic carbon content as high as about 0.95 percent and averaging 0.66 percent and genetic potential ranging from 0.35 to 0.75 milligrams of hydrocarbon per gram of rock and averaging 0.5 (Newell and others, 1993). The lower half of the unit contains much less organic matter, having total organic carbon contents of about 0.15–0.2 percent. T_{max} values for the entire unit are mostly in the range of 445˚C–450˚C, well within the oil generation window (435˚C–465˚C). These maturity values contrast dramatically with the decidely higher maturity values for the Minnesota and Iowa segments of the Midcontinent Rift system (table 1).

In summary, although the deepest penetration of Precambrian rock (Poersche well) indicated no hydrocarbon source-rock potential, the 1–4 Finn well, only 21 mi (34 km) northeast of the Poersche well, demonstrates that some gas and (or) oil source potential is present. Because of the structural complexity and abrupt facies changes, individual subbasins should be examined before complete source-rock evaluation is made of the Kansas part of the rift system.

GRAND CANYON AREA, NORTHERN ARIZONA

The Late Proterozoic Chuar Group is exposed in the eastern part of the Grand Canyon. This 5,370-foot (1,636 m)-thick succession of predominantly very fine grained siliciclastic rocks contains thin sequences of sandstone and stromatolitic and cryptalgal carbonate rocks (figs. 3, 4) (Reynolds and others, 1988). More than half the succession consists of organic-rich gray to black mudstone (or shale) and siltstone. Fossil micro-organisms, such as *Chuaria* (discoidal megaplanktonic algae), tear and flask-shaped chitinozoa (?), filamentous algae, and individual and clusters of spheroidal, cystlike planktonic organisms, are abundant to common throughout successions of dark mudstone and siltstone (Vidal and Ford, 1985).

Geochemical analyses indicate that the 922-foot (281 m)-thick Walcott Member, the uppermost unit of the Kwagunt Formation (fig. 3), has good to excellent petroleum source-rock potential. The lower half of the Walcott is characterized by total organic carbon content as high as 8.0–10.0 percent (average ≈3.0 percent), hydrogen index as high as 204 milligrams of hydrocarbon per gram of total organic carbon (average ≈135), genetic potential (S_1+S_2) of almost

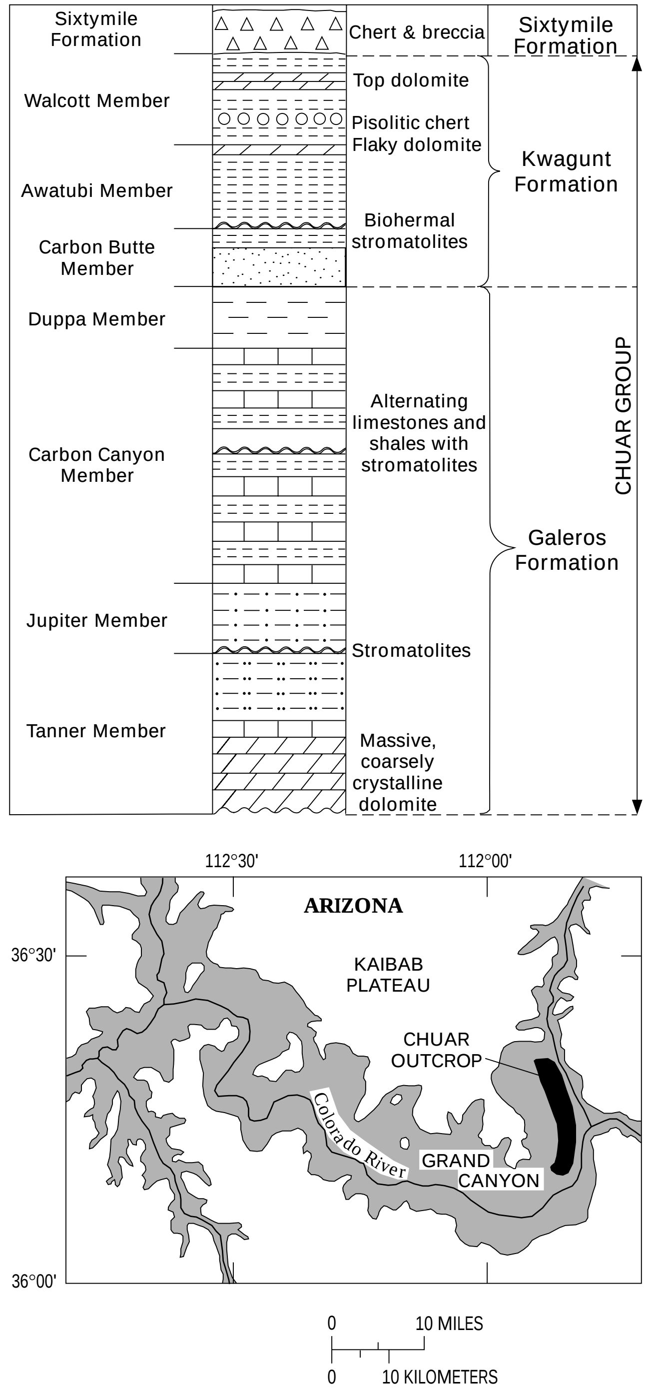

Figure 3. Map of the eastern Grand Canyon, in northern Arizona, showing sampling locality (solid black pattern) and simplified geological section of the Chuar Group. Modified from Vidal and Ford (1985).

16,000 ppm (average ≈6,000 ppm), and chloroform-extractable organic matter as high as 4,000 ppm (Palacas and Reynolds, 1989; Palacas and Reynolds, unpublished data). Data for the upper part of the Walcott are incomplete but suggest that these rocks are as rich as the lower part of the

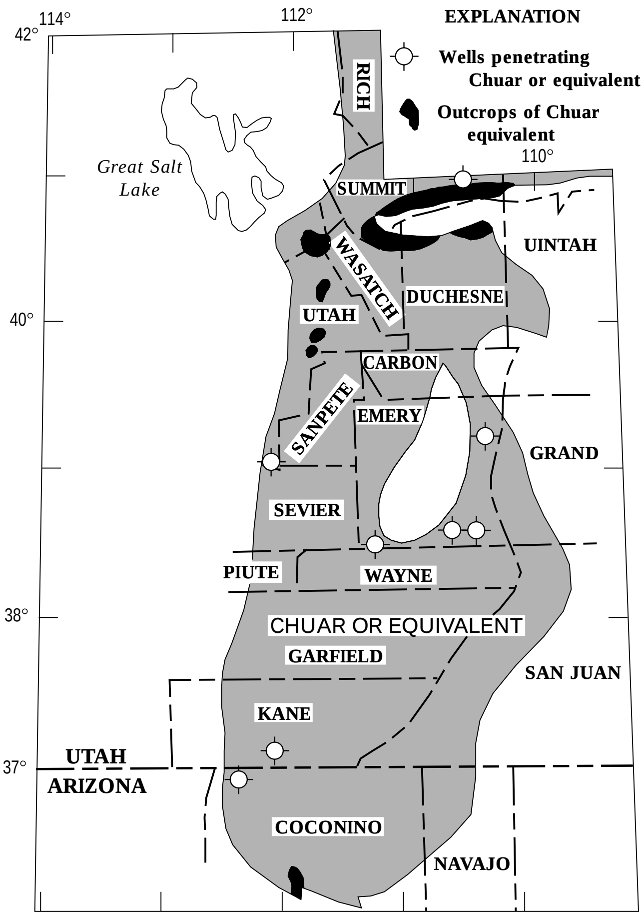

Figure 4. Map showing possible distribution of Late Proterozoic Chuar Group or equivalent rocks in northern Arizona and Utah. Modified from Utah Geological and Mineral Survey (1990) and Rauzi (1990).

Walcott. Maturity assessment indicates that source rocks of the Walcott are within the oil-generation window.

Strata of the underlying thermally mature Awatubi Member of the Kwagunt and the thermally mature to overmature Galeros Formation (below the Kwagunt) are, in general, rated as poor oil sources and have genetic potential of generally less than 1,000 ppm, but they probably are acceptable to good source rocks for gas generation.

Strata of the Chuar Group may be potential sources for economic accumulations of gas and oil in Late Proterozoic or lower Paleozoic reservoir rocks in northwestern Arizona and southern Utah. The relative proportion of gas or oil in any one area depends in large part on the degree of thermal maturation that the rocks have undergone.

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