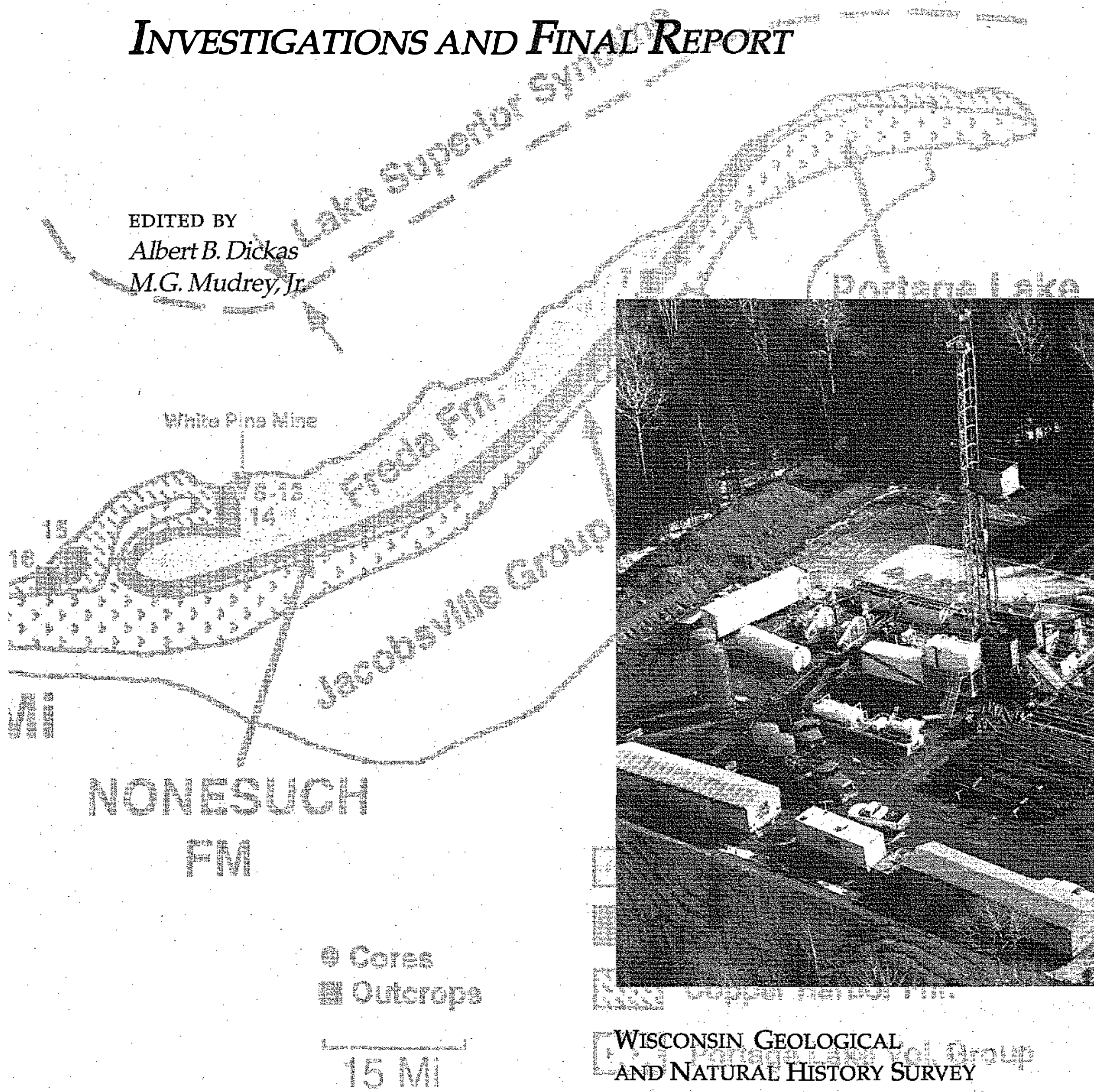
# TERRA–PATRICK #7-22 DEEP HYDROCARBON TEST, BAYFIELD COUNTY, WISCONSIN: *INVESTIGATIONS AND FINAL REPORT*

EDITED BY
*Albert B. Dickas*
*M.G. Mudrey, Jr.*




WISCONSIN GEOLOGICAL
AND NATURAL HISTORY SURVEY
MISCELLANEOUS PAPER 97-1 1999

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James M. Robertson, *Director and State Geologist*



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*The Survey conducts earth-science surveys, field studies, and research. We provide objective scientific information about the geology, mineral resources, water resources, soil, climate, and biology of Wisconsin. We collect, interpret, disseminate, and archive natural resource information. We communicate the results of our activities through publications, technical talks, and responses to inquiries from the public. These activities support informed decision-making by government, industry, business, and individual citizens of Wisconsin.*

# Contents

# Chapter 1. Summary

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## Introduction

In March 1992 Terra Energy, Ltd., Traverse City, Michigan, drilled the Terra–Patrick #7-22 petroleum exploration borehole, as a farm-out from Amoco Production Company, Houston, Texas, east of Ino, Wisconsin, in central Bayfield County, Wisconsin (SW¼, SW¼, NE¼ sec. 22, T47N, R6W). This well was the first test in Wisconsin of the hydrocarbon potential of the Midcontinent Rift System (MRS), a 1.1 billion-year-old intracontinental extensional structure that extends from northeastern Kansas to southern Michigan by way of the Lake Superior Basin. Although economic reservoirs of Precambrian hydrocarbon are unusual in rocks as old as those of the Midcontinent Rift System, subsurface seeps of crude oil have been reported for decades in the White Pine Copper Mine located in the Upper Peninsula of Michigan.

The Terra–Patrick well was drilled to a measured total depth of 4,966 ft. The borehole penetrated 290 ft of Pleistocene material unconformably overlying 4,676 ft of sandstone, shale, and conglomerate composing the Oronto Group of Middle Proterozoic (Keweenawan) age. No liquid petroleum was encountered during the month-long period of drilling, but very minor occurrences of natural gas were detected within carbonaceous shale of the Nonesuch Formation, the central formation of the Oronto Group of the Lake Superior Basin. The well was subsequently plugged and abandoned.

Drill cuttings were collected at 10-ft intervals from the surface to total depth, a mudlog was recorded, and a series of wireline logs was produced. These borehole data, supplemented by the addition of all reflection seismology collected along the Midcontinent Rift trend of Wisconsin during the period 1984–88, were ultimately released through agreements arranged by the senior editor of this volume with Terra Energy, Ltd., Amoco Production Company, and Texaco Exploration and Production Inc. Through sponsorship of the Wisconsin Geological and Natural History Survey, and the addition of the junior editor, a series of investigations was initiated by geologists from the U.S. Geological Survey (Denver, Colorado), Vastar Resources Inc. (Houston, Texas), Earth Resources International, L.C. (Kalamazoo, Michigan), Wisconsin Geological and Natural History Survey (Madison, Wisconsin), Purdue University (Indiana), the University of Wisconsin–Superior, and a consultant from Menlo Park, California. These studies were directed toward a comprehension of the geology, hydrocarbon potential, structural development, and history of exploration, along the Midcontinent Rift trend of western and northwestern Wisconsin, with an emphasis on that immediate region surrounding the Terra–Patrick #7-22 borehole. The final results of these studies constitute the contents of this volume.

## Site geology

The Oronto Group, a 14,000-ft clastic sequence composed of the Freda, Nonesuch, and Copper Harbor Formations, was the target of the Terra–

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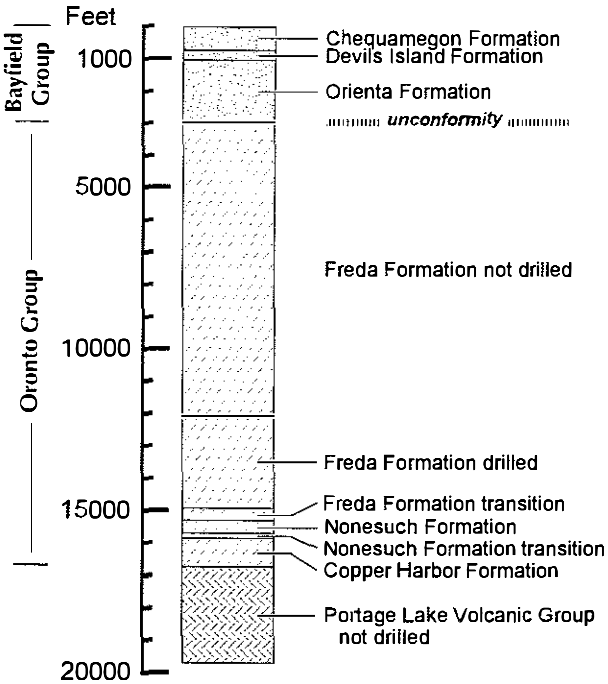


**Figure 1.** *Generalized composite stratigraphic section of the Oronto Group and overlying Bayfield Group in the vicinity of the Terra–Patrick #7-22 borehole, Bayfield County, Wisconsin. Diagram represents 20,000 ft of section.*

Patrick #7-22 exploratory borehole (fig. 1). Reflection seismology suggested that this target is a structural trap, interpreted to be south of and adjacent to the Douglas Fault (fig. 2). Specifically, the seismology data suggested a large, 6 to 10 mi long, east–west trending, 6,000-ft crest-to-trough (amplitude) anticline, cored with Lower Keweenawan basalt. This structural trap is believed to have been formed by drag stresses created by reverse faulting displacements. Potential reservoir strata were anticipated in three units: the upper part of the Copper Harbor Formation, a basal sandstone of the Nonesuch Formation, and throughout the Freda Formation (fig. 3).

On the basis of wireline dipmeter survey analyses, the drilled sequence dips approximately 20° southeast, indicating the borehole was drilled on the southeast limb of the anticline. Borehole deviation at a drilling depth of 4,626 ft, near the bottom of the hole, was 16° from vertical. The borehole was finished in the Copper Harbor Formation.

## Results of Investigations

In this volume, Dickas and Mudrey describe the regional, segmented structure of the Superior Zone, that section of the Midcontinent Rift extending from southern Minnesota north and east into eastern Lake Superior. The Superior Zone is divided into a series of four half-grabens composed of rift-derived igneous and sedimentary rock stratigraphic packages separated by accommodation structures. Each half-graben is defined principally on the basis of major breaks in gravity and magnetic patterns, and opposing stratigraphic geometries as identified by reflection seismology interpretation.

On the basis of an interpretation of new geologic and geophysical information, Allen, Hinze, Dickas, and Mudrey further clarify the structural heterogeneity of the Superior Zone. Two ridges of pre-rift basement rocks are identified by the pinchout of rift volcanic strata and the lower section of the overlying sedimentary rock sequence. These accommodation structures also control the termination of the Douglas and Isle Royale Faults, formerly considered by many investigators to be continuous.

A detailed history of hydrocarbon leasing and reflection seismic field collection for the period 1983–92 is discussed by Dickas. During this period, at least 2,671 mi of reflection seismology was collected by five contractors and more than 718,000 acres was leased by eight exploration companies. This search, unprecedented in a state historically considered void of hydrocarbons, produced a comprehensive geologic and geophysical data bank of inestimable value in the interpretation of the Midcontinent Rift System in Wisconsin.

Dickas presents technical information about the Terra–Patrick borehole, the central theme of this volume. The hole was spudded on March 9, 1992, and plugged and abandoned on April 1, 1992, after reaching a total depth of 4,966 ft. Total drilling costs were $533,308, for an average cost of $107.39 per foot.

Employing a combination of wireline data, especially gamma ray and acoustic logs, and borehole drill cuttings, Daniels defines a series of "electro-stratigraphic" sequences encountered

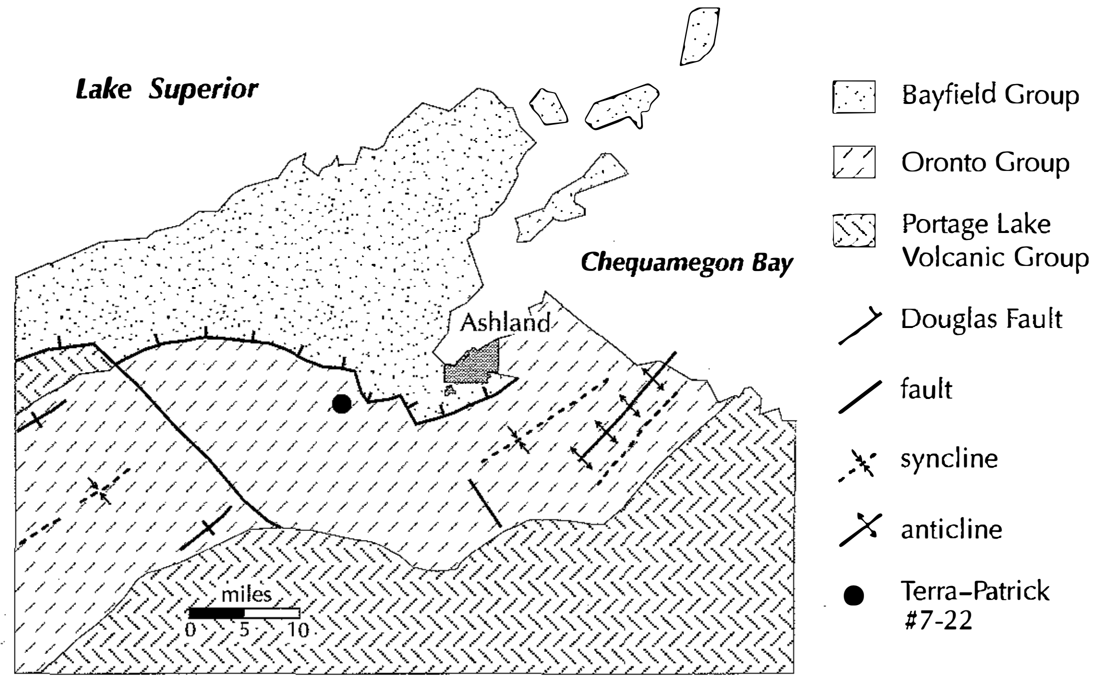


**Figure 2.** *Simplified geologic map in the immediate vicinity of the Terra–Patrick #7-22 exploratory borehole, Bayfield County, Wisconsin.*

during drilling and correlates them to the Oronto Group. In the Lake Superior district, this group is subdivided into (oldest to youngest) the Copper Harbor, Nonesuch, and Freda Formations.

A second analysis of the drill cuttings, by Burruss and Palacas, addresses the potential of the lacustrine-deposited Nonesuch as a source rock for hydrocarbons. Using conventional Rock-Eval pyrolysis assay techniques, they conclude that although the Nonesuch is marginally mature with respect to hydrocarbon generation, regional variability of depositional environments would suggest that similar Rock-Eval analyses elsewhere could produce more optimistic results.

Moving from the borehole-site specific to the regional, Uchytil, Steffensen, and Jarvie further address the hydrocarbon potential of the Nonesuch Formation using core and outcrop samples collected along a 200-mi long trend extending from northwestern Wisconsin northeast to the Keweenaw Peninsula of Michigan.

An evaluation of the suite of Terra–Patrick wireline logs was undertaken by Lindblom. The field analyses of these data were difficult because charts employed for interpretation were devised for evaluation of quartz-bearing clastic rock, not volcaniclastic strata as encountered in the Terra–Patrick borehole. Lindblom verifies this "iron-rich sediment" contamination problem in his presentation of density and sonic porosity, and relationships between various wireline "signatures" and downhole lithologies.

## Conclusions

When the Terra–Patrick #7-22 borehole was abandoned on April 1, 1992, an eight and one-half year period of exploration for hydrocarbon in Middle Proterozoic rocks of the Midcontinent Rift trend of Wisconsin came to termination. During this period, extended beyond normal limits by initial lack of protective legislation, environmental concerns, and crude oil price fluctuation, the combined and varied interests of industry, government, and academia in the Midcontinent Rift trend yielded an invaluable volume of geologic and geophysical data important in the analyses of Precambrian terranes in the central United States.

The Terra–Patrick borehole was an economic failure, when measured by the discovery of only the minimal amount of natural gas expected as a

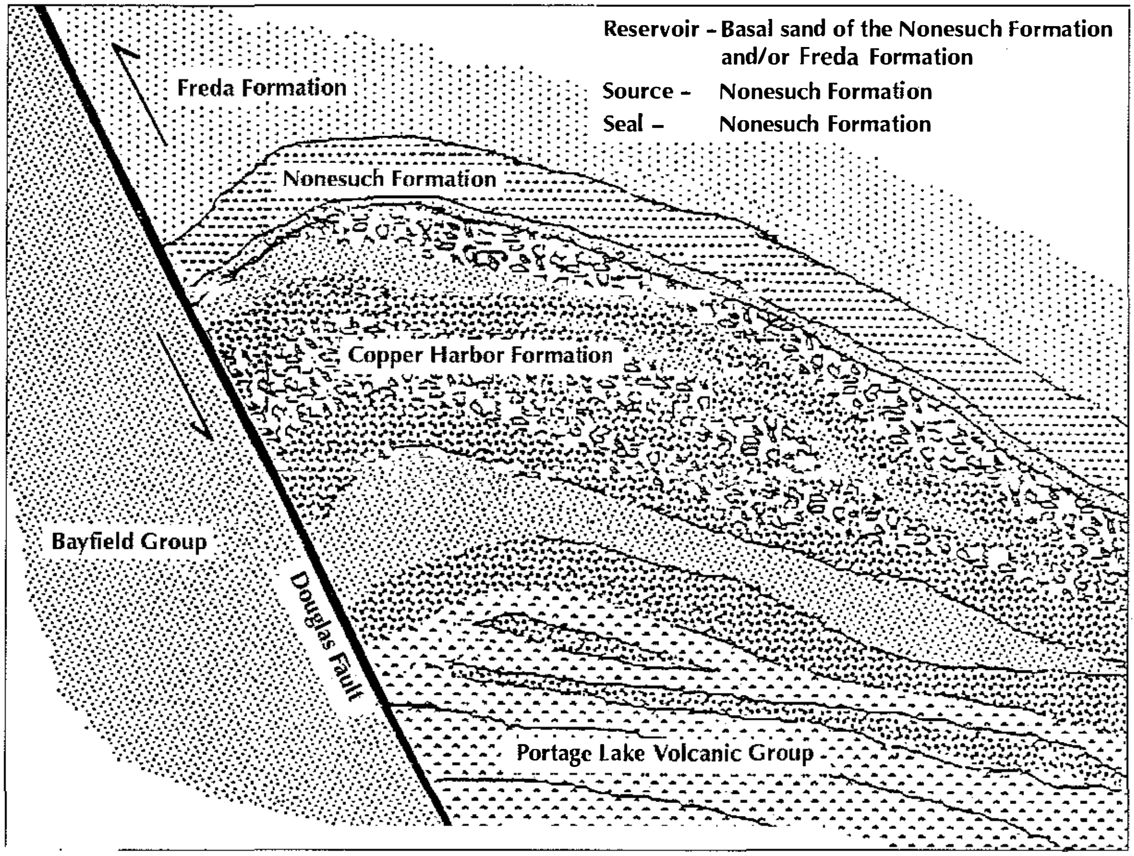


**Figure 3.** *Conjectural cross section drilling target for the Terra–Patrick #7-22 borehole, Bayfield County, Wisconsin.*

result of the penetration by the drill bit of any fine-grained, carbonaceous sedimentary rock. The geologic epitaph of this venture, and the events leading to it, must, however, read success because they aided in the development of new concepts in the understanding of the Precambrian tectonic history of central North America. In turn, these new concepts may prove valuable in the future discovery of hydrocarbon in the Middle Proterozoic strata of Wisconsin.

# Chapter 2. Introduction

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The drilling of the Terra–Patrick #7-22 wildcat borehole in Bayfield County, Wisconsin, in March 1992 was the culmination of an extraordinary series of events that began in the Lake Superior Basin in November 1983. These events were associated with the exploration for economic reservoirs of oil and natural gas within Middle Proterozoic rocks of the Midcontinent Rift System of Wisconsin.

Prior to 1992, and since the drilling of the first oil well in the United States by "Colonel" Edwin Drake near Titusville, Pennsylvania, in 1859, 49 known boreholes had been drilled in Wisconsin in the search for hydrocarbons (oil or natural gas). These boreholes were drilled by little-known companies characterized by undercapitalization and a brief history of operation. The only extant information from these endeavors is a listing of their names, locations, and total drilled depths (Peters, 1985). The combined economic success of these 49 wildcats can be summarized by the fact that each was ultimately classified as "dry and abandoned." Because of this record of non-success, the American oil and gas industry has long labeled the bedrock geology of Wisconsin, briefly described as Phanerozoic sedimentary rock cover overlying Proterozoic and Archean igneous and metamorphic terranes, as discouraging to the formation and preservation of hydrocarbons.

With the discovery in 1962 of economic deposits of Precambrian indigenous oil and gas in Siberia, and thereafter in Australia, China, and Oman, geologists began to reconsider the hydrocarbon potential of correlative rock sequences in North America. By 1980, the attention of geologic exploration staffs of several major U.S. petroleum exploration corporations had centered on the 2,000-mi-long Middle Proterozoic trend of the Midcontinent Rift System, extending from Kansas to Ohio by way of, and including, the classic Keweenawan outcrop belt of the Lake Superior Basin.

With the public disclosure of the presence of oil and gas lease agents in Ashland, Bayfield, and Iron Counties in 1983, a new era in natural resource exploration was initiated in a state historically affiliated with iron- and lead-ore mining. Because Midcontinent Rift rock was principally known only from limited outcrop exposure in the Lake Superior region and because extensive exploration for hydrocarbon within Precambrian rocks in the United States had no precedent, the Midcontinent Rift System trend was labeled a "frontier play"—that is, exploration in a defined geographic region associated with minimal geologic information.

The drilling of the Terra–Patrick #7-22 borehole established historic significance for Wisconsin and the western half of the Lake Superior Basin—it was preceded by an unprecedented collection of reflection seismic profiles, and accompanied by the assembly of a wide array of borehole-specific information (wireline and mudlogs, drilling reports, and well cuttings). These sets of data represent an estimated expenditure, in Wisconsin and the western half of the Lake Superior Basin, of \$22.2 to \$31.5 million by those corporations involved in the Midcontinent Rift play over the period 1983–92.

This dollar amount can be divided into the following three categories:

- 2,671 line miles of reflection seismology collected at an estimated \$7,000 to \$10,000 per line mile for a subtotal of \$18.7 to \$26.7 million;
- the leasing of a cumulative 718,000 acres of land over a multi-year period at the typical

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rate of $1 per acre per year, for a subtotal of $2.8 to $4.0 million;

- borehole-site costs of an estimated $0.7 to $0.8 million, including cumulative drilling costs of $533,000, plus associated site preparation and abandonment and miscellaneous well-service costs.

These figures do not include additional unknown costs associated with thousands of hours of data reduction and analysis in offices located throughout the United States on the part of the staff of the eight known companies (for details, see paper discussing the history of Midcontinent Rift hydrocarbon exploration by Dickas, ch. 5, this volume) involved in the Wisconsin part of the Midcontinent Rift play.

By dint of perseverance and good fortune, the senior editor of this report was able, over a period of eight years, to assemble what is believed to be the entirety of geologic and geophysical information, exclusive of proprietary corporate reports, created in the industrial search for hydrocarbon in Wisconsin over the period 1983–92. This volume represents a compilation of the analysis of this geologic and geophysical information. The contained reports are primarily directed toward a history of activities leading up to the 1992 drilling of the Terra–Patrick #7-22 borehole and the investigation of the petrology, stratigraphy, and regional structure of the rock column encountered in that borehole. To improve readability, several reports in this volume express units of depth and distance in the language of the American hydrocarbon industry, that being in English units (feet and miles), rather than in the traditional scientific use of metric equivalents.

Between 1983 and the date of this publication, four deep wildcat tests, including the Terra–Patrick #7-22 borehole, explored the hydrocarbon potential of the Midcontinent Rift System. The Texaco Poersch #1 borehole in Kansas was drilled in 1985 to a state record depth of 11,301 ft (Berendsen, 1988). In Iowa in 1987 the Amoco M.G. Eischeid #1 borehole reached a state record depth of 17,851 ft (Anderson, 1990). Both boreholes were completed as dry and abandoned. A third test was drilled as the Amoco St. Amour #1-29 to a total depth of 7,251 ft in Alger County, Michigan, in 1987. Information about this dry-and-abandoned borehole remained proprietary until March 1995.

This volume is presented as a follow-up, not only to the Kansas and Iowa publications, but also to an earlier publication (Mudrey, 1986), a discussion of the geology of the Midcontinent Rift play of Wisconsin as known before the Terra–Patrick #7-22 borehole was drilled.

## Technical information about the Terra–Patrick #7-22 borehole

**Location.** Lat 91° 6' N, long 46° 32' 20" E; SW¼, SW¼, NE¼, 330 ft from south line and 330 ft from east line, sec. 22, T47N, R6W, Town of Keystone, Bayfield County, Wisconsin.

**Drill-rig elevations.** Ground level, 867 ft; kelly bushing, 879 ft.

**Spud time and date.** 12:45 a.m., March 9, 1992.

**Abandonment time and date (rig released).** 9:00 a.m., April 1, 1992.

**Total depth drilled.** 4,966 measured feet.

**Borehole diameters.** 26 in. to 73 ft; 17½ in. to 412 ft; 10⅝ in. to 2,002 ft; 7⅞ in. to total depth.

**Stratigraphic column penetrated (from surface to total depth).** Glacial and lacustrine sediment of Pleistocene age; Freda Formation; Nonesuch Formation; Copper Harbor Formation. The latter three formations compose the Middle Proterozoic Oronto Group. Thicknesses of all units are dependent upon individual log interpretation and are presented in this volume.

## Logs collected

- Drilling mudlog, from surface to 4,966 ft.
- Dual Induction Laterolog/Gamma Ray/Spontaneous Potential log, from 93.6 to 4,789.0 ft.
- Long Spaced Sonic/Gamma Ray log, from 364.5 to 4,878.0 ft.

- Spectral Density/Dual Spaced Neutron/Spectral Gamma Ray log, from 1,853.4 to 4,911.9 ft.
- High Resolution Induction/Digitally Focused/Gamma Ray log, from 1,961.1 to 4,978.1 ft.
- Compensated Spectral/Natural Gamma Ray log, from 1,853.4 to 4,911.9 ft.
- Monitor/Six Arm Dipmeter Survey log, from 2,025.1 to 4,820.9 ft.
- Shiva Computation/Six Arm Dipmeter Survey log, from 2,025.1 to 4,820.9 ft.

**Drilling mud cuttings.** Cuttings were collected in intervals of 10 ft from the surface to 4,966 ft.

**Well-site contractors.**

- Site preparation: Domres Construction Company, Manistee, Michigan.
- Well drilling: Begard Drilling, Mount Pleasant, Michigan.
- Mudlogging: Tarrant Mudlogging Consultants, Traverse City, Michigan.
- Wireline electronic logging: Halliburton Logging Services, Inc., Mount Pleasant, Michigan.

**Borehole operators.** The drilling of this borehole was conducted under farm-out (partnership) arrangements from Amoco Production Company, Houston, Texas.

- Terra Energy, Ltd., Traverse City, Michigan (on-site operator).
- Patrick Petroleum Company, Jackson, Michigan.

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CHAPTER 3.

# *Segmented structure of the Middle Proterozoic Midcontinent Rift System, North America*

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## ABSTRACT

**We interpret recently acquired on-shore and off-shore reflection seismic data and deep mineral-exploration drill-holes to show that the Middle Proterozoic Midcontinent Rift System is similar to the East African Rift, where a series of opposed half grabens, principally infilled with rift-derived igneous and sedimentary rock stratigraphic packages, are separated by accommodation strnctures. Employing the East African Rift as a structural model, we suggest that the Midcontinent Rift System (MRS) is composed of both first-order and second-order rift segments. Five first-order segments, termed zones, constitute the entire MRS extending from Kansas to lower Michigan by way of the Lake Superior Basin. These zones are identified on the basis of major breaks in gravity and magnetic patterns, seismic geometry, lithologic packages, and terrane composition. First-order segments are themselves divided, by the degree of local structural maturity, into second-order rift segments. Within the Superior Zone, geologically and geophysically the most thoroughly documented zone of the MRS, four such second-order segments are identified and described.**

**This interpretation suggests that stratigraphic and structural correlation within the MRS may not be valid within the framework of a regional symmetric model. Instead, correlation must consider isolated igneous and sedimentary packages created unequally and in direct response to local rift developments.**

## INTRODUCTION AND HISTORIC BACKGROUND

The 1.1-Ga Middle Proterozoic Midcontinent Rift System (MRS) is a major intracontinental, thermo-tectonic structure that has been traced by regional gravity (Lyons and O'Hara, 1982) and magnetic data (King and Zietz, 1971), subsurface drilling, and outcrop control over a length of 2,000 km within the central United States (Fig. 1). Outcrops are known only in the Lake Superior region and define a structural basin that has been filled by plateau lava and sedimentary rock comprising the Keweenawan Supergroup (Fig. 2). Basalt, underlain by thin quartz sandstone and interbedded with polymictic red-bed units (Merk and Jirsa, 1982), was extruded along the rift during the short geologic time interval from ca. 1,109 Ma to ca. 1,094 Ma (Paces and Davis, 1988). Beginning during the late stages of volcanic activity, a suite of maturing upward, clastic sedimentary rock was deposited.

In 1943 George Woollard reported a major positive gravity anomaly near Clay Center, Kansas, and subsequently (Woollard, 1943) reported the existence of a long narrow belt of positive gravity anomalies stretching at least 1,200 km from Lake Superior southwestward into Kansas (Fig. 1). Thiel (1956, p. 1088) called this feature the "midcontinent gravity high" and noted the strong spatial relationship of this gravity anomaly to

Dickas, A. B., and Mudrey, M. G., Jr., 1997, Segmented structure of the Middle Proterozoic Midcontinent Rift System, North America, *in* Ojakangas, R. W., Dickas, A. B., and Green, J. C., eds., Middle Proterozoic to Cambrian Rifting, Central North America: Boulder, Colorado, Geological Society of America Special Paper 312.

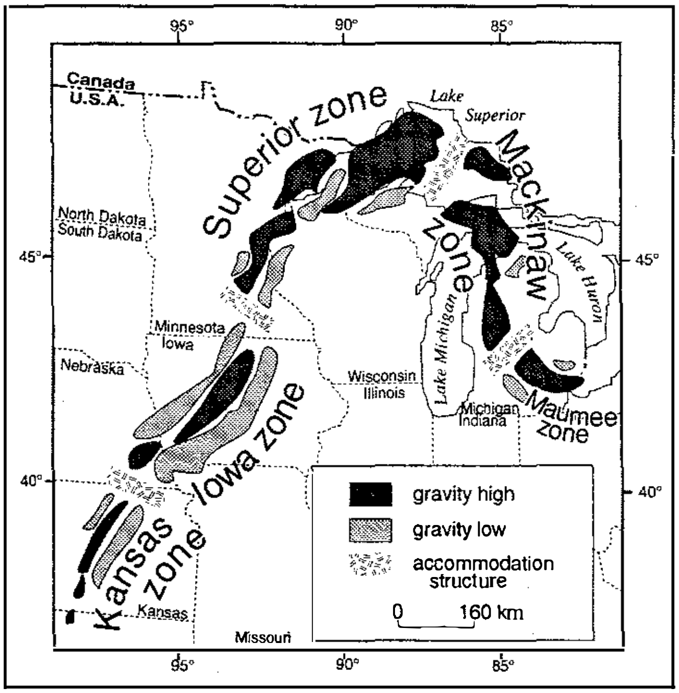


Figure 1. Simplified map of the Midcontinent Gravity High and the Mid-Michigan Gravity High. The Midcontinent Gravity High extends from Kansas northeast to the central section of the Lake Superior Basin. The Mid-Michigan Gravity High extends from the eastern section of the Lake Superior Basin southeast to the Michigan-Ohio border. The rock sequences causing these geophysical trends constitute the Midcontinent Rift System (MRS). Also shown, as hachured bars cutting across the axis of the MRS, is the location of the four accommodation features of first-order structural significance, as proposed in this study. These accommodation structures subdivide the MRS into five zones, named on the basis of principle geographic location. Gravity trend modified from Lyons and O'Hara (1982).

Keweenawan rock in the Lake Superior area. His geophysical modeling was limited but led him to state "the high anomaly gradients bounding the lava mass suggest faults between high-density lava and low-density sandstone and shale" (Thiel 1956, p. 1089).

By the 1960s, a broad consensus emerged that the MRS was an aborted, structurally symmetric, intracontinental rift of major proportions, extending from the Oklahoma–Kansas state line northeast to Lake Superior, and then southeast under the Michigan Basin, terminating in the vicinity of Detroit, Michigan. Within the southwest Lake Superior Basin, field geology identified the center of the rift as the St. Croix Horst, flanked by half-graben basins (Fig. 2). Summaries of variations of this tectonic model may be found in Steinhart and Smith (1966), Wold and Hinze (1982), and Dickas (1986a).

A major revision in the tectonic interpretation of the MRS emerged in the 1980s when Serpa et al. (1984) evaluated a deep reflection seismic profile extending across the southern part of this rift in Kansas. Their model, which was compatible with other well-studied modern rifts, incorporated asymmetric basins, fault block rotations, and fanning of sedimentary layers. Dickas (1986b) suggested that these structural model differences were a reflection of differing stages of tectonic maturity. In the mid-1980s, some data from reflection seismic programs conducted for petroleum exploration along the MRS became available. Interpretation of these data suggest that an asymmetric, segmented structure may well be the correct model for the MRS, particularly for the Lake Superior portion of this trend.

## FUNDAMENTAL RIFT UNIT

Seismic analysis of the East African Rift System (Rosendahl and Livingstone, 1983) led to new ideas regarding phased development of intracontinental rifts. These concepts resulted from observations that Lakes Nyasa (Malawi) and Tanganyika (Tanzania) were "divided into natural structural units with a certain dimensional repeatability" (Lorber, 1984, p. 15). This geometric duplication was identified as the "fundamental rift unit." A review of the literature permits us to formulate a composite picture of a typical "fundamental rift unit."

### *Geometry*

In plan view the fundamental unit is approximately a parallelogram with length of 50 to 190 km, and widths from 20 to 60 km. Length to width ratios vary from 2 to 4. A worldwide study of fundamental rift units (Reynolds, 1984) indicates an average length of 119 km and an average width of 40 km, resulting in a typical length to width ratio of 3.

In cross-section view the fundamental unit is commonly triangular, defining a half-graben. Reynolds (1984) reports this half-graben structure in the Suez, Rio Grande, and Viking Rifts; Logatchev et al. (1983) in the Baikal Rift; Schuepbach and Vail (1980) in the Greenland margin; and Bosworth et al. (1986) in the North Sea Graben, Connecticut River Rift, and the Rhinegraben. Although displaying geometries of first-order rift segments, rift units should also possess unique second-order geometries, expressed in their structural, morphological, and depositional histories.

### *Longitudinal structures*

When the half-graben structure is initiated, it is bordered on its deep side by a major curvilinear, normal, listric fault system, and on the shallow side by a monocline, or series of normal, small displacement step faults. These structural elements are consistent with those denoted in the "taphrogeosyncline" of Kay (1951).

### *Terminal structures*

Fundamental units are bounded by complex structures striking obliquely to the rift axis. These structures, named "accommodation zones" by Bosworth et al. (1986), are vari-

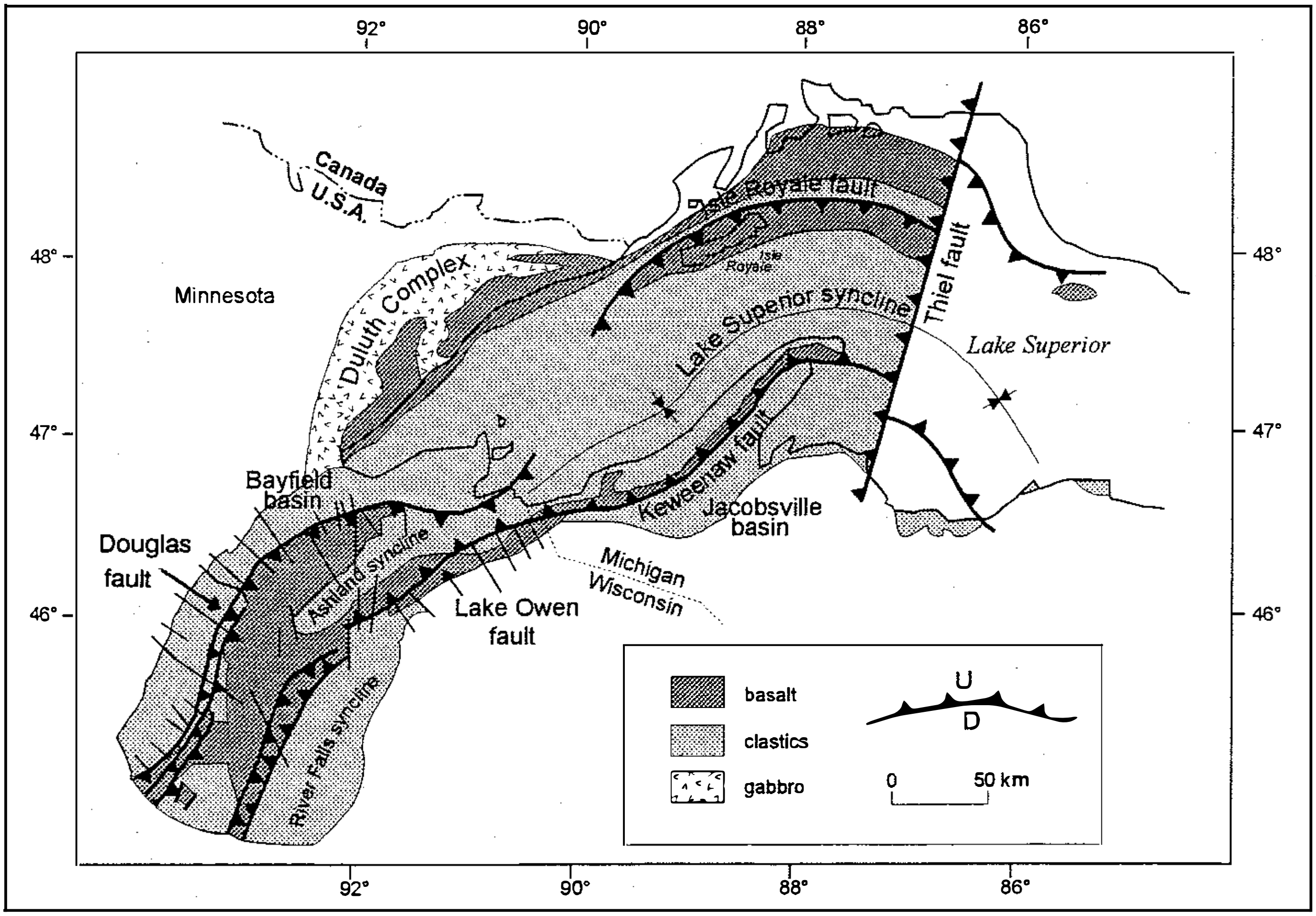


Figure 2. General geology of the western Lake Superior Basin part of the MRS. The central, St. Croix Horst, originally a graben, is flanked by half-graben basins and bordered by regional fault systems. The strikes of these faults parallel the rift axis, but fault dip directions are inward toward the rift axis. After Dickas (1986a).

ously reported in the literature as including: interbasinal highs, ridges, deeply buried "humps," basement sills, "antiform" highs, transverse structures, transform faults, and regions of uplifted basement. In active rifts terminal structures are often coincident with changes in boundary fault orientation, hot springs, and high heat flow (Reynolds, 1984), the preferential occurrence of intrusive and extrusive igneous activity (McConnell, 1980), and geomorphic discontinuities (Rosendahl and Livingstone, 1983).

### *Relation to rift system*

Rift systems often are composed of amalgamated fundamental units consisting of half grabens (Scott and Rosendahl, 1989). Along the rift trend, juxtaposed half grabens typically display alternating structural and depositional polarities (orientations; Reynolds, 1984). Separate half-graben basins may thus contain differing spatial, lithic, and temporal stratigraphic packages.

## DATA BASE IN LAKE SUPERIOR REGION

Encouraged by discoveries in Precambrian rocks in Siberia, Australia, and China, the petroleum industry began conducting extensive reflection seismic programs in the Lake Superior region in late 1983 (Dickas, 1997). In 1985 the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE), a consortium formed to improve the information data base on crustal structure in the Great Lakes region, recorded 630 km of seismic data in Lake Superior to a time-depth of 20 seconds (Behrendt et al., 1988; Cannon et al., 1989). Portions of GLIMPCE profiles A and C (Fig. 3) have been of particular value to this study and are briefly described here.

GLIMPCE seismic profile A extends from the northern apex of Lake Superior southward to the south shore in the vicinity of Marquette, Michigan (Fig. 3). Within the central third of this section (between shot points 1000 and 2800), Cannon et al. (1989) interpreted a thick sequence of seismic reflectors as Middle Proterozoic volcanic (pre–Portage Lake and

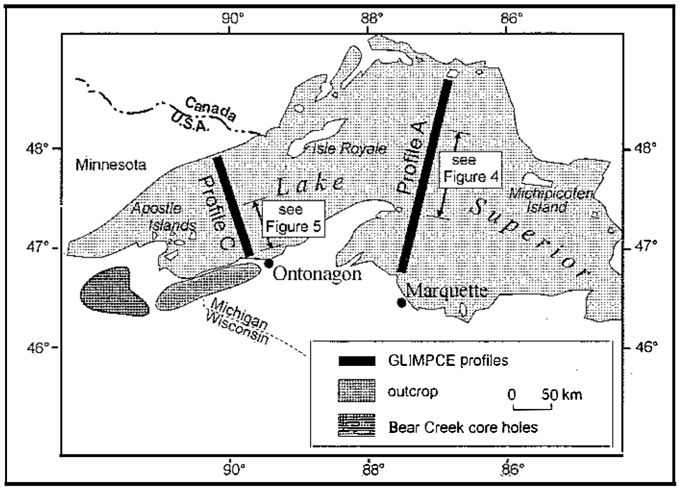


Figure 3. Distribution of data used in this report to reinterpret the structural geology of the MRS.

Portage Lake) and interbedded sedimentary rock lying above Archean basement and directly overlain by the conformable Oronto Group, consisting of conglomerate, sandstone, and shale (Fig. 4). A prominent southward increase in thickness of the pre–Portage Lake and Portage Lake section during the Middle Proterozoic is displayed in this interpretation. The southern border of this stratigraphic wedge is the Keweenaw fault, which crops out along the Keweenaw Peninsula to the west of the profile. The northern border is marked by the Isle Royale fault. The southerly increase in section thickness suggests that this sector of the Keweenaw fault was tectonically active, while the corresponding Isle Royale fault was passive, during the Middle Proterozoic, allowing ponding of basaltic infill against the topographic ramp caused by the Keweenaw fault scarp.

GLIMPCE seismic profile C was recorded from the Minnesota shoreline of Lake Superior southeast to offshore Ontonagon, Michigan (Fig. 3). Cannon et al. (1989) again document a stratigraphic wedge created by geometric fanning within the Portage Lake and pre–Portage Lake sequences (between shot points 1000 and 1800; Fig. 5). However, the direction of thickening along profile C is reversed from that observed in profile A, showing an increase to the north. Thus during the Middle Proterozoic, the infill history of this particular rift sector was directly influenced by displacement along the Isle Royale, and not the Keweenaw, fault.

Additional data supplement information obtained from GLIMPCE profiles. A late 1950s Bear Creek Mining Company exploration program included the drilling of 48 shallow core holes (maximum depth of 1,005 m) in northwestern Wisconsin (Fig. 3). This program unsuccessfully sought cupriferous mineralization within the Nonesuch Formation, the central unit of the Middle Protozeroic Oronto Group. As Nonesuch deposition did not extend throughout the geographical extent of this drilling program, only 15 of 48 cores intersected a Nonesuch section (Table 1). Isopach mapping of these 15 Nonesuch Formation sections discloses increasing thickness to the south (Fig. 6). Because the Oronto Group is regionally conformable with the underlying Portage Lake Volcanics, as evidenced by outcrop study, this southerly increase in Nonesuch Formation thickness suggests the older volcanic sequence also thickens to the south. This sedimentary and volcanic rock wedge was formed by Middle Proterozoic activity along the Lake Owen fault, located to the immediate south (Fig. 2). In contrast the Douglas fault, the northern boundary of this half-graben shaped stratigraphic package, was apparently passive during this time.

The Nonesuch Formation is exposed exclusively along the

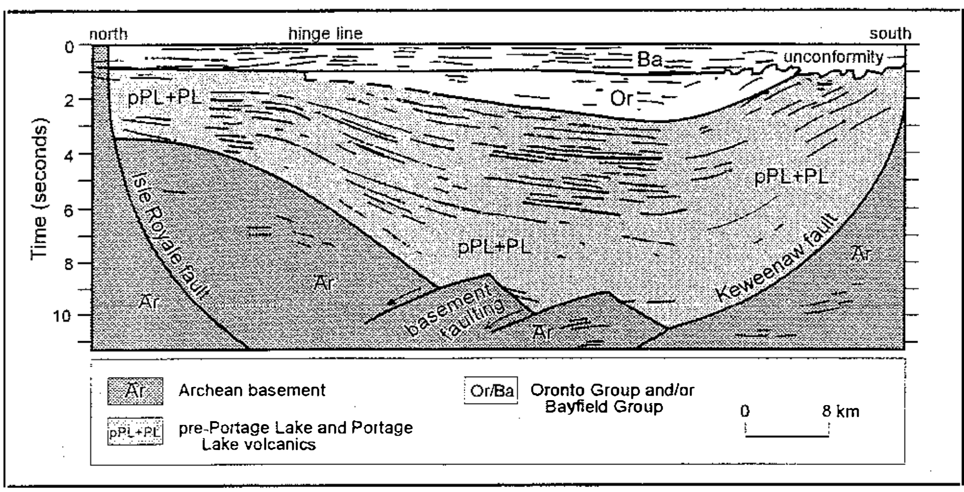


Figure 4. Line diagram interpretation of seismic reflection data along GLIMPCE profile A, located in the eastern section of Lake Superior. The profile displays that portion of the central MRS structure bounded by the Isle Royale fault (SP 2825) and the Keweenaw fault (SP 1030) (see Fig. 3 for location). Vertical scale is in seconds of two-way travel time. Note southward increase in thickness of pre–Portage Lake and Portage Lake volcanic rocks and conformable Oronto Group sedimentary strata. The angular unconformity shown is local in extent. Modified from Cannon et al., 1989.

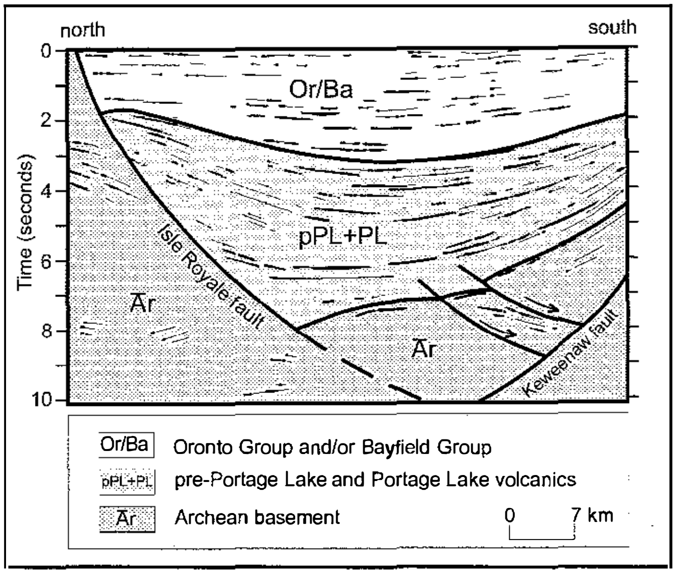


Figure 5. Line diagram interpretation of seismic reflection data along GLIMPCE profile C, located in western Lake Superior. The south half of profile C is shown from the Isle Royale fault (SP 1000) to the south end of profile C (SP 1850; see Fig. 3 for location). Note that the northward direction of increase in rock thickness is opposite to that displayed in GLIMPCE profile A (Fig. 4). Vertical scale is in seconds of two-way travel time. Modified from Cannon et al., 1989.

southwest shoreline of Lake Superior in the vicinity of the Wisconsin-Michigan border (Fig. 3). Thirteen measured sections of this formation have been collected, corrected for structural dip, and mapped (Table 1). The resulting isopach pattern displays a distinct and uniform increase in thickness to the north, under Lake Superior (Fig. 6). This thickness orientation agrees with that interpreted from the GLIMCPE seismic profile C, but is the opposite of that interpreted from the GLIMCPE profile A and the isopach data from Bear Creek cores. This reversal in direction of increasing isopach thickness, as seen on GLIMPCE profiles A and C, suggests the development in the western Lake Superior Basin of axially juxtaposed fault blocks of similar strike but opposing structural dip orientations.

## STRUCTURAL DIFFERENTIATION OF THE MIDCONTINENT RIFT SYSTEM

The structural and tectonic history of the Midcontinent Rift System (MRS) presented here is based on a hierarchical classification of rift elements proposed by Rosendahl (1987), whereby individual rift units join to form rift zones, which in turn form rift branches that finally, in sum, create a rift system. Rosendahl (1987) demonstrated this descriptive scheme by adopting it to the morphology and structure of the East African Rift System, with "system" representing the largest rift scale (Table 2).

The entire 2,000-km trend of the Midcontinent Rift, extending from Kansas to the Lower Peninsula of Michigan via the Lake Superior Basin (Fig. 1), constitutes the Midcontinent Rift System. In scale, this system is comparable to the East African Rift System (Table 2). The Midcontinent Rift System is subdivided into two branches, which join within the central Lake Superior Basin (Klasner et al., 1982). These branches were originally identified by their geophysical characteristic as the Midcontinent Gravity High (Thiel, 1956), which trends northeast-southwest and displays a strong potential field signature, and the Mid-Michigan Gravity High (Hinze et al., 1975), which trends southeast-northwest and is identified by a subdued gravity anomaly caused by thick overlying Phanerozoic strata.

We subdivide the MRS into five first-order zones, separated by terminal (accommodation) structures and differentiated on the basis of rift-geometry and tectonics. Clockwise, from the southwest termination of the system in Kansas, we name the zones Kansas, Iowa, Superior, Mackinaw, and Maumee (Fig. 1). The geologic characteristics of these segments (Table 3) suggest that structural maturity, as measured by amount of rift extension, type and depth of faulting, and degree of structural asymmetry, decreases both southeast and southwest of the Superior Zone (Dickas, 1986b; McSwiggen et al., 1987).

The least mature appear to be the Maumee and Mackinaw Zones, which jointly compose the eastern arm of the Midcontinent Rift System. The Maumee Zone is a symmetrical, unfaulted extensional structure (Brown et al., 1982) associated with a low-amplitude gravity signature and Precambrian "redbed" stratigraphy (Sleep and Sloss, 1978). The Mackinaw Zone is also similar in geometry, but differs from the Maumee Zone because it is associated with listric normal faults (Behrendt et al., 1988), suggestive of a higher stage of structural development than the unfaulted Maumee Zone.

The Kansas Zone, which forms the most southwesterly segment of the western branch of the MRS, is isolated from its counterpart in Iowa by a granitic terrain in southeast Nebraska (Muehlberger et al., 1967). This zone narrows to the south to a region of deep crust feeder dikes (Anderson, 1992). The Kansas Zone was originally identified, by interpretation of a COCORP seismic survey, as an extensional asymmetric basin plunging to the west and bounded by easterly dipping normal faults (Serpa et al., 1984). A deep test of the hydrocarbon potential of this segment of the MRS, however, drilled a Precambrian igneous and underlying sedimentary clastic rock sequence that is stratigraphically transposed to lithologic sequences present to the north in Iowa (Berendsen et al., 1988) and Wisconsin (Dickas, 1986a). Woelk and Hinze (1991) have reinterpreted the Kansas COCORP line as displaying a westerly plunging structure bounded by reverse faults, traceable in depth to ~10 km.

The Iowa Zone is bounded by accommodation structures defined by an interruption of the central gravity maxima displayed by the Midcontinent Gravity High in southeastern Nebraska (at its contact with the Kansas Zone), and a left-lateral shift in the same gravity anomaly in south-central Minnesota (at its contact with the Superior Zone). Further evidence for these terminal (accommodation) structures include the pres-

TABLE 1. MEASURED DRILL CORE AND OUTCROP SECTIONS OFTHE NONESUCH FORMATION, NORTHWESTERN WISCONSIN, AND ADJACENT UPPER PENINSULA OF MICHIGAN*

| Location | Thickness (m) | Source of Data† |
|---|---|---|
| 19-47N-10W DO-5, Wisconsin | 72 | Bear Creek |
| 15-47N-10W DO-6, Wisconsin | 67 | Bear Creek |
| 03-45N-10W DO-8, Wisconsin | 128 | Bear Creek |
| 34-47N-11W DO-11, Wisconsin | 42+ | Bear Creek |
| 08-46N-10W DO-13, Wisconsin | 88 | Bear Creek |
| 11-46N-10W DO-14, Wisconsin | 96 | Bear Creek |
| 06-45N-06W WC-2, Wisconsin | 109 | Bear Creek |
| 15-45N-06W WC-3, Wisconsin | 117 | Bear Creek |
| 36-47N-08W WC-9, Wisconsin | 147 | Bear Creek |
| 36-46N-09W WC-13, Wisconsin | 120 | Bear Creek |
| 32-48N-09W WC-14, Wisconsin | 63 | Bear Creek |
| 08-45N-06W WC-16, Wisconsin | 77+ | Bear Creek |
| 03-45N-07W WC-17, Wisconsin | 99 | Bear Creek |
| 06-45N-09W WC-18, Wisconsin | 137 | Bear Creek |
| 03-45N-08W WC-22, Wisconsin | 133 | Bear Creek |
| 17-45N-02W Brownstone Falls, Wisconsin | 113 | Elmore, 1981 |
| 18-46N-01W Potato River Falls, Wisconsin | 92 | Elmore, 1981 |
| 30-47N-01E Parker Creek, Wisconsin | 114 | Elmore, 1981 |
| 20-47N-01E Montreal River, Wisconsin | 99 | Elmore, 1981 |
| 10-49N-46W Black River, Michigan | 20+ | Elmore, 1981 |
| 30-50N-45W Presque Isle River, Michigan | 183 | Elmore, 1981 |
| 03-50N-42W Porcupine Mountains, Michigan | 175 | Daniels, 1982 |
| 13-51N-42W Big Iron River, Michigan | 229 | Elmore, 1981 |
| 13-51N-42W Big Iron River, Michigan | 179 | White and Wright, 1954 |
| 01-50N-43W Little Iron River, Michigan | 57+ | Elmore, 1981 |
| 01-50N-43W White Pine Area, Michigan | 185 | Daniels, 1982 |
| 23-55N-34W Swedetown, Michigan | 138+ | Elmore, 1981 |
| 10-56N-34W Calumet Area, Michigan | 215 | Daniels, 1982 |

*All data have been corrected for structural dip.
†All Bear Creek localities refer to drill core; remainder are outcrop.

ence of plutonic intrusions in southeast Minnesota and northeastern Iowa (Chandler et al., 1989), and the documentation of the Belle Plaine fault system of southern Minnesota (Sloan and Danes, 1962). Analyses of exploration company seismic profiles from central Iowa (Anderson, 1992) identify a central horst associated with deep structures and bounded by multiple systems of reactivated reverse faults, one of which can be traced to a depth of 20 km (Chandler et al., 1989). A combination of seismic and gravity modeling suggests these deep middle and lower crust structures are dominated by a solid, mafic intrusive core averaging 35 km in width and extending to a depth of at least 40 km (Chandler et al., 1989). This well-developed rift core is in contrast to the less-developed rift core in the Kansas Zone, modeled by Woelk and Hinze (1991) as composed of isolated mafic intrusive pillows.

The Superior Zone appears to be the most mature of all proposed MRS tectonic segments. It is bounded by terminal (accommodation) structures that are associated with large-scale, regional faulting, and it includes the area of maximum MRS width development of 150 km (Klasner et al., 1982). The Superior Zone is characterized by a central horst bounded by reverse fault systems that can be studied in outcrop, the Duluth Gabbro Complex (Miller, 1989), and a mafic intrusive rift core that in model analysis averages 50 km in width and extends to a depth of approximately 50 km (Van Schmus and Hinze, 1985). The Belle Plaine fault system, a major northwest-trending structural zone located in southern Minnesota, forms an accommodation structure juxtaposing the Superior and the Iowa Zones (Chandler et al., 1989). The accommodation structure bounding the northeastern edge of the Superior Zone, identified as the Thiel fault (Hinze et al., 1975), geographically coincides with a region of crustal thickening known as the Trans-Superior tectonic structure (Klasner et al., 1982).

The fundamental rift unit concept (Rosendahl and Livingstone, 1983) can be applied to the Lake Superior Basin, the only sector of the MRS with outcrops of rift-related igneous and sedimentary rocks. Here we identify four such units, named Manitou, Ontonagon, Brule, and Chisago (Fig. 7), averaging

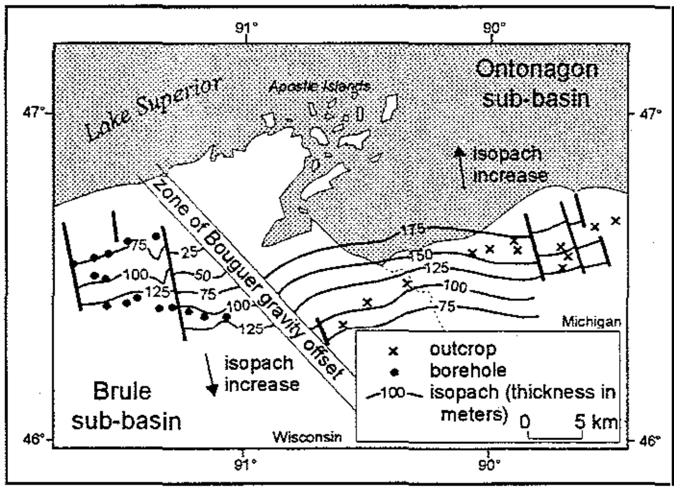


Figure 6. Isopach map of the Nonesuch Formation of the upper Keweenawan Oronto Group, southwestern shoreline of Lake Superior. The large dots are exploratory drill sites in northwestern Wisconsin; for details see Table 1. The x patterns represent thicknesses of Nonesuch Formation outcrops from the Wisconsin-Michigan border area; see Table 1 for details. Note the different directions of thickening shown by black arrows, suggesting these two sets of isopach data are associated with differing rift units, separated by an accommodation structure. The location of such an accommodation structure is indicated by a zone of Bouguer gravity offset, as identified from mapping by Craddock et al. (1969) and Klasner et al. (1979). The Ontonagon and Brule subbasins shown here are two of the four rift units composing the Superior Zone of the MRS.

**TABLE 2. A COMPARISON OF EAST AFRICA RIFT SYSTEM AND MIDCONTINENT RIFT SYSTEM REGIONAL STRUCTURAL ELEMENTS***

| Element | African Model | U.S. Model |
|---|---|---|
| **System** | East African Rift | Midcontinent Rift |
| **Branch** | Eastern | Mid-Michigan Gravity High† |
| | Western | Midcontinent Gravity High† |
| **Zone** | Gregory (Kenya) | Kansas§ |
| | Stefanie (Chow Bahir) | Iowa§ |
| 500-700 km | Tanganyika | Superior§ |
| in length | Usno-Omo-Kibish | Mackinaw§ |
| | Malawi | Maumee§ |
| **Unit**** | Turkana | Manitou§ |
| | Baringo-Bogoria‡ | Ontonagon§ |
| 80-160 km | Nakura-Naivasha‡ | Brule§ |
| in length | Magadi-Natron‡ | Chisago§ |
| l/w ratio 2-4/1 | | |

*After the rift scale classification by Rosendahl, 1987. The architectural elements listed here should be considered typical, rather than correlative, examples.
†Known principally as a geophysical entity.
§Terminology as proposed in this chapter.
**Fundamental rift building structural block.
‡After Bosworth et al., 1986.

150 km in length by 60 km in width and having a length/width ratio of 2.5. In other geometric and geologic aspects these units are consistent with the description of the typical fundamental unit presented earlier in this chapter. Cross-sectional geometry and stratigraphic polarity characterizing these units has been clearly identified (Figs. 4 and 5) and verified by seismic analysis by McSwiggen et al. (1987), Nyquist and Wang (1988), Chandler et al. (1989), Cannon et al. (1989), and McGinnis et al. (1989), and by surface and subsurface isopach mapping (Fig. 6). Igneous and sedimentation wedges of alternating isopach patterns distinguish juxtaposed rift units.

Three (accommodation) structures of second-order tectonic significance are identified within the Lake Superior Zone (Table 3). The structure separating the Chisago from the Brule Unit (Fig. 7) is located on the basis of a constriction in the regional gravity pattern in Anoka County, Minnesota (Craddock et al., 1969), the recent identification of the Bloomer fault of Wisconsin by Mudrey et al. (1987), and the inclusion of a "very deep—large excess of mass" into a potential field model used by Chandler et al. (1989, p. 271) to interpret a seismic profile across this section of the Midcontinent Rift System. The accommodation structure located to the northeast, separating the Brule from the Ontonagon Unit and isolating the opposing Nonesuch Formation core and outcrop dips mapped in northwest Wisconsin (Mudrey and Dickas, 1988), has been recognized as "lineament D" by Klasner et al. (1982), and as the Mineral Lake fault by Mudrey and Brown (1988). Additional evidence for this structure includes a major bifurcation in the regional gravity field (Klasner et al., 1979), and vertical Oronto Group outcrops in the on-land sector of this feature. The third accommodation structure, separating the Ontonagon from the Manitou Unit, is located along the trend of a principle left lateral shift of the Lake Superior Bouguer gravity field (Klasner et al., 1979), and separates the middle and upper Keweenawan sedimentary and igneous rock packages that are apposed to each other both by structural dip and thickening patterns, as seen on GLIMPCE seismic profiles A and C (Figs. 4 and 5).

The Superior Zone rift units (Fig. 7) have a distinctive stratigraphic thickening polarity, as identified by seismic, subsurface, and outcrop studies; southerly in the Brule and Manitou units and northerly in the Ontonagon and Chisago units. These rift units are further distinguished by limited spatial distribution of the Duluth Complex intrusion (Miller, 1989), and differing Oronto Group organic petrologies (Elmore et al., 1989). This lack of continuity of rift trend patterns is an argument for the presence of the half-graben basins and their opposing structural and stratigraphic polarity.

The increased burial depth of rift rocks beneath Phanerozoic strata in both directions away from the Lake Superior area and the absence of published geophysical data along the rift prevent such detailed differentiation outside the Superior Zone. The possibility, however, of such differentiation must be con-

**TABLE 3. PRESENTATION OF GEOLOGICAL, GEOPHYSICAL, AND GEOCHEMICAL INFORMATION TO DIVIDE THE MIDCONTINENT RIFT SYSTEM INTO ZONES SEPARATED BY ACCOMMODATION STRUCTURES OF FIRST-ORDER TECTONIC SIGNIFICANCE***

| Rift Division | Supporting Evidence |
|---|---|
| Maumee Zone | Sag basin on COCORP seismic lines. McClure #1-8 Sparks well stratigraphy. |
| First-order accommodation structure | Gravity "dogleg," Montcalm Co., Michigan. First Seismic Corp. seismic interpretation. |
| Mackinaw Zone | GLIMPCE profile F extension faulting. McClure #1 Beaver Island test. Coalescing of Midcontinent Rift structure. |
| First-order accommodation structure | Thiel fault previously identified. Fault break on GLIMPCE line G. Major change in MRS strike. Interrupted gravity and magnetic patterns. |
| Superior Zone | Structural Detail† → |
| First-order accommodation structure | Interrupted gravity and magnetic patterns. Granitic intrusions, southeast Minnesota. Belle Plaine (transform?) fault system. Borehole and gravity control, southern Minnesota |
| Iowa Zone | Identified Iowa central horst structure. Presence of extension and contraction faulting. Published regional well control. |
| First-order accommodation structure | Broken gravity and magnetic trends. Granite terrane, southeastern Nebraska. Local well control. South-central magnetic lineament. |
| Kansas Zone | Extension faulting on COCORP seismic lines. Asymmmetric central graben. Texaco #1 Noel Poersch test and stratigraphy. |

| | |
|---|---|
| Manitou Unit | S isopach. GLIMPCE A. |
| Second-order accommodation structure | Altered gravity trend. |
| Ontonagon Unit | N isopach GLIMPCE C. Duluth Complex intrusion. Remanent magnetic reversals. N outcrop thickening. |
| Second-order accommodation structure | Terminated gravity trend. Transverse basement ridge. Archean fault trend. Vertical outcrop dips. |
| Brule Unit | Different organic petrologies. S isopach Bear Creek Cores. S isopach Petty-Ray Seismic. |
| Second-order accommodation structure | Bloomer fault (field evidence). Constricted gravity trend. |
| Chisago Unit | W isopach Petty-Ray Seismic. |

*Left side of table. Because of the greater wealth of such information available within the Superior Zone, this rift segment is further divided into four rift units, separated by accommodation structures of second-order tectonic significance (right side of table).
†N, S, and W refer to compass directions of isopach and outcrop thickening.

sidered in evaluating the structural and stratigraphic histories of other zones and units of the Midcontinent Rift System. Such consideration could explain the contrasting estimates for Precambrian hydrocarbon reported in recent studies. Hatch and Morey (1985) reported early thermal maturity and pre-Phanerozoic loss of hydrocarbon from Middle Proterozoic strata on the central horst within the Chisago Unit of the Superior Zone. Kelly and Nishioka (1985), in contrast, document the presence of indigenous, live crude oil dating to at least 1,047 Ma associated with similar age strata of the Ontonagon Unit within the same MRS zone. Considering the differing geologic development of these fundamental rift units, the economic prospects for the intervening Brule Unit could mimic either adjacent unit.

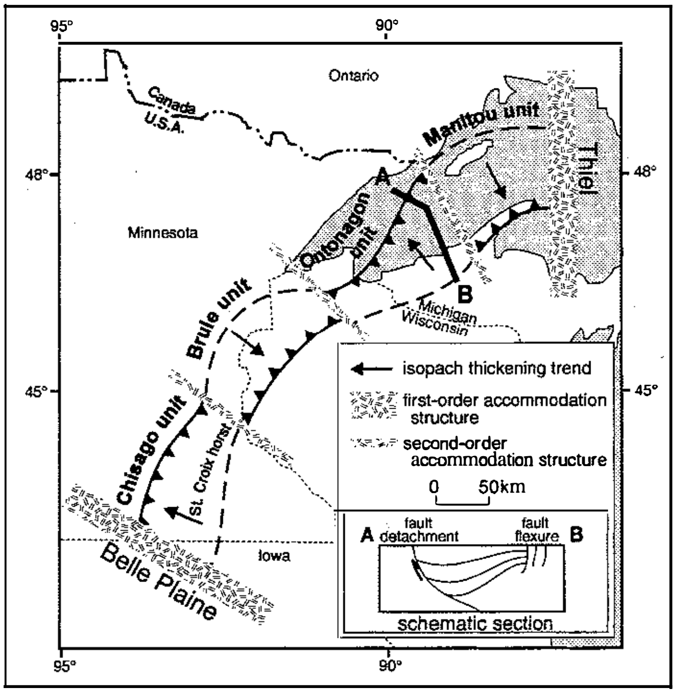


Figure 7. Structural interpretation of the Superior Zone of the Midcontinent Rift System. The Superior Zone is bounded by the Belle Plaine (southern Minnesota) and the Thiel (eastern Lake Superior Basin) faults and is subdivided into four rift units by three accommodation structures of second-order tectonic significance. Note each of the four identified rift units possesses a sediment thickening direction opposite to that of an adjacent rift unit. The barbed border of each rift unit represents the location of upper Keweenawan faults bounding the thick wedges of volcanic and associated sedimentary rocks. The dashed line identifies the position of a hinge line that became active during the later contractional phase of the rift system, creating the present-day horst structure.

## CONCLUSIONS

The adaptability of the fundamental rift unit concept to the MRS, especially in the region of the Lake Superior Basin, is demonstrated by the analysis of newly acquired geologic and geophysical data. This analysis shows that the MRS, through its history of evolution, followed tectonic and sedimentation processes similar to those operating in the present-day East African Rift System. We suggest that an East Africa Rift type of structural development controlled differential infilling of individual MRS units, particularly in the Lake Superior Basin. Our analysis includes only that time from the inception of rifting through the early development of the MRS during pre-Oronto and Oronto time. We suggest that tectonic adjustments continued into post-Oronto time, however these later adjustments were not necessarily in response to the same stresses that led to initial development of the MRS.

The recognition of the principle of individual tectonic development of fundamental rift units, jointly composing larger rift zones and branches, requires that any determined geologic history of one rift unit does not necessarily offer tectonic insight into the development of adjacent rift units. Thus the exploration of the MRS, whether for mineralization or hydrocarbons, should be based on structural, sedimentation, and maturation studies on a basin-to-basin basis.

## ACKNOWLEDGMENTS

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CHAPTER 4.

# *Integrated geophysical modeling of the North American Midcontinent Rift System: New interpretations for western Lake Superior, northwestern Wisconsin, and eastern Minnesota*

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## ABSTRACT

**Integrated geophysical investigations of the North American Midcontinent Rift System have resulted in a new understanding of the structure, stratigraphy, and evolution of this 1,100-Ma aborted continental rift. Interpretation of seismic reflection, gravity and magnetic anomaly, seismic refraction, rock physical property, and geologic data has identified a great degree of structural heterogeneity of the rift system in eastern Minnesota, northwestern Wisconsin, and western Lake Superior. In the western Lake Superior region, two ridges of pre-rift basement rocks are identified by pinch out of the rift's volcanic strata and lower portion of the overlying sedimentary sequence. In addition, regional rift reverse faults terminate above these ridges. Three-dimensional gravity modeling, constrained by seismic reflection profiles, suggests that both ridges are underlain by and composed of a belt of granitic rocks within the buried Archean greenstone-granite province beneath the rift basin, suggesting a significant influence of ancestral structures throughout the evolution of the rift system. Magnetic modeling indicates that magmatism did not occur uniformly along the length of the rift. In Minnesota and Wisconsin, the great majority of the rift's volcanic rocks are normally polarized and probably younger than the recorded ca. 1,098-Ma magnetic reversal, in contrast to western Lake Superior, where the lower half of the volcanic sequence is reversely polarized and was probably erupted before ca. 1,098-Ma. Gravity modeling snggests that the mass deficiency associated with crustal thickening along the rift is probably compensated by the positive effect of dense rift intrusions in the lower crust. The volume of magma trapped in the lower crust may be similar to that erupted into the rift basin.**

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**The spatial distribution of pre-Keweenawan ridges, termination of regional fault systems, and other structural detials more completely define the relation between regional rift tectonics and localized structural and stratigraphic asymmetry. The nature of accommodation structures dividing the Lake Superior basin into individual unit, previously identified by gravity, magnetic, and isopach mapping, is further clarified by seismic reflection analysis and potential field modeling.**

## INTRODUCTION

The most striking anorogenic geologic feature of the basement rocks of the North American craton is the Middle Proterozoic (Keweenawan) Midcontinent Rift System (MRS) . The 1,100-Ma MRS is a major Precambrian magmatic and sedimentary province and tectonic disruption of the lithosphere that extends ~2,000 km from Kansas through Lake Superior and into southern Michigan (Fig. 1; Thiel, 1956; Hinze et al., 1966; King and Zietz, 1971; Hinze et al., 1975; Dickas, 1986a). The MRS is one of the world' s great continental rifts and is unique among paleorifts in its extensive length and enormous volume of igneous and sedimentary rocks.

Rocks of the Midcontinent Rift System are exposed only in the Lake Superior region; elsewhere, they are buried beneath Phanerozoic platform sedimentary strata. Even in the Lake Superior region, the rift rocks are poorly exposed due to a thick mantle of Pleistocene glacial deposits and the waters of Lake Superior. Consequently, geophysical surveys play a critical role in investigating the structure and stratigraphy of the MRS (Hinze et al., 1992).

This study focuses on the application of geophysical techniques to investigate critical problems concerning the structure, stratigraphy, and evolution of the Midcontinent Rift System in western Lake Superior, northwestern Wisconsin, and eastern Minnesota. Seismic reflection and refraction, gravity and magnetic anomaly, rock physical property, and geologic data are interpreted in an integrated manner to develop two- and three-dimensional quantitative geophysical models of the rift. These models lead to a clearer picture of the rift's structural and stratigraphic relations, resulting in an improved understanding of the temporal and spatial evolution of the MRS.

## GEOLOGIC ELEMENTS

The rocks of the Midcontinent Rift System in the Lake Superior region constitute the 1.1-Ga Keweenawan Supergroup (Morey and Van Schmus, 1988) The supergroup consists of two major suites: a lower, predominantly volcanic sequence, and an overlying clastic sedimentary package. Seismic reflection studies indicate total rift fill thicknesses of ~30 km in Lake Superior (e.g., Behrendt et al., 1988; Cannon et al., 1989).

The igneous sequence consists mainly of basaltic volcanic flows with lesser proportions of predominantly mafic intrusions and interflow clastic sedimentary strata. In western Lake Superior, seismic reflection data image a maximum of 16 km of volcanic flows beneath as much as 9 km of post-volcanic sedimentary strata (Allen, 1994). The volcanic and plutonic rocks of the Lake Superior region have U-Pb ages that range between 1,109 and 1,087 Ma (Davis and Sutcliffe, 1985; Palmer and Davis, 1987; Davis and Paces, 1990; Heaman and Machado, 1992; Miller, 1992; Van Schmus, 1992). Moreover, Paces and Miller (1993) suggest that most of the magmatism in the Lake Superior region occurred during two major pulses, from 1,109 to 1,106 Ma and from 1,099 to 1,094 Ma. The consensus among current investigators, based on both geochemical and physical evidence, is that magmas were derived from both lithospheric and mantle plume sources (e.g., Berg and Klewin, 1988; Paces and Bell, 1989; Hutchinson et al., 1990; Nicholson and Shirey, 1990; Klewin and Berg, 1991; Cannon, 1992; Klewin and Shirey, 1992; Van Schmus, 1992; Miller and Chandler, this volume). Early magmas may have been derived from the lithosphere, by partial melting due to heat provided by an ascending mantle plume, and also by assimilation of lithospheric material by plume-derived magmas as surface conduits developed. Later magmas are geochemically primitive and were most probably derived from partial melting of the plume head, with minimal lithospheric contamination as the magmas rose to the surface.

As volcanism and plutonism waned, sedimentary strata were deposited in the subsiding volcanic basins and in flanking sedimentary basins floored principally by pre-Keweenawan basement rocks. The textural and compositional maturity of the Keweenawan sedimentary sequence increases upsection, from the older, relatively immature Oronto Group (Daniels, 1982) to the younger, relatively mature Bayfield Group (Kalliokoski, 1982; Morey and Ojakangas, 1982). The Oronto Group strata contain a substantial proportion of rock fragments, derived primarily from Keweenawan igneous rocks along the margins of the volcanic basins. The Bayfield Group, on the other hand, is composed almost entirely of quartz and feldspar, suggesting that volcanic source rocks were either removed or buried, and that these sediments were derived from erosion of older Archean granitic rocks (Ojakangas and Morey, 1982) and, possibly, reworking of Oronto Group clastic sedimentary rocks. Progressing upsection, the Oronto Group consists of the Copper Harbor Conglomerate, Nonesuch Formation, and Freda Sandstone, which have maximum exposed thicknesses of 1,800 m, 200 m, and 3,600 m (Daniels, 1982). The thickness of the overlying Bayfield Group is poorly constrained because the Oronto-Bayfield contact is neither well-understood nor well-exposed. A deep drill hole in northern Michigan, however, penetrated more than 1,000 m of Bayfield Group sandstones (Bacon, 1966), and

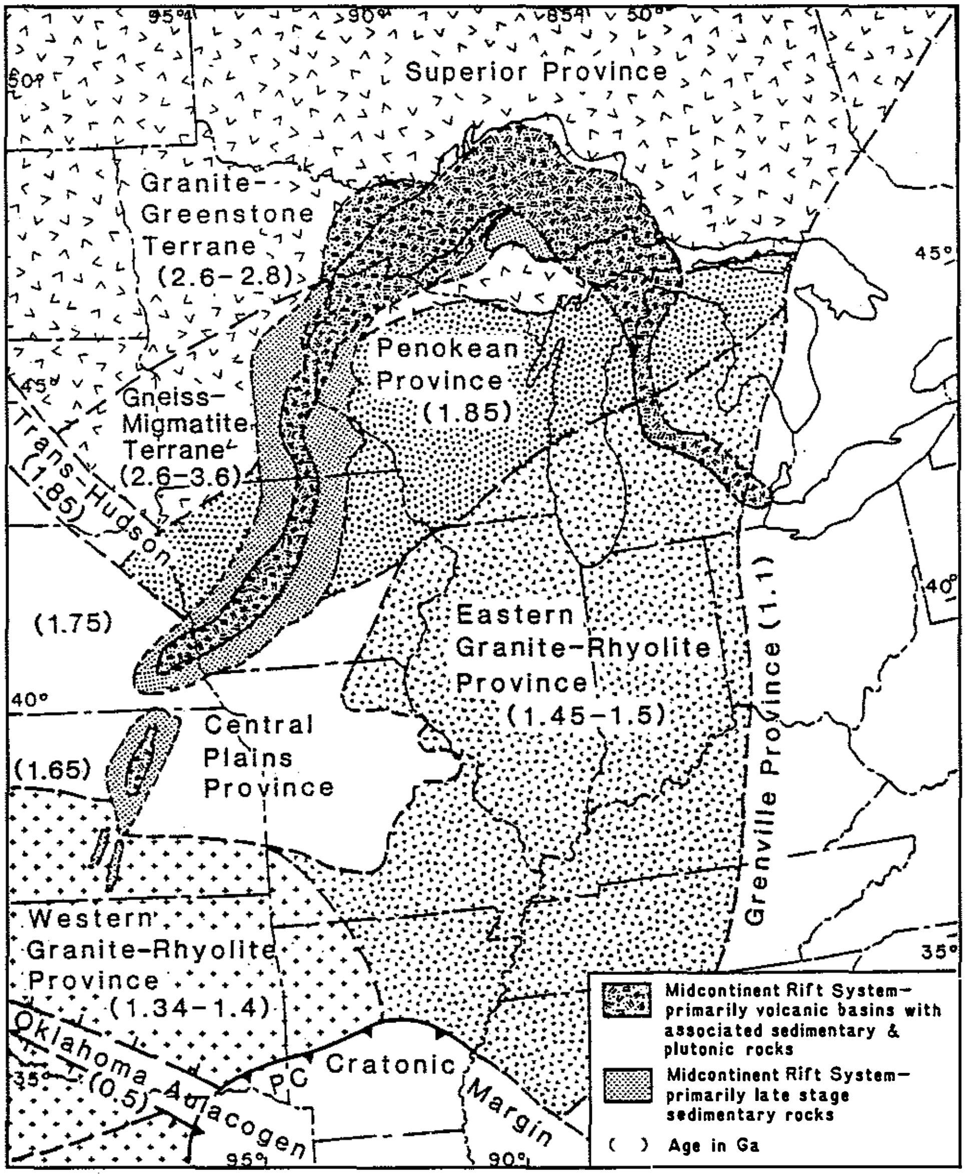


Figure 1. Basement provinces of the Midcontinent of North America (modified from Van Schmus et al., 1982), showing the position of the Midcontinent Rift System (after Hinze and Kelly, 1988).

recent geophysical interpretations (Allen, 1994) suggest even greater thicknesses in the flanking sedimentary basins along the margins of the MRS.

The present distribution of Keweenawan igneous and sedimentary rocks (Fig. 2) is largely the result of late-stage compressional stresses that resulted in structural inversion of the MRS. These stresses may have been related to convergence between the Grenville Province allochthon (Fig. 1) and the proto–North American continent within which the MRS developed (e.g., Cannon, 1994), although the relation between these provinces remains elusive. Reverse faults (Fig. 2) thrust older volcanic rocks and Oronto Group strata over younger Bayfield Group rocks and delineate the margins of uplifted volcanic-rooted horsts (Thiel, 1956; White, 1966b; Dickas, 1986b), such as the St. Croix Horst of Minnesota and Wisconsin (SCH, Fig. 2). Thrusting was in part concurrent with deposition of the Bayfield Group, but continued after Keweenawan sedimentation ended (Kalliokoski, 1969). Based on Rb-Sr closure ages Cannon et al. (1990) suggest that thrusting occurred at ca. 1060 ± 20 Ma.

Although the pre-rift crust was attenuated during the rifting process, the present crust is relatively thick, as much as 55 km (Halls, 1982; Hamilton and Mereu, 1993), due to the great thickness of Keweenawan volcanic and sedimentary strata. In addition, the lower crust beneath the rift basin has been intruded and underplated (Behrendt et al., 1990; Green, 1991;

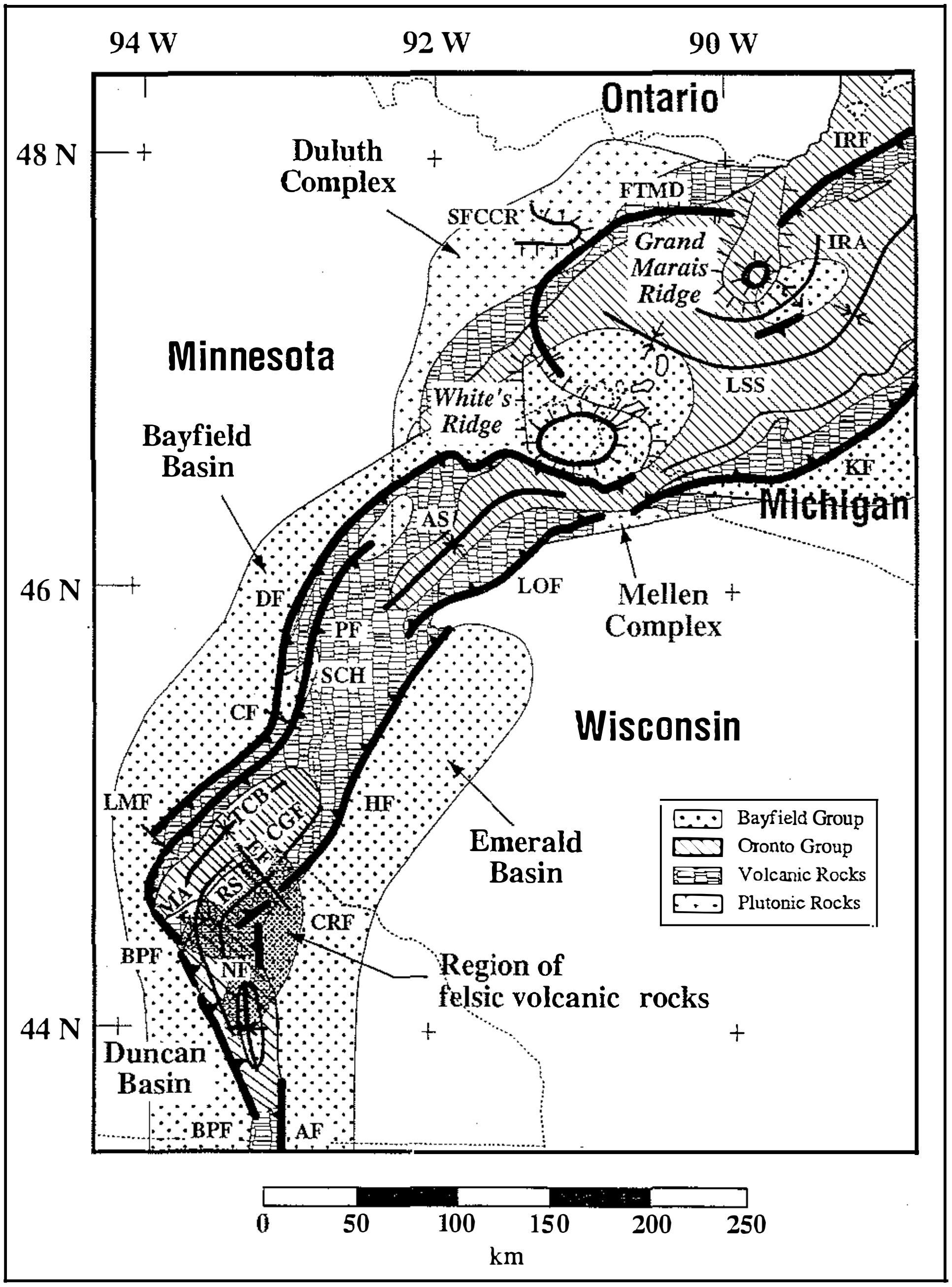


Figure 2. Geologic map of the Midcontinent Rift System, western Lake Superior, northwestern Wisconsin and eastern Minnesota, showing lithologies and major structures. Bold hachured lines within White's ridge and Grand Marais ridge encompass regions where Keweenawan volcanic rocks are absent. Reverse faults: KF, Keweenaw fault; LOF, Lake Owen fault; HF, Hastings fault; CRF, Castle Rock fault; NF, Northfield fault; AF, Austin fault; IRF, Isle Royale fault; DF, Douglas fault, PF, Pine fault; CGF, Cottage Grove fault. Cross-faults: BPF, Belle Plaine fault; LMF, Lake Minnetonka fault; CF, Chisago fault. Folds: IRA, Isle Royale anticline; LSS, Lake Superior syncline; AS, Ashland syncline; MA, Montgomery anticline; RS, Rice syncline; TCB, Twin Cities Basin. Other features: SCH, St. Croix Horst; SFCCR, Schroeder-Forest Center crustal ridge; FTMD, Finland Tectono-Magnetic Discontinuity normal fault.

Trehu et al., 1991; Hamilton and Mereu, 1993), and the upper mantle may have also been altered during the rifting process (Allen et al., 1992).

## GEOPHYSICAL ELEMENTS AND METHODOLOGY

Seismic reflection data are of enormous value to investigations of the MRS because of the layered nature of the rift's volcanic and sedimentary strata. Figure 3 shows the locations of the seismic profiles relevant to this study, superimposed on a Bouguer gravity anomaly map. In western Lake Superior, the data set consists of eleven eight-second profiles (Fig. 3) obtained from Grant-Norpac, Inc., and released by Argonne National Laboratory (McGinnis and Mudrey, 1991) and one twenty-second profile obtained as part of the Great Lakes Multidisciplinary Program on Crustal Evolution (GLIMPCE; Behrendt et al., 1988). Twenty-one five- or six-second proprietary profiles in Wisconsin and Minnesota (Fig. 3) provide information concerning the southwestern extension of the MRS from western Lake Superior. As shown in Figure 3, only three of the onshore profiles in Wisconsin and Minnesota have been previously interpreted. In addition, just one prior investigation (Sexton and Henson, 1994) has focused on the application of the Grant-Norpac/Argonne profiles to the investigation of the rift's structure in western Lake Superior.

Seismic refraction data provide important information concerning the gross structure of the lithosphere along the MRS, and are especially valuable for investigating lower crustal structure, as only one of the seismic reflection profiles of this study (GLIMPCE line C, Fig. 3) images the Moho. Refraction data indicate that the crust is anomalously thick and dense along the rift axis (Halls, 1982; Trehu et al., 1991; Hamilton and Mereu, 1993), probably the result of deep mafic intrusions beneath the rift basin.

Gravity data provide important information concerning the MRS because of the intense density contrasts among the rift's igneous and sedimentary rocks and pre-Keweenawan basement rocks. Positive gravity anomalies, such as over the St. Croix Horst in Minnesota and Wisconsin, over the Duluth Complex in northeastern Minnesota, and in portions of western Lake Superior (Fig. 3; compare with Fig. 2), are associated with thick sections of mafic igneous rocks (density ~2,950 kg/m$^3$, Allen, 1994). The negative anomalies that flank the St. Croix Horst in Minnesota and Wisconsin (Fig. 3) are associated with marginal basins that contain mainly low-density (~2,400 kg/m$^3$; Halls, 1969) Bayfield Group sandstones overlying thin sequences of older Oronto Group strata and volcanic rocks. The gravity anomaly signature of the rift in western Lake Superior (Fig. 3) is remarkably different and more complicated than the signature in Wisconsin and Minnesota. Of particular interest are two negative, roughly circular anomalies located in Lake Superior and on the Bayfield Peninsula of Wisconsin (Fig. 3). These intense anomalies are not well understood, although Hinze et al. (1982) and Dickas (1986c) suggest that they might be produced by relatively thick sections of low-density Bayfield Group sedimentary rocks, thinning of the rift's dense volcanic sequence, or low-density sources beneath the rift basin. White (1966b) suggested that the southern (Bayfield Peninsula) negative anomaly is produced by a ridge of pre-Keweenawan basement rocks above which the rift's volcanic rocks are relatively thin or absent. Until this study, however, no quantitative models have been proposed.

Magnetic data are useful for investigating both the structure and stratigraphy of the rift's igneous rocks. The Keweenawan volcanic strata are associated with intense, short-wavelength, linear magnetic anomalies that strike parallel to the bedding of the volcanic flows (Fig. 4). The correlation between the volcanic strata and the magnetic anomalies is the result of vertical (stratigraphic) variations in the magnetization of the dipping Keweenawan volcanic section (Allen and Chandler, 1993) and represents a powerful tool for mapping the structure of the MRS (Allen and Chandler, 1992; Allen, 1994). Paleomagnetic data are useful for estimating the relative ages of the rift's rocks (Green, 1982; Halls and Pesonen, 1982; Van Schmus et al., 1982; Palmer and Halls, 1986; Palmer and Davis, 1987). A change in polarity from reversed to normal, dated at ca. 1,098 Ma (Davis and Paces, 1990; Paces and Miller, 1993), is widely observed in the Lake Superior region and is therefore useful as a stratigraphic correlation tool. However, evidence for another reversal period (Palmer, 1970; Robertson, 1973) of probable short duration in the Mamainse Point volcanic sequence in the eastern Lake Superior region (Klewin and Berg, 1991) and possibly in the lower portion of the Powder Mill Volcanic Group of northern Michigan (Books, 1972) complicates the use of magnetic polarity as a stratigraphic correlation tool.

By themselves, the seismic, gravity, and magnetic data are important tools for investigating the structure and stratigraphy of the MRS. When interpreted together, however, they reveal additional information that is not contained in any of the individual data sets. For example, the magnetic data can be used to precisely locate faults and contacts where seismic and geologic data are inconclusive or unavailable. The seismic reflection data then become very useful for placing constraints on configurations of igneous and sedimentary bodies of quantitative gravity models. Moreover, the gravity data can also help to resolve ambiguities in interpretation of the seismic reflection data. The gravity models are further constrained by seismic refraction data, which provide evidence concerning the configuration of the lower crust and upper mantle, information that typically is not provided by seismic reflection profiles. Finally, using the body configurations that evolve from the combined seismic interpretation and gravity modeling, quantitative magnetic models are constructed to evaluate the magnetic properties of the rift's volcanic and plutonic rocks. By determining the approximate proportions of normally and reversely polarized rocks in the Keweenawan igneous section, it is possible to estimate the amounts of magma that may have cooled before and after the magnetic reversal at ca. 1,098 Ma, and therefore determine the relative ages of different segments of the MRS.

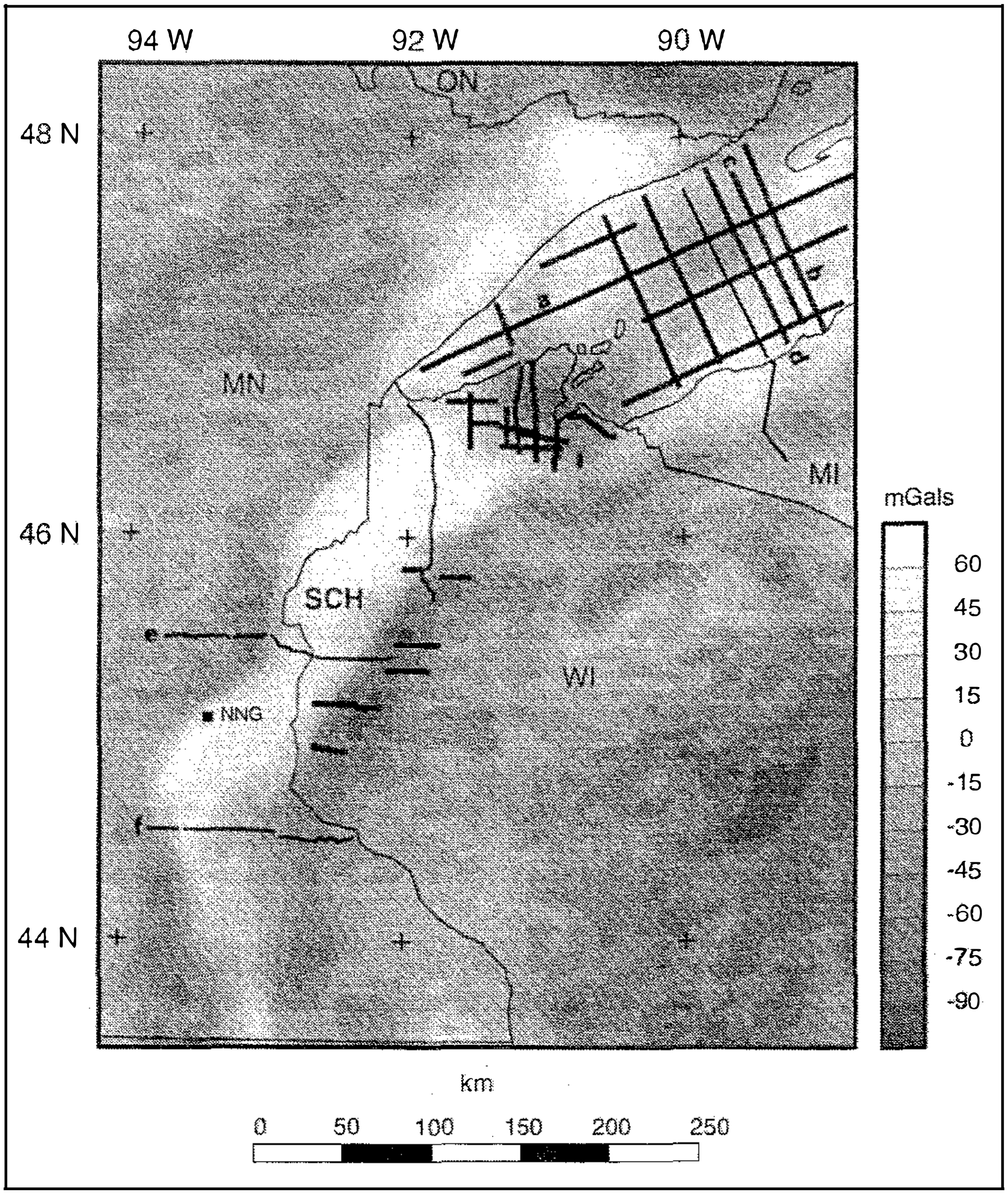


Figure 3. Bouguer gravity anomaly map with locations of seismic profiles used in this study. Thin lines indicate profiles that have been discussed in detail in journal articles. Thin line in Lake Superior is GLIMPCE profile C. Thick lines show recent profiles that have not previously been interpreted in detail. Lines identified as a, b, c, d, e, and f represent locations of Figures 7, 8, 9, 11, 16, and 17, respectively. SCH, St. Croix Horst; NNG, Northern Natural Gas deep drill hole (not discussed in this chapter).

## GEOLOGIC INTERPRETATION

In the early 1980s, the identification of the MRS as a frontier hydrocarbon province marked the beginning of a modern era of interpretation of the structure and evolution of the MRS. This era of interpretations, based on seismic reflection profiles, gravity and magnetic data, and isotopic studies of the Keweenawan volcanic rocks of the rift, contrasts with earlier interpretations that relied principally on geologic field information, regional seismic refraction profiles, and limited gravity and magnetic data. Over the past decade, studies of the MRS have become more definitive with the increasing availability of seismic reflection, gravity, and magnetic data, both public and proprietary (Dickas, 1986a; Behrendt, et al., 1988; Berendsen et al., 1988;

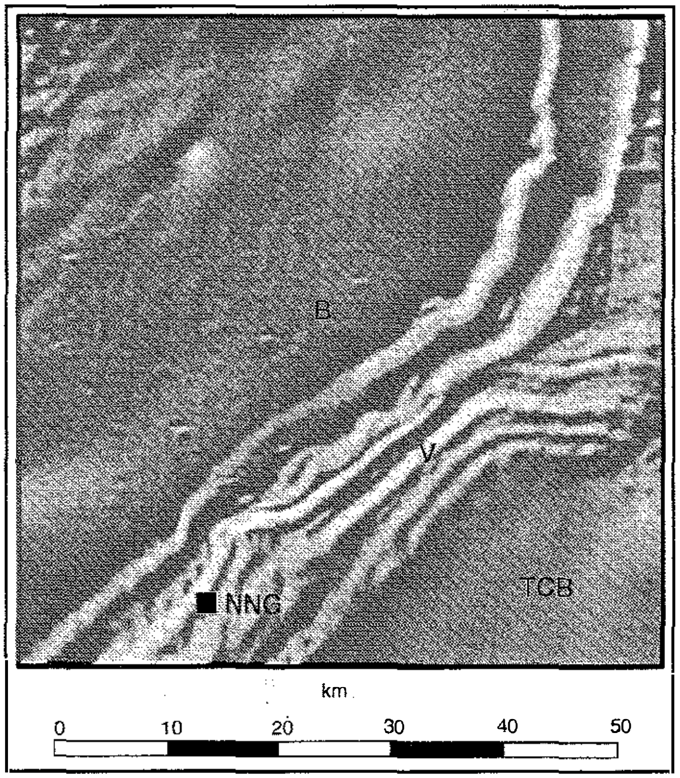


Figure 4. Shaded relief aeromagnetic map of a portion of the Midcontinent Rift System in east-central Minnesota. Northwestern illumination. TCB, Twin Cities Basin; V, Keweenawan volcanic strata; B, Bayfield Basin; NNG, Northern Natural Gas deep drill hole (not discussed in this chapter).

Cannon et al., 1989; Anderson, 1990; Hinze et al., 1992). Within the western Lake Superior region of the MRS, additional interpretational details are given by Allen (1994).

### *Stratigraphic relations, western Lake superior region*

Interpretations of seismic reflection profiles in and near western Lake Superior are summarized in Figures 5 and 6. These maps indicate respectively the thicknesses of the Portage Lake and Chengwatana Volcanic Groups (equivalent to the total thickness of the Keweenawan igneous sequence, except in northeastern Minnesota and within ~20 km of the Minnesota shoreline) and the Keweenawan sedimentary sequence (Oronto and Bayfield Groups combined). Interpretations of offshore profiles are linked to exposed Keweenawan geology in Michigan by an onshore profile (Hinze et al., 1990) that terminates just 4 km southeast of GLIMPCE profile C (Fig. 3). The seismic interpretations in western Lake Superior are enhanced because all horizons must be consistent at points of profile intersections, greatly reducing the ambiguity associated with interpreting a single seismic profile.

Figure 5 indicates the Keweenawan volcanic sequence is thickest in Lake Superior along the Lake Superior syncline (5 s two-way travel time ~16 km) and in Wisconsin along the St. Croix Horst (4 s two-way travel time ~13 km), but is very thin or absent above two ridges of pre-Keweenawan (Archean) basement rocks. Both ridges coincide with intense negative gravity anomalies (compare Figs. 3 and 5), confirming previous interpretations (Weber and Greenacre, 1966; White, 1996a; Wold and Ostenso, 1966; Dickas, 1986c) that the negative anomalies are produced, at least in part, by thinning of the dense Keweenawan igneous rocks. Figure 7 is a long profile extending northeast from the southwestern corner of Lake Superior (see Fig. 3 for location), traversing White's ridge (to the southwest) and the Grand Marais ridge (to the northeast). This and other profiles indicate the rift's volcanic strata thin gradually to a feather edge onto both ridges (Fig. 7), with no evidence for substantial normal or reverse faulting. Hence, these ridges, composed of Archean rock, remained positive Keweenawan topographic features as the adjacent volcanic basins gradually subsided.

As shown in Figure 6, the thickest section of Keweenawan sedimentary strata in western Lake Superior occurs along the Lake Superior syncline (3.5 s two-way travel time ~9 km). The synclinal axis bends west and then northwest toward Minnesota, and is not continuous with the Ashland syncline in Wisconsin (Fig. 6). Rather, the two synclines are separated by White's ridge, which remained a positive topographic feature after volcanism ceased. In fact, the Copper Harbor Conglomerate and Nonesuch Formation actually pinch out, and the Freda Sandstone lies directly above the pre-Keweenawan basement along the crests of both White's ridge and the Grand Marais ridge (Fig. 7). (The dashed line in Figure 7 represents a prominent reflection within the lower Freda Sandstone, correlated offshore by means of the onshore profile in Michigan [Fig. 3] that traverses the Oronto Group.)

Seismic data also indicate the great majority of Keweenawan sedimentary strata in western Lake Superior belong to the Oronto Group. For example, Figure 8 shows nearly horizontal reflections just northwest of exposed, gently-dipping (5° NW) Freda Sandstone (Oronto Group) along the Michigan shoreline, indicating that the overlying Bayfield Group, if present, must be very thin along this profile. Similar seismic-geologic relations along other profiles reveal that the Bayfield Group is relatively thin or absent throughout most of western Lake Superior.

As suggested by Figures 7 and 8, Oronto Group sedimentary strata typically lie conformably above the volcanic flows. In several locations in western Lake Superior, however, unconformable relations are observed (Fig. 9), indicating local uplift and erosion of the Keweenawan volcanic flows prior to their burial beneath the Oronto Group. These unconformities occur along the margins of White's ridge and the Grand Marais ridge (Fig. 10), and coincide approximately with regions where the Copper Harbor Conglomerate and Nonesuch Formation are absent (Fig. 10). The ridges, therefore, were uplifted and eroded after volcanism waned, and

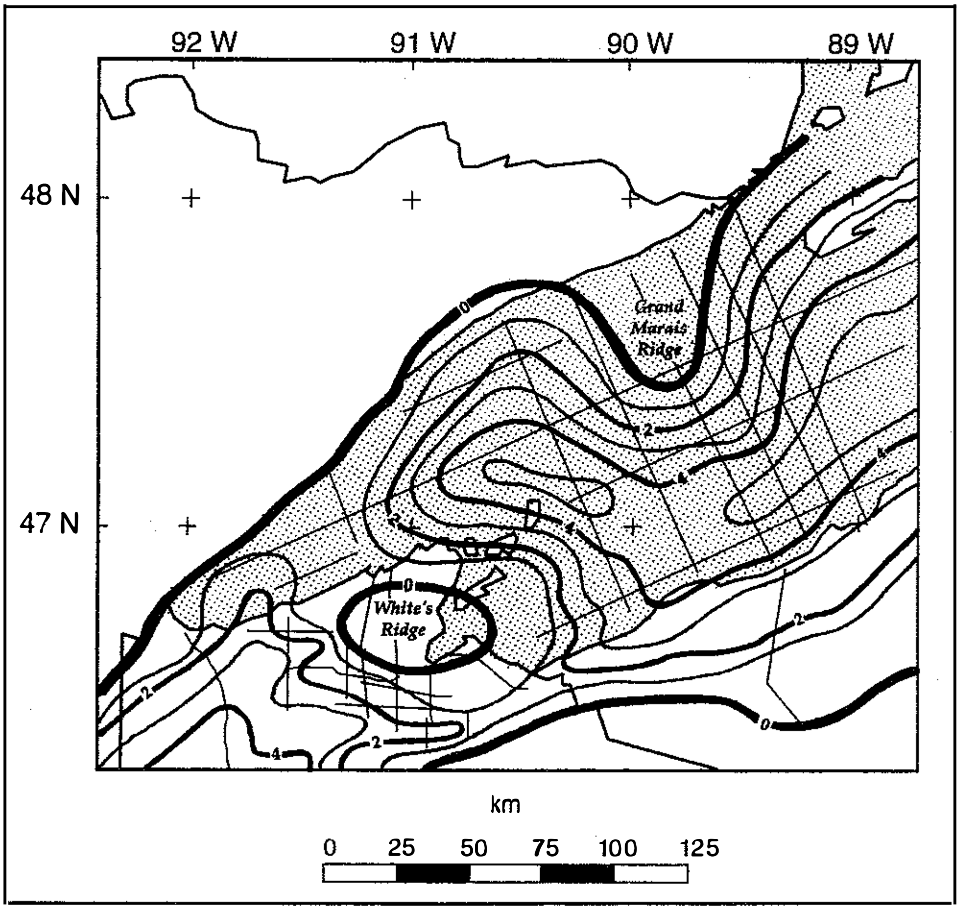


Figure 5. Contour map, thickness of the Portage Lake and Chengwatana Volcanic Groups. Thin lines indicate seismic reflection profiles. Contour interval is 1 s two-way travel time (1 s ~ 3.3 km). Dotted pattern identifies Lake Superior.

remained positive features until the Freda Sandstone was deposited on top of them.

***Structural relations, western Lake Superior region***

The structure of the MRS in western Lake Superior is different from that of the St. Croix Horst to the southwest and of central Lake Superior to the east in that major reverse faulting is absent. As shown in Figure 6, the Isle Royale reverse fault terminates ~40 km southwest of the Isle. Displacement across the fault decreases, from ~3 km along the seismic profile nearest the Isle (Fig. 8) to <1 km along the adjacent profile to the southwest, and the fault terminates before crossing the next seismic profile (Fig. 11; see Fig. 3 for profile location). Along this profile, however, the Keweenawan rocks are deformed (Fig. 11), indicating that late-stage contraction was accommodated by folding instead of thrusting. The Isle Royale anticline (near 65 km along Fig. 11), extends parallel to the Lake Superior syncline (Fig. 6) and is faulted along the southern margin of the Grand Marais ridge (Fig. 6). This small fault is imaged only along GLIMPCE profile C and is therefore a local feature, in contrast to the interpretation by Sexton and Henson (1994) who name this feature the Ojibwa fault.

In Wisconsin, proprietary seismic reflection data indicate that displacement across the Douglas fault decreases to the east (Figs. 6 and 12). East of 91°W, the fault flattens to a décollement within the Oronto Group, and the Douglas fault then diminishes to a monocline east of Ashland, Wisconsin (Fig. 12). This interpretation is confirmed by the dissipation of the gravity anomaly (second vertical derivative) signature of the Douglas fault in northwestern Wisconsin (Fig. 13). Moreover, the seismic data in Lake Superior show no evidence for an eastern extension of the Douglas fault, and are incompatible with interpretations (e.g., Sexton and Henson, 1994) that suggest the fault extends into the lake.

***Nature of the Pre-Keweenawan basement ridges***

White's Ridge represents a significant discordant structure within the MRS. This ridge separates the deep volcanic basin of western Lake Superior from the deep basin along the St. Croix Horst (Fig. 5), and delineates the accommodation structure

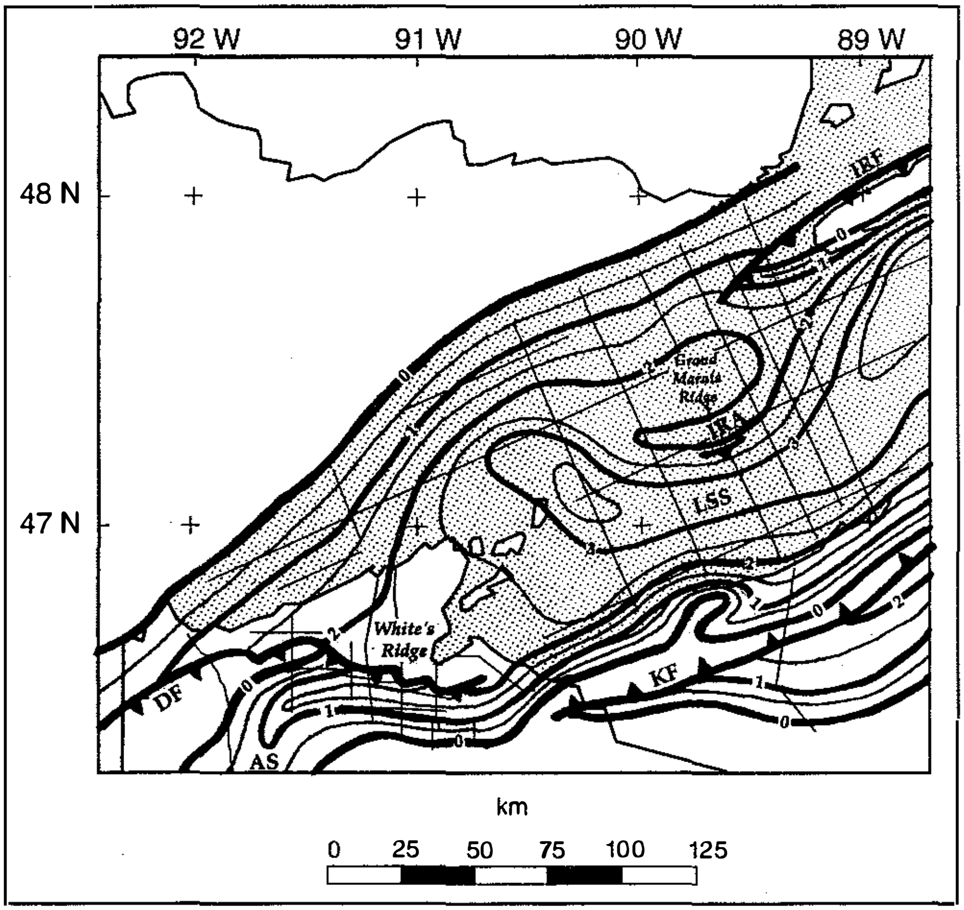


Figure 6. Contour map, base of Oronto Group. Thin lines indicate seismic reflection profiles. Contour interval is 0.5 s two-way travel time (1 s ~ 2.5 km). DF, Douglas Fault; KF, Keweenaw fault; IRF, Isle Royale fault; AS, Ashland syncline; LSS, Lake Superior syncline; IRA, Isle Royale anticline. Dotted pattern identifies Lake Superior.

between the Brule and Ontonagon rift units as identified by Dickas and Mudrey (1989, this volume) and Cannon et al. (1989). The rift widens abruptly as it crosses White's Ridge (Figs. 1 and 2), and the rift basin is much deeper in western Lake Superior than along the western limb (Figs. 5 and 6). Southwest of White's Ridge, the rift structure consists of a central basaltic horst bound by reverse faults and flanked by clastic sedimentary basins. Northeast of the ridge, however, major reverse faulting is absent, and flanking sedimentary basins are less common (Fig. 2).

The Grand Marais ridge, a counterpart to White's ridge (Fig. 7), is located immediately southwest of Isle Royale (Fig. 2). This structure delineates the accommodation feature separating the Ontonagon and Manitou rift units (Dickas and Mudrey, this volume).

Gravity modeling provides critical insight into the nature of White's ridge and the coeval Grand Marais ridge. Figure 14 is a residual gravity anomaly map, prepared by subtracting the (three-dimensionally) calculated effect of the Keweenawan volcanic and sedimentary strata from the observed gravity anomaly (Fig. 3). The prominent northeast-striking negative residual anomaly (Fig. 14) is robust and not greatly altered as the model densities of the volcanic, sedimentary, and pre-Keweenawan basement rocks are varied within reasonable limits (Allen, 1994). The negative anomaly encompasses both pre-Keweenawan ridges (compare Figs. 5 and 14), and must be produced by a mass deficiency within the middle or upper crust, because the moderate to steep gravity gradients (Fig. 14) preclude sources at greater depths. In addition, the anomaly cannot be produced by variation in the density of the Keweenawan volcanic rocks, because the anomaly extends across the basement ridges where the volcanic sequence is absent. Moreover, the anomaly is probably not the result of low-density (Bayfield Group) sedimentary rocks because more than 2.5 km of such strata are necessary to properly model the anomaly, much greater than the maximum thickness of these rocks (~1.0 km) allowed by seismic-geologic relations (e.g., Fig. 8).

Therefore, the negative residual anomaly is likely produced by a mass deficiency within the pre-Keweenawan basement beneath the rift basin. Beyond the margins of the MRS, negative anomalies of comparable amplitude, width, and orientation (G, Fig. 14) are associated with granitic belts in the Archean

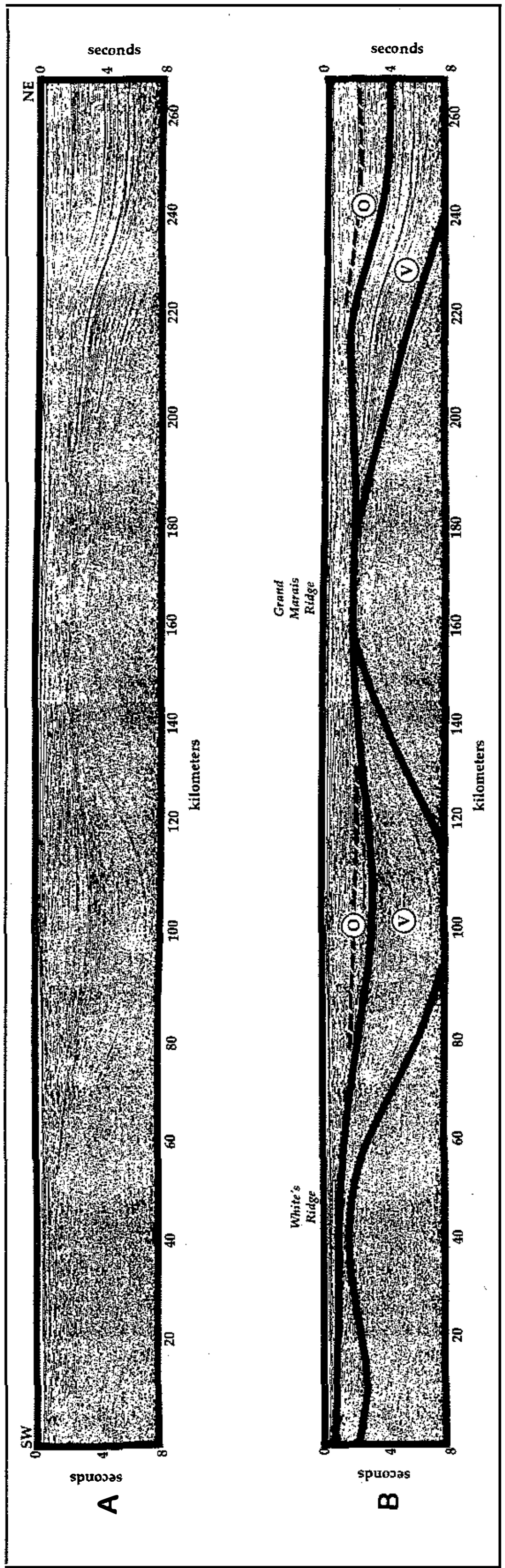


Figure 7. Portion of Grant-Norpac/Argonne seismic reflection profile LS-08 (line a, Fig. 3). A, migrated seismic section; B, interpretation. V, volcanic flows; O, Oronto Group sedimentary strata. Dashed line indicates a prominent reflection within the lower Freda Sandstone.

greenstone-granite province (Fig. 1). A similar feature may be present within the buried Archean basement beneath the rift basin, an interpretation that is supported by quantitative gravity modeling by Allen (1994). A relatively thick section (~10 to 15 km) of buried pre-Keweenawan crustal rocks is required to model the observed residual anomaly (Allen, 1994). Consequently, previous models involving a nearly complete separation of the continental crust along the MRS (e.g., Cannon, 1992) may require modification in western Lake Superior. Perhaps the large volume of Archean rocks preserved beneath the Keweenawan sequence indicates that the rift basin in western Lake Superior formed (in part) by subsidence of the crust, and that extension may have been accommodated by the injection of dikes or by ductile stretching of the crust rather than by extensive normal faulting.

The proposed Archean granitic belt constitutes the pre-Keweenawan basement along most of White's ridge and the Grand Marais ridge (compare Figs. 5 and 14), and apparently played an influential role throughout the evolution of the MRS. First, the trend of the MRS (southwesterly in easternmost western Lake Superior and along the St. Croix Horst) is disrupted (northwesterly) near the interpreted granitic belt (compare Figs. 6 and 14). Hence, this pre-Keweenawan feature may have influenced the development of the MRS by acting as a buttress. A minimally fractured and nonfoliated mass of granite should have relatively great strength compared with the surrounding crustal rocks and would probably resist deformation (Klasner et al., 1982). Perhaps tensional stresses were more effective and the rift propagated more easily across the buttress (northwesterly) than along its axis (southwesterly), resulting in the dramatic change in strike of the MRS and the local absence of volcanic strata along the crests of the ridges. Second, post-volcanic uplift and erosion of the ridges (Figs. 9 and 10) may have been an isostatic response, as the granitic rocks are considerably less dense (~2,650 kg/m$^3$) than the surrounding basaltic volcanic flows (density ~2,950 kg/m$^3$). This uplift may also reflect an early pulse of contraction associated with the initial stages of the Grenvillian collision east of the MRS (Fig. 1). In fact, such contraction might have also been responsible for the termination of volcanism. Finally, the Douglas and Isle Royale faults terminate as they approach White's ridge and the Grand Marais ridge, respectively, and the Isle Royale anticline follows the southern margin of the Grand Marais ridge (Fig. 6). Apparently, the pre-Keweenawan basement ridges continued to play active roles during late-stage contraction along the MRS, probably by acting as buttresses that resisted contractional deformation, resulting in the absence of reverse faulting in most of western Lake Superior.

Geologic and geophysical data support the existence of a third pre-Keweenawan basement ridge in the western Lake Superior region. The Schroeder–Forest Center crustal ridge (Miller and Chandler, this volume) extends west-northwest–east-southeast beneath the Duluth Complex and North Shore Volcanic Group of northeastern Minnesota (Fig. 2) and may actually be a

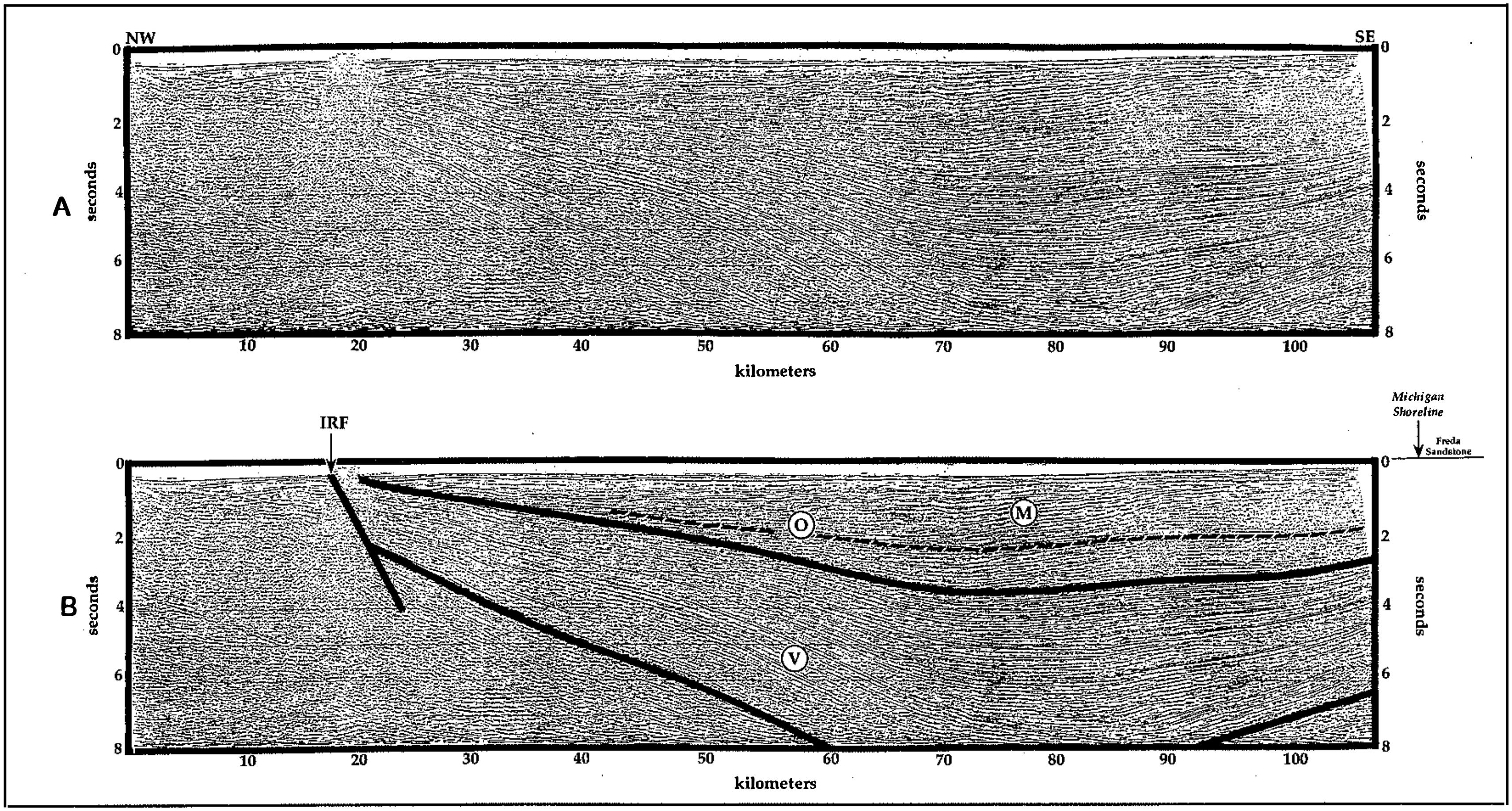


Figure 8. Grant-Norpac/Argonne seismic reflection profile LS-43 (line b, Fig. 3). A, migrated seismic section; B, interpretation. V, volcanic flows; O, Oronto Group sedimentary strata; M, lake-bottom multiple reflections; IRF, Isle Royale fault. Dashed line indicates a prominent reflection within the lower Freda Sandstone.

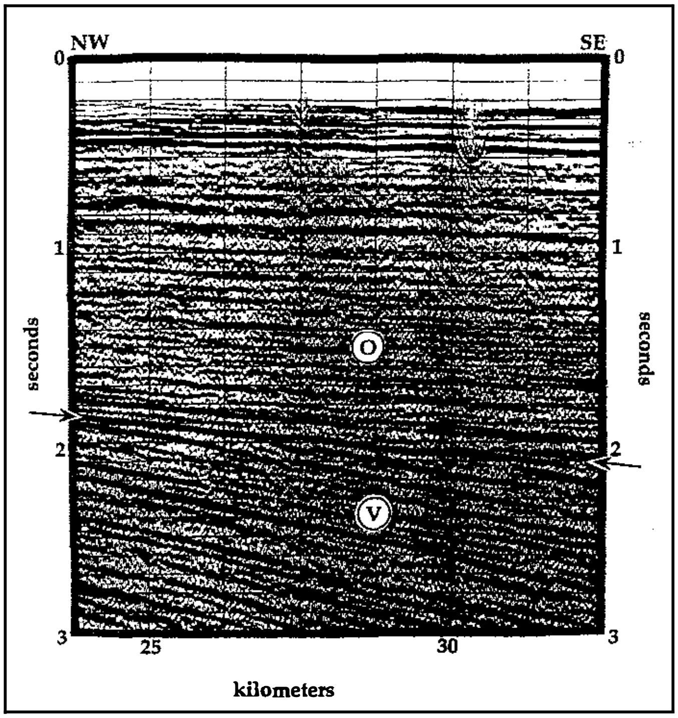


Figure 9. Portion of Grant-Norpac/Argonne migrated seismic reflection profile LS-45 (line c, Fig. 3). Arrows delineate unconformable contact between volcanic flows (V) and Oronto Group strata (O).

northwestern extension of White's ridge (Allen, 1994). The crustal ridge is inferred by an abundance of Archean xenoliths within the overlying Keweenawan intrusive rocks (Boerboom, 1994), a pronounced thinning of the Keweenawan Beaver Bay Complex (Miller and Chandler, this volume), a paleotopographic high during the deposition of the North Shore Volcanic Group (Jirsa, 1984), discontinuities within the North Shore Volcanic Group (Grout et al., 1959; Green, 1972, 1983; Miller and Chandler, this volume), and also a thinning of the Early Proterozoic Biwabik and Gunflint iron formations (Morey, 1972a, b). Moreover, the local negative gravity anomaly (saddle) associated with this feature (compare Figs. 2 and 3) also suggests that the Keweenawan mafic igneous rocks are relatively thin in this area, consistent with interpretations by White (1966b), Ferderer (1982), and Chandler (1990).

### *Stratigraphic relations, western limb of the Midcontinent Ridge System*

The stratigraphy of the marginal basins that flank the St. Croix Horst in Wisconsin and Minnesota (Fig. 2) must be inferred geophysically due to poor exposure of Keweenawan rocks and a lack of deep drill holes. The dense coverage of seismic reflection profiles (Fig. 3) along the eastern flanking basin and associated negative gravity anomaly (which attains its maximum negative values near Emerald, Wisconsin) permits a detailed investigation of the Keweenawan stratigraphy in this area. Historically, this basin has been referred to as the River Falls syncline because overlying Paleozoic rocks are deformed in such a manner. The seismic data, however, indicate that the Keweenawan structure is not synclinal, but is instead a wedge-shaped, westward-deepening basin (Fig. 15), more appropriately named the Emerald Basin (Allen, 1994). To reproduce the intense negative gravity anomaly associated with this basin (Fig. 3), the sedimentary strata must belong predominantly to the low-density Bayfield Group (density ~2,400 kg/m$^3$) or the lithostratigraphic-equivalent Fond du Lac Formation and Hinckley Sandstone. Older, intermediate-density (~2,650 kg/m$^3$) Oronto Group strata, if present, compose a very thin basal layer (e.g., Fig. 16). Similar combined analysis of seismic reflection and gravity data in Minnesota indicates that the Bayfield Basin, the counterpart to the Emerald Basin situated west and northwest of the St. Croix Horst (Dickas, 1986a), also contains mainly Bayfield-equivalent strata (Fig. 16). However, Oronto Group strata are relatively thick in the southern Emerald Basin along the eastern margin of the Midcontinent Rift System (MRS) in southeastern Minnesota (Fig. 17). This is the only location where these strata are regionally prevalent in a Keweenawan flanking sedimentary basin; elsewhere, the distribution of the Oronto Group roughly coincides with that of the underlying volcanic strata. Perhaps the southern Emerald Basin subsided preferentially due to the combined loads of the volcanic basins to both the northwest and southwest (e.g., Figs. 2 and 18).

Gravity modeling, constrained by three long seismic reflection profiles across the St. Croix Horst in Wisconsin and Minnesota (Fig. 3), indicates that the Keweenawan volcanic rocks typically have an average density (~2,950 kg/m$^3$) consistent with basaltic volcanic flows (Fig. 16). In southeastern Minnesota, however, the relatively low average density of the upper volcanic sequence along the southernmost seismic profile (Fig. 17; see Fig. 3 for profile location) indicates a large proportion of low-density felsic volcanic flows or the prevalence of interflow clastic sedimentary strata. In fact, felsic rocks are encountered in deep drill holes north of this profile, just west of the Minnesota-Wisconsin border (FV, Fig. 18). In addition, combined gravity and magnetic modeling by Allen (1994) supports the interpretation that felsic rocks are abundant in the Keweenawan igneous sequence over a large area in southeastern Minnesota (Fig. 2). The prevalence of felsic rocks implies that the rift magmas in this area may have been derived (to a large degree) from melting of the crust or assimilation of crustal material by plume-derived magmas. Notably, the felsic rocks occur where the MRS bends to the southeast (Fig. 2). Tensional stress (which was probably oriented northwest-southeast) may have been less effective in opening the north-northwest-striking segment of the MRS in southeastern Minnesota, and plume-derived magmas may have encountered greater resistance while rising through the lithosphere. Consequently, plume magmas may have incorporated a large amount of crustal material; additional magmas may have been derived from crustal melting due to the heat provided by trapped plume magmas.

As shown in Figure 18, the Keweenawan volcanic sequence is thickest north of 46°N and south of 45°N. These areas correspond to the Ashland syncline and Twin Cities

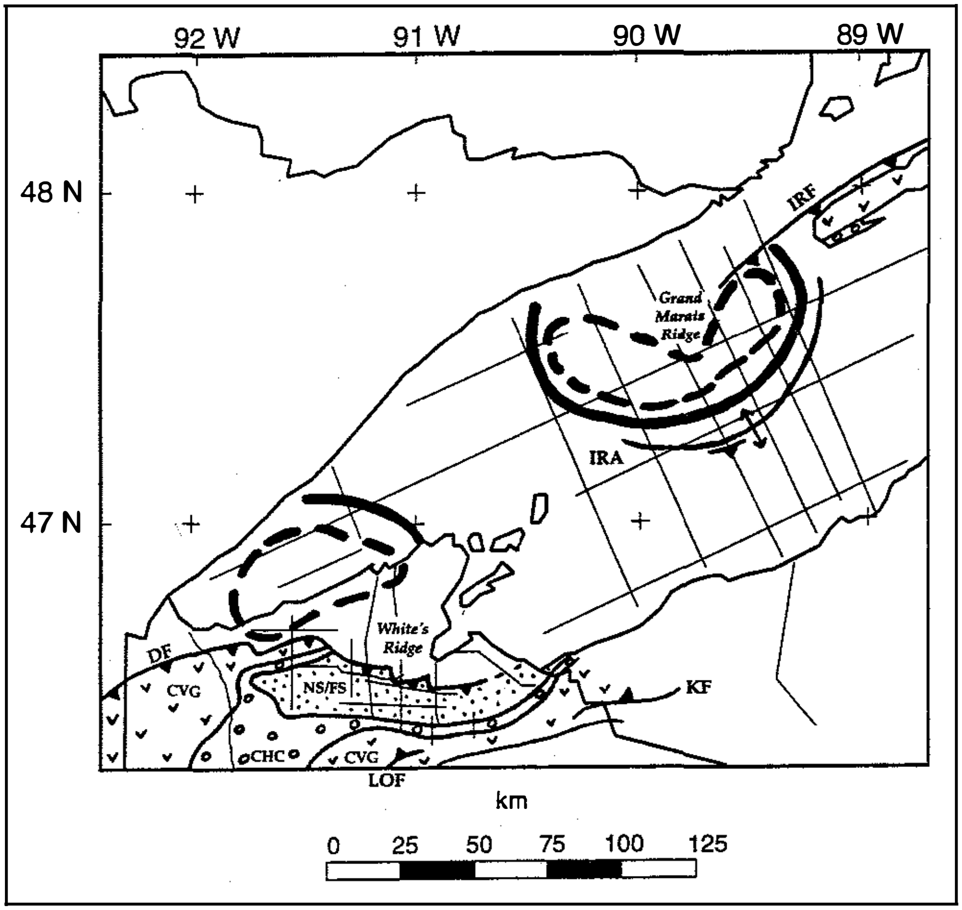


Figure 10. Map of the MRS indicating significant stratigraphic relations of the Oronto Group in northwestern Wisconsin and western Lake Superior. Thin lines indicate seismic reflection profiles. Thick dashed lines enclose areas where Oronto Group strata lie unconformably above volcanic flows. Thick solid lines delineate pinch-out of the Copper Harbor Conglomerate (CHC) and Nonesuch Shale (NS) onto pre-Keweenawan basement ridges. FS, Freda Sandstone; CVG, Chengwatana Volcanic Group; DF, Douglas fault; LOF, Lake Owen fault; KF, Keweenaw fault; IRF, Isle Royale fault; IRA, Isle Royale anticline.

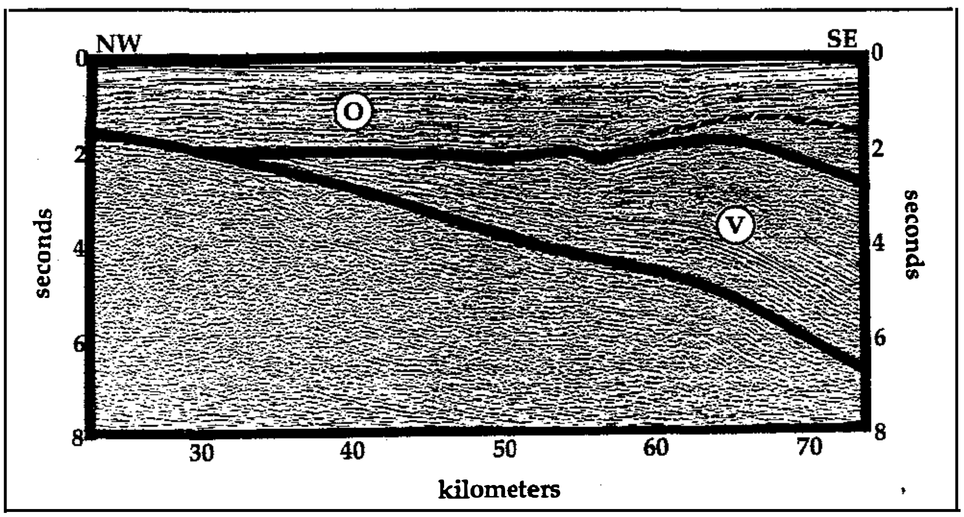


Figure 11. Portion of Grant-Norpac/Argonne migrated seismic reflection profile LS-47 (line d, Fig. 3). V, volcanic flows; O, Oronto Group sedimentary strata. Dashed line indicates a prominent reflection within the lower Freda Sandstone.

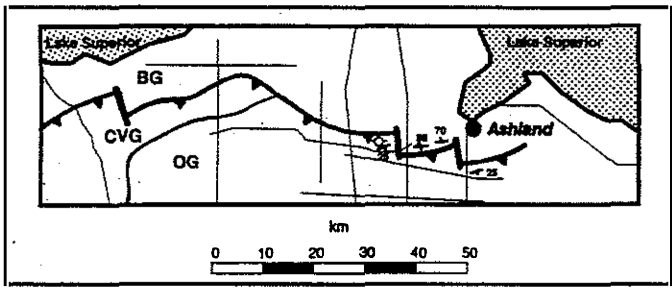


Figure 12. Map of the Douglas fault in northwestern Wisconsin. Thin lines indicate seismic reflection profiles. CVG, Chengwatana Volcanic Group; OG, Oronto Group; BG, Bayfield Group. Strike-dip symbols indicate attitude of the Freda Sandstone, the youngest formation of the Oronto Group. Well location marks the site of the deep Midcontinent Rift Terra-Patrick #7–22 hydrocarbon test, drilled to a total depth of 1,514 m in 1992.

Basin, respectively, and are associated with the thickest sections of overlying Oronto Group strata. The intervening segment of the St. Croix Horst (near 45°30'N), however, is characterized by a relatively thin volcanic sequence (Fig. 18) without an overlying section of Keweenawan sedimentary strata (Fig. 2). This distribution of rift igneous and sedimentary rocks may reflect varying degrees of magmatism and sedimentation along the MRS. Alternatively, variation in the thickness of the Keweenawan section may be the result of nonuniform uplift and erosion of the St. Croix Horst (e.g., Fig. 22).

*Structural relations, western limb of the MRS*

Shaded relief magnetic anomaly maps (Figs. 19 and 20) are very useful for investigating the structure of the western limb of the MRS due to the intense magnetization contrasts between the rift's volcanic and sedimentary rocks and also within the volcanic sequence (Allen and Chandler, 1993). Magnetic anomaly data are often the primary means by which rift structures are identified due to a lack of exposure of the Keweenawan sequence and relatively few long seismic reflection profiles (Fig. 3). Magnetic data, in conjunction with gravity, seismic, and geologic data, reveal several structural complexities pertaining to the reverse faults along the rift's western limb in Wisconsin and Minnesota.

***Reverse faulting.*** The southeastern margin of the St. Croix Horst (Fig. 2) has traditionally been interpreted as a single reverse fault, the Lake Owen fault (White, 1966b). Geologic evidence concerning this fault is limited, and the fault is delineated primarily on the basis of gravity and magnetic data. The Lake Owen fault is associated with a pronounced magnetic anomaly signature (Fig. 19) and an intense, paired positive-negative second vertical derivative gravity anomaly (Fig. 13). As indicated by

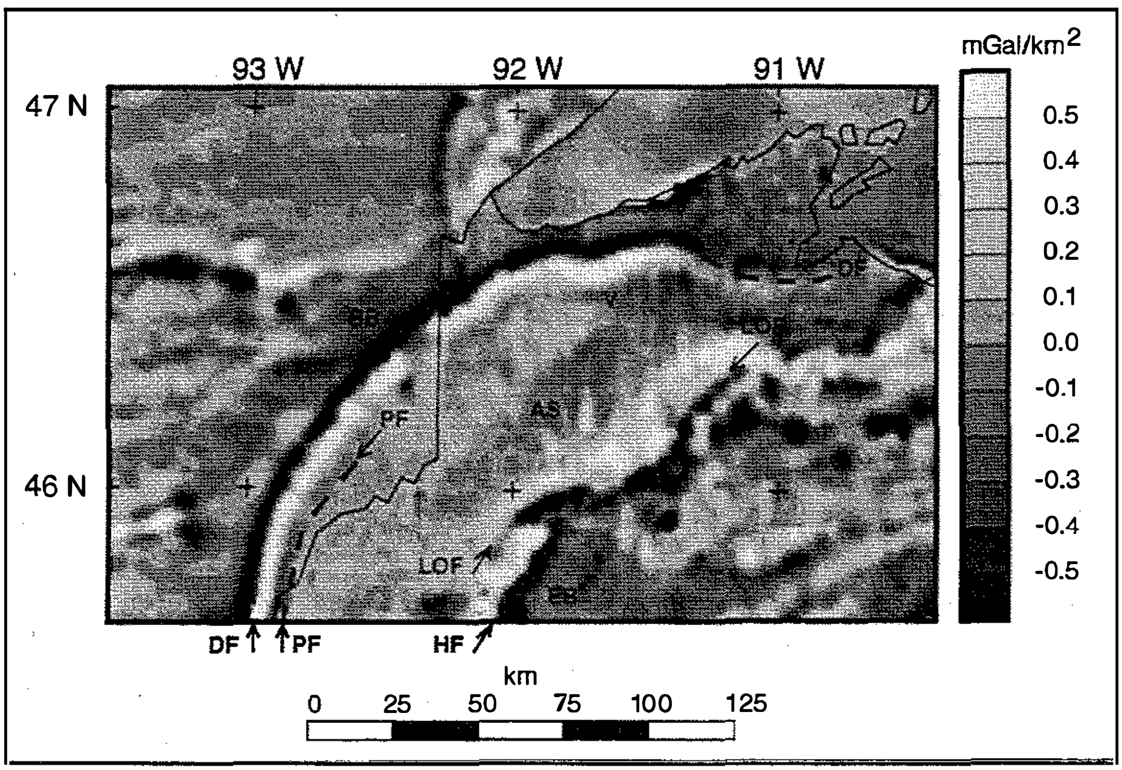


Figure 13. Second vertical derivative Bouguer gravity anomaly map, northern St. Croix Horst region. DF, Douglas fault (dashed line is extension of the fault based on gravity and seismic reflection data); LOF, Lake Owen fault; HF, Hastings fault; PF, Pine Fault; AS, Ashland syncline; V, abrupt thinning of the outcrop belt of volcanic rocks; BB, Bayfield Basin; EB, Emerald Basin.

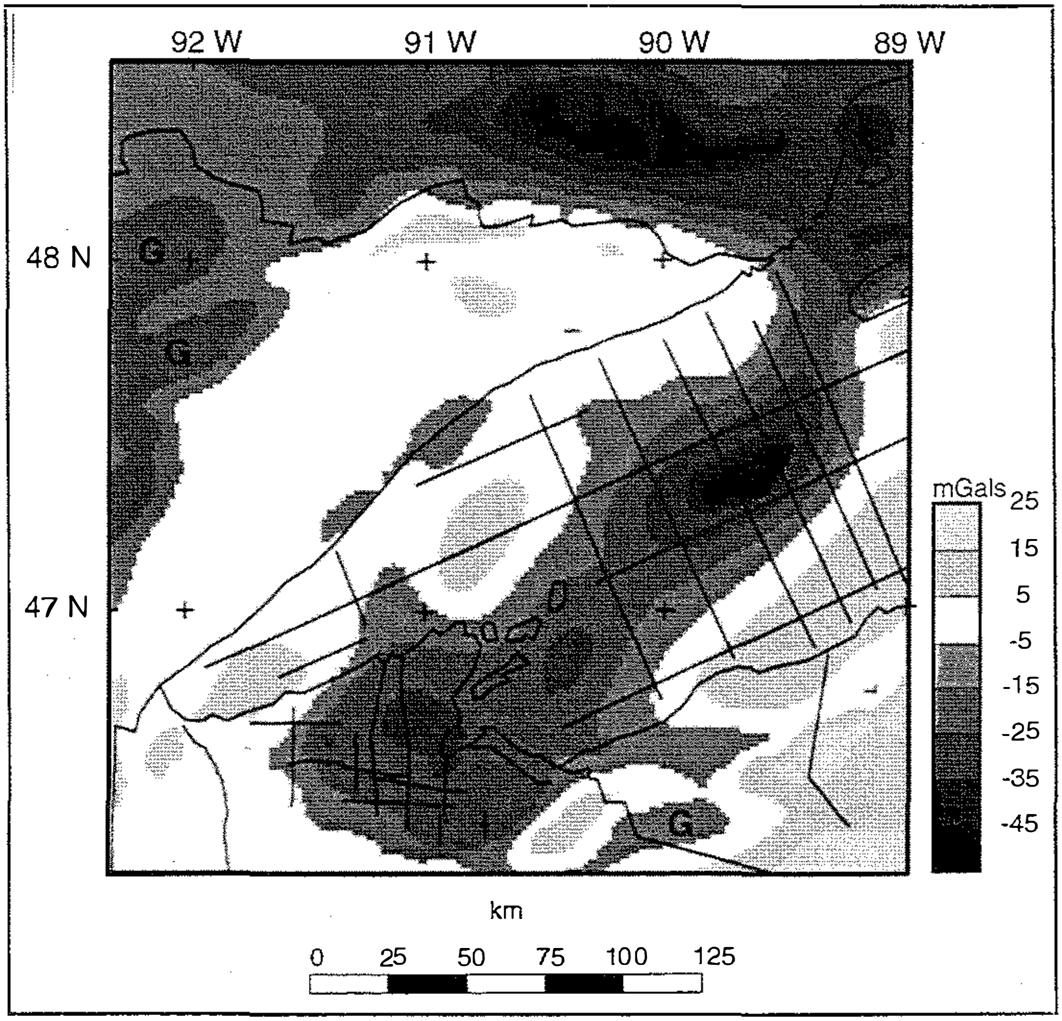


Figure 14. Residual gravity anomaly map prepared by subtracting calculated gravity values from observed gravity values. Values between -5 and +5 mGal are indicated by white. G, negative anomalies associated with Archean granitic rocks. Thin lines indicate seismic reflection profiles. Calculation based on densities of 2,400, 2,650, 2,950, and 2,750 kg/m$^3$ for the Bayfield Group, Oronto Group, volcanic strata, and average pre-Keweenawan basement, respectively, and a regional base level of -45 mGal (e.g., Allen et al., 1992).

Figures 13 and 19, the Lake Owen fault terminates just south of 46°N, approximately 15 km west of the northeastern termination of the Hastings fault, a reverse fault extending southwest into Minnesota. The relation between the Hastings and Lake Owen faults is unclear. These faults might represent fault splays that merge at depth. Alternatively, the two faults may have been a single reverse fault that was displaced ~15 km by a left-lateral strike-slip fault, although there is no evidence that such a fault disrupts the interior of the St. Croix Horst or the pre-Keweenawan rocks to the southeast. Moreover, a left-lateral strike-slip fault would be inconsistent with the predominance of right-lateral Keweenawan strike-slip faulting in northwestern Wisconsin (e.g., Fig. 12; Dickas and Mudrey, 1991).

The discontinuity between the Lake Owen and Hastings faults coincides with the northern margin of the Emerald Basin (Fig. 15). The northern margin of the basin is clearly delineated by exposure of the pre-Keweenawan Barron Quartzite (Fig. 15; Mudrey et al., 1987) and further identified by termination of the negative gravity anomaly (Fig. 3) associated with the basin. This correlation suggests that the Emerald Basin may be genetically related to the Hastings fault. Perhaps, the Emerald Basin represents a foreland basin that subsided under the weight of the adjacent St. Croix Horst. The textural and compositional maturity of the Bayfield Group (i.e., the predominant strata in this basin), however, suggests a pre-Keweenawan provenance for the basin, combined with possible erosion of Oronto Group strata, and minimal contribution from the uplifted volcanic rocks. The absence of a flanking sedimentary basin southeast of the Lake Owen Fault (Fig. 2) suggests that this fault may have experienced only minimal reverse motion.

The Lake Owen–Hastings fault discontinuity occurs near the Great Lakes Tectonic Zone (GLTZ), a suture that extends northeast across Minnesota (Fig. 21) and into northern Wisconsin (Sims et al., 1980). The GLTZ divides the northern, ~2.7-Ga greenstone-granite terrane from the southern, ~3.5-Ga gneiss-migmatite terrane (Fig. 21; Sims et al., 1980). The Lake Owen-Hastings fault discontinuity also occurs near the Niagara fault, the southern boundary of the Archean Superior Province with the Early Proterozoic Penokean magmatic terrane of central Wisconsin (Fig. 1; Sims et al., 1989). Perhaps differences in crustal strength, thickness, and rheological properties between adjacent pre-Keweenawan terranes caused the reverse faults to become segmented along the southeastern margin of the St. Croix Horst.

To the southwest in Minnesota, the Hastings fault terminates at the Empire fault, a northwest-southeast cross structure within the MRS (Fig. 20). Reverse faulting southwest of the Empire fault occurs along the Castle Rock fault (Fig. 20), a structure imaged by seismic reflection data (Fig. 17), and along the Northfield fault (Fig. 22), which is inferred by the presence of volcanic rocks at shallow depth (Allen, 1994). South of the Northfield fault, reverse faulting is equivocal (Fig. 22), although gravity and magnetic modeling by Allen (1994) indicates that displacement would be relatively minor (<1 km).

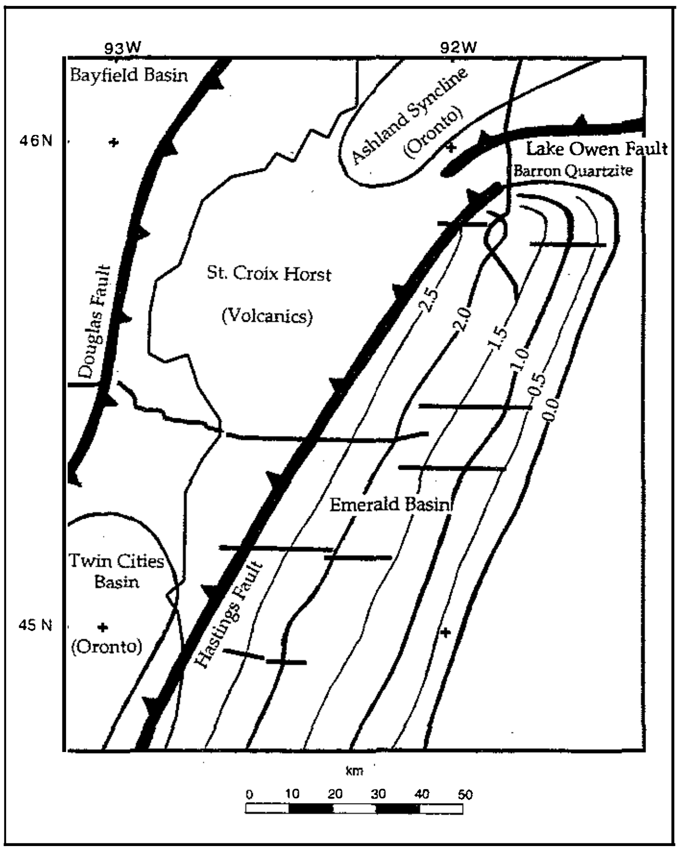


Figure 15. Contour map, base of tbe Keweenawan sedimentary strata within the Emerald basin. Thick lines indicate seismic reflection profiles. Contour interval is 0.5 s two-way travel time (1 s ~ 2.0 km).

The western margin of the St. Croix Horst is delineated by two parallel reverse faults, the Douglas fault and the Pine fault (Sims and Zietz, 1967; Allen and Chandler, 1992). The Pine fault is identified by an abrupt discontinuity in the strike of the short-wavelength linear magnetic anomalies (Fig. 19) associated with the Keweenawan volcanic flows. The Douglas and Pine faults are disrupted by the Chisago fault, a minor cross fault north of the Twin Cities Basin (Fig. 20), and either terminate at or are substantially disrupted by the Lake Minnetonka fault, another cross fault along the western margin of the St. Croix Horst (Fig. 20). Southwest of the Lake Minnetonka fault, magnetic anomaly data indicate reverse faulting, although it is unclear whether this is a southwestern extension of the Pine fault or a northern extension of the Belle Plaine fault (PF?, Fig. 20).

***Nature of the Belle Plaine fault.*** The northwest-striking Belle Plaine fault is a major cross structure that extends from the southwestern termination of the St. Croix Horst to the northern termination of the Iowa Horst (Figs. 2 and 20; Gibbs et al., 1984; Chandler et al., 1989). The Belle Plaine fault delineates the southern margin (accommodation structure) of the Superior zone (Dickas and Mudrey, this volume). Knowledge of the fault's structure is based primarily on gravity and magnetic data due to a relatively thick (~500 m) section of lower Paleozoic sedimentary strata. As shown in Figure 20, the Belle Plaine fault is not a single fault, but rather a series of en echelon fault segments.

Deformation of Paleozoic strata along the trace of the Belle Plaine fault near the city of Belle Plaine (BP, Fig. 20; Sloan and Danes, 1962) and in Waseca County (WC, Fig. 20; Bloomgren, 1993) indicates post-Ordovician reactivation of the fault. Stratigraphic relations within Paleozoic rocks suggest that the northeast side of the fault was uplifted, at most ~300 m, during Phanerozoic time. The amplitudes of the associated gravity and magnetic anomalies, however, indicate a much greater magnitude of displacement across the fault during Keweenawan time (Allen, 1994). The abrupt increase in the thickness of the volcanic sequence across the Belle Plaine fault (Fig. 17 and 18) suggests this fault may have originally developed as a normal growth fault.

In addition, the Belle Plaine fault may have been reactivated as a reverse fault during late-stage contraction along the MRS. For example, the magnetic data indicate a juxtaposition of Keweenawan volcanic and sedimentary strata just west of the Montgomery anticline (Fig. 20), suggesting that volcanic rocks were thrust west over younger sedimentary strata. The axis of the Montgomery Anticline is nearly parallel to the Belle Plaine fault (Fig. 20), suggesting that this fold may be a rollover structure produced by dragging within the hanging wall of the Belle Plaine fault, an interpretation also suggested by seismic reflection data (Fig. 17).

The MRS bends abruptly to the southeast along the Belle Plaine fault. Sloan and Danes (1962) suggested that the fault

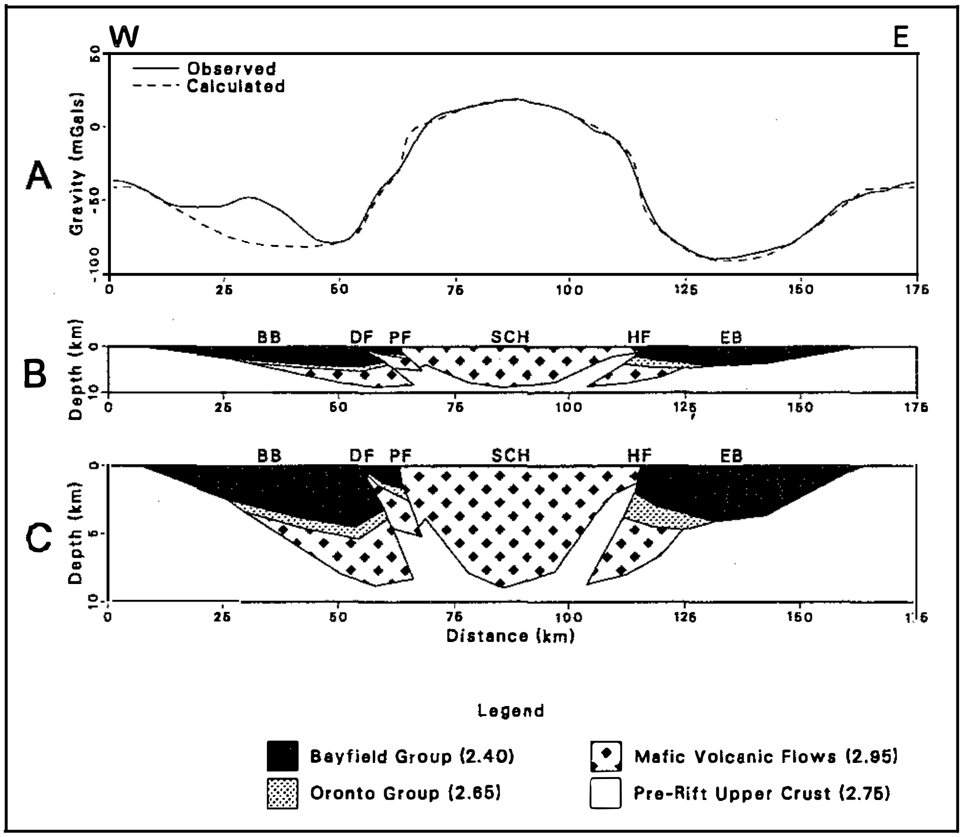


Figure 16. Two-dimensional gravity model of the Midcontinent Rift System along the seismic profile across the central St. Croix Horst in Minnesota and Wisconsin (line, Fig. 3). A, observed and calculated profiles; B, model, vertical exaggeration 1:1; C, model, vertical exaggeration 3:1. Densities are expressed in g/cm$^3$ (1 g/ cm$^3$ = 1,000 kg/m$^3$). SCH, St. Croix Horst; DF, Douglas fault; PF, Pine fault; HF, Hastings fault; BB, Bayfield Basin; EB, Emerald Basin. The positive gravity anomaly near 30 km is a local, north-northwest-striking feature (see Fig. 3) that is probably produced by a positive density contrast in the pre-Keweenawan basement beneath the Bayfield Basin.

experienced ~150 km of left-lateral strike-slip motion, and that the St. Croix and Iowa Horsts were originally a single, continuous feature. Beyond the margins of the MRS, however, geophysical and geologic data do not suggest the presence of major strike-slip faulting disrupting older pre-Keweenawan terranes. Moreover, it is not possible to obtain a continuous gravity anomaly signature by restoring the proposed strike-slip motion along the fault. In fact, the continuity of the rift's central positive gravity anomaly in southeastern Minnesota (Fig. 3) suggests that the MRS merely bends to the southeast.

It is unclear why the MRS is deflected in this area. However, older structures within the pre-Keweenawan terranes are parallel to and along strike with the Belle Plaine fault. In central Minnesota, for example, the western terminations of both the Animikie Basin outliers and the Penokean fold and thrust belt occur ~150 km northwest of the MRS, and on-line with the strike of the Belle Plaine fault (Fig. 21). In addition, V. W. Chandler (personal communication, 1993) speculates that the Belle Plaine fault may occur along the eastern margin of the Archean gneiss-migmatite terrane of southwestern Minnesota (Fig. 1). On the basis of an intense magnetic anomaly just west of the Belle Plaine fault, McSwiggen et al. (1987) propose that the MRS was deflected east of a strong, pre-Keweenawan granitic intrusion. In any event, it appears likely that the development of the rift in southeastern Minnesota was influenced by ancestral zones of weakness in the older Proterozoic and Archean basement.

***Magnitude of uplift.*** Quantitative gravity and magnetic modeling (e.g., Figs. 16 and 17) is useful for investigating the structure of the MRS at depth. Figure 22 summarizes the results of combined gravity and magnetic modeling along eight profiles across the MRS in Minnesota and Wisconsin (Allen, 1994). Reverse faulting is not uniform along the rift system. Across the Belle Plaine fault, vertical displacement (Fig. 22) is typically ~1 km or less, and never greater than ~3 km. Uplift of the central volcanic basin increases along the St. Croix Horst in a northeast direction, from ~1 km across the Northfield fault, to ~3 km across the Castle Rock fault, and to ~8 km across the Hastings fault (Fig. 22). Reverse displacement across the Lake Owen fault cannot be estimated (or even proven) because the

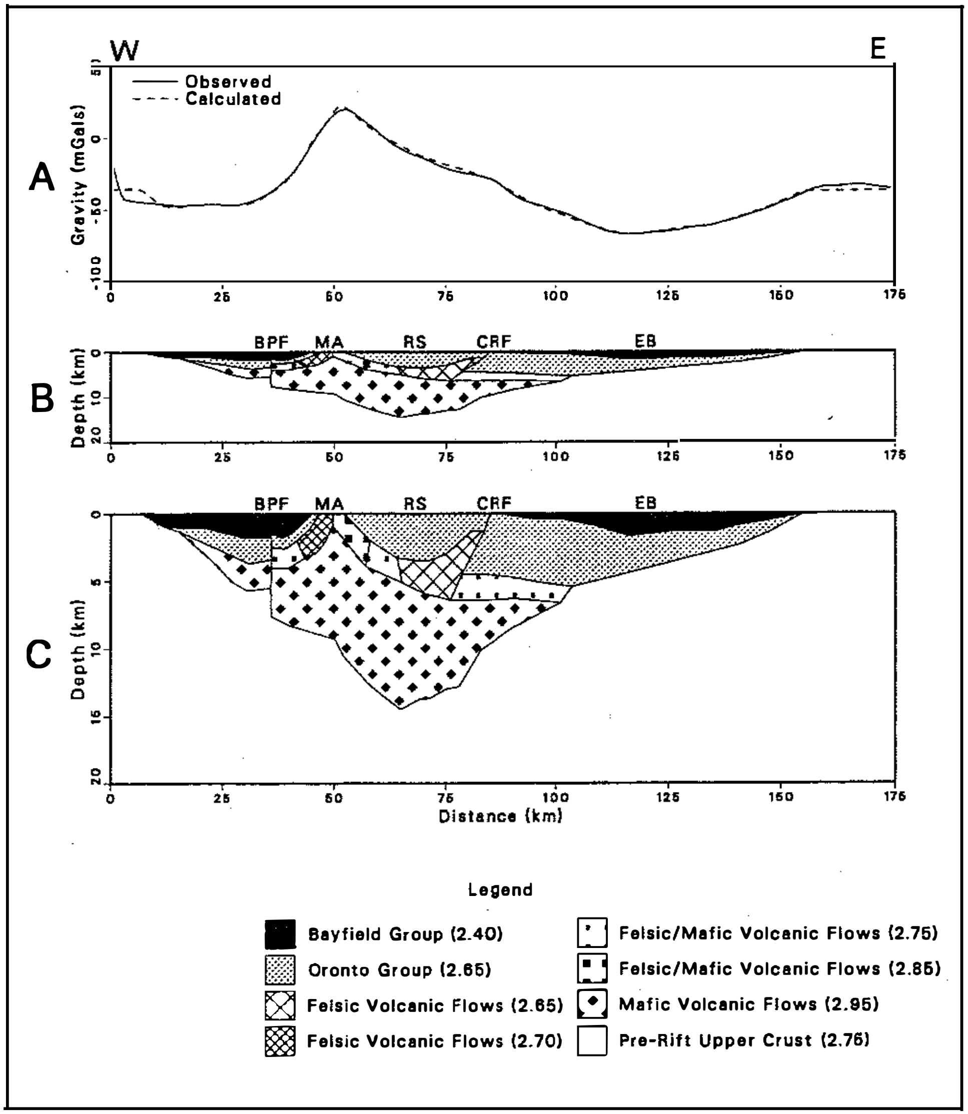


Figure 17. Two-dimensional gravity model of the Midcontinent Rift System along the seismic profile across the southern St. Croix Horst in Minnesota (line f, Fig. 3). A, observed and calculated profiles; B, model, vertical exaggeration 1:1; C, model, vertical exaggeration 3:1. Densities are expressed in g/cm$^3$ = 1,000 kg/m$^3$). BPF, Belle Plaine fault; CRF, Castle Rock fault; MA, Montgomery anticline; RS, Rice syncline; EB, Emerald Basin.

fault apparently thrusts Keweenawan volcanic strata over older Keweenawan and pre-Keweenawan rocks.

Along the western margin of the St. Croix Horst, displacement across the Douglas-Pine fault system increases to the northeast in Minnesota (Fig. 22), but then decreases to the east-northeast in Wisconsin, as required by the termination of the Douglas fault (Fig. 12 and 13). Perhaps, cross structures, such as the Empire fault, Lake Minnetonka fault, Chisago fault, and transition zone between the Hastings and Lake Owen faults (Figs. 19 and 20), developed to accommodate differential uplift between adjacent segments of the St. Croix Horst. Maximum uplift of the horst apparently occurred within its central portion between the Ashland syncline and Twin Cities Basin (Fig. 2 and 22), suggesting that Oronto Group strata may have been deposited and later eroded from this portion of the St. Croix Horst.

The remarkable difference in the magnitude of uplift between the southeastern Minnesota segment of the MRS and the St. Croix Horst (Fig. 22) may be related to the orientation of the rift segments with respect to late-stage compressional stresses. For example, Cannon (1994) interprets that these stresses were oriented southeast-northwest, perpendicular to the St. Croix Horst but nearly parallel to the MRS in southeastern Minnesota, offering a possible explanation for the relatively minor reverse displacement across the Belle Plaine fault.

Figure 22 also indicates interpreted normal faults along the western limb of the MRS. Normal faulting is suggested by an abrupt increase in the thickness of the Keweenawan volcanic sequence, such as in Figures 16 (across the Pine fault) and 17 (across the Belle Plaine fault). The interpreted normal faults often coincide with known reverse faults, suggesting the reverse faults (in many instances) are reactivated normal growth faults.

### *Lower-crustal structure*

Seismic refraction data (Halls, 1982; Hamilton and Mereu, 1993) indicate that the crust is as thick as ~55 km along the axis of the MRS in the Lake Superior region, in contrast to the surrounding craton where it is ~40 km thick. This amount of crustal thickening would be expected to produce a ~50-mGal,

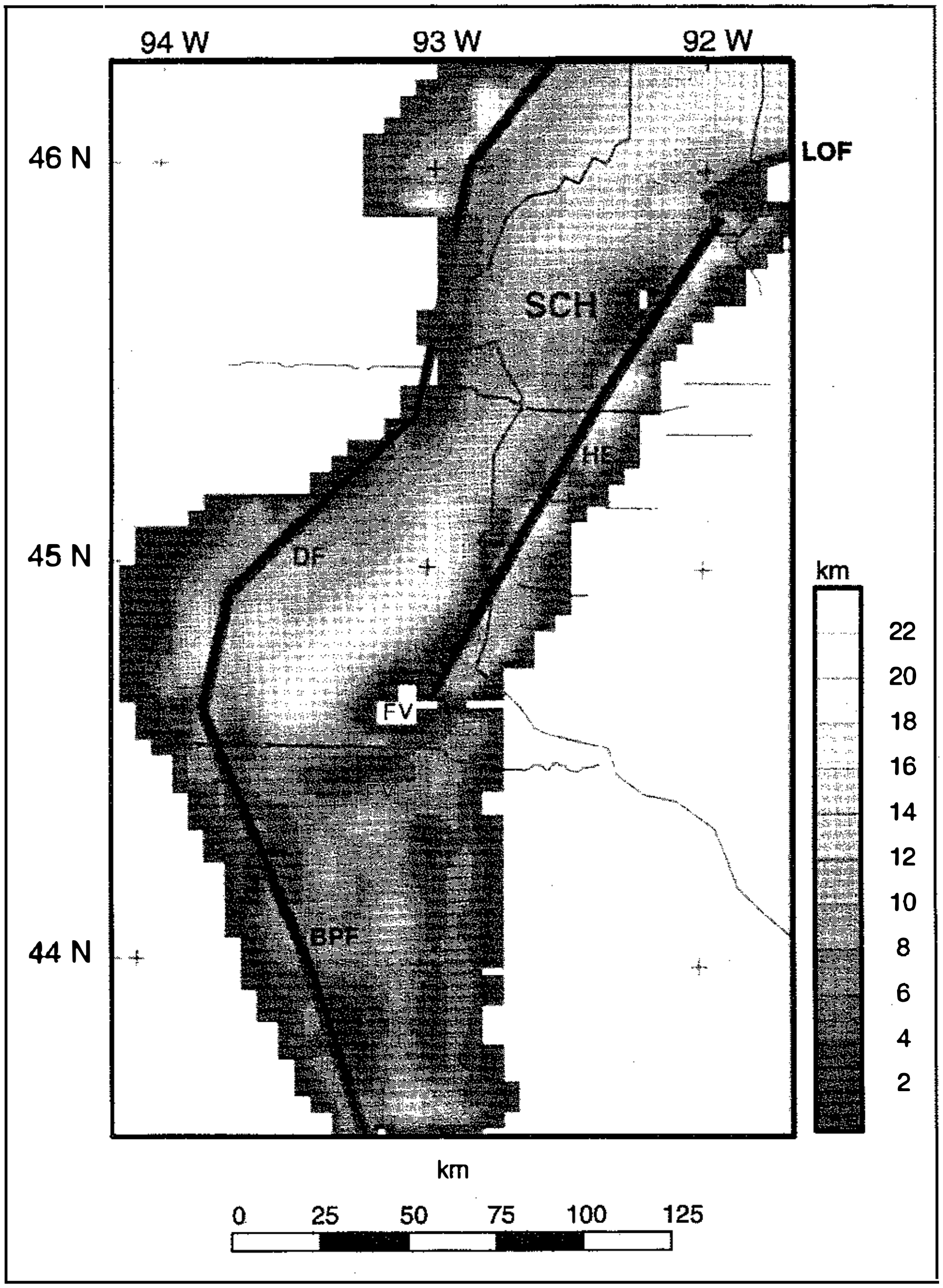


Figure 18. Thickness of Chengwatana Volcanic Group based on three-dimensional gravity modeling. Thin lines indicate seismic reflection profiles. BPF, Belle Plaine fault; DF, Douglas fault; HF, Hastings fault; LOF, Lake Owen fault; SCH, St. Croix Horst; FV, felsic volcanic rocks.

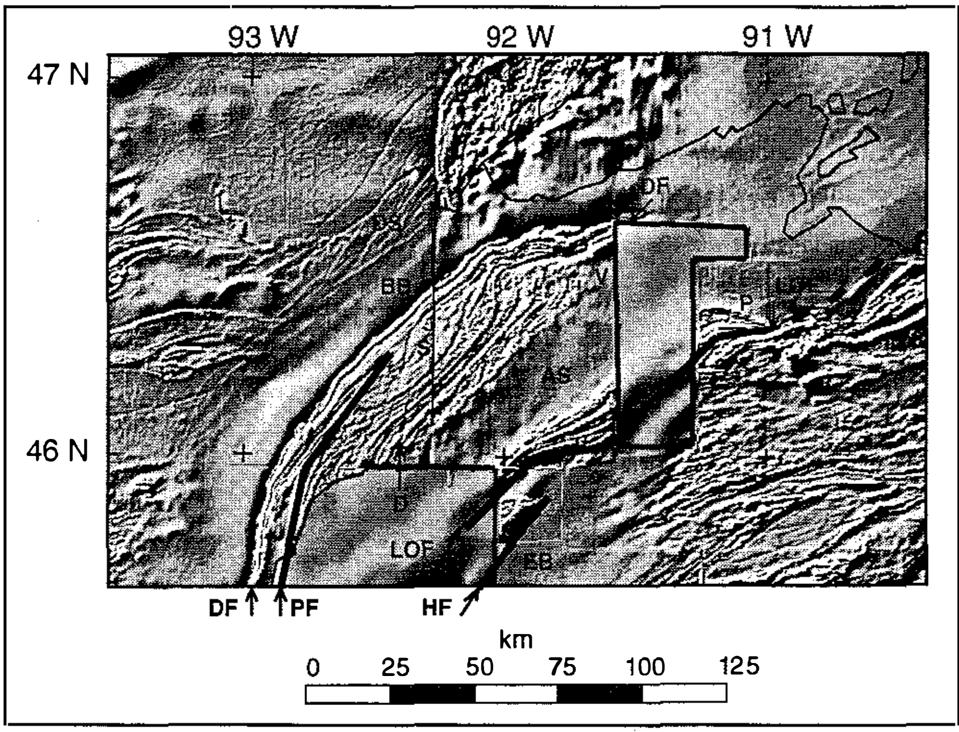


Figure 19. Shaded relief aeromagnetic map, northern St. Croix Horst region. Northwestern illumination. DF, Douglas fault; LOF, Lake Owen fault (dashed line is possible extension of the fault; Cannon et al., 1993); HF, Hastings fault; PF, Pine fault: AS, Ashland syncline; V, abrupt thinning of the outcrop belt of volcanic rocks; BB, Bayfield Basin; EB, Emerald Basin; DS, Keweenawan dike swarm; D, interpreted dike; S, interpreted sill-like intrusion (also shown in Fig. 2); P, pinch-out of volcanic strata. Heavy rectangular lines denote aeromagnetic survey boundaries.

long-wavelength negative gravity anomaly (Allen, 1994). The residual gravity anomaly map (Fig. 14), however, contains no such broad negative anomaly. Moreover, no permutation of (reasonable) model densities for the various Keweenawan units results in a residual regional negative anomaly (Allen, 1994). Consequently, the negative gravitational effect of the thickened crust in western Lake Superior is likely compensated by a positive mass imbalance, probably due to dense lower-crustal intrusions or crustal underplating. This interpretation is consistent with tomographic inversion of seismic refraction data in central Lake Superior (Hamilton and Mereu, 1993), which image a zone of high velocity (and presumably high density) in the lower crust along the rift axis.

To properly compensate the regional negative effect of the thickened crust in western Lake Superior, Allen (1994) suggests (based on gravity modeling) that between 30 to 50% of the Keweenawan rift magma was trapped in the lower crust, while the remaining 50 to 70% was erupted. Estimates for other rifts, however, suggest that extrusive rocks typically compose just 5 to 35% of the mantle-derived igneous rocks (Ramberg, 1976; Mohr, 1983; Crisp, 1984; Ramberg and Morgan, 1984; Shaw, 1985; Neumann et al., 1986; Riciputi and Johnson, 1990). Perhaps the higher proportion of Keweenawan magma that reached the surface is indicative of a more rapid rate of extension of the MRS.

Information concerning the lower-crustal structure of the MRS in Wisconsin and Minnesota is relatively limited. Refraction data, however, indicate ~5 km of crustal thickening along the axis of the St. Croix Horst (Ocola and Meyer, 1973), an interpretation that is consistent with the results of teleseismic tomographic inversion by Green (1991). In addition, Green (1991) detected a zone of high velocity between 28 and 46 km, suggesting that the lower crust may have been intruded by Keweenawan magmas. Hence, the lower-crustal structure of the MRS along its western limb may be similar to that in Lake Superior.

### *Relative ages along the Midcontinent Rift System*

As indicated by magnetic modeling along eight profiles in Minnesota and Wisconsin (Allen, 1994), the Keweenawan volcanic sequence of the St,. Croix Horst and in southeastern Minnesota is predominantly normally polarized. Reversely polarized rocks are either absent or form relatively thin layers along the base of the volcanic basin (e.g., Fig. 23). Consequently, the majority of the Keweenawan igneous sequence along the western limb of the Midcontinent Rift System (MRS) is probably younger than the ca. 1,098 Ma magnetic reversal documented in the Lake Superior region (Paces and Miller, 1993). This interpretation is consistent with the magnetic modeling results of Chandler et al. (1989) in Wisconsin and Minnesota, and Woelk (1989) in Kansas who also interpreted large proportions of normally polarized volcanic rocks.

Northeast of White's ridge, however, magnetic modeling (Allen 1994) indicates that roughly half of the volcanic sequence in western Lake Superior is reversely polarized and probably older than ca. 1,098 Ma. In addition, Mariano and Hinze (1994) discovered that ~80% of the volcanic sequence in eastern Lake Superior is reversely polarized. Consequently, major magmatic pulses did not occur at the same time along the length of the MRS. Instead, major magmatic activity began first in eastern Lake Superior, then in western Lake Superior, and finally along the rift's western limb.

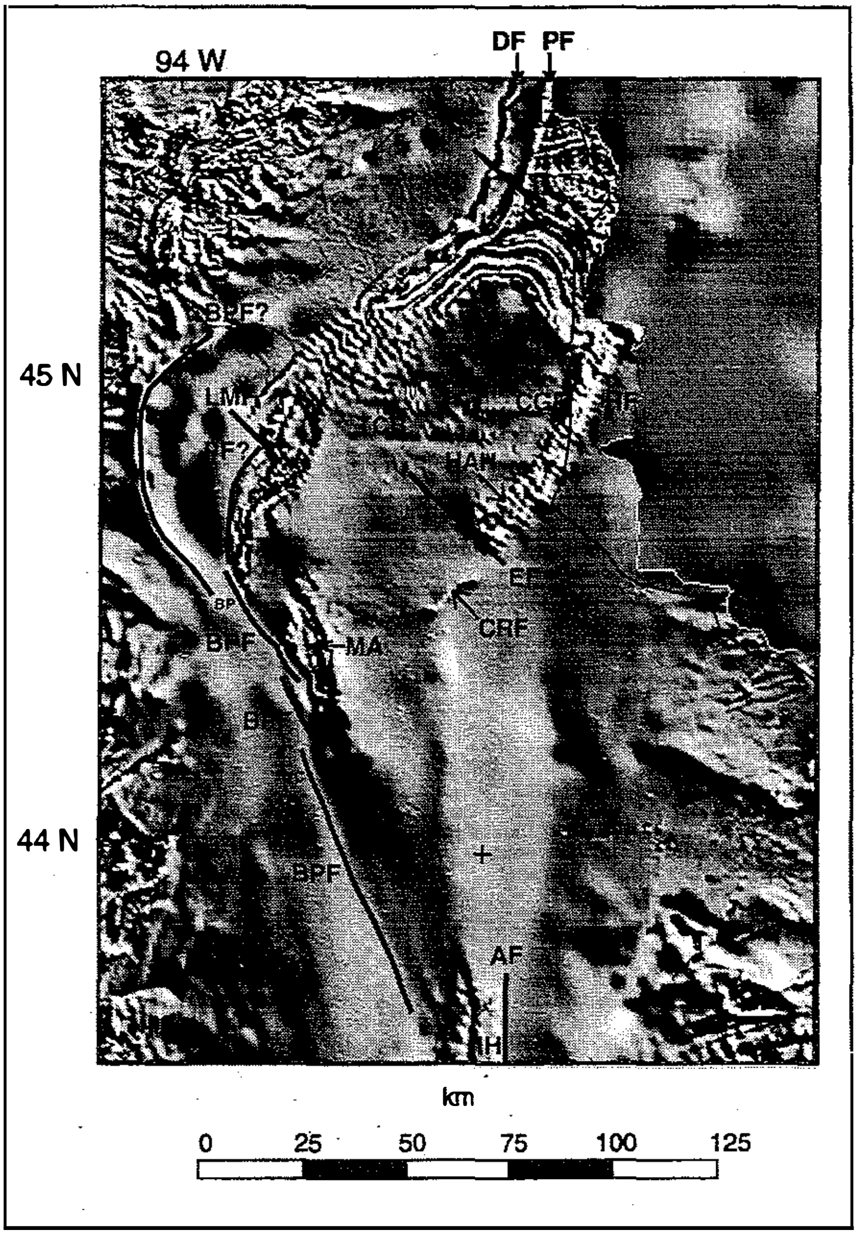


Figure 20. Shaded relief aeromagnetic map, southern St. Croix Horst region. Northeastern illumination. Reverse faults: DF, Douglas fault; PF, Pine fault; HF, Hastings fault; CGF, Cottage Grove fault; CRF, Castle Rock fault; AF, Austin fault. Cross-faults: BPF, Belle Plaine fault; CF, Chisago Fault; LMF, Lake Minnetonka fault; EF, Empire fault. Other structural features: TCB, Twin Cities Basin; MA, Montgomery anticline; IH, Iowa Horst; HAH, Hudson-Afton Horst; R, reversely polarized intrusion. BP, city of Belle Plaine; WC, Waseca County.

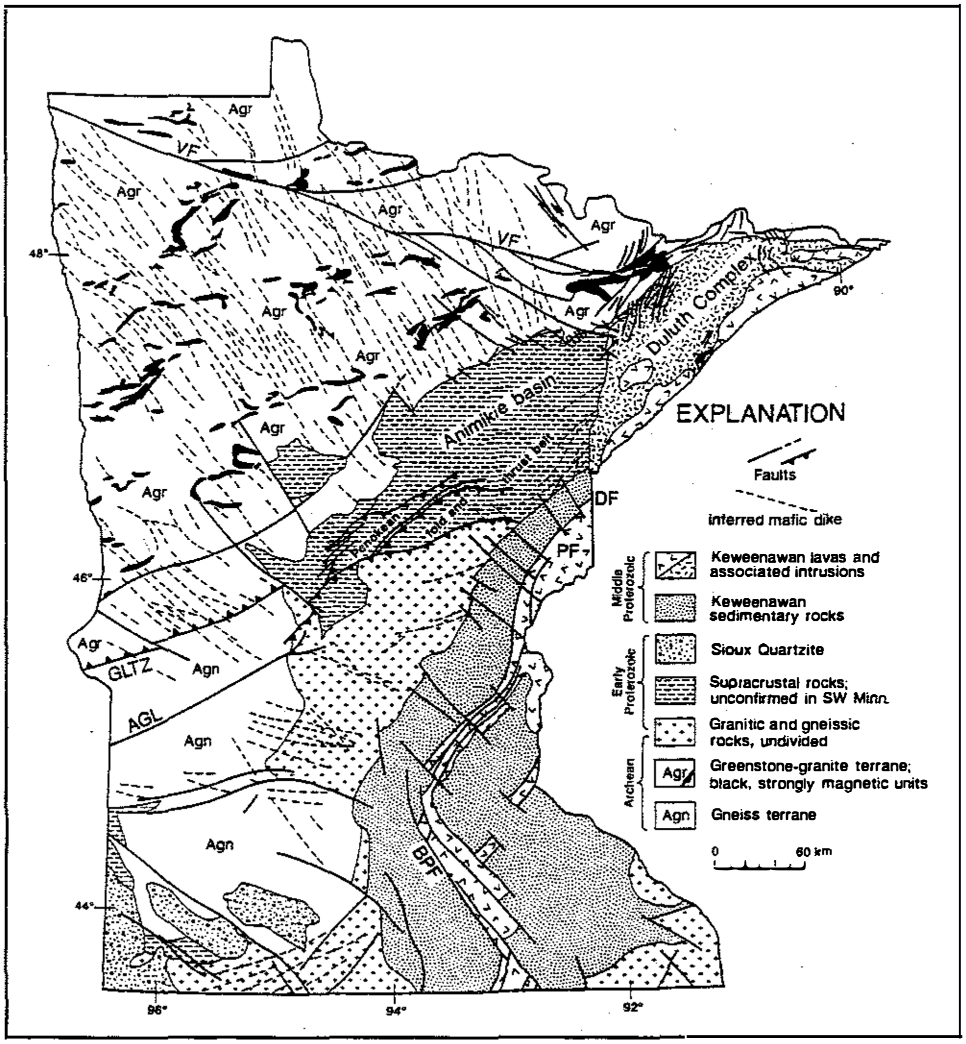


Figure 21. Simplified geologic map of Archean and Proterozoic rocks of Minnesota (from Chandler and Schaap, 1991). BPF, Belle Plaine fault; DF, Douglas fault; PF, Pine fault; VF, Vermillion fault; GLTZ, Great Lakes Tectonic Zone; AGL, Appleton Geophysical Lineament.

The presence of reversely polarized Keweenawan igneous rocks in Kansas (Van Schmus et al., 1990), in Nebraska (Marshall, 1994), and in the lower portions of some magnetic models across the St. Croix Horst (e.g., Fig. 23), however, indicates that at least some magmatic activity occurred in these areas before ca. 1,098 Ma. Hence, magmatism may have been contemporaneous along the length of the MRS, but at any one time occurred at different rates along the various rift segments.

## CONCLUSIONS

Integrated interpretation of geologic and geophysical data, collected mainly for hydrocarbon exploration along the Midcontinent Rift System during the 1980s, has produced a new understanding of the structure, stratigraphy, and evolution of the rift in western Lake Superior, northwestern Wisconsin, and eastern Minnesota. Ancestral features, contained within pre-Keweenawan basement terranes, played influential roles throughout the history of the rift system. Such features are responsible for the remarkable structural and stratigraphic heterogeneity of the MRS in the Superior zone (the greater western Lake Superior region).

The most significant structure identified by this study is an Archean granitic belt extending between and including White's ridge and the Grand Marais ridge. These ridges, acting as local accommodation features, greatly influenced the distribution of rift volcanic and post-volcanic sedimentary rocks in western Lake Superior.

In west-central Wisconsin, seismic reflection and gravity data delineate the geographic extent, depth, and stratigraphy of the asymmetric Emerald Basin, formerly suspected only as a downward continuation of a poorly understood synclinal structure of Paleozoic age.

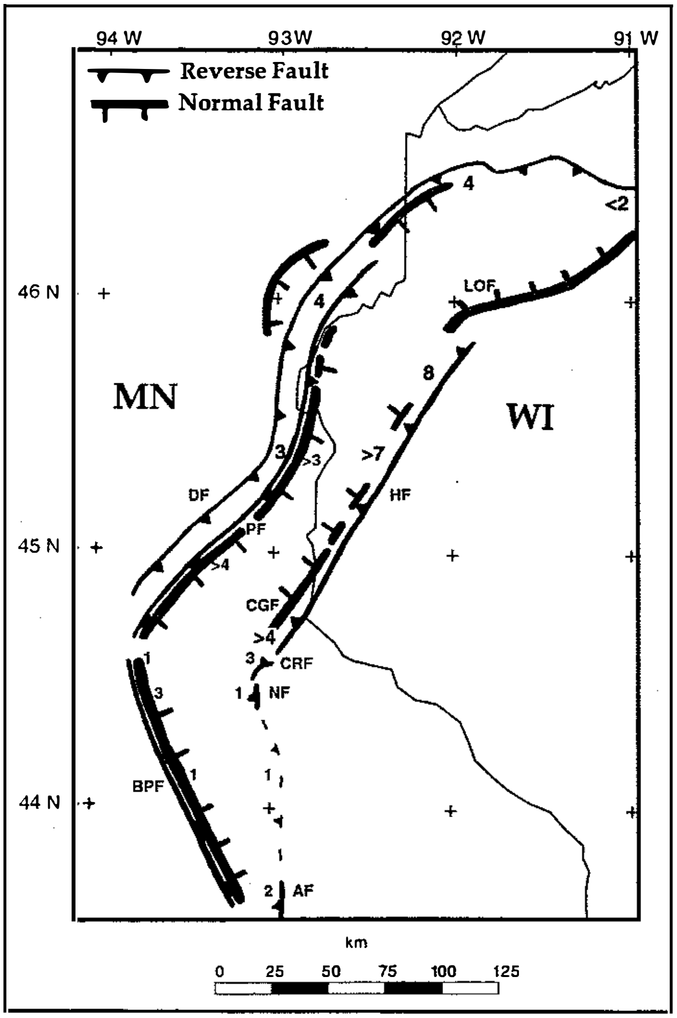


Figure 22. Map of the MRS in eastern Minnesota and northwestern Wisconsin indicating reverse faults (thin barbed lines) and interpreted normal faults (thick hachured lines). BPF, Belle Plaine fault; DF, Douglas fault; PF, Pine fault; AF, Austin fault; NF, Northfield fault; CRF, Castle Rock fault; CGF, Cottage Grove fault; HF, Hastings fault; LOF, Lake Owen fault. Estimates of vertical displacement (km) across the reverse faults are indicated in their appropriate locations on the hanging wall. Dashed line represents an equivocal reverse fault between the AF and NF.

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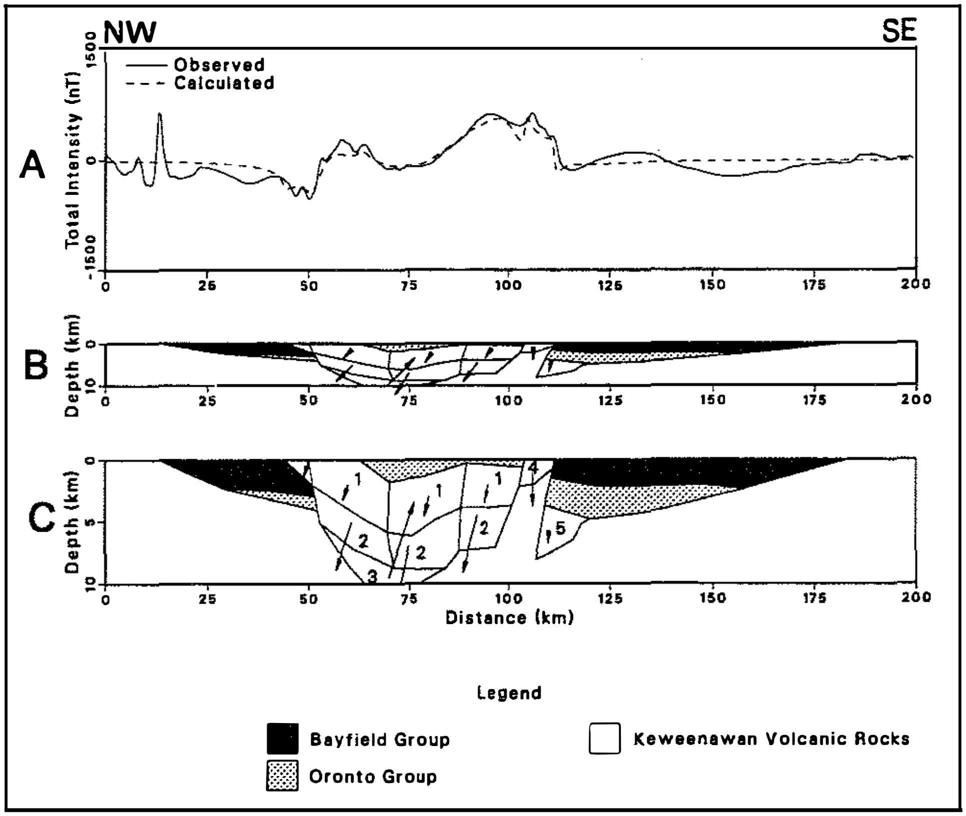


Figure 23. Two-dimensional magnetic model of the Midcontinent Rift System along a profile across the Twin Cities Basin in Minnesota. A, observed and calculated profiles; B, model, vertical exaggeration 1:1; C, model, vertical exaggeration 3:1. Arrows denote direction of total magnetization in the plane of the profile; lengths of arrows are proportional to the magnetization. Magnetic properties [susceptibility (SI)/remanent magnetization (A/m) (direction)/Koenigsberger ratio (Q)]: 1, 0.0075/1.20 (N) /3.4; 2, 0.0239/3.80(N)/3.4; 3, 0.0.591/9.40(R)/3.4; 4, 0.0754/1.50(R)/ 0.4; 5, 0.0126/0.00/0.0. N, normal polarization; R, reversed polarization.


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# Chapter 5. Exploration for hydrocarbon along the Midcontinent Rift System trend of Wisconsin and the Lake Superior Basin: 1983–92

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## Abstract

*In the autumn of 1983, oil and gas exploration was publicly undertaken within the Proterozoic terrane of northwestern and western Wisconsin. The initial stage of exploration began with land-leasing activities, and was followed, beginning in the summer of 1984, by the arrival of field reflection seismology, gravity, and magnetic crews operating on land and offshore Lake Superior. The target of this evaluation was the Keweenawan Supergroup, a sequence of volcanic and clastic rocks forming the Midcontinent Rift System. This intracontinental structure is a major tectonic feature known, by field mapping, study of subsurface samples, and interpretation of geophysical anomalies, to extend from Kansas to Ohio by way of the Lake Superior Basin.*

*Over the 1983–92 period covered by this report, approximately three-quarters of a million acres was taken under lease by the oil and gas industry in northern and western Wisconsin. Also during this time period, at least 2,671 mi of reflection seismic profiles was collected and recorded in Wisconsin and adjacent offshore waters of Lake Superior. In some programs, gravity and magnetic data were obtained concomitant with the seismic data.*

*In May 1985 Amoco Production Company (USA) made public its interest in drilling a wildcat borehole in Bayfield County, Wisconsin. Soon after, as a result of the sharp decline of the domestic price of crude oil during the first half of the 1980s, followed by the beginning of an industry-wide recession, this exploration program was placed on suspended status by Amoco. In spite of economic decline and the initial lack in Wisconsin of legislation protecting state interests against environmental hazards potentially associated with deep drilling, the most active company (Amoco Production Company) maintained its corporate and lease interest in Wisconsin, while other corporate interests faded.*

*In October 1990, with improvement in hydrocarbon economics and passage of enabling oil and gas exploration legislation, Terra Energy, Ltd., of Traverse City, Michigan, announced its decision to drill a wildcat borehole in Bayfield County. Following a 17-month period of extensive state environmental review and several capacity-crowd public hearings, Terra Energy was granted an oil and gas drilling permit. On March 9, 1992, eight and one-half years after Wisconsin was targeted as an hydrocarbon exploration frontier, the Terra–Patrick #7-22 borehole was spudded, under a farm-out agreement with Amoco Production Company (USA).*

*With the drilling of this well, an unprecedented period of environmental, geologic, and geophysical data collection, assimilation, and review of the Precambrian rocks forming the Midcontinent Rift structure of northern and western Wisconsin came to a (temporary?) conclusion.*

## Introduction

Since 1865 sporadic attempts have been made in the hope of discovering economic volumes of oil and gas in Wisconsin. Exploratory boreholes were concentrated within the Phanerozoic belt of strata that cover the west-central, southern, and southeastern part of the state. These "wildcat" tests were drilled by small organizations and all were unsuccessful. In 1983 land-lease agents, represent-

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ing oil and gas corporations that had undertaken an economic evaluation of the hydrocarbon potential of the stratigraphic column of the Midcontinent Rift System, entered Wisconsin. The target of their exploration was the sedimentary strata of the Oronto and Bayfield Group, a part of the Proterozoic Keweenawan Supergroup. This supergroup overlies the Precambrian crystalline basement of Wisconsin from Pierce County north to Douglas County, and east through Iron County into the Upper Peninsula of Michigan.

An unexplored and ancient geologic frontier had been opened by the American hydrocarbon industry, and Wisconsin was in the forefront of this exploration activity. This report documents the ten-year (1983–92) phase of evaluation that preceded the drilling of the Terra–Patrick #7-22 borehole in Bayfield County in March 1992. The chronology of actual drilling of the Terra–Patrick borehole is presented in chapter 6 of this volume.

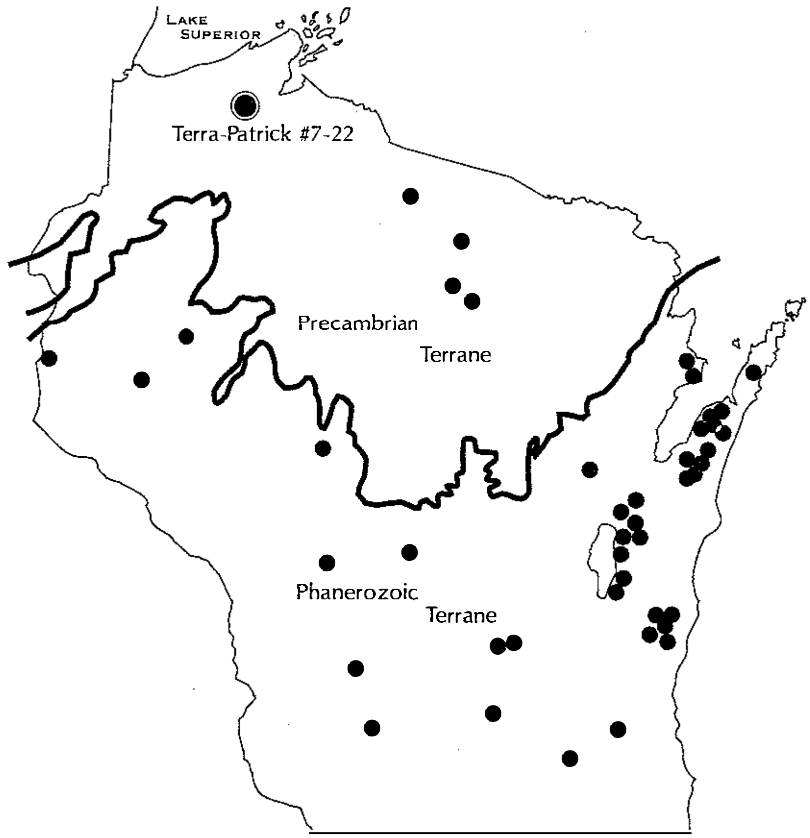


**Figure 1.** *Distribution of exploratory wells drilled in the search for oil and gas in the state of Wisconsin since 1865 (Peters, 1985).*

## Exploration before 1983

Prior to the 1983 public disclosure of industrial interest in the hydrocarbon potential of the Midcontinent Rift System, the exploration for oil and gas in Wisconsin was conducted by operating companies characterized by limited resources and the complete absence of success. Six years after "Colonel" E.L. Drake initiated the hydrocarbon industry in the United States by discovering oil in northwest Pennsylvania, the first known Wisconsin exploratory borehole was sited in Jefferson County in 1865 by the Palmyra Petroleum Corporation (Peters, 1985). This test bottomed at 750 ft in Cambrian strata and reported "no oil." From that inauspicious beginning and continuing through 1991, 48 additional attempts in the state resulted in a similar "dry and abandoned" status.

According to Peters (1985), these drilling programs ranged from the entrepreneurial (the "Ernie T. Company") and the spiritual (a 1923 test "located by a dream") to multiple well efforts organized by corporations whose letterheads read Texas–Wisconsin Exploration, Mission Hills Oil, and Cambria Oil and Lead. As conventional exploration philosophy would suggest, the most of these boreholes (93%) were located in the Phanerozoic sedimentary rock belt of central and southern Wisconsin (fig. 1). Of these, a 1949 test in Sheboygan County established the early state drilling-depth record of 4,405 ft. The remaining four boreholes (7%) were drilled in the Precambrian igneous and metamorphic regions of Langlade, Lincoln, Oneida, and Vilas Counties. The sketchy stratigraphic-column record left by the Northern Gas and Oil Company in Langlade County is typical of these latter efforts: glacial sediments to 236 ft and then schist to a total depth of 1,220 ft (Peters, 1985).

During these first 121 years of unorganized exploration in Wisconsin, the oil and gas industry recorded no interest in the Precambrian Keweenawan sedimentary rock trend exposed along the southwestern shoreline of Lake Superior. Contrary to reports, published as early as the 1860s, of oil seeps in the Upper Peninsula of Michigan (Dickas, 1991), bias established in the early and middle twentieth century regarding the supposed lack of porosity, permeability, and fossil evidence in rocks predating 570 Ma maintained the dictum that Precambrian rocks could not be associated with indigenous hydrocarbons.

With the discovery in 1962 of Precambrian source and economic reservoir beds in the Lena–Tunguska Province of the former Soviet Union (Meyerhoff, 1980), the publication of numerous papers in the 1960s and 1970s describing Precambrian life as old as 3.5 Ga (Glaessner, 1961; Schopf, 1968; Dunlop and others, 1978), and the developing recognition of the world-wide significance of extension (rift) structures as hydrocarbon source and trap mechanisms (Klemme, 1980), the aforementioned bias was gradually transformed into new exploration philosophies. By the early 1980s these attitude changes had been instrumental in the initiation of a new era of petroleum exploration along the Midcontinent Rift System trend of Wisconsin.

## Land-leasing activities

The first oil and gas exploration leases obtained within the Midcontinent Rift trend in Wisconsin were signed on behalf of Amoco Production Company (USA) (Houston, Texas), during the final week of October 1983. By the end of that year Amoco had leased exclusive drilling rights to 24,002 acres in Ashland, Bayfield, and Iron Counties (table 1).

During 1984 Amoco increased its land position five-fold; H and H Star Energy, Inc. (Traverse City, Michigan), Texaco USA (Denver, Colorado), Chevron Corporation (San Francisco, California), Hunt Oil (Dallas, Texas), and Beard Oil (Oklahoma City, Oklahoma) also built Wisconsin lease packages, expanding the Midcontinent Rift play into Burnett, Douglas, Pierce, Polk, Sawyer, St. Croix, and Washburn Counties. By the end of 1984, total lease holdings exceeded 220,000 acres.

In 1985, the year of peak oil and gas leasing activity in Wisconsin, Conquest Exploration (Denver, Colorado) and T.O. Higgins (Bowling Green, Kentucky) initiated activity in Burnett and six adjacent counties. All previously active companies, with the exception of the Chevron Corporation, strengthened their positions, bringing the total area under lease in 11 counties to 717,402 acres.

The national decline of crude oil values, from a five-year high of $35 per barrel in 1981 to approximately $10 per barrel in 1986, caused several companies to reassess their Wisconsin holdings. In 1986, Conquest Exploration chose not to renew leases held with the Federal Land Bank of St. Paul in Ashland, Burnett, Douglas, Pierce, Sawyer, and St. Croix Counties; in 1987 H and H Star Energy dropped 800 acres in Burnett County. Opposing this trend, Amoco Production Company (USA) won U.S. Forest Service approval to lease additional acreage in the Chequamegan National Forest. As a result of these actions, the total area under hydrocarbon exploration lease in Wisconsin on the last day of 1987 was 718,032 acres (table 1).

Throughout the period of 1983–87, a typical lease agreement paid $1 per acre per year, with a ten-year renewal option. In a few instances leases were acquired at $0.50 per acre. A minimum of signing bonuses was reported. In all known cases the industry standard of a 12.5 percent royalty was offered.

During the period 1988–91, no additional oil and gas lease acquisitions occurred along the Midcontinent Rift trend of Wisconsin. The total area under lease declined to the 400,000 acre range (T.J. Evans, Wisconsin Geological and Natural History Survey, verbal communication, 1992). This decline is attributed to the withdrawal by Texaco from the rift play in Wisconsin and to the decision by H and H Star Energy to drop approximately 290,000 acres of county forest-land leases in Douglas County. This large block of land was then advertised for lease by the Douglas County Board of Supervisors in late 1989. In response, bids were received from Three Bears Oil and Gas Inc. (a north-

**Table 1.** *Oil and gas leasing chronology and acreage distribution along the Midcontinent Rift trend of northern and western Wisconsin over the period 1983–87. Headings are given by oil and gas exploration company along with their representing lease agency (or agencies) in parentheses. No known new lease positions were established by any listed company after 1987. All data are in acres. Sources: Harkin (1984, 1985, 1986, and 1988); Evans (1986; verbal communication): U.S. Forest Service, Chequamegan National Forest (verbal communication, 1987). Discrepancies between this and Harkin (1988) are due to inclusion of U.S. Forest Service data in this report; Harkin (1988) totals were derived entirely from county records of deeds.*

| Year/ County | Amoco (Perkins) | H&H Star (Benchmark) | Texaco (Neece) | Chevron (Meany and Johnson) | Conquest | Higgins | Hunt | Beard | Total |
|---|---|---|---|---|---|---|---|---|---|
| **1983** | | | | | | | | | |
| Ashland | 4,295 | | | | | | | | **4,295** |
| Bayfield | 19,589 | | | | | | | | **19,589** |
| Iron | 118 | | | | | | | | **118** |
| **Subtotal** | 24,002 | | | | | | | | **24,002** |
| **1984** | | | | | | | | | |
| Ashland | 24,096 | 6,954 | 1,196 | | | | | 740 | **32,986** |
| Bayfield | 76,790 | 6,798 | 14,533 | | | | | | **98,121** |
| Burnett | | 4,270 | | | | | 1,841 | | **6,111** |
| Douglas | | 3,607 | 7,433 | | | | | | **11,040** |
| Iron | 727 | 1,540 | | | | | | | **2,267** |
| Pierce | | 662 | 4,169 | 22,455 | | | | | **27,286** |
| Polk | | 4,855 | | | | | 1,169 | 2,161 | **8,185** |
| Sawyer | | 5,959 | | | | | | | **5,959** |
| St. Croix | | | 2,215 | | | | | | **2,215** |
| Washburn | | 2,218 | | | | | | | **2,218** |
| **Subtotal** | 101,613 | 36,863 | 29,546 | 22,455 | | | 3,010 | 2,901 | **196,388** |
| **1985** | | | | | | | | | |
| Ashland | | | | | 1,243 | | | | **1,243** |
| Barron | | | | | | | | | **0** |
| Bayfield | 20,526 | 2,427 | 130 | | | | 3,696 | | **26,779** |
| Burnett | | 118,180 | | | 6,107 | 601 | | 4,021 | **128,909** |
| Douglas | 1,397 | 286,473 | | | 4,448 | | | | **292,318** |
| Pierce | | 400 | | | 4,706 | | | | **5,106** |
| Polk | | 2,058 | | | 14,601 | | | | **16,659** |
| Sawyer | | | | | 1,320 | | | | **1,320** |
| St. Croix | | | | | 18,110 | | | | **18,110** |
| Washburn | | | | | 6,568 | | | | **6,568** |
| **Subtotal** | 21,923 | 409,538 | 130 | | 57,103 | 601 | 3,696 | 4,021 | **497,012** |
| **1986** | | | | | | | | | |
| Ashland | 934 | | | | (1,243) | | | | **(309)** |
| Bayfield | 18,401 | | | | | | | | **18,401** |
| Burnett | | | | | (6,107) | | | | **(6,107)** |
| Douglas | | | | | (4,448) | | | | **(4,448)** |
| Pierce | | | | | (4,706) | | | | **(4,706)** |
| Sawyer | | | | | (1,320) | | | | **(1,320)** |
| St. Croix | | | | | (18,110) | | | | **(18,110)** |
| **Subtotal** | 19,335 | | | | (35,934) | | | | **(16,599)** |
| **1987** | | | | | | | | | |
| Bayfield | 18,029 | | | | | | | | **18,029** |
| Burnett | | (800)* | | | | | | | **(800)** |
| **Subtotal** | 18,029 | (800) | | | | | | | **17,229** |
| **Total** | **184,902** | **445,601** | **29,676** | **22,455** | **21,169** | **601** | **6,706** | **6,922** | **718,032** |

* Data in parentheses are non-retained acreage.

ern Wisconsin independent operator) and the Gas Energy Corporation (Cincinnati, Ohio). Both were rejected as unacceptably low. With this action, the leasing history of Wisconsin lands for oil and gas exploration in central and northern Wisconsin during the 1980s came to an end.

In retrospect, this chronology of events developed in a subdued manner, in contrast to often frenzied activities historically associated with exploration in United States frontier provinces. On more than one occasion county boards were stymied in their attempts in encouraging a bidding competition, and landowners hoping to "bid-up" their acreage value were disappointed. This noncompetitive atmosphere is largely explained by the association of this rift-leasing program with potential source and reservoir rocks of red-bed lithology and Proterozoic age—high-risk characteristics that have historically discouraged exploratory initiatives.

## CORPORATION INVOLVEMENT

By any economic measure, such as annual exploration budget or total assets, the eight petroleum exploration or leasing corporations that had entered the state by 1985 can be separated into two classifications. The "major" category was composed of Amoco Production Company (USA), Texaco USA, and the Chevron Corporation. The remaining five organizations constitute a "non-major" grouping.

Because the Midcontinent Rift trend in Wisconsin had never been geographically overstamped by earlier oil and gas leasing activities, certain exploration approaches might be deduced by comparing geographic lease patterns acquired in the 1980s to rift geology. A simplified map of Midcontinent Rift geology of those Wisconsin counties involved in the rift lease play is presented in figure 2. Figures 3, 4, 5, and 6 display geographic lease patterns as established by the major and non-major operators or their lease agents. Conclusions based on a comparison of these lease patterns with geology are as follows:

- Amoco Production Company (USA) (Houston, Texas), the first company to enter the Wisconsin Midcontinent Rift System play, did so after thoroughly reviewing regional Proterozoic geology and after identifying specific drilling targets. Their lease pattern (figs. 3 and 4) centered on the Bayfield County Gravity Low (H, fig. 2; Hinze and others, 1982) and that adjacent part of the Ashland Syncline (F, fig. 2) known to be underlain by Proterozoic aged hydrocarbon source beds (Daniels, 1982). Of the three geologic interpretations regarding the Bayfield Gravity Low available in the mid-1980s (White, 1966), the model suggesting an abnormally thick column of Upper Keweenawan sedimentary rock (Thiel, 1956) appeared to place the Amoco lease pattern in a favorable position. (For an updated interpretation of the Bayfield County Gravity Low, based upon seismic and geopotential computer analysis, see Allen and others, ch. 4, this volume). By the end of 1987 Amoco controlled approximately 185,000 acres, 26 percent of all Midcontinent Rift System acreage in Wisconsin (table 1). Amoco Production Company (USA) continued to be the lead company in the search for hydrocarbon in Wisconsin.
- H and H Star Energy, Inc. (Traverse City, Michigan), after several years of intense activity, became the largest lease holder in the state. Their 445,601-acre package, obtained through the Benchmark Resources Corporation of Evansville, Indiana, was distributed over a nine-county region (table 1; fig. 5). Because 91 percent of these holdings were located in Douglas and Burnett Counties (in the form of two county forest-land contracts) and because these holdings were more closely associated with Proterozoic volcanic rock and not potential hydrocarbon source or reservoir strata, it became apparent H and H Star obtained leases for speculative rather than geologic rationale. This acreage package was significantly reduced when the Douglas County forest-land contract was dropped in 1988.
- Texaco USA (Denver, Colorado), on its behalf (fig. 3) and through an agent, Buel Neece of Sperry, Oklahoma (fig. 4), established a five-county lease position, with majority holdings in Bayfield and Douglas Counties (table 1).

These latter holdings were positioned mainly in the Bayfield Basin (C, fig. 2) of northern Bayfield and Douglas Counties, off the west flank of the Bayfield County Gravity Low (H, fig. 2). Communication with personnel of the U.S. Forest Service in 1985 suggested Texaco identified a similar area of geologic interest within the forest lands of Douglas and Bayfield Counties as had Amoco, but entered the Lake Superior district too late to establish an opportune position. Additional acreage was signed in the Emerald basin (D, fig. 2), St. Croix and Pierce Counties, Wisconsin.

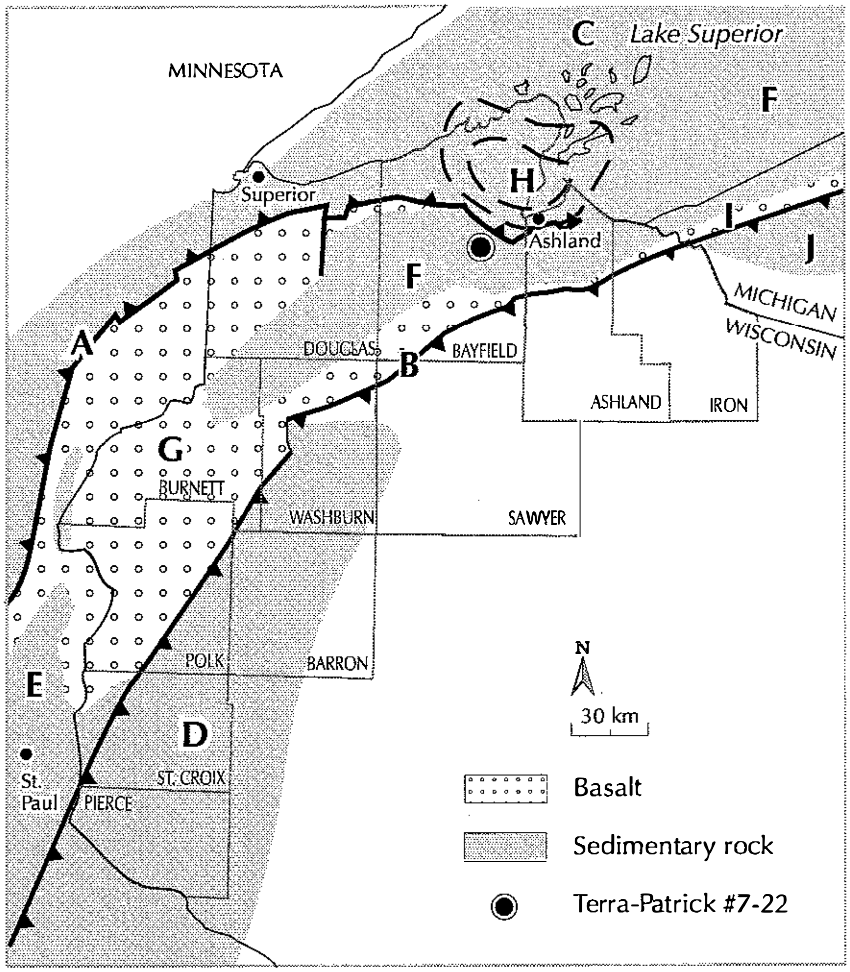


**Figure 2.** *Principal geologic structure and related elements associated with the Midcontinent Rift System in northwestern Wisconsin and adjacent waters of Lake Superior. A: Douglas Fault; B: Lake Owen Fault; C: Bayfield Basin; D: Emerald Basin; E: Minneapolis (Twin City) Basin; F: Ashland Syncline; G: St. Croix Horst; H: Bayfield Gravity Low; I: oil seeps (White Pine Copper mine); J: Jacobsville Basin.*

- Chevron Corporation (San Francisco, California), through its leasing agent Meany and Johnson, obtained 22,455 acres in 1984 in Pierce County (fig. 3). Although geographically concentrated, this small lease package did not represent a major commitment on the part of this principal domestic exploration company to the Midcontinent Rift System trend of Wisconsin.

- Conquest Exploration (Denver, Colorado) entered Wisconsin in 1985 and soon controlled a modified checkerboard pattern of 57,103 acres distributed over an eight-county region extending from Pierce County northeast to Ashland County (fig. 6). This non-concentrated spatial pattern, and the low profile this company maintained in the state during lease acquisition, would suggest these holdings were gathered primarily for purposes of speculation. It is known (Geosource Inc. [later Halliburton Geophysical Services, Inc., Houston, Texas], written communication, 1987), that Conquest undertook basic geophysical evaluation of the Midcontinent Rift structure of Wisconsin. In 1986 Conquest dropped its leases with the Federal Land Bank of St. Paul in six counties, but retained those in Polk and Washburn Counties (Harkin, 1988).

- The T.O. Higgins organization (Bowling

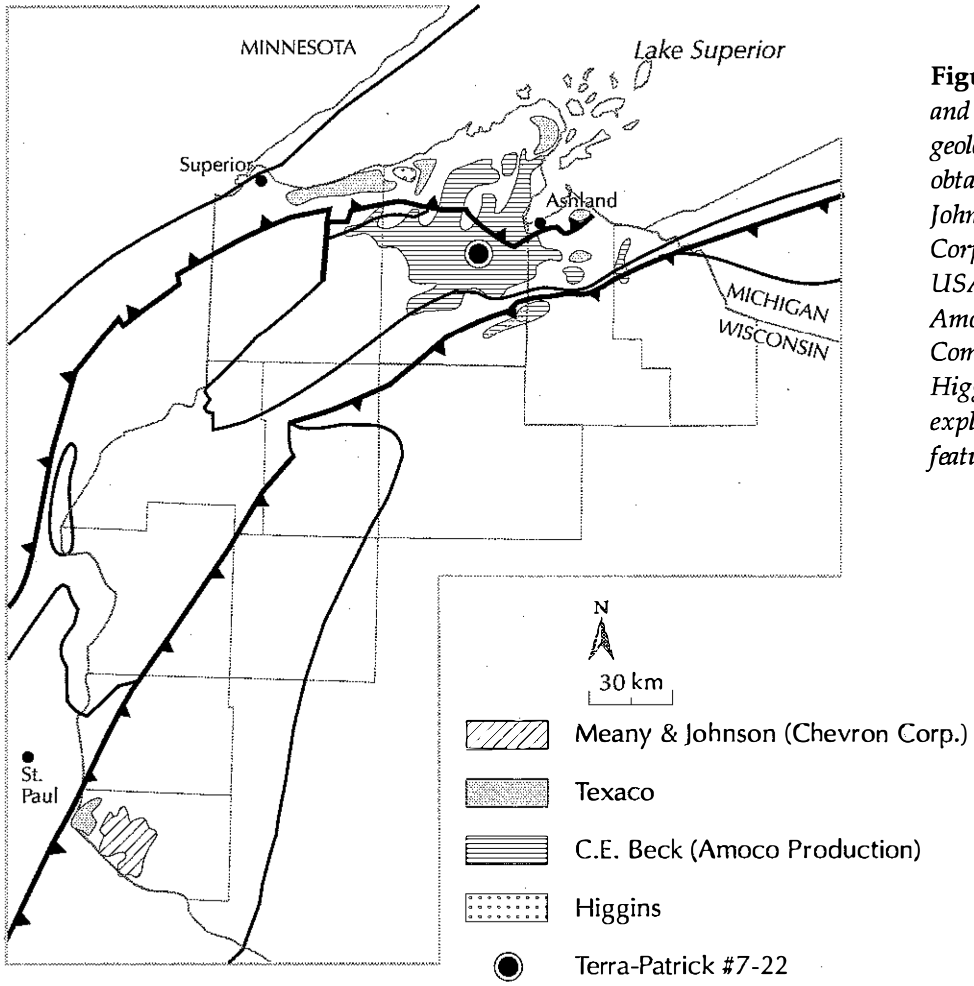


**Figure 3.** *Distribution and spatial relationship to geologic structure of leases obtained by Meany and Johnson (for Chevron Corporation), Texaco USA, C.E. Beck (for Amoco Production Company USA), and T.O. Higgins. See figure 2 for explanation of structural features.*

Green, Kentucky), Beard Oil Company (Oklahoma City, Oklahoma), and Hunt Oil Company (Dallas, Texas) jointly held less than 3 percent of Wisconsin acreage leased through 1987. Because of these small land positions and their distribution over a five-county region (figs. 3 and 4), none of these companies are considered to have entered the Midcontinent Rift play in Wisconsin with serious exploration intent.

A composite of the geographic distribution of individual corporate leasing patterns in Wisconsin, as presented in figures 3, 4, 5, and 6, was developed. It is interesting to relate this composite pattern to regional geology of the Midcontinent Rift (fig. 7).

The southern half of figure 7 is marked by a sporadic leasing pattern and can be divided by the northeast-striking Hastings Fault. Those leases that lie west of this fault in St. Croix, Polk, and Burnett Counties were apparently obtained with minimal geologic consideration because they are situated over that part of the central St. Croix Horst of the Midcontinent Rift composed principally of layered basalts. West of the Hastings Fault, leasing was largely confined within the boundary of the newly identified Emerald Basin (see Allen and others, ch. 4, this volume, for new information regarding the geology of this rift-flanking basin).

North of the Lake Owen Fault, the structure that forms the southern boundary of the St. Croix Horst (and the Midcontinent Rift System) in northern Washburn, Douglas, Bayfield, Ashland, and Iron Counties, the leasing pattern is more pervasive and is equally distributed between the central Ashland Syncline and the northern flanking Bayfield Basin. Within the Ashland Syncline, the

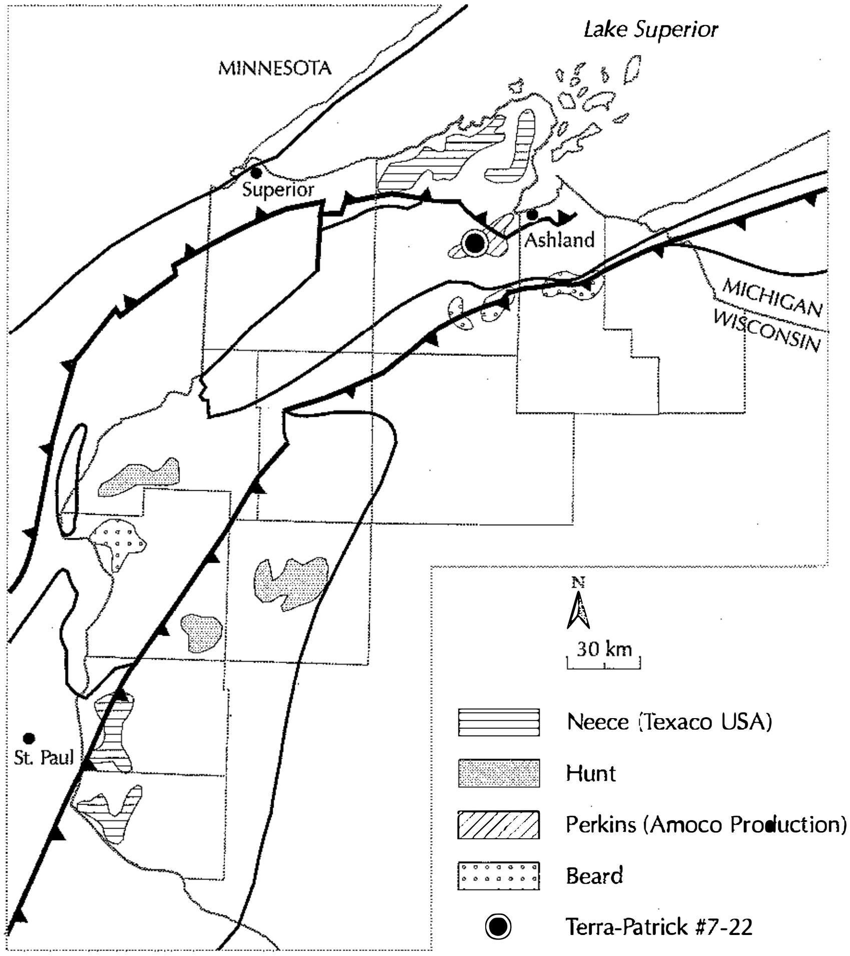


**Figure 4.** *Distribution and spatial relationship to geologic structure of leases obtained by B. Neece (for Texaco USA), Hunt Oil Company, David L. Perkins (for Amoco Production Company USA), and Beard Oil Company. See figure 2 for explanation of structural features.*

heaviest concentration of leasing occurred in central Bayfield County, the location of the Terra–Patrick #7-22 wildcat borehole. Most leases within western Douglas County overlie layered basalt rocks.

A review of figure 7 suggests that all leasing parties, with the exception of those operating in Sawyer County (see figs. 5 and 6), were aware of the geologic boundaries of the Midcontinent Rift System. Specifics regarding this geology, however, were not universally known, as evidenced by the large number of leases obtained within layered basalt terranes forming the St. Croix Horst of Wisconsin.

## Geophysical exploration in Wisconsin

The most intensely studied and best known segment of the Midcontinent Rift System is that region of maximum rift-trend curvature that centers on the Lake Superior Basin (see Dickas and Mudrey, ch. 3, this volume). Because this segment is lacking a post-rift Phanerozoic sedimentary rock cover, it has long been the target of geological field investigations. Two early offshore Lake Superior studies merit mention. During the 1963 Lake Superior Experiment, the deep crust and upper mantle were studied using seismic refraction data (Steinhart, 1964; Berry and West, 1966; Smith and others, 1966; Steinhart and Smith, 1966a; O'Brien, 1968; Ocola and Meyer, 1973). Three years later, Project Early Rise added to the understanding of the deep structure of the basin (Mereu and Hunter, 1969; Iyer and others, 1969). Onshore, Mooney and others (1970) studied the Midcontinent Rift System of northern Wisconsin and eastern Minnesota after collecting 87 short refraction profiles.

Results of magnetic and gravity field surveys, conducted as a secondary objective of the Lake Superior Experiment, were reported in a review of subcontinental geology edited by Steinhart and Smith (1966b). In subsequent years a series of maps depicting Lake Superior gravity and magnetics was published by Wold and Berkson (1977), Klasner and others (1979), and O'Hara (1981). The state of geologic and geophysical knowledge of the Lake Superior Basin immediately prior to the initiation of hydrocarbon exploration programs in the early 1980s was comprehensively reviewed by Wold and Hinze (1982).

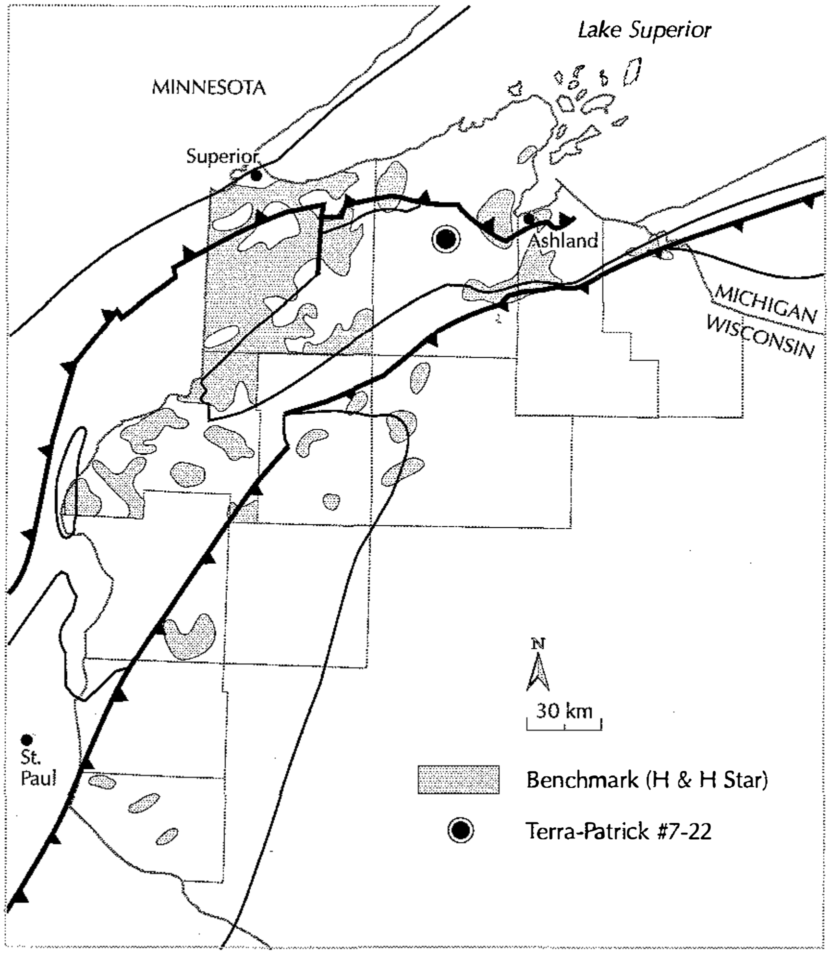


**Figure 5.** *Distribution and relationship to geologic structure of leases obtained by Benchmark Resources Corporation for H and H Star Energy, Inc. See figure 2 for explanation of structural features.*

During the 1960s and 1970s, studies in the Lake Superior district were of a regional nature and focused upon general geologic problems rather than evaluation of economic potential. This emphasis altered abruptly in the early summer of 1984 with the appearance in Bayfield County of seismic reflection crews under contract to Texaco USA and Amoco Production Company (USA) (table 2).

Grant Geophysical Computing Corporation (later Grant Geophysical Inc., Houston, Texas) crews, under assignment to Texaco USA, was the first contractor to appear in Wisconsin. During the summer of 1984, 18 vibration reflection profiles, totaling 261 mi, were collected by Grant in St. Croix, Polk, Barron, Washburn, Douglas, Bayfield, and Ashland Counties (fig. 8). One additional line of unknown length was collected in Michigan in Ontonagon and Houghton Counties. These were the first seismic reflection profiles ever collected within the Midcontinent Rift structure of Wisconsin.

Operating during the same time and often within a few miles of Grant Geophysical Computing Corporation crews, a Seismograph Service Corporation (SSC) unit gathered reflection data under contract to Amoco Production Company (USA). These operations, employing a four-vehicle vibration crew, were conducted in Iron, Ashland, and Bayfield Counties, with principal concentration in Bayfield County (fig. 9). In 1987 Amoco returned to the Lake Superior district by contracting with Grant Norpac (later Grant Geophysical Inc., Houston, Texas) to assemble a 31-mi profile near Munising, Michigan, and collect an additional 12.5 mi in the heart of their lease holdings in Bayfield County. Apparently encouraged by the analyses of these efforts, Amoco again contracted with SSC in the summer of 1988 to collect a final 67 mi of reflection data in Bayfield County. Overall, during the period 1984–88, Amoco Production obtained 15 reflection profiles in Wisconsin, totaling approximately 245 mi.

The third seismic field crew operating in the Wisconsin Lake Superior district in 1984 represented the Petty-Ray Geophysical Division of Geosource Inc., Denver, Colorado (later Halliburton Geophysical Services, Inc., Houston, Texas). This speculative program involved the collection of 833 mi of data along 12 profiles extending from the Upper Peninsula of Michigan west and southwest along the western arm of the Midcontinent Rift System to southwest Iowa. Of this set, four profiles totaling 275 mi were collected within the Lake Superior Basin (fig. 10). These data, with accompanying magnetic and gravity information, were recorded to a two-way-time depth of 18 seconds (Chandler and others, 1989) and offered for sale at a time depth of 6 seconds.

In 1985 a major offshore Great Lakes geophysical data acquisition program was announced by Grant Norpac (later Grant Geophysical Inc., Houston, Texas). This public disclosure prompted a concerned response from the political and environmental community. The governor of Michigan, supported by state legislation banning offshore drilling for hydrocarbons, attempted to deny access to Michigan waters to Grant Norpac. This attempt failed as a result of Grant Norpac successfully demonstrating to public officials that the collection of air-gun seismic data was not harmful to the aquatic environment. As originally conceived, approximately 8,850 mi of seismic, gravity, and magnetic data was to be collected from Lake Superior. Under a scaled-down implementation of this plan (Evans, 1986), 1,142 mi was recorded using the Motor Vessel Mai, owned and operated by Sefel Geophysical, Ltd., a Calgary, Alberta, sub-contractor to Grant Norpac (fig. 11; table 2).

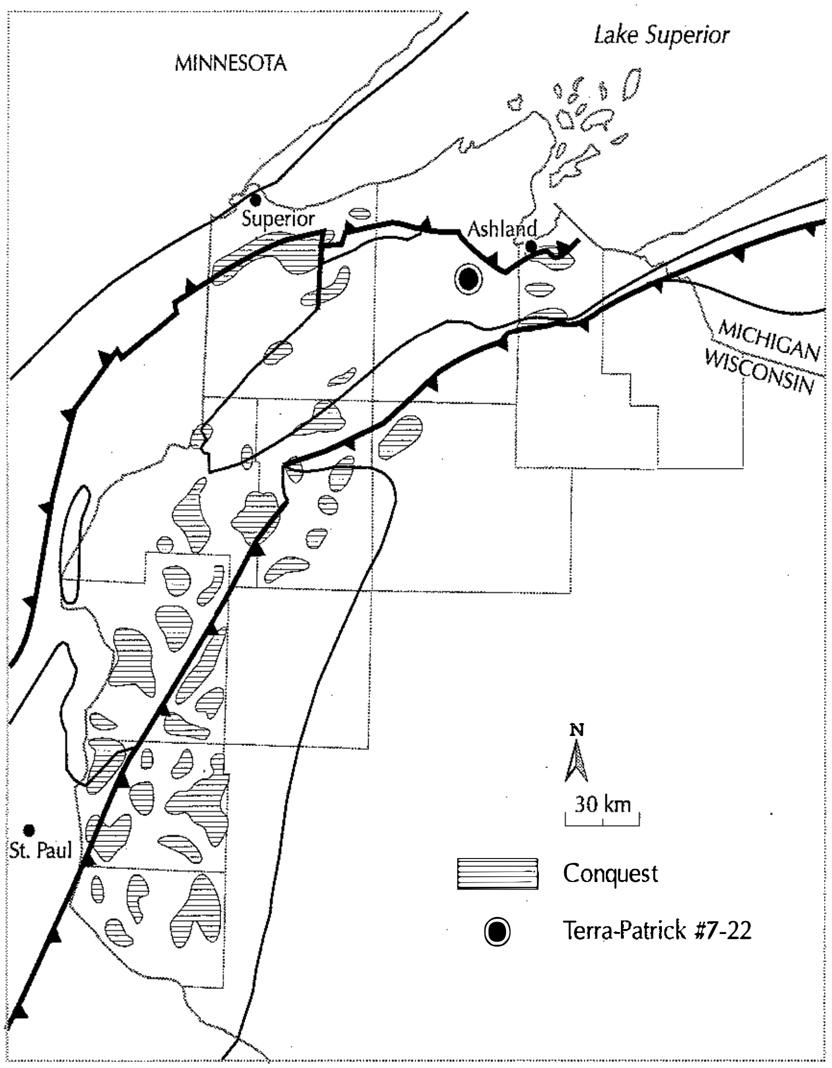


**Figure 6.** *Distribution and spatial relationship to geologic structure of leases obtained by Conquest Exploration. See figure 2 for explanation of structural features.*

During the same year, an informal coalition called the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) was formed for the purpose of improving upon the knowledge base of the crustal structure of the Great Lakes region. This consortium consisted of representatives from Canadian and United States federal agencies, state and provincial geological surveys, and universities, and was funded through the Geological Survey of Canada and the U.S. Geological Survey. One of its priorities was to contract for the gathering of 392 mi of reflection data, recorded to a two-way-time depth of 20 seconds, along five profiles in Lake Superior (fig. 11). This program was conducted in September 1986, by Geophoto Services, Ltd., a subsidiary of Geophysical Service, Inc. (GSI), of Calgary, Alberta, on board the Canadian motor vessel Fred J. Agnich. The GLIMPCE data set was released to the public domain in 1989. Analyses of

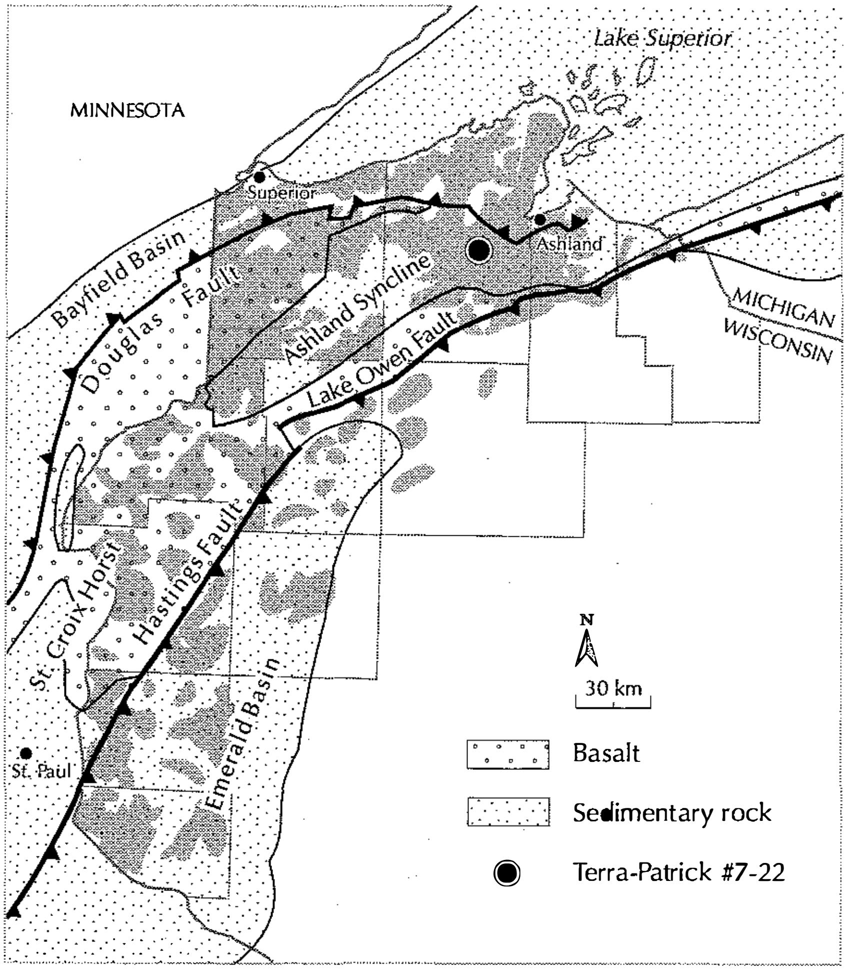


**Figure 7.** *Composite map of individual corporate leases (fine dot pattern), as shown on figures 3, 4, 5, and 6, superimposed upon the generalized geology of the Midcontinent Rift System in northwestern Wisconsin and adjacent eastern Minnesota.*

these data have been reported by Behrendt and others (1988), Cannon and others (1989), and Dickas and Mudrey (ch. 3, this volume). After Geophysical Service, Inc., completed its GLIMPCE contract, it continued to collect on a speculative basis an additional 325 mi of offshore Lake Superior seismic data (fig. 11).

Over the period 1990–93 seismic profiles collected in 1984 under contract by Texaco USA and Amoco Production Company (USA) as well as speculative profiles obtained in 1984 by Petty-Ray Geophysical Division of Geosource Inc., were gradually released to the senior editor of this volume. Although the distribution of these data is still controlled by signed agreements of confidentiality, information approved for release is contained within Allen and others (ch. 4, this volume).

In sum, geophysical field operations conducted both onshore and offshore in the western Lake Superior Basin over the period 1984–88 totaled approximately 2,671 mi of seismic reflection profiles, plus additional gravity and magnetic information.

## LEGISLATIVE, ECONOMIC, AND ENVIRONMENTAL FACTORS

Although 1984 was the year of peak onshore geophysical field activity along the Midcontinent Rift System trend of Wisconsin (as measured by number of field crews) and 1985 was the peak year offshore (by total length in miles of collected data), 1985 was the year of initial drilling expectation. At a May 7, 1985, meeting conducted in Madison, Wisconsin, and attended by 17 state and industry representatives, Amoco Production Company (USA) announced the intent of drilling a wildcat exploration borehole in Bayfield County. This well, proposed to be drilled to a total depth of 12,000 ft in the NE¼ sec. 13, T46N, R7W, would be a record depth borehole for the state of Wisconsin. The spud date was planned for July 1, 1985, and overall drilling time was expected to be from 3 to 6 months.

The most debated agenda item of this meeting involved the confidentiality of geologic data obtained while drilling below the horizon of near-surface freshwater strata. The discussion of this, and other matters of concern ranging from the

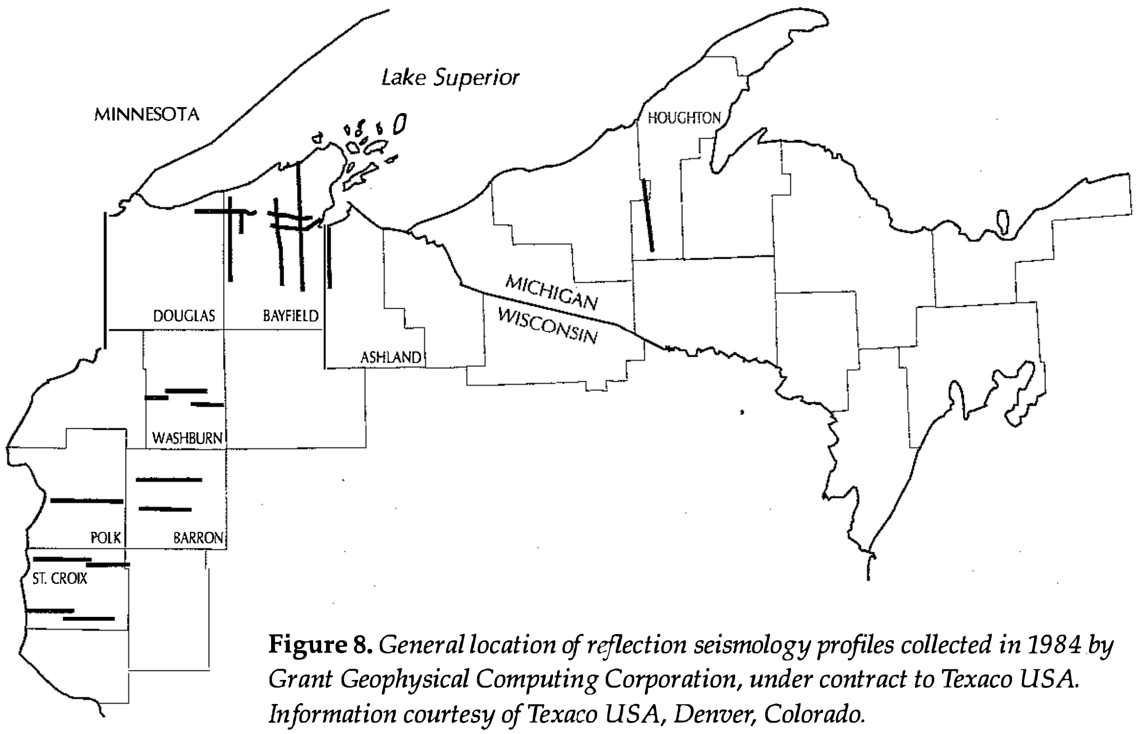


**Figure 8.** *General location of reflection seismology profiles collected in 1984 by Grant Geophysical Computing Corporation, under contract to Texaco USA. Information courtesy of Texaco USA, Denver, Colorado.*

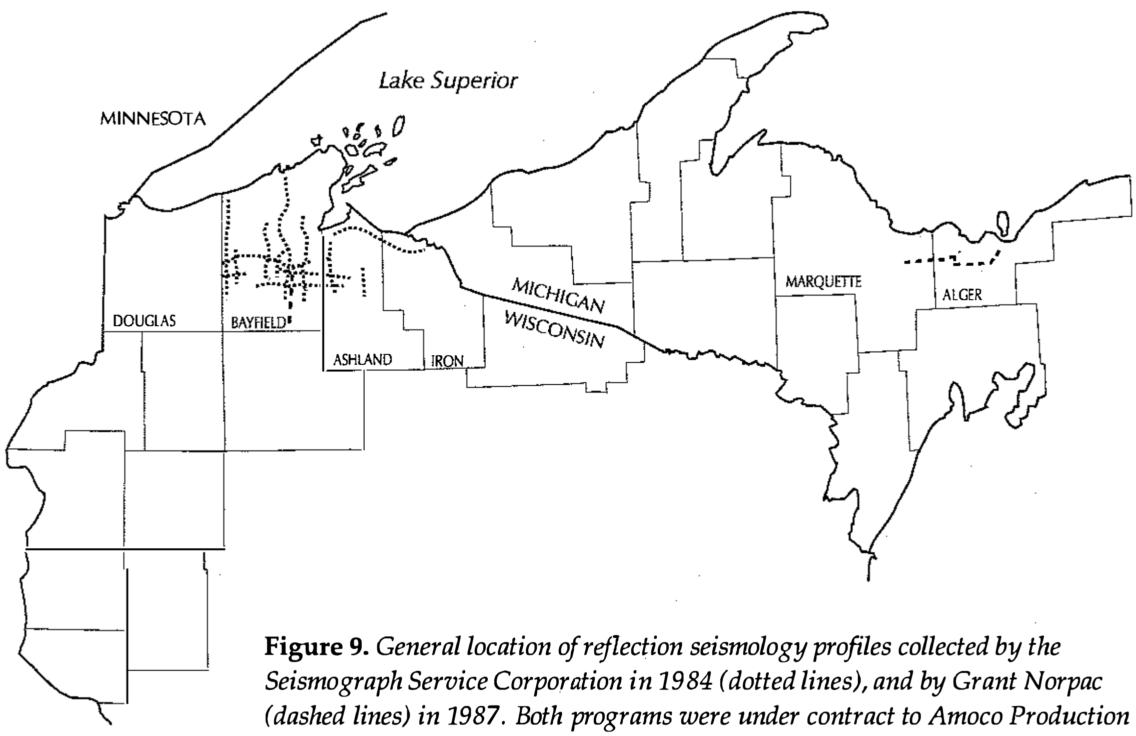


**Figure 9.** *General location of reflection seismology profiles collected by the Seismograph Service Corporation in 1984 (dotted lines), and by Grant Norpac (dashed lines) in 1987. Both programs were under contract to Amoco Production Company (USA). An additional 1988 program collected for Amoco by the Seismograph Service Corporation effectively overprinted the 1984 and 1987 profile locations. Information courtesy of Amoco Production Company (USA), Houston, Texas.*

protection of groundwater and surface water to the disposal of drilling wastes, became moot. Although the Wisconsin Department of Natural Resources had begun the drafting of oil and gas drilling legislation, at this time the state was not prepared to regulate deep drilling operations. At the end of the month, with Wisconsin still lacking enabling legislation, Amoco officials announced their Bayfield County drilling plans were temporarily suspended, citing the need for additional geologic information.

In September 1985 Governor James Blanchard of Michigan, capitalizing on the precedent of an existing ban on offshore drilling in Michigan state waters, called for Great Lakes

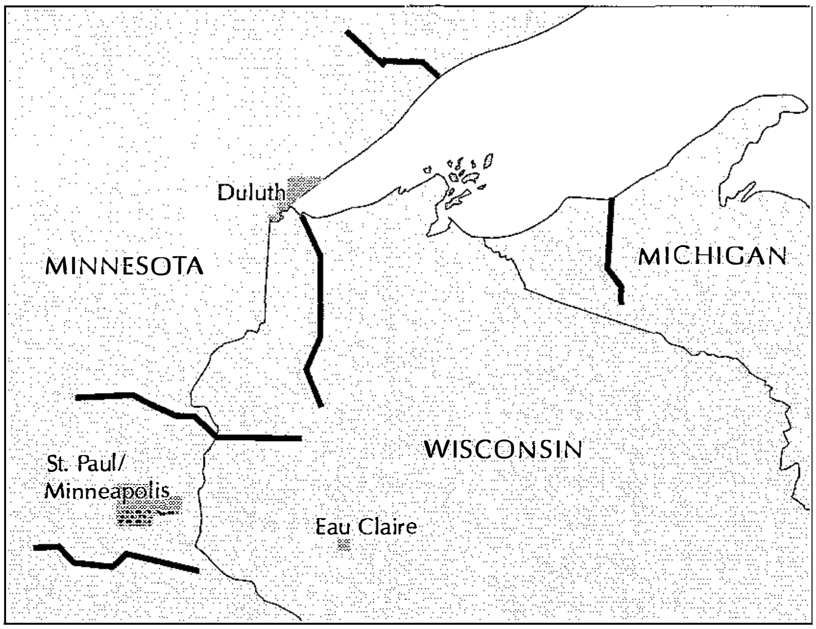


**Figure 10.** *General location of reflection seismology profiles collected in 1984 in the Lake Superior Basin region by Petty-Ray Geophysical Division of Geosource Inc., of Denver, Colorado, on a speculative basis. Additional profiles of this survey, collected farther south in Minnesota and Iowa, are not shown. Information courtesy of Halliburton Geophysical Services, Inc., Houston, Texas.*

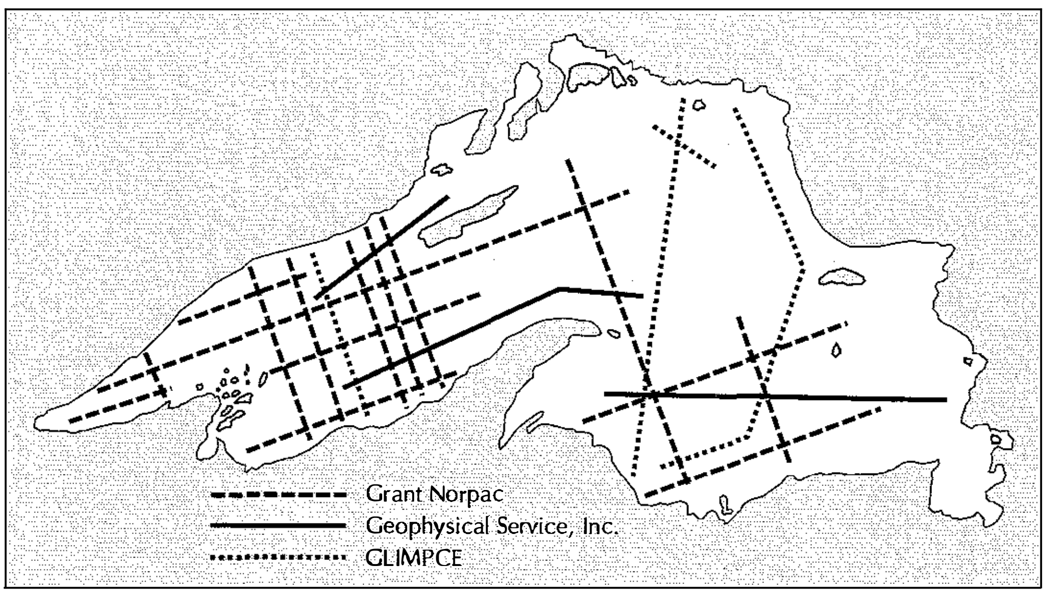


**Figure 11.** *General location of reflection seismology field programs conducted in the waters of Lake Superior by Grant Norpac in 1985 and Geophysical Service, Inc., in 1986. Both of these surveys were obtained on a speculative basis. In addition, Geophoto Services, Ltd., collected five offshore Lake Superior reflection profiles during 1986 for the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) consortium.*

governors to jointly support an agreement banning hydrocarbon exploration in all Great Lakes waters. This "Statement of Principle Against Oil Drilling in the Great Lakes" was signed on February 23, 1986, during the winter meeting of the National Governors Association by the governors of Michigan, Wisconsin, Pennsylvania, Minnesota, Indiana, Ohio, Illinois, and New York. This one-half page "document . . . [of] evidence of our continued joint stewardship of the Great Lakes," although a psychological deterrent, was not legally binding upon any signatory state.

During this same period, protective hydrocarbon exploration legislation was being completed in Wisconsin. In October 1985 the Wisconsin Department of Natural Resources Chapter NR 134,

**Table 2.** *Tabulation of seismic reflection and associated gravity and magnetic surveys conducted from 1984–88 onshore and offshore Lake Superior along the Midcontinent Rift System trend of the western Lake Superior Basin, inclusive of the Upper Peninsula of Michigan. Similar geophysical surveys, neither listed here nor discussed in this report, were obtained in Minnesota and Iowa over the same time period.*

| Year/contractor[1] | Contractee | W/grav | W/mag | Area | Length (in mi) | Depth (in sec) | Comments |
|---|---|---|---|---|---|---|---|
| **1984** | | | | | | | |
| Petty Ray Geophysical | Speculative | Yes | Yes | MI, MN, and WI | 275.0 | 6 | Lines MCR-1, MCR 2, MCR-3 and MCR-4, 4a, 4b, 4c[2] |
| Seismograph Service Corporation | Amoco Production Company (USA) | No | No | WI | 165.5 | 6 | 8 lines in 3 WI counties |
| Grant Geophysical Computing Corp. | Texaco USA | No | No | WI and MI | 261.4 | 4–6 | 18 lines in 7 WI counties; 1 line in MI |
| **1985** | | | | | | | |
| Grant Norpac, Inc. | Speculative | Yes | Yes | Lake Superior | 1141.9 | 8 | 15 lines: LS 04, 08, 10, 12, 15, 18, 25, 26, 36, 43, 45, 47, 53, 57, 69 |
| **1986** | | | | | | | |
| Geophoto Services, Ltd. | GLIMPCE[3] | No | No | Lake Superior | 391.5 | 20 | 5 lines: A, B, C, F, G Also refraction shot |
| Geophysical Services, Inc. | Speculative | No | No | Lake Superior | 324.9 | 20 | 4 lines: 1, 2B, 3, 4 |
| **1987** | | | | | | | |
| Grant Norpac, Inc. | Amoco Production Company, Inc. | No | No | MI and WI | 43.5 | 6 | 1 line WI; 1 line MI. Coring on MI line |
| **1988** | | | | | | | |
| Seismographi Service Corporation | Amoco Production Company (USA) | ? | ? | WI | 67.0 | 6 | 6 lines |
| **Total** | | | | | **2,670.7** | | |

[1] Contractor name given as known at time of field survey
[2] Part of a broader program that extended into Iowa. Only the profiles that pertain to this report are listed here.
[3] Great Lakes International Multidisciplinary Program on Crustal Evolution.

titled "Oil and Gas Exploration" had been approved and adopted into the Wisconsin Administrative Code.

An additional consideration of vital importance to exploration efforts along the trend of the Midcontinent Rift System emerged during the mid-1980s. The dramatic half-decade decline in domestic crude oil prices, from a 1981 high of $35 per barrel to a low of less that $10 per barrel in 1986, left the hydrocarbon industry in a state of recessive shock. With discovery costs in the United States ranging from $8 to $11 per barrel of petroleum, the economic incentives for exploration for new reserves were sharply reduced. By early 1988, as compared to the expansive 1980–82 period, this negative price trend had caused within the continental United States an 85 percent decline in working-rig count, a 77 percent decline in seismic crew count, and a 79 percent decline in industrial expenditures for exploration and development (Taylor, 1987). In the midst of this period of retrenchment, Amoco Production Company (USA) announced in December 1985 their intent in drilling a 15,000-ft wildcat test on the west flank of the Midcontinent Rift System in Carroll County, Iowa. The worsening economic situation, however, soon prompted Amoco to list this well under the same temporarily suspended classification as that given prior to their proposed Bayfield County, Wisconsin, borehole.

In spite of the curtailment of hydrocarbon exploration in the United States, the Petroleum Information Corporation, an industrial news service, stated in its December 19, 1985, newsletter (p. 2) that the rift had become "the largest play in the history of the oil industry." As an active partner in this historic play, the state of Wisconsin was prepared for responsible participation. With the enactment of exploration legislation, the maintenance of important lease positions, and the continuation of geophysical and geological evaluation, all interested parties waited for the inevitable improvement in the support price of crude oil.

Exploration activities along the Midcontinent Rift System trend of the Lake Superior area remained dormant throughout the late 1980s. In mid-October, 1990, however, this situation changed when the Wisconsin Department of Natural Resources was informed by Terra Energy, Ltd., of Traverse City, Michigan, of their interest in drilling a wildcat well in Bayfield County. Terra Energy, through a farm-out agreement with Amoco Production Company (USA), and later joined by Patrick Petroleum Company of Jackson, Michigan, as a partner, sought a permit to drill in sec. 22, T47N, R6W, a site approximately 5 mi northeast of the proposed 1985 Amoco well site. On January 17, 1991, Terra Energy, Ltd., was granted Oil and Gas Exploration License l, the first such approval granted by Wisconsin pursuant to Chapter NR 134 of the Administrative Code. This license allowed continued planning and review, but was not a permit to drill.

In early February 1991 the print and television media released reports on the "Chequamegon Prospect," the name given by Terra Energy to their Bayfield County drilling project. Because the overwhelming percentage of citizens of northern Wisconsin, whether farmer, clerk, county commissioner, or homemaker, was unfamiliar with the scientific procedure of hydrocarbon exploration and the mechanical process of rotary drilling, the next year was characterized by numerous public meetings in consideration of variously expressed environmental, health, economic, and agricultural concerns.

Following an extensive review through the Environmental Impact Assessment process by the Wisconsin Department of Natural Resources, approvals by the Bayfield County Zoning Department and the Bayfield County Board of Commissioners, and capacity attendance (250 attendees) at public hearings conducted in Washburn, Wisconsin, on July 9, 1991, and in Benoit, Wisconsin, on September 19, 1991 (275 attendees), Terra Energy, Ltd., received state approval "to construct an exploration oil and gas well for test purposes," effective February 6, 1992. Thus, eight years and four months after land-lease agents first appeared in northern Wisconsin, the final approval necessary had been granted for the drilling of a wildcat borehole in search of hydrocarbons within Precambrian strata of the Midcontinent Rift System of the Lake Superior Basin region. During the early morning of March 9, 1992, the Terra–Patrick #7-22 borehole was spudded, with a projected total depth of 6,000 ft. The daily drilling chronology of this borehole is given in Dickas (ch. 6, this volume).

## Assessment pertinent to Wisconsin

Between 1984 and 1990 three deep wildcat tests were drilled within segments of the Midcontinent Rift System lying outside the state of Wisconsin. A short report is presented here on each of these boreholes because of their significance to the drilling of the Terra–Patrick test in Bayfield County, Wisconsin, in 1992.

In July 1984, Texaco USA staked a wildcat well in sec. 31, T5S, R5E, Washington County, northeastern Kansas. Listed as the Texaco #1 Noel Poersch, this well was sited on a 124,000-acre package Texaco had acquired in Washington, Riley, Clay, and Geary Counties. Projected total depth was 13,000 ft into the Precambrian Rice Formation, stratigraphic equivalent to the Bayfield and Oronto Groups of Wisconsin. At that time, the Kansas drilling depth record was 8,715 ft. Spudded on September 12, 1984, this well was plugged and abandoned on March 6, 1985, after reaching a total depth of 11,300 ft. No oil or gas shows were encountered. After the drilling, Texaco USA continued to obtain new lease positions in the northeastern Kansas area. These new lease agreements differed from those signed prior to drilling by containing a metallic minerals clause. Stratiform sulfide mineralization has long been known to be associated with Keweenawan shales and basalt flows in Michigan, suggesting sulfide shows had been encountered in the Poersch borehole. For a comprehensive report on the drilling and geology of the #1 Noel Poersch test, see Berendsen and others (1988).

Thirty-one months after the completion of the Poersch well, Pan American Petroleum Corporation (Amoco Production Company operator) spudded their Carroll County, Iowa, test on March 16, 1987. This was the project Amoco had originally announced in December 1985 and then suspended due to the sharp decline in oil price support. This test, M.G. Eischeid #1, was located in sec. 6, T83N, R35W, and was projected to be drilled to a depth of 15,000 ft, with an option allowing an additional 4,000 ft. At the time the Iowa drilling depth record was 5,305 ft, established in Page County in 1930. In late October 1987 this test had reached its objectives and was plugged and abandoned at a total depth of 17,851 ft. Although gas shows were reported, no commercial zones of oil or gas were encountered. A complete report on the geology of this borehole is given in Anderson (1990).

On October 26, 1987, Amoco Production Company (USA) spudded, in the Upper Peninsula of Michigan, their second test of the hydrocarbon potential of the Midcontinent Rift System using experimental, highly automated SHADS (Stratigraphic High-Speed Advances Drilling System) equipment. This borehole, the Amoco St. Amour #1-29, was located in sec. 29, T46N, R18W, Munising Township, Alger County. Information on this borehole remained proprietary until March 1995. This test was drilled, and 100 percent cored below the glacial drift, to a total depth of 7,230 ft. The well was plugged and abandoned on January 1, 1988, after drilling through three separate volcanic units. No commercial zones of oil or gas were encountered (Dickas, 1995).

Other wells have been drilled into the Proterozoic red-bed sequence associated with the western arm of the Midcontinent Rift System trend, but none was targeted as a test of hydrocarbon potential. Most were drilled for the purpose of analyzing Phanerozoic structures and ceased operations when Precambrian red-bed sequences were reached (Dickas, 1986). A few wells were drilled to Proterozoic horizons along the rift trend in order to evaluate these strata as potential natural-gas storage zones. These operations were discussed by Austin (1970) and Morey (1977).

## Summary

The unprecedented exploration for oil and gas that began in Wisconsin in late 1983 opened a new chapter in statewide economic geologic evaluation. In contrast to the prior history of petroleum exploration in Wisconsin, which was conducted in a sporadic, poorly organized, and low-cost manner, the Midcontinent Rift System play not only focused upon rocks of Proterozoic age, but also produced a significant data bank of modern geological and geophysical information. With leases averaging $1 per acre per year and reflection seismology costing at least $7,000 per linear field mile, a minimum of $21 million was spent in the search for hydrocarbon in the Lake Superior Basin region prior to the drilling of the Wisconsin record-depth Terra–Patrick #7-22 borehole in March 1992.


## ACKNOWLEDGMENTS

The compilation of this history would not have been possible without the cooperation of many individuals and organizations. I would like to express my sincere thanks to the following companies: Grant Geophysical Inc. (Houston, Texas); Amoco Production Company (USA), (Houston, Texas); Petty-Ray Geophysical Division of Geosource, Inc., (Houston, Texas); Texaco Exploration and Production Inc. (Denver, Colorado); and Terra Energy, Ltd. (Traverse City, Michigan). I am also most appreciative of the cooperation given me by the Wisconsin Department of Transportation, the Wisconsin Geological and Natural History Survey, the Wisconsin Department of Natural Resources, the University of Wisconsin Cooperative Extension, the U.S. Department of Agriculture, and the U.S. Forest Service. Finally, a special thank you to Duncan Harkin and Thomas J. Evans, both University of Wisconsin–Extension, for sharing their annual compilations of oil and gas lease activities.


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# Chapter 6. Chronology of events associated with the drilling of the Terra–Patrick #7-22 borehole, Bayfield County, Wisconsin

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## Introduction

Because one-third of Wisconsin is geologically a part of the southern extremity of the Canadian Shield, and the remainder is covered by a thin veneer of Lower Paleozoic platform sedimentary rocks, the hydrocarbon industry has long considered Wisconsin to be generally unworthy of serious exploration efforts. This evaluation, however, has not prevented independent operators from undertaking exploration programs in Wisconsin.

Between the first discovery of oil in the contiguous United States in 1859 and the drilling of the Terra–Patrick #7-22 borehole in 1992, 49 wells had been drilled in Wisconsin in the search for oil or natural gas. None of these operations was commercially successful.

Because the drilling of the Terra–Patrick #7-22 borehole received national attention, and the total depth of this well constitutes a Wisconsin drilling-depth record, this abbreviated chronology of events has been prepared from a diary, written by the author, recording frequent visits to the drilling site, and from the daily drilling report as maintained by Terra Energy, Ltd.

## Pre-drilling phase chronology

**Early October 1990.** Terra Energy, Ltd., of Traverse City, Michigan, notifies the state of Wisconsin of its interest in drilling an exploratory ("wildcat") borehole in Bayfield County, Wisconsin, in association with Amoco Production Company (USA), Houston, Texas. A review of environmental and economic considerations is undertaken by the Wisconsin Department of Natural Resources.

**October 25, 1990.** Telephone discussions with Terra Energy indicate the borehole location will be in the SE¼ NE¼ sec. 22, T47N, R6W.

**January 17, 1991.** Oil and Gas Exploration License # OG-1 is issued to Terra Energy, Ltd., by the Wisconsin Department of Natural Resources, pursuant to ss. 144.025, Wisconsin Statutes, and Chapter NR 134, Wisconsin Administrative Code. This license is effective for the period January 17, 1991 through June 30, 1991. This is the first license issued by the state under recently approved oil and gas drilling regulations.

**May 23, 1991.** The announcement is made that Patrick Petroleum Company, Jackson, Michigan, has joined Terra Energy in this drilling venture.

**May 28, 1991.** Terra Energy, with a minimum of 22,000 acres under lease, requests leasing of additional 3,906 acres under control of Bayfield County, at a County Board of Supervisors meeting. The request is approved by a vote of 13 to 4 to lease the subject acres at the rate of $1 per acre per year. The request is forwarded to the Bayfield County Zoning Committee.

**May 31, 1991.** Terra Energy applies to the Wisconsin Department of Natural Resources for an oil and gas drilling permit and for a renewal of the existing oil and gas exploration license.

**June 1991.** An Environmental Impact Assessment (draft) is completed by the Wisconsin Department of Natural Resources, and is reviewed by June 25, 1991, by the Bayfield County Zoning Committee (fig. 1).

**July 9, 1991.** A public hearing, hosted by Bayfield

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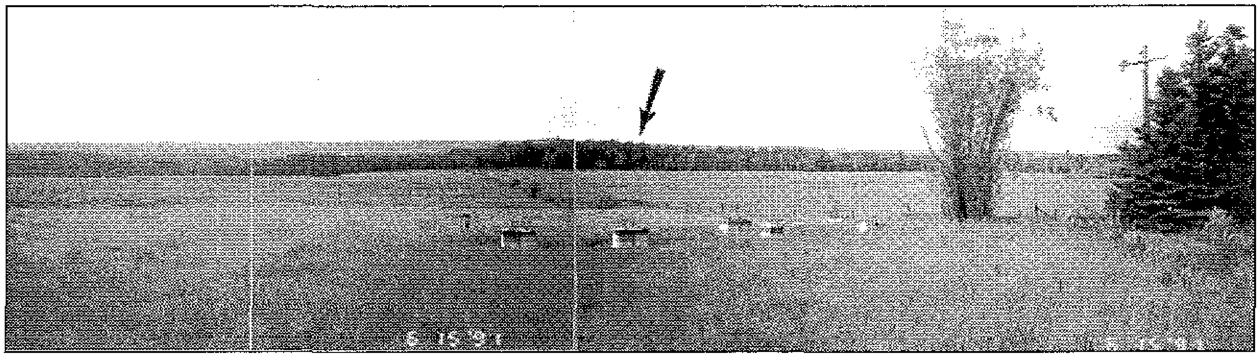


**Figure 1.** *June 15, 1991. Overall view looking north of Terra–Patrick #7-22 drilling location (arrow). Photograph taken from Highway 2, 3.5 mi east of Ino, Wisconsin, approximately nine months prior to spud date of March 9, 1992.*

County Zoning Committee, is held in Washburn, Wisconsin. Approximately 250 citizens are in attendance for the 6:00 p.m. meeting. After six hours of testimony and discussion, the Zoning Committee approves a land-use permit to drill an exploratory borehole, conditional upon completion of an Environmental Impact Study.

**September 19, 1991.** A second public hearing is conducted in the Benoit Community Building, Benoit, Wisconsin, to review the re-application by Terra Energy for a conditional land-use permit to drill an oil and gas test borehole 1,000 feet from the initially proposed borehole location. Approximately 275 citizens are present for the four-hour meeting. The re-application is approved by the Bayfield County Zoning Committee by a vote of 3 to 2.

**December 16, 1991.** Upon completion of an Environmental Impact Assessment, the Wisconsin Department of Natural Resources invites public input at an open-house meeting, conducted at Benoit Community Center, Benoit, Wisconsin, preparatory to the issuance of an oil and gas drilling permit.

**February 6, 1992.** An oil and gas drilling permit is granted to Terra Energy by the Wisconsin Department of Natural Resources.

## Drilling phase chronology

Site-clearing operations in preparation for the drilling of the Terra–Patrick #7-22 borehole begin on Wednesday, February 12, 1992. The chronology of events from February 12 until Wednesday, April 1, 1992, the date the drill rig is officially released, spans a time period of exactly 50 days.

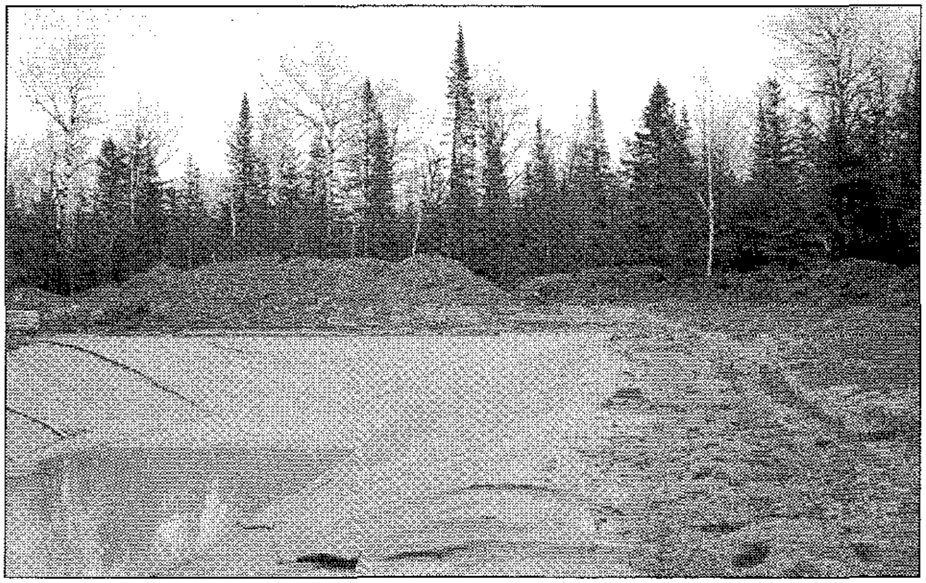
**February 12, 1992.** Work begins on clearing approximate 300 ft by 300 ft drilling site and entry road. Final location of borehole changed to 330 feet from south line and 330 feet from east line of SW¼ SW¼ NE¼ sec, 22, T47N, R6W.

**February 13, 1992.** Clear, 28°F. A four-man crew is bulldozing a road and cutting timber. The drill-rig floor location is marked by orange tape on a dead poplar tree.

**February 20, 1992.** The ground is covered by a 2- to 4-in. snow fall. The first 300 ft of the access road is completed; the remaining road surface is covered with loose sand. Three bulldozers are on location.

**February 27, 1992.** Little progress. Recent snow, warm weather, and much truck traffic have seriously deteriorated roadbed. Bulldozers are pulling gravel trucks out of mud. Drill-rig site is completed and bermed, but the mud pit is yet to be dug.

**March 4, 1992.** Cloudy, 40°F. Water well is being drilled; depth is now at 75 ft level. The mud pit is completed and plastic liner installation is underway. The drill rig is en route by truck caravan from Michigan. Drilling pipe is en route from Texas. A



system. The cement tanks are in the final stage of installation; however, the mud-circulating system is not yet in full operation. Additional phone lines have been installed. The mudlogger is not yet prepared for operations. Crew members from the Begard Drilling Company, Mt. Pleasant, Michigan, have arrived and have moved into area motels (fig 2).

**Figure 2.** *March 8, 1992. A part of the drilling site was occupied by this 1,850 cubic yard maximum capacity drilling fluid (mud) pit, composed of 40-mil-thick lining made of PVC resin.*

Wisconsin Department of Natural Resources environmental specialist is now on site. Entry from U.S. Highway 2 is protected by locked gate. Access to drilling location by non-operation individuals will be by card permit only. Access-road is completed and site telephones are installed and operational.

**March 7, 1992.** Foggy and rainy. Drilling site is a "sea of mud." Drill rig is in process of being moved by mud skid and bulldozer. Two trailers are on site. Dowell–Schlumberger cement trucks are temporarily parked on highway entrance berm. The initial water well is abandoned at 120 ft; the 14 gal/min flow is determined to be inadequate; minimum 70 gal/min flow is required. The plan is to bring water to the site by truck tanker. Drill-rig construction is completed and the rig is topped by flags of the United States and Wisconsin. The continuing mud problem is alleviated by truckloads of crushed brick. Approximately 20 individuals are now on site, in addition to many vehicles. Glen Tarrant of Tarrant Mudlogging Consultants, Traverse City, Michigan, arrives and sets up his mudlogging unit.

**March 8, 1992.** Cloudy and foggy. Drill site is very muddy. Calcium chloride is being added to water

**March 9, 1992.** The Terra–Patrick #7-22 borehole is spudded at 12:45 a.m. into sandy drift by drilling a 12¼-in. pilot hole to 41 ft. Bit #1, a 26-in. type HTC-RI, is attached to the drill string and hole is drilled to 73 ft. A 20-in. conductor pipe is welded and is being installed. Ground level at the drill rig is 867 ft, and the kelly bushing elevation is 879 ft. Projected total depth (TD) of the borehole is 6,000 ft.

**March 10, 1992.** The evening temperature drops to 0°F, freezing the ground. The conductor pipe is installed at a depth of 61 ft after 14 hours of reaming several bridges at the 24- and 61-ft levels. The pipe is secured with 110 sacks of Dowell class A cement. The borehole is deepened to 134 ft using bit #2, a 17½-in. type HTC-RI model. A directional survey, conducted by Directional Drilling Consultants Inc., of Traverse City, Michigan, records a borehole angle of 1° at 107 ft.

**March 11, 1992.** Snow flurries, 15°F at noon. The borehole is deepened to 413 ft. At 220 ft the mudlogging unit comes on-line. The top of the Freda Formation is encountered at 293 ft measured depth. Volume of the freshwater base mud is increased to 300 barrels. The mud lines occasionally freeze and are thawed. In preparation for the running of 13-in. casing, the hole is conditioned by mud circulation, and the drill pipe is tripped out.

**March 12, 1992.** The casing cannot be run because of tight spots in the borehole caused by heaving rock material. Swelling clay is probably the cause. The day is spent reaming the hole. A new water well is being dug and is at a depth of 110 ft. The borehole is at a depth of 413 ft.

**March 13, 1992.** Problems continue with the setting of casing because of tight spots.

**March 14, 1992.** The borehole is being reamed.

**March 15, 1992.** The swelling borehole problem is solved by changing the casing diameter to 11¾-in., rather than 13-in. Casing is installed at 412 ft and cemented with 250 sacks of class A Dowell cement. Drilling out of the cement begins at 10 p.m. The top of the cement in the borehole is recorded at 357 ft depth.

**March 16, 1992.** Fair weather. Daytime temperature is 40°F. Cement is drilled out to 412 ft. The borehole is deepened to 824 ft using bit #3, a 10-in. RTC-HP51 model. A directional survey is run at 793 ft and indicates a deviation of 2.5°. Today the drill-rig site is designated as an open-house for VIPs for purposes of easing expressed concerns regarding environmental damage caused by drilling operations. Approximately 50 individuals are given guided tours of all operations. The group is representative of local and state political, environmental, and landownership interests. Representatives from all three Duluth, Minnesota–based television stations and from Superior, Duluth, and Ashland print media are present.

**March 17, 1992.** Sixteen hours are spent attempting to straighten borehole as the directional survey shows a deviation of 4° at 1,150 ft and 4.75° at 1,339 ft. The borehole is at a depth of 1,550 ft in the Freda Formation.

**March 18, 1992.** Borehole is deepened to 1,771 ft. A directional survey indicates a 5.75° angle at 1,522 ft, increasing to 7.25° at 1,715 ft. The borehole axis is now deviating at the rate of 0.44° per 100 ft. At this rate, the borehole will deviate 8° at the planned casing depth of approximately 2,000 ft, and will be at an angle of 26.5° at the projected TD of 6,000 ft.

**March 19, 1992.** Hole is drilled to 2,002 ft (driller depth), 2,003 ft (logger depth). A series of downhole wireline surveys is initiated by Halliburton Logging Services, Inc., from the Mt. Pleasant, Michigan, office. Logging program #1 consists of a Dual Induction Laterolog/Gamma Ray log surveyed over the interval of 2,001 to 100 ft, and a Long Spaced Sonic Log/Gamma Ray log surveyed over the interval of 1,994 to 397 ft. A directional survey records a borehole angle of 7.75° at 1,868 ft, with a reduction to 5° at 1,961 ft resulting from use of reamers and the alteration of weight on the drill string.

**March 20, 1992.** Sunny and clear. Log program #1 is completed. An 8-in. casing is run to 2,002 ft depth and set with 300 sacks of Class A Dowell cement. The blow-out preventor and casing is successfully tested to 1,500 pounds. Plans call for the installation of 5½-in. production casing, if needed, at a TD of 6,000 ft.

**March 21, 1992.** Cement is drilled out from 1,939 to 2,002 ft and drilling is resumed with bit #4, a 7-in. type HTC-J22 model. The borehole depth is increased to 2,390 ft. A directional survey indicates angle of deviation is ranging between 6° at 2,252 ft and 7.25° at 2,091 ft. Drilling continues in the Freda Formation.

**March 22, 1992.** Sunny; temperature is approximately 25°F. The borehole depth is increased to 2,935 ft. The borehole axis ranges from a low of 2° at 2,496 ft to a high of 7.5° at 2,748 ft.

**March 23, 1992.** A depth of 3,400 ft is reached. A borehole deviation of 10° is recorded at 3,356 ft.

**March 24, 1992.** The borehole is at a depth of 3,602 ft. The bottom-hole deviation increases to 12°. A discussion takes place as to whether the deviation problem is geologic (perhaps borehole is deviating into the dip of the Freda Formation) or mechanical (associated with the drilling-string assembly). An investigation indicates one set of reamers is under

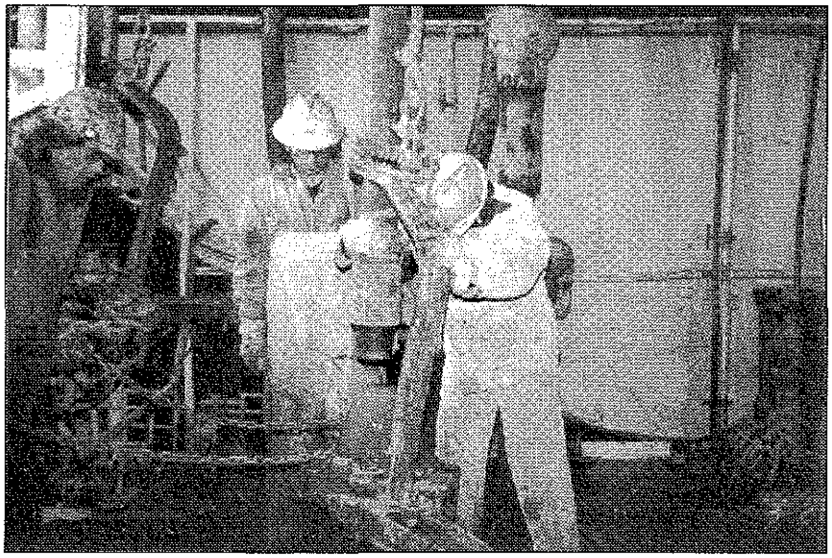


**Figure 3.** *March 26, 1992. Begard Drilling Company of Mt. Pleasant, Michigan, crew adds a joint of 30-ft drill pipe to the drill stem at the 3,900-ft level.*

gauge. The suggestion is made that the reamers are the cause of the deviation.

**March 25, 1992.** No new footage is recorded today. The entire day is spent in mechanical repairs and the testing of various rig components. Bit #5, a 7-in. type RTC-HP51, is installed.

**March 26, 1992.** Depth is increased to 3,995 ft (fig. 3). Mudlogging data indicate a sharp change in color in the cuttings between 3,730 and 3,740 ft. The top of the Nonesuch Formation is established by the mudlogger at 3,732 ft measured depth. Assuming the logger tops to be correct, the Freda Formation is 3,442 ft thick (measured, not true thickness). The first minor gas show is recorded below 3,833 ft (101 ft into the Nonesuch Formation). A directional survey indicates a borehole deviation of 14° at 3,915 ft. (Note: Above a measured depth of 3,833 ft, the "hydrocarbon analysis" part of the mudlog indicates no presence of oil or gas in the drilling mud. Between the measured depths of 3,833 and 4,084 ft, the drilling mud yields gas shows of up to 39 units of methane, but no oil shows. Below a measured depth of 4,084 ft, and continuing to total depth, the drilling mud yields a continuous gas show of 2 units of methane. These levels of gas shows are not commercial. See fig. 4 for further explanation).

**March 27, 1992.** The borehole is deepened to 4,603 ft. The top of the Copper Harbor Formation is picked by the mudlogger at 4,168 ft. This formational top is not based on a change in color of drill cuttings, but rather on an increase of needle-like laths of quartz/metaquartz, which change from trace amounts in the Nonesuch Formation to approximately 25 percent by volume in the Copper Harbor Formation. If the top is correct, the Nonesuch Formation here is 436 ft (measured depth thickness) thick. The borehole deviation is in the 14° to 14.25° range. Minor gas shows begin to decrease below 4,010 ft depth. A Halliburton wireline logging crew and truck is ordered from the Traverse City, Michigan, office. Their travel route over the Mackinac Bridge in Michigan is delayed until midnight because of a restriction caused by the transport of radioactive material.

**March 28, 1992.** Overcast and 35°F. The borehole depth of 4,966 ft is reached at 6:00 a.m. in the Copper Harbor Formation. The deviation is up to 16° at 4,626 ft. The Halliburton logging crew begins wireline logging program #2 at noon (fig. 5). On this day the following logs are completed: High Resolution Induction/Digitally Focused/Gamma Ray log (interval 4,978.1–1,961.1 ft), Spectral Density/Dual Spaced Neutron/Spectral Gamma Ray log (interval 4,911.9–1,853.4 ft), and Compensated Spectral/Natural Gamma Ray log (interval 4,911.9–1,853.4 ft). Logging is still underway at midnight.

**March 29, 1992.** The borehole depth is at 4,966 ft. The downhole part of the logging program is completed at approximately 2:00 p.m. (fig. 6). On-site computer logging analysis is underway. Logs completed on this date include: Shiva Computation/Six Arm Dipmeter Survey (interval 4,820.9–2,025.1 ft), Monitor/Six Arm Dipmeter Survey log (inter-

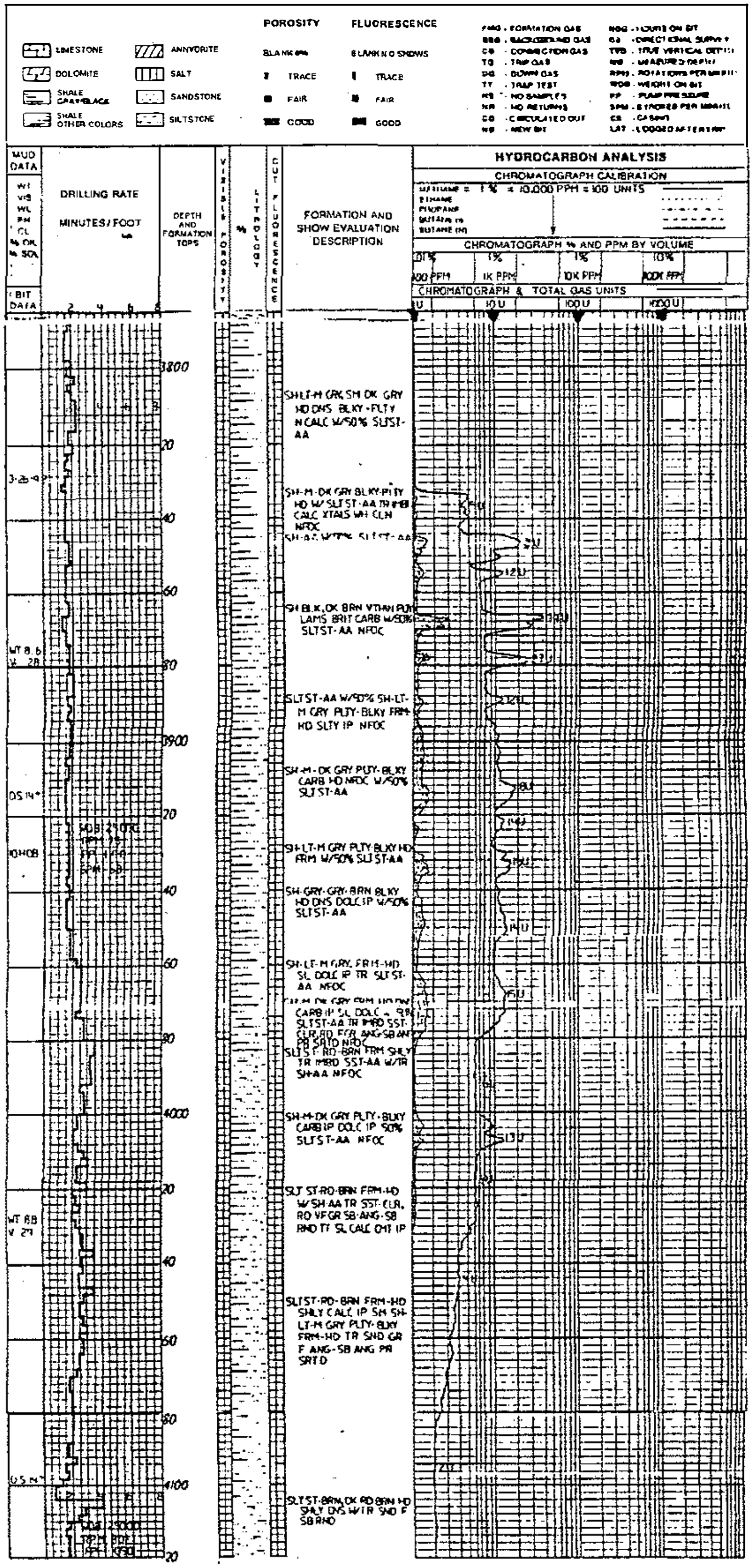


**Figure 4.** *A display of the part of the mudlog below the borehole depth of 3,800 ft in which gas shows were recorded. Gas shows are recorded between depths of 3,833 and 4,084 ft. (See borehole depth column at left center of log.) The maximum recorded gas show of 39 units is listed at 3,866 ft. According to the hydrocarbon analysis heading, 100 units is the equivalent of 10,000 ppm in the drilling mud. Thus, 39 units would equal 3,900 ppm methane gas by volume in the drilling mud. Mudlog courtesy of Tarrant Mudlogging Consultants and Terra Energy, Ltd.*

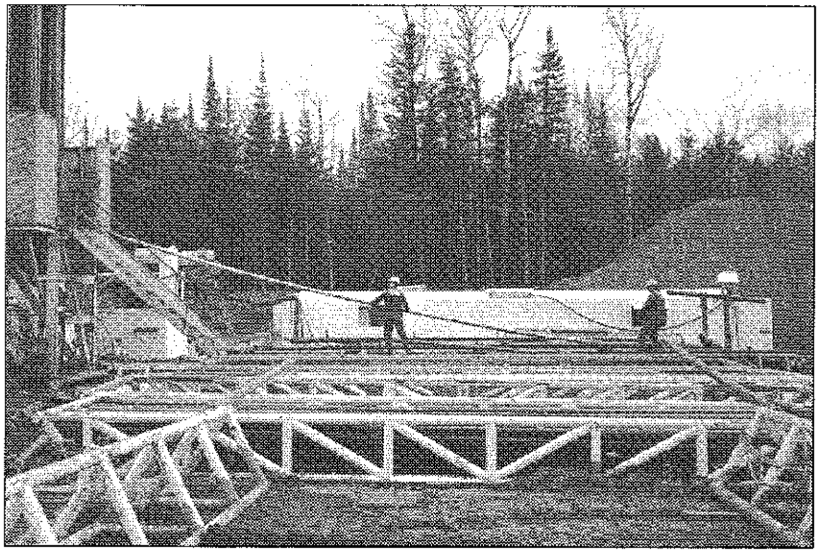


**Figure 5.** *March 28, 1992. Halliburton Logging Services, Inc., crew (Mt. Pleasant, Michigan) making up string of specialized downhole tools prior to initiation of logging program 2.*

val 4,820.9–2,025.1 ft), Dual Induction Laterolog/Gamma Ray log (interval 4,789.0–93.6 ft), and Long Spaced Sonic/Gamma Ray log (interval 4,878.0–364.5 ft). It is decided no side-wall or conventional cores will be collected. The on-site log review is discouraging. A decision is made that unless a computer analysis is more optimistic, a "plug and abandon" (P and A) operation will begin as soon as possible. A home-cooked lunch, prepared especially for the drilling crew, is brought to the site by area landowners in appreciation of the attempt made, in the drilling of the borehole, to improve the local economy.

**March 30, 1992.** The rig is circulating the mud system at TD of 4,966 ft (measured depth). Al Hackman, a logging consultant under contract to Terra Energy, Ltd., is having difficulty interpreting the logs due to the high percentage of matrix and volcanic material in the rock column. (Note: The Halliburton interpretation charts are modeled after quartz, rather than volcaniclastic, sandstone.) The maximum recorded bottom-hole temperature of 86°F is considered normal. The dipmeter log indicates the following structure: Dips in the Copper Harbor Formation range from 1° to 34° (quality poor); in the Nonesuch Formation, the range is from 15° to 24° (quality is very good except for the lower 138 ft, where the range is 12° to 32° and generally of fair to poor quality); in the Freda Formation, the range is from 7° to 35°. The highest quality data range from 18° to 30°. The best quality data show a consistent southeasterly dip. The decision is made to P and A.

**March 31, 1992.** Plugging operations are underway. Site is visited by key Terra Energy, Ltd., officials (fig. 7).

**April 1, 1992.** Plugging operations are completed. The plugging information, as determined by the

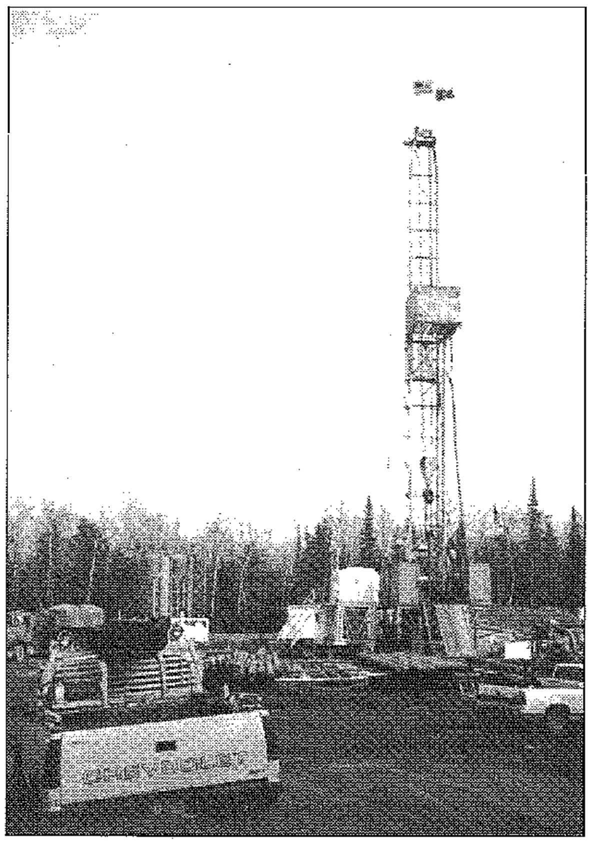


**Figure 6.** *March 29, 1992. View of drilling site while completing Halliburton logging run 2. At this time the borehole had reached its final total depth of 4,966 ft.*

**Figure 7**. *Terra Energy, Ltd., personnel on site during the last full day of operations. From let to right: Al Hackman (downhole logging consultant, Craig Tester (Vice President), and Stephen Savoie (site geologist).*

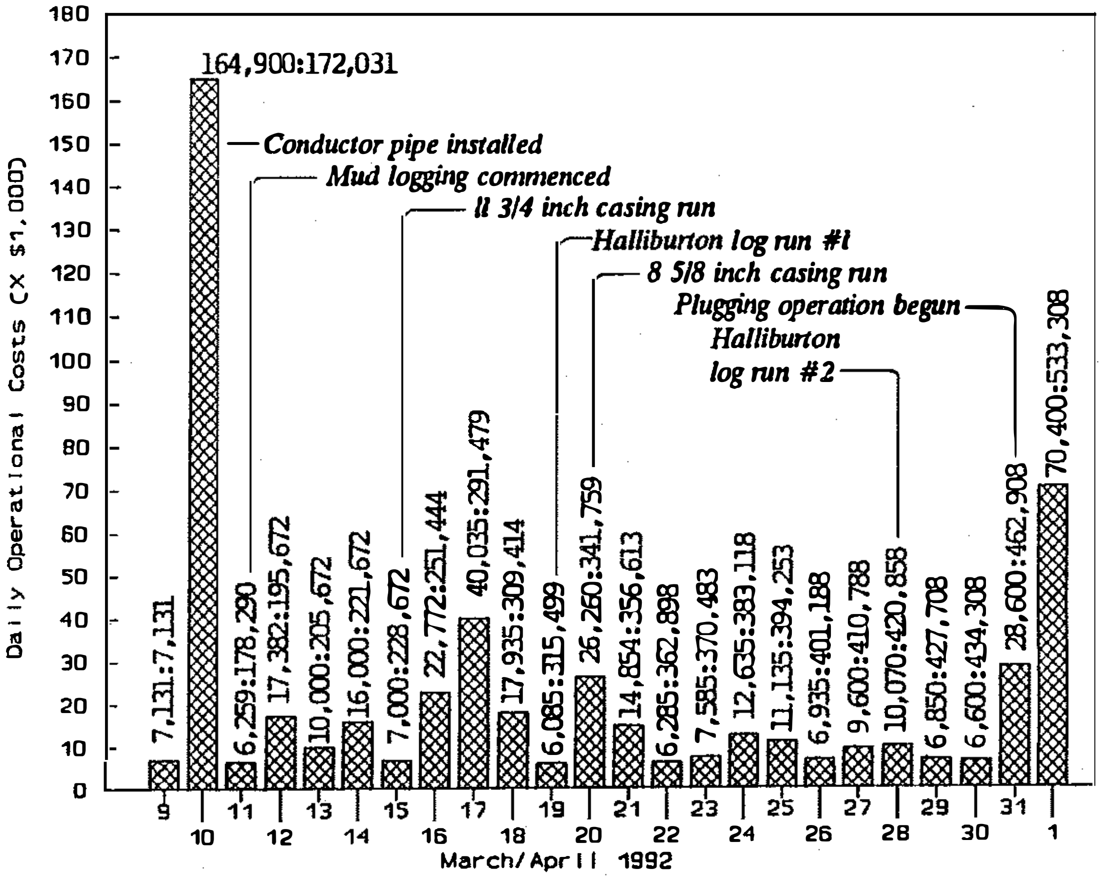



**Figure 8.** *Bar diagram plot of daily drilling costs for the Terra–Patrick #7-22 borehole. The spud date for this test was March 9, 1992, 12:45 a.m. The drill rig was released at 9:00 a.m., April 1, 1992, after the borehole was declared plugged and abandoned. Total daily operation rig costs are presented in bar and numerical (figure preceding colon) format. Daily cumulative operational costs are given in figure following colon. Daily drilling report information courtesy of Terra Energy, Ltd., Traverse City, Michigan.*

Dowell–Schlumberger crew, is as follows: 500 sacks Class A cement are set over the interval 4,960 to 3,660 ft, 150 sacks Class A cement are set over the interval 2,152 to 1,852 ft, and 190 sacks Class A cement are set over the interval 500 ft to surface. The plug is down at 1:30 a.m. The drill rig is released at 9:00 a.m. The total drilling cost is calculated to be $533,308. See figure 8 for a record of the daily and cumulative drilling costs.

# Chapter 7. Stratigraphy and lithology of Keweenawan sedimentary rocks penetrated by the Terra–Patrick #7-22 borehole, Bayfield County, Wisconsin

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## Abstract

*The Terra–Patrick #7-22 wildcat well in Keystone Township (SW¼ SW¼ NE¼ sec. 22, T47N, R6W), Bayfield County, Wisconsin, provided an excellent opportunity to examine the stratigraphy of the Keweenawan clastic rift-fill sequence (Oronto Group) in this part of the Midcontinent Rift System trend.*

*Wireline logs from this well were very useful in the delineation of sediment "packages" as potentially correlatable "electro-stratigraphic" sequences that are reflective of lithology and depositional environment. The wireline logs are particularly useful in illustrating the gradational character of formation contacts in the Oronto Group in this area.*

*Geophysical logs of the Terra–Patrick #7-22 borehole allow the subdivision of the Oronto Group sediments into not only the three traditional formations (Freda, Nonesuch, and Copper Harbor Formations), but also two informal transitional units to the formations overlying and underlying the Nonesuch. Such transitional units contain lithologies typical of the underlying and overlying formations and reflect fluctuations in depositional environment, energy, and chemistry. These informal units identified are herein referred to as the Freda–Nonesuch Transition Zone and Nonesuch–Copper Harbor Transition Zone. Also of note is that even though hydrocarbon deposits were not discovered, the recordings from on-site chromatograph equipment indicated that hydrocarbon generation had occurred in the lower Nonesuch Formation.*

## Introduction

The Terra–Patrick #7-22 wildcat well in Keystone Township (SW¼ SW¼ NE¼ sec. 22, T47N, R6W), Bayfield County, Wisconsin, was drilled to explore for hydrocarbon accumulations that could be structurally or stratigraphically trapped in the subsurface. Although this well failed to identify commercial volumes of hydrocarbons, it does provide an excellent opportunity to examine the stratigraphy of the Keweenawan clastic rift-fill sequence (Oronto Group) in this part of the Midcontinent Rift System trend. This is particularly important due to the general lack of continuous surface outcrops in northwest Wisconsin suitable for measuring and describing the complete thickness of the rift sequence. The well was drilled and lithologically logged to a total depth of 4,966 ft and geophysically logged to a depth of 4,889 ft.

The reference depth datum for this well is the rotary kelly bushing, located on the drill-rig floor at an elevation of 879.8 ft above sea level. This reference datum was located 12.8 ft above the permanent ground level datum of 867.0 ft above mean sea level. Near total depth, borehole inclination reached a maximum recorded deviation from vertical of 16°, a condition probably exacerbated by structural dip. This condition created difficulties in borehole evaluation.

The data available for study in the Terra–Patrick #7-22 were limited to lithologic samples (drill cuttings) collected at 10-ft intervals from a depth of zero to 4,966 ft; a lithologic sample log (mudlog) that recorded factors such as characteristics of the drilling fluids, lithology by description and percentage, drilling rate in minutes per foot, and amounts of gas detected by the on-site chromatograph; and wireline logs (also known as borehole geophysical logs). The wireline suite, logged by Halliburton Logging Services, Inc., consisted of spectral gamma ray and neutron radioactivity, density, induction and lateral electric, acoustic, and dipmeter surveys. The gamma ray and acoustic logs were the most useful in analysis of this borehole. In addition, thin sections of grain mounts were available, but problems with the lithologic samples from which these were made precluded extensive quantitative analysis.

## PROBLEMS OF DATA QUALITY AND BOREHOLE EVALUATION

### *Quality of lithologic samples*

Detailed evaluation of drill-cutting samples was difficult due to apparent sample collection problems related to borehole conditions and the drilling process. Most of the samples were interpreted to be excessively contaminated with cavings from higher stratigraphic intervals. This interpretation is based on the pervasive presence of red siltstone, characteristic of the Freda Formation, from a depth of 3,528 ft (geophysical log top of the Nonesuch Formation) to 3,732 ft (mudlog top), and the periodic recurrence of these lithologies farther downhole. Other problems included the predominance of fine to very fine grain size of the individual cuttings, suggesting that the material may have been recirculated. The lack of discrete sand grains or cuttings of sandstone with a grain size exceeding the fine-grained class was also a problem. The latter situation typically occurs when samples are not collected from a sluice box or when excessive weight is placed on the drill bit. Other problems included the presence of lost circulation material in the cuttings and heavy contamination of the samples by cavings.

### *Correlation of lithologic samples to borehole depth*

The lithologic samples collected at the surface are interpreted to be improperly corrected to subsurface depths (lagged). This situation may result from the hydraulic shape factor of the more plate-shaped rock fragments (cuttings originating at the same depth can rise to the surface at a different rate than the associated gas and at different rates from each other due to the cuttings geometry), difficulties with the viscosity of the mud system, and/or other adverse conditions encountered at the well site. In particular, low drilling mud viscosity will contribute to drill cuttings being ineffectively swept from the borehole and often results in improper lag calculations relative to carbide lag tests.

### *Correlation of lithologic sample log (mudlog) to wireline logs*

Inaccurate sample lag times contributed to imprecise mudlog vs. gamma log formation top picks for the Freda Formation–Nonesuch Formation contact of 3,732 ft vs. 3,528 ft, respectively, a 204-ft difference. Similarly, picks of the Nonesuch Formation–Copper Harbor Formation contact of 4,168 ft on the sample log vs. a gamma ray log pick of 4,093 ft reflects a 75-ft difference. Frequent weight-on-bit variations ($\pm$5000 psi) precluded accurate drilling-time log to gamma ray log correlations. However, within intervals of constant drilling rate (constant weight on bit and revolutions-per-minute), fluctuations in drilling time may be reflective of changes in lithology, bedding thickness, or degree of cementation. Under such controlled conditions, drilling rate fluctuation can provide an approximate estimate of vertical lithologic heterogeneity within a borehole.

### *Wireline logs*

Because of the stated problems with the drill cuttings and resulting sample log of the Terra–Patrick #7-22 well, this study determined that the wireline logs were the best tools for evaluation of the general stratigraphic succession and the interpretation of depositional environments. However, these tools also had limitations due to difficulties experienced with maintaining drilling fluid and borehole integrity. The two major impacts were the following:

- Iron minerals were not effectively removed from the drilling mud. This resulted in variable invasion and contamination of permeable zones, essentially rendering the density, lithol-

**Table 1.** *Formation tops and thicknesses from wireline logs of the Terra–Patrick #7-22 borehole, Bayfield County, Wisconsin. Formation thickness measurements are not corrected for either structural dip of the formations or the variable inclination of the borehole.*

| Stratigraphic unit | Log depth[1] | Elevation of unit top[2] | Apparent thickness |
|---|---|---|---|
| Glacial drift ["GD"] | 13 ft | +867 ft | 277 ft |
| Freda Fm. ["F"] | 290 ft | +590 ft | 2,877 ft |
| Freda–Nonesuch Transition Zone ["F/NTZ"] | 3,167 ft | -2,287 ft | 361 ft |
| Nonesuch Fm. ["N"] | 3,528 ft | -2,648 ft | 403 ft |
| Nonesuch–Copper Harbor Transition Zone ["N/CHTZ"] | 3,931 ft | -3,051 ft | 162 ft |
| Copper Harbor Fm. ["CH"] | 4,093 ft | -3,213 ft | 873 ft |

[1]Measured from rotary kelly bushing.
[2]Measured from sea level.

ogy (photoelectric factor, or PEF), and resistivity–conductivity logs nondiagnostic.

▼ Numerous borehole washouts exceeded 13 in. This condition precluded the logging tool sensor pads from contacting the wall of the borehole, resulting in nondiagnostic readings on the neutron and density logs.

## STRATIGRAPHY

### *Introduction*

From older to younger, the Oronto Group of Middle Proterozoic age consists of the Copper Harbor, Nonesuch, and Freda Formations, the targeted drilling objectives. This sequence of formations represents a classic fluvial-lacustrine-fluvial sedimentary rift-fill sequence, deposited in direct response to the tectonic regime creating the Midcontinent Rift System. Rock sequences that are similar, at least in part, to the Oronto Group were created by similar environments of deposition and are known to occur elsewhere along the Midcontinent Rift System (Anderson, 1990).

In this study it was possible to refine the vertical succession of the Oronto Group on the basis of the character of the wireline logs, especially the gamma ray log. Two additional stratigraphic units were defined by using wireline logs. These informal units are interpreted to be transitional zones containing lithologies typical of the underlying and overlying formations and reflect fluctuations in depositional environment, energy, and chemistry. The existence of such transitional units proves the gradational character of the formation contacts within the Oronto Group in the subject area. The wireline log formation tops and apparent thicknesses of the Oronto Group and the two additional subdivisions are interpreted to represent transitional sedimentary packages (table 1). Only apparent thickness measurements are provided because corrections have not been made for either structural dip of the formations or the variable inclination of the borehole. A dipmeter survey was conducted from the base of the borehole to a log depth of 2,030 ft (lower Freda). This survey indicates apparent structural dip amounts of about 20° to 30°, generally to the south or southeast, to be common. The most consistent dip data (typically 20°–22°) were recorded in the Nonesuch Formation and the two transitional zones.

### *Copper Harbor Formation*

The Copper Harbor Formation is a basinward-thickening wedge of ferruginous volcanogenic

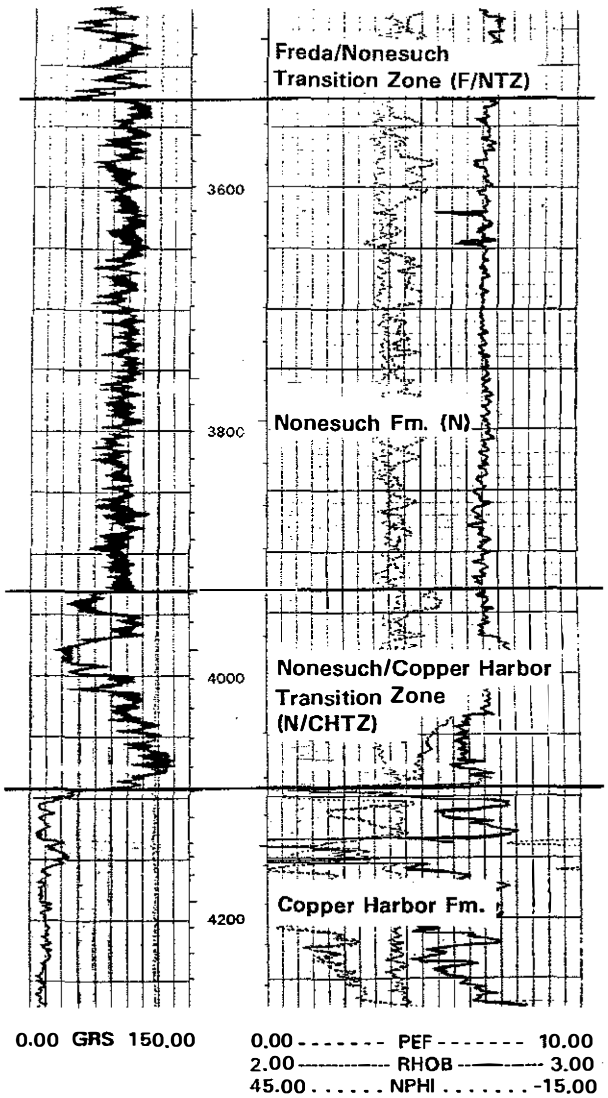


**Figure 1.** *Log character of the upper Copper Harbor Formation, Nonesuch–Copper Harbor Transition Zone, and Nonesuch Formation, Terra–Patrick #7-22 borehole, Bayfield Co., Wisconsin. GRS = Spectral Gamma Ray (API); NPHI = neutron porosity (%); PEF = photoelectric factor; RHOB = density (gm/cc).*

clastics that become finer-grained distally (basinward) and vertically (upsection). Subordinate volcanics occur near the base of the unit. The maximum known thickness of this unit exceeds 4,333 ft near Calumet on the Keweenaw Peninsula of Michigan (White and Wright, 1960). The general depositional environment of the Copper Harbor is that of a prograding alluvial fan complex, possibly deposited under monsoonal conditions (Elmore and Daniels, 1980; Daniels, 1982; Elmore, 1983, 1984; Catacosinos and Daniels, 1991). Part of this complex fits braid-delta models; other parts exhibit fan-delta components (Daniels and Elmore, 1988).

As illustrated in figure 1, the top of the Copper Harbor Formation was picked on the Spectral Density/Dual-Spaced Neutron/Spectral Gamma Ray Log at a depth of 4,093 ft. The logged thickness of the Copper Harbor in this borehole was 873 ft. In general, the gamma ray signature of the Copper Harbor Formation is low, clean, and blocky. The readings are consistent, with few readings greater than 15 API units. These are the lowest bedrock gamma ray readings recorded in the well and indicate that the logged part of the formation at this location contains low percentages of potassium feldspars or clay-size materials. Porosity in the Copper Harbor Formation was calculated from the Long Spaced Sonic log. Porosity ranges from 0 to 6 percent, with 3 percent being common.

A generalized lithology for the Copper Harbor Formation at this location is as follows:

- ▼ Sandstone (95%+): Clear; very fine grained; subangular to rounded; slight calcite cementation.
- ▼ Siltstone: Red-brown, dark red-brown; firm to hard; shaly; possibly recirculated and reworked cavings.
- ▼ Vein quartz: White with orange iron staining, in part; angular; decreasing with depth.
- ▼ Vein calcite (trace): White.

Examination of thin-section grain mounts by D. Barnes (Western Michigan University, written communication, March 1994) revealed the presence of red, oxidized, micaceous siltstone throughout this interval. According to Barnes, also present are "basaltic volcanic rock fragments with various, generally low grade, alteration material, including; chalcedony, clinoptilolite, heulandite (?), chlorite, epidote, calcite, and possibly laumontite."

It is interpreted that the uppermost part of the

Copper Harbor Formation changes to a fining-upward sequence because of a decrease in hydraulic gradient due to local base level rise caused as the Nonesuch "lake" transgressed onto the Copper Harbor alluvial fan. The Copper Harbor contact appears gradational on the wireline logs, and marks the initiation of a transitional facies between the Copper Harbor Formation and the overlying Nonesuch Formation. A fine-grained facies overlying the contact marks the initial onlap of progradational lacustrine facies at this location.

### *Nonesuch–Copper Harbor Transition Zone*

The stratigraphic interval between 3,931- and 4,093-ft log depth represents a sedimentary sequence interpreted to be transitional between predominantly fluvial depositional environments that are characteristic of the Copper Harbor Formation, and the lacustrine depositional environment characteristic of the Nonesuch Formation. In this paper I informally call that interval the Nonesuch–Copper Harbor Transition Zone (fig. 1). Porosity in the Nonesuch–Copper Harbor Transition Zone was calculated from the Long Spaced Sonic log. Porosity of the sandstone units within the Nonesuch–Copper Harbor Transition Zone averages approximately 1 percent in the lower progradational member and about 3 percent in the upper sandstone unit.

Immediately overlying the upper Copper Harbor Formation contact is approximately 31 ft of shale and siltstone with a gamma ray signature exceeding 120 API units. These are the highest gamma readings seen in the borehole, and they exist, at least in part, because of increased potassium content. Also, the gamma ray log through this interval may indicate an organic facies of increased total organic carbon. If this is the case, it would be consistent with field observations of outcrops where shale facies of the darkest color and greatest fissility development commonly occur in a 30-ft thick zone that immediately overlies the Copper Harbor Formation.

The high-gamma facies noted above is overlain by an additional 26 ft of formation with an average gamma reading exceeding 105 API units. At this point (4,036 ft), the gamma ray log signature (Serra, 1985) is interpreted to indicate the incipient development of a probable fan delta that is fully developed at a depth of 3,990 ft and culminates at a depth of 3,969 ft. A secondary fluvial pulse of coarser-grained clastics into the lacustrine environment occurs between the log depths of 3,949 ft and 3,951 ft. Correlation with the Spectral Gamma Ray log indicates that the potassium percentage in these sediments decreases upsection in an inverse ratio to delta development. It is apparent from the wireline log that delta progradation was insufficient to keep ahead of the deepening lake because approximately 20 ft of lacustrine facies of an average gamma count of between 90 to 100 API units directly overlies the delta facies. However, before the final encroachment of lacustrine deposition at this location, an additional 18 ft of deltaic sediments was deposited as the final progradational event of the delta. This depositional event terminated the Nonesuch–Copper Harbor Transition Zone at a depth of 3,931 ft.

Examination of a thin-section grain mount within this interval revealed a dominance of green to colorless (unoxidized) siltstone and "the one true mudstone" (D. Barnes, Western Michigan University, written communication, March 1994), the color of which ranges from dark amber to brown-black. Barnes reports that this rock is fissile and organic-rich.

### *Nonesuch Formation*

Overlying the Nonesuch–Copper Harbor Transition Zone is approximately 403 ft of sediments representing the Nonesuch Formation. The Nonesuch is an unoxidized sequence of gray-black siltstone, fine-grained sandstone, and shale. In certain areas, the Nonesuch is petroliferous and/or metalliferous.

At the location of this borehole, the Freda–Nonesuch contact is gradational to such an extent, and the environment of deposition sufficiently transitional, that picking any upper contact from the drill-cutting samples is, at best, equivocal. Consequently, the top of the Nonesuch Formation was picked from the gamma ray log at a depth of 3,528 ft (fig. 1). Confirmation of this formation top is provided by a significant increase in potassium content, as shown on the Spectral Gamma Ray log. Gamma ray log values through the Nonesuch interval have a range of 70 to 110 API units (with only two small excursions below 75 API). The average value through this interval exceeds 90 API units and represents the highest average gamma ray value recorded in the borehole. This high and consistent gamma ray signature is primarily due to elevated potassium values of 5 to 7 percent. Such potassium values are about 50 percent higher than those noted for the Freda Formation, and at least five times the values for the Copper Harbor Formation at this location. Average porosity in the Nonesuch Formation, as determined from the Long Spaced Sonic log, ranges from 10 to 13 percent.

A gross generalized lithology for the Nonesuch Formation at this location is as follows:

- Siltstone and mudstone (70%±): Light to medium gray; red-brown and dark red-brown (possible reworked cavings); firm to hard; dense; calcareous, in part.
- Shale (30%±): Medium to dark brown, black, gray-brown; silty; platy-blocky; thinly laminated and brittle, in part; firm to hard; dense; calcareous, in part; with white vein calcite.
- Sandstone (trace): Clear; very fine to fine grained; shaly; poor sorting; subrounded to round.

Examination of thin-section grain mounts from the Nonesuch Formation interval revealed that it is dominated by green or colorless (unoxidized) micaceous siltstone (D. Barnes, Western Michigan University, written commmunication, March 1994).

High gamma ray readings the magnitude of those found in the Nonesuch are commonly interpreted to be indicative of quiet water sedimentation of siltstone and shale from suspension in a low energy depositional environment (for example, standing water). Above the 3,528-ft depth, the wireline log records a marked increase in the variability of gamma ray values. The environment of deposition for the Nonesuch is interpreted to be a series of anoxic, rift-flanking, lacustrine basins thought to exist along much of the length of the Midcontinent Rift System (Daniels, 1981, 1982, 1986; Daniels and Elmore, 1988; Elmore and others, 1988; Catacosinos and Daniels, 1991).

### *Freda–Nonesuch Transition Zone*

Overlying the Nonesuch Formation, as defined above, is a sedimentary package referred to in this paper as the Freda–Nonesuch Transition Zone (fig. 2). The top of this interval is picked from the gamma ray log at a depth of 3,167 ft.

Within the Freda–Nonesuch Transition Zone there is evidence of fining- and coarsening-upward sequences, as illustrated by the gamma ray log. A relatively thin-bedded character for this unit is indicated by the variation in the drilling time log. As previously noted, gamma ray log variability significantly increases above the 3,528-ft depth. Although the interval gamma ray values range from approximately 110 to 44 API units, a 66-API unit range with 13 readings had values below 90 API units. Porosity in the Freda–Nonesuch Transition Zone was determined from the Long Spaced Sonic log, and averages approximately 6 percent in the sandstone units.

Containing elements similar to the overlying and underlying formations, this sediment package is interpreted to be transitional between the lacustrine Nonesuch and the fluvial Freda environments.

### *Freda Formation*

Conformably overlying the Freda–Nonesuch Transition Zone is the Freda Formation (3,167–290 ft). The Freda mainly consists of stacked cyclic sequences of red-brown sandstone, siltstone, mudstone, and shale (conglomerates are rare). Like the underlying Freda–Nonesuch Transition Zone, the Freda Formation contains fining- and coarsening-upward sequences.

A gross generalized lithology for the Freda Formation at this location is as follows:

- Siltstone (95%): Red-brown, purple, some gray-green (reduced); soft to firm, friable in part; shaly and sandy in part; micaceous; with sandstone: clear; very fine to medium grained; sub- to well rounded; poor to moderate sorting; slight calcite cementation; with a trace of sandstone: clear; coarse grained; very angular; silica cemented.

- ▼ Sandstone (5%): Light gray, colorless, red-brown, orange, gray-green; very fine to medium grained; poor sorting; angular to subrounded; shaly; some clay matrix and calcite cement.

Examination of thin-section grain mounts from the Freda Formation indicated an abundance of red (oxidized) micaceous siltstone and the presence of green to clear micaceous siltstone, microcline feldspar, and lithic rock fragments (D. Barnes, Western Michigan University, written communication, March 1994). Porosity in the Freda was determined from the Long Spaced Sonic log and commonly averages approximately 7 to 10 percent in the sandstone units. Above an approximate depth of 2,525 ft, the typical porosity in the mudstone units is 21 percent. Below this depth, mudstone porosity decreases to about 14 percent.

The depositional environment for the Freda is interpreted to be predominantly various braided stream facies. These deposits initially interfingered with, and ultimately prograded over, the Nonesuch sediments (Daniels, 1982; Daniels and Elmore, 1988; Catacosinos and Daniels, 1991).

### *Pleistocene glacial sediment*

The base of the glacial sediment (also called glacial drift) is recorded on the lithologic sample log at 290 ft below datum (277 ft below ground level). The glacial cover as described on the mudlog, compiled by Tarrant Mudlogging Consultants of Traverse City, Michigan (1992), is composed of various light-colored (oxidized) heterogeneous mixtures of clay, sand, and gravel. Zones comprised predominantly of clay are recorded at depths of 0 to 40 ft, 100 to 140 ft, and 192 to 240 ft. Zones of sand and gravel occur between these depths and between 240 to 290 ft.

## Discussion

### *Gas chromatograph readings*

The on-site gas chromatograph recorded elevated levels of natural gas while drilling through the lower Nonesuch Formation and the Nonesuch–Copper Harbor Transition Zone. The gas chromatograph was calibrated for methane such that a gas concentration of 1% = 10,000 ppm = 100 units of gas on the log. Typical initial methane readings were recorded on the log at a depth of 3,831 ft with ethane being recorded at 3,832 ft, normal (N) butane at 3,833 ft, propane at 3,834 ft, and isobutane at 3,836 ft. All these hydrocarbons probably exist in the formation at the same

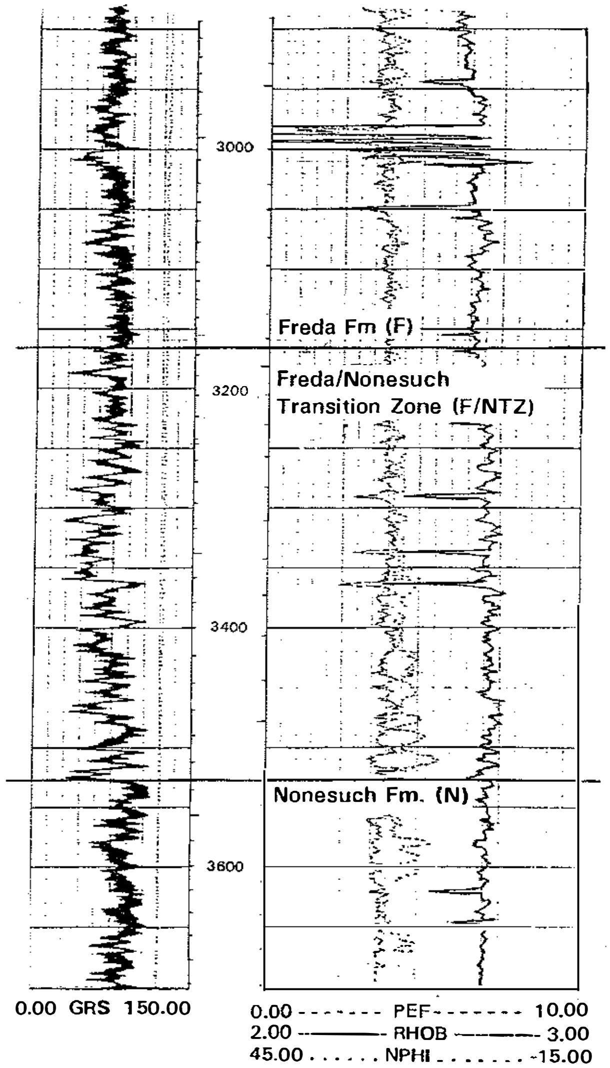


**Figure 2.** *Log character of the Freda–Nonesuch Transition Zone and lower Freda Formation, Terra–Patrick #7-22 borehole, Bayfield Co., Wisconsin. GRS = Spectral Gamma Ray (API); NPHI = neutron porosity (%); PEF = photoelectric factor; RHOB = density (gm/cc).*

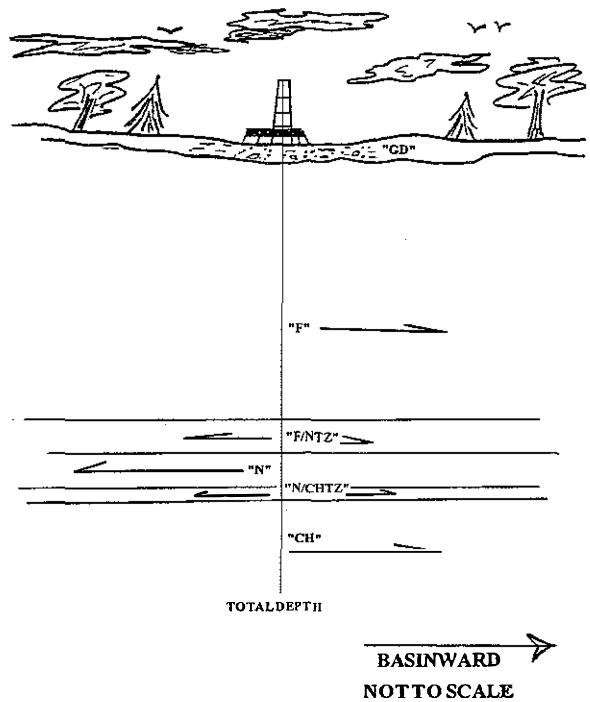


**Figure 3.** *Schematic stratigraphic model illustrating the sedimentary sequences penetrated by the Terra–Patrick #7-22 borehole, Bayfield County, Wisconsin. Arrows indicate relative direction of stream flow and/or lacustrine regression/progradation, as appropriate. GD: Glacial drift; F = Freda Formation; F/NTZ = Freda–Noneshuch Transition Zone; N = Nonesuch Formation; N/CHTZ = Nonesuch–Copper Harbor Transition Zone; and CH = Copper Harbor Formation. Not to scale.*

depth, but with a longer time being required for the heavier compounds to arrive at the surface and be detected. Also, it is probable that depth control for the gas was better than that for the drill cuttings. This is possible due to the similarity in performance and behavior of the formation gas to the gas released by the carbide lag tests. Control on the lag time of gas is provided by a timed carbide test detected and recorded at 3,638 ft.

The on-site chromatograph detected a maximum methane reading of 39 units (3,900 ppm, or 0.39%) at a depth of 3,867 ft. Elevated gas readings, generally between 10 to 20 units, persisted to 4,008 ft and then gradually decreased to a background level of two units at a depth of 4,084 ft. This background level was maintained until well termination at total depth. These gas readings may be conservative because two holes were later discovered in the drillpipe. The chromatograph readings showed that hydrocarbon generation had occurred, although other hydrocarbon indicators (fluorescence and solvent cut) were not observed and no commercial hydrocarbon deposits were discovered.

### *Oronto Group stratigraphy*

Two major sequences of lacustrine regression, separated by a period of lacustrine progradation, are recognized in the Oronto Group at the location penetrated by the Terra–Patrick #7-22 borehole (fig. 3). The stratigraphically lower lacustrine regression is interpreted to have coincided with the deposition of the Copper Harbor Formation, and the upper regression is interpreted to coincide with deposition of the Freda Formation. The lacustrine progradation, or high-stand, is marked by deposition of the Nonesuch Formation. These interpretations are based on regional stratigraphic relationships (Daniels, 1982; Daniels and Elmore, 1988; Elmore, and others, 1988; Catacosinos and Daniels, 1991) and interpretations of depositional environments indicated by wireline logs from the Terra–Patrick #7-22 borehole.

### *Comparison with other locations*

***Amoco M.J. Eischeid #1, Carroll County, Iowa.*** The Keweenawan sequence penetrated by this borehole has been divided into upper and lower depositional packages informally referred to as the Upper and Lower "Red Clastic" Sequences (Witzke, 1990). The Upper Red Clastic Sequence is reported to be generally similar to the Bayfield Group of northern Wisconsin and Michigan. The Lower Red Clastic Sequence, which is subdivided into three informal units (B, C, and D), is reported by Witzke (1990) to be very similar to the Oronto Group with the exception that ". . . reduced gray to black shales occur in all units of the lower sequence in varying lithologies. . . ." The lowest unit of the Lower Red Clastic Sequence, Unit B, is lithologically sandstone dominated and occupies a similar stratigraphic position to the Copper Harbor Formation, but is reportedly (Witzke, 1990) much more texturally and compositionally mature. The overlying Unit C is noted as differing from "... all other Keweenawan units by the general abundance of gray to black shales and siltstones." (Witzke, 1990). The stratigraphically highest unit of the Lower Red Clastic Sequence, Unit D, is a thick fining-upward sequence that is dominantly sandstone in the lower half and siltstone and shale dominated in the upper half (Witzke, 1990). This general lithologic sequence is similar to that for the Freda Formation.

Significant similarities and differences between the Lower Red Clastic Sequence in the Iowa borehole and the Oronto Group formations penetrated in the Terra–Patrick #7-22 borehole in Wisconsin include the following:

- Lithologies interpreted to indicate the presence of similar depositional environments are present in both boreholes.
- Chemically reduced lithologies (gray to black siltstones and shales) occur in the Lower Red Clastic Units B, C, and D). Such lithologies are reported by Witzke (1990) to be generally more abundant in Unit C, thus raising the possibility that Unit C may represent a Nonesuch equivalent.
- Sandstones of the Lower Red Clastic Sequence contain fewer rock fragments than those in the Upper Sequence, and reportedly (Ludvigson and others, 1990) contain fewer volcanic grains. According to Ludvigson and others (1990), Unit B is the most quartz rich and is not known to contain conglomerates. In comparison, the Oronto and Bayfield Groups generally become more compositionally and/or texturally mature upsection.
- Some sandstone descriptions (Unit D) and chromatographic analyses (Units B, C, and D) indicated the presence of relict hydrocarbons in the Amoco M.J. Eischeid #1 (Witzke, 1990). Traces of hydrocarbons were also detected in the Nonesuch Formation in the Terra–Patrick #7-22 borehole.
- Borehole deviations exceeding 15° in the Keweenawan sequences characterized both boreholes and are interpreted to reflect structural complexities.

***McClure–Sparks #1-8, Gratiot County, Michigan.*** Keweenawan age sediments within the Midcontinent Rift System structural trend are also known from the McClure–Sparks #1-8 well in Gratiot County, Michigan. This Midcontinent Rift System well, centrally located in southern peninsular Michigan, penetrated more than 5,290 ft of pre-Mount Simon clastics (Fowler and Kuenzi, 1978). These sediments are considered time equivalents of the Freda Formation (Catacosinos, 1981; Fisher and others, 1988). The overall depositional environment of these rocks is equivocal, alternatively considered marine turbidites (Fowler and Kuenzi, 1978), continental lacustrine (Catacosinos, 1981), or fluvial (Ojakangas and Morey, 1982).

## SUMMARY AND CONCLUSIONS

The deviated and washed-out condition of the borehole greatly diminished the utility of traditional lithologic sample and thin-section grain-mount analysis and prohibited detailed comparison with similar sedimentary sections in other parts of the Midcontinent Rift System. Apart from these conditions, however, important findings from the analysis of the well-site data include the following:

- Wireline logs have proven very useful in the delineation of sediment "packages" as potentially correlatable "electro-stratigraphic" sequences that are reflective of lithology and depositional environment. Such logs are particularly useful in illustrating the gradational character of formation contacts in the Oronto Group in this area.
- The Oronto Group sediments penetrated by the Terra–Patrick #7-22 borehole can be subdivided into the three traditional formations (Freda, Nonesuch, and Copper Harbor Formations). In addition, two informal transitional units to the formations overlying and underlying the Nonesuch, referred to here as the Freda–Nonesuch Transition Zone and Nonesuch-Copper Harbor Transition Zone, are

identified. These transitional units contain lithologies typical of the underlying and overlying formations, reflecting fluctuations in depositional environment, energy and chemistry.

- ▼ Readings from on-site chromatograph equipment indicated that hydrocarbon generation had occurred, even though hydrocarbon deposits were not discovered.

## ACKNOWLEDGMENTS

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# Chapter 8. Evaluation of the petroleum source-rock potential of the Middle Proterozoic Nonesuch Formation, Terra–Patrick #7-22 borehole, Bayfield County, Wisconsin

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## Abstract

*The Terra–Patrick #7-22 wildcat well, Bayfield County, Wisconsin, was drilled in March 1992 to test the petroleum source-rock potential of Middle Proterozoic sediment of the Midcontinent Rift System. Rock-Eval pyrolysis assay was performed on 25 samples of cuttings, 22 of which are from the 436-ft section of the Nonesuch Formation. Each sample represented one 10-ft interval. Total organic carbon (TOC) content ranged from below detection limits to 0.44 percent and averaged 0.1 percent. These values may be minimum values due to the potential of mixing of up-hole cavings into the samples or due to the presence of thin, organic-rich beds within thicker, red-brown, organic-lean rocks in some 10-ft intervals of the Nonesuch Formation. The potential impact of mixtures of organic-lean and organic-rich lithologies on source-rock parameters was tested by high-grading one duplicate sample by hand-picking chips of individual gray cuttings. In the duplicate analysis, the TOC increased from 0.1 to 0.44 percent.*

*Of the 22 samples of Nonesuch Formation analyzed, only three gave apparently reliable maximum temperature ($T_{max}$) and hydrogen index (HI) values, which averaged 438°C and 190, respectively. The data indicated that these rocks are marginally mature with respect to hydrocarbon generation, consistent with maturities measured by previous workers on samples from other localities in the northern part of the Midcontinent Rift System.*

*The low average TOC value, the average HI of 190, and genetic potentials within the poor category of source potential suggest that the Nonesuch Formation at this locality has little potential to generate commercial quantities of hydrocarbons.*

## Introduction

For more than a decade, the Middle Proterozoic Midcontinent Rift System of North America has been considered a frontier area for petroleum exploration (Lee and Kerr, 1984). The organic-rich shales in the Nonesuch Formation of the Middle Proterozoic Midcontinent Rift System are known to have potential to generate petroleum and are identified as the source of oil in the workings of the White Pine Copper Mine, Michigan (Mauk and others, 1992; Mauk and Hieshima, 1992). The organic geochemical characteristics of the Nonesuch Formation and correlative units are known at a number of localities along the length of the Midcontinent Rift from Kansas (Newell and others, 1993) to Iowa (Palacas and others, 1990) and Minnesota (Hatch and Morey, 1985), with the most extensive work on outcrop, mine, and core material in Wisconsin and Michigan (Barghoorn and others, 1965; Eglinton and others, 1964; Elmore and others, 1989; Hieshima and Pratt, 1991; Ho and others, 1990; Hoering, 1976; Imbus and others, 1990; Imbus and others, 1988; Mauk and others, 1992; Mauk and Hieshima, 1992; Pratt and others, 1991).

The Terra–Patrick #7-22 well was drilled in

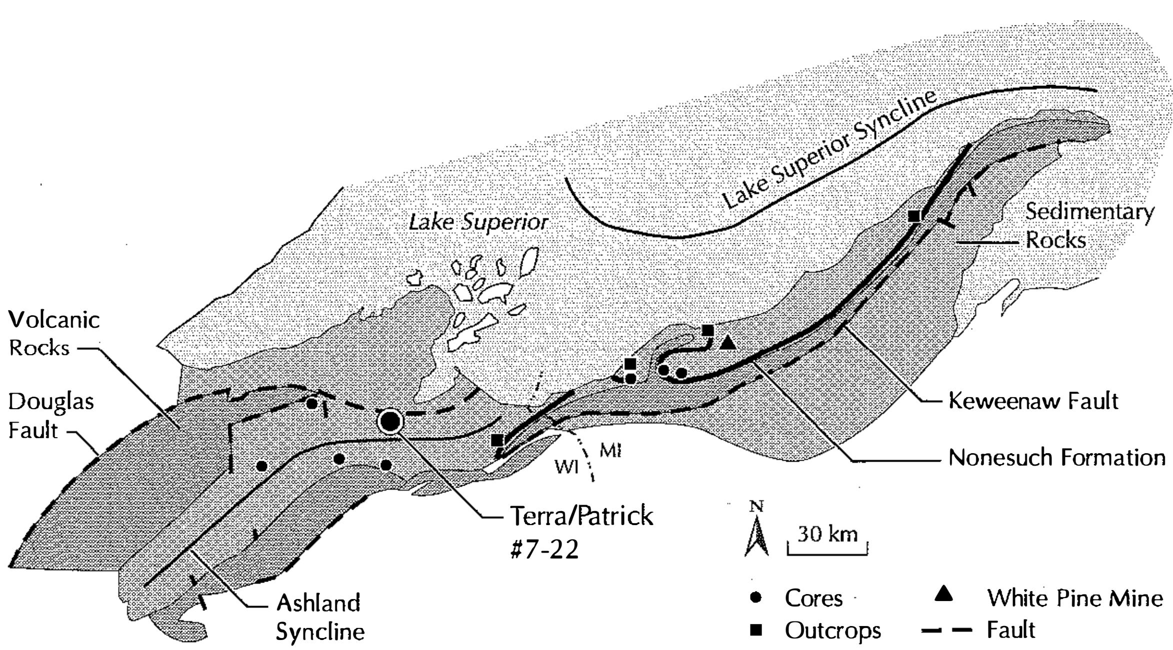


**Figure 1.** *Map showing the location of the Terra–Patrick #7-22 borehole, the general geology, and the location of core and outcrop localities sampled by other investigators in northern Wisconsin (WI) and Michigan (MI) near Lake Superior. Modified from Imbus and others (1990).*

March 1992, in Bayfield County, Wisconsin (fig. 1), in a previously untested part of the Midcontinent Rift. The well site's geologic setting is presented by Allen and others in chapter 4 of this volume. This report evaluates the petroleum source-rock potential of the Nonesuch Formation at this locality.

## Methods

Samples of washed cuttings at 10-ft intervals were provided to us in paper envelopes. Every other sample (one sample in each 20-ft interval) from the base of the Freda Formation through the Nonesuch Formation to the top of the Copper Harbor Formation was selected for analysis. Examination under a low-power stereo microscope showed that the samples were contaminated with metallic particles, plastic fibers, and, in some cases, small patches of woven material. The fibrous material may be a residue of material used during drilling to control circulation loss (Daniels, ch. 7, this volume). Iron-rich metallic particles were removed with a hand-held magnet. Plastic fibers were removed by repeated flotation in deionized water. After drying overnight at room temperature, samples were re-examined under the microscope and a 1 to 2 g aliquot separated for grinding. Any obvious fibers remaining in this aliquot were removed by hand under the microscope. Samples were powdered in an agate mortar and pestle and stored in glass vials prior to analysis.

All 25 samples were dominated by red to red-brown siltstone chips. It was impossible to identify a distinct lithologic break between the cuttings of the Freda Formation and the underlying Nonesuch Formation. The proportion of gray siltstone chips did appear to increase with depth in the Nonesuch Formation cuttings. No attempt was made to select only gray siltstone chips for source-rock evaluation because it was impossible to distinctly identify up-hole cavings that could be justifiably removed from individual samples. In a few cases, however, unusually large red-brown chips of cuttings that may be up-hole cavings were removed from the samples prior to grinding.

Daniels (ch. 7, this volume) indicated that samples of cuttings from the Terra–Patrick #7-22 borehole within the Nonesuch Formation are "excessively contaminated with cavings from upper stratigraphic intervals." His interpretation is based on "the pervasive presence of red siltstone, charac-

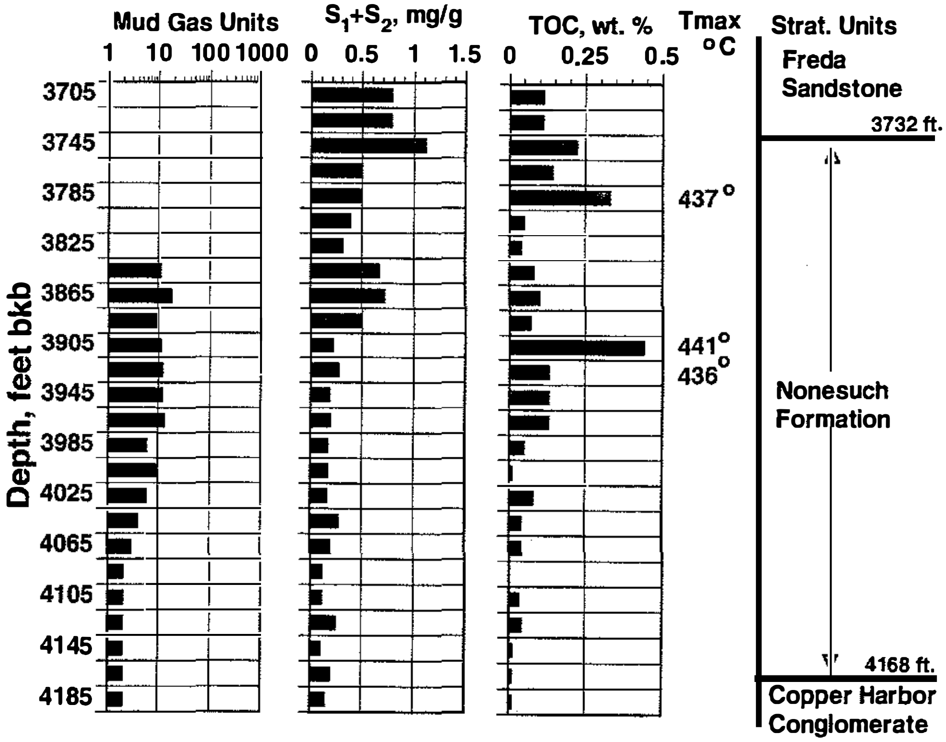


**Figure 2.** *Plot of geochemical parameters measured on cuttings samples as a function of depth and stratigraphic position in the Terra–Patrick #7-22 well. Mud-gas units are from the driller's log (10 units = 1,000 ppm). The mud-gas value at each depth is the average for the 10-ft interval for which cuttings were analyzed by Rock-Eval pyrolysis. TOC = total organic carbon in weight percent. $S_1$+$S_2$ = genetic potential in mg HC/g TOC; $S_1$ = amount of volatile hydrocarbons released; $S_2$ = amount of hydrocarbons generated by pyrolytic degradation of kerogen; $T_{max}$ = temperature at which the maximum amount of $S_2$ hydrocarbons is generated; bkb = below kelly bushing. Depths are mudlog depths. To correlate with geophysical log depths, see discussion in text and Daniels (ch. 7, this volume).*

teristic of the Freda Formation, from a depth of 3,528 ft (geophysical log top of the Nonesuch Formation) to 3,732 ft (mudlog top), and the periodic recurrence of these lithologies farther downhole."

Source-rock properties were evaluated using Rock-Eval pyrolysis assay methods. Pyrolysis data were obtained with a Rock-Eval II instrument. The data were evaluated using published methods (Espitalié and others, 1977; Katz, 1983; Peters, 1986; Philp and Galvez-Sinibaldi, 1991).

The Rock-Eval pyrolysis assay of source-rock potential is generally used as a screening technique to identify the intervals of highest hydrocarbon source potential. These samples are then analyzed by more sophisticated methods based on solvent extraction of the rich intervals with analysis of the extracts by gas chromatography and gas chromatography–mass spectrometry. As discussed below, the samples from the Terra–Patrick #7-22 well showed poor source-rock potential and did not warrant additional analysis.

## Results

The parameters used to evaluate hydrocarbon source-rock potential include total organic carbon (TOC), genetic potential ($S_1$+$S_2$, in mg/g), hydrogen index ($S_2$/TOC), and $T_{max}$. These parameters and mud-gas measurements are plotted as a function of depth and stratigraphy in figure 2. For comparison, the range and average values of TOC and genetic potential published for all samples from the Midcontinent Rift System and the Late Proterozoic Walcott Member of the Kwagunt Formation of the Chuar Group, Grand Canyon, USA, are shown in figure 3. Total organic carbon content of the Nonesuch Formation in the Terra–Patrick

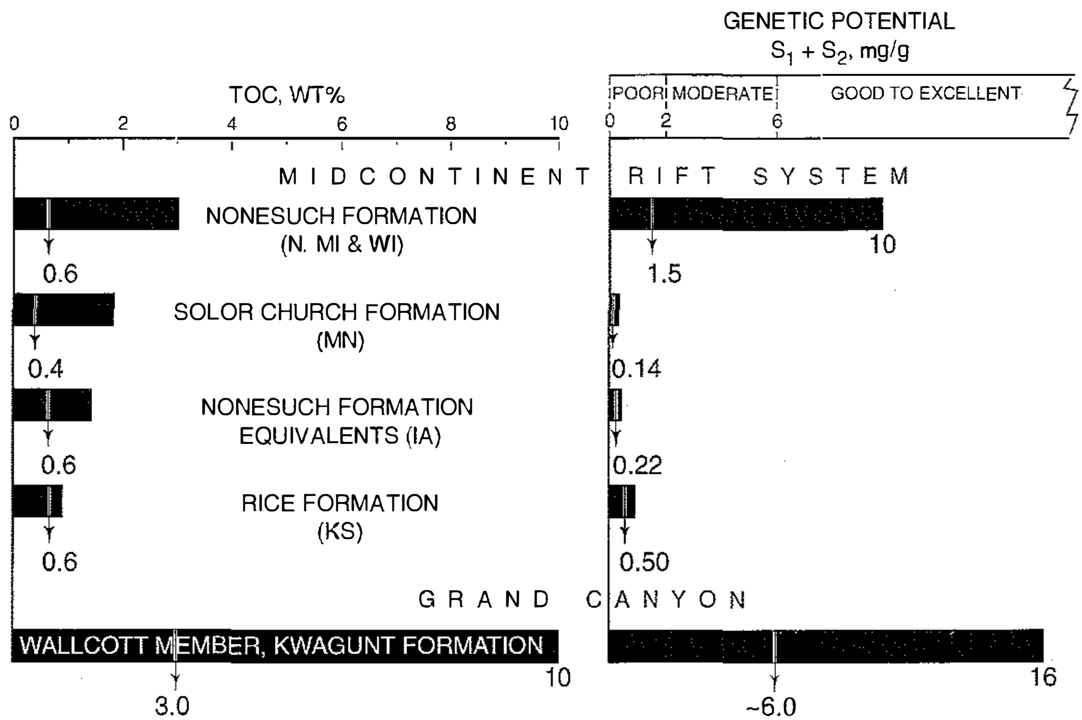


**Figure 3.** *Bar chart showing the range and average values of TOC and genetic potential measurements on sediments from four localities in the Midcontinent Rift. In addition, values for the Late Proterozoic Walcott Member of the Kwagunt Formation of the Chuar Group sediments in the Grand Canyon, Arizona, USA, are shown for comparison. The value below the arrow in each bar is the average for that formation. N. MI=northern Michigan; WI=Wisconsin; MN=Minnesota; IA=Iowa; KS=Kansas. Data from Hatch and Morey (1985); Imbus and others (1988, 1990); Newell and others (1993); Palacas and Reynolds (1989); Palacas and others (1990); Pratt and others (1991).*

borehole ranges from below the limit of detection to 0.44 percent and averages about 0.1 percent (fig. 2). The average value of TOC for the Nonesuch Formation at this borehole is significantly lower than the averages for all other Midcontinent Rift System localities (fig. 3). For the Terra–Patrick #7-22 well, the average value of the genetic potential ($S_1$+$S_2$), 0.33 mg/g, although higher than that of some other localities shown in figure 3, is very low and well within the poor source-rock classification. In examining the Rock-Eval pyrograms of the Nonesuch Formation samples, we observed that low or questionable $S_2$ values (< 0.2 mg/g) commonly yielded meaningless hydrogen index (HI) values and hence are not reported. Three samples (3,780–3,790 ft, 3,900–3,910 ft, and 3,920–3,930 ft), however, provided apparently reasonable results, yielding HI values of 136, 227, and 207, respectively, with an average of 190. In general, the low TOC content and very low $S_1$ and $S_2$ yields made it difficult to interpret the Rock-Eval data as a function of depth at this locality.

Three duplicate samples were re-analyzed by Rock-Eval pyrolysis. Cuttings from two sample intervals (3,900–3,910 ft, and 3,920–3,930 ft) were combined into one aliquot and meticulously hand picked to select the darkest gray chips of cuttings. In this sample, the TOC value increased from 0.1 to 0.44 percent; the results from the other two samples were identical to the first bulk analysis of the sample interval. This suggests that some 10-ft samples of cuttings may be averages of interbedded, relatively thick, organic-lean, red-brown rocks (or cavings) and thin (0.5–2 ft) gray beds with higher TOC contents, possibly on the order of 1.0 to 2.0 percent TOC. The $T_{max}$ values of the three samples with acceptable pyrograms fall in the range 436°C to 441°C with an average of 438°C. This value is in the range of marginally mature source rocks.

In figure 2, sample depths are plotted according to mudlog depths. Caution should be exercised when correlating these depths to those picked by geophysical log responses. Daniels (ch. 7, this volume) showed that mudlog depths are inaccurate because of sample lag times. For example, the mudlog pick of the contact between the Freda and Nonesuch Formations is at 3,732 ft in contrast to the gamma-ray-log pick at 3,528 ft, a 204-ft difference. Similarly, at the contact between the Nonesuch and Copper Harbor Formations, the mudlog pick at 4,168 ft differs by 75 ft from the gamma-ray-log pick at 4,093 ft.

## Discussion

The TOC values and Rock-Eval pyrolysis parameters indicated that the Nonesuch Formation at the Terra–Patrick #7-22 well site has poor potential as a hydrocarbon source rock. The average TOC content (0.1%) at this locality is much less than the average TOC (0.6%) for all published measurements on shallow cores and outcrop samples of the Nonesuch Formation from northern Wisconsin and Michigan (fig. 3). These low values initially were unexpected because the increase in the mud-gas log response in Nonesuch Formation interval (fig. 2) suggested some source-rock potential in these rocks. This contrast could be caused by contamination of the cuttings from the Nonesuch Formation interval by up-hole cavings. Daniels (ch. 7, this volume) argued that the red, oxidized chips of cuttings originated as cavings from the overlying Freda Formation. If this is true, then the presence of extremely organic-lean red siltstone cavings, together with cuttings from indigenous, organic-lean thick interbeds, could mask the presence of thinner shale beds that have higher TOC contents. Higher TOC values (1% to possibly 3%) are reported by other investigators for samples of the Nonesuch Formation from nearby mineral exploration boreholes and outcrops (Hieshima and Pratt, 1991; Imbus and others, 1990; Imbus and others, 1988; Pratt and others, 1991)

The average $T_{max}$ value for those samples with a well defined maximum in the $S_2$ peak is 438°C. This value is essentially identical to the average value of 436°C from studies of shallow cores and outcrops (Imbus and others, 1990). These $T_{max}$ values indicated levels of thermal maturity that are marginally mature with respect to hydrocarbon generation.

The poor source-rock potential of the Nonesuch Formation at the Terra–Patrick #7-22 well locality strongly contrasts with previous published results throughout the northern Midcontinent Rift System that demonstrated a significant potential of the Nonesuch Formation to generate hydrocarbons (Hieshima and Pratt, 1991; Imbus and others, 1990; Imbus and others, 1988; Pratt and others, 1991). One possible explanation of this variability in source potential is the interpretation (Elmore and others, 1989) that the Nonesuch Formation has a lacustrine origin. Only the deepest lacustrine depositional environments allow accumulation of organic-rich sediments with significant source-rock potential. Laterally equivalent, marginal lacustrine environments with sediment accumulation in mudflats and sandflats or interfingering lacustrine and fluvial sediments are too oxidizing to accumulate organic-rich sediments. Geochemical evidence has suggested an alternative model for the depositional environment of the Nonesuch Formation as nearshore marine or estuarine (Heishima and Pratt, 1991; Pratt and others, 1991). This is also a setting in which there are strong controls on organic matter deposition and preservation by depositional environment. All of these depositional environments imply that we should expect lateral variations in the source-rock potential of the Nonesuch Formation. The strong dependence of source-rock quality on depositional environments in nearshore marine and lacustrine rocks suggests that a key component in identification of exploration prospects in the Midcontinent Rift System will be the relationship of possible traps to the distribution of organic-rich facies in the Nonesuch Formation.

## Conclusions

The Nonesuch Formation at the site of Terra–Patrick #7-22 well, Bayfield County, Wisconsin, has very low TOC content, averaging 0.1 percent over 10-ft thicknesses, and poor source-rock generative potential. On the basis of very limited $T_{max}$

data, we estimated that the thermal maturity at this locality is marginally mature with respect to hydrocarbon generation. The poor source-rock quality at this site could to be due to lateral variability within the depositional environments of the Nonesuch Formation.


## Acknowledgments

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# Chapter 9. Hydrocarbon potential of the Middle Proterozoic Nonesuch Formation in northwestern Wisconsin and Michigan

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## Abstract

*The Middle Proterozoic Nonesuch Formation, often described as a hydrocarbon generating source rock, partially composes the sedimentary rock infill sequence of the Midcontinent Rift in northern Wisconsin and Michigan; this formation was the primary hydrocarbon exploration target within the Terra–Patrick #7-22 well, Bayfield County, Wisconsin. The exploration potential of the Nonesuch Formation, acting as a potential hydrocarbon source rock and reservoir unit, is supported by oil seeps in the White Pine Copper Mine, White Pine, Michigan, and numerous organic geochemical studies that demonstrated that the oil in the White Pine Mine is derived from the Nonesuch Formation.*

*This paper presents total organic carbon content and Rock-Eval pyrolysis assay data that place the Nonesuch Formation into a more regional framework than that presented by R.C. Burruss and J.G. Palacas in chapter 8 of this volume. In addition, the rate of kerogen decomposition was measured on a Nonesuch Formation shale core sample. The kinetic results suggested that a high thermal exposure is required to convert Nonesuch Formation kerogen into hydrocarbons.*

*Outcrop samples, subsurface core samples, and an oil sample from the White Pine Copper Mine were collected and analyzed for their organic geochemical characteristics. The samples were acquired along an approximate 150-mi transect extending from northwest Wisconsin northeast to the Keewenaw Peninsula of Michigan. These data suggested that the Nonesuch Formation is a poor to fair source rock in the areas examined and presumably was never a high quality hydrocarbon source rock. On the basis of this interpretation, successful hydrocarbon exploration targeting the Nonesuch Formation in the northern Midcontinent Rift for major reserves (>10 million barrels of oil equivalent) is unlikely.*

## Introduction

The petroleum potential within the Midcontinent Rift has intrigued many individuals and several companies since subsurface oil seeps were first recorded within the White Pine Copper District in 1929 (A.B. Dickas, University of Wisconsin–Superior, verbal communication, 1994). For more than 30 years the Middle Proterozoic Nonesuch Formation has been the subject of numerous publications, predominantly regarding the organic geochemical characteristics of the formation. Barghoorn and others (1965) presented the first detailed organic geochemical analysis of the None-

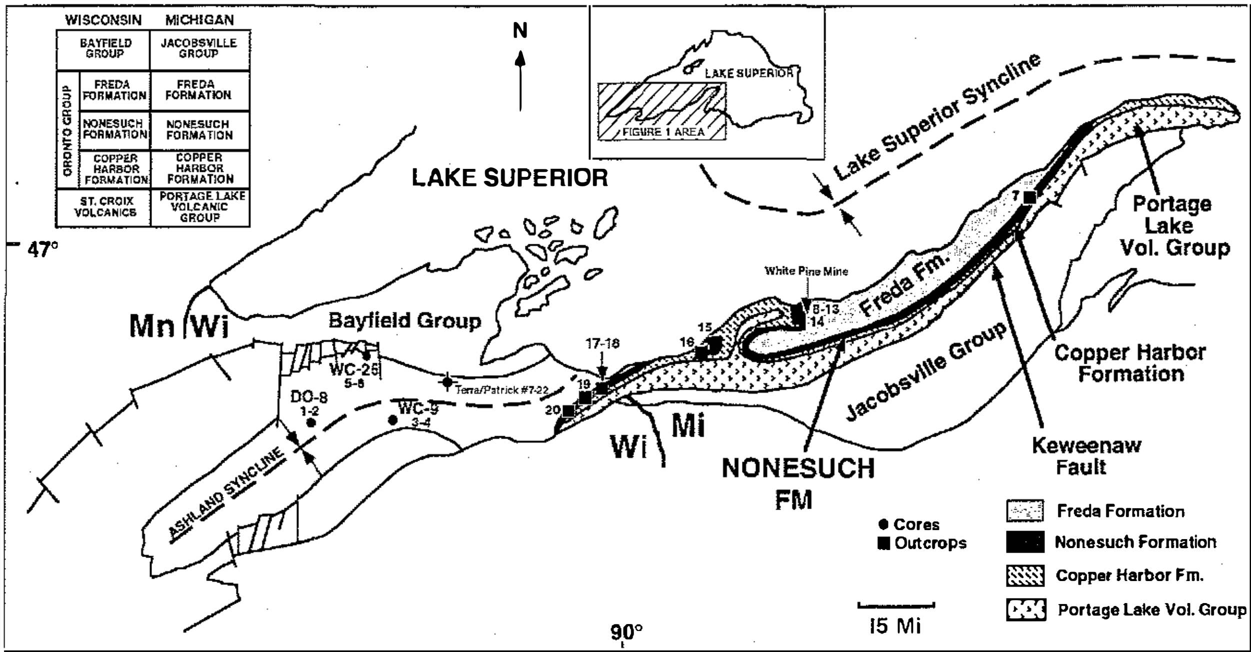



**Figure 1.** *Geologic and location map of the southern Lake Superior region. The Nonesuch Formation crops out along the thick line drawn between the Copper Harbor Formation and the Freda Formation. Distribution of the Copper Harbor, Nonesuch, and Freda Formations within the Ashland Syncline is not shown due to extreme sparsity of outcrop. Circles identify cored sites (1–6) of the Nonesuch Formation by the Bear Creek Mining Company; squares identify outcrop section (7–20) where Nonesuch Formation samples were collected for analysis. Generalized stratigraphic column for northwestern Wisconsin and Michigan is included for correlation. Map is from Elmore and others (1989) and Allen and others (ch. 4, this volume).*

such Formation. Their analysis suggested that the oil found within the Nonesuch Formation in the White Pine Mine, White Pine, Michigan (fig. 1), was derived from the Nonesuch Formation itself. Several studies have followed, for example, Elmore (1981), Imbus and others (1988), Elmore and others (1989), Imbus and others (1990), Pratt and others (1991), Imbus and others (1992), among others, which have given more detailed analyses of the depositional environment and organic geochemical characteristics of the Nonesuch Formation. These analyses have supported the supposition of Barghoorn and others (1965) that the oil in the White Pine Mine is derived from the Nonesuch Formation.

The Nonesuch Formation has had a variety of depositional environment interpretations. White and Wright (1954), and Ehrlich and Vogel (1971) suggested a nearshore and deltaic depositional environment. Elmore (1981) and Milavec (1986) suggested environments ranging from marginal lacustrine to lacustrine to fluvial lacustrine. Hieshima and others (1989) and Pratt and others (1991) suggested an estuarine depositional environment. Elmore (1981) and Elmore and others (1989) presented strong evidence for a lacustrine depositional environment, especially when put into a regional context with the interpreted facies above and below the Nonesuch Formation.

The Terra–Patrick #7-22 well in Bayfield County, Wisconsin (fig. 1) was drilled in an attempt to find commercial quantities of hydrocarbons that were thought to have been generated by the Nonesuch Formation. The fact that the Terra–Patrick #7-22 well was a dry hole does not prove that oil was not generated from the Nonesuch Formation, only that the location where this well was drilled was not presently charged by hydrocarbons. The overall prospectiveness of the northern part of the Midcontinent Rift may be negligibly impacted by the results of the Terra–Patrick #7-22 well, but only if it is considered as a single hydrocarbon exploration penetration in this large area. A single well drilled in a new basin rarely, if ever, condemns the entire region. This was the first designated petroleum test in the Wisconsin part of the northern Midcontinent Rift region. However, there have been nearly 50 boreholes drilled in this area prospecting for copper within the Nonesuch Formation. Minor shows have been recorded within the Nonesuch Formation, consisting of oil staining and oil in vugs in cores taken in northwestern Wisconsin in 1958–60 by Bear Creek Mining Company (A.B. Dickas, University of Wisconsin–Superior, and M.G. Mudrey, Jr., Wisconsin Geological and Natural History Survey, verbal communication, 1994). Normally, hydrocarbon exploration wells target structural features or stratigraphic traps as areas for potential accumulations. Mineral deposits can occur in similar traps, but may have other factors affecting the accumulations, such as original depositional environment, proximity to thermal source, or chemistry of the thermal solutions. Although the density of drilling locations—mineral wells and the Terra–Patrick #7-22 hydrocarbon test—in northwestern Wisconsin is sparse, the regional distribution of locations indicates that a significant part of the area has been tested and the results do not suggest any commercial hydrocarbon accumulations. This significantly larger data set used to assess the potential for hydrocarbon accumulations within the Nonesuch Formation in the northern part of the Midcontinent Rift suggests that the potential for significant hydrocarbon accumulations has a probability far less than originally thought.

## Locations and sampling

We present analytical data from seven outcrop sites in northwestern Wisconsin and Michigan, three subsurface samples from cores taken by Bear Creek Mining Company in northwestern Wisconsin, a sample taken from a mine dump at the White Pine Mine (sample provided by A.B. Dickas), and an oil sample taken from within the White Pine Mine (sample also provided by A.B. Dickas). These sample locations cover a distance of approximately 150 mi from west to east (fig. 1). Outcrop samples were collected in December 1994, by authors Uchytil and Steffensen while in the field with A.B. Dickas and R.D. Elmore (University of Oklahoma). Samples obtained from subsurface cores were also collected in December 1994 and are housed at the Wisconsin Geological and Natural History Survey Core Repository, Milwaukee, Wisconsin, courtesy of M.G. Mudrey, Jr.

Outcrop sample locations are presented in figure 1, numbered 7 through 20. These locations were selected by A.B. Dickas and R.D. Elmore on the basis of their extensive experience sampling Nonesuch Formation outcrops. Samples labeled 1 through 6 in figure 1 are from subsurface cores by Bear Creek Mining Company. All samples were collected from what appeared to be the most organic prone facies, assuming the darkest shaly facies would contain the highest organic content. Also, Elmore's experience in collecting and analyzing the shale facies directed our attention to the dark shale facies with carbonate laminae that characteristically contain some of the highest organic content within the Nonesuch Formation (Elmore and others, 1989; R.D. Elmore, verbal communication, 1994). These outcrop sample locations were selected to obtain a regional perspective relative to the source-rock characteristics of the Nonesuch Formation and to verify previous organic geochemical work, such as Elmore and others (1989), and analyze outcrop samples close to the Terra–Patrick #7-22 location.

## Methods

Collected samples were analyzed to evaluate organic richness, thermal maturity, and kerogen type through determination of total organic carbon (TOC) content and Rock-Eval pyrolysis. Pyrolysis data ($S_1$, $S_2$, $S_3$, $T_{max}$, and TOC) were obtained with a Rock-Eval plus TOC instrument and are presented in table 1. Kinetic data were acquired on a Humble Instruments SR Analyzer and Lawrence Livermore National Laboratory's Kinetics2000™ program was used for the calculation.

## Results

Total organic carbon results of the 20 samples and Rock-Eval data are presented in table 1. Outcrop sample numbers from table 1 correspond to out-

**Table 1.** *Rock-Eval data for outcrop and subsurface samples, northwestern Wisconsin and adjacent Upper Peninsula of Michigan. See figure 1 for locations. TOC = weight percent organic carbon; $S_1$, $S_2$ = mg hydrocarbons/g rock; $S_3$ = mg carbon dioxide/g rock; $T_{max}$ in °C; HI = $S_2$ x 100/TOC; OI = $S_3$ x 100/TOC; PI = $S_1/(S_1 + S_2)$; $S_1$/TOC = $S_1$ x 100/TOC.*

| Sample number | Location | Total organic carbon and Rock-Eval data | | | | | Interpretive ratios | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | TOC | $S_1$ | $S_2$ | $S_3$ | $T_{max}$ | HI | OI | $S_2/S_3$ | PI | $S_1$/TOC |
| **Core** | | | | | | | | | | | |
| 1 | Bear Creek DO-8 | 0.43 | 0.07 | 0.35 | 0.08 | 446* | 81 | 19 | 4.38 | 0.17 | 16 |
| 2 | Bear Creek DO-8 | 0.34 | 0.36 | 0.90 | 0.20 | 416 | 265 | 59 | 4.50 | 0.29 | 106 |
| 3 | Bear Creek DO-9 | 0.81 | 0.21 | 1.35 | 0.12 | 438 | 167 | 15 | 11.25 | 0.13 | 26 |
| 4 | Bear Creek WC-9 | 0.12 | 0.03 | 0.08 | 0.13 | 439* | 67 | 108 | 0.62 | 0.27 | 25 |
| 5 | Bear Creek WC-25 | 0.21 | 0.04 | 0.19 | 0.11 | 435* | 90 | 52 | 1.73 | 0.17 | 19 |
| 6 | Bear Creek WC-26 | 1.17 | 0.07 | 2.50 | 0.16 | 439 | 214 | 14 | 15.63 | 0.03 | 6 |
| **Outcrop** | | | | | | | | | | | |
| 7 | Boat Dock Quarry | 0.09 | 0.08 | 0.15 | 0.21 | 380* | 167 | 233 | 0.71 | 0.35 | 89 |
| 8 | Big Iron River, W | 0.18 | 0.02 | 0.08 | 0.46 | 435* | 44 | 256 | 0.17 | 0.20 | 11 |
| 9 | Big Iron River, W | 0.59 | 0.18 | 0.29 | 0.17 | 407* | 49 | 29 | 1.71 | 0.38 | 31 |
| 10 | Big Iron River, W | 0.85 | 0.28 | 0.37 | 0.04 | 435* | 44 | 5 | 9.25 | 0.43 | 33 |
| 11 | Big Iron River, W | 0.54 | 0.29 | 0.34 | 0.10 | 400* | 63 | 19 | 3.40 | 0.46 | 54 |
| 12 | Big Iron River, E | 0.73 | 0.15 | 0.26 | 0.44 | 425* | 36 | 60 | 0.59 | 0.37 | 21 |
| 13 | Bonanza Falls | 0.82 | 0.25 | 0.49 | 0.43 | 412* | 60 | 52 | 1.14 | 0.34 | 30 |
| 14 | White Pine Mine Dump | 0.05 | 0.02 | 0.06 | 0.07 | 331* | 120 | 140 | 0.86 | 0.25 | 40 |
| 15 | Presque Isle Park | 0.05 | 0.01 | 0.05 | 0.17 | 382* | 100 | 340 | 0.29 | 0.17 | 20 |
| 16 | Black River | 0.06 | 0.02 | 0.07 | 0.23 | 349* | 117 | 383 | 0.30 | 0.22 | 33 |
| 17 | Parker Creek | 0.06 | 0.02 | 0.06 | 0.07 | 364* | 100 | 117 | 0.86 | 0.25 | 33 |
| 18 | Parker Creek | 0.17 | 0.02 | 0.04 | 0.03 | 373* | 24 | 18 | 1.33 | 0.33 | 12 |
| 19 | Potato Falls | 0.10 | 0.01 | 0.05 | 0.13 | NR | 50 | 130 | 0.38 | 0.17 | 10 |
| 20 | Copper Falls | 0.05 | 0.02 | 0.07 | 0.37 | 434* | 140 | 740 | 0.19 | 0.22 | 40 |
| **Standard** | IFP 55000 | 2.82 | 0.19 | 8.55 | 0.98 | 419 | | | | | |

*Data unreliable due to low $S_2$ values.

crop sample numbers in figure 1. Only one of the samples analyzed had greater than 1.0 percent TOC. The average TOC content (0.4%) is less than the average of 0.6 percent reported by Burruss and Palacas (ch. 8, this volume) and is consistent with other analyses reported on the Nonesuch Formation by Imbus and others (1988), Imbus and others (1990), and Imbus and others (1992).

The remaining potential to generate hydrocarbons, as measured by Rock-Eval $S_2$, is very low on all but two of the samples, indicating poor quality source facies or samples that have reached a high enough level of thermal maturity to have generated hydrocarbons, thereby decreasing the generative potential of the source unit. Likewise, the hydrogen indices (HI, the remaining potential to generate hydrocarbons normalized against organic richness) are quite low. In sediments younger than the Late Silurian, this could be explained by having a high percentage of Type III kerogen in the samples. Type III kerogen, or woody-coaly organic material, did not exist in the Precambrian; therefore, the low hydrogen index values are most likely low due to either increased thermal maturation of the sediments or poor quality source rocks. In addition, the evaluation of hydrogen indices must be considered with regard to careful evaluation of surface weathering.

Surface weathering and the resultant oxidation and alteration of organic matter can affect the assessment of kerogen quality (Clayton and Swetland, 1978). Weathering may have had an impact on accurately measuring the petroleum potential of the outcrop samples, but the very low organic content of these samples precludes a substantial change in our evaluation of their source potential. The core samples show minimal impact of surface weathering.

Organic facies evaluation by chemical techniques can be affected by thermal maturity. Maturation processes result in conversion of organic matter to hydrocarbons, resulting in reduced hydrogen indices. Therefore, interpretation of hydrogen indices requires consideration of thermal maturity. If overly mature, even strongly oil-prone organic matter could be mistakenly identified as gas prone from hydrogen indices alone. Accurate evaluation of maturity is complicated by the absence of vitrinite particles prior to the Late Silurian. Rock-Eval $T_{max}$ values, although dependent on organic facies, can be used as a maturity indicator. Only two of the twenty samples analyzed have sufficient remaining potential ($S_2$) and normally shaped pyrolysis peaks to yield valid $T_{max}$ values; however, these values, 438°C to 439°C, are indicative of early to early–middle oil window maturity. This maturity assessment is also supported by biological marker maturity data as reported by Hieshima and others (1989), Imbus and others (1992), and Mauk and Hieshima (1992), along with illite–smectite geothermometry data by Price and McDowell (1993).

Generation of hydrocarbons near the White Pine Copper Mine apparently began as early as the Middle Proterozoic (1047 ±35 Ma), on the basis of an entrapment age derived from Rb-Sr age dating techniques on petroleum fluid inclusions in calcite veins within the mine (Kelly and Nishioka, 1985). Whatever mechanism that resulted in copper mineralization within the Copper Harbor–Nonesuch stratigraphic interval, the thermal impact was enough to generate liquid hydrocarbons, as shown by oil fluid inclusions embedded in native copper (Kelly and Nishioka, 1985). This suggests geologically early, possibly localized, hydrocarbon generation relative to the age of these units. The Nonesuch Formation west of the White Pine Copper Mine area appears to be at least in the hydrocarbon generation window according to Imbus and others (1992), Price and McDowell (1993), and as determined by $T_{max}$ values from samples 3 and 6 (table 1). Price and McDowell (1993), in comparing illite–smectite geothermometry results to organic geochemical data, supported the organic geochemical data, with both techniques suggesting higher thermal maturities near White Pine as well as the southern part of the Keweenaw Copper District, located approximately 50 mi east of the White Pine Copper Mine.

Evaluation of organic facies by pyrolysis gas chromatography supports an oil prone facies evaluation of the Nonesuch Formation (Imbus and others, 1992). Oil-like products have been generated from these experiments. Likewise, a saturate hydrocarbon fraction gas chromatographic fingerprint from the Bear Creek WC-26 core sample of the Nonesuch Formation has a fingerprint similar to the oil recovered from the White Pine Copper Mine (figs. 2 and 3). In addition, fractionation of the Nonesuch Formation extract of this sample and the White Pine Mine oil yield 52 percent and 72 percent saturated hydrocarbons, respectively, indicative of the paraffinic character of the Nonesuch Formation. This also supports the correlation between the Nonesuch Formation and the White Pine Mine oil, as shown by Barghoorn and others (1965), Elmore and others (1989), Hieshima and Pratt (1991), Pratt and others (1991), and Mauk and Hieshima (1992).

The low hydrogen indices reported in table 1 do not affect our assessment of the Nonesuch Formation as containing oil-prone organic matter. For example, the lacustrine Eocene age Green River Shale of Wyoming, Colorado, and Utah has tremendous variability in organic carbon, petroleum potential, and hydrogen indices. Values for hydrogen indices within the Green River Shale range from less than 100 to in excess of 900 and values for TOC range from 0.06 percent to nearly 35 percent (data analyzed and supplied by Humble Geochemical Services, 1995). These data suggest that the Green River Shale, known as a potential world class source rock, has enough organic variability that different facies may be non-source units; others act as the main hydrocarbon source intervals. This analogy to the Nonesuch Formation suggests that organic variability is not uncommon even in high quality source rocks; therefore, the or-

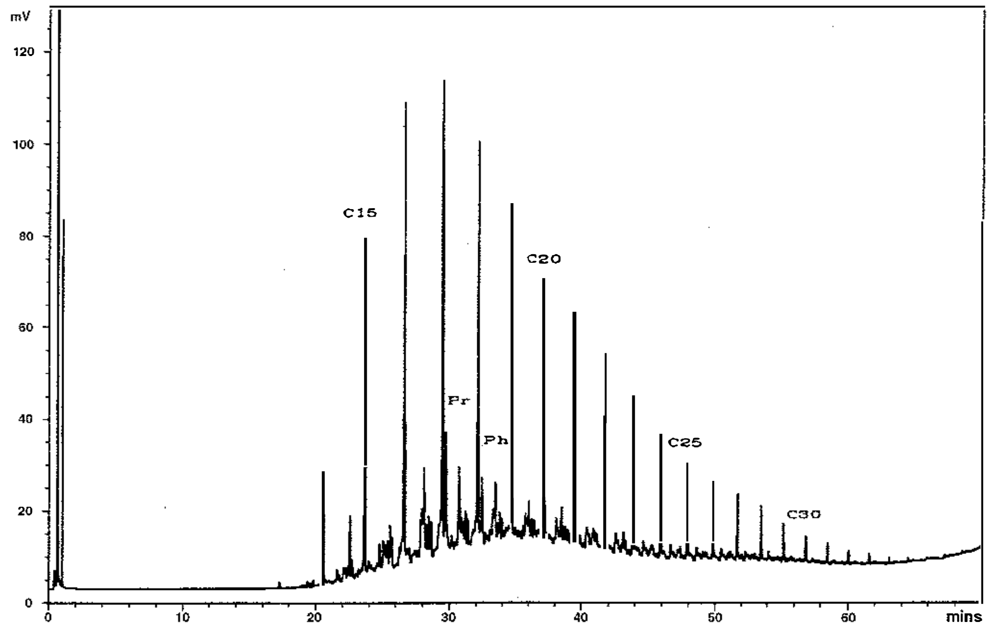



**Figure 2.** *Saturate fraction gas chromatographic fingerprint of Bear Creek WC-26 core hole, Nonesuch Formation.*

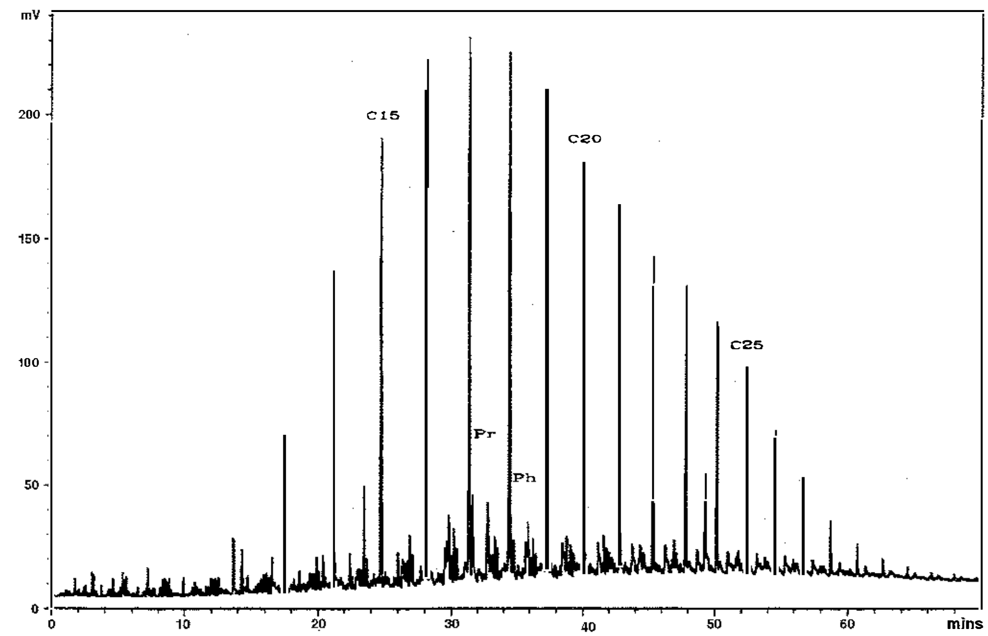
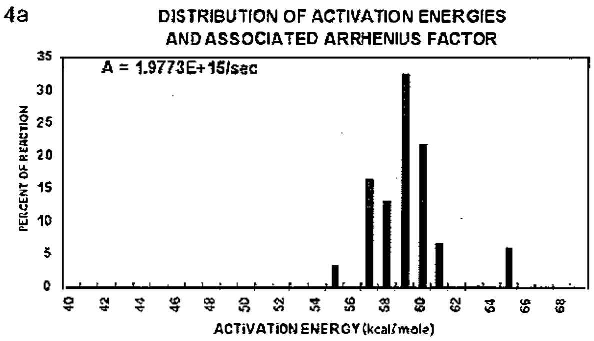



**Figure 3.** *Whole oil gas chromatographic fingerprint of White Pine Copper Mine oil seep.*

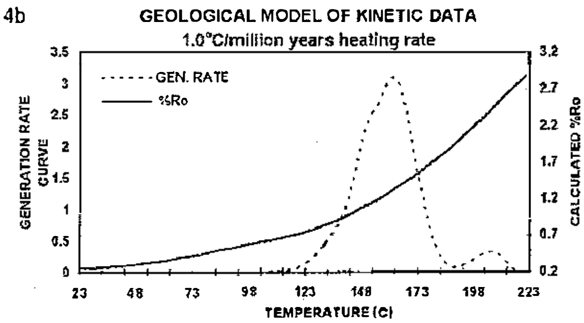
ganic variability within the Nonesuch Formation should not be viewed as anomalous.

The conversion of organic matter to hydrocarbons normally occurs as a result of increased subsurface temperatures with increasing depth of burial. The rate of conversion of kerogen into hydrocarbons can be described by determining kinetic parameters using laboratory pyrolysis techniques. The technique employed here uses open-system pyrolysis at different heating rates. The resulting pyrolysis curves are used to find the best fit solution for kinetic parameters—a distribution of activation energies and a single Arrhenius factor. These data may be used to describe the rate of

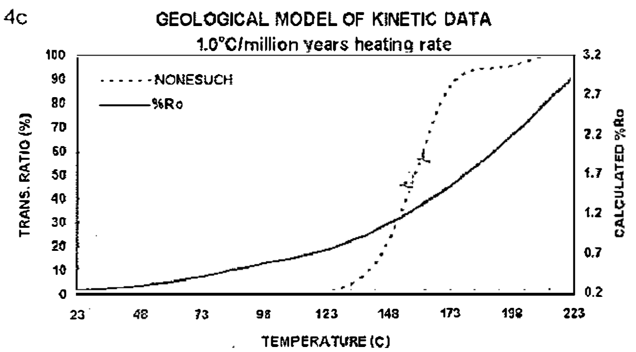
4a




4b




4c




| | |
|---|---|
| WELL NAME: | Bear Creek WC-26 (core) |
| SAMPLE: | Nonesuch Formation |
| TMAX: | 438°C |
| MODEL USED: | Discrete |
| COMPUTED FIT: | Fair |

| | |
|---|---|
| COMPUTED ONSET (10%TR) TEMPERATURE: | 141°C |
| COMPUTED ONSET (10% TR) %Ro VALUE: | 0.97 |
| COMPUTED PEAK GENERATION TEMPERATURE: | 163°C |
| COMPUTED PEAK GENERATION %Ro VALUE: | 1.35 |

**Figure 4.** *Graphical summary of kinetic data using the Nonesuch Formation kinetics. A. The distribution of activation energies and Arrhenius factor. B. Geological model of the generation rate and calculated vitrinite reflectance values from these kinetic data. C. Geological model of the transformation rate and calculated vitrinite reflectance.*

decomposition of organic matter using rate equations combined with the Arrhenius equation ($k$=A$e^{-Ea/RT}$), where $k$ is the reaction rate constant, A is the Arrhenius factor ($sec^{-1}$), Ea is the activation energy (calories/mole), R is the gas constant (1.987 cal/°K mole), and T is the temperature (°K). Experimental determination of kinetic data for a Nonesuch shale sample from the Bear Creek WC-26 core was completed and the results are summarized in table 2.

These activation energies, Arrhenius factor, and the reaction rate at 1°C/my are summarized graphically in figure 4. These kinetic data for the Nonesuch Formation shale sample are indicative of 1) a refractory kerogen requiring a relatively high temperature to decompose into hydrocarbons, and 2) a distribution of activation energies, suggesting some compositional heterogeneity. On the basis of these kinetics, peak decomposition of the organic matter at a heating rate of 1°C/my would not be reached until approximately 163°C. In addition, the distribution of activation energies suggests a more complex composition because the breaking of multiple bonds of different strengths is reflected in such a distribution.

A comparison of the rates of hydrocarbon formation between the Nonesuch Formation, the De-

**Table 2.** *Kinetic data for Bear Creek Mining Company core sample WC-26, northwestern Wisconsin. See figure 1 for location.*

| Percent of reaction | Activation energy (cal/mole) | Arrhenius factor ($sec^{-1}$) |
|---|---|---|
| 0.16 | 54000 | 1.9773E + 15 |
| 3.33 | 55000 | 1.9773E + 15 |
| 16.39 | 57000 | 1.9773E + 15 |
| 13.17 | 58000 | 1.9773E + 15 |
| 32.57 | 59000 | 1.9773E + 15 |
| 21.75 | 60000 | 1.9773E + 15 |
| 6.63 | 61000 | 1.9773E + 15 |
| 5.99 | 65000 | 1.9773E + 15 |

vonian Woodford Formation (shale sample from an outcrop near Woodford, Oklahoma), and the Cretaceous Kimmeridge Formation (shale sample from a core in a Norwegian North Sea well) is shown in figure 5.

The Woodford and the Kimmeridge samples were chosen for comparison with the Nonesuch Formation because 1) shale from the Woodford Formation, despite being a marine Type II kerogen, has refractory decomposition kinetics, resulting in peak generation at higher temperatures similar to the lacustrine Type I Green River Shale, and 2) shale from the Kimmeridge Formation represents a much less refractory Type II marine kerogen, reaching peak generation at lower temperatures than either the Woodford or Green River Shales. The lacustrine Green River Shale was not used, even though it may be more analogous from a depositional environment standpoint to the Nonesuch Formation because it is difficult to ascertain hydrocarbon maturity on the basis of $T_{max}$ values and it has a narrow distribution of activation energies (approximately 80% at 54 kcal/mole). However, modeling of the immature Green River Shale decomposition kinetics resulted in nearly an identical peak generation temperature (150°C), but over a narrower time span than the Woodford shale. A Type III kerogen was not used because terrestrial organic matter was not present during the Precambrian. The resulting kinetic data reflect reaction rates at a simple constant heating rate geological model of 1°C/million years, which is arbitrarily used for these comparisons.

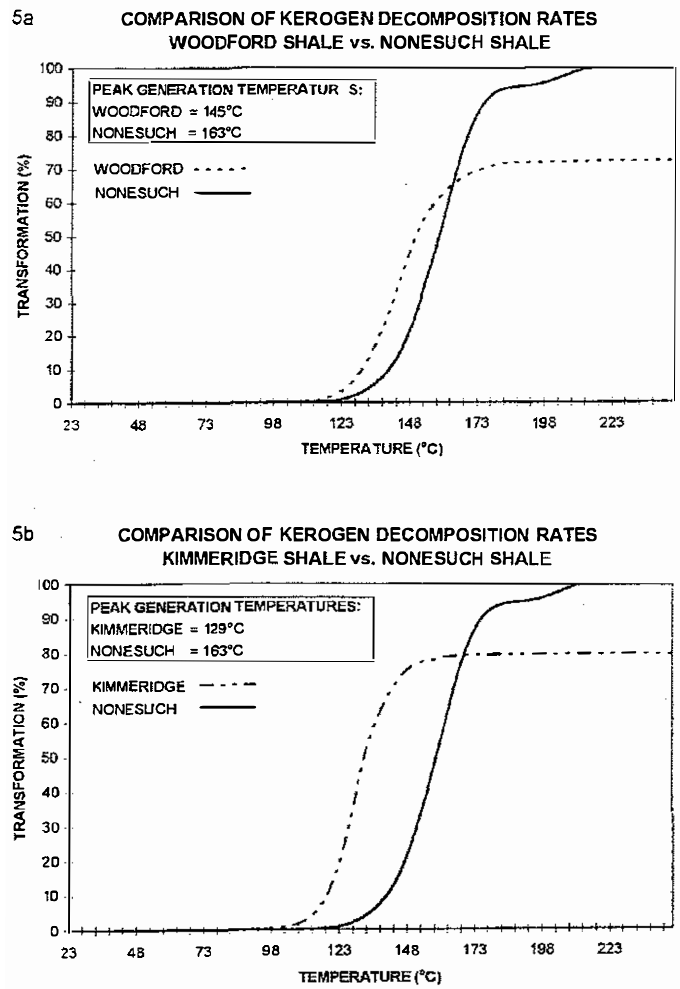



**Figure 5.** *Comparison of transformation rates of (A) Woodford and (B) Kimmeridge kerogens to the Nonesuch Formation based on the Bear Creek WC-26 sample kinetics. The Woodford and Kimmeridge kerogens have been 27 percent and 30 percent transformed to give comparable $T_{max}$ values as the Nonesuch Formation to offset any difference due to thermal maturity.*

The graphs in figure 5 illustrate that the Nonesuch Formation kinetics are indicative of a more refractory kerogen than either the Woodford or Kimmeridge shales at comparable levels of thermal maturity. The Woodford and Kimmeridge shale samples are at similar thermal maturities compared to the Nonesuch Formation on the basis of identical Rock-Eval $T_{max}$ values on all three samples (438°C). At this $T_{max}$ value the Kimmeridge kerogen is approximately 30 percent transformed into hydrocarbons; the Woodford kerogen is approximately 27 percent converted. At these higher thermal maturities most kerogens do become more refractory, that is, more difficult to crack into hydrocarbons, but the Nonesuch Formation requires higher temperatures to decompose than either the partially converted Woodford or Kimmeridge Formations. On the basis of the decomposition kinetics of these three samples at comparable levels of thermal maturity, the Kimmeridge, Woodford, and Nonesuch samples would reach peak hydrocarbon generation at temperatures of 129°C, 145°C, and 163°C, respectively, in this arbitrary model.

The Nonesuch Formation kinetics (table 2) are characterized by seven different activation energies, each accounting for approximately 5 to 35 percent of the decomposition reactions. These several activation energies suggest a chemical heterogeniety within the Nonesuch Formation. This may suggest something other than a totally freshwater environment for the deposition of the lacustrine Nonesuch Formation. Multiple sequences of mud cracks and syneresis cracks have been observed within Nonesuch Formation outcrops north of the White Pine Copper Mine (Imbus and others, 1988). Outcrop samples of calcite pseudomorphs after gypsum and anhydrite as well as gypsum nodules and crystals within Bear Creek Mining WC-25 core were reported by Elmore and others (1989).

These observations are suggestive of periodic exposure and potential variations in salinity of the fluid in which the Nonesuch Formation was deposited. The Nonesuch Formation may have been deposited within a lacustrine environment, but the salinity of the water may have been quite variable. We have not attempted to quantify the actual salinity of the water in which the Nonesuch Formation was deposited. Within this potentially variable salinity environment, there may have been a variety of organic constituents preserved within the Nonesuch Formation. Hieshima and Pratt (1991) have suggested a marine embayment dominated by seawater as the environment of deposition for the Nonesuch Formation. Even though a marine interpretation is plausible, we believe the sedimentological evidence for a lacustrine environment of deposition (Elmore and others, 1989) and the present discussion of the kinetic data still support a lacustrine environment of deposition, albeit one with variable salinities.

## Discussion

The hydrocarbon source-rock characteristics of the Nonesuch Formation have been the subject of several recent studies. The data we present only add to this already extensive volume of information. Source rock-to-oil correlations have also been completed, and the data convincingly demonstrate the oil from the White Pine Copper Mine in northern Michigan is derived from the Nonesuch Formation (figs. 2 and 3), as previously reported by Hieshima and Pratt (1991), Imbus and others (1992), Mauk and Hieshima (1992), and Pratt and others (1991).

Price and McDowell (1993) have interpreted the thermal history of the Oronto Group (fig. 1) in the northern Midcontinent region via illite–smectite geothermometry. The results of their work agreed with the organic geochemical evaluations of Imbus and other (1990 and 1992) and Elmore and others (1989). Price and McDowell (1993) have recommended the following two-stage alteration model for the Oronto Group sediments:

- ▼ Stage 1: a thermal event associated with Midcontinent rifting, which provided the energy to diagenetically alter the smectite-rich clays to more structured illitic clays and was presumably responsible for the initial generation of hydrocarbons within the area;
- ▼ Stage 2: a compressional event that terminated rifting and caused uplift and accelerated cooling within the rift.

During the second stage, epigenetic fluids migrating along fractures and faults presumably transported copper-rich fluids and deposited copper within the Copper Harbor and Nonesuch Formations and within visicular units of the underlying Portage Lake Volcanic Group (fig. 1). As mentioned previously, oil and native copper were incorporated within calcite fluid inclusions in the White Pine Copper Mine and have been age dated at 1,047 ±35 Ma (Kelly and Nishioka, 1985). A discussion of the origin of copper mineralization within the Nonesuch Formation, Copper Harbor Formation, and Portage Lake Volcanics is beyond the scope of this paper. Interested individuals should consult the wealth of materials written on the subject matter, such as Ohle (1962), Hamilton (1967), Vogel and others (1976), Gustafson and Williams (1981), Mauk and Hieshima (1992), and Mauk and others (1992).

On the basis of this information, Price and McDowell (1993) suggested that initial hydrocarbon generation could have begun in their stage 1, where higher heat flow in the western Upper Peninsula of Michigan accounts for the predominance of more structured illitic clays. Uplift associated with stage 2 would have interrupted the progression toward more structured clays and would essentially "freeze" the clay reactions. Price and McDowell (1993) and Price and others (1996) suggested that the Nonesuch Formation was probably at its peak thermal maturity approximately 1,075 Ma and has not experienced temperatures any higher since. Therefore, on the basis of their interpretation, hydrocarbon generation occurred very early in the thermal history of the Nonesuch Formation in the northern part of the Midcontinent Rift. Oil generated, and found, in the White Pine Copper Mine has most likely been contained in these rocks for more than one billion years.

There may be additional problems associated with hydrocarbon exploration within the Nonesuch Formation other than source, such as trap, timing of migration, reservoir, and seal, among others. These other components may be just as important as the hydrocarbon source, but the essential element in hydrocarbon exploration is a need for quality source rocks to generate hydrocarbons at an appropriate time to fill a reservoir within a trap. A single wellbore, the WPB-8 well near the White Pine Copper Mine, has good source facies developed (see the Rock-Eval data from Imbus and others, 1992). Barring the WPB-8 analysis, data from the other few hundred analyses reported in Imbus and others (1990 and 1992), Burruss and Palacas (ch. 8, this volume), and data presented here, suggest a relatively lean, early to moderately mature, hydrocarbon source rock. There is a possibility that other areas may have better petroleum source-prone facies, but they most likely are regionally restrictive because they have not been identified with the current density of data.

## Conclusions

The analyses presented here, along with the data published by others, indicate that the Nonesuch Formation has fair to poor source facies in the areas examined. The probability of the Nonesuch Formation ever acting as a high quality generative source rock, and therefore having it ever generate commercially significant quantities of hydrocarbons, is quite low.

Although we do not discount the possibility of Midcontinent Rift hydrocarbon accumulations, it is the opinion of the authors that the potential for field reserves greater than 10 million barrels of oil equivalent is also unlikely. Infrastructure (service companies, pipelines, processing plants, and so forth) for the petroleum business is very sparse within northwestern Wisconsin and the Upper Peninsula of Michigan; therefore, reserves would need to be at least this large to justify a major exploration effort. We would recommend that future explorationists prospecting for hydrocarbons within the onshore part of the Midcontinent Rift in northwestern Wisconsin and Michigan be aware of these and other potential problems associated with Nonesuch Formation exploration. The offshore part of the northern Midcontinent Rift (areas within Lake Superior) has been excluded from our discussion due to the absence of rock data.

## Acknowledgments

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# Chapter 10. Review and analysis of wireline logs: The Terra–Patrick #7-22 borehole, Bayfield County, Wisconsin

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## Introduction

The Terra–Patrick #7-22 well was drilled by Terra Energy, Ltd., in March 1992 to evaluate the oil and gas potential of the Freda, Nonesuch, and Copper Harbor Formations of Middle Proterozoic geologic age (Daniels, 1982). The well is located in Bayfield County, Wisconsin, midway between the cities of Iron River and Ashland and approximately 10 miles from the south shore of Lake Superior. It may be considered the fourth major wildcat well drilled in the Midcontinent Rift System since 1984. Previous deep tests in this major tectonic feature include the Amoco Eischeid #1 drilled in 1987 in Iowa, the Texaco Poersch #1 drilled in 1984-85 in Kansas (Fritz, 1985; 1988; 1992), and the Amoco St. Amour #1-29R drilled in Alger County, Michigan in 1987 (Dickas, 1995).

The Terra–Patrick #7-22 well was drilled to 4,966 measured feet total depth and mudlogged from surface to total depth. Halliburton Logging Services, Inc., ran a suite of wireline logs at the intermediate casing depth of 2,002 ft and at total depth. The permanent datum of the location is ground level at 867 ft above sea level. The logs were measured from the kelly bushing (KB) on the drill-rig floor at an elevation of 879.8 ft above sea level, or 12.8 ft above the permanent datum.

The presence of iron-rich sediment sourced from the penetrated formations unfortunately limited the use of a number of log parameters in various evaluation procedures. The salinity of the mud system was also affected by the iron-rich rock. A marked decrease in mud resistivity from 2.91 ohmmeters on March 19 to 0.74 ohmmeters on March 29 was noted on the log headings. The "type fluid in hole" on the log headings was listed as "fresh mud" on both dates. The integrity of the hole was sufficient to allow a satisfactory wireline logging operation. A few instances of extreme hole rugosity, indicated by the caliper log, did affect some log parameters.

## Log descriptions

### *Dual Induction Laterolog/Gamma Ray/ Spontaneous Potential log*

Halliburton Logging Services, Inc. (now Halliburton Energy Services) performed two wireline logging operations on the subject Terra–Patrick #7-22 well. Table 1 lists the specific logs obtained during each operation. The Dual Induction Laterolog/ Gamma Ray/Spontaneous Potential (DIL/GR/SP) was run May 19 as an intermediate log prior to setting 8-in. casing at 2,002 ft. A second run of the DIL was made at total depth on March 29.

The DIL tools use electromagnetic coil arrays to determine formation resistivity in boreholes. Receiver coils detect variations in the resistivity in the borehole and adjacent formations that correspond to the variations from the electromagnetic field. Tool corrections are made to remove the effect of the borehole on formation resistivities. The DIL produces two resistivity values—induction log medium resistivity of the invaded zone and induction log deep resistivity of the uncontaminated zone (true formation resistivity). A third resistivity device with a shallow depth of investigation, Laterolog 3, was recorded to measure the resistivity of the flushed zone (Halliburton, 1992). The applications of the DIL are to distinguish between saltwater-bearing and hydrocarbon-bearing formations, determine true formation resistivity for calculating water saturation, estimate diameter of invasion, and indicate movable hydrocarbons and correlate rock formations (Halliburton, 1992).

The GR log was run with the DIL primarily for

**Table 1.** *Log suite, Terra–Patrick #7-22 borehole.*

| Log | Date | Interval (ft) | Tool mnemonic |
|---|---|---|---|
| Dual Induction Laterolog/ Gamma Ray/Spontaneous Potential | 3/19/92 | DIL/SP 412–2,001 GR 100–2,001 | DIL/GR/SP |
| Dual Induction Laterolog/ Gamma Ray/Spontaneous Potential | 3/29/92 | 2,002–4,788 | DIL/GR/SP |
| Long Spaced Sonic/ Gamma Ray | 3/19/92 | 397–1,994 | LSS/UGR |
| Long Spaced Sonic/ Gamma Ray | 3/29/92 | 2,030–4,810 | LSS/UGR |
| High Resolution Induction/ Gamma Ray/Spontaneous Potential | 3/28/92 | 2,002–4,909 | HRI/UGR/SP |
| Spectral Density/ Dual Spaced Neutron/ Spectral Natural Gamma Ray | 3/28/92 | 2,002–4,887 | SDL/DSN/CSNG |
| Spectral Natural Gamma Ray | 3/28/92 | 2,002–4,861 | CSNG |
| Six Arm Dipmeter Survey | 3/29/92 | 2,030–4,820 | SED/UGR |

formation correlation information. The tool detects gamma ray emissions from subsurface formations. The gamma rays originate from naturally occurring radioactive elements of the uranium and thorium groups and potassium. Other applications of this tool are to indicate potential hydrocarbon-bearing zones, to estimate shale volume, to detect ore deposits, to correlate depths on logs run in the same well, to delineate bed boundaries, and to detect water migration (Halliburton, 1992).

A spontaneous potential (SP) curve was recorded with the DIL from total depth to 412 ft (depth of surface casing). The curve is the result of a potential created in the wellbore when fluids of different salinities come in contact with each other. A current flow may occur opposite permeable zones (such as sands and limestones) invaded by drilling-mud filtrate. The SP measurement reflects permeability and reservoir rock type. It also can be used for correlations, determining the resistivity of formation water (Rw), and calculating volume of shale (Halliburton, 1992; Ellis, 1987).

The Downhole Tension Device is commonly run with various logging toolstrings. It is used to measure tension and compression on the toolstring. In highly deviated boreholes, it is used to help determine whether the toolstring is in motion. The assembly can also be combined with temperature and tool-orienting devices. In Drillpipe-Conveyed and Coiled Tubing-Conveyed logging systems, the tension data aid in determining stresses applied to the toolstrings (Halliburton, 1992). The Downhole Tension Device was a part of all logging runs in the Terra–Patrick #7-22 well, with the exception of the dipmeter survey.

*Long Spaced Sonic/Gamma Ray log*

The Long Spaced Sonic/Gamma Ray log was recorded from 4,878.0 to 364.5 ft over runs 1 and 2. The compensated sonic tools determine the time required for a compressional sound wave to travel through 1 ft of formation. The formation's porosity, lithology, and type of pore content determine the sonic travel time ($\delta$T). If the type of pore fluid and rock lithology are known, travel time can be related to porosity. Compressional travel times are integrated and shown on the log by tick marks indicating depth intervals through which sonic waves travel in one second. This feature has important use in the interpretation of seismic data. Sonic tools contain two acoustic transmitters and two acoustic receivers. Travel-time measurements are made with transmitter to receiver spacings of 3 and 5 ft. The multiple travel-time measurements allow for compensation of borehole fluids, borehole rugosity, and sonde tilt (Halliburton, 1992). In the Terra–Patrick #7-22 well, a long spaced sonic (LSS) compensated tool was employed. This LSS tool allows travel-time measurements with transmitter-to-receiver spacings of 8, 10, and 12 ft. This feature gives a greater depth of investigation than tools with standard spacing,

The LSS log runs in the Terra–Patrick #7-22 well were combined with the gamma ray, tension, and caliper tools. The caliper log measures the diameter of the borehole and will indicate washouts or other anomalous borehole conditions. The tool also indicates mudcake buildup, gives data for calculating cement volume, and is used to pick sidewall core points and select packer seating depths (Halliburton, 1992).

### *High Resolution Induction/Gamma Ray/ Spontaneous Potential log*

The High Resolution Induction/Gamma Ray/ Spontaneous Potential (HRI/GR/SP) log was run from 4,978.1 to 1,961.1 ft. The HRI tool uses electromagnetic coil arrays similar to the DIL. There are, however, special arrays and signal processing techniques developed by Halliburton that allow the tool to investigate deeper into formations, to have better vertical bed resolution, and to determine more accurate formation resistivity values. The two resistivity curves recorded reflect the resistivity of the invaded zone (HMRS) and the resistivity of the uncontaminated zone (HDRS). The resistivity of the flush zone is also recorded with a digitally focused device (DFL). The vertical response of the DFL is matched to the two high resolution measurements, HMRS and HDRS, to allow determination of more accurate invasion profiles. Thin, potentially productive zones are also better defined by this combination of resistivity measurements (Halliburton, 1992). The HRI log run was combined with the gamma ray, spontaneous potential, and tension tools.

### *Spectral Density/Dual Spaced Neutron/Spectral Gamma Ray log*

The Spectral Density/Dual Spaced Neutron/Spectral Gamma Ray (SD/DSN/SGR) log was run from 4,911.9 to 1,853.4 ft. This combination of log signatures is commonly run on one toolstring. The density–neutron logs complement each other in their applications to indicate shale and determine shale volume, to indicate gas and determine gas saturation, and to identify formation lithology.

The Spectral Density tools have a chemical source of gamma radiation and two gamma detectors to determine formation bulk density ($\rho_b$) and photoelectric factor ($P_e$). Between the source and the detectors, the gamma rays are attenuated by the formation matrix and the pore content. The drilling mud and mudcake may also affect the travel of the gamma rays. The attenuation is a function of the electron densities and photoelectric absorption properties of these materials. Density measurements are used to determine formation porosity when the formation lithology is known. The $P_e$ can indicate formation lithology in single-mineral formations. In more common multi-mineral formations, $\rho_b$ and $P_e$ can be combined and cross plotted with neutron and sonic data for porosity and lithology determinations (Halliburton, 1992; Bateman, 1985).

The compensated neutron tool has a chemical source of neutrons and two thermal neutron detectors. Formation porosity is determined by measuring the intensity of thermal neutron radiation produced by bombarding the formations with fast neutrons. The energy of the fast neutrons is reduced by collisions with formation elements. Hydrogen is the best material for slowing down a neutron.

The gas effect from a neutron tool is caused by its sensitivity to hydrogen. In gas-bearing formations where the concentration of hydrogen is low, the tool will give a low reading. In combination with the density log, the crossover appearance by the two curves is a good indication of gas. The combination of neutron porosity with other porosity measurements, density and sonic, also helps identify lithology and calculate shale volume (Halliburton, 1992; Bateman, 1985). The Spectral Density and Compensated Neutron log run was combined with the Spectral Gamma Ray, caliper, and tension tools.

The Spectral Gamma Ray measures gamma ray intensity and energy to determine formation concentrations of the elements potassium (K), uranium (U), and thorium (Th). Specific concentrations of these elements allow more detailed formation stratigraphic and depth correlation than can be obtained from conventional gamma ray tools.

The applications of this tool include indicating potential hydrocarbon-bearing zones; distinguishing reservoir rock type containing accessory minerals from those containing clays; locating highly permeable or fractured reservoirs; determining clay types, volumes, and cation exchange capacities; evaluating shale source rock; detecting uranium, potash and coal deposits; providing well-to-well and log-to-log stratigraphic and depth correlations; defining bed boundaries; and detecting water migration (Halliburton, 1992; Bateman, 1985). The tool can be run in any fluid in a cased or uncased hole and may be combined with other logging tools. In the Terra–Patrick #7-22 well, the log was run with the caliper and tension tools.

*Six Arm Dipmeter Survey log*

The Six Arm Dipmeter Survey tool (SED) was run from 4,820.9 to 2,025.1 ft. As the name of the tool states, six pad-mounted, focused current electrodes measure resistivity at six azimuths around the borehole. The tool also measures borehole drift angle, drift azimuth, borehole diameter, and such related features as washouts and rugosity. The applications of this information include determining magnitude and direction of formation dip, identifying formation structural and sedimentary features, and determining borehole drift, azimuth, vertical depth, and bottom hole location. The tool also provides borehole profile and cement volume calculations (Halliburton, 1992). A gamma ray curve for correlation use with other logs was also run with the dipmeter survey tool.

A master set of Halliburton Logging Services, Inc., logs for the Terra–Patrick #7-22 borehole, filed as BA-104, is available for viewing and study by appointment at the Wisconsin Geological and Natural History Survey offices, Madison, Wisconsin.

**Log analyses**

In discussion of analysis of the various log signatures acquired in the subject well, the individual log responses will be related to each of the penetrated geologic formations. The formation depths and lithologies are from Daniels (ch. 7, this volume).

*Glacial sediment (13–290 ft)*

From ditch sample descriptions, the mudlog shows the base of the Pleistocene glacial sediment at 290 ft. There were no wireline-log surveys made at this depth except the GR log on the DIL/GR/SP survey, run 1. The log shows a possible lithologic or bed boundary at 280 to 290 ft.

*Freda Formation (290–3,528 ft)*

This rock interval includes a transition unit of Freda–Nonesuch Formations from 3,167 to 3,528 ft. The Freda Formation is primarily siltstone with very minor amounts of sandstone; the transitional zone consists of siltstones, mudstones, and shales from the underlying Nonesuch Formation and fluvial type sediments of the Freda Formation.

***Spontaneous potential.*** There is very little definition to the SP curve due to the impermeable nature of the rock. Opposite some intervals, the SP and the gamma ray curve track each other, possibly indicating a more permeable bed or zone. The difference in appearance of the two SP curves on the DIL/GR/SP log (run 2) and the HRI/GR/SP log may be due to digital recording and format in the HRI tool. The lower mud salinity may have lessened the tool response in both runs opposite more permeable beds if the mud resistivity and formation water resistivity had minimal contrast. The SP log has little value in correlation of formation boundaries.

***Gamma ray.*** The GR log was run with all the wireline surveys of the borehole. The log shows good definition of the formation boundaries. Gamma ray values based on spectral radioactive element percentages were used in defining formation tops and depositional environment (Daniels, ch. 7, this volume). Some intervals in the Freda Formation and deeper transition zone show bed definition with 20 to 30 API units relative to an adjacent shale reference line. Higher resistivity values are also found in the same interval. Two examples are found at 2,524 to 2,565 ft and 3,002 to 3,018 ft.

These intervals may represent thin, tight sands, partly interbedded with siltstones or shales.

The gamma ray curves in the density and spectral GR surveys were logged as a gamma-gamma curve and gamma ray spectral curve (see SD/DSN/SG log). The gamma-gamma curve shows the total gamma ray emissions; the gamma ray spectral curve shows the total emissions minus the uranium emission contribution. High uranium readings could indicate a "hot zone" or shale because of the mobile nature of this element in permeable beds such as sands. These high gamma-gamma readings would suggest a shale; however, it may actually be a sand. Showing a gamma ray curve without uranium's contribution could identify this sandstone lithology and a potential reservoir (Frank Cooper, Halliburton Logging Services, verbal communication, 1995). The uranium curve can also be used in fracture identification (Bateman, 1985).

***Resistivity***. The induction log was run for medium and deep formation resistivity values. A shallow guard log (Laterolog) was run to obtain values of the flushed zone. The deep and medium resistivity values in the Freda Formation averaged 20 ohm-meters with a gradual increase within the transition zone to 150 ohmmeters. The high concentrations of iron oxide material in the mud system may have lowered recorded resistivity values. The resistivity log headings note the presence of iron ore by the comments "iron ore present in drilling fluid causing anomalous spikes on the HRD (High Resolution Deep) and HRM (High Resolution Medium)." The presence of iron oxides in the drilling mud was also verified by placing a magnet on the cable at the drum with abundant mud material adhering to the magnet (Frank Cooper, Halliburton Logging Services, verbal communication, 1995).

***Density/neutron***. The density values average 2.6 to 2.7 g/cc through the Freda Formation with a slight increase to 2.7 to 2.75 g/cc in the transition zone. The neutron porosity values average 21 percent with a decrease to 15 percent near the base of the transition zone. From the known lithologies of the Freda Formation, the recorded density values are slightly higher than expected. This may be attributed to the iron-rich mud system or to a high percentage of iron minerals present in the mudcake. The thickness of the mudcake, however, may not be significant opposite the generally impermeable Freda Formation. The sonde contact with the borehole wall may remove any influence of the mudcake. With this working hypothesis, the recorded density values may be used in determining porosity and related formation evaluation analyses.

There are intervals on the SD/DSN/SGR log that show extreme scatter/noise probably due to high rugosity of the borehole revealed by the caliper log. An example is the interval 2,183 to 2,305 ft.

Two intervals were chosen for porosity determination from the density log, From 2,530 to 2,570 ft values of 2 percent porosity (2.65 g/cc matrix density) to 11 percent porosity (2.85 g/cc matrix density) were determined. By cross plotting neutron porosity and density values, a matrix density was determined approximately equal to a dolostone/dolomite density of 2.85 to 2.87 g/cc. (Note: dolostone/dolomite lithologies are not known in the Terra–Patrick #7-22 borehole).

A similar evaluation was made in the interval 3,000 to 3,020 ft. Porosity values of 2 percent and 11 percent were determined based on, respectively, 2.65 g/cc and 2.85 g/cc matrix densities. The cross plot of neutron/density values also equaled a dolostone/dolomite lithology density.

The $P_e$ can serve as a lithology indicator in single-mineral formations. The index can also be combined with bulk density, neutron, and sonic data to determine lithology and porosity in multiple-mineral formations. In the Freda–Nonesuch Formation transition interval, the $P_e$ averaged 3.5 to 4.0. The $P_e$ index for a clean to dirty sandstone averages 1.7 to 2.7 and an average shale is 2.7. The $P_e$ index for hematite is 21.5. These values, again, may indicate some influence that the iron contaminated mud has on the density log measurements.

***Sonic log***. A Long Spaced Sonic/Gamma Ray log was run in the Terra–Patrick #7-22 well. This type of sonic log has a detector configuration that allows a more reliable measurement of transit time of the undamaged formation (Ellis, 1987). The formation travel time in the Freda Formation averaged 80 microsec/ft to a depth of 2,700 ft and increased to an average 65 to 70 microsec/ft through the transition zone. Comparing sonic porosity in the interval 2,530 to 2,570 ft to density porosity with the two travel-time matrices, 55 for sand and 43 for dolostone/dolomite, the sonic values were 15 percent and 21 percent, respectively. In the interval 3,000 to 3,020 ft, sonic porosity values were 7 percent and 13 percent with the two matrices. The presence of iron oxides (or "iron ore" as listed on the log heading) in the mud system may affect the recorded sonic travel time because of its matrix travel time of 46 microsec/ft. Typically, sonic derived porosities are higher than porosity values from the density log.

The primary use of the sonic log is the utilization of sonic velocity times of penetrated geologic formations in optimizing the interpretation of seismic surveys in the area of the borehole. The sonic data can also be used in various cross-plot applications for lithology and porosity determination.

*Nonesuch Formation (3,528–3,931 ft)*
The Nonesuch Formation represents sediments from primarily a lacustrine environment. It consists of siltstones, mudstones, shale, and rare amounts of sandstone. A transition zone between the Nonesuch Formation and the underlying Copper Harbor Formation occurs from 3,931 to 4,093 ft (Daniels, ch. 7, this volume). This interval will be included with the Copper Harbor Formation in discussion of the wireline logs.

There are a few comments to make on the log responses in the Nonesuch Formation. The SP log has a typical shale response. The GR log shows some definition with higher shale-type readings in an average range of 75 to 110 API units. The spectral GR log was used in confirming formation boundaries and depositional environments (Daniels, ch. 7, this volume),

Nonesuch Formation resistivity gradually increases from 100 ohmmeters to 200 ohmmeters over its thickness. Sonic travel time averages 70 to 65 microsec/ft, with a slight decrease in travel time near the base of the formation. Two instances of apparent cycle skipping or low density shale response were noted at depths 3,565 and 3,650 ft. The caliper log showed no unusual intervals of high rugosity at these depths. The Spectral Density/Dual Spaced Neutron/Spectral Gamma Ray log showed somewhat typical signatures of a shale–silt sequence. Average density for the Nonesuch Formation was 2.70 g/cc and neutron porosity (limestone index) averaged 18 percent.

*Copper Harbor Formation (3,931–4,966 ft, total depth)*
The lithology of the Copper Harbor Formation consists of sandstone that is very fine grained with calcite cementation and red-brown micaceous siltstone. Also present are volcanic rock fragments. A transition zone from 3,931 ft to 4,093 ft reflects the fluvial–alluvial depositional environment of the Copper Harbor Formation and the overlying lacustrine environment of the Nonesuch Formation (Daniels, ch. 7, this volume). There are two well defined sands from 3,931 to 3,949 ft and 3,669 to 4,013 ft.

*Spontaneous potential and gamma ray.* The SP curve shows some definition with responses of up to -30 millivolts. However, the correlation and meaning to the formation and other logs are not clear except to reflect a rather impermeable formation and show a possible influence from a higher salinity mud system.

The GR log shows two discrete sandy intervals in the transition zone and reveals a blocky signature over the Copper Harbor Formation below 4,093 ft. The gamma-gamma and spectral GR logs overlie each other closely below 4,093 ft, suggesting little contribution from uranium to the total gamma ray count. The transition zone shows a 10 to 15 API unit effect by uranium as similar to the overlying Nonesuch and Freda Formations. The Spectral Natural Gamma Ray log shows a significant decrease in potassium, from 5 percent and 8 percent to 2 percent, below 4,093 ft. The two sand intervals also reflect lower potassium percentages. The ppm amount of thorium decreases below 4,093 ft. Daniels (ch. 7, this volume), uses the GR signatures to develop depositional environments

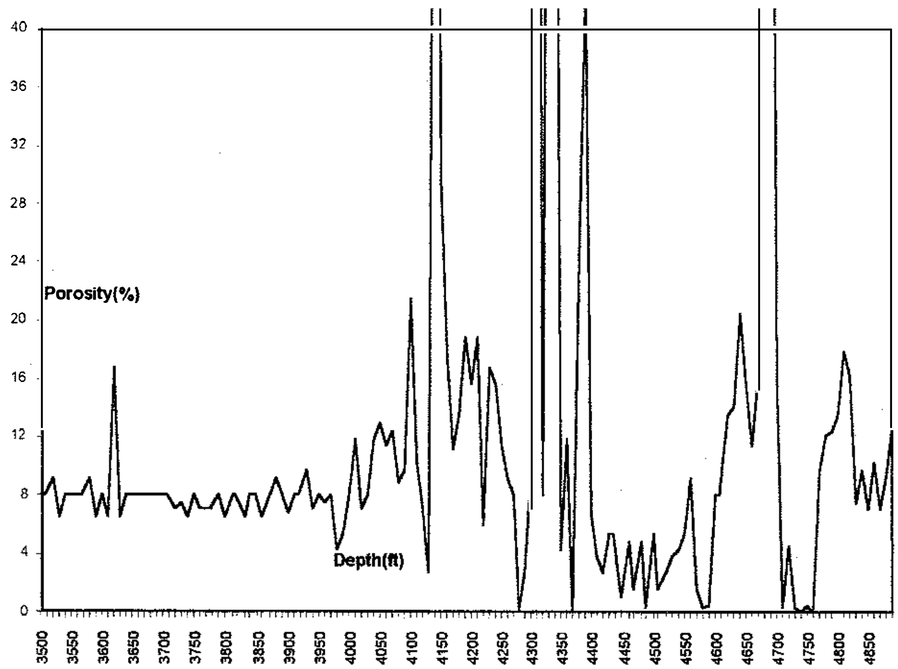


**Figure 1.** *Nonesuch and Copper Harbor Formations. Plot of density porosity (%) vs. depth (feet). A matrix density of 2.85 g/cc is used in calculating porosity values. Cross plots of various log signatures were made in determining this matrix density, The anomalous spiking below 4,000 ft is due to extreme borehole rugosity.*

for the Nonesuch-Copper Harbor transition zone and the Copper Harbor Formation.

The logging engineer noted on the GR log heading that "iron ore (was) present in the drilling fluid" and a "gamma ray spike at 4795 [ft was] possibly due to neutron charging the formation while setting up on mag. mark."

***Resistivity.*** Very high resistivity readings are found in the sand intervals of the transition zone and the main body of the Copper Harbor Formation. The HMRS (medium) and HDRS [deep] readings have values up to 1,000 ohmmeters. The logging engineer noted "iron ore present in drilling fluid [is] causing anamolous spikes in the HRD and HRM [curves]s." The caliper log over one interval, 4,300 to 4,400 ft, shows extreme "out of gauge" conditions and may have influenced the readings. After discussions with Halliburton personnel, it is suggested that with such high ohmmeter readings, a Dual Laterolog suite of tools may have been advantageous to run instead of the DIL and HRI tools.

***Density/neutron.*** Bulk densities averaged 2.70 to 2.75 g/cc in the Nonesuch-Copper Harbor transition zone and 2.60 to 2.85 g/cc in the main body of the Nonesuch Formation. Neutron porosities varied from 15 to 40 percent below 3,931 ft. A separation of the neutron and density curves suggests the presence of shale in the rare sands of the formation.

A plot of depth to porosity from 3,500 to 4,889 ft was made for two matrices, 2.85 and 2.65 g/cc. The 2.85 g/cc matrix was determined the best value to use in calculating porosities at these depths. This was based on neutron/density/sonic cross plots for lithology and porosity. The Hingle cross plot (Batemen, 1985) of resistivity and bulk density values was also used in determining the density matrix.

Figure 1 is based on a 2.85 g/cc matrix, and figure 2 is based on a 2.65 g/cc matrix. The anomalous intervals of spiking, showing high porosity values on both figures, is due to extreme out-of-gauge/rugose hole conditions.

The $P_e$ averaged 4.0 to 4.5 below 3,931 ft. The recorded $P_e$ for the entire penetrated stratigraphic section was consistent, with values from 3.5 to 4.5. The impact of iron-contaminated drilling fluid on the density/neutron log is negligible based on these $P_e$ indices.

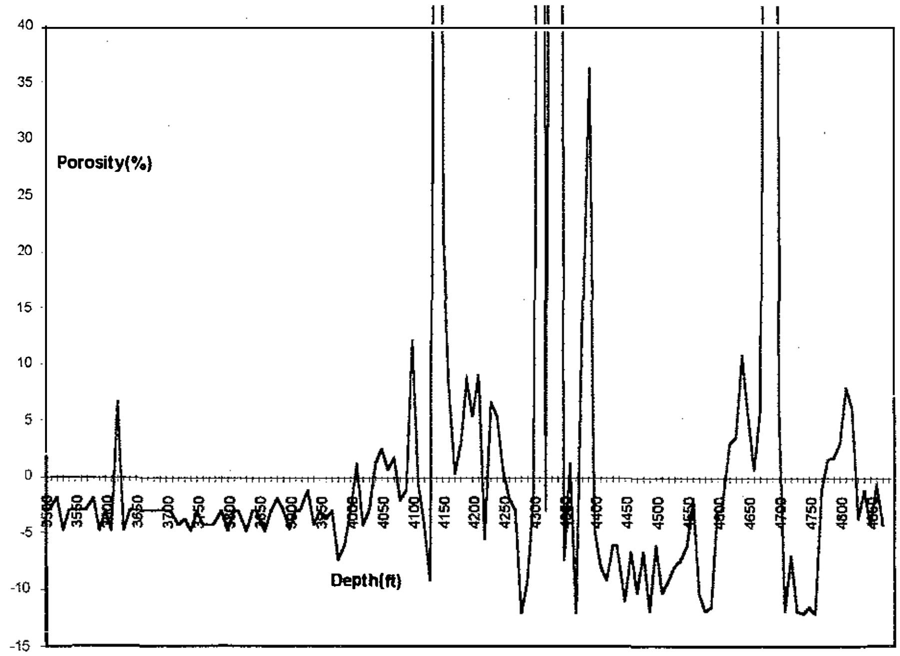


**Figure 2.** *Nonesuch and Copper Harbor Formations. Plot of density porosity (%) vs. depth (feet). A matrix density of 2.65 g/cc was used in calculating porosity values, This matrix density is commonly used for a sandstone lithology. The anomalous spiking below 4,000 ft is due to extreme borehole rugosity.*

***Sonic log.*** Travel times below 3,931 ft averaged 50 to 55 microsec/ft except from 4,100 to 4,250 ft where readings up to 65 and 85 microsec/ft were noted with porosities to 24 percent. Figure 3 shows a plot of depth (3,500 to 4,820 ft) to porosity based on a matrix of 55.6 microsec/ft.

Further porosity analysis from the sonic log was not pursued. The primary uses of the sonic data would be in lithology–porosity cross plots and velocity integration in the interpretation of seismic surveys.

***Logs that spanned more than one formation***

Two additional logs from the Terra–Patrick #7-22 well will be briefly discussed: the Six Arm Dipmeter Survey and the Tarrant Mudlog.

***Dipmeter survey.*** Using the dipmeter survey data, special software programs calculated dip and strike of the formations penetrated in the borehole. The results were presented on a tadpole–pollywog plot with arrows indicating direction of dip and a graduated grid from 0° to 90° showing dip angle. There are also statistical plots over specific depth intervals showing average clustered azimuths.

The caliper log is displayed on the left track with the GR log. The four-arm caliper gives an excellent display of intervals with extreme hole rugosity. The gamma ray curve is used to correlate the rugose features to other tool measurements that may be affected by these features.

An interpretation of dip data in the Terra–Patrick #7-22 well is given by Daniels (ch. 7, this volume). The formation dips were in a general southeast direction with a magnitude of 20° to 30°. Erratic dips were noted or dips absent, in part, in intervals with high borehole rugosity. This is caused by lack of or uneven pad contact with the borehole wall. Overall, however, the dipmeter was of good to excellent quality.

The borehole had a gradual increase in drift angle from 10° to 18° over the logged interval. At the surface-casing depth, 2,002 ft, the borehole was already deviated 9° at north 10° east. These data are shown on the right track of the log. In drilling to total depth, the bit migrated up structure to the north–northwest in an expected direction of drilling through southeast dipping beds. In oilfield parlance, this is mentioned as "letting the bit find the oil." Unfortunately, it did not happen in this well.

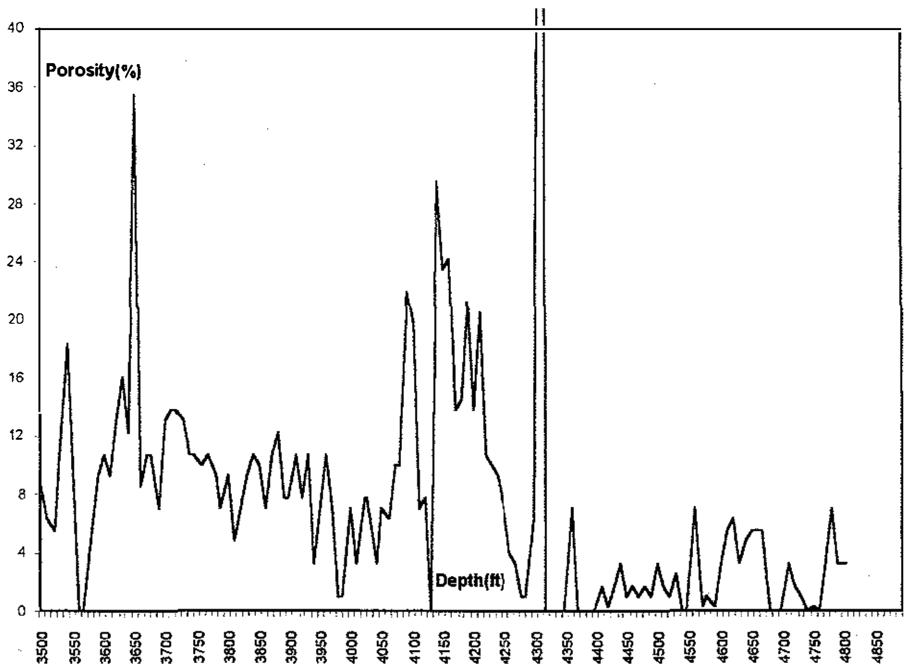


**Figure 3.** *Nonesuch and Copper Harbor Formations. Plot of sonic porosity (%) vs. depth (feet). A matrix travel time of 55.6 sec/ft is used in calculating porosity values. This matrix travel time is commonly used for a sandstone lithology. The anomalous spiking below 4,000 ft is due to extreme borehole rugosity.*

The intervals of extreme rugosity out-of-gauge were probably due to fracture zones in situ to the formations. The magnitude of deviation from vertical does not seem substantial enough to cause such fracturing. Dog-leg severity may also contribute to washouts; however, this borehole does not have such a feature (Kenneth R. Weeks, consultant, written communication,1995).

*Mudlog*. The subject well was mudlogged by Tarrant Mudlogging Consultants, Traverse City, Michigan. This important and critical log to a wildcat well such as the Terra–Patrick #7-22 gives the first qualitative and quantitative indications of hydrocarbons present in geologic formations that are penetrated during the drilling process. The log contains drilling-log statistics, rate of penetration, a column with well depths and rock lithology symbols, a written description of the collected formation ditch samples, and a gas analyzer and chromatograph. The well was logged from surface to 4,966 ft, total depth.

There were no indications of ditch gas or other hydrocarbon shows until 3,833 ft. In fact, a review of the mudlog above this depth may lead one to question whether the gas analyzer was on or properly functioning. Periodic carbide lag time tests were made, however, which disproved that possibility. Ditch gas readings reached a maximum recorded value of 39 units at 3,867 ft and declined to two units at 4,084 ft and remained at two units to total depth. Very minor amounts (trace up to 3¾ units) of methane, ethane, and propane were recorded from 3,833 to 4,030 ft.

Daniels (ch. 7, this volume), commented on the quality of lithologic samples, sample lag times, and other related mudlog matters. Adequate intervals for determining lag times were made, but improper calculations to arrive at the lag time may have occurred. The top of the gas show at 3,833 ft might be expected to correlate to the top of the Nonesuch–Copper Harbor transition zone sand at 3,931 ft. A miscalculation on a lag time of this magnitude is unusual. There must be a continuing communication with the driller on drill-pipe tally, mud-pump strokes, and other concerns important to the mudlogging operation.

In the mudlogging process, the mudlogging geologist(s) must be accurate in their work and record everything they see and describe. Any interpretation of the mudlog data is the sole responsibility of the well-site or company geologist.

## SUMMARY

The suite of wireline logs run by Halliburton Logging Services, Inc., in the Terra–Patrick #7-22 well contained considerable data useful in the formation evaluation of the well and subsequent contributions to the geology of the area. It was unfortunate that circumstances were present that affected the drilling-mud system and probably had an impact on log values from some of the recorded signatures.

Most disappointing was the absence of hydrocarbons in the objective geologic formations explored by the test well. The true value, worth, and challenge of wireline surveys are brought to focus when such recordings are made in formations that contain economic quantities of oil and gas.

## ACKNOWLEDGMENTS

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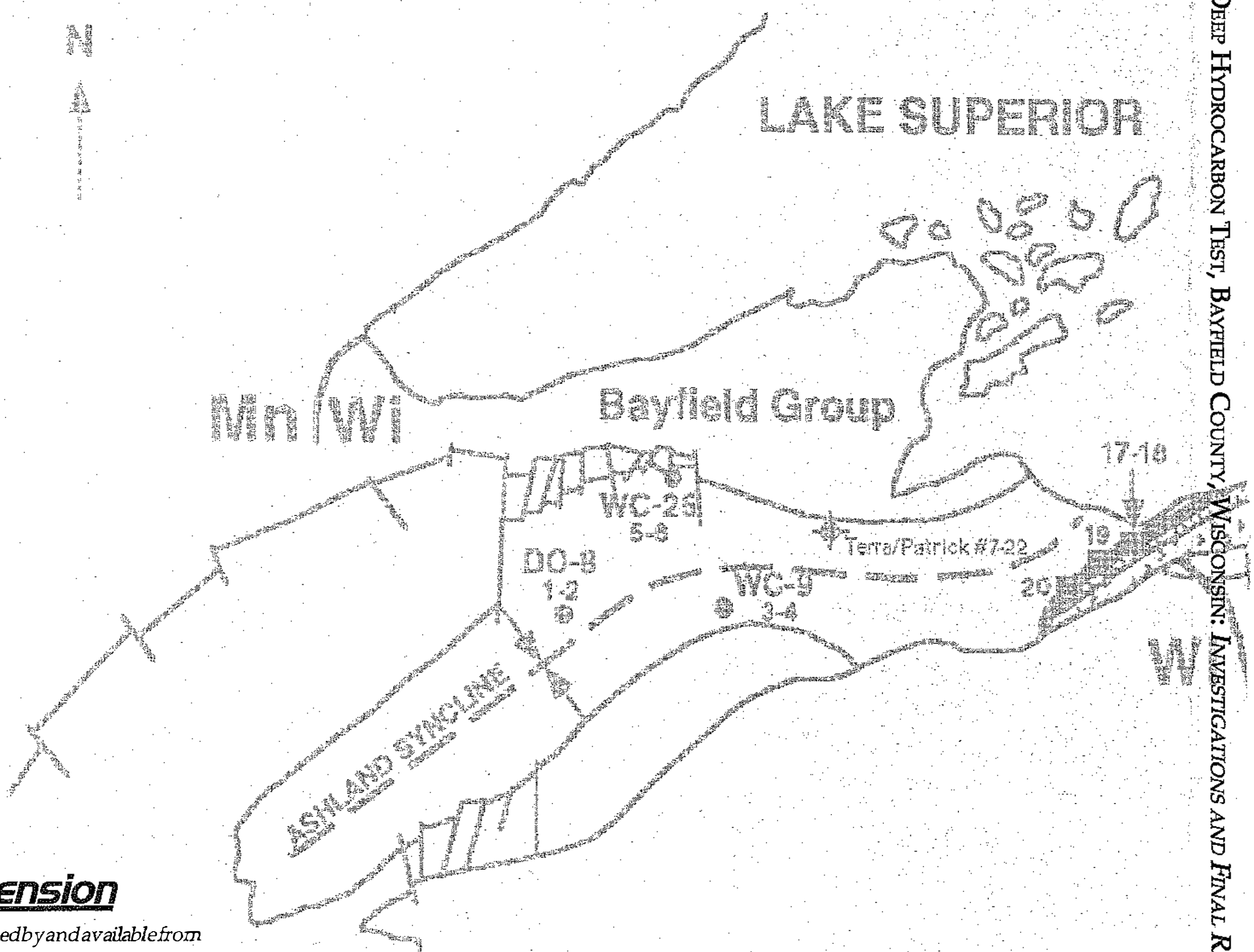
The editors also extend their appreciation for the contribution of time and expertise on the part of each author associated with the reports contained within this volume. Their sole compensation was the knowledge that their participation in the evaluation of new information obtained through the exploration for hydrocarbon in Wisconsin from 1982 to 1992 has greatly increased the geologic record of the Lake Superior Basin.

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