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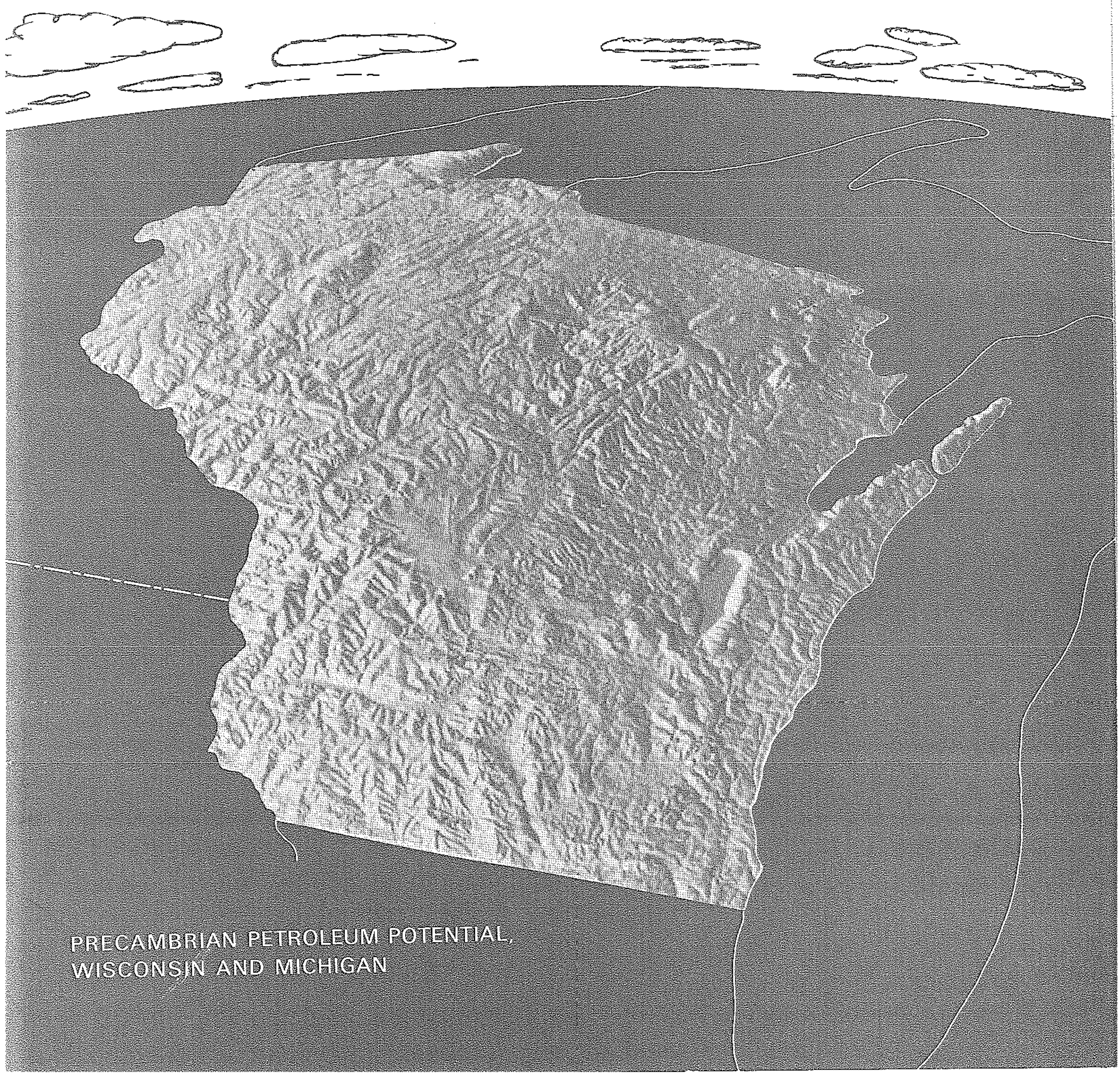

PRECAMBRIAN PETROLEUM POTENTIAL, WISCONSIN AND MICHIGAN

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PRECAMBRIAN PETROLEUM POTENTIAL, WISCONSIN AND MICHIGAN

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PREFACE

"Geoscience Wisconsin" is a serial that addresses itself to the geology of Wisconsin--geology in the broadest sense to include rocks and rocks as related to soils, water, climate, environment, and so forth. It is intended to present timely information from knowledgeable sources and make it accessible with minimal time in review and production to the benefit of private citizens, government, scientists, and industry.

Manuscripts are invited from scientists in academic, government, and industrial fields. Once a manuscript has been reviewed and accepted, the authors will submit a revised copy of the paper, and the Geological and Natural History Survey will publish the paper as funds permit, distribute copies at nominal cost, and maintain the publication as a part of the Survey list of publications. This will help to insure that results of research are not lost in the archival systems of large libraries, or lost in the musty drawers of an open-file.

The papers in this volume represent supplemental information for the 16th Annual SEPM Field Conference on Precambrian oil and gas potential along the Midcontinent Trend (Wisconsin Geological and Natural History Survey Field Trip Guide Book No. 13). The organizers of the field trip, M.G. Mudrey, Jr., A.B. Dickas, and R.W. Ojakangas, chose to summarize the general geologic relations of Keweenawan rock in the Lake Superior area, summarize information on Proterozoic petroleum in Australia and Asia, evaluate newly acquired seismic data, and evaluate the major structural elements in the Lake Superior area.

We encourage submission of manuscripts relating to Wisconsin Geology. Special consideration will be given papers which deal with timely topics, present new ideas, and have regional or statewide implications.

M.G. Mudrey, Jr.
Editor-Geoscience Wisconsin
Wisconsin Geological and Natural History Survey

I. OVERVIEW

M.G. Mudrey, Jr.

INTRODUCTION

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

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

PROTEROZOIC PETROLEUM

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

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

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

Barghoorn and others (1965) detected metalloporphyrins from an extract of the 1,100 Ma Nonesuch Shale in Michigan. Furthermore, the recovery of alkanes from petroleum seepage in the Copper Range Mine in White Pine, Michigan (White and Wright, 1954), lends strong emphasis to the fact that petroleum, at least as a possible source bed, occurs in the Precambrian of North America (Kelly and Nishioka, 1985). Four events have been proposed as leading to the creation of the Midcontinent Rift System: graben development about 1,100 Ma, and the outpouring of basaltic plateau lava flows; isostatic sinking of the volcanic rock and associated gabbroic complexes that led to erosion and clastic sedimentation; reactivation and uplift of graben and erosion of material on the horst and deposition of clastics in horst flanking basins; and erosion of the horst into Phanerozoic time, perhaps with minor tectonic adjustments continuing as late as Middle Ordovician.

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

MIDDLE PROTEROZOIC GEOLOGY OF THE LAKE SUPERIOR AREA

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

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

Dominantly vertical faulting continued intermittently throughout the time of active sedimentation and into the Paleozoic Era. This most recent tectonic event is characterized by the development of an axial horst along the main rift trend and subsequent subsidence of the rifted region to form the major embayments that existed during the Paleozoic Era.

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

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

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

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

II. PRECAMBRIAN PETROLEUM

PRECAMBRIAN AS A HYDROCARBON EXPLORATION TARGET

Albert B. Dickas

ABSTRACT
As recently as 1950 it was generally accepted that sedimentary rock of Precambrian age located within basins, geosynclines, and platforms could not contain hydrocarbon deposits. The absence of pre-Paleozoic Era life and the lack of reservoir rock characterisitics in these Precambrian rock columns were the most often presented reasons why Precambrian terranes should be ignored by the petroleum geologist. Within the past three decades evidence for varied forms of life has been discovered in sedimentary rock as old as 3.6 Ga. Simultaneously many Precambrian rock columns have been recognized as possessing excellent reservoir characteristics. With the discovery of commercial deposits of indigenous Precambrian-age hydrocarbons, sedimentary rock deposited throughout the world during this early chapter in earth history is being analyzed by the oil and gas industry.

INTRODUCTION
The seven basic requirements necessary for the formation of any hydrocarbon deposit are deposition of organic source material, maturation of source rock, migration of developed hydrocarbons, accumulation under reservoir characteristics, concentration by trapping mechanisms, containment by sealing conditions, and preservation of hydrocarbons through geologic time.

Of these, the three most often denied serious consideration within the time-frame of the Precambrian are those of presence of source and reservoir strata and potential for preservation of hydrocarbon.

PRECAMBRIAN SOURCE ROCK POTENTIAL
To many, Precambrian rock is seen as the end geologic product of thousands of millennia, during which molten and turbulent events created earth environments entirely unfavorable to the development of petroleum and natural gas. The exploration philosophy of many active petroleum geologists is directed by the belief that extensive, prolonged tectonism, characterisitic of the Cryptozoic, did not allow the evolution or preservation of life forms. Jones (1956) emphasized this bias and stated that "the recognition of evidence of life in Pre-Cambrian strata is one of the most controversial problems in all geology, and there is considerable doubt expressed by many paleontologists concerning the nature of the microfossils which have been reported." Meinschein (1965) agreed that "until 10 years ago [that is, 1955] it was widely believed that life on earth originated near the beginning of the Cambrian time."

These statements expressed 30 and 20 years ago aided in the development of undergraduate and graduate school philosophies of many petroleum geologists presently operating at the district, division, and board level. That these philosophies still undergird exploration philosophies in many American organizations is documented by the timidity with which American geologists, even today, approach the Precambrian as a hydrocarbon frontier. This timidity is startling when compared to successful Precambrian exploration programs undertaken by geologists in the Soviet Union, China, and Australia since the early 1960s.

By 1965 less than 300 papers dealing with the subject of Precambrian life had been published (Murray and others, 1980). This record has increased more than fivefold and includes discoveries of fossil life from both shield and non-shield areas of all the principal landmasses. The following short list of significant occurrences, arranged in order of decreasing geologic age, is illustrative of the richness and extent of the Precambrian fossil record.

Warrawoona Group of Western Australia: single-celled spheres, filaments and stromatolites, approximately 3.5 Ga (Dunlop and others, 1978). Onverwacht Series of South Africa: spheroidal and hemispheric-shaped algae-like bodies, minimally dated at 3.2 Ga (Engel and others, 1968), possibly the oldest known structurally preserved fossil organisms (McKirdy, 1974), occurring in the oldest "little-altered sedimentary rocks on earth" (Levin, 1983).

Fig Tree Group of South Africa: rod-shaped, bacteria-like, blue-green algae spheroidal bodies, approximately 3.1 Ga (Barghoorn and Schopf, 1966).

Bulawayan Group of southern Rhodesia: occurrence of stromatolites (McKirdy, 1974) dated from 2.7 to 3.0 Ga; carbon 12/13 ratio is suggestive of biologically produced atmospheric oxygen and fixation of carbon dioxide by photosynthesis (Levin, 1983).

Gunflint Iron Formation of the Lake Superior region: a varied and spectacular assemblage of thread bacteria and blue-green algae, 1.9 Ga (Tyler and Barghoorn, 1954), discovery of these fossils "represented the first definitive evidence of life before the age of visible animal life" (Cooper and others, 1986).

Bitter Springs Formation of Australia: possibly oldest known evidence of eukaryotic (nucleated) celled fossils, 900 Ma, beginnings of life with genetic variability and sexual reproduction capacities (Schopf, 1968).

Pound Quartzite, Ediacara Hills of southern Australia: appearance of metazoan (multicellular) jellyfish, corals, flatworms, echinoderms, and arthropod-like animals, 570 to 650 Ma (Glaessner, 1961).

The Precambrian era was the time when life originated on earth. Yet the recognition that fossil- and organic-rich sedimentary rock form a significant part of the Precambrian record is a recent development (McKirdy, 1974). The above examples and other Precambrian beds rich in organic material do not differ in any respect from much younger Phanerozoic beds in their potential as hydrocarbon source units. Studies have shown that certain Precambrian sections are distinguished by containing as much organic carbon as considerably younger rock of equivalent lithofacies (Nanz, 1953; Shaw and others, 1967). This is especially true of Proterozoic sedimentary rock, in which a sixfold enrichment of organic carbon is found compared to older strata (McKirdy, 1974). The suggestion that even these late Precambrian beds might not contain quantities of organic matter sufficient for the formation of hydrocarbon is negated by oil seeping from the 1.04 Ga Nonesuch Formation in the Lake Superior region and the significant reserves of indigenous Proterozoic oil and gas discovered since 1962 in the Siberian Platform (Vassoyevich and others, 1971).

PRECAMBRIAN RESERVOIR ROCK POTENTIAL

J.J. Sederholm is reported to have been one of the first geologists to realize that "there was no obvious reason why Hutton's principle [of uniformitarianism] should be limited to the Cambrian and later period" (Holmes, 1965). Thus was adopted the hypothesis that the tectonic development of the earth's crust has been a continuum since early Precambrian time. Over the past several decades it has been noted and emphasized that Precambrian erosional and depositional processes created sedimentary columns lithologically similar to those of younger sedimentary rock sequences. McKirdy (1974) placed the continuum of sedimentary processes in perspective by observing that the "overall continuity of similar sedimentary facies and their lithologic expressions into the Phanerozoic provides little evidence of sudden sedimentological or geochemical change accompanying, or immediately preceding, the onset of Cambrian sedimentation."

Today, Precambrian columns the world over are recognized as containing sedimentary rock unaffected by severe regional metamorphism and possessing porosity, permeability, sedimentary, and thermal history characteristics favorable to the accumulation of hydrocarbon. These columns include the Riphean and Venian of Russia, the Sinian of China, the Vindhyan of the Hindustan Platform, the Lalun and Hormuz of Iran, the Bundu and Volta of Africa, and Belt and Keweenawan of North America. In Australia alone more than 20 basins, geosynclines, or platform areas are recognized as containing normal Proterozoic sedimentary columns (Compton and Arriens, 1968). Becker and Patton (1968) summarize the potential for reservoir characteristics within Precambrian rock by stating that "evidence does not support the view that a particular system of sedimentary rocks is the lower limit of petroleum entrapment solely because of its great age."

PRESERVATION OF PRECAMBRIAN HYDROCARBON

The third consideration regarding the supposed improbability of Precambrian hydrocarbon reservoirs requires little discussion here. Debate suggesting a lack of Precambrian oil or gas reserves is generally supported by several courses of reasoning.

The decline of known hydrocarbon reserves as a function of increasing geologic time would suggest absolute minimal to zero volumes indigenous to Precambrian sedimentary rock columns; the lapse of approximately 600 m.y. since the termination of the Precambrian Eon, accompanied by continuing burial and diagenesis would suggest that any Precambrian hydrocarbon accumulation discovered today would have been reduced to the tar residue stage; and even if hydrocarbon accumulations had been formed during the Precambrian, such would in all probability have been subsequently lost due to destruction of the trapping mechanism by erosion or faulting.

The presence of economic deposits of indigenous Precambrian oil and gas in the Soviet Union and China negate these positions.

CONCLUSIONS

Precambrian sedimentary rock terranes should not remain outside the exploratory domain of the petroleum geologist. All factors necessary for the formation of economic hydrocarbon deposits have been in operation throughout the past 3.5 b.y. The initiation of sedimentary rock processes some 3.7 Ga and the advent of life some 3.5 Ga brought into co-existence the factors necessary for the creation of oil and gas fields.

WORLDWIDE DISTRIBUTION OF PRECAMBRIAN HYDROCARBON DEPOSITS

Albert B. Dickas

ABSTRACT

Bias against the economic discovery of hydrocarbon from Precambrian rock is of long standing. Historically, the professed deterrents to the discovery of oil and gas production from rock older than 580 Ma have ranged from lack of life, and thus absence of source beds, to excessive maturation of existing organic material, to lack of sedimentary reservoir beds. Repeated studies have shown that hydrocarbon is distributed world-wide, principally in Mesozoic and Cenozoic sedimentary rock sequences.

Prior to the 1960s a minor amount of "Precambrian" production was known. These fields normally were created by hydrocarbons derived from Phanerozoic sources migrating into fractured Precambrian igneous rock because of favorable structural associations. Since the 1960s, however, at least a dozen oil and gas fields, several of considerable size, have been discovered in Precambrian reservoir rock, the oil of which was supplied from Precambrian source strata. Such relationships have been made or reported in the East Siberian Platform and the Ural-Volga regions of the U.S.S.R., the Amadeus Basin of Australia, the Sichean and Bohai Bay Basins of China, and the Montana and Lake Superior areas of the United States.

RECENT PRECAMBRIAN HYDROCARBON DISCOVERIES

The geologic literature prior to the 1960s contains reports of commercial and non-commercial hydrocarbon reservoirs associated with Precambrian rock. In these reports the usual explanation involves fractured igneous or metamorphic sequences that have absorbed migrating hydrocarbons derived laterally or vertically from younger source beds. Instances of Precambrian hydrocarbon discoveries reported since the 1960s from the Soviet Union, China, Australia, and the United States are significant because in each the hydrocarbon production is not only reservoir associated, but also initially reported to be source associated with Precambrian rock.

East Siberian Platform

The East Siberian Platform (Irkutsk Amphitheater) Petroleum Province, U.S.S.R., contains the largest proved reservoir of indigenous Proterozoic gas, oil, and condensate. The fact that the marine, shallow-water platform sedimentary rock found here has been subjected to an almost total absence of tectonic activity and is rich in organic matter adds greatly to the potential as hydrocarbon reservoirs of major significance. The potential for this area is so great that Meyerhoff (1980) suggests that "several hundred, perhaps, several thousand, oil and gas fields remain to be found."

At least ten commercial oil or gas fields or both have been reported from the East Siberian Platform; all possess at least one reservoir horizon within the Precambrian section.

In 1962 oil and gas were discovered within arenaceous strata of the Markovo horizon, the upper unit of the Ushakovka suite of Riphean age 450 km northeast of Irkutsk, Siberia (fig. 1). The Markovo horizon is 680 Ma (Meyerhoff, 1980), and possesses good reservoir qualities with porosity up to 13 percent and permeability up to 214 md (Trofimuk and others, 1969). The discovery well tested 549 barrels of condensate and 8,655 Mcf of gas per day on a 25 mm choke. Continued drilling in the area of discovery led to the development of the Markovo field with recent proved reserves in excess of 622 Bcf of gas and 16 million barrels of condensate, contained in stratigraphic traps (Meyerhoff, 1980).

Hydrocarbon has been found associated with two additional Precambrian zones in the Markovo sector. The lithology, age, and commercial rating of all three zones are, from oldest to youngest (Meyerhoff, 1980): Bezymyannyy horizon, Ushakovka suite, Riphean age (680 to 925 Ma), 5 to 25 m of angular, poorly sorted, terrigenous sandstone and conglomerate, non-commercial gas reservoir, 4 to 6 percent porosity and less than 1 md permeability; Markovo (Osinskiy) horizon, Usakovka suite, Riphean age (680 to 925 Ma), up to 30 m of quartzose to feldspathic, medium-grained sandstone, oil and gas within possibly the oldest commercial hydrocarbon reservoir in the world, 2 to 13 percent porosity and up to 20 md permeability; and Parfenovo horizon, Motka suite, Venian age (570 to 680 Ma), 15 to 90 m of moderately well sorted, partially feldspathic, quartz sandstone, commercial oil and gas reservoir considered the most important and widespread Precambrian reservoir rock of the East Siberian Platform, 8 to 23 percent porosity and up to 4,300 md permeability.

At least one additional Precambrian hydrocarbon zone was discovered outside of the Markovo section in 1971: Yaraktin horizon, believed to be of ap-

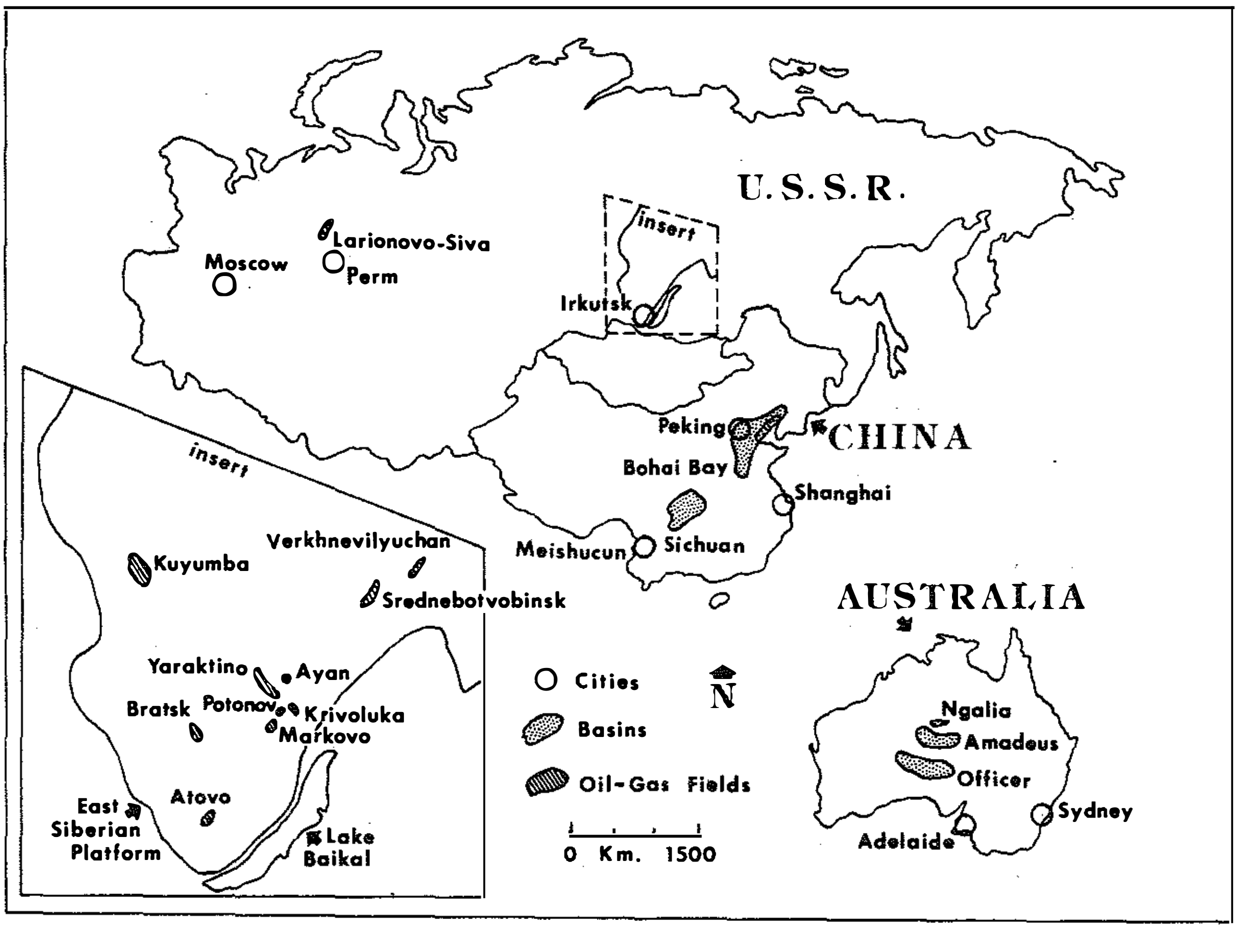

Figure 1. Location of existing and potential Precambrian oil and gas production in Australia, China, and the Soviet Union.

proximate Parfenovo horizon age, 26 m of bar type sandstone, 9 to 10 percent porosity and unknown permeability.

Northern Ural-Volga Region

The upper Precambrian in the northern Ural-Volga region in the vicinity of Perm, U.S.S.R. (fig. 1) is composed of terrigenous-carbonate sedimentary rock of Riphean age and terrigenous rock of Vendian age. The four recognized formations of the Riphean sequence are composed of sandstone and conglomerate redbeds, which grade upward into dark gray siltstone, marl, and carbonate, which, in turn, are overlain by gray sandstone. The Vendian sequence is made up of two formations described as gray, medium-grained clastic rock and shale overlain by green and red clastic rock and shale. The reservoir rock belongs to the Kairovo Formation of Lower Vendian age, and the Kaltasa Formation of Riphean age (Balashova and others, 1983). The general lithology of these units is, respectively, fine- to medium-grained sandstone having a porosity range of 7 to 13 percent, and overlapped carbonate and terrigenous-carbonate strata. Both formations were deposited under reducing environmental conditions, but the older Kaltasa Formation played "the principal role" in the generation of the hydrocarbon (Balashova and others, 1983).

Geochemical indicators demonstrate that the oil differs from and is genetically independent of Paleozoic oil found in the same general region. Murray and others (1980) support a Precambrian age by suggesting that the different chemical composition of the younger oil is one test of an oil being indigenous to the Proterozoic.

Although hydrocarbon reserve data for these strata are not known, apparently commercial prospects have been discovered in the Larionovo and Siva oil fields west-northwest of Perm. Shows of gas are also known in this region.

Amadeus Basin

The Amadeus Basin of central Australia encompasses an area of approximately 180,000 square km within the southwestern part of the Northern Territory, Australia (fig. 1). This basin is composed of unmetamorphosed Proterozoic sedimentary rock conformably overlain by a Paleozoic section of Cambrian and Ordovician strata. The north and south limits of this basin are marked by outcrop of unprospected Archean and Proterozoic igneous basement rock (Webb, 1965). In 1963 the Ooraminna #1, a 1,861 m test, was drilled in this basin. Murray (1965) expressed his belief that this was "the first well ever deliberately programmed to search for oil and gas in Proterozoic sedimentary rocks outside of Russia."

The Ooraminna #1 was spudded in basal Cambrian clastic material of the Arumbera Sandstone and bottomed in Proterozoic halite strata. Overlying this salt the remaining Proterozoic section is composed of carbonate or the Bitter Springs Formation, carbonate and clastic material of the Areyinga Formation, and the Ertatataka Formation, composed of in excess of 600 m of black to green shale containing a thin, 6 m-thick dolomitic limestone. A drill stem test of this limestone flowed 12 Mcf/D methane gas (Murray, 1965). Unfortunately, this was the only significant reservoir facies penetrated, requiring this test to be abandoned (Gardner, 1963). Although a commercial failure, this test was a geologic success as it constituted the "irrefutable evidence of indigenous hydrocarbons in the Precambrian of Australia" (Murray and others, 1980).

In 1963 a limestone reef structure was tested by the Alice #1 well, located 24 km northwest of the Ooraminna #1. The Alice #1 was abandoned, but not until oil shows were reported from Lower Cambrian carbonate. In late 1963 the first of a series of wells was drilled on the Mereenie structure, which is situated in the central section of the Amadeus Basin. The initial well tested 11 MMcf/D of wet gas from the Stairway and Pacoota Sandstones of Ordovician age. By 1965 commercial gas-condensate production, along with evidence of an oil column, was proved in the lower Paleozoic along the axis of the Mereenie structure (Webb, 1965). Lindner (1985) reported that the "Mereenie field [was] brought on steam in September, 1984, at an initial production rate of approximately 1,500 BOPD."

Testing of the central Australian Proterozoic section has continued in recent years. In 1981 the Davis #1 was drilled in the Ngalia Basin, a small sedimentary trough located immediately north of the Amadeus Basin. It encountered minor gas shows from a "basal Proterozoic shale section" (Durkee, 1982). A year later the Hussar #1 was drilled in the Officer Basin located to the south of the Amadeus Basin and encountered "gas shows in the Proterozoic Browne Beds" (Durkee, 1983). In 1983 the Finke #1, an Amadeus test, reported "hydrocarbon shows in the Proterozoic" (Lindner, 1984).

Although commercial Precambrian hydrocarbon production in central Australia has not been established to date, conditions for such remain encouraging. The thick Proterozoic shale section, continuity of the sedimentation from Precambrian through Ordovician time, and oil and gas production in Lower Paleozoic strata suggest that the Precambrian here may eventually prove commercial.

Sichuan and Bohai Bay Basins

In 1964 the discovery well for the Weiyuan gas field in the central Sichuan Basin, approximately 1,500 km west-southwest of Shanghai, was announced (fig. 1). The principal producing interval of this field lies within the Dengying Formation of Upper Sinian (Late Proterozoic) age. The Dengying Formation is a fractured and vuggy, marine limestone and massive bedded, algal dolomite unit. The low (1%) average matrix porosity and 0.01 to 5 md permeability range is compensated by the regional depositional extent of the tidal flat, platform facies sedimentary rock. Developmental drilling has extended the Weiyuan gas field to 23 km by 9 km.

The gas reservoir rock of the Dengying Formation was deposited under frequent crustal elevation and subsidence, resulting in the creation of numerous sedimentary cycles. Shicong and others (1980) stated that commonly "the lower part of the [typical Dengying] cycle representing the transgressive stage is the source bed; the middle and upper parts of the cycle in the regressive stage are the reservoir bed; and occasionally a sealing bed may be developed at the top of the cycle in the latest regressive state. In the Sichuan Basin as an example, there are at least 20 sedimentary cycles and corresponding source-reservoir-seal combinations in late Sinian ... marine sediments," and the "source and reservoir rocks of the platform facies of the Dengying Formation are very thick."

Without directly addressing the question of source bed, these statements imply that the source rock for the Weiyuan gas field is of the same age as the reservoir rock. In determining the "total quantity of oil generation," Shicong and others (1980) stated that the "Lower Cambrian [yielded] the largest amount, [whereas the] Lower Ordovician ranks second, ..." and "the amount of accumulated oil is in the same order." This comparison suggests that certain of the Late Precambrian rock of China may one day be accepted as a source of hydrocarbons.

The Bohai Bay Basin, also known as the North China Basin, lies to the northeast of the Sichuan Basin. In 1975 the first of more than 40 oil fields producing from the Precambrian in this region was discovered. The initial discovery, the Renqui oil field, is located in the western part of the Bohai Bay Basin, approximately 125 km south of Peking in Hebei Province. The principal reservoir is a stromatolite-rich limestone and siliceous dolomite sequence of the Wumishan Formation of Sinian age. Reservoirs of secondary importance are found in pre-Sinian granite-gneiss and sandstone of the Sinian Changcheng Formation.

Fault-block movements in the Tertiary uplifted this Precambrian section and created fracture porosity. Later weathering and leaching of the carbonate enhanced the porosity to the range of 5 to 10 percent. This leaching was concentrated along pre-existing fractures and created horizontal and vertical karst zones. During the Eocene the potential reservoir rock was overlapped by lacustrine deposits of the Shahejie Formation (Quanheng, 1984). As oil was generated, it migrated along the fault zones into the karst-fracture system of individual buried hills (Qi and Xie-Pei, 1984). The carbonate reservoirs are excellent producers, averaging over 4,000 barrels daily per well, and account for 85 percent of the buried hill oil pools.

Dunshi and Guangming (1980) suggest associations other than Tertiary age petroleum in Proterozoic reservoir rock in the Bohai Bay Basin. They predict discovery of "pools ... associated with Sinian and Paleozoic source and reservoir rocks."

Northern Rockies and Southern Lake Superior Region

In September 1983, the #1 Paul Gibbs well was spudded in Flathead County, northwestern Montana, by the Atlantic Richfield Company and was a search for "subthrust Paleozoic sediments underlying the Precambrian Belt Series" (Teselle and others, 1985). The hole was drilled to 5,418 m and the bit never exited from Precambrian overthrust rock. Although a disappointment to the operator, this test made national news when reports indicated "natural gas shows [were encountered] in the Precambrian rocks from about 2,200 m total depth" (Shirley, 1985). These gas shows "intercepted in rocks 1.43 billion years old represent very possibly the oldest indigenous hydrocarbons that have been drilled in the world" (Shirley, 1985). The reservoir rock for the gas show is metasiltstone and quartzite of the Pritchard Formation of the Belt Series. Porosity and permeability have been created by fracturing. The rock contains 0.2 to 0.3 percent total organic carbon, and analysis of reservoir water "tested fairly fresh -- implying maybe the reservoir has been flushed and the gas may not be indigenous" (verbal communication, E. Frodeson, geologist, Atlantic Richfield, 1985). This suggestion of post-Proterozoic-age gas migrating into fractured Precambrian rock is enhanced by the report that the "highest gas shows" were encountered at a thrust fault penetrated at 5,180 m (Shirley, 1985).

Hydrocarbon has been known for decades to exist in the southern Lake Superior region. Hydrocarbon in the form of crude petroleum and solid material similar in appearance to gilsonite (Daniels, 1982) is contained principally within the basal 10 m of the Nonesuch Formation of Proterozoic age. This source formation has been variously dated from 1,075 Ma ("a close upper limit to the time of deposition") by Chaudhuri and Faure (1967) to 1,047 Ma by Ruiz and others (1984). This latter age is considered by Kelly and Nishioka (1985) to be "a minimum age for the oil."

No surface seeps are known. Published reports describing this oil are based upon samples collected underground in the Copper Range Mine, White Pine, Michigan. The oil is considered indigenous to the Nonesuch because of the presence and type of contained fossil micro-organisms (Meinschein and others, 1964), and correlation of chemical properties of the oil to pulverized source shale (Eglinton and others, 1964; Barhoorn and others, 1965). The oil and its extracts resemble parafinic crude oil of Paleozoic age (Meinschein and others, 1964). The oil has been preserved because temperatures within the Nonesuch Formation have apparently never been high (Barghoorn and others, 1965) nor have they exceeded 100° C (Brown, 1971). The hydrocarbon is the oldest known crude oil (Daniels, 1982; Barghoorn and others, 1965). The oil has been determined as biological in origin (Eglinton and others, 1964) and is the final product of primary photosynthetic processes (Barghoorn and others, 1965). The source bed for the oil is suggested to have been deposited under conditions of a near-shore, deltaic (Barghoorn and others, 1965), estuarine-lagoonal environment subject to marine (Moore and others, 1969) or fresh water (Pettijohn, 1957) influxes.

CONCLUSIONS

The discovery within the past 25 years of accumulation of oil and gas in Precambrian reservoir rock supplied by Precambrian source strata proves that geologic age is not an indicator of the presence or absence of hydrocarbon. Rather, the distribution of hydrocarbon anywhere within the geologic column is controlled by conditions of structure, extent of maturation or organic material, lithology, and the effective presence of source, reservoir and trap rock. Any Precambrian province which possesses an idealized combination of these factors must be considered priority exploration territory.

III. SETTING AND EVOLUTION OF THE MIDCONTINENT RIFT

MIDCONTINENT RIFT AS A FRONTIER HYDROCARBON TARGET

Albert B. Dickas

RIFT IDENTIFICATION AND DEVELOPMENT

Woollard (1943) conducted a transcontinental gravity traverse and identified a significant positive gravity anomaly in Clay County, Kansas. This and other surveys established a linear positive gravity trend beginning near Abilene, Kansas, and extending northeastward 1,300 km into the Lake Superior Basin (fig. 1). Thiel (1956) named this feature the Midcontinent Gravity High. Today, it is recognized as the most sharply defined trend on the Gravity Anomaly Map of the United States (Lyons and O'Hara, 1982). Rudman and others (1965) suggested that an extension of the Midcontinent Gravity High, the Mid-Michigan Gravity High, could be traced across the eastern axis of Lake Superior and then south into the Lower Peninsula of Michigan. By so doing, they genetically related the Michigan Basin to the thick series of synclinal Keweenawan sedimentary rock and basalt found in northern Wisconsin.

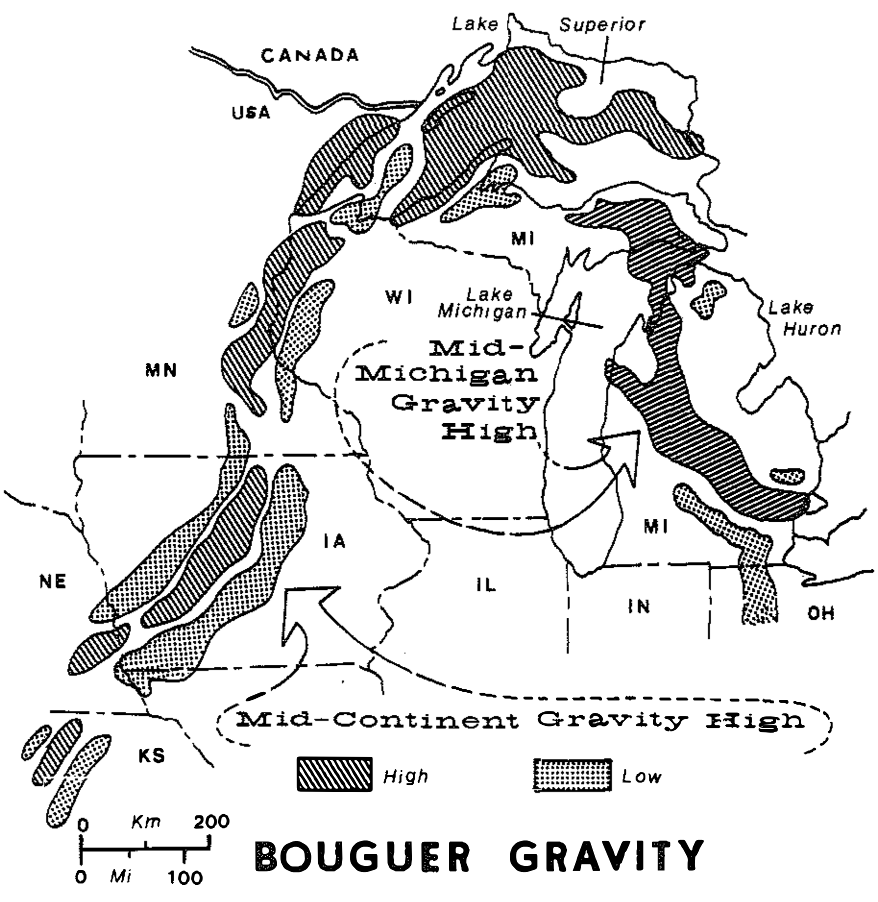

Figure 1. Location of the Midcontinent Gravity High.

Thiel (1956) interpreted the Midcontinent Gravity High as being caused by a thick sequence of uplifted Keweenawan basalt (central gravity maxima), flanked by an equally thick clastic sequence (adjacent gravity minima) of the same general age. King and Zietz (1971) compared the Midcontinent Gravity High with the gravity field associated with present day oceanic rift systems, and suggested that this maxima was created as part of a worldwide continental rift. King and Zietz (1971) postulated that the "midcontinent rift may well have been part of a Keweenawan global rift system with initial offsets consisting of transform faults along preexisting fractures, but apparently it never fully developed laterally into an ocean basin, and the upwelling mafic material was localized along a relatively narrow belt." Ocola and Meyer (1973) named this trend the "central North American rift system," but the title "Midcontinent Rift System" as suggested by Wold and Hinze (1982) is today the most commonly employed term.

Chase and Gilmer (1973) determined to their satisfaction that the Midcontinent Rift System and its gravity expression was developed by Precambrian "plate tectonic interaction." According to their calculations, rift extension amounted to 40 km in Kansas, and 90 km in the Lake Superior Basin. Chase and Gilmer (1973) proposed an evolution for continental rifting, employing known rifts as sequential examples, as follows: (1) initial stage -- initiation of the Baikal and Rhinegraben rifts; (2) second stage -- development of East African rift-type valley structures; (3) third stage -- evolution into a Midcontinent rift structure, similar to the northern Red Sea; and (4) the final stage -- production of oceanic crust by sea floor spreading, as in southern Red Sea and the Atlantic Ocean.

The sequence of tectonic events that led to the Midcontinent Rift System is discussed in detail by Morey (1972) and Anderson and Black (1982). Graben development by crustal extension approximately 1.1 Ga, followed by infilling by numerous basaltic flows, and isostatic sinking of volcanic rock created erosion and deposition of older (Oronto Group) sedimentary rock with reactivation and uplift of the central (St. Croix) horst. The Oronto Group was eroded and the sediment deposited as Bayfield Group sedimentary rock in the flanking basins; erosion of St. Croix Horst continued into Paleozoic time until terminated by transgression of Lower Paleozoic units.

RIFT STRUCTURE AND STRATIGRAPHY

The basic structure of the Midcontinent Rift System southwest of Lake Superior is a central horst block flanked by basins. The trend of the central St. Croix Horst is not continuous but rather divided into separate units by left-lateral, northwest-southeast-oriented faults located on the Kansas-Nebraska border and immediately south of Minneapolis-St. Paul, Minnesota. In Wisconsin the rift rock is Middle Keweenawan mafic volcanic rock having densities in the range of 2.80 to 3.00 g/cc, and a thickness approaching 6,000 m. Overlying the volcanic rock is feldspathic clastic rock of the Upper Keweenawan Oronto Group. Along the horst axis this group is contained in basins such as the Ashland-Lake Superior Syncline in Wisconsin, and in localized grabens. The basal unit, the Copper Harbor Conglomerate, is a maximum 2,100 m thick sequence of volcanic-derived conglomerate and sandstone, containing interlayered flows near the base (fig. 2).

Conformably overlying the Copper Harbor Conglomerate is the Nonesuch Formation, which consists of fine-grained sandstone, siltstone, and shale that averages 130 m thick. The Nonesuch Formation is rich in organic material and copper. It is this unit, along with an evolving philosophy that worldwide rift belts offer potential for hydrocarbon development, that has drawn explorationists into the Lake Superior region. The Nonesuch Formation is the host of the chalcocite and native copper-bearing ore zone of the Copper Range Mine in the western upper peninsula of Michigan.

Sporadically located throughout the lower 9 m of the copper ore zone of the Nonesuch Formation are solid and liquid hydrocarbons. This juxtaposed affiliation of hydrocarbon and copper has been hypothesized to have been formed by copper precipitation facilitated by the indigenous presence of organic material. Subsurface oil seeps are common in the mine, with a freshly fractured shale exposure yielding approximately 1 liter of crude oil over several months.

The Freda Formation conformably overlies the Nonesuch Formation. This fining-upward sequence of reddish brown sandstone, siltstone, and shale has a maximum thickness of 4,300 m, and is similar to the sandstone in the older Copper Harbor Conglomerate. The composite thickness of the Oronto Group could locally exceed 6,500 m. The three formations in the Oronto Group are considered by Elmore and Daniels (1980) to be a "transgressive-regressive alluvial fan/lacustrine/fluvial system that filled the [Midcontinent] rift basin during the last stages and following cessation of volcanic activity."

In Wisconsin the Oronto Group is associated with the Ashland-Lake Superior Syncline. To the southwest a 580 m column of Oronto-like sedimentary rock was drilled south of Minneapolis-St. Paul in search of suitable natural gas storage

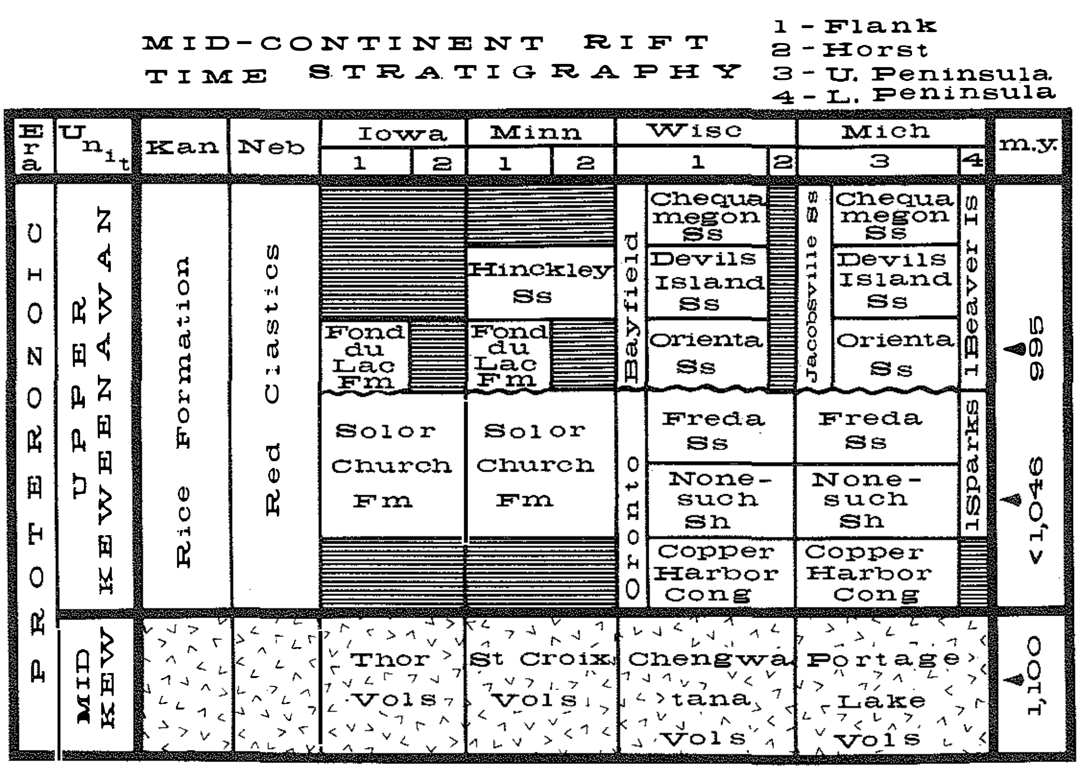

Figure 2. Stratigraphic terminology and time relationship along the Midcontinent Rift System trend.

reservoir. Morey (1977) described this section in detail, named it the type Solor Church Formation, and assigned it a stratigraphic position equivalent to the Oronto Group in Wisconsin (fig. 2). The Solor Church Formation exceeds 975 m in thickness, and is known only in the subsurface. Its gross lithology consists of interbedded sandstone, siltstone and shale; however, Morey (1977) concluded that "precise equivalents of the Copper Harbor conglomerate and Nonesuch shale cannot be defined [in Minnesota] using the data now available." Solor Church equivalents are also recognized in the subsurface of Iowa.

The projection of sedimentary rock equivalent to the Oronto Group along the Midcontinent Rift System into the Lower Peninsula of Michigan is tentative at this time. Most of the 30 Precambrian tests that have been drilled in Michigan enter the crystalline basement of the Penokean-Central-Grenville province (Hinze and others, 1975). One deep test (McClure-Sparks, 1-8) drilled 1,612 m of red mudstone, siltstone, and sandstone that has been correlated with the Freda Formation (Catacosinos, 1981). Inasmuch as this well was drilled in the center of the Mid-Michigan Gravity Anomaly, some basis exists for extension of rift stratigraphy southeastward from the Lake Superior region.

The St. Croix Horst is bounded by high-angle reverse faults, which are identified by outcrop and high gravity gradients. These faults form the northwest and north flank of the horst in Minnesota and Wisconsin, and the Pine-Douglas-Isle Royale Fault System. The southeastern horst flank is marked by the Hastings-Lake Owen-Keweenaw Fault System (fig. 3). For the most part these faults are buried under Phanerozoic strata, but four excellent exposures of the Douglas Fault can be studied in Douglas County, Wisconsin. The total throw associated with the faults range from 2,400 to 3,400 m.

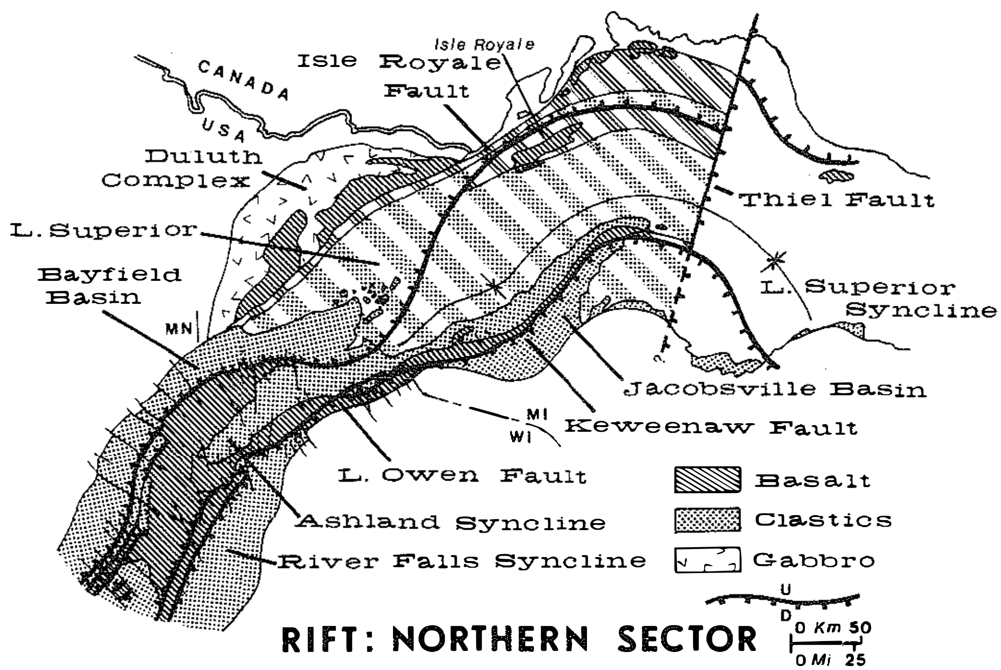

Figure 3. Midcontinent Rift System trend and geology from southeastern Minnesota into the Upper Peninsula of Michigan. Projection of Keweenawan geology under Lake Superior shown in hatched patterns.

Paralleling the central horst along the entire rift zone from Lake Superior to Kansas are linear gravity minima that mark the site of thick deposits of Keweenawan sedimentary rock. In Wisconsin the most prominent of these minima, the Bayfield low, appears to be on trend with the horst axis gravity maxima. This anomaly may represent a rift flank sedimentary basin offset by right-lateral faulting. Immediately to the southwest of the Bayfield low, the Midcontinent Gravity High appears to bifurcate (fig. 1). The southern bifurcated branch traces the Middle Keweenawan Portage Lake Volcanic Group outcrop up the center of the Keweenaw Peninsula; the northern branch outlines the Duluth Gabbro Complex and the North Shore Volcanic Group northeastward to the Canadian border.

The geometry of the flanking basins is usually depicted as resembling the Kay (1951) taphro-geosyncline, "sediment filled, deeply depressed rift blocks bounded by one or more high angle faults." In northwestern Wisconsin the northern flanking basin sedimentary rocks are identified in outcrop as type strata of the Bayfield Group, composed of from oldest to youngest, the Orienta Sandstone, Devils Island Sandstone, and the Chequamegon Sandstone. These three formations average 89 percent quartz; the middle unit is classified as an orthoquartzite. The Bayfield Group is subhorizontal, mineralogically and texturally more mature and much thinner than the Oronto Group. Minimum thickness is 815 m (Myers, 1971); overall total subsurface thickness for the Bayfield Group may approach 2,100 m. In Minnesota and Iowa the presence of Bayfield Group equivalent strata is based on deep well, refraction seismic, and gravity data analysis.

LITHOSPHERIC FLEXURE AND EVOLUTION OF THE MIDCONTINENT RIFT

Jonathan E. Nyquist and Herbert F. Wang

In 1984 Petty Ray Geophysical ran a speculative seismic reflection survey across the Midcontinent Rift System crossing the Wisconsin-Minnesota border near St. Croix Falls, Wisconsin. The basement profile suggests that the sedimentary basins flanking the Midcontinent Rift System formed by flexure of the lithosphere rather than as half grabens. We modeled the lithosphere as an elastic plate of thickness (h) floating on a fluid mantle. A line load of magnitude (V_0) acting at the center of the plate deforms the lithosphere and sediments fill the depression (fig. 1). The elastic thickness of the lithosphere is a modeling fiction. It is the thickness of an elastic plate that approximates the long-term behavior of the lithosphere and is always thinner than the thermal lithosphere.

The best model fit to the seismic data is for a flexural parameter of $a = 35$ km and a load of 6.3×10^{12} N/m (fig. 2). This surprisingly low value is reflected in the narrow basin width and indicates that the lithosphere was thinned at the time of basin formation, possibly by a combination of extension and high heat flow. The magnitude of the central load required to produce the flexure is too great to be explained by volcanics; a major mountain range would be required. We suggest that mantle material intruded the lower crust, an idea supported by the anomalously high compressional velocities seen in the lower crust by deep refraction.

Deep seismic refraction data disclose that the Moho "basin" beneath the rift has also been deformed by flexure. However, the Moho is much wider, implying that the lithosphere cooled and thickened after rifting. Compensation for the intracrustal load now occurs at a greater depth.

The seismic reflection and refraction data give two snapshots of basin evolution. The reflection data show the sedimentary basin shape, which probably formed within the first 50 m.y. after rifting; the surface flexure represents the situation when the plate cools. The refraction data show the present shape of the Moho a billion years later. We suggest the following scenario for the evolution of the Midcontinent Rift System in this region:

(1) Extension and high heat flow thins the lithosphere, and the mantle material intrudes the lower crust. Isostatic adjustment creates a gently dipping basin that fills with sediments and fissure-fed volcanics (fig. 3).

(2) Volcanic activity ceases and the cooling intrusion contracts, increasing in density and loading the crust; sedimentation keeps pace with the deepening basin. The elastic thickness of the lithosphere rapidly increases with cooling (fig. 4).

(3) Subsidence stops when the intrusive body has cooled. The St. Croix Horst is thrust up along the Douglas and Lake Owen Faults. The intracrustal body is preserved by the stable cratonic environment, but as the lithosphere thickens compensation occurs at a greater depth and with a longer wavelength reflected in the present day deformation of the Moho (fig. 5).

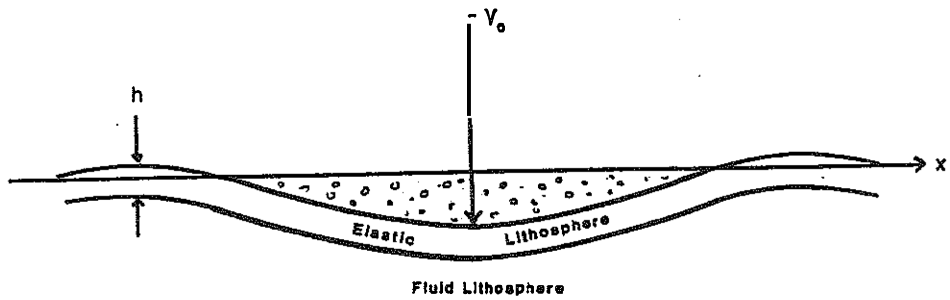

Figure 1. Flexural model.

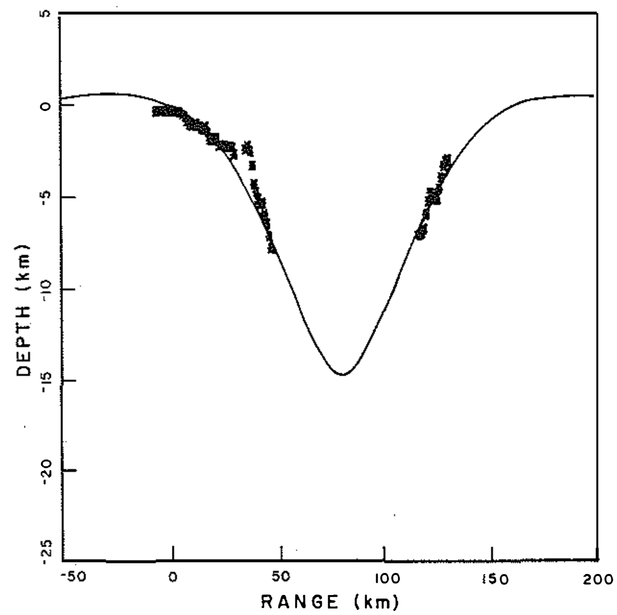

Figure 2. Least squares fit of unbroken plate model to seismic data, a=35 km; load, v_o =6.3 X 10^{13} N/M.

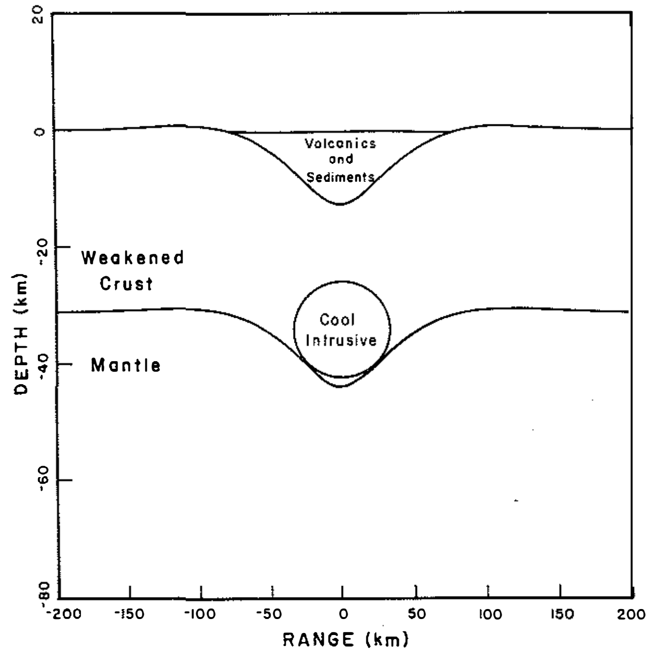

Figure 3. Extension and high heat flow thin the elastic lithosphere. The weight of hot, dense material intruding the lower crust flexes the lithosphere and produces a gentle basin.

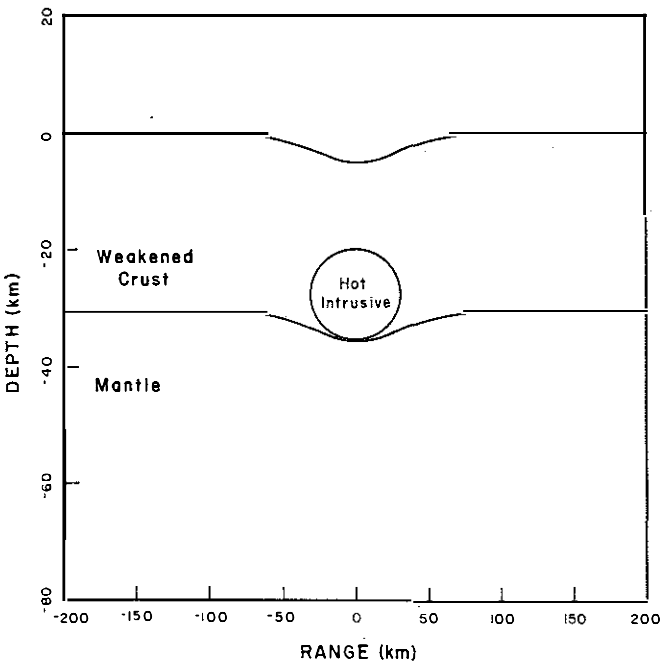

Figure 4. The intrusive cools and increases in density flexing the lithosphere further. Volcanics and sediments accumulate in the basin.

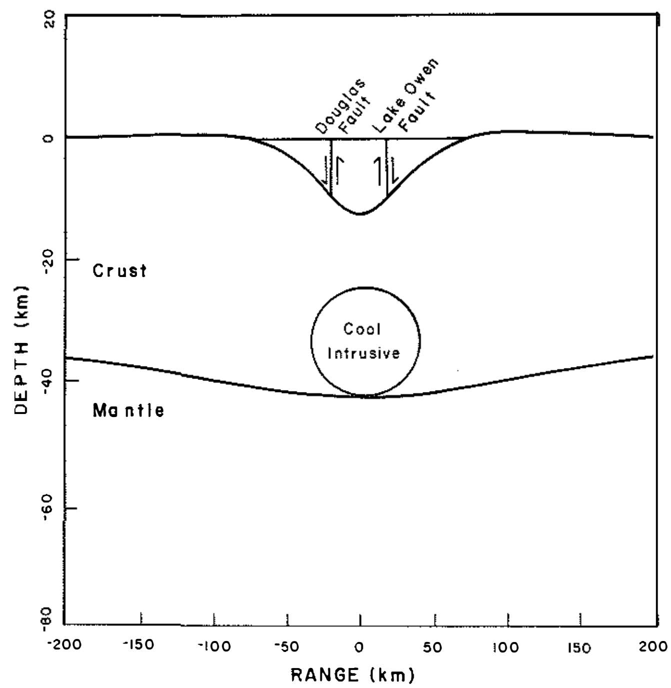

Figure 5. The elastic lithosphere thickens as the normal geothermal gradient is restored. The surface deformation is frozen in, but intrusive body is preserved by the stable cratonic environment and is now compensated at great depth over a wider region. The St. Croix Horst is uplifted along the Douglas and Lake Owen Faults in a later compressional event.

IV. UPPER KEWEENAWAN STRATIGRAPHY

SUMMARY STRATIGRAPHY

M.G. Mudrey, Jr. and M.E. Ostrom

The boundary between the uppermost volcanic rock of the Middle Keweenawan and the Upper Keweenawan is not resolved. The volcanic rock grades upward with increasing abundance of interbedded immature volcanic sediments, until no more flows are found. The classical boundary is drawn at the top of the uppermost lava flow; many modern studies suggest that the boundary should be drawn at a lower level (Hubbard, 1975). In Wisconsin the Upper Keweenawan sedimentary rock is divided into two groups with an apparent unconformity between them. This division, with changes in formational names, is generally accepted for Minnesota. In Michigan, however, correlation of the upper group is more difficult. (See figure 2 on page 17.)

ORONTO GROUP

Daniels (1982) considered the three formations of the Oronto Group to be a transgressive-regressive alluvial fan/lacustrine system that filled the (Midcontinent) rift basin during the last stages and following cessation of volcanic activity. The basal unit of the Oronto Group within Wisconsin is the Copper Harbor Conglomerate, which is gradational and interbedded with the upper part of the Portage Lake Lavas. The Copper Harbor Conglomerate is 150 to 2,000 m thick, and is a reddish brown, lithic conglomerate and sandstone (Hite, 1968). The conglomerate varies considerably, but consists dominantly of subangular to rounded fragments of Middle Keweenawan volcanics and intrusives, and a lesser amount of Lower Proterozoic rock. The Nonesuch Formation overlies the conglomerate and appears in places to interfinger with it. Barghoorn and others (1965) described the Nonesuch Formation as thinly laminated gray siltstone and black shale, visually distinguishable from enveloping red-brown coarser grained units; conglomeritic horizons occur locally. Both solid and liquid hydrocarbon is found sporadically in the copper-bearing ore zone in the lower 9 m of this formation. Subsurface oil seeps are quite common at the Copper Range Mine in White Pine, and a fresh exposure of fractured shale can yield about 1 liter of oil even after several months. In Wisconsin the maximum thickness on the east is 120 m, but it thins rapidly westward to 40 m near Mellen (Aldrich, 1929, p. 111). The Freda Formation is the major unit of the Oronto Group. It has an estimated thickness of 4,000 m. It is noted for its red color, which is present throughout except for local leaching or bleaching along fractures or within the more porous and permeable coarse units in the upper part of the section. The Freda Formation is both compositionally and texturally immature. The sedimentary structures of the Freda have long been interpreted as evidence of a fluvial depositional environment. Hite (1968, p. 60) provided details on the stratigraphy and sedimentology.

BAYFIELD GROUP

The basal unit of the Bayfield Group is the Orienta Formation, a feldspathic sandstone up to 900 m thick (Myers, 1971). It thins rapidly to the west and pinches out west of Washburn, Wisconsin. The critical lower contact with the underlying Freda Formation is not exposed. The best interpretation is that the Orienta lies with slight angular discordance upon the underlying Freda, and elsewhere it is known to be in fault contact with Middle Keweenawan volcanics. The Devils Island Formation overlies the Orienta Sandstone, is a fine- to medium-grained quartz sandstone, and is thin bedded and laminated. Although not exposed, the lower contact of the Devils Island with the Orienta appears to be conformable. This formation is estimated to be 100 m thick. The Chequamegon Formation is the youngest formation of the Bayfield Group. The Chequamegon is predominantly a medium-grained grayish red to pale red feldspathic sandstone. The lower contact of the Chequamegon appears to be gradation with the Devils Island Formation. This sandstone appears to be about 330 m thick. Some data suggest that the Chequamegon may be Cambrian in age (Ostrom and Slaughter, 1967). An alternate interpretation of Upper Keweenawan sedimentary rock is possible. Ostrom recognizes some stratigraphic relationships in the Lake Superior region that suggest to him that the Chequamegon and the Orienta might be correlative, and that the overlying Devils Island might be equivalent to the Galesville Formation of Late Cambrian age. This would necessitate an unconformity at the base of the Devils Island.

JACOBSVILLE FORMATION

A large area of Jacobsville Formation occurs immediately south of the Keweenaw Peninsula and along the Lake Superior shoreline near Marquette, Michigan. It is a thick red bed sequence about 3,500 m thick and consists of sandstone with some conglomerate and siltstone. The Jacobsville is generally assigned to the Upper Keweenawan, although others, such as Dorr and Eschmann (1973), assign the sandstone to the Cambrian. The sandstone is known to overlie Middle Keweenawan volcanics, and to the east the sandstone can be shown to rest on a paleosol (Kalliokoski, 1975). The paleosol formation is significant in that it represents a period of subareal erosion and intense chemical weathering in the source area.

CORRELATION

The Bayfield Group has been correlated with the Jacobsville Formation of the northern Peninsula of Michigan (Thwaites, 1935; Raasch, 1950; Hamblin, 1961; Hite, 1968) and with the Hinckley of Minnesota (Tyler and others, 1940; Raasch, 1950). There is a possibility that it also correlates with all or part of the Cambrian Mt. Simon Sandstone.

The Bayfield Sandstone was named by Lane and Seaman (1907) for exposures of red and brown and white-striped quartz sandstone with streaks of red clay shale located near Jacobsville, Michigan, and which Irving (1883) called the "Eastern Sandstones." This sandstone is conglomeratic in its base where it overlaps older formations.

The Jacobsville Formation differs from the Bayfield in its heavy mineral composition. According to Denning (1949), who sampled 14 outcrops of Jacobsville, 12 outcrops contain epidote and apatite, one contains only apatite, and one contains neither apatite nor epidote. These minerals occur in the Oronto Group and in the Orienta Formation. They are not found in the overlying Devils Island Formation.

Hamblin believes that a signficant break in sedimentation occurred between deposition of the Freda red feldspathic sandstone and the Jacobsville quartz sandstone in the Northern Peninsula. Hamblin (1961) stated that "suggestions of an angular conformity between the Freda and Jacobsville are ... found in several outcrops in Whitefish Bay." In 1958 he reported the existence of a pre-Jacobsville erosion surface. Van Hise and Leith (1911, p. 614) described this as a "profound unconformity ..." and went on to say that "the manner in which the Cambrian sandstone cuts unconformably across the several series of the Precambrian is well illustrated on the east side of the Precambrian area of the Upper Peninsula of Michigan and northern Wisconsin." In the absence of the Freda Formation, the Jacobsville overlies basement rock.

The feldspar content of the Jacobsville is similar to the whole of the Freda and the Orienta. Analyses of outcrop samples collected from the Jacobsville Formation between Marquette and Munising in the Upper Peninsula of Michigan indicate feldspar contents of from 20 to 40 percent, although some beds may contain less than 5 percent.

The lithologic, mineralogic, and textural character of the Jacobsville, plus paleomagnetism and other characteristics, is interpreted to indicate that the Jacobsville may be equivalent to either or both the Freda and the Orienta.

Rock units in southern Wisconsin and southeastern Minnesota that are tentatively correlated with the Devils Island Formation include the Hinckley Formation of northeastern Minnesota, the "Hinckley-Mt. Simon" of southeastern Minnesota, and the Mt. Simon Sandstone of Wisconsin. The bases for correlation are (1) similar stratigraphic position, namely above either Precambrian crystalline rock or rock of the Oronto Group and below the Eau Claire Formation; (2) lithologic and mineralogic similarity; (3) contact relationships that show conformity and unconformity at the base and conformity and transition at the top; and (4) occurrence within the same geological and structural province, namely the structural feature manifest as the Midcontinent Gravity High.

RESERVOIR CHARACTERISTICS OF THE KEWEENAWAN SUPERGROUP, LAKE SUPERIOR REGION

Richard W. Ojakangas

INTRODUCTION

This is a brief review of the stratigraphic, sedimentologic, and petrographic characteristics of the several thousand meter thick, post-volcanic, siliciclastic Keweenawan Supergroup in the Lake Superior region with an emphasis on petroleum reservoir potential. It has been known for several decades that the black Nonesuch Shale, low in the post-volcanic rock column, is rich in organic material and even exudes petroleum in the Copper Range Mine, White Pine, Michigan. During late Precambrian time, many sedimentary and volcanic rock units were deposited in the Lake Superior region. The upper Precambrian rock column can be thought of as consisting of three sequences: pre-volcanic quartz sandstone (Ojakangas and Morey, 1982a), Keweenawan volcanic rock (Green, 1982b), and the post-volcanic sedimentary rock units that are the subject of this paper.

Keweenawan Supergroup rock, a red bed sequence that includes the Oronto Group and the overlying Bayfield Group, and their correlative rock units, are dominated by coarse clastic units that have potential as reservoir rock for petroleum that may have been generated within the Nonesuch Shale during deep burial. Few published data are available on porosity and permeability of these units. Petrography has focused on the framework composition of the sandstone and conglomerate, rather than on diagenesis.

STRATIGRAPHY AND SEDIMENTOLOGY

The post-volcanic sedimentary rock units were deposited in and adjacent to the Midcontinent Rift all along its 1,400 km length, but are exposed only in the

Lake Superior region. Following the first rather thorough field study by Thwaites (1912), several geologists studied the post-volcanic sedimentary rock in the Lake Superior region. A recent review has been provided by Dickas (1986) and more detailed data on the Oronto and Bayfield Groups, respectively, can be found in Daniels (1982) and Morey and Ojakangas (1982). A summary of Keweenawan sedimentation is also available (Ojakangas and Morey, 1982b). A generalized rock column is presented as figure 1.

Paleocurrent studies for each of the units show that the depositing currents moved from the edges toward the center of the basin that existed during late Keweenawan time in the Lake Superior region (fig. 2).

The lowest and coarsest formation, the Copper Harbor Conglomerate, exhibits characteristics typical of alluvial fan-braided stream deposition, and fines both upward and basinward (Daniels, 1982). Mudstone and limestone, including stromatolitic beds, represent less than 1 percent of the formation.

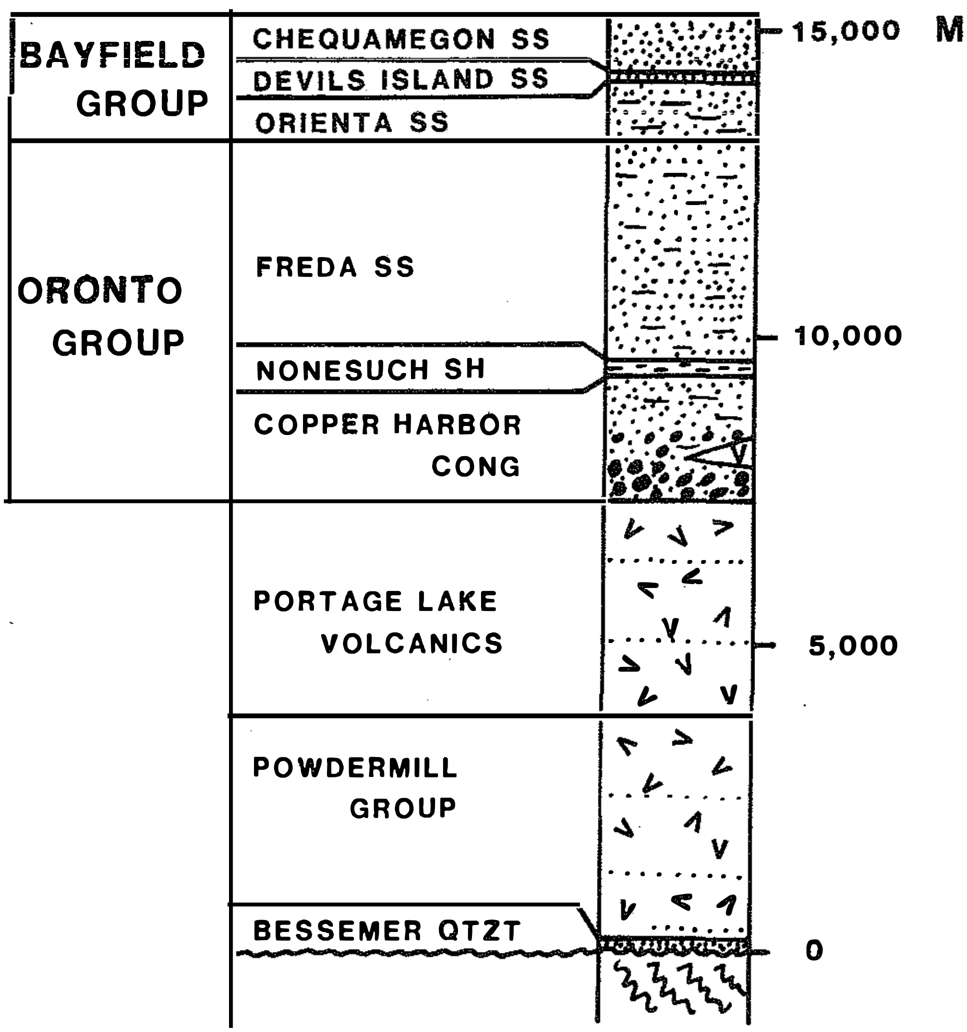

Figure 1. Generalized column of the Keweenawan Supergroup.

Conglomerate composed of volcanic rock is dominant in the lower half of the formation, and sandstone in the upper half.

The Nonesuch Shale is a dominantly black, organic-rich, shale-mudstone that exudes thick, black petroleum from joints in the Copper Range Copper Mine at White Pine, Michigan. The 180 m of black shale probably accumulated in a lacustrine environment, with the lower part equivalent in age to the upper part of the Copper Harbor Conglomerate, as summarized by Daniels (1982). The contact with the Copper Harbor is gradational, and some conglomerate is present. For example, one 3-m thick bed in the valley of Parker Creek, Wisconsin, near the Wisconsin-Michigan border is graded from 20 cm boulders at the base to fine sand at the top, and may be the product of a large turbidity current. The sandstone in the lower part of the formation, as seen in the Copper Range Mine, is abundantly trough cross-bedded with sets on the order of 25- to 50-cm thick. Various tool and scour marks are present on the sole of the "upper sandstone" (a bed as thick as 1.2 m) that forms the roof in many areas of the mine. The formation in general displays a myriad of primary bedding plane and internal sedimentary structures, including mudcracks and mudchip layers.

The Freda Sandstone has been studied by numerous workers, including Hamblin (1961), Hite (1968), and Daniels (1982). The formation, consisting largely of sandstone but including 10 percent siltstone and some conglomerate, is generally interpreted as a fining-upward fluvial sequence.

The Orienta Sandstone (Myers, 1971) is also fluvial. The correlative Fond du Lac Formation to the west in Minnesota is probably continuous with the

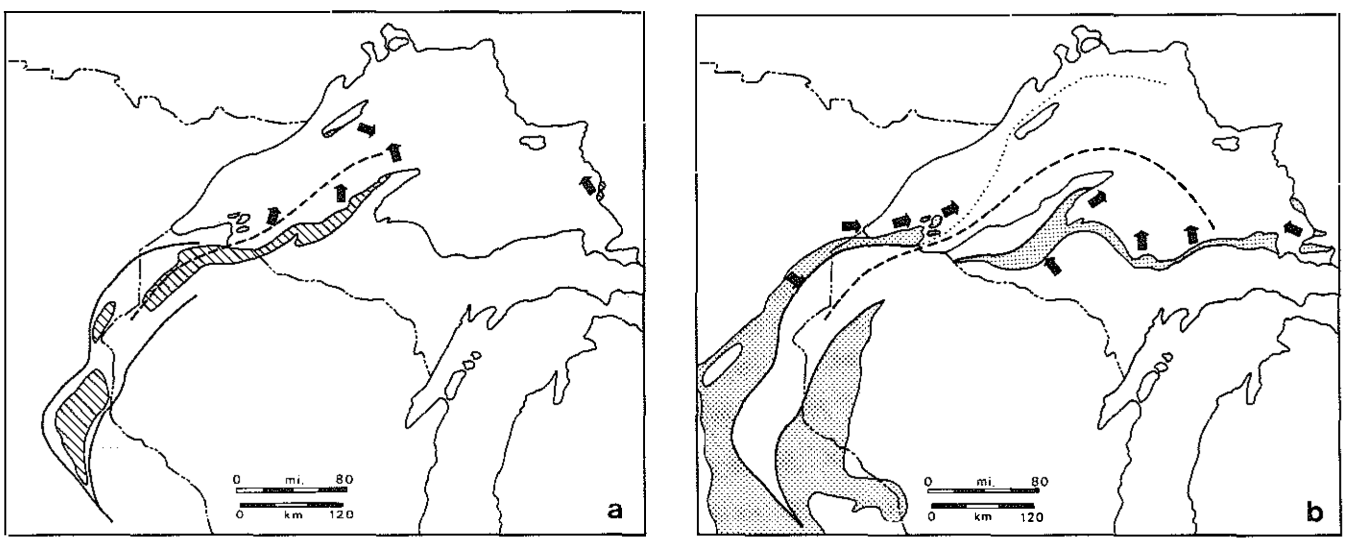

Figure 2. Paleocurrent trends in the Oronto and Bayfield Groups and equivalent units (from Ojakangas and Morey, 1982b). In (a), the arrow on the east end of Lake Superior represents the "Mica Bay Sandstone"; the cross-hatched areas in southeastern Minnesota are subsurface occurrences, the dashed line is the axis of the Lake Superior Syncline, and the solid heavy lines are major faults. In (b), the two westernmost arrows represent the Fond du Lac Formation and the Hinckley Sandstone, and those in Michigan and Ontario represent the Jacobsville Sandstone. The strippled areas in southeastern Minnesota and adjacent Wisconsin are subsurface occurrences.

Orienta in the subsurface and has a similar history (Morey, 1967; Morey and Ojakangas, 1982).

The orthoquartzitic Devils Island Sandstone (Myers, 1971) and the correlative and perhaps continuous Hinckley Sandstone to the west in Minnesota (Tryhorn and Ojakangas, 1972) may be products of the reworking of Fond du Lac feldspathic and lithic detritus in a lacustrine environment. However, it seems likely that eolian action on the vegetationless Fond du Lac and Orienta alluvial plains was a major factor in the maturation of the sediment, perhaps prior to final deposition in a lake or lakes.

The Chequamegon Sandstone (Myers, 1971) is similar to the Orienta and appears to be fluvial.

The Jacobsville Sandstone is as thick as 300 m and is the youngest unit from the Keweenaw Peninsula on eastward. It is variable in texture and composition, ranging from feldspathic and orthoquartzitic sandstone to shale, siltstone, and conglomerate (Kalliokoski, 1982). I observed places where the conglomerate consists largely of resistant pebbles and cobbles, including iron-formation, jasper, chert, quartzite, and vein quartz. Kalliokoski (1982) has described palesols from beneath the formation; the mineralogical maturity of the conglomerate is compatible with this finding.

A dominant alluvial fan-fluvial environment is indicated (Kalliokoski, 1982). Further evidence of fluvial processes is provided by the variance (the square of the standard deviation) calculation on cross-bedding measurements. Groups of cross-beds measured at three Jacobsville localities near Sault St. Marie, Ontario, at the east end of Lake Superior (N = 10); on Cisco River northeast of Marenisco, Michigan (N = 10); and in railroad and river cuts northwest of Wakefield, Michigan (N = 32), have calculated variances of 3,723, 2,284, and 1,903, respectively. Variances of less than 4,000 (Long and Young, 1978) or 6,000 (Potter and Pettijohn, 1977) are thought to be typical of fluvial environments.

PETROGRAPHY

The sandstone of the Keweenawan Supergroup (fig. 1) in general becomes more mature mineralogically and texturally upward in the column (fig. 3). An exception is the Chequamegon, which presumably is younger than the Devils Island but which has about the same composition as the Orienta and Fond du Lac Sandstones. It has been suggested (Mudrey, 1979) that the Chequamegon does not overlie the Devils Island, but is instead the Orienta; this is a problem that may be resolvable with detailed field study. On figure 3 the lithic pole consists largely of volcanic rock fragments derived from the underlying Keweenawan flows, whereas most of the feldspar and the quartz probably had an extra-basinal source.

There is nearly a total lack of porosity data. Original porosity in some Copper Harbor sandstones has been estimated at 20-25 percent by White and Wright (1954) and Wolff and Huber (1973), and Daniels (1982) listed the present average porosity of the Copper Harbor at 3 percent. To crudely estimate porosity, I point-counted two random thin sections of sandstone from each formation (300 points on each), delineating only sand-sized grains, matrix-cement, and pores. The results (table 1) indicate as expected, low porosity in the lower formations and a higher porosity in the upper formations. Low in the sequence, most primary pore space has been filled by various cements, including calcite,

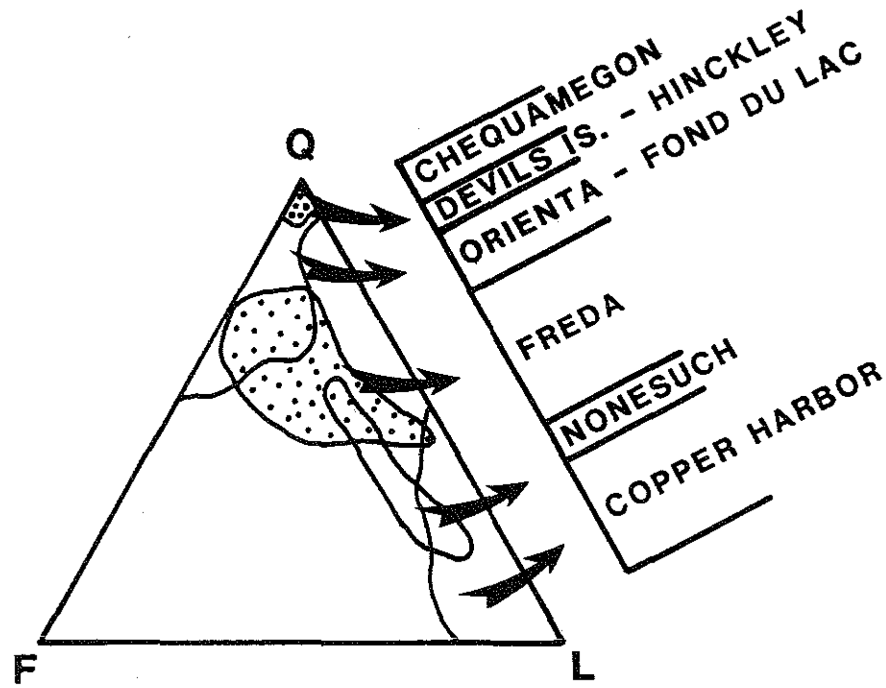

Figure 3. QFL triangle with fields of five sandstone units. Based on data from Daniels (1982), Morey (1967; 1974), Myers (1971), and Tryhorn and Ojakangas (1972). The Chequamegon Sandstone is not shown, but its plot is nearly identical to that of the Orienta Sandstone.

Table 1. Crude estimate of porosity of Lake Superior sandstones, based on averages of only two thin sections of sandstone per formation with 300 points counted on each. Some porosity estimates may be high due to grains lost during thin-section preparation.

	Framework matrix		
	Grains	Cement	Pores
Chequamegon Sandstone	70%	16%	14%
Hinckley Sandstone	66	14	20
Jacobsville Sandstone	76	18	6
Fond du Lac Formation	77	16	7
Freda Sandstone	72	26	2
Nonesuch Shale	70	25	5
Copper Harbor Conglomerate	77	20	3

silica, zeolite (laumontite), hematite, chlorite, other clay minerals, and feldspar. The highest grade of metamorphism, lower greenschist facies, occurs low in the sequence, and zeolite facies is prevalent (Hubbard, 1975). Therefore, both diagenesis and metamorphism contributed to the elimination of original porosity. In the upper mature quartzose sandstone units, original porosity should have been higher than in the more poorly sorted sandstone of the lower formations, most of which contained some original clayey matrix. However, cementation by silica, kaolinite, and feldspar has eliminated much of the original porosity.

Secondary porosity may exist, especially at depth, but has not been documented in the Keweenawan Supergroup. Obviously much needs to be done on both primary and secondary porosity studies before reservoir potential can be given a valid appraisal.

PETROLEUM TRAPS

Several types of traps are likely to be present within the sequence, including anticlinal, fault, unconformity, and varieties of stratigraphic traps.

An anticline has been interpreted from seismic data beneath Lake Superior off the Bayfield Peninsula (fig. 4); this anticline can be projected onshore. Others, large and small also exist, especially in the Oronto Group, as summarized by Craddock (1972a).

Numerous faults are present and the movement of reservoir beds into contact with impermeable shale or lava is possible. The most detailed information

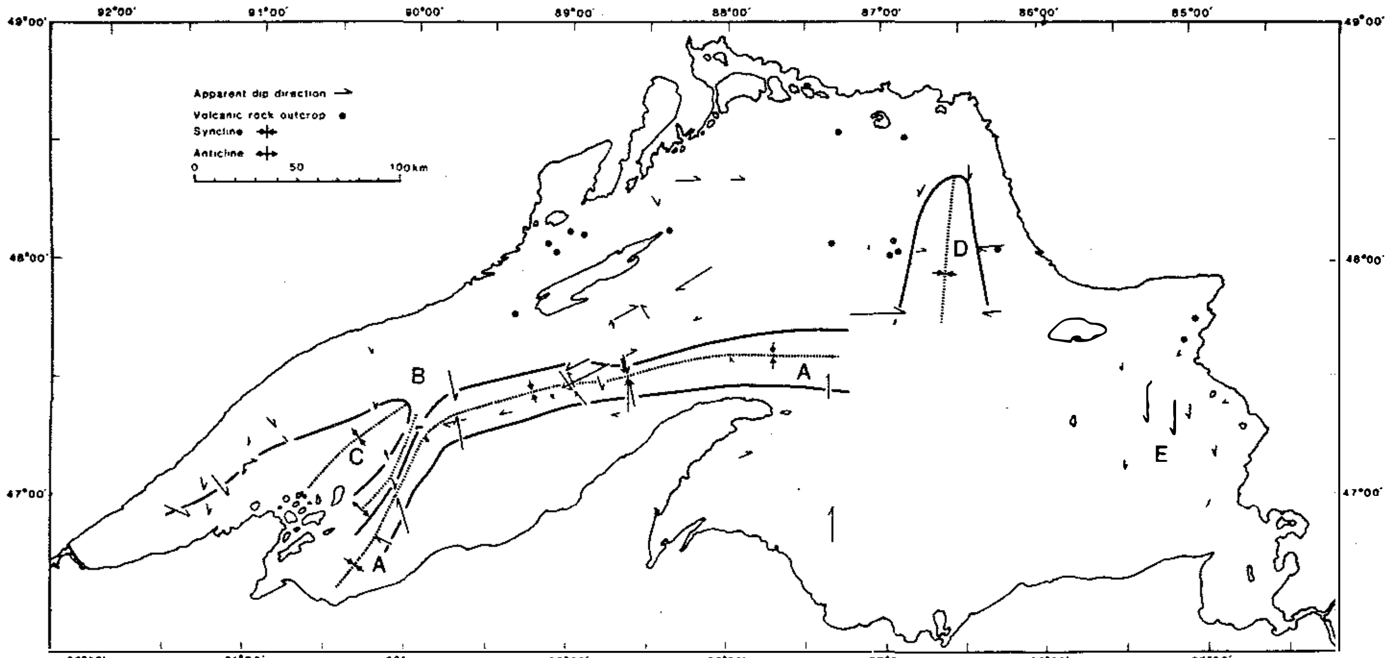

Figure 4. Apparent dip directions to subcrops observed on seismic-reflection profiles. A = Lake Superior depositional syncline; B = Anticline; C = southwest-plunging syncline; D = south-plunging syncline; E = south apparent dips. (from Wold and others, 1982).

relevant to fault traps is a subsurface geological study by Morey (1974) in the vicinity of the St. Croix Horst in east-central Minnesota. His cross section indicates that such traps are likely.

A major unconformity may exist between the Oronto Group and the overlying Bayfield Group. This speculation is based on the fact that the Oronto Group rock commonly has steep dips (some beds are vertical or overturned); the Bayfield Group rocks are subhorizontal. For example, south of Ashland, Wisconsin, steeply-dipping Freda rock form the flanks of the Ashland syncline; a few kilometers to the north, Bayfield Group rock is subhorizontal. However, the importance of drag along faults (such as the Douglas Fault) is difficult to evaluate. If there is indeed an unconformity at this stratigraphic horizon, a regolith may be required as an impermeable seal over the Oronto Group. Paleosols could form cap rock at other unconformities, as between the Solor Church and the Hinckley where the Fond du Lac is missing, and below the Upper Cambrian units, where they rest unconformably upon the Precambrian sedimentary units.

Stratigraphic traps of various types could be present. The fining-upward sequences so common in fluvial rock commonly contain shale units in their upper parts and these would serve as a local impermeable cap on the lower sandy part of the cycle. Such traps should be common, for the Copper Harbor, Freda, Orienta, Fond du Lac, Chequamegon, and Jacobsville appear to be fluvial deposits. For example, Morey (1974) described microcycles and megacycles in the subsurface Solor Church Formation. I have logged a 656-m thick drill core of Fond du Lac Formation about 65 km southwest of Duluth and counted 171 fining-upward fluvial cycles that composed 88 percent of the core (see Morey and Ojakangas, 1982, p. 142). Some of the thicker cycles are 18 m thick and the average thickness is 3.4 m; thus, some could constitute sizeable traps for petroleum (and uranium), perhaps in a stacked sequence. Such fluvial traps have been reviewed by Galloway and Hobson (1983).

Other miscellaneous sand lenses could be present in all the fluvial formations, including miscellaneous sand beds and lenses in the Nonesuch Shale itself. With the steep attitudes of the formations of the Oronto Group, it is even possible that stratigraphically lower Copper Harbor sandstones updip from Nonesuch source rocks could be a reservoir. The quartzose units of the Bayfield Group and their equivalents may be the best reservoirs from a textural point of view, but cap rock is lacking unless the regolith at the Upper Cambrian-Precambrian unconformity constitutes an impermeable cap.

CONCLUSIONS

The thick Keweenawan Supergroup, despite its age of about 1,100 to 1,000 Ma, possesses characteristics favorable to petroleum accumulation. These characteristics include source beds, reservoir beds, structural and stratigraphic traps, and cap rock. However, much work needs to be done to properly evaluate the potential.

ACKNOWLEDGMENTS

Much of the sedimentology contained herein is based on the work of G.B. Morey and Paul A. Daniels. Conversations with them, both in and out of the field, have been useful. Part of this work was accomplished while I was on WAE status with the U.S. Geological Survey.

EXTENT OF ORONTO GROUP

Albert B. Dickas

ABSTRACT

The Nonesuch Formation of the Proterozoic Oronto Group of northern Wisconsin and Upper Michigan contains known hydrocarbon source strata. Other Oronto Group sedimentary rocks contain potential reservoir beds. Deposition of the Oronto Group was controlled by development of the Midcontinent Rift System. Within the central horst of the rift, formations are confined to the limits of the Ashland Syncline. Several areas of Precambrian sedimentation equivalent in age to the Oronto Group are known in adjacent rift-horst sections of Minnesota.

INTRODUCTION

Outcrop is rare in the sedimentary basins that flank the central horst. Significant Oronto exposures along the Middle River in Douglas County, Wisconsin, several wells drilled into Proterozoic clastic rock in Sawyer County, Wisconsin, and seismic and other geophysical information suggest that Oronto Group rock is distributed throughout the subsurface of these flanking basins. Geophysical data collected in Lake Superior also suggest the presence of source and reservoir rock of Oronto age.

Thwaites (1912) named and subdivided the predominantly red clastic rock of the Oronto Group into five formations: the Outer Conglomerate, Nonesuch Formation, Freda Sandstone, Eileen Sandstone, and the Amnicon Formation from oldest to youngest. On the basis of the heavy-mineral assemblage of the Oronto Group and the younger Bayfield Group, Tyler and others (1940) proposed assigning the Eileen Sandstone to the basal Orienta Sandstone of the Bayfield Group and equating the Amnicon Formation with the upper Freda Sandstone. White and others (1953) combined the Outer Conglomerate of Thwaites (1912) with the older Lake Shore Traps and the Great Conglomerate, and termed this series the Copper Harbor Conglomerate. Recent use of the name Oronto Group includes the Copper Harbor Conglomerate, Nonesuch Formation, and Freda Sandstone (Craddock, 1972a; Davidson, 1982).

All of the known Oronto Group strata of northwest Wisconsin were derived from and distributed by the processes of intracontinental rifting (Fowler and Kuenzi, 1978; Daniels, 1982; Morey and Ojakangas, 1982; Van Schmus and Hinze, 1985). Because of this relationship, this discussion of the presence, distribution, thickness, and lithology of the Oronto Group formations will be divided into three structural areas of the Midcontinent Rift System: central or St. Croix Horst, southerly or River Falls Syncline Basin; and northerly or Bayfield Basin; and the distribution of the Oronto Group in Lake Superior (fig. 1).

ST. CROIX HORST

The St. Croix Horst was identified from gravity studies by Thiel (1956) and named by Craddock and others (1963). The northerly and northwesterly flank is defined by the Pine (Minnesota)-Douglas (Minnesota and Wisconsin)-Isle Royale (Michigan) Fault System. The southerly and southeasterly border is defined by the Hastings (Minnesota)-Lake Owen (Wisconsin)-Keweenaw (Michigan) Fault System. The structural configuration of the St. Croix Horst is established by the Ashland Syncline. Within the fault boundaries of the St. Croix Horst within the Ashland Syncline the distribution of Oronto Group sedimentary strata can be controlled by ten outcrop sites and a number of mineral exploration bore holes. The location, formational status, and approximate stratigraphic thickness of these outcrop sites are:

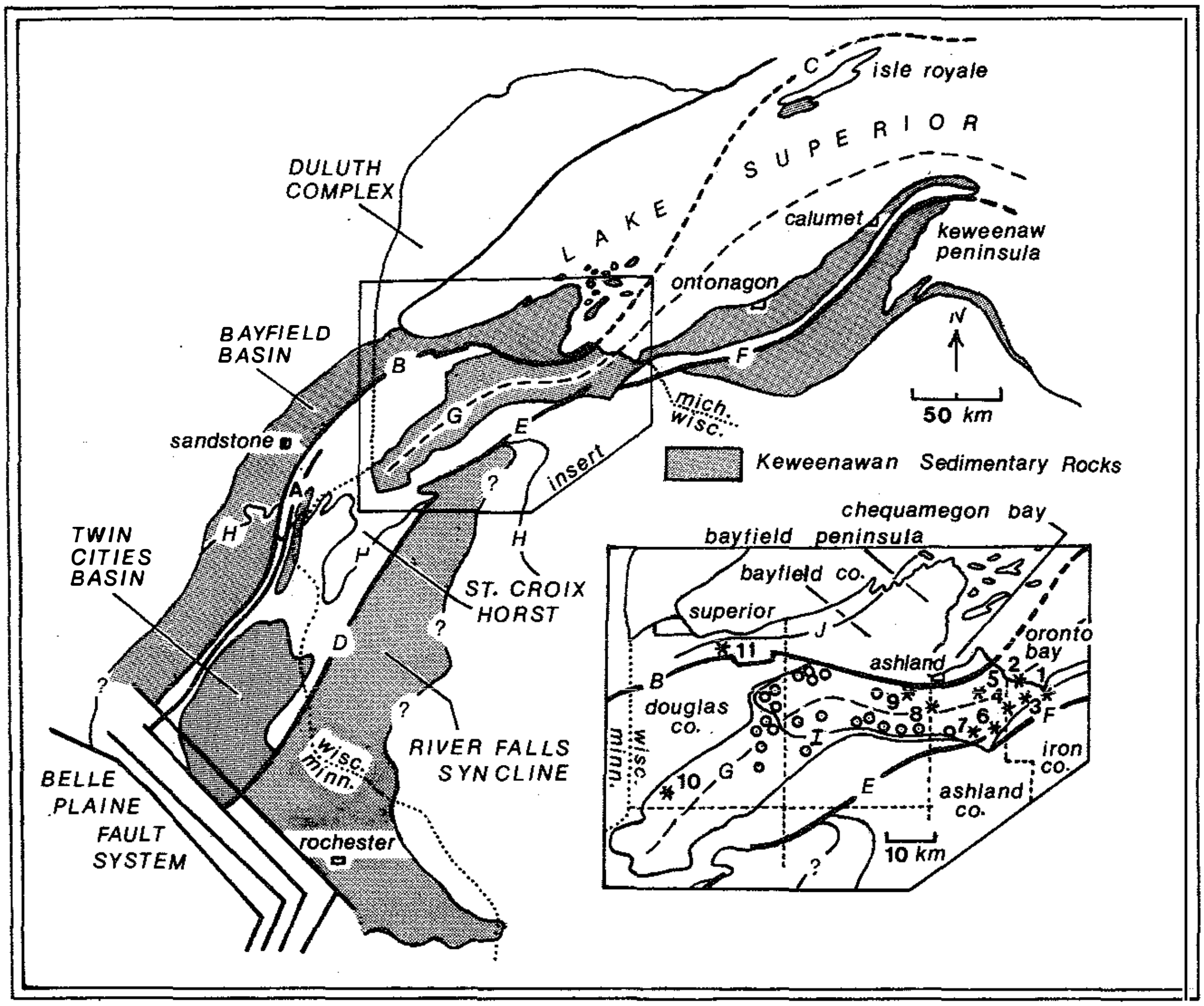

Figure 1. Generalized geologic map of the Midcontinent Rift System in the Lake Superior region. Faults forming boundaries of the St. Croix horst are A. Pine, B. Douglas, C. Isle Royale, D. Hasting, E. Lake Owen, and F. Keweenaw. Secondary faults not shown. Principal outcrop areas are 1. Montreal River and Oronto Bay, ". Marble Point, 3. Potato River, 4. Copper Falls, 5. Bad River, 6. Silver Creek, 7. Brunsweiler River, 8. White River, 9. South Rish River, 10. St. Croix River, and 11. Middle River. Circles represent Bear Creek core sites. Other identifiers are G. Axis of the Ashland Syncline, H. Paleozoic sedimentation limit, I. Nonesuch Formation limit, and J. Oronto Group sedimentation limit north of the St. Croix Horst, after White (1966a).

1. Montreal River-Oronto Bay: T. 47 N., R. 1 E. and R. 1 W.
   Freda Sandstone: 3,650 m (Hite, 1968)
   Nonesuch Formation: 110 m (Hite, 1968)
   Copper Harbor Conglomerate: 365 m (Hite, 1968)

2. Marble Point: T. 47 N. and T. 48 N., R. 1 W.
   Freda Sandstone: underwater outcrop (Myers, 1971)
3. Potato River: T. 46 N., R. 1 W. and R. 2 W.
   Freda Sandstone: 2,750 m (Hite, 1968)
   Nonesuch Formation: 110 m (Myers, 1971)
   Copper Harbor Conglomerate: 250 m (Hite, 1968)

4. Copper Falls: T. 45 N. and T. 46 N., R. 2 W.
   Freda Sandstone: 1,850 m (Hite, 1968)
   Nonesuch Formation: 110 m (Hubbard, 1975)
   Copper Harbor Conglomerate: 140 m (Hite, 1968)

5. Bad River: T. 47 N., R. 3 W.
   Freda Sandstone: not measured (Myers, 1971)

6. Silver Creek: T. 45 N., R. 3 W.
   Freda Sandstone: 1,350 m (Myers, 1971)

7. Brunsweiler River: T. 45 N., R. 4 W.
   Freda Sandstone: not measured (Myers, 1971)

8. White River: T. 46 N., R. 4 W. and R. 5 W.
   Freda Sandstone: 1,150 m (Myers, 1971)

9. South Fish Creek: T. 47 N., R. 5 W.
   Freda Sandstone: 1,300 m (Myers, 1971)

10. St. Croix River: T. 43 N. and T. 44 N., R. 13 W. and R. 14 W.
    Copper Harbor Conglomerate: not measured (Myers, 1971)

Thwaites (1912) believed that the northern-most exposures at the South Fish Creek outcrop correlate with the Orienta Sandstone of the Bayfield Group. In their regional study of the heavy-mineral assemblages of both Oronto and Bayfield Group strata, Tyler and others (1940) determined that the epidote abundance of the total Oronto Group heavy-mineral suite ranged from 12 to 35 percent. In contrast equivalent epidote percentages within Bayfield Group formations ranged from zero to a trace. Myers (1971), in describing the South Fish Creek section, stated that "The abundance of epidote in [these] beds ... is much greater than any other exposure of Oronto." Myers considered all outcrops in these three sections to belong to the Freda Formation. In this same general area, but several kilometers to the southwest, a 550 m section of fine-grained, arkosic sandstone crops out. Thwaites (1912) established this exposure as the type section of his Eileen Formation. Tyler and others (1940) found absolutely no epidote associated with these same strata and consequently suggested that the Eileen Formation is "probably basal Orienta," a position compatible with the paleomagnetic data of DuBois (1962). By redefining the age of these outcrops, Tyler and others (1940) recognized that they were advocating the placement of Bayfield Group strata southwesterly of Oronto Group strata, a mapping anomaly considering the regional distribution of outcrops belonging to both groups. Tyler and others (1940) offered two solutions, both involving faulting.

In 1959 and 1960 the Bear Creek Mining Company conducted a mineral exploration program in Bayfield and Douglas Counties, Wisconsin. Nonesuch Formation strata were cored as far west as Lake Nebagamon, Douglas County (T. 46 N., R. 11 W.), and as far south as T. 45 N. (open-file information, U.S. Bureau of Mines core repository, Minneapolis, Minnesota). As recently as 1982, Daniels reported that the Nonesuch Formation thinned southwesterly from 215 m in the Calumet area of Michigan to 76 m at Copper Falls, Wisconsin. Bear Creek Mining Company core data indicate this thinning trend is reversed west of Copper Falls with as much as 140 m of Nonesuch Formation cored in western Bayfield County (T. 45 N., R. 9 W.). This same Bayfield County core contained six occurences of a "hydrocarbon filled veinlet."

Interpretation of profiles 16, 17, and 30 of the refraction seismic data of Mooney and others (1970) suggested this column is composed of units associated with their "middle" and "lower seismic unit." They loosely correlated these seismic units in northwest Wisconsin with strata of the Oronto Group. Thus, geologic and geophysical data indicate that the basaltic basement of the St. Croix Horst in northwest Wisconsin is partially covered by sedimentary units of the Oronto Group. The Copper Harbor Conglomerate defines the limits of the Ashland Syncline. Core data indicate that the Nonesuch Formation and the Freda Formation are restricted to that part of the syncline between central T. 45 N. and southern T. 48 N. and east of R. 11 W. To the southwest an Oronto Group equivalent, the Solor Church Formation, is found underlying Paleozoic rock within the Twin Cities Basin lying on top of the St. Croix Horst in east-central Minnesota. The hydrocarbon source rock evaluation of this formation is discussed by Hatch and Morey (1985).

To the north of the Twin Cities Basin, an elongate basin covering approximately 300 square km contains Oronto Group-equivalent sedimentary rock. Farnham (1967) identified this structure as a graben and, on the basis of seismic refraction velocities, correlated the rock as principally Oronto Group in age. Farnham (1967) determined this Oronto equivalent sequence ranged from 1,200 m in the north to 6,000 m at the southern border of this structure. Craddock (1972b) differed in interpretation only in showing this area of rock to be a half-graben, bounded only on the east by faults. A small part of this outlier of sedimentation to the Ashland Syncline and the Twin Cities Basin extends from Minnesota into Burnett and Polk Counties, Wisconsin.

RIVER FALLS SYNCLINE

Thwaites (1931) mentioned the presence of pre-Paleozoic red clastic rock in the subsurface of a "considerable part of northwest Wisconsin." Thwaites (1935) depicted Oronto Group sedimentary rock associated with the River Falls Syncline on his Lake Superior Basin structural map. Stauffer (1927), presented a log of a deep well located 2 km east of Rochester, Minnesota, that includes 620 m of a pre-Hinckley Sandstone "red clastic series" and makes reference to a 56 m interval "showing of oil." After model analysis of the eastern segment of their gravity traverse (Craddock and others, 1963) indicate that "Precambrian strata [here] could reach a thickness of almost 3,350 meters" in the River Falls Syncline. Refraction data of Mooney and others (1970) confirm the existence of "an important sedimentary basin ... considered Cambrian and Upper Keweenawan" in age and located east of the St. Croix Horst in west-central Wisconsin in the River Falls Syncline and on the basis of seismic velocity values, concluded that "rocks considered probably equivalent to the Upper Keweenawan Oronto Group occur ... widely distributed in the eastern basin." The rocks are depicted to be as thick as 1,250 m. These studies thus support the suggestion of Thiel (1956) that the regional gravity low located east and southeast of the St. Croix Horst in Wisconsin "reflects a thick accumulation of Upper Keweenawan sediments."

THE BAYFIELD BASIN

Any evaluation of the extent of Oronto Group sedimentation to the north of the St. Croix Horst in Wisconsin must include outcrop along the Middle River, Douglas County (sec. 24 and 25, T. 48 N., R. 12 W.). The outcrop is not unanimously accepted as belonging to the Bayfield Group. Because Bayfield Group exposures are rather common along the southwest shore of Lake Superior from Superior, Wisconsin, northeasterly around the Bayfield Peninsula, there is no dispute regarding the existence of the Bayfield Basin. In fact, this is the specific region to which Thiel (1956) correlated gravity with geology in his classic determination of a geologic tectonic model of the Midcontinent Gravity High. The dispute concerns the age of basin sedimentary rock fill. Is the basin fill entirely of Bayfield Group strata or is a deeper Oronto Group sequence present?

A review of recent literature indicates an Oronto Group correlation for at least a part of the Middle River section is accepted by Halls (1966), White (1966a), Farnham (1967), Hite (1968), Myers (1971), and Watts (1981). White (1966a) emphasized the significance of this outcrop by stating that "this exposure is important because it shows that rocks of the Oronto Group do occur beneath the Bayfield Group north of the Douglas fault."

Because the geologic distribution of the Oronto Group north of the St. Croix Horst and into the region of Lake Superior proper is dependent upon the age of this outcrop, a review of its stratigraphic and petrographic interpretation is in order. Thwaites (1912) described in detail the Middle River sequence. Upper Keweenawan, structurally overturned, red clastic rock is found in fault contact with Middle Keweenawan basalt. Downstream, to the north, these beds become younger in age and the dip gradually declines with horizontal beds being found approximately 450 m from the fault contact. On the basis of field lithologic comparison, Thwaites (1912) assigned the oldest 111 m of this sequence to the Freda Sandstone and considered the remaining beds to be Orienta Sandstone (Bayfield Group) in conformable contact with the Oronto-age sedimentary rock. Thwaites (1912) felt so confident in this correlation that he wrote, "In the field the lithologic likeness of the lower beds of this section to the upper part of the known Amnicon formation of the Oronto Group is more striking than any description can make it, so that the writer has no reasonable doubt of the correlation as given." In their regional heavy-mineral study, Tyler and others (1940) accepted the basic premise of Thwaites (1912) and added to this evaluation by determining that Oronto and Bayfield sedimentary rock could be distinguished by the presence (Oronto) or absence (Bayfield) of the mineral epidote. In their analysis of Middle River outcrop beds termed Orienta Sandstone by Thwaites (1912), Tyler and others (1940) reported no epidote; those classified as Oronto Group by Thwaites (1912) contained epidote ranging from 6 to 38 percent of the total heavy mineral suite. Hamblin (1961) substantiates this heavy-mineral group differentiation by identifying the Freda Formation as containing epidote ranging from 6 to 35 percent; his equivalent analysis of Bayfield Group clastic rock ranged from zero to 4 percent. Hite (1968) reported the Middle River Oronto Group (Freda Sandstone) units contain 9.71 percent epidote, and Bayfield Group (Orienta Sandstone) units from the same area possess 0.1 percent epidote.

Myers (1971) reported high epidote, relatively high illite and low kaolinite content, plus a relative abundance of feldspar, shale beds, and sparry calcite cement to the Middle River outcrop. He concluded that "the steeply dipping Middle River beds belong to the Oronto Group," although Myers (1971) correlated the horizontal beds at this site with the basal Bayfield Group and thus argued for the presence here of an angular unconformity.

Mooney and others (1970) conducted six east-west seismic refraction profiles north of the Douglas fault from north-central Douglas County to east-central Bayfield County. They recognized six distinct velocity groups. Three of these "layer identifications" they named the Upper, Middle, and Lower Oronto Group, and correlated these respectively with the Freda Formation, Nonesuch Formation, and Copper Harbor Conglomerate. Their portrayal of a section across the Bayfield Basin suggests that the Nonesuch Formation and the Copper Harbor Conglomerate maintain a uniform thickness in Douglas and Bayfield Counties and the Freda Formation thins to the west. These conclusions support the interpretation reached by White (1966a).

The presence and geologic extent of these Oronto Group correlatives west of the St. Croix Horst in Minnesota, as determined by drill hole and seismic analysis, is discussed by Austin (1970), Mooney and others (1970), Morey (1974), and Hatch and Morey (1985). Farnham (1967) mentioned a Bayfield Basin well-log sample that is described as a "volcanic pebble conglomerate" and speculated that this might be evidence for the presence of the Copper Harbor Conglomerate in the subsurface of Minnesota. Morey and Ojakangas (1982) supported the conclusions of these Oronto Group equivalent distribution studies but pointed out that seismic evidence suggests an absence of strata of this age in the Bayfield Basin from the region of Superior, Wisconsin, southwest to the vicinity of Sandstone, Minnesota. Morey and Ojakangas (1982) suggested that this distribution is controlled by the presence of vertical displacement, northwest-trending faults that offset the strike continuity of the Douglas Fault.

EXTENSION UNDER LAKE SUPERIOR

Watts (1981) pointed out that the presence of Middle Keweenawan basalt in the Lake Superior Basin records an initial tensional phase in the development of the Midcontinent Rift. The earlier work of Butler and Burbank (1929) and Halls (1966) observed that the basalt increases in thickness toward the center of Lake Superior.

Daniels (1982) indicated that both the Copper Harbor Conglomerate and the Nonesuch Formation increase in thickness to the north under Lake Superior from the Keweenaw Peninsula of Michigan. In the vicinity of Ontonagan, Michigan, this thickening takes place at the rate of 25 m per km for the Copper Harbor Conglomerate and 5 m per km for the Nonesuch Formation. This trend and the distribution pattern of the Nonesuch Formation suggested by White (1966a) might indicate that although the Nonesuch Formation is present and of maximum thickness under central Lake Superior, it might thin to the point of becoming absent in the western Lake Superior region.

Hamblin (1961, 1965) studied the sediment dispersal patterns in Upper Keweewanan sedimentary rocks. He believed that the Oronto basin was "the topographic basin which received Keweenawan sediments and basalts ... in approximately the present site of Lake Superior .... The northern boundary of the basin was probably very near the northern shore of the Lake [Superior]."

In developing a tectonic history for the Midcontinent Rift System, Hamblin (1958), White (1966a and b), Farnham (1967), Morey and Ojakangas (1982), Kalliokoski, (1982), and Green (1983) have shown that the boundary faults of the St. Croix Horst were involved in major, if not principal, movements after the cessation of Oronto time. Thus, this structure may not have been developed to the point of influencing the depositional extent of Oronto Group sedimentation.

It appears the extent of Oronto Group sedimentation in northwestern Wisconsin is much greater than indicated by the geologic and geographic extent of outcrop of the sedimentary rock. This extent is greater than the conventional protrayal of confinement to the central part of the St. Croix Horst.

CONCLUSIONS

The distribution of Oronto Group rock within the Lake Superior region is central in importance to the search for hydrocarbon because the middle unit of the Oronto Group, the Nonesuch Formation, is a known oil source. The extent and history of the Oronto Group was directly influenced by Midcontinent Rift tectonic activity.

Within the central horst of the Midcontinent Rift System, Oronto Group rock in Wisconsin is well known from outcrop and drill-core data. The limit of the rock is determined by the limits of the Ashland Syncline. To the southeast in Minnesota, Oronto-age equivalents have been identified in the Twin Cities Basin by drill core and within an unnamed graben by seismic analysis.

To the south of the horst, Oronto rock within the River Falls Syncline is suggested by several shallow wells that penetrated Precambrian clastics and by refraction analysis. To the north of the horst, the presence of Oronto strata within the Bayfield Basin is supported by seismic data and heavy-mineral data of the well studied Middle River site.

Oronto Group under Lake Superior is suggested by numerous studies of the lithology, thickness, and focus changes of Oronto sedimentary rock exposed along the south shore of Lake Superior. There appears to be sufficient evidence to suggest that Oronto Group sedimentary rock, including the organic-rich Nonesuch Formation, can be found at depth throughout the extent of the Midcontinent Rift.

V. LOCAL GEOLOGIC ISSUES IMPACTING EXPLORATION

NATURE OF THE NORTHERN BOUNDARY OF THE ST. CROIX HORST

Albert B. Dickas

ABSTRACT

Within the northern Midcontinent Rift System the boundaries of the central horst are defined by major reverse faults: Hastings, Lake Owen, and Keweenaw Faults on the south, and Douglas and Isle Royale Faults on the north. The continuity of the fault system remains a matter of dispute. The connection of the Douglas Fault in northwestern Wisconsin with the Isle Royale Fault, located in north-central Lake Superior, has been variously proposed as an angular unconformity, a conformable sequence, a fold trend, as well as a fault offset or curvilinear continuation of the Douglas Fault. The weight of geologic and geophysical data favors either a fault-offset or curvilinear continuation of the Douglas Fault through Bayfield County, Wisconsin, and offshore under Lake Superior.

DISCUSSION

Thiel (1956) used gravity, geology, and structure of the rock in the Wisconsin-Minnesota area to suggest a horst. He identified the northwest border of this horst with the Douglas Fault. The St. Croix Horst, the central structural segment of the Midcontinent Rift System in Minnesota and Wisconsin, was named by Craddock and others (1963) as an uplifted block of Middle Keweenawan igneous rock, mainly basalt interlayered with thin sandstone beds. Upper Keweenawan conglomerate, sandstone, and shale of the Oronto Group partially mantle this block. This structure has been traced from western Bayfield County, Wisconsin, west and southwest into east-central Minnesota, where it terminates against the northwest-trending sinistral, strike-slip, Belle Plaine Fault (Sloan and Danes, 1962; Morey, 1977; Dickas, 1986).

Where the St. Croix Horst is buried beneath Phanerozoic sedimentary rock in east-central Minnesota, the known and inferred trace of the Douglas Fault is identified by a high gravity gradient (Thiel, 1956; Craddock and others, 1963), by linear aeromagnetic anomalies (King and Zietz, 1971), and by refraction seismic analysis (Mooney and others, 1970). Although the fault plane is not actually exposed here, Farnham (1967) reported basalt and sandstone that are found 8 m apart 6 km east of Hinckley as a good approximation for the location of the Douglas Fault.

Similar fault location criteria are applicable in northwestern Wisconsin. In Wisconsin the Douglas Fault is exposed at only four locations: Black River, poorly exposed in SE1/4, sec. 21, T. 47 N., R. 14 W.; Copper Creek, one distinct exposure in SE1/4, sec. 15, T. 47 N., R. 14 W.; Amnicon River, three good exposures in SE 1/4, sec. 29, T. 48 N., R. 12 W.; and Middle River, three good exposures in NE1/4, sec. 25, T. 48 N., R. 12 W. The best site for determining general fault characteristics is in Amnicon Falls State Park (fig. 1, location A). At the base of the waterfall on the main channel, basalt dipping 40 degrees SE is separated from Keweenawan sandstone by a 2.5-m thick gouge and breccia zone marking the fault plane. Orienta Sandstone dips to the southeast at angles up to vertical adjacent to the fault, but decreases to horizontal within 30 m of the fault gouge. The upper surface of the fault gouge trends N. 85 degrees E., 37 degrees SE. Slickensides indicate that displacement is predominantly dip-slip. Craddock (1972a) estimated throw from 2,500 to 3,500 m.

The Douglas Fault can be traced by gravity data as far east as T. 48 N., R. 8 W.. The extension of this fault further east into Lake Superior is a matter of considerable controversy. A fault continuation is presented in Mudrey and others (1982) and Cannon and Davidson (1982). A sedimentary contact projection is supported on the version by Morey and others (1982). Dutton and Bradley (1970) assumed a neutral point-of-view with their interpretation of a questionable fault extension.

East of T. 48 N., R. 8 W. into the region of Chequamegon Bay, the continuation of the Douglas Fault is complicated by sparse outcrop of sedimentary rock, a complete lack of outcrop of the basalt that is always associated with the upthrown side of this fault in Douglas County, and the presence of a well documented and pronounced (-92 mgal) gravity low centered northwest of Ashland, Wisconsin (fig. 1).

There are five alternatives for fault continuation.

A. The Douglas Fault continues to the east with the strike curving to the southeast around Bayfield County gravity low and then is projected into Lake Superior east and northeast around Isle Royale.

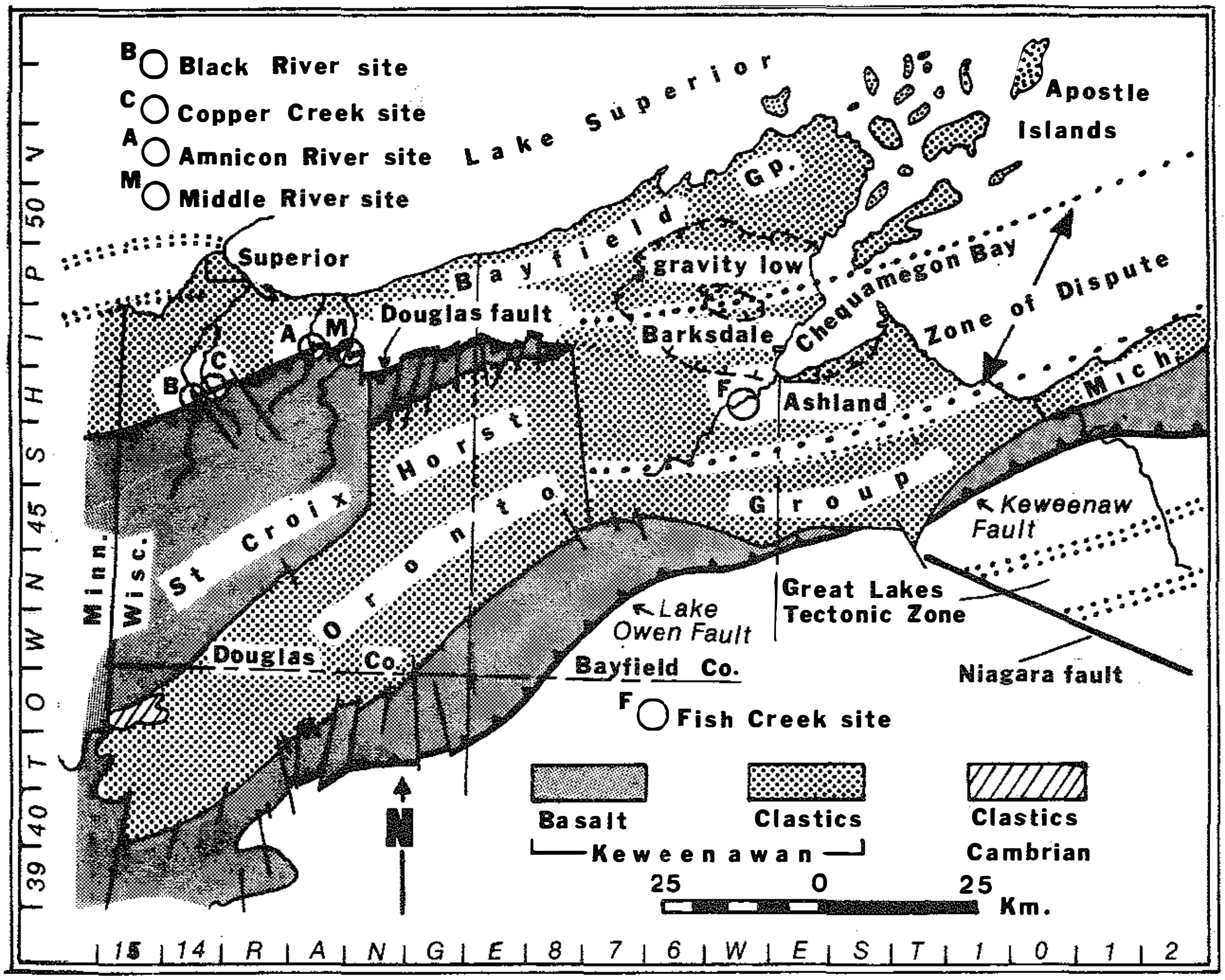

Figure 1. Generalized geologic map of the Midcontinent Rift System in northwestern Wisconsin.

Evidence in support includes:

* The northwest-southeast trending Bouguer gravity gradient marking the abutment of the trend of the St. Croix Horst against the Bayfield County gravity low in T. 48 N, R. 7 W. (Craddock and others, 1970).

* Outcrop of vertically dipping clastic sedimentary rock along the south fork of Fish Creek (fig. 1, location F) in sections 11, 14, and 15, T. 47 N., R. 5 W., Bayfield County (Thwaites, 1912; Tyler and others, 1940; Halls, 1966). To the west in Douglas County the known location of the Douglas Fault is generally marked by structural disturbance of the sedimentary rock adjacent to the fault (Myers, 1971).

* The position of the northeastward-trending zone of Bouguer gravity gradient offshore Lake Superior from southeast of Chequamegon Bay to north of Isle Royale (Hinze and others, 1982; Weber and Goodacre, 1966). This gravity trend appears to be geographically coincident with a "major structural ridge, which may be faulted ... [and] which is best evidenced by magnetics" (Wold and Ostenso, 1966). Further evidence for possible faulting here is shown by a change in magnetic character (Hinze and others, 1982). In the immediate vicinity of this projected sub-lake trace of the Douglas Fault, the geometric pattern of the magnetic data alters from a northerly to an easterly direction.

* Position and characteristic of the Isle Royale thrust fault as mapped by Van Hise and Leith (1911) and White (1966a). Wold and Ostenso (1966) extend the Isle Royale Fault west of Isle Royale. The Isle Royale Fault is considered by Halls and West (1971) to be an extension of the Douglas Fault into north-central Lake Superior.

* Interpretation of Lake Superior seismic refraction profiles (Smith and others, 1966; Hinze and others, 1982; and Luetgert and Meyer, 1982).

In addition, the possibility, but not necessarily the rationale, of this alternative is supported by geologic studies or maps presented by Thwaites (1935), Hamblin (1965); White (1966a, b), Myers (1971), Ocola and Meyer (1973), Watts (1981), Green (1982a), Morey and Green (1982), Morey and Ojakangas (1982), Wold and others (1982), and Van Schmus and Hinze (1985).

B. The Douglas Fault continues its easterly trend but is offset to the southeast by a right-lateral fault and then continues into Lake Superior as in alternative A. This model is really a variation of alternative A, but with the addition of right-lateral offset of the fault trend. Such an offset fault would have a northwest-southeast trend, and be located in central Bayfield County.

Evidence in support includes:

* Geologically and geophysically documented offset is known to cut across or offset the borders of the St. Croix Horst along its entire extent from east central Minnesota to western Bayfield County, Wisconsin (fig. 1) (Myers, 1971; King and Zietz, 1971; Morey and Green, 1982; Morey and Ojakangas, 1982).

* In their accessory-mineral study of the Lake Superior district sedimentary rock, Tyler and others (1940) redefined the stratigraphic nomenclature of Thwaites (1912). Their analysis is partially centered upon structural interpretation of the dipping units exposed on Fish Creek. The writers believed

that either the Douglas thrust or an associated minor fault may have caused the displacement of the Orienta and Freda sandstone at this locality. Within the confinement of outcrop geography, this postulated north-striking minor fault may well have been portrayed with a northwest strike with equal effect. Although the redefined outcrop nomenclature and associated offset might suggest faulting here, difficulty arises by alternative B being left-lateral rather than right-lateral displacement.

* The possibility of a lateral displacement in Bayfield County is further supported by Morey and Sims (1976), Sims and others (1980), and Klasner and others (1985). In each, a part of the discussion relates to the boundary between two Archean crustal tectonic terranes identified in the western Lake Superior region. The boundary separates a Superior province granite-greenstone terrane (2.7 Ga) from an older gneiss terrane (3.5 Ga) to the south. This feature has been named the Great Lakes Tectonic Zone by Sims and others (1980) and is traceable for 1,200 km from Minnesota eastward to Ontario. In northwestern Wisconsin the continuity of this zone is transected by right-lateral displacement associated with the Midcontinent Rift System. The trend of this zone is variously placed as coincidental with the northwest-southeast-oriented high gravity gradient referenced in part 1 of alternative A. In as much as the Douglas Fault and associated cross faults were active during the compressive or latter phase of midcontinent rifting, it is possibly a cross fault developed at this time in eastern Bayfield County along the trend of, or parallel to, this zone of transection. If present, this zone of transection should be confined to Wisconsin and not extended into Minnesota as shown by Morey and Sims (1976). Recently acquired high resolution aeromagnetic data in Minnesota argue against the presence of this zone of transection in Minnesota (Morey, verbal communication, 1985).

* This possible right-lateral cross fault might be related to Keweenawan-aged reactivation of Early Proterozoic or older fault systems mapped within the Penokean fold belt of north-central Wisconsin (Van Schmus and Bickford, 1981). The most logical fault to consider for such reactivation is the Mineral Lake Fault as suggested by Sims and others (1978).

* Such a postulated northwest-southeast striking fault through Bayfield County might be tectonically associated with a Middle Keweenawan ridge, mapped in the same vicinity by White (1966b). White carefully pointed out that this ridge, separating basins of thick from thin basalt deposition, is "strikingly parallel ... to some of the more conspicuous cross faults ... cutting the north limb of the Ashland Syncline." White concluded that these cross faults "seem to mark places where the thickness of lava changes abruptly."

* In developing a rigid-plate tectonic-interaction model for Midcontinent Rift System development, Chase and Gilmer (1973) suggested a transform fault through the Bayfield County area. Green (1983) presented several reservations concerning this alternative, and thus the existence of such a transform fault.

* Synthesis of refraction, gravity, magnetic, outcrop, and borehole data led Farnham (1967) to conclude that the Douglas Fault is offset in strike by a "north-trending cross fault" located in Bayfield County.

C. The Douglas Fault decreases in structural displacement, increases in depth or passes into an anticline to the east. Thwaites (1912) was the first to consider this alternative. He stated (p. 89) that the Douglas Fault "origin is a broken anticline" and considering its extension into Bayfield County (p. 90), "The Douglas fault does not pass through the Apostle Islands, but appears to die out into a fold which in turn becomes gentler and finally flattens out beneath the drift-covered area of the Bayfield ridge." Forty-four years later, Thiel (1956) conducted two local north-south gravity traverses across the projected trace of the Douglas Fault immediately south of Ashland, Wisconsin. The consistent and uniform decrease of gravity from south to north without the usual anomaly associated with faulting in this area suggested to Thiel that should the Douglas Fault be present here in the subsurface the throw is reduced to a point no longer distinguishable by surface gravity. He also considered the possibility of this fault being buried at a great depth as well as the fault phasing structurally into a deeply buried fold.

* Patenaude (1966) conducted aeromagnetic surveys through northwestern Wisconsin and found a progressive decrease in amplitude from R. 9 W. to R. 7 W. Patenaude interpreted the data to suggest a decrease in fault throw eastward. However, after comparing this field data with computed theoretical model magnetic profiles, Patenaude reconsidered this interpretation and suggested that "the anomaly over the fault would be difficult to identify in the observed profiles if the displacement on the fault were less than 500 to 1000 feet at depths in excess of 10,000 feet below the level of observation." Thus, the possibility of the Douglas Fault extending into Bayfield County is preserved.

Patenaude (1966) identified an anticlinal structure, from magnetics. The anticline trends southeastward from T. 47 N., R. 8 W., with the Douglas Fault.

D. The Douglas Fault phases to the east into an angular unconformity separating Oronto Group from Bayfield Group sedimentary rocks. Irving (1883) studied the contact of basalt and sandstone along the Douglas Fault at the four Douglas County sites. Irving concluded that "These disturbances find their explanation, in part, ... in the irregularities of an unconformable contact, ... There seems to be no escape from the conclusion that ... the Douglas County contact line is one of unconformability complicated by faulting."

* In 1969 Hubbard visited the Amnicon River exposure of the Douglas Fault and subsequently decided that the generally accepted, fault-related breccia and gouge zone exposed there was in reality a mudstone containing angular blocks of volcanic clasts (verbal communication, H.A. Hubbard, 1969). He considered this "mudstone" to be in conformable contact with the overlying basalt a "thin, underlying sandstone." In turn he believes the base of the thin sandstone to be in angular unconformable contact with Keweenawan aged clastic sedimentary rock. Hubbard did not consider what he identified as "mudstone" to be the gouge zone caused by Douglas Fault displacement.

Although Myers (1971) believed the Hubbard interpretation of the Amnicon River site was "decidedly unconventional," he retained the concept of an angular unconformity after studying the vertically plunging Freda Formation (Oronto Group) outcrop found along Fish Creek southwest of Ashland, Wisconsin (fig. 1). Contrasting these dips with the essentially horizontal altitude of the Chequamegon Sandstone (Bayfield Group) exposed 7 km to the northeast along the Lake Superior shoreline at Barksdale, Wisconsin, he suggested that this structural discordance could be evidence of an angular unconformity. The subsurface trace of this possible unconformity would lie coincidental with the projected extension of the Douglas Fault as presented in alternative A or B.

E. The Douglas Fault passes to the east into a conformable contact separating Oronto Group from Bayfield Group sedimentary rock. Thwaites (1912) interpreted the Fish Creek exposure in Bayfield County and stated that "there is [here] a conformable gradation from quartz sandstone of the general type of the Bayfield group downward into red shales and arkose sandstone or conglomerate of the same general type as the main body of the Oronto group ... it is believed ... that the Bayfield and Oronto groups are conformable." Of course, this conformable contact concept is directly related to the question of whether or not this outcrop displays rock associated with both the Oronto and Bayfield Groups. Thwaites harbored no doubts regarding the lowermost strata being of Oronto lithologic character, and stated that "correlation of the upper quartzose beds with the Bayfield Group is much less definite."

Two recent dissertations have included the Fish Creek outcrop section in their discussion, but they are mixed in their interpretation. Hite (1968) accepted the conclusion of Thwaites (1912) by stating, "close examination of the South Fork of Fish Creek (section) ... strongly suggests a conformable contact between the Freda Sandstone and the Bayfield Group." Myers (1971) addressed the question of formational conformability along Fish Creek. His detailed description of this outcrop indicates that he believes these strata belong in their entirety to the Freda Formation of the Oronto Group.

Since Thwaites (1912) described the sole outcrop in the region of possible extension of the Douglas Fault eastward of its most easterly accepted position, there has been no resolution of the question of fault extension.

In the summer and early autumn of 1984 several hundred kilometers of seismic reflection lines were conducted throughout Douglas and Bayfield Counties by three different and competing seismic crews. Until these data are released to the public, or a deep test well is drilled in the area of dispute, the additional geologic information necessary for the definitive solution to this question will remain buried by the 30 to 180 m of Pleistocene sediment cover that masks the Midcontinent Rift System in this region.

CONCLUSIONS

It is suggested that the trend of the Douglas Fault continues through central Ashland County and then northeastward into the central Lake Superior area, where it links up with the Isle Royale Fault. This suggestion is supported by the vertical dip and heavy-mineral interpretation of outcrops located along Fish Creek in Bayfield County, the orientation and displacement of the Isle Royale Fault, the nature of offset faulting along the north flank of the St. Croix Horst, and the structural fabric of the pre-Midcontinent Rift terrane. Geophysical support for the extension includes the position and shape of the Bayfield County gravity minima, the orientation of steep gravity gradients located offshore Lake Superior, and interpretations of regional seismic refraction profiles. The effect of extending the trend of the Douglas Fault east and northeastward from Bayfield County, Wisconsin, is to increase the width of the Bayfield Basin north and east of the area of Chequamegon Bay, and to project the St. Croix Horst into the central sector of the Lake Superior Basin.

SEISMOLOGIC ANALYSIS OF ARRESTED STAGE DEVELOPMENT OF THE MIDCONTINENT RIFT

Albert B. Dickas

ABSTRACT
Since Thiel (1956) first modeled the geology of the Midcontinent Gravity High, numerous modifications of this model have been advanced. Although these modifications differ principally in their progressive search for deeper geologic causes of the observed gravity field, all contain a central horst separated from enveloping sedimentary rock-filled basins by reverse faults.

From 1978 through 1981 the Consortium for Continental Reflection Profiling (COCORP) conducted deep seismic programs in southern Michigan and northeastern Kansas, across the southern extremities of the Mid-Michigan and the Midcontinent Gravity Highs. The consensus of interpretations of these models is an asymmetric rift-extension basin. The Kansas structure is depicted as being bordered by gravity faults; the Michigan rift-basin appears to be characterized by a lack of faults.

In 1984 commercial seismology was conducted along the extent of the Midcontinent Gravity High. Analysis of profiles from the northern Wisconsin and Lake Superior sections of these programs support the premise of the Thiel (1956) model and contrasts sharply with the COCORP interpretation.

These differences in tectonic evolution of the underlying rift structure causing the Mid-Michigan and Midcontinent Gravity Highs can be resolved by recognition that different stages of rift development are represented. Four such stages, representative of earliest to more advanced rifting, are suggested for southern Michigan, northeast Kansas, Iowa, and the Lake Superior region.

DISCUSSION
For the past three decades, geophysical model analysis of the geologic structure causing the Midcontinent Gravity High along its trend in Iowa, Minnesota, and Wisconsin has been directly traceable to the intracratonic rift model suggested by Thiel (1956). Thiel correlated the regional Bouguer gravity field with near-surface Keweenawan geology of the southwestern Lake Superior region and developed a model incorporating the following geologic components (fig. 1A):

1. The central gravity maximum of the Midcontinent Gravity High is related to multi-layered basalt, associated with thin, interflow clastic rock extruded into a syncline of Middle Keweenawan age. The basalt has a density of 2.9 g/cc.

2. Localized gravity minima mitigating the intensity of the central gravity maxima are depicted as Upper Keweenawan clastic rock having a density of 2.4 g/cc and conformably overlying the basalt forming the central horst.

3. Gravity minima situated along both flanks of the central gravity maxima are attributed to thick sections of Upper Keweenawan sedimentary rock, principally sandstone and conglomerate.

4. The high gravity gradients separating the central gravity maxima from adjacent gravity minimia are correlated with high angle, reverse faults that juxtapose Middle Keweenawan basalt and Upper Keweenawan clastic rock.

Craddock and others (1963) extended this model into Minnesota with only slight modifications in the densities of the causative rocks. As recently as 1982 the basic Thiel (1956) model was employed by Anderson and Black (1982) in their review of the Midcontinent Gravity High in southwest Iowa.

Contemporary utilization of the Thiel model should not convey the implication this model concept has remained unchanged over the past thirty years. Thiel (1956) correlated observed gravity with near-surface geology and did not verify his model with theoretical gravity. The application of theoretical gravity to the Thiel model by Weber and Goodacre (1966), Ocola and Meyer (1973), and Hinze and others (1982) demonstrated the need for considering geology not only near the surface but also as deep as the Moho. Thiel (1956) sought answers in the outer 10 km of the Lake Superior region; today geophysical models analyze the Midcontinent Gravity High to structures as deep as 60 km. Throughout the evolution of Midcontinent Gravity High analysis one aspect has remained constant -- a near-surface central horst separated from adjacent sedimentary rock-filled basins by high angle, thrust faults. This depiction creates the persuasive, but not necessarily correct, implication that the principal forces responsible for Midcontinent Gravity High geology were those of compressive stress.

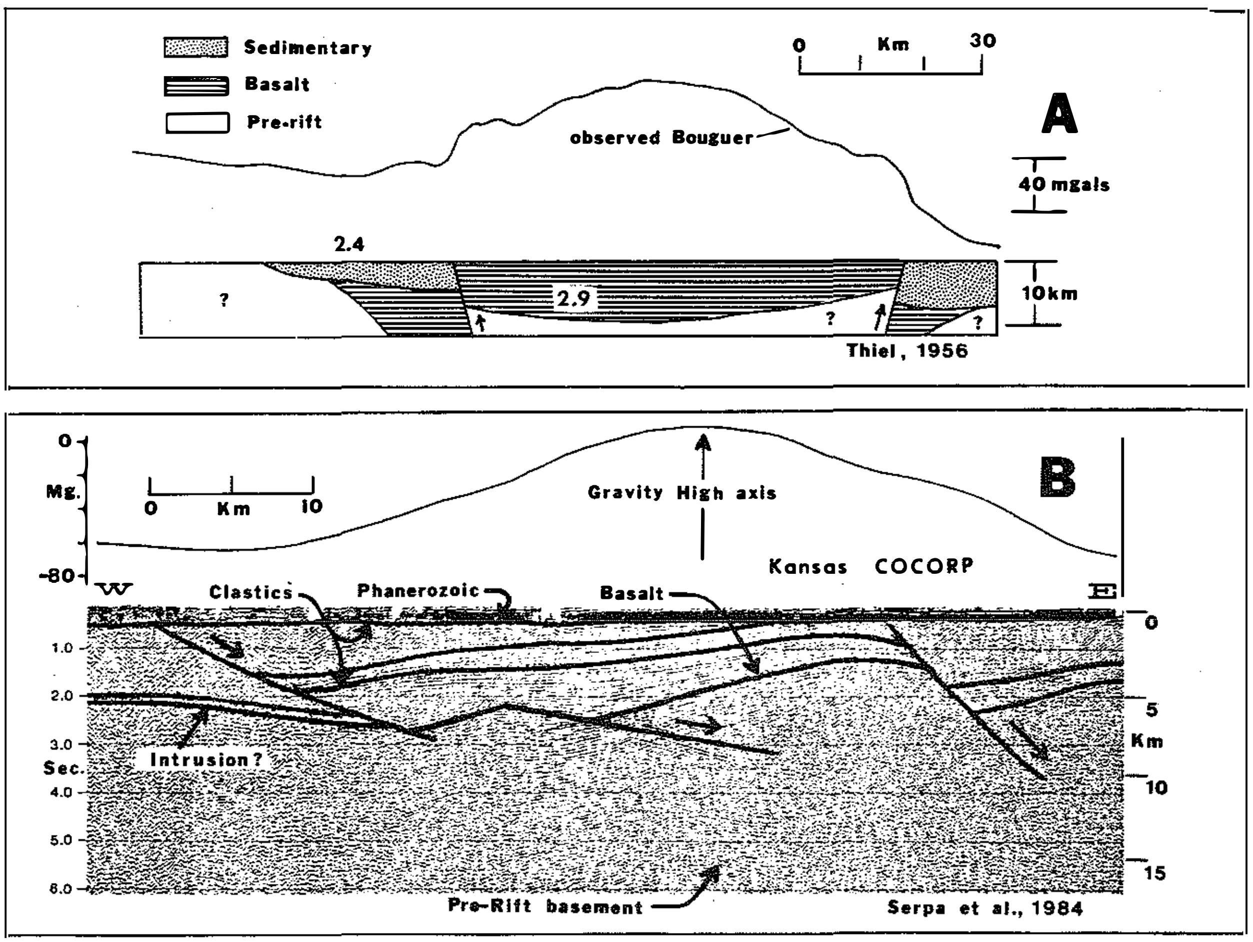

Figure 1. A. Profile of gravity model of Midcontinent Rift System as devised by Thiel (1956). B. Seismic section interpretation across the Midcontinent Rift in northeastern Kansas, after Serpa and others (1984).

In 1978 the COCORP conducted approximately 130 km of deep profiling across the distal part of the Mid-Michigan Gravity High (fig. 2). Seismic events were recorded to 10 seconds (28 km). The purpose of the survey was to investigate the geologic structure causing the Mid-Michigan Gravity High. Brown and others (1982) recognized three suites of reflection strengths, as follows (fig. 3):

1. A shallow sequence of relatively horizontal reflectors approximately 1.5 sec. (3.8 km) deep (line 1). These represent the Paleozoic section found within the Michigan basin.

2. A reflection-poor zone, lying (line 1) between 1.5 sec. (3.8 km) and 2.3 sec. (5.8 km), related to the Upper Keweenawan assemblage of clastic sedimentary rock as lithologically defined in the southwestern Lake Superior Basin.

3. A deep, strong reflector zone, lying (line 1) between 2.3 sec. and 4.0 sec. (10.1 km), correlated to Middle Keweenawan basalt interbedded with thin layers of clastic rock. The strong acoustic contrast within this suite is caused by "contacts between the volcanic rocks and interfingered clastic rocks."

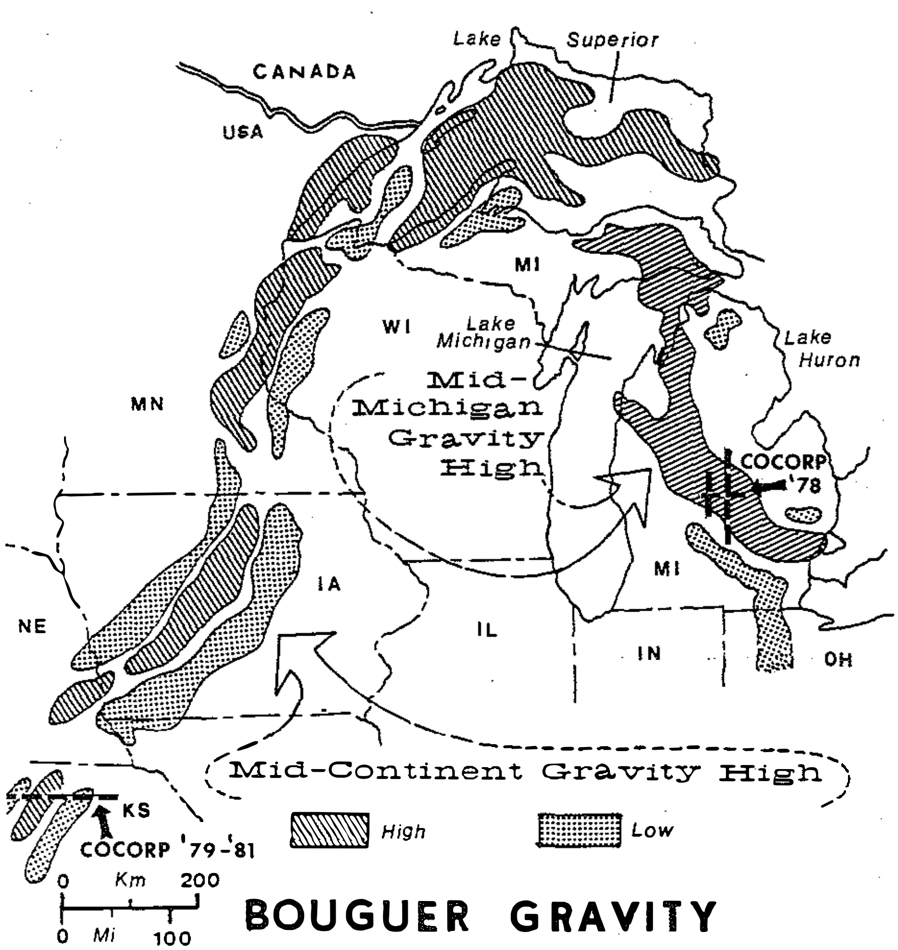

Figure 2. Location of COCORP seismic lines in Michigan and Kansas.

Brown and others (1982) described this geologic structure as a narrow, 60-km wide, asymmetric basin in which "direct evidence of faulting within the inferred volcanic sequence is lacking."

Between 1979 and 1981 COCORP conducted 317 km of deep seismic profiling across the Midcontinent Gravity High of northeastern Kansas (fig. 2). The purpose of this survey was to investigate the geologic structure associated with this geophysical anomaly. The data acquisition and processing procedures of this project produced seismic events ranging from 0.2 seconds (200 m) to approximately 15 seconds (45 km). Steeples (1976) determined that the base of the crust lies at approximately 40 km in northern Kansas. Thus, this COCORP line gives a seismic view of the entire crust across the southwestern part of the Midcontinent Gravity High.

Serpa and others (1984) characterized the Midcontinent Gravity High as follows (fig. 1B):

1. An asymmetric basin 40 km wide identified by reflection events with an apparent dip of approximately 25 degrees to the west.

2. A deeper set of events that are strong reflectors and interpreted as a maximum thickness of 5 km of interbedded basalt and clastic rock of Middle Keweenawan age.

3. A shallower set of events that are weak reflectors and interpreted as a maximum thickness of 3 km of sedimentary rocks of Upper Keweenawan age.

4. Planar, eastward dipping (approximately 30°), gravity faults that truncate the basalt basin on the eastern and western margins of the basin.

Serpa and others (1984) concluded that the Kansas part of the Midcontinent Gravity High represents a "rift basin formed by the rotation of fault bounded blocks during crustal extension." This graben subsidence model is in structural contrast to the central horst model used in the Lake Superior region.

During the summer of 1984 reflection seismology data were collected in support of the exploration for oil and gas in the clastic sequence of the Midcontinent Rift System. It was conducted along the entirety of the Midcontinent Gravity High by several contractors. Analysis of three onshore profiles con-

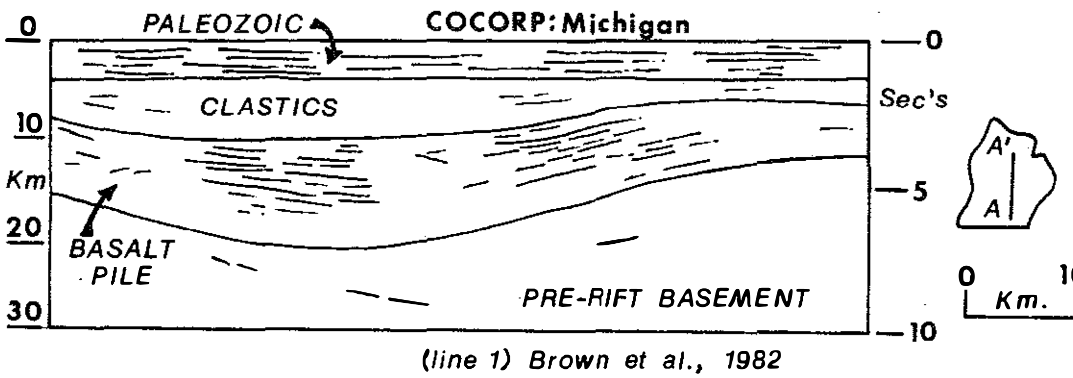

Figure 3. Seismic section line interpretation across Midcontinent Rift System in southern Michigan, after Brown and others (1982).

ducted at right angles to the trend of the Midcontinent Rift System within the Lake Superior region suggests a geologic interpretation that is in direct contrast with the Michigan and Kansas COCORP interpretations, but which is quite compatible with surface geology and the central horst model. Interpretation of the seismic profiles, on loan to the author courtesy of Petty-Ray Geophysical, Inc., are presented in schematic form in figure 4. Using interpretative procedures developed by Brown and others (1982) and Serpa and others (1984), the Petty-Ray profiles display the following characteristics:

1. Sedimentary rock, comprising both the Oronto and the Bayfield Groups, are represented as reflection-poor to reflection-transparent zones.

2. The presence and extent of the basalt pile, underlying the Oronto and Bayfield Groups, is easily recognized by its strong reflectability.

3. Boundary faults are positioned by the lateral cessation of reflections related to the basalt pile. The near surface positions of the faults are verified by steep gravity gradients and magnitude oscillations along the magnetic profiles.

4. The reverse nature of these faults is indicated by the association of high gravity with the shallow depths of the basalt pile. In contrast, the flanking basins contain relatively thick sequences of reflection-poor clastics overlying basalt piles located at considerable depths. The basalt piles are not discernable within the flanking basins, probably because of assimilation of the seismic wave by overlying clastic rock.

During the summer of 1985, seismic reflection employing airgun techniques was conducted in Lake Superior. I have been permitted to interpret two profiles shot at right angles to the Midcontinent Rift trend across Lake Superior, courtesy of Grant-Norpac, Inc. (fig. 5). Generalizations regarding these 8-second-deep profiles include the following:

1. Reflection-transparent zones elsewhere associated with the Upper Keweenawan clastic sequence appear to be absent from these sections. This may be a function of the airgun technique employed here versus the vibration technique employed on land.

2. The Upper Keweenawan clastic sequence can be subdivided into group classification by an apparent angular unconformity separating the structurally simple Bayfield Group from the folded Oronto Group.

3. Regional Midcontinent Rift System faults (Douglas and Keweenaw) are indicated by the lack of horizontal continuity of strong reflections associated with the Middle Keweenawan basalt pile. Reverse movements are suggested by relative displacements of the basalt.

4. Section B (fig. 5) shows strong evidence for the presence of the Douglas Fault in the area of Lake Superior west of Isle Royale, thus further supporting the extension of this fault into Lake Superior.

The interpretation of the Grant-Norpac Lake Superior seismic program, as schematically presented here, is offered in further support of the basic horst model.

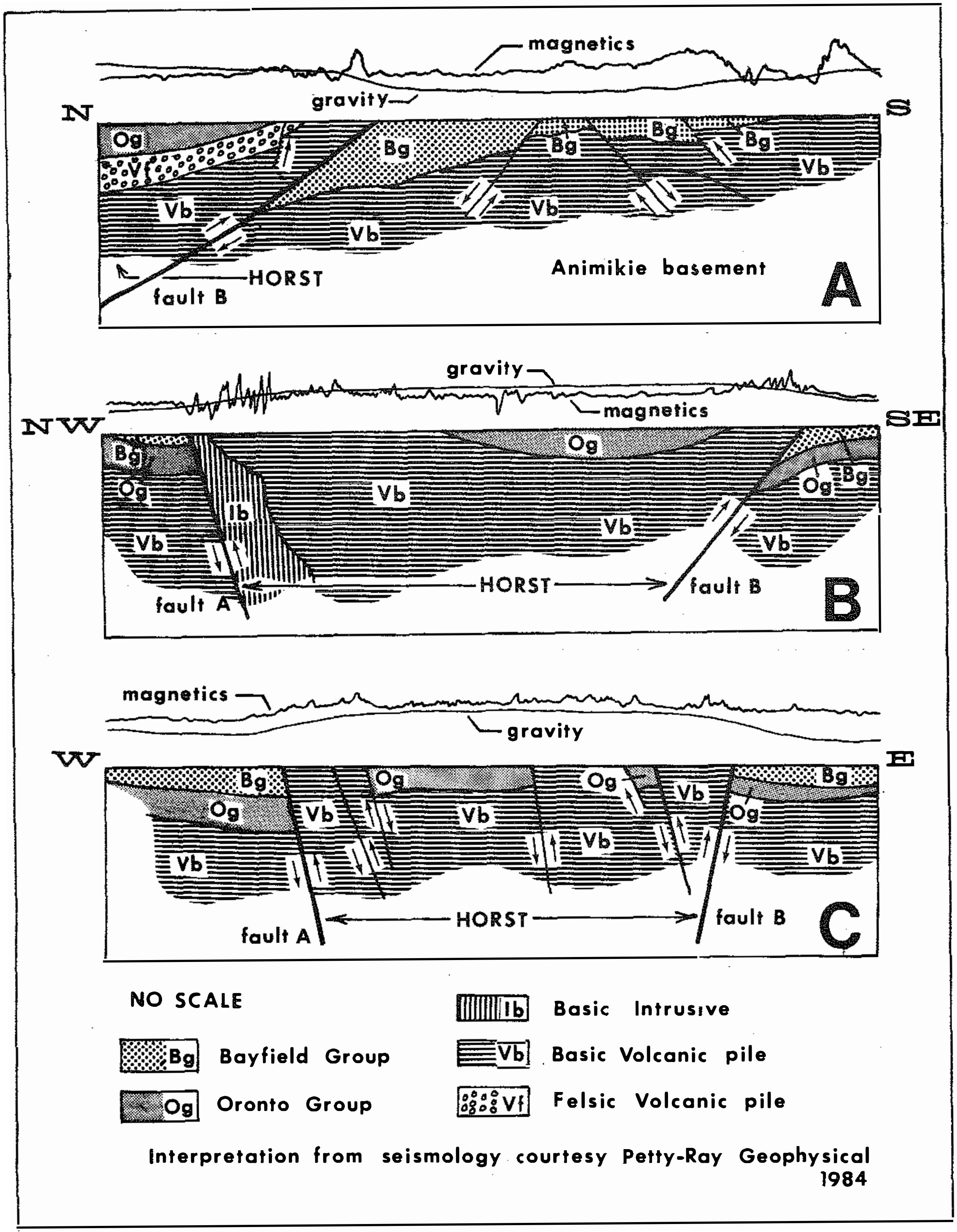

Figure 4. Schematic geologic interpretation of seismic profiles across northern axial part of the Midcontinent Rift System.

STAGES OF RIFT DEVELOPMENT
The geologic interpretation, associated with different parts of the Mid-Michigan and Midcontinent Gravity Highs should not be considered incorrect due to the absence of structural conformity. The Midcontinent Rift System structure from Kansas to southern Michigan might be considered a composite of various stages of arrested rift development. From earliest to latest the geologic characteristics of these suggested stages and their geographic locale are (fig. 6)

> Stage I. Simple gravity trend, minimal crustal separation, formation of an extensional basin, characterized by a lack of faults - locale: southern Michigan
> Stage II. Simple gravity trend, minimal crustal separation, formation of an extensional basin, characterized by normal faults - locale: northeastern Kansas
> Stage III. Simple gravity trend, intermediate crustal separation, formation of an extensional basin reactivated by compressional forces, characterized by reverse faults - locale: Iowa
> Stage IV. Bifurcated gravity trend, maximum crustal separation, formation of an extensional basin reactivated by compressional forces, intrusion by gabbroic masses, characterized by reverse faults - locale: Lake Superior Basin

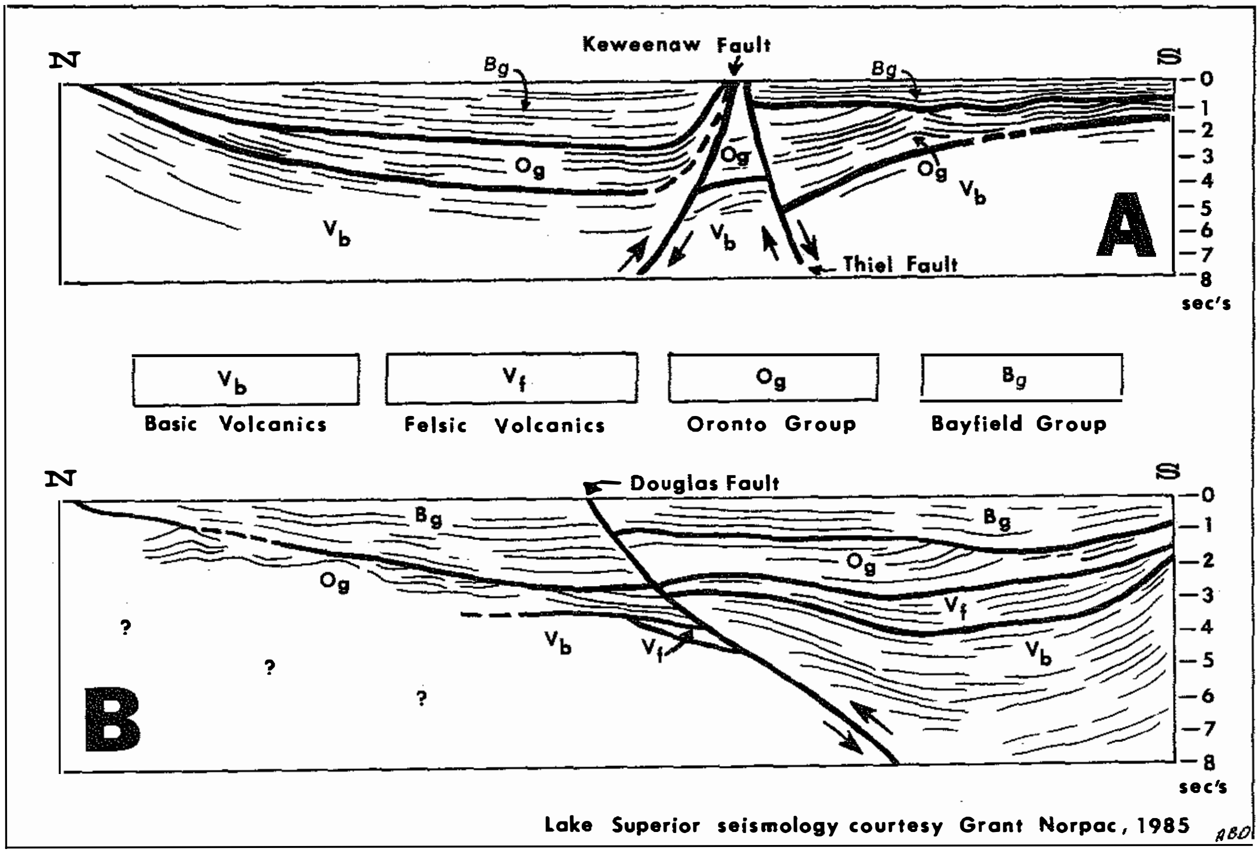

Figure 5. Schematic geologic intepretation of seismic profiles across axis of Midcontinent Rift System, offshore Lake Superior.

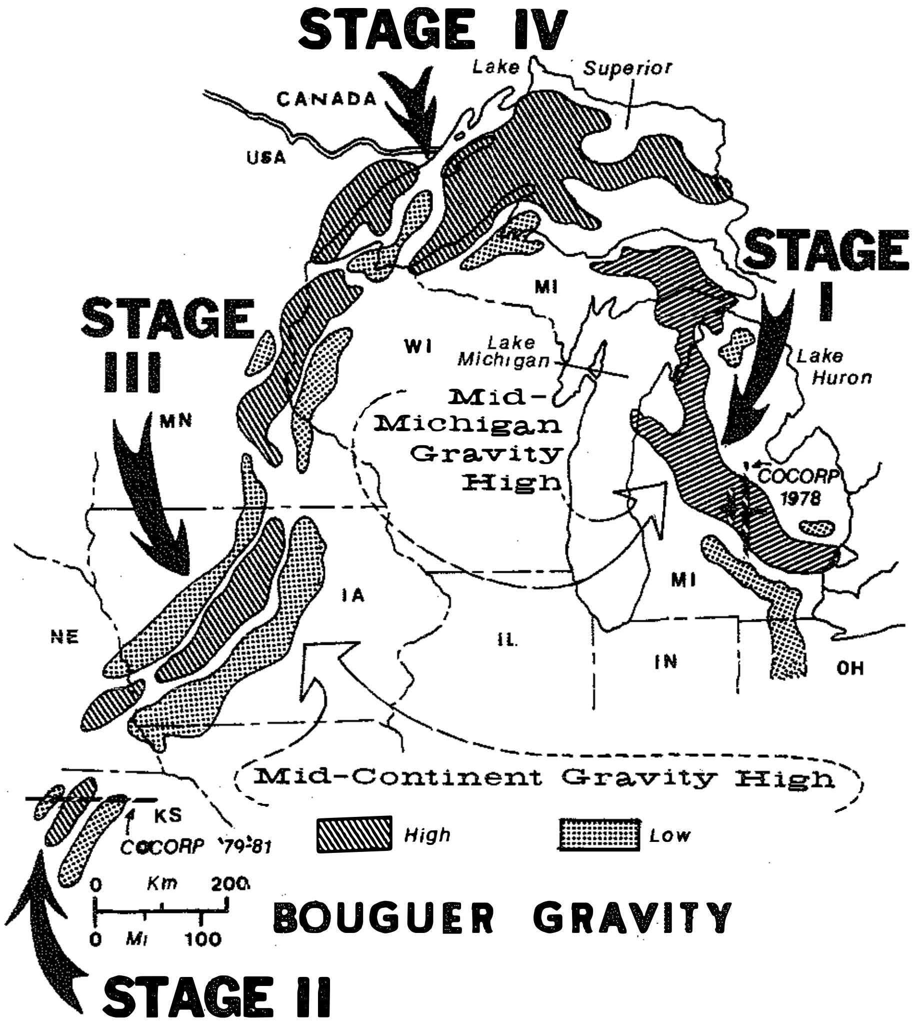

Figure 6. Location of various stages of arrested tectonic development of the Midcontinent Rift System.

CONCLUSIONS

The significance of the Michigan and Kansas COCORP seismic lines lies in their structural implications which, if interpreted correctly, suggest a drastic difference from previous geologic models, and from structural interpretations based on recently conducted industrial seismology. This difference can be attributed to various arrested stages of tectonic development. This approach suggests that several structural concepts should be considered in modeling this rift; different models are suggested for different geographic segments. The more advanced stage can be geologically and geophysically studied within the area of Lake Superior, which suggests that rifting was initiated in this region and was later extended to the southwest and southeast along the trend identified by gravity. The more immature stages of rifting are found associated with the apparent distal parts of the gravity high in southern Michigan and northeastern Kansas.

INTERPRETATION OF THE WESTERN LAKE SUPERIOR GRAVITY LOW

Albert B. Dickas

INTRODUCTION

The Midcontinent Gravity High is closely associated with gravity minima along its entire extent from Kansas northeastward into the Lake Superior region. No gravity minima along this trend have attracted as much attention or analysis as have the Bayfield (gravity) low and the Chefswet (gravity) low, herein combined as the Western Lake Superior Gravity Low. The significance of the geologic interpretation of the Western Lake Superior Gravity Low is related to its geophysical magnitude, its proximity to Keweenawan outcrop, and its on-trend association with the central gravity maxima axis of the Midcontinent Gravity High.

Interpretation over the past three decades has concentrated on causitive geology within Upper Keweenawan sedimentary rocks, Middle Keweenawan volcanic rock, and deeper crustal or mantle associations.

The discovery, geographic delineation, and geologic interpretation of the Midcontinent Rift System has been greatly aided through the collection and analysis of gravity data. Woollard (1943) first reported "a very strong (gravity) high" centered on station 378 near Clay Center, Kansas, situated along a transcontinental survey he supervised between New Jersey and California. He suggested that this anomalous gravity reading, the highest recorded between Pennsylvania and Nevada, was caused by a subsurface gabbroic mass approximately 20 km in width. On the basis of a series of gravity traverses conducted in the midwestern United States, Woollard (1951) again reported that the Kansas anomaly extended north and northeast into the Lake Superior district, a distance of 1,300 km. Thiel (1956) named this gravity feature the "midcontinent gravity high" and proclaimed it "one of the most prominent gravitational features in the United States," and Lyons (1959) proclaimed it to be "the most significant gravity maxima anomaly on the North American continent ...."

The term "midcontinent gravity high" might be considered a misnomer because along a majority of its length, this feature is flanked by gravity lows. These minima are equally distributed on both sides of the gravity maxima axis, and they display negative magnitudes of comparable value to the centrally located positive magnitudes. The local gravity relief between these magnitudes ranges from 125 mgal in southwest Iowa, to 170 mgal in northeastern Iowa, and to 130 mgal in west-central Wisconsin. At these same sites the width of the Midcontinent Gravity High, as measured from gravity minimum flank axis to adjacent gravity minimum flank axis is, respectively, 105 km, 80 km, and 97 km.

Except for the Lake Superior region, the geologic structure causing the Midcontinent Gravity High is buried beneath Phanerozoic strata. In northwest Wisconsin, particularly Douglas, Bayfield, Ashland, and Iron Counties, exposures of Precambrian sedimentary and igneous rock are randomly distributed. These rocks belong to the Middle and Upper Keweenawan of the Middle Proterozoic. The rock associated with the Midcontinent Gravity High in Wisconsin is classified into three series: a dense and thick series of gabbro and basalt, the latter with thin layers of inter-flow sedimentary rock; an overlying series of conformable clastic rock termed the Oronto Group; and a second unit of clastic rock unconformably overlying the Oronto Group, the Bayfield Group. Both the Oronto and Bayfield Groups are composed of three formations. From oldest to youngest the Oronto Group is composed of the Copper Harbor Conglomerate, the

Nonesuch Formation, and the Freda Formation. The Bayfield Group is made up of, in the same order of age, the Orienta Sandstone, Devils Island Sandstone, and the Chequamegon Sandstone. The Oronto and Bayfield Groups have been combined in recent years by the U.S. and Ontario Geological Surveys into the Keweenawan Supergroup (Morey and Green, 1982).

Thiel (1956) demonstrated that the Midcontinent Gravity High inclusive of the associated flank gravity lows was the geophysical expression of Keweenawan geology in northwestern Wisconsin and adjacent parts of the Upper Peninsula of Michigan. Thiel (1956) stated that "the positive anomalies correlate with Keweenawan lava and gabbro," whereas the flanking minima were correlated to wedge-shaped basins filled with sedimentary rock that thinned away from the central structural high. This central high, later named the St. Croix Horst by Craddock and others (1963), is bounded by high angle reverse faults. The north and northwest flank of the St. Croix Horst is marked by the Douglas-Isle Royale Fault System (fig. 1). The Thiel model was subsequently extended southwestward along the Midcontinent Gravity High trend into Minnesota (Mooney and others, 1970; Morey, 1974), Iowa (Anderson and Black, 1982), and Nebraska (Lidiak, 1972). In Kansas recent studies indicate the Thiel model is being discarded in favor of an asymmetric basin model associated with granitic or interbedded basaltic and clastic units (Yarger, 1983; Somanas, 1984; Serpa and others, 1984).

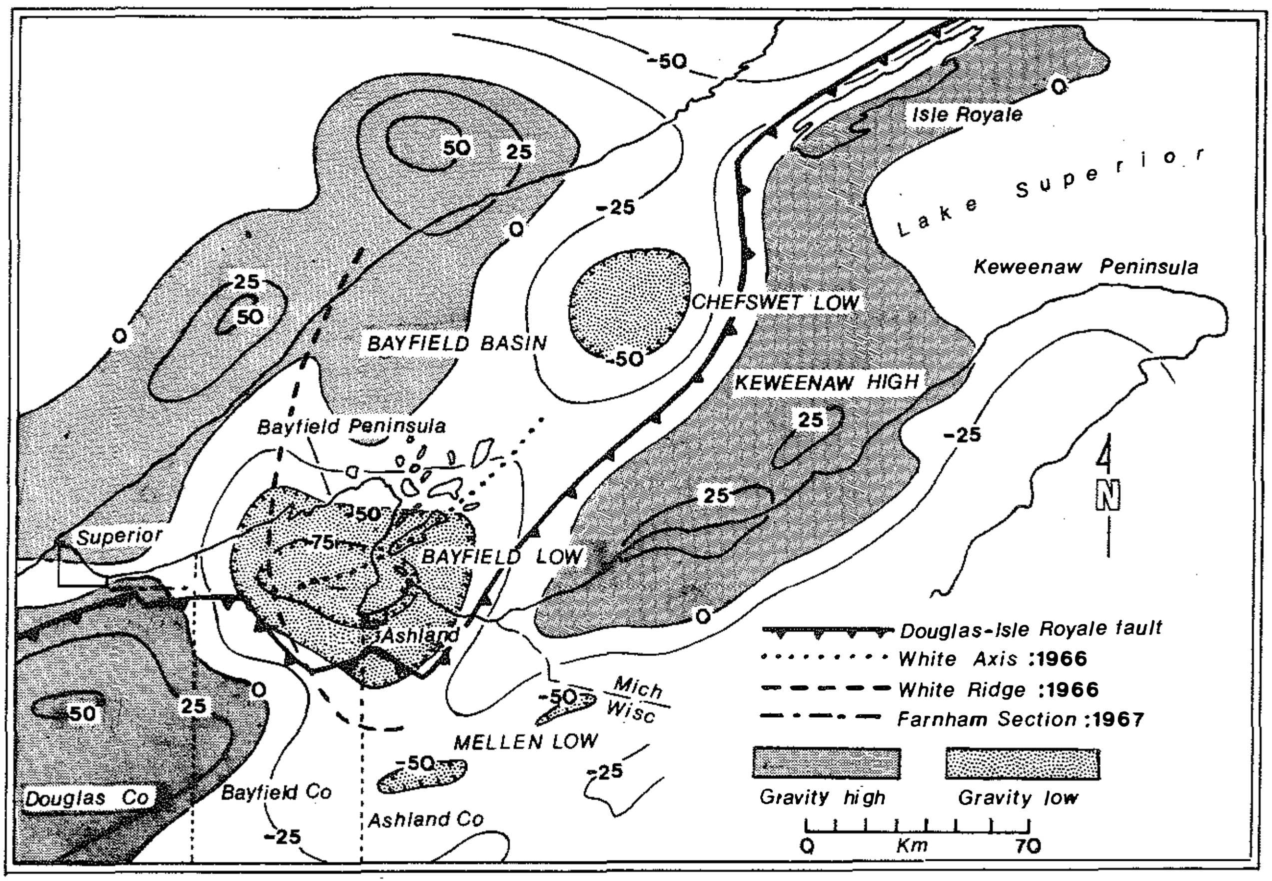

Figure 1. Simplified Bouguer Gravity Anomaly map of the western Lake Superior area. Contour interval 25 mgal.

After general acceptance of the uniqueness and geographic extent of the Midcontinent Gravity High, the tectonic feature was formally named the "central North American rift system" by Ocola and Meyer (1973). In 1982 Wold and Hinze simplified this nomenclature to the "Midcontinent Rift System." This rift system, strictly defined to extend from northeastern Kansas north and northeastward through Nebraska, Iowa, Minnesota, Wisconsin and into the Upper Peninsula of Michigan, is exemplified by its simplicity of gravity expression. The Midcontinent Gravity High maintains its average width of 95 km and is interrupted only twice between Kansas and Wisconsin: at the Kansas-Nebraska border and immediately south of the Minneapolis-St. Paul, Minnesota. Both of these interruptions are along displacements of apparent left-lateral movement. The Kansas-Nebraska border displacement can be seen on aeromagnetic data (King and Zietz, 1971) and is suggested to be a major transcurrent or wrench-fault system (Arvidson and others, 1982). The offset in Minnesota is better documented and attributed to strike-slip movement of approximately 160 km along the Belle Plaine Fault (Sloan and Danes, 1962).

GRAVITY LOW INTERRUPTIONS

In Bayfield County, Wisconsin, the basic continuity of the axis of the Midcontinent Gravity High is abruptly terminated and replaced by a gravity minima of more than 90 mgal. This low, herein termed the Bayfield low, is situated over the Bayfield Peninsula and is centered 18 km northwest of Ashland, Wisconsin. Further to the northeast a second low of 65 mgal, herein named the Chefswet low after the modern Lake Superior topographic basin of that name (Kemp and others, 1978), is located at midpoint between the Bayfield Peninsula and Isle Royale (fig. 1). Discussion in this paper combines the Bayfield low and the Chefswet low as the Western Lake Superior Gravity Low. This regional low is parallel to and lies immediately northwest of the Douglas-Isle Royale Fault and the Keweenaw (gravity) high as mapped by Weber and Goodacre (1966). They considered the Keweenaw Gravity High to "be on offset of the Midcontinent Gravity High." Since discovery of the Western Lake Superior Gravity Low, the geologic cause or causes of either one or both of its components has been discussed by Wold and Ostenso (1966), Coons (1966), White (1966a), Mooney and others (1970), King and Zietz (1971), Wold and others (1982), Hinze and others (1982), Luetgert and Meyer (1982), and Van Schmus and Hinze (1985).

A review of this literature indicates the cause of the Western Lake Superior Gravity Low can be related to one, or some combination of, three contrasting geologic associations: an abnormally thick column of relatively low density, Upper Keweenawan sedimentary rock; change in either thickness or density of the Middle Keweenawan volcanic rock; or pre-Keweenawan deep crustal or upper mantle effects.

UPPER KEWEENAWAN SEDIMENTARY ROCK MODEL

Prior to the mapping of the Chefswet low by Weber and Goodacre (1966), the Bayfield low was described by Thiel (1956) as being associated with a maximum accumulation of "low-density sandstones and shales of the Upper Keweenawan." Thiel (1956), after conducting several shallow refraction seismic shots along a northsouth traverse through the center of the Bayfield gravity low, ruled out attributing any part of the Bayfield low to a thick accumulation of Pleistocene glacial sediments. The results, however, show till thicknesses ranging from 100 m to 175 m, higher than normal for northwestern Wisconsin. Coons (1966) reported thicknesses of 2,450 m to 3,000 m for the sedimentary rock underlying the Bayfield Peninsula. Farnham (1967) combined a series of refraction lines into a 90 km long east-west seismic section situated along the axis of the Bayfield Basin (fig. 1). Although he was unable to designate depth to the Middle Keweenawan basalts, Farnham seismically analyzed sedimentary units down to the Copper Harbor Conglomerate and determined this part of the Keweenawan section to increase from a minimum of 1,850 m near Superior, Wisconsin, to more than 3,050 m over the center of the Bayfield low.

In an attempt to determine depth to basalt basement over the Bayfield low, Mooney and others (1970) suggested that the Middle Keweenawan basalt basement could not occur at depths of "less than 4 km" anywhere in northern Bayfield County. The low gradient of aeromagnetic data as mapped by Wold and Ostenso (1966) supports this seismic interpretation. If correct, the stratigraphic thickness differential reported between the studies of Farnham (1967) and Mooney and others (1970) suggests that the Copper Harbor Conglomerate is at least 1,000 m thick in the vicinity of the Bayfield low, as compared to the 120 m to 250 m exposed in outcrop section approximately 50 km to the southeast of the Bayfield low in Ashland County. Mooney and others (1970) concluded by stating that the thickening of the Keweenawan Supergroup into the Bayfield low area is due entirely to thickening within the Oronto Group, whereas the Bayfield Group, which unconformably overlies the Oronto Group, thins in the direction of Oronto thickening. The unconformable relationship between these groups would explain the lack of conformity of surface strike and dip patterns to the expected morphology of this postulated sedimentary basin.

White (1966a) concluded his tectonic review of the Lake Superior Basin by recognizing an "axis of a sedimentary trough of late Keweenawan time ... along which the section of Upper Keweenawan sedimentary rocks, both Bayfield and Oronto Groups, is assumed to be thickest." The majority of this axis of sedimentation spatially coincides with the Bayfield gravity low (fig. 1). Wold and others (1982) verified this sedimentation trough by seismic-reflection profiling and identified it as a "southwestward-plunging syncline trending under the Bayfield Peninsula."

If the Bayfield low is the geophysical result of an abnormally thick sequence of Upper Keweenawan sedimentary rock, it would appear logical to assume the same cause for the Chefswet low. In this volume, in "Nature of the northern boundary of the St. Croix Horst," I suggest that high gravity gradients on the southeast flank of the Western Lake Superior Gravity Low are evidence for the extension of the Douglas Fault trace into Lake Superior and connecting with the Isle Royale Fault. Thus, both the Bayfield and the Chefswet lows should be considered sites of local deepening within the Bayfield Basin because this basin is positioned immediately to the northwest of the Douglas-Isle Royale Fault System.

MIDDLE KEWEENAWAN VOLCANIC MODEL

The residual gravity field of the Lake Superior area shows a 70 mgal low over the Bayfield Peninsula and an approximate 30 milligal low located over the Chefswet low (Hinze and others, 1982). Hinze and others (1982) suggested that such remaining lows meant that the mafic volcanic rock is "absent or thin" in the area. In an earlier study King and Zietz (1971) had a similiar concept in mind when they stated "if the volcanic rocks are present under the Bayfield gravity low, they must be thin and very deeply buried."

White (1966a) has probably considered the cause of the Bayfield low more than any other researcher. Although he did not possess data pertinent to the Chefswet low at the time of his report, he promoted a dual, rather than a single, cause for the Bayfield low by stating that "the anomaly marks the high-angle intersection of the axis of a thick prism of Upper Keweenawan sedimentary rock with a ridge of pre-Keweenawan rock -- an area in which the middle Keweenawan lavas are thin or absent." The pre-Keweenawan ridge was identified after White (1966a) mapped a thin trend line of Middle Keweenawan basalt running from south of Ashland, Wisconsin, north and northeast through the Bayfield Peninsula and onto the north shore of Lake Superior (fig. 1). White also suggested that where present, Middle Keweenawan lava might contain a higher than normal percentage of lower density rhyolite as compared to higher density basalt, thus further contributing to the gravity minima.

PRE-KEWEENAWAN MODEL

Specifics of deeper structures in the Lake Superior Basin are not well known and involve fundamental questions relating to the extent of crustal separation across the Midcontinent Rift System, the degree to which this rift was initiated as a triple (rrr) junction and increased crustal thicknesses into the Lake Superior Basin. White (1966a) attempted to explain the Bayfield low as partially resulting from density distribution within the pre-Keweenawan rock, especially as these may relate to the northeast trending gravity low found south of Mellen, Wisconsin (fig. 1), but admitted such analysis must remain in the "realm of speculation." Hinze and others (1982), however, further encouraged this idea by pointing out that lows such as the Bayfield low "are of the same order of magnitude as (those) north of the lake (Superior) where pre-Keweenawan crystalline rocks crop out," and therefore consideration must be given to "the possible presence of anomalies arising from pre-Keweenawan rocks underlying the (Lake Superior) basin."

In developing his rift tectonic model Thiel (1956) adjusted the regional Bouguer gravity field of northwestern Wisconsin by eliminating the effect associated with Middle Keweenawan basalt. He found that this exercise still resulted in a negative gravity field over the Bayfield Peninsula and suggested one explanation might "be a contribution from depths deeper than here considered." This concept of crustal deepening, or warping, down to the Moho appears to have been initially applied to the general area of the Midcontinent Gravity High by Lyons (1959) and Farnham (1967), who considered the structure to be a tectogene, a "downwarp or trough" caused by the crust being forced downward by "convection currents in the mantle." This compressional concept was subsequently altered to one of initial extensional movements followed by compressional forces, as the processes of rifting became better understood. Significant to the newer interpretation was the Lake Superior (seismic) Experiment, conducted in 1963 and 1964 (Steinhart and Smith, 1966). In summarizing these studies, Halls (1982) presented a crustal thickness map showing "a region of anomalously thick crust centered on eastern and central Lake Superior, on the axis of the Midcontinent Rift System ... that connects with similarily thick crust ... reported further west along the rift in Wisconsin." The actual increase shown within the Lake Superior basin by Halls (1982) is on the order of 35 percent, with a maximum thickness of approximately 54 km reported for the area off the Keweenaw Peninsula (fig. 1), as compared to a regional thickness of 40 km. Such crustal thickness, also reported by Luetgert and Meyer (1982), would have the effect of producing broad, regional gravity minima that, in turn, would contribute to the intensity of localized negative anomalies such as the Western Lake Superior Gravity Low.

In their review of refraction seismic surveying in Lake Superior, Halls and West (1971) discussed the geologic sources of the 85 mgal low that occupies the area of Keweenaw Bay, southeast of the Western Lake Superior Gravity Low. They suggest that approximately 28 percent of this gravity anomaly results from Upper Keweenawan sedimentary rock with the remainder attributed to Middle and pre-Keweenawan effects with "primary" emphasis on pre-Keweenawan "deep crustal effects." The applications of these percentages and their associated geologic conditions to the underlying causes of the Bayfield and Chefswet lows should result in a Bouguer gravity distribution similiar to that mapped in the subject area of this paper.

CONCLUSIONS

Of the numerous gravity lows associated with the Midcontinent Gravity High, none have attracted as much attention or analysis as has the Western Lake Superior Gravity Low located in northwestern Wisconsin and adjacent offshore waters of Michigan. Interest in the Western Lake Superior Gravity Low has been sustained by its unique spatial association with outcrop of Middle and Upper Keweenawan rocks, generally accepted as the principal cause of the Midcontinent Gravity High, and by its geographic location, whereas other Midcontinent Gravity High minima of residual magnitude in excess of 50 milligals occupy flank positions, the Western Lake Superior Gravity Low lies on trend with the central gravity maxima of the Midcontinent Gravity High.

In spite of numerous geological and geophysical studies within the Lake Superior Basin area over the past three decades, the cause of the Western Lake Superior Gravity Low is still being debated. Enough information has been gathered, however, to suggest the ultimate answer will be associated with some combination of the following causes: (1) an abnormally thick column of relatively low density, Upper Keweenawan sedimentary rocks, (2) alteration in either the thickness or density of Middle Keweenawan volcanic rock, and (3) pre-Keweenawan deep crustal or upper mantle effects.

Until further investigations are conducted, the most significant of which would be the on-land drilling of a deep (4,000 m to 6,000 m) stratigraphic bore-hole within the geographic confines of the Bayfield low, the prioritization of this list of geologic causes must remain speculative.

VI. EXPLORATION AND LEASING

Thomas J. Evans

The general public became aware of the recent interest in petroleum exploration along the Midcontinent trend in northern Wisconsin in the fall of 1983. At that time, oil and gas leases were first recorded in Register of Deeds Offices in Bayfield, Ashland, and Iron Counties. Corporate interest in the petroleum potential of this area extends at least as far back as 1972, but it was the recent leasing activity that drew the public's attention to the possibility of oil and gas reserves in the state. Leasing and seismic evaluation programs have occurred along the Midcontinent trend in Kansas, Iowa, and Minnesota, as well as in Wisconsin, but the focus of this discussion is on the northwestern counties of Wisconsin from Lake Superior southwestward.

SEISMIC EVALUATION

Seismic programs onshore and in the Great Lakes have been an important part of the recent play along the trend. To date, only 1984 data are available for onshore seismic work but 1985 data are due to be released. In 1984 onshore seismic crews accounted for more than 1,500 line-miles of seismic data with 365 line-miles in Wisconsin, just under 1,100 line-miles in Iowa, and the remainder in Minnesota. Much of the data is available for purchase; other proprietary data are known to have been collected for confidential evaluation.

In the summer of 1985, Grant-Norpac, Inc., conducted seismic lines in the Great Lakes. A total of over 1,140 line-miles was acquired on Lake Superior, with 625 line-miles acquired in Lake Michigan using the M/V Mai. Nearly 200 line-miles of data in Wisconsin are about evenly divided between the Lake Superior and Lake Michigan. In addition to the seismic data, gravity and magnetic information has also been collected.

WISCONSIN LEASING ACTIVITY

A review of mineral leasing records for 1983 to 1985 shows nearly 700,000 acres of land have been leased in Wisconsin for purposes of oil and gas exploration and development. Table 1 lists leaseholders by county and acreage held (see also fig. 1). These data were compiled by D. Harkin, University of Wisconsin Extension Department of Agricultural Economics, on the basis of public records available in county register of deeds offices.

The leasing activity was typically carried forward by broker companies acting on behalf of corporate clients. For example, C.E. Beck and Associates handled most of the lease acquisitions for Amoco Production Company. For a short time, there was some local concern and confusion with leasing by brokers because this is not a typical practice for metallic minerals leasing--the only other comparable activity commonly understood by landowners in the region. The leases offered by the brokers or companies are quite uniform in their principal provisions. Generally the leases include no signing bonuses, acreage rental payments of $1 per acre per year, primary lease terms of 10 years, and a one-eighth royalty upon production. The limited variation in lease offerings and the restricted financial terms offered reflect the high risk nature of petroleum exploration in the truly frontier hydrocarbon province known as the Midcontinent trend.

These basic leases were offered to private and public landowners. The major public landowners in northwestern Wisconsin are the counties with their extensive holdings of county forest lands. Although these larger blocks of land

Table 1. Lease holders by county and acerage held for petroleum exploration in Wisconsin, 1983-1985

Leaseholder / County	Amoco	Benchmark Resources	Texaco	Chevron	Hunt Oil	Beard Oil	Conquest Exploration	T.O. Higgins	Totals
Ashland	28,391	6,954	1,196			740			37,281
Barron					3,696				3,696
Bayfield	104,311	9,225	14,553					601	128,690
Burnett		122,450			1,841		6,107		130,398
Douglas	1,397	290,080	7,843				4,448		303,358
Iron	845	1,540							2,385
Pierce		1,062	4,169	22,455			4,706		32,392
Polk		6,913			1,169	2,161	14,601		24,844
Sawyer		5,433							5,433
St. Croix			2,215				18,110		20,325
Washburn		2,218					6,568		8,786
Totals	139,944	445,875	29,566	22,455	6,706	2,901	54,540	601	697,588

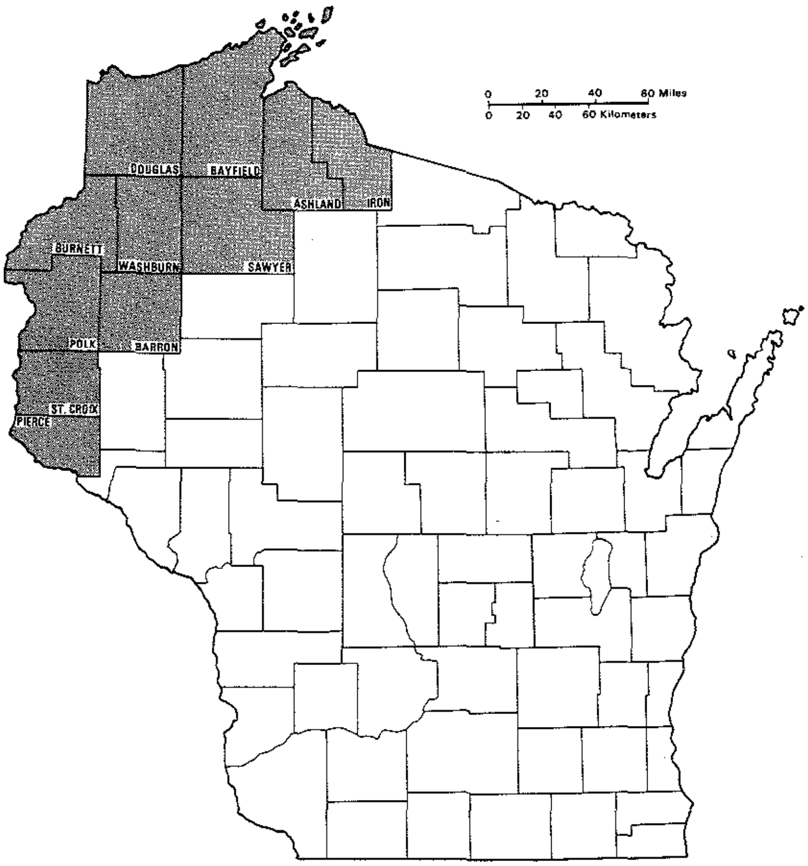

Figure 1. Wisconsin counties in which oil and gas exploration leases have been taken.

would appear to provide the counties with some bargaining advantages, the actual signed leases vary only in minor ways from the standard leases signed by private landholders. Some counties attempted to hold competitive lease offerings, but these competitive sales were hurriedly put together and were ineffective because there was only a single bidder. This lack of competition reflects the different perspectives among companies concerning the acreage having the best hydrocarbon potential and their unwillingness to compete head-on in such unproven terrane. Should the petroleum potential of the Midcontinent trend ever be demonstrated, the competitive character of leasehold acquisitions will be much more evident.

REGULATORY RESPONSE TO PETROLEUM INTEREST

County forest lands, although owned by the counties, are managed jointly by the State of Wisconsin (specifically, the Department of Natural Resources) and the county government's forestry department. Mineral leases on county forest lands must be approved by the Department of Natural Resources (DNR); lease offerings to counties brought the DNR into the petroleum leasing picture, which led to the development by DNR personnel of a model oil and gas lease. The model lease was designed not only to meet the legal requirements of the county forest statutes, but also to guide county governments in identifying those elements of a mineral lease that would be particularly important to the public-land manager. The model lease was developed in partial cooperation with a petroleum company to insure that its basic elements were consistent with common industry practice and understanding.

In early 1984 the DNR also initiated the process leading to the adoption of NR 134, Wisconsin administrative code, regulations for oil and gas exploration. Following metallic mineral regulations, the petroleum regulations are specific to exploration, which is by definition synonymous with drilling. However, unlike the extensive regulations applicable to metallic mineral extraction, the DNR has assumed no authority over petroleum production and has restricted NR 134 to exploration only. NR 134 went into effect in October 1985, following a series of public hearings and legislative review.

Also in the spring of 1984, the Legislature briefly considered 1983 Senate Bill 638, which specifically provided authority to the Department of Natural Resources to promulgate exploration regulations. SB 638 was introduced too late in the legislative session to receive action and the DNR proceeded with development of NR 134 citing their general authority to protect the waters of the state under 144.025, Wis. Stats.

The push by the DNR to promulgate exploration regulations was spurred on by Amoco Production Company's plans to drill Amoco #1 Hazel Hills, a proposed 12,000-foot test for hydrocarbon potential along the flanks of the St. Croix Horst in the Midcontinent Rift System. This test, located about 2 miles south of Ino in Bayfield County, would have been the first action subject to the new regulation, but corporate plans changed and the $3- to 5-million test was postponed.

The issue of state regulatory authority over petroleum production was not addressed in SB 638, and in 1986, Senate Joint Resolution 59 was proposed to address this fundamental issue. SJR 59 called for a legislative council study committee to be created to deal specifically with the broad issues of petroleum development in the state. This one-year study was to be completed by January 1, 1987. SJR 59, however, was referred to the Senate Energy and Environmental Resources committee, where it quietly died.

Early 1986 brought action by the governors of eight Great Lakes states concerning petroleum exploration on state-owned submerged lands in the lakes. Led by Governor Blanchard of Michigan, the governors of Minnesota, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania, and New York issued a Statement of Principle Against Oil Drilling in the Great Lakes asking that plans for petroleum exploration in the Great Lakes be dropped and that their respective state (and federal) governments take action appropriate to enforcing a ban on Great Lakes drilling.

The present lack of petroleum leasing activity and the postponement of plans by Amoco to drill its Bayfield County test (drilling announced on May 7, 1985 and postponed just two weeks later) has led to a general cessation of legislative interest in the major policy ramifications of oil and gas resource development for Wisconsin. To date, beyond NR 134 now in effect, no regulatory or legislative activity affecting oil and gas development is pending.

VII. RESOURCE EVALUATION

PETROLEUM EXPLORATION POTENTIAL OF THE MIDCONTINENT RIFT, U.S.A.

Donald M. Davidson Jr. and M.G. Mudrey, Jr.

The 1.1 Ga Midcontinent Rift System extends more than 2,000 km, from Kansas through Lake Superior into the Lower Peninsula of Michigan. The rift itself is a horst up to 50 km wide consisting of Keweenawan volcanic rock that exhibits pronounced gravity and magnetic signatures within four geographically identifiable segments: Kansas, Nebraska, Iowa, Minnesota-Wisconsin, and Michigan.

Assessment of the potential for petroleum of Proterozoic age in rift-related marginal and overlying axial basins indicates a possible 5 billion barrel TOC (total organic carbon content) resource. However, source volume constraints curtail that estimate to 70 million barrels of oil and 420 billion cubic feet of gas. Proterozoic source rock units identified to date include the Nonesuch Formation and the Solor Church Formation, although the latter unit has been shown to be overly mature locally.

Fault-related structures along the horst vary in structural style within the various rift segments: rotated, half-graben (Kansas); over-thrust (?) and normal (Iowa); and listric (?) high-angle, reverse (Minnesota, Michigan).

Adequate volumes of reservoir rock have been identified in all rift segments. The most promising horsts are fault-related clastics of Proterozoic age or more extensive basal Paleozoic sandstone that locally occurs in marginal basins along and in sheets adjacent to the rift. Migration is assumed to have occurred under normal hydrodynamic conditions (load) with close spatial proximity between source and reservoir units. Permeability problems related to diagenesis are not anticipated.

We postulate that both structural and stratigraphic traps are likely to occur. Because probable fields are small, faults with minor displacements and small amplitude folds are considered prospective. Seals along faulted structures are assumed to be gouge-related and their effectiveness will depend upon the abundance and types of clay within individual faults. Post-rift fault displacements are generally believed insufficient to seriously affect reservoir geometries. Seals created by unconformable structures are most likely lithologic in nature, resulting from differential capillary pore pressures between units. Unconformities involving Proterozoic and possibly Paleozoic units may occur in all rift segments.

Geochemical and vitrinite reflectance studies of available oil and natural gas samples from identified accumulations in the Minnesota part of the rift yield values in the mature to immature range. The degree of preservation will vary with sedimentation, erosion, and structural factors within the specific rift segments.

Production considerations will have to include corporate infrastructure including transportation, available refineries, environmental, and geopolitical questions, as well as the price of oil and gas.

OIL AND GAS POTENTIAL OF KEWEENAWAN MIDCONTINENT RIFT SYSTEM IN NORTHWESTERN WISCONSIN

Richard A. Paull

ABSTRACT

Extensive leasing and seismic exploration along the Keweenawan Midcontinent Rift System from Upper Michigan into Kansas centered in northwestern Wisconsin during 1983 - 1985. Detailed geochemical and geophysical justification for this petroleum play remains confidential, but regional geological knowledge encourages speculation.

Continental rifting with extrusion and intrusion of igneous rocks caused subsidence in northwestern Wisconsin, and 6,100 m of Upper Keweenawan conglomerate, shale, and sandstone accumulated to form the Oronto Group (Copper Harbor Conglomerate, Nonesuch Shale, and Freda Sandstone). The slightly metamorphosed rock is dominantly red beds deposited as alluvial fans grading upward into finer, texturally and mineralogically more mature lacustrine and fluvial deposits. After 50 to 90 km of separation the rift failed and axial uplift created the St. Croix Horst with subsiding flank basins. Up to 1,500 m of sandstone with minor shale (Bayfield Group) accumulated in basins adjacent to the eroding horst.

Shale and siltstone of the Nonesuch contain sufficient organic matter that oil seeps occur within the formation in Upper Michigan. As the only source rock and the most continuous seal, the persistence of the Nonesuch is critical to the petroleum potential of northwestern Wisconsin. A flawed analogy with giant oil and gas fields in Siberia, U.S.S.R., provides additional support. Possible traps include anticlines, reverse faults with upthrown basalt seals, depositional truncation against basement highs, porous lenses, and an angular unconformity.

Keweenawan petroleum potential is heightened by inexpensive leases for large tracts of public land, relatively cheap drilling in a politically stable area, and the potential for discovering gas storage. Wisconsin, however, has high taxes and strong environmental laws, and drilling in Lake Superior would be prohibited even if a lakeside field were discovered.

Exploration activity has waned due to current economics in the petroleum industry, and Amoco cancelled a 1985 wildcat in Bayfield County that would have evaluated the St. Croix Horst. A significant upturn in hydrocarbon prices will be required to rekindle interest in northwestern Wisconsin.

INTRODUCTION

Interest in the petroleum potential of the Keweenawan Midcontinent Rift System in northwestern Wisconsin was initially stimulated by oil seeps from the Upper Keweenawan Nonesuch Formation in the Copper Range Mine, White Pine, Ontonagon County, Michigan (fig. 1). This occurrence was described by Eglinton and others (1964), Barghoorn and others (1965), and Johns and others (1966). Subsequently, the oil was sampled and studied by several major oil companies in the early 1970s. Industry interest in the Keweenawan oil occurrence undoubtedly was stimulated by the 1962 discovery of significant gas and oil reserves within Upper Precambrian rocks in Siberia, U.S.S.R. (Meyerhoff, 1980). More recent hydrocarbon occurrences in Upper Precambrian rock in Australia, China, and Montana helped to sustain the enthusiasm for the potential of the Midcontinent Rift System.

The presence of oil at White Pine established source and generation, and surface studies indicated potential reservoirs and traps were present. This information, coupled with the belief that oil prices would exceed $50/barrel and natural gas would reach at least $8.00/Mcf in the late 1980s, resulted in extensive geophysical activity, intensive leasing, and some recent drilling along the Keweenawan Rift System from upper Michigan to Kansas during the early 1980s (fig. 1).

Leasing for oil and gas exploration in northwestern Wisconsin started in 1983, and more than 690,000 acres were under contract to at least 7 oil companies by 1986. Standard terms per acre were $1.00 bonus and $1.00 rental/year. Royalty interest was 1/8, and the terms of most leases were 3 years. In addition to leasing activity, more than 500 miles of contract and speculative seismic lines were run in Ashland and Bayfield Counties, Wisconsin.

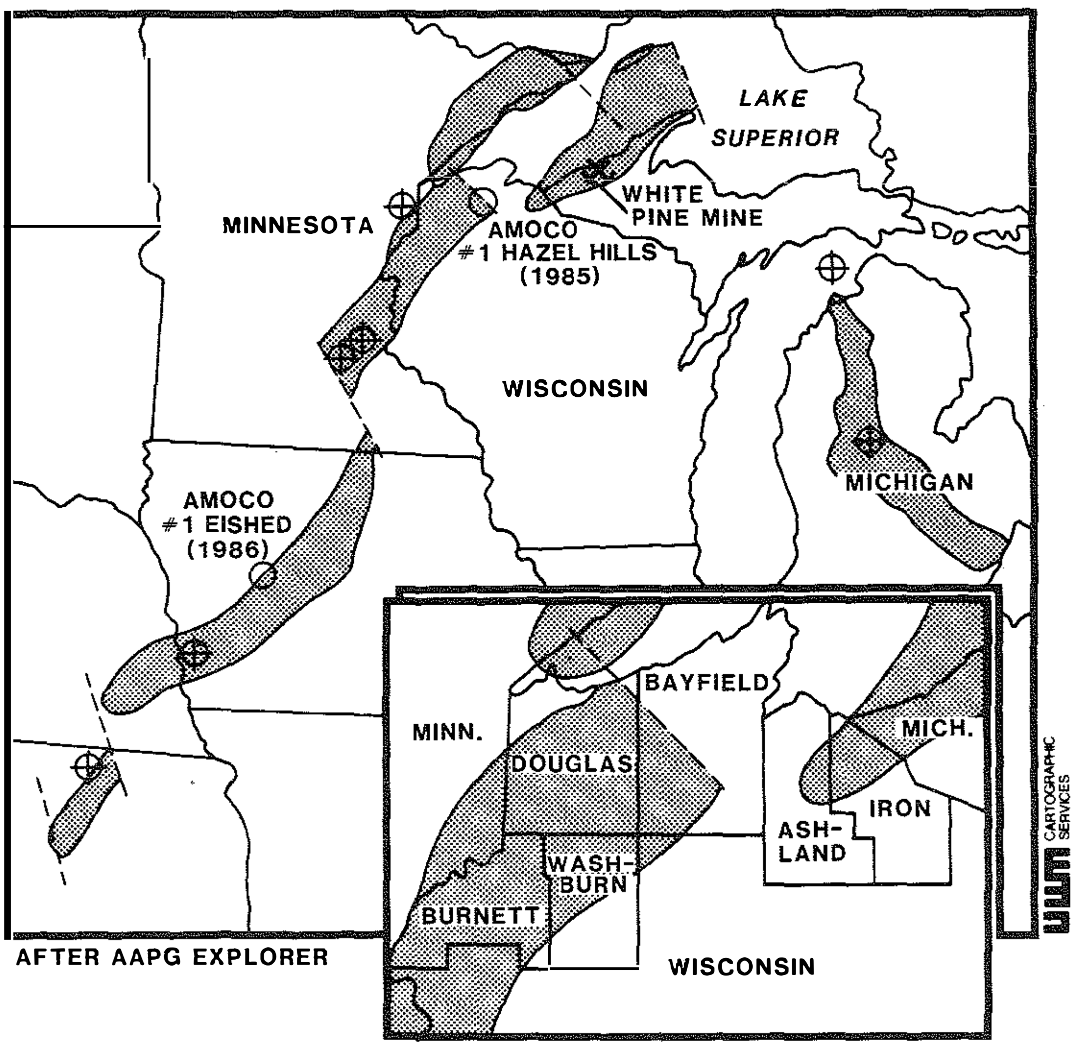

Figure 1. The Keweenawan Midcontinent Rift System is delineated by the stippled pattern. Selected dry holes are shown by crossed circles, and the location of the Copper Range Mine is indicated. Open circles are two suspended test wells announced by Amoco in 1985 (No. 1 Hazel Hills) and 1986 (No. 1 Eished).

GEOLOGIC SETTING

The Keweenawan Midcontinent Rift System is defined in the subsurface by the Midcontinent Gravity High, which cross-cuts older Precambrian structural patterns (Lyons and O'Hara, 1982). This feature may also extend southeastward from Upper Michigan through Lower Michigan, and possibly farther southward (fig. 1). The geologic evolution of the entire Midcontinent Rift System was systematically reviewed by Dickas (1986).

Surface exposures of the Keweenawan Rift System are limited to Upper Michigan and northwestern Wisconsin, where the veneer of Paleozoic rocks was removed by erosion. A brief summary of the geologic history of this region follows.

Continental rifting of 50 to 90 km due to crustal attenuation associated with extensive extrusion and intrusion of Lower and Middle Keweenawan rocks formed a subsiding sedimentary basin about 1.1 Ga (table 1). This basin was filled in by up to 6,100 m of the Oronto Group (basal Copper Harbor Conglomerate with associated volcanic, medial Nonesuch Shale, and uppermost Freda

Table 1. Comparison of Siberian and Midcontinent petroleum basins.

E. SIBERIA, U.S.S.R. PROTEROZOIC ANALOGY

	SIBERIA	WISCONSIN
TECTONICS:	Craton-Platform Deposits Little Deformation C Evaporite Seals	Craton-Failed Rift Uplift and Erosion No Paleozoics Remain
SOURCE:	Max. Burial 600m Generation Established Marine Sh. Interbeds Proterozoic <925 Ma Gas, Condensate, Oil	Max. Burial 600m? Generation Established Lacustrine Sh. Unit Proterozoic <1040 Ma Gas?, Condensate?, Oil??
RESERVOIR:	Marine Ss. Intergranular - Low	Fluvial Ss. Intergranular - Low
TRAP:	Interbedded Sh. Seals Pinchout on Highs Lenses Major Folds 2000+m Depth	Nonesuch & Freda Ss. w/Sh Pinchout on Highs? Lenses? Anticlines Reverse Faults 2000+m Depth
POTENTIAL:	Huge Area 200 Tcf Gas 100 Bill. Bbls. Oil	Small Area Potential Unknown

Note: Siberian information is from Meyerhoff (1980).

Sandstone) (fig. 2). This group is dominated by a fining upward, texturally and mineralogically immature sequence of red beds deposited as alluvial fans and fluvial sediments. The exception is the Nonesuch Formation, which is an anoxic lacustrine deposit.

The rift failed after deposition of the Oronto Group, and compression resulted in the uplift of a central horst block (St. Croix Horst) flanked by sub-

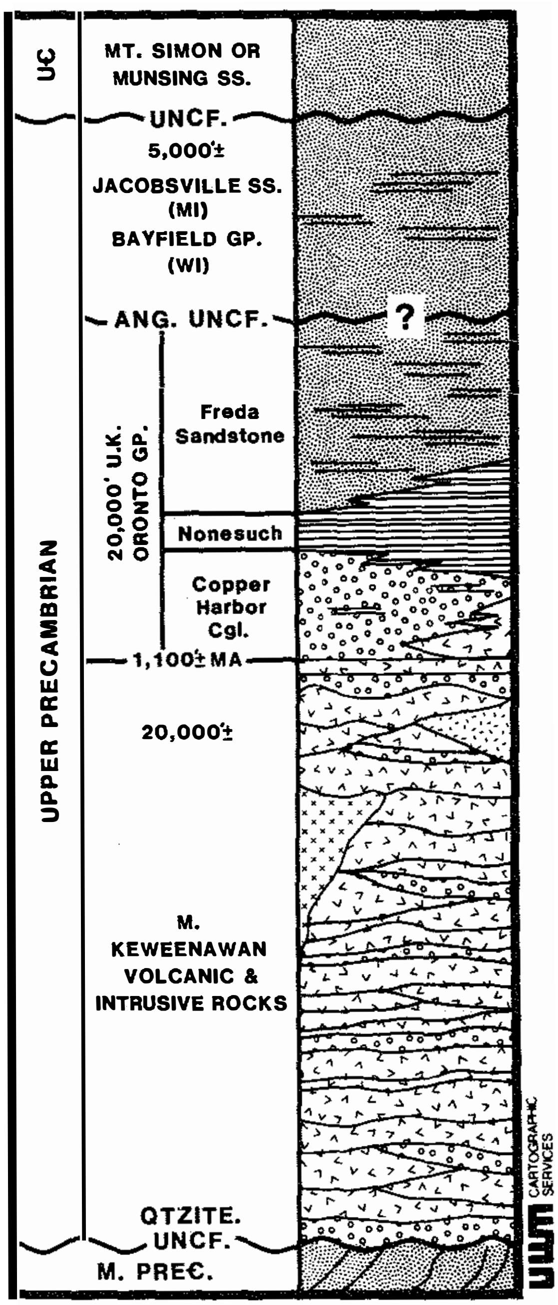

Figure 2. Summary of upper Precambrian (Keweenawan) stratigraphy in Upper Michigan and northwestern Wisconsin.

siding basins (fig. 3). Up to 1,500 m of uppermost Precambrian Bayfield Sandstone accumulated in angular discordance on the Freda Sandstone in the flank basins (fig. 2). The Bayfield is a texturally and mineralogically upward-maturing succession of nonmarine sandstone that was derived, at least in part, from erosion of the Oronto Group on the St. Croix Horst.

An erosional interval in northwestern Wisconsin preceded Paleozoic deposition during the Late Cambrian, Ordovician, and Silurian. It is also possible that Devonian and Upper Cretaceous rocks were deposited in this area. In all, some 650 m of post-Precambrian sedimentary rocks were deposited and subsequently removed prior to deposition of Pleistocene glacial deposits, which mantle much of the countryside and obscure bedrock relations.

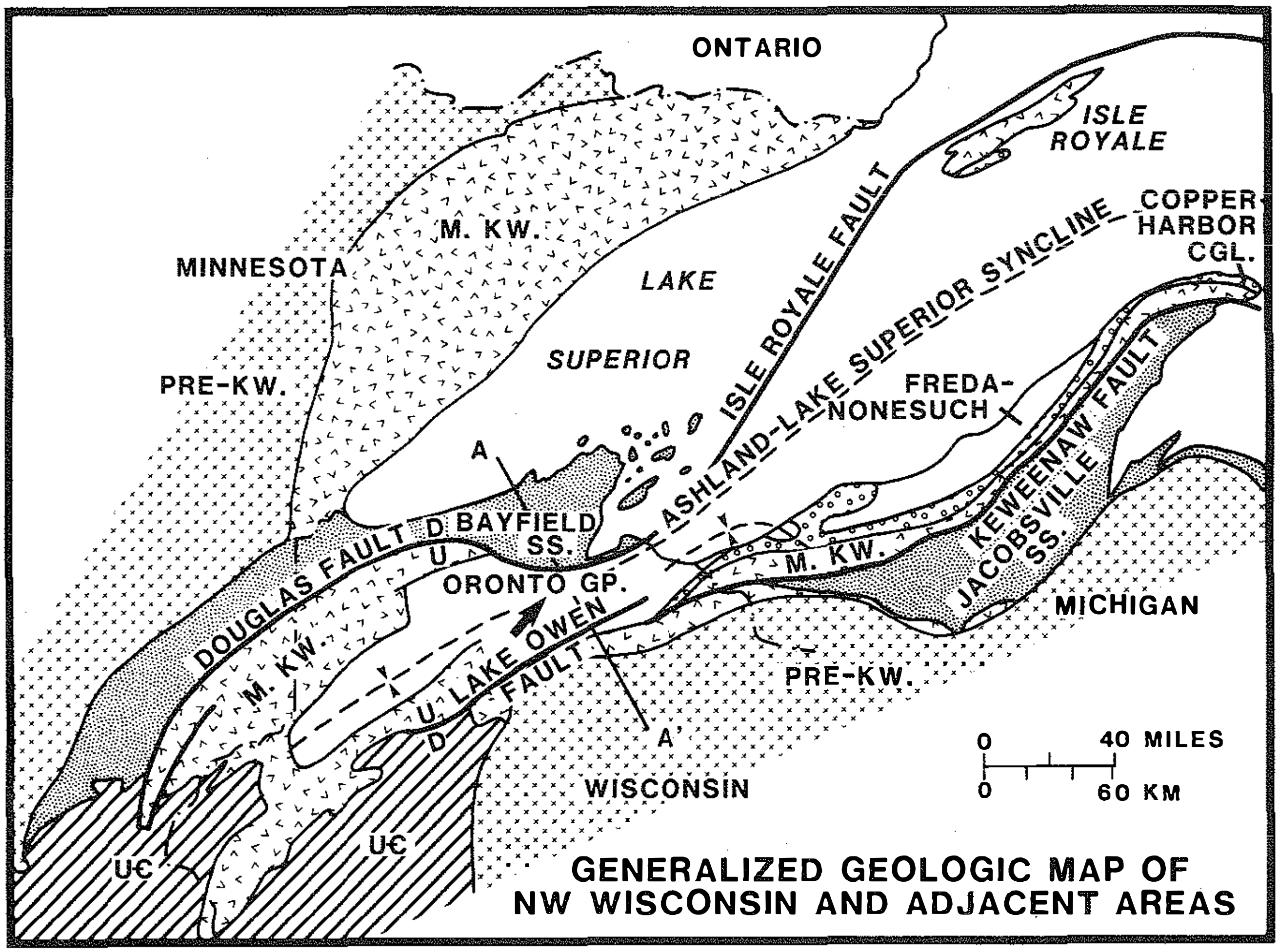

Figure 3. Generalized geologic map of northwestern Wisconsin and adjacent areas. The St. Croix Horst is defined by the Douglas and Lake Owen Faults. The location of the suspended Amoco test well in the Ashland-Lake Superior Syncline is indicated by the arrow near the center of the map. The abbreviation KW is used for Keweenawan, and the throw of major faults is indicated by U (up) and D (down).

PETROLEUM POTENTIAL

The petroleum potential of a frontier area like the Midcontinent Rift System is dependent upon the fortuitous association in time and space of source, reservoir, and trap. Each of those aspects is considered below.

Source

As previously described, the shale of the Nonesuch Formation is the only potential source rock in the dominantly red bed sequence of Upper Precambrian rock in northwestern Wisconsin (figs. 4 and 5). The organic content of samples associated with oil seepage at White Pine is about 0.5 perent C (Dickas, 1986, p. 232). The origin of the oil is attributed to fungi, algae-like "sporomorphs", and bacteria deposited in a lacustrine environment (Moore and others, 1969).

Rock in Minnesota (Solar Church Formation) correlative with the Nonesuch Formation is lower in organic content, and well past the stability stage for oil (Hatch and Morey, 1985). The paleogeothermal history of Upper Keweenawan rock in northwestern Wisconsin is unknown, but the presence of low-grade metamorphic minerals suggests the possibility of high heat flow. Maximum burial of about 6,000 m in the basins flanking the St. Croix Horst seems feasible. If we assume that this depth estimate is correct and the geothermal gradient was "normal" (1° F/50 ft), an extrapolation back 1.1 Ga would suggest that no hydrocarbons remain in the deeper part of the flanking basins. Although temperature was less severe on the St. Croix Horst and oil is stable at White Pine, I would expect only methane gas in this block in northwest Wisconsin.

The Nonesuch Formation is up to 200 m thick in Michigan, and it thins southwestward. It may, however, thicken basinward (northwestward) (Daniels, 1982). The thickness, eastward extent, and organic character of this formation in the subsurface of Bayfield and Douglas Counties, Wisconsin is the most important consideration in assessing the petroleum potential of northwestern Wisconsin.

Reservoir

Potential reservoir rocks within the Upper Keweenawan sequence are conglomerate and sandstone. As previously described, textural and mineralogical maturity increase upward, and these changes result in improved reservoir characteristics in younger rock. Unfortunately, the best reservoirs are farther from the Nonesuch Formation.

Carbonate cement, which is ubiquitous within Upper Keweenawan clastic rock, severely limits the porosity and permeability of many potential reservoir rocks. In spite of this general concern, surface samples indicate porosities up to 15 percent are locally present in all units except the Nonesuch. Some of this porosity may result from the leaching of carbonate cement at outcrops.

Traps

Both stratigraphic and structural traps can be expected in the Midcontinent Rift System within northwestern Wisconsin. Stratigraphic traps include lenticular sand and conglomerate bodies deposited as bars, beaches, alluvial fans, and turbidites in the subsiding Lake Superior Basin during deposition of the lacustrine Nonesuch Formation (fig. 4).

Although small stratigraphic plays are not a primary objective in frontier exploration, petroleum accumulations in such traps are favored in areas of high heat flow. Furthermore, these types of traps are important producers in the Precambrian of eastern Siberia.

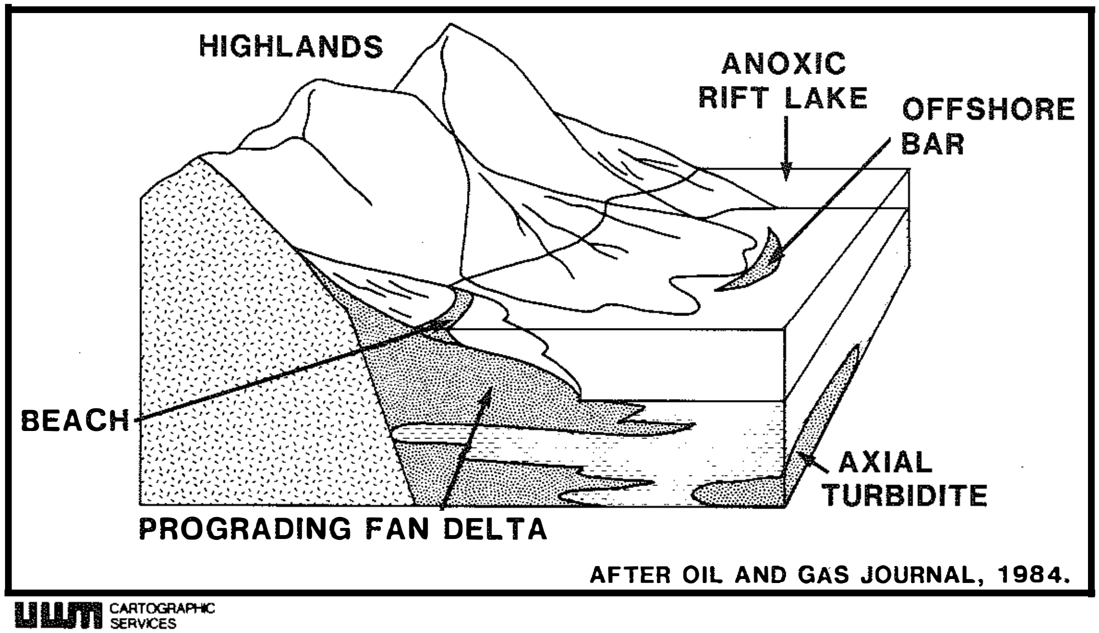

Figure 4. Hypothetical depositional setting for potential reservoir rock associated with accumulation of the Nonesuch Formation in an anoxic rift lake.

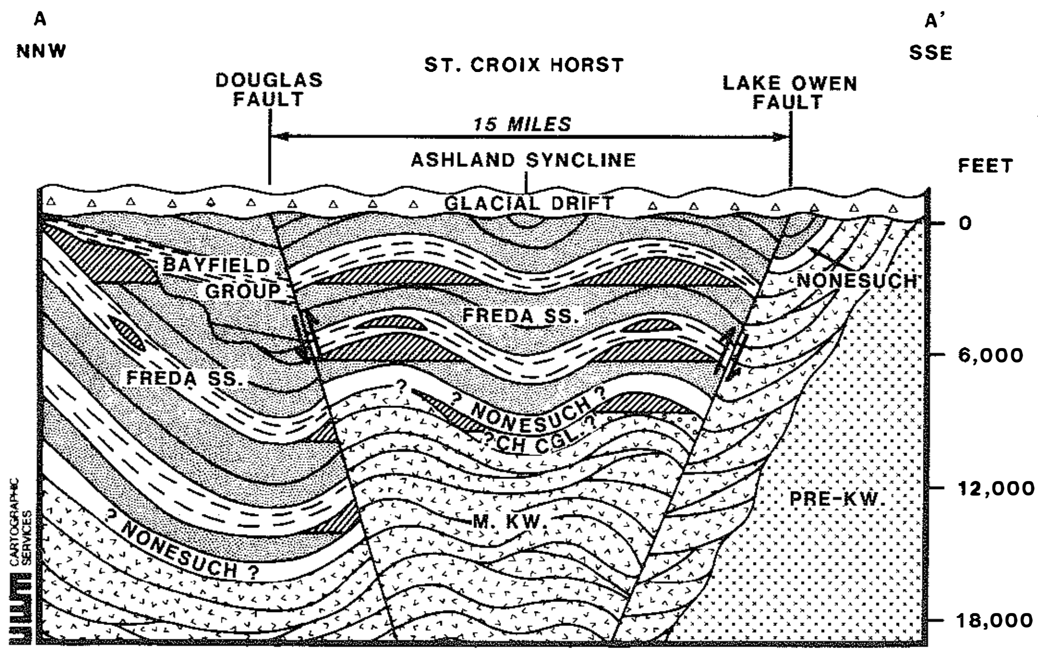

Figure 5. Hypothetical cross section A-A' (fig. 3) across the St. Croix Horst illustrating a veriety of entrapment possibilities within Upper Keweenawan rock in northwestern Wisconsin. Possible oil and gas accumulations are indicated by steep diagonal lines, and include depostional pinchouts against basement highs, lenticular sand bodies, anticlines, an angular unconformity, and the placement of impervious lavas against porous sediment along the Douglas Fault. The approximate position of the suspended Amoco location is near the probable axis of the Ashland-Lake Superior Syncline.

Other possibilities for stratigraphic entrapment include sedimentary pinch-outs of the Copper Harbor Conglomerate against impervious highs on the Middle Keweenawan volcanic basement, and along the angular unconformity between the Freda Formation and the overlying Bayfield Group (fig. 5). In both instances seals of impervious shale are required.

Structural traps include anticlines formed during the compressional episode that created the St. Croix Horst (fig. 5) The reverse Douglas Fault brings impervious Middle Keweenawan lavas over porous Upper Keweenawan sedimentary rock to provide another potential structural trap (fig. 5). The existence of both types of structures is supported by surface observations.

The structures described above formed during development of the St. Croix Horst. If the geothermal gradient was high, hydrocarbon migration may have occurred prior to the formation of these traps. If so, the petroleum potential of the area is minimal. A similar concern for the Minnesota segment of the Midcontinent Rift System was described by Hatch and Morey (1985).

One of the primary concerns with most of the entrapment possibilities described above involves the general paucity of shale to form effective seals. The Nonesuch is the thickest and most extensive impervious horizon within the Upper Keweenawan succession. Interbedded shales make up 60 percent of the Oronto Group, but less than 1 percent of the Bayfield Group (Dickas, 1986). The vertical distribution, sealing effectiveness, and lateral persistance of shale interbeds in both units is a critical unknown.

SIBERIAN ANALOGY

The early publicity on the Keweenawan Midcontinent Rift System by trade journals, industry newsletters, and local newspapers repeatedly referenced the significant occurrences of gas and oil in upper Precambrian rock in eastern Siberia, U.S.S.R. (Lee and Kerr, 1983; Dickas, 1984). Analysis of this comparison discloses significant differences in the geologic history of the two areas (table 1).

The most important flaws with the Siberian analogy include major differences in the general tectonic setting and depositional environment. The hydrocarbon-rich, Precambrian rocks in Siberia are marine cratonic sedimentary rock, whereas those of the U.S. midcontinent Keweenawan are nonmarine sedimentary rock that accumulated within a failed rift. Another significant difference involves the high percentage of interbedded shale within the Precambrian sequence and the evaporites within the Cambrian in Siberia. These provide a series of very effective seals, which are probably lacking in the Keweenawan of northwestern Wisconsin. Finally, there is a major size discrepancy involved in the comparison between the productive Precambrian area in eastern Siberia and the entire Midcontinent Rift System (fig. 6).

RECENT DEVELOPMENTS

In 1985 Amoco announced and subsequently suspended a 12,000-foot test well about 15 miles southwest of Ashland, Wisconsin, in Bayfield County (figs. 1, 3, and 5). Another rift test was announced by Amoco late in 1985 for Carroll County, Iowa. As oil and gas prices plunged in early 1986, this well was also suspended.

During the summer of 1985, Grant-Norpac, Inc., conducted an extensive speculative seismic survey on several of the Great Lakes, including Lake Superior. This action infuriated the governors of the eight Great Lakes states, and re-

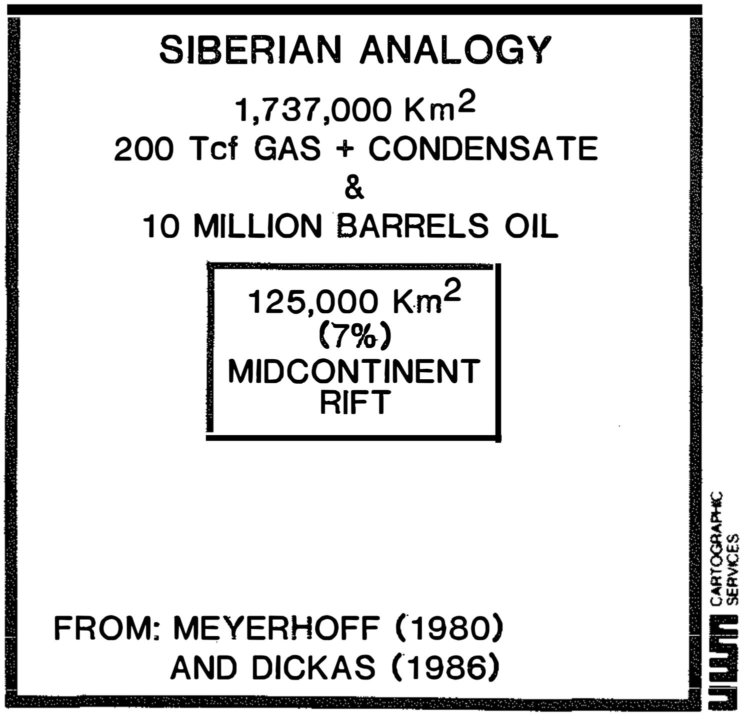

Figure 6. Diagrammatic areal comparison of the productive Precambrian region in eastern Siberia with the Midcontinent Rift System from Kansas through Lower Michigan. As shown, the Rift is only 7 percent of the Siberian area.

sulted in a proclamation in February 1986, opposing petroleum exploration and drilling in the lakes.

A significant indication of continuing industry interest in the petroleum potential of northwestern Wisconsin will be forthcoming in the fall of 1986 when many early leases are due to expire. The ultimate test, however, will require a wildcat.

CONCLUSIONS

The petroleum potential of the Midcontinent Rift System in northwestern Wisconsin is marginal. Although significant production from Proterozoic rock in eastern Siberia establishes the hydrocarbon potential of older rock, failed rifts are high risk prospects throughout the world (Kingston and others, 1983). In the rare cases when failed rifts are productive, the favored setting is central horst blocks (Kingston and others, 1983).

Volumetrically modest amounts of source rock with relatively low carbon content (Nonesuch Formation) and of uncertain lateral extent are also bothersome. The probable lack of sufficient shales to serve as trap seals is another concern.

On the positive side, the Wisconsin part of the Midcontinent Rift System is a frontier area with large, inexpensive tracts of public acreage available. This situation allows major companies the opportunity to control large acreage blocks so they may employ technology (seismic and organic geochemistry) to minimize risk. Drilling will be comparatively shallow, and relatively low cost.

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Robert Seasor and Timothy Rohrbacher made it possible for me to examine the Nonesuch oil seepages in the Copper Range Mine, White Pine, Michigan, in 1972. Rachel K. Paull contributed on numerous field excursions to examine Keweenawan rock in Upper Michigan and Wisconsin during the past 15 years. Recent conversation with Albert B. Dickas and M.G. Mudrey, Jr. helped to refine my understanding of the petroleum potential of northwestern Wisconsin. In spite of all this help, I accept responsibility for any speculation that proves erroneous when the first well tests my theories.

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