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.

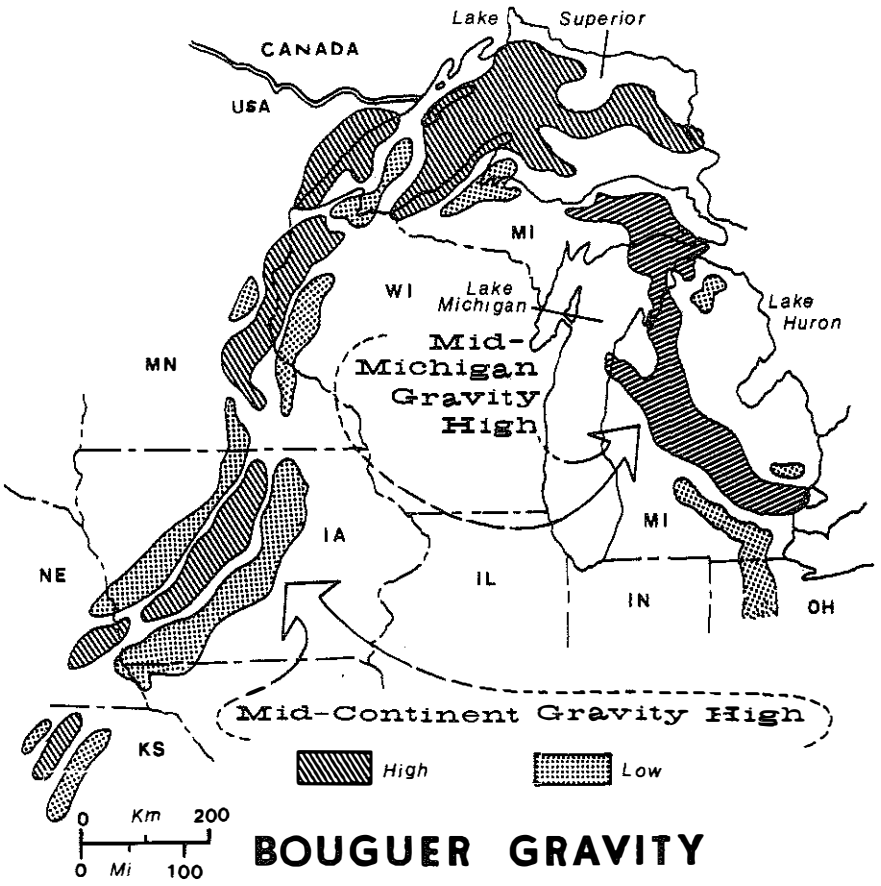

Figure 1. Location of the Midcontinent Gravity High.

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

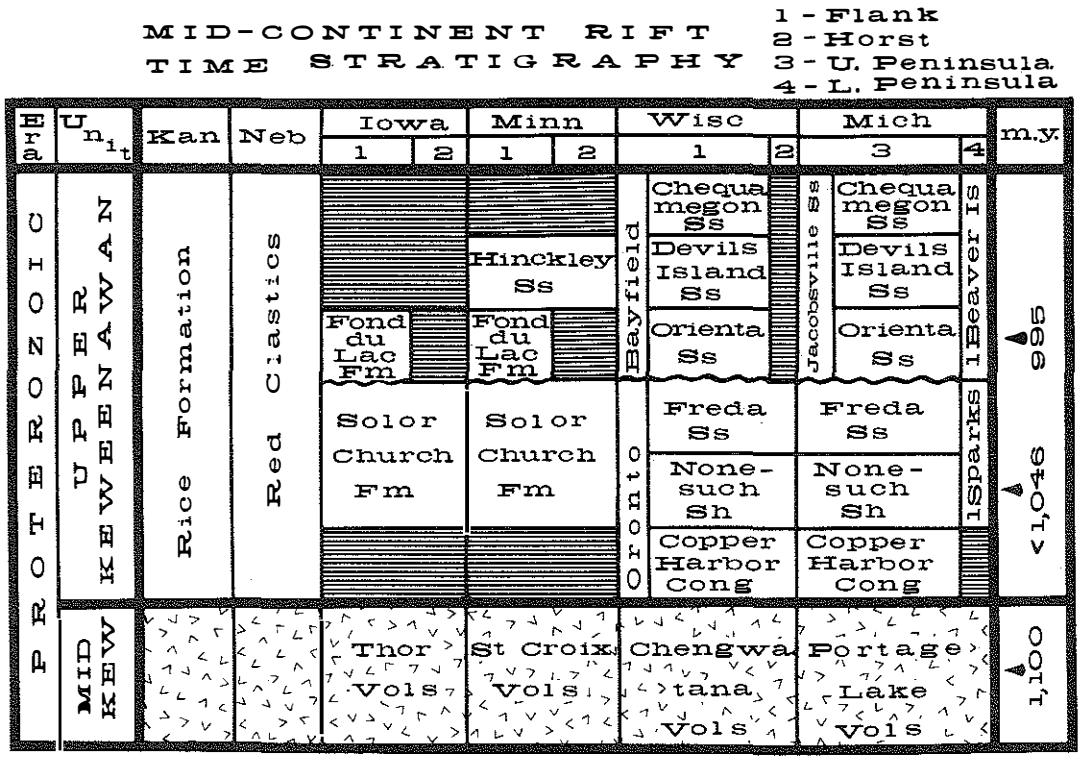

Figure 2. Stratigraphic terminology and time relationship along the Midcontinent Rift System trend.

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.

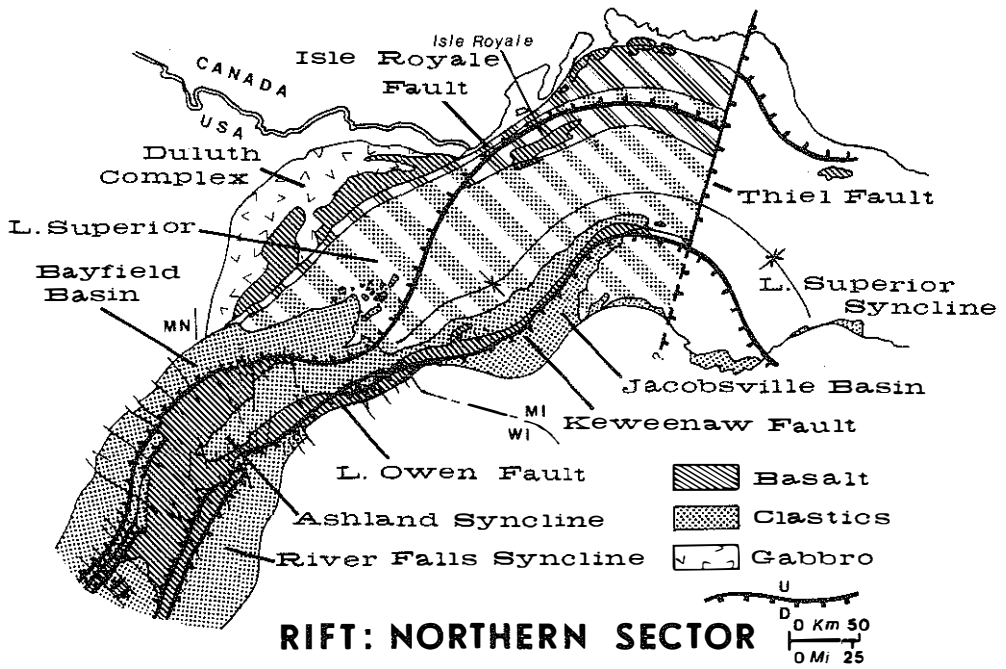

Figure 3. Midcontinent Rift System trend and geology from southeastern Minnesota into the Upper Peninsula of Michigan. Projection of Keweenawan geology under Lake Superior shown in hatched patterns.

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_o) 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.

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