Geoscience Wisconsin
Volume 11, September 1986

SEISMOLOGIC ANALYSIS OF ARRESTED STAGE DEVELOPMENT OF THE MIDCONTINENT RIFT

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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.

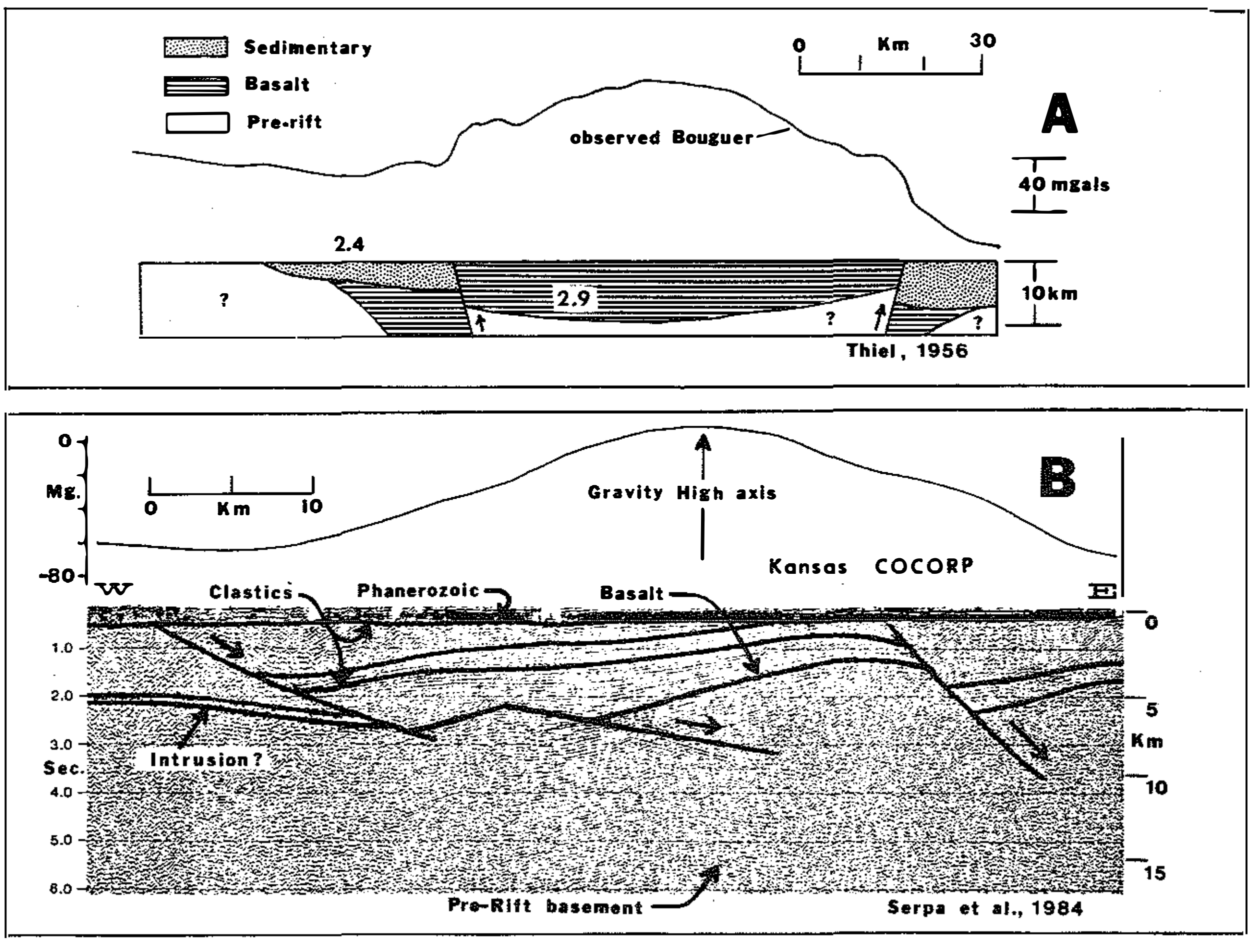

Figure 1. A. Profile of gravity model of Midcontinent Rift System as devised by Thiel (1956). B. Seismic section interpretation across the Midcontinent Rift in northeastern Kansas, after Serpa and others (1984).

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."

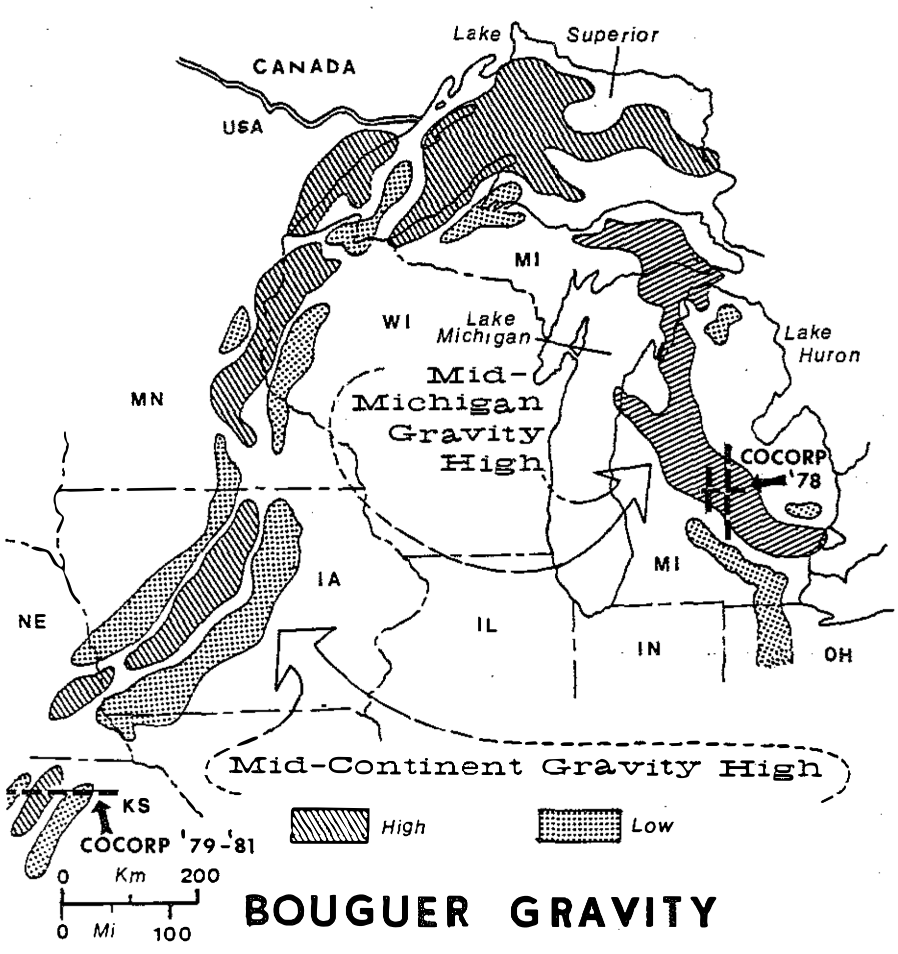

Figure 2. Location of COCORP seismic lines in Michigan and Kansas.

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-

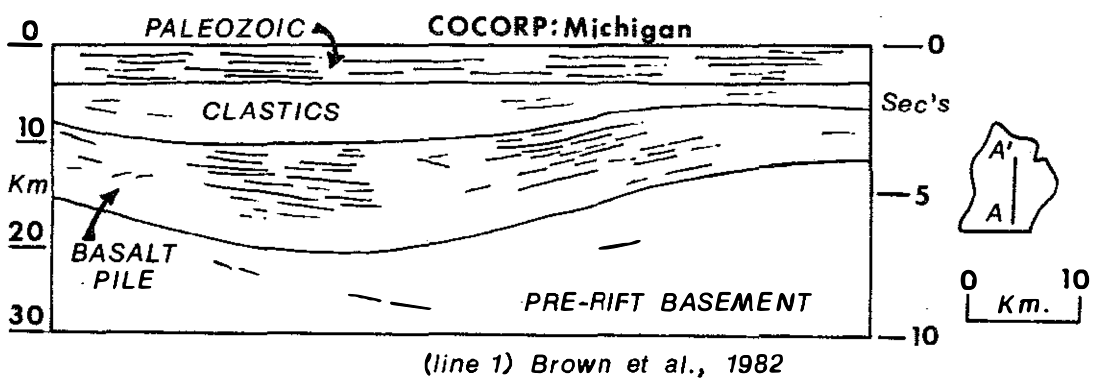

Figure 3. Seismic section line interpretation across Midcontinent Rift System in southern Michigan, after Brown and others (1982).

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.

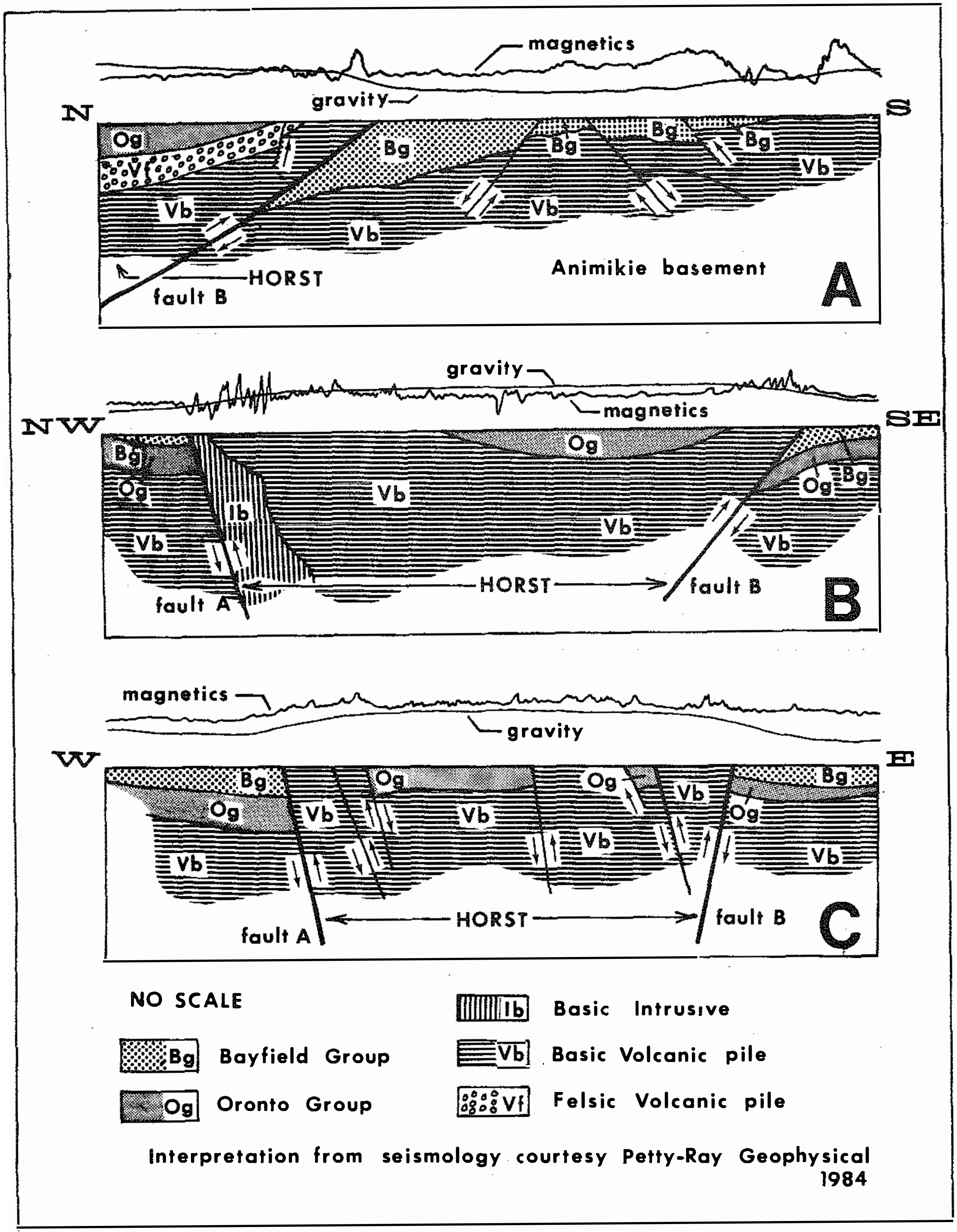

Figure 4. Schematic geologic interpretation of seismic profiles across northern axial part of the Midcontinent Rift System.

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

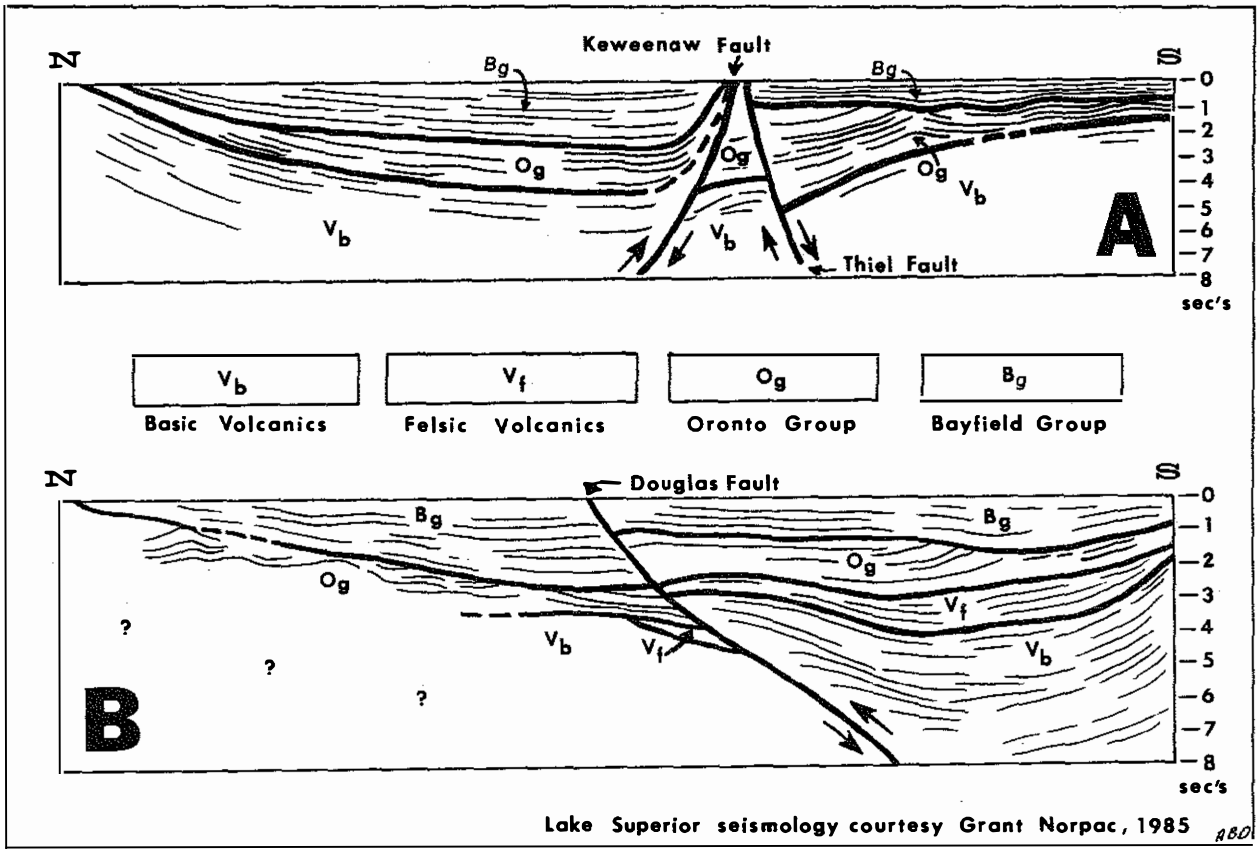

Figure 5. Schematic geologic intepretation of seismic profiles across axis of Midcontinent Rift System, offshore Lake Superior.

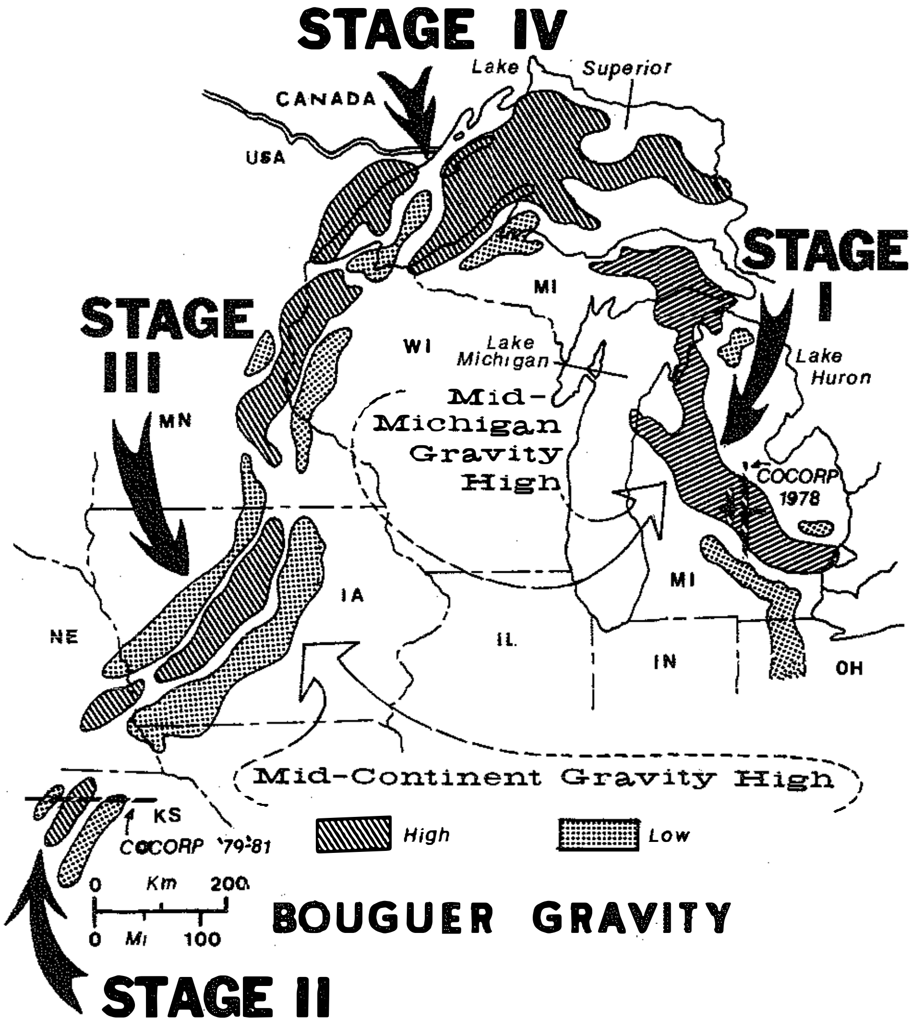

Figure 6. Location of various stages of arrested tectonic development of the Midcontinent Rift System.

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.

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