The North American Midcontinent and the Genesis Flood

Part II: Rifting and the Flood

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Abstract

If rifting in the North American Midcontinent reflects early Flood processes, then defining the thickness and distribution of the total diluvial record requires mapping the base of these rifts. Using publicly available data, we created a 3D map of the base of the largest, the Midcontinent Rift. Combined with similar maps of the East Continent Basin, the Reelfoot Rift-Rough Creek Graben, and Rome Trough, we propose a basal diluvial boundary for the upper Midcontinent Region. The scale of the rifting is seen in the volume of fill; rift fill comprises well more than half of the total diluvial volume. Despite significant erosion, the rifts remain as stunning reminders of crustal disruption at the onset of the Flood, revealing significant geological activity—structural, erosional, volcanic, intrusive, and depositional—before the transgressive marine front of the Flood. Using these maps, quantitative estimates of all of the Flood and Ice Age rock records can be estimated, providing a solid basis for forensic interpretation.

Key Words: Early Flood, East Continent Basin, Midcontinent Rift, Precambrian, Reelfoot Rift, rifting, Rome Trough, Rough Creek Graben, sedimentary basin, Sudbury impact, volcanism

Introduction

The North American Midcontinent Region (Figure 1) is geologically well known but remains to be interpreted in terms of the Flood. Understanding that diluvial perspective requires good data; among the most basic are the thickness and distribution of key sedimentary volumes (Figure 2). We provide these for (1) Ice Age and recent sediments, (2) marine diluvial sediments, and (3) rift fill. These logically require four gridded surfaces: (1) DEM (Digital Elevation Model), (2) subglacial bedrock, (3) the base of marine post-rift diluvial sediments, and (4) the base of the region's rifts.

Reed et al. (2024) presented the results of mapping the first three boundaries and first two volumes, showing the volume and distribution of Ice Age and diluvial marine sediments by state (Figure 3) and by sedimentary basin (Reed et al., 2024). Large sedimentary basins are found over a broad cratonic region—the Michigan, Illinois, and

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Williston Basins—as well as parts of the Appalachian, Anadarko, and Denver Basins. Small basins, such as the Salina and Forest City Basins are also present. The Williston, Michigan, and Illinois Basins range in depth to over 13,000 ft. (3,962 m), 16,000 ft. (4,877 m), and 14,000 ft. (4,267 m) deep, respectively.

In addition to the basins, the study area exhibits five major rifts. In the south, the Reelfoot Rift, Rough Creek Graben, and Rome Trough have been mapped and described (Drahovzal et al., 1992; Dart, 1995; Drahovzal and Noger, 1995; Csontos et al., 2008; Dart and Swolfs, 2008; Hickman, 2011, 2013). They are much deeper than the basins; the Rough Creek Graben reaches more than 38,000 ft. (11,582 m) below sea level. These rifts contain few volcanics and most of their fill is marine sedimentary rock.

The other two rifts are larger, less-defined, and contain significant volcanic and non-marine sedimentary fills. The largest by far is the North American Midcontinent Rift. Its size reveals the magnitude of crustal disruption at the beginning of the Flood (Reed, 2000; Clarey, 2020). Though many studies continue to be published and significant data accumulated (i.e., Miller and Nicholson, 2013; Stein et al., 2015; Woelke and Hinze, 2015; Stein et al., 2016; Fairchild et al., 2017; Stein et al., 2018; Grauch et al., 2020; Hinze and Chandler, 2020), maps of the Midcontinent Rift are limited to its surface or bedrock (sub-glacial) two-dimensional extent, showing the distribution of volcanics and sediments at the erosional unconformity that forms its top.

In the Lake Superior Basin, thick sediments of the rift overlie thicker basalt flows and intrusive rocks. In its western arm, running from Minnesota and Wisconsin through Iowa and Nebraska and into Kansas, a central volcanic horst is flanked by sedimentary basins. Horst-top and flanking basins have been characterized (e.g., Anderson, 1990; Jirsa et al., 2012; Woelke and Hinze, 2015). The configuration of the eastern arm, running the length of Michigan, is poorly described; whether or not it shows the same flanking basins as the western arm is unknown.

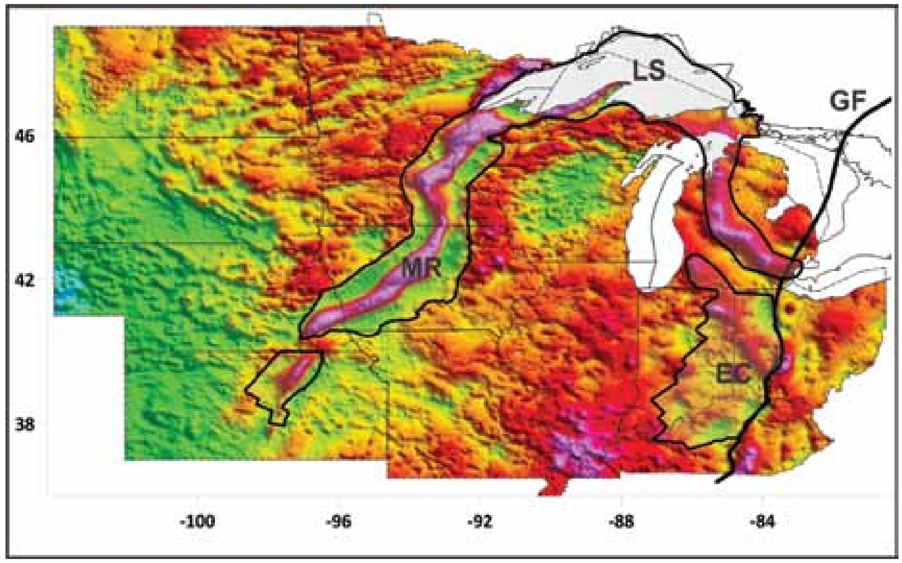

Figure 1. The study area of this paper is shown on the Bouguer Gravity Anomaly map (Kucks, 1999), including the Midcontinent Rift (MR), East Continent Basin (EC), and Grenville Front (GF). The largest, deepest part of the Midcontinent Rift is in the Lake Superior Basin (LS). Pink, purple, and red are positive gravity anomalies, while green colors are negative gravity anomalies. Notice in the MR that high gravity anomalies, representing horsts of uplifted denser rocks, are found in the center. They are surrounded by low gravity anomalies, representing sedimentary basins along the edge.

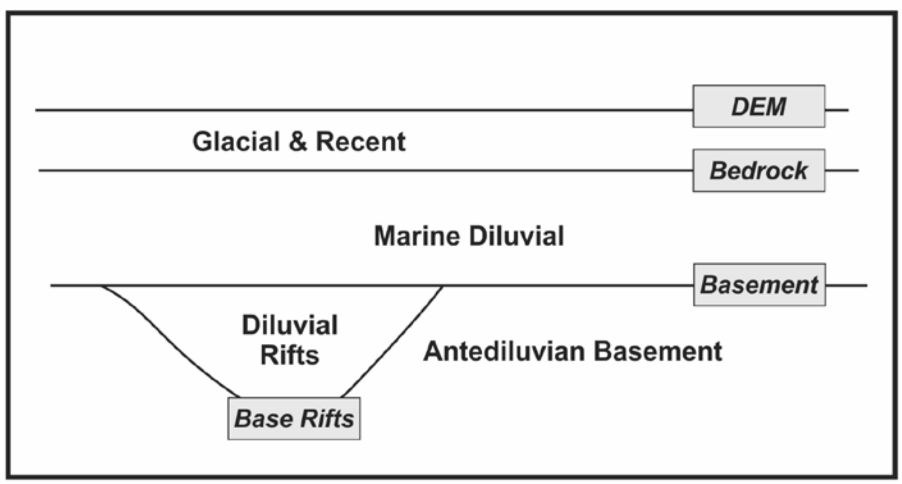

Figure 2. Determining volumes and their distribution requires mapping of four major surfaces. The first three were presented in Reed et al. (2024).

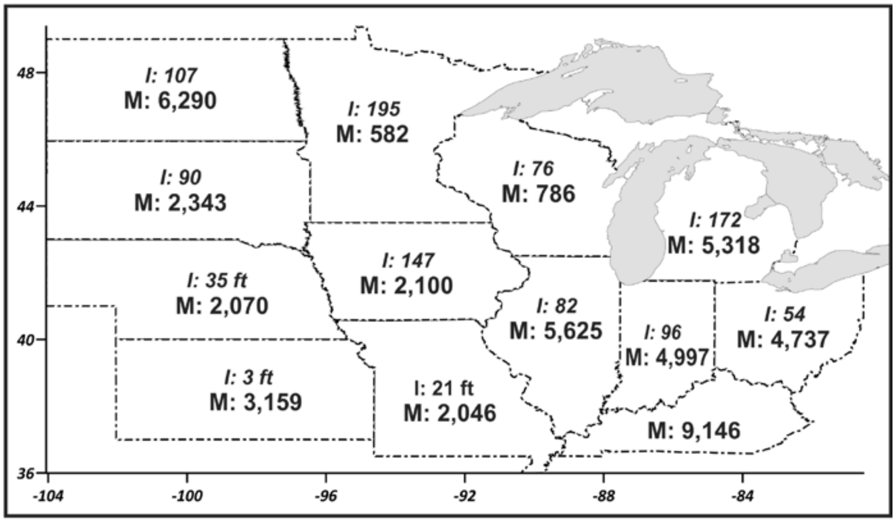

Figure 3. Average thicknesses in feet, by state, of Ice Age (I) and marine diluvial (M) sediments for the study area.

The East Continent Basin has been described (Drahovzal et al., 1992; Baranowski et al., 2009), although there is significant uncertainty about its depth and debate about its extent. Like the Midcontinent Rift, it contains Proterozoic basalt and terrestrial sediment of the Middle Run Formation. It extends across western Ohio into Indiana and Kentucky, where it either intersects or terminates at the Rough Creek Graben. Combined with the existing maps of the southern rifts, we propose that three-dimensional maps of the northern rifts, combined with the map of the unconformity underlying mostly marine sediments would show the actual basal diluvial boundary for the study area. Mapping the basal diluvial boundary allows calculation of the volume and distribution of Flood rocks, including both marine and non-marine portions.

Mapping the Midcontinent Rift and East Continent Basin

Mapping the rifts is difficult. They are covered by thousands of feet of sediment. There are few wells because there has been little economic incentive to drill. So they are known primarily from seismic data and maps of gravity (Kucks, 1999) and magnetic (Bankey et al., 2002) anomalies. Well penetrations help define their two-dimensional extents, as do outcrops around Lake Superior. Oil and gas prospecting in the southern rifts (Reelfoot, Rough Creek, Rome), combined with their shallower depths, has resulted in more wells and seismic lines, and a better definition of their 3D morphology (e.g., Hickman, 2013).

The Midcontinent Rift's present configuration suggests segmentation (Dickas and Mudrey, 1997), but estimates of significant erosion (Green et al., 1987; Hutchinson et al., 1990), based on dike swarms away from its margin, indicate a larger original extent. Green et al. (1987) estimated up to 2 million km^3 of basalt was originally emplaced. If significant erosion took place, some of the rift segments (e.g., Kansas and Iowa-Nebraska) might have been once joined. For convenience, we will address five geographic segments: (1) Kansas, (2) Iowa-Nebraska, (3) Minnesota, (4) the Lake Superior Basin, and (5) Michigan.

A greater understanding of the Midcontinent Rift and its place in the Flood requires a three-dimensional map. Reed (2000) drew a strike section but no map has been published. Despite limited data, it is well worth attempting to constrain its total volume and its relative volumes of volcanic and sedimentary rocks. This can be done as a whole, by state, and by basin. Our map is developed from publications and data from state geological surveys, publications from journals, and dissertations. Although there are only four deep test wells into the Midcontinent Rift—in Kansas, Iowa, Wisconsin, and Michigan—numerous shallow wells help constrain the two-dimensional boundaries of the rift. Publications of the state surveys were essential in working at any level of detail.

In Reed et al. (2024), we showed the surface of the erosional unconformity between Precambrian crystalline rock and Phanerozoic sediments. This surface (Figure 4) also shows where crystalline basement is exposed or immediately underlies glacial sediments—in other words, where marine diluvial strata are absent, primarily in Minnesota, Wisconsin, and Michigan. Smaller exposures of crystalline basement occur in the Black Hills of South Dakota and the St. Francois Mountains of Missouri. All of these were blanked during gridding. We also blanked areas of Proterozoic metaquartzites (the Sioux and Baraboo) since we have no data for mapping their base. We believe that these are likely early Flood deposits, but their total volume is very small relative to the study area.

The Midcontinent Rift

The first step in mapping the rift is an accurate outline of its lateral extents. In places around Lake Superior,

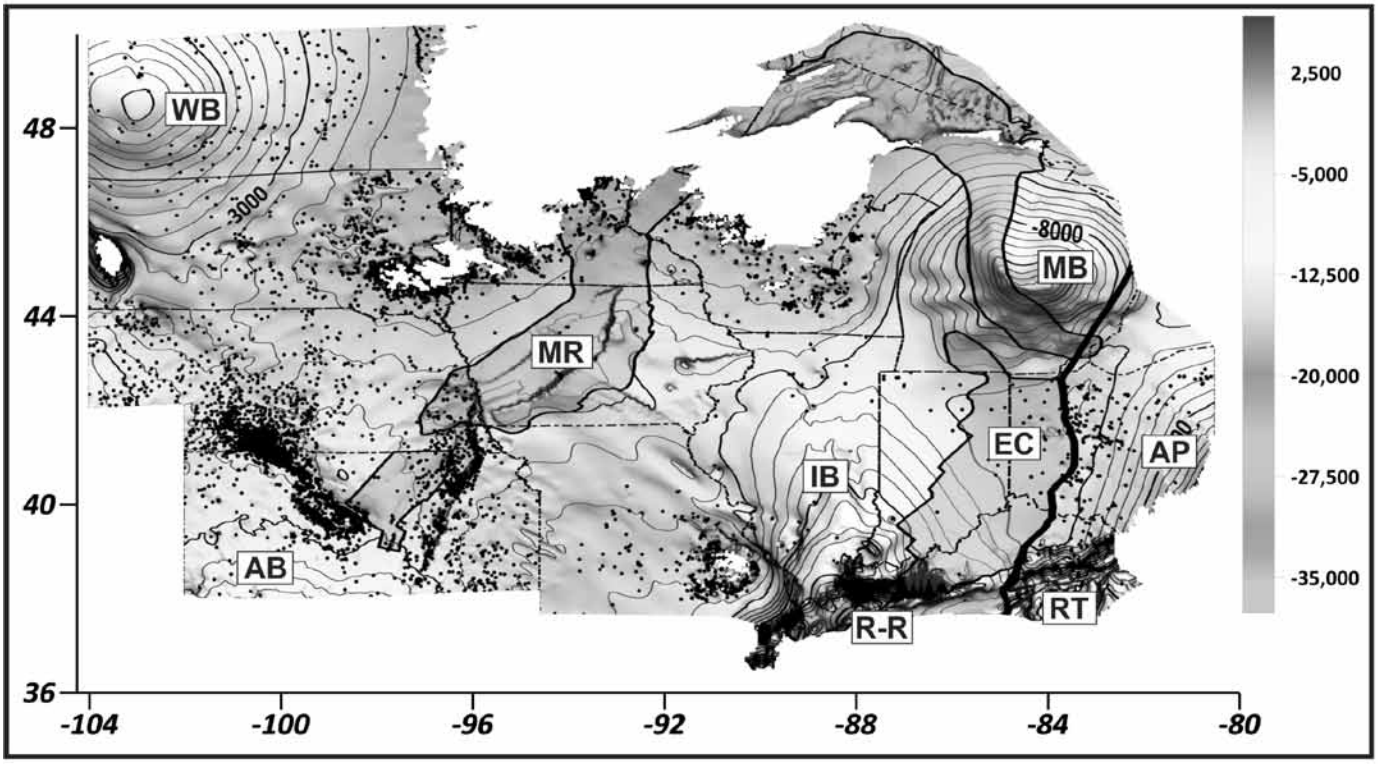

Figure 4. The base of marine diluvial rocks in the upper Midcontinent Region in feet A S L. The contour interval is 1000 feet. Blanked areas show exposed or subglacial Precambrian crystalline rock, the Sioux Ridge in southeastern South Dakota, the Black Hills in southwestern South Dakota, the Baraboo quartzites in Wisconsin, and the St. Francois Mountains in southeastern Missouri. Major sedimentary basins in the study area include the Anadarko (AB), Williston (WB), Illinois (IB), Michigan (MB), and Appalachian (AP) Basins. This surface also forms the top of the Proterozoic Midcontinent Rift (MR) and East Continent Basin (EC), shown outlined. The Reelfoot Rift-Rough Creek Graben (R-R) and Rome Trough (RT) form deep grabens along the southern boundary of the study area. Well control is shown by black dots.

this is constrained by outcrops and shallow wells. In other places, it is constrained by bedrock geological maps, seismic lines, and gravity and magnetic anomaly maps. For example, the Bouguer Gravity Anomaly map of the region (Figure 1) clearly shows the outline of the rift.

In Kansas, additional control is provided by well penetrations, interpretive maps (Cole, 1976; Bickford et al., 1979; Berendsen and Blair, 1996a, 1996b), and a COCORP seismic line across the northern part of the rift (Serpa et al., 1984; Berendsen et al., 1988; Woelk and Hinze, 1991; Berendsen, 1997; Woelk and Hinze, 2015). In Nebraska, control is provided by well penetrations, gravity and magnetic data, and interpretive maps (Burchett and Carlson, 1986), primarily those in Iowa (Anderson, 1995, 2006). Control in Iowa is provided by gravity and magnetic data, a few deep wells, and seismic data (Chandler et al., 1989; Anderson, 1990). The extent in Minnesota and Wisconsin is constrained by significant outcrop and well penetration data (Dickas and Mudrey, 1999) and in Minnesota by detailed County Atlas Maps and a statewide geologic maps (Jirsa et al., 2011). These include data from numerous outcrops and thousands of wells. Wisconsin's bedrock geological map (Mudrey et al., 1982) is relatively old, though the state survey is working on an update. In Michigan, control based on outcrops around Lake Superior, a bedrock geological map (Michigan Geological Survey Division, 1987), and by studies of the Lake Superior Basin provide control in the northern part of the state, but otherwise, control is limited to geophysical data, three COCORP seismic lines (Brown et al., 1982; Zhu and Brown, 1986), and sparse well control in the Michigan Basin.

We evaluated two boundaries for the rift because of current disagreements in Michigan and in Kansas. In Kansas, deep-well data were used in Bickford et al.'s (1979) map of Precambrian basement rocks in Kansas

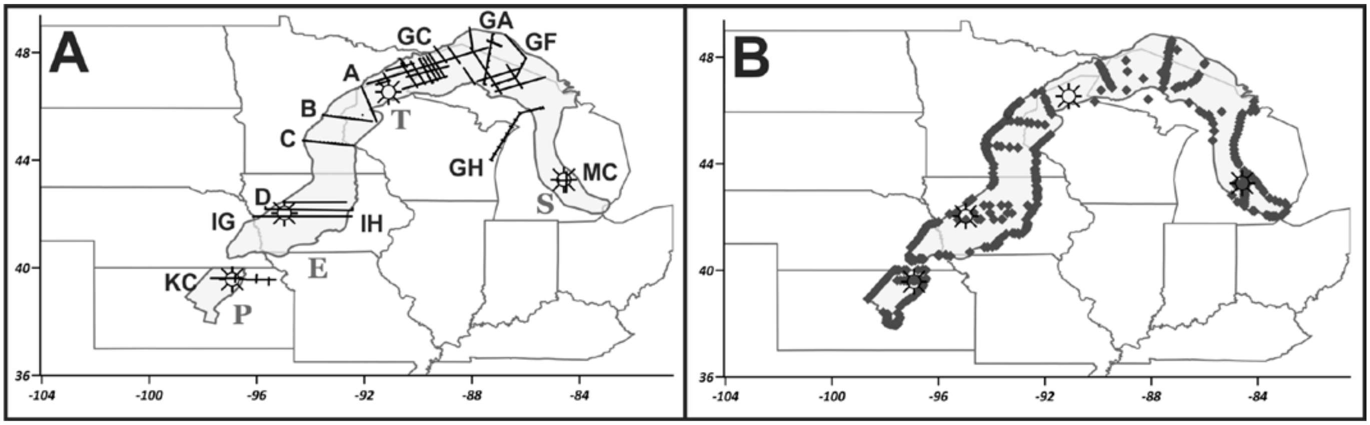

Figure 5. A = Data sources for mapping the base of the Midcontinent Rift. Wells include the Poersch #1 in Kansas (P), the Eischeid #1 in Iowa (E), the Terra-Patrick #1–7 in Wisconsin (T), and the Sparks McClure #1–8 in Michigan (S). Seismic lines include the COCORP lines in Kansas (KC) and Michigan (MC), the GLIMPCE lines in Lake Superior and Lake Michigan (GC, GA, GF, and GH), the Chandler et al. (1989) seismic line sections in Iowa and Minnesota (A, B, C, and D), Halliburton Lines in Iowa (IG and IH), and other seismic lines in Lake Superior (see text). Data points from the intersection of top Precambrian contours with the boundary of the rift resulted in the perimeter control points shown in B.

to show the extent of the rift. However, Berendsen and Blair (1996b) later drew a subcrop map of the Precambrian, showing different boundaries for the rift's volcanics and sediments, shaped by their interpretive fault patterns. But Woodruff et al. (2021) show a map more in line with Bickford et al. (1979).

In Michigan, there is an ongoing debate over whether or not the rift terminates at the Grenville Front. We created one boundary using Woodruff et al.'s (2021) Kansas boundary and terminating the rift at the Grenville Front in Michigan. Another boundary used Berendsen and Blair's (1996b) map in Kansas and extended the rift past the Grenville Front, following the gravity anomaly of Kucks (1999). We also drew the rift in Michigan slightly wider than some depictions (e.g., https://project.geo.msu.edu/geogmich/rift_zone.html) based on the COCORP lines in southern Michigan (Brown et al., 1982).

In addition to the 13 states, the study area extends slightly into Ontario, adjacent to Lake Superior. We set this boundary to improve gridding accuracy along the northern boundary of the rift. This total defined study area covered 2,295,682 km^2. Our Boundary 1 of the Midcontinent Rift enclosed 285,464 km^2, including 20,308 km^2 in the Kansas segment, or 12.43% of the study area. Our Boundary 2 enclosed 280,948 km^2, including 21,684 km^2 in Kansas, or 12.24% of the study area. These numbers are very close and, for simplicity, we use Boundary 2 in the rest of this paper.

Mapping the Base

Data defining the base of the Midcontinent Rift come from seismic reflection profiles. Although four wells along the rift margins play a role in understanding rift fill geology and calibrating seismic velocities, they do not penetrate the deep rift. These include the Texaco Noel Poersch #1 well in Kansas (Berendsen et al., 1988), the Amoco M.G. Eischeid #1 well in Iowa (Anderson, 1990), the Terra-Patrick #7–22 well in Wisconsin (Dickas et al., 1999), and the McClure Sparks et al. 1–8 well in Michigan (Sleep and Sloss, 1978). In addition to COCORP lines in Kansas and Michigan (Figure 5), seismic data are available through a Halliburton line in Iowa (Anderson, 1990), Petty-Ray geophysical lines described by Chandler et al. (1989) in Iowa and Minnesota, and several generations of seismic data around and under Lake Superior (Halls and West, 1971; Halls, 1982; Luetgert and Meyer, 1982; Hutchinson et al., 1986; Behrendt et al., 1988; Canon et al., 1989, 1991; Allen, 1997; McGinnis and Mudrey, 2003). Of primary interest are the 1986 lines from the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) program (Agena et al., 1988). Depth control points from these sources used to map the Midcontinent Rift base are shown in Figure 5B.

Additional depth control was provided by the intersection of the rift margins and contours of the Precambrian surface (from the map used to create Figure 4), as shown in Figure 5B. These depths range from above sea level to -16,000 ft. (-4,877 m) in the Michigan Basin. Contouring was also constrained by the structural interpretation of features such as the White's

Ridge and Grand Marais Ridge (Allen et al., 1997).

The base of the rift (Figures 6 and 7) was mapped by contouring the control points using the rift morphology shown on the seismic lines. Though interpretive and general, it provides an initial picture of the rift relative to its surrounding crust. Once a map was constructed, the resulting contours and data points were gridded and a 3D surface was generated. Figure 6 includes the base of the East Continent Basin and other cratonic rifts. It therefore forms a true diluvial basal unconformity surface. The map of the Precambrian surface shown in Figure 4 (Reed et al., 2024) forms an upper rift surface and allows volumetric calculations of the Midcontinent Rift, as well as the East Continent Basin. Combined with the volumes of the southern rifts and the diluvial marine volume (Reed et al., 2024), we were able to calculate the total diluvial rock volume for the region.

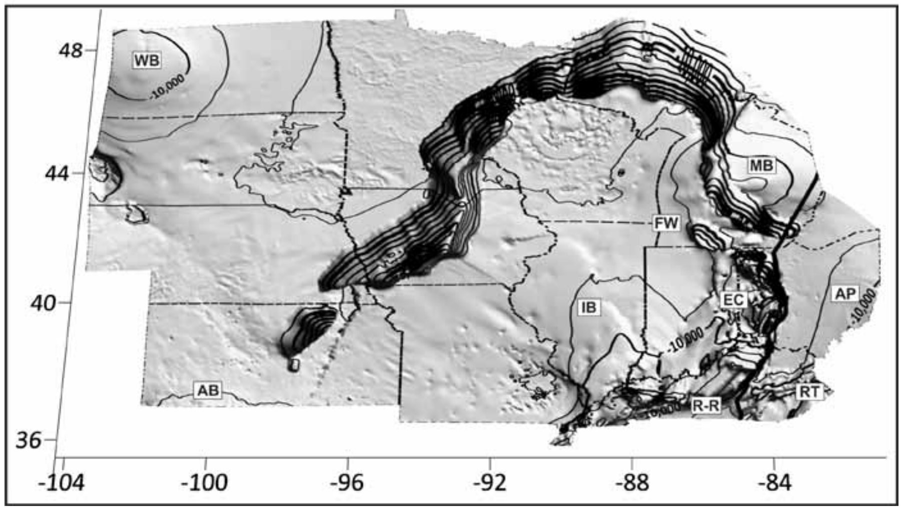

Figure 6. Configuration of the Upper Midcontinent Precambrian surface including the base of Midcontinent Rift and East Continent Basin (EC) in feet ASL. The contour Interval is 5,000 feet. The Williston (WB), Anadarko (AB), Illinois (IB), and Michigan (MB) basins are dwarfed by the Midcontinent Rift. The East Continent Basin (EC), Reelfoot Rift-Rough Creek Graben (R-R), Fort Wayne Rift (FW), and Rome Trough (RT) are likely all a result of continent-scale crustal deformation at the onset of the Flood. The Grenville Front (GF) forms the eastern boundary of the East Continent Basin.

Figure 6 reinforces the proposal of Dickas and Mudrey (1997) that the feature is segmented, though perhaps more in the sense of eruptive centers rather than continent-scale, strike-slip faulting. Local factors obviously affected the morphology, as seen in the impact of basement ridges under western Lake Superior that the rift bypassed (Allen et al., 1997).

The rift was once larger. Significant erosion occurred after the emplacement of rift fill. Green et al. (1987) and Hutchinson et al. (1990) suggested, based on the distance of possible feeder dikes from the rift, that up to half of its volume had been removed. Erosion is also visible in large horst top basins, which appear to be scours in the central horst along the western arm. The shallower depth of the Kansas segment as compared to the Lake Superior Basin and the Iowa segment, combined with the basement separation of the Kansas and Nebraska segments suggests that either rifting and volcanism were less in Kansas or that erosion was greater. The greater depth and size of the rift in the Lake Superior Basin and the Iowa segment indicate centers of deformation and volcanism.

The East Continent Basin

Basement data for the Midcontinent Rift, though sparse, exceeds that for the East Continent Basin. The East Continent Rift Basin (Figure 6) was described by Drahovzal et al. (1992), and their monograph included a boundary that extended into northern Tennessee and a basement surface map based on available seismic data. Since then, little additional information has been published. Baranowski et al. (2009) proposed that the East Continent Rift was distinct from the younger East Continent Basin, which they considered a later foreland basin of the Grenville thrust front, based on reprocessing of the Ohio COCORP Line 1. They proposed several Precambrian seismic stratigraphic units. However, their cross section little resembled the earlier basement map. Moecher et al. (2018) used seismic and well data to develop a new boundary that terminated the basin at the northern edge of the Reelfoot Rift-Rough Creek Graben-Rome Trough system, shown also in Clay et al. (2021).

The Drahovzal et al. (1992) basement map ended in northern Ohio. In the absence of data, we used the Moecher et al. (2018) outline of the East Continent Basin, continued the contours from the Drahovzal et al. (1992) map, and contoured to a conservative 20,000-ft. depth for the Fort Wayne Rift (Figure 6). Contouring north of the Reelfoot Rift-Rough Creek Graben and Rome Trough is also based on Drahovzal et al. (1992). The East Con-

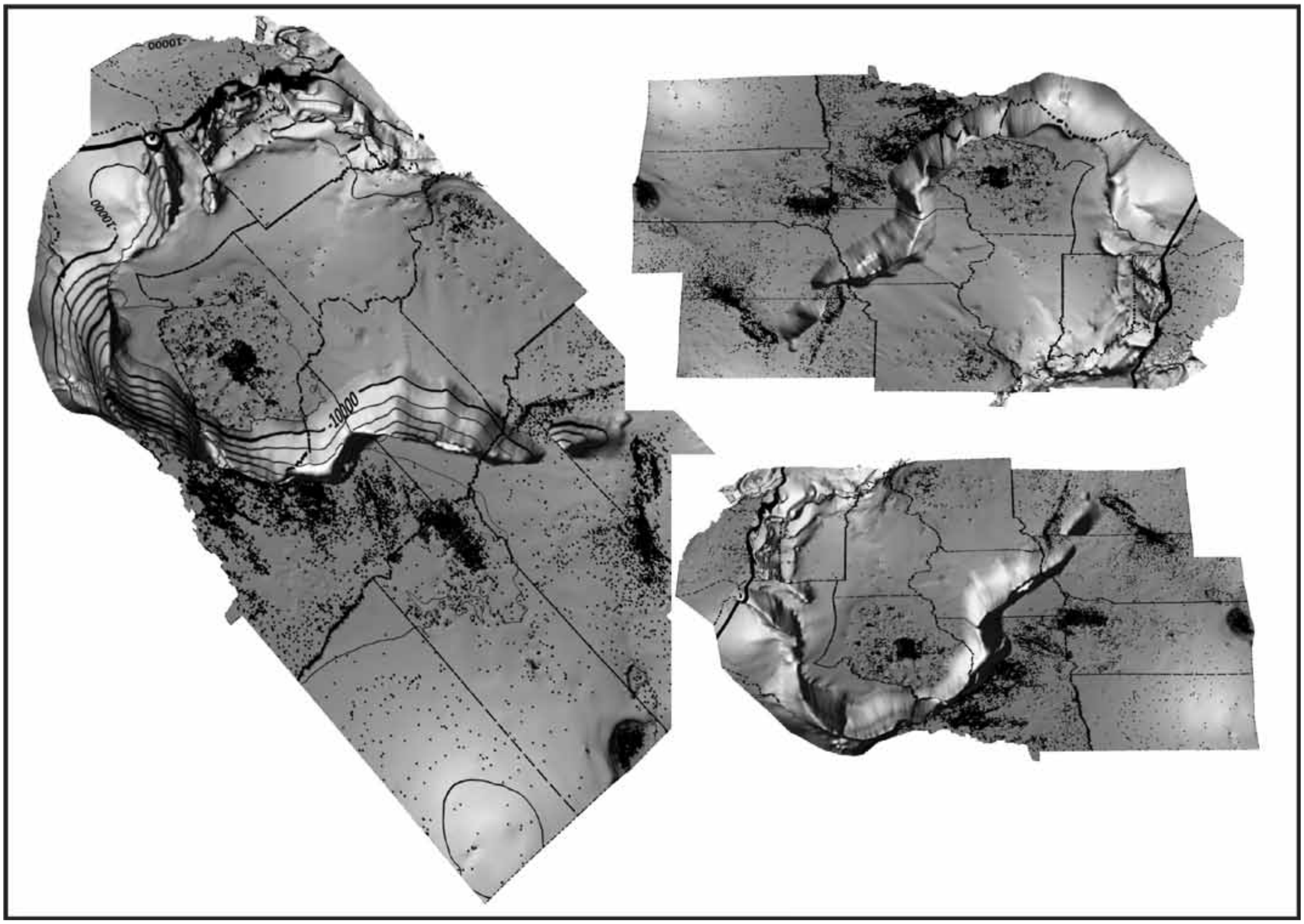

Figure 7. Different angles help visualize the configuration of the base of midcontinent rifting, which probably marks the onset of the Flood. The Grenville Front is shown by a black line in the eastern area and black dots show well control for the surrounding basement.

tinent Basin is a feature that requires significantly more data and effort to understand.

Results

These maps allow initial calculations of both marine diluvial and rift-fill volumes. The volume of the Midcontinent Rift is over 2.3 million km^3. This is greater than published estimates and nearly an order of magnitude more than the volume of the East Continent Basin of 238,435 km^3. Figures 6 and 9 illustrate that difference by simply comparing the cratonic basins (Illinois, Michigan, Williston, etc.) to the rifts. Although the East Continent Basin (and the southern rifts) exceed 10 km in depth and are certainly impressive compared to the cratonic basins, the Midcontinent Rift exceeds 30 km in depth in places and its areal extent dwarfs that of the other rifts.

The Midcontinent Rift and East Continent Basin together occupy a little over 17% of the study area, but account for over 53% of the *total* diluvial and Ice Age volume. For 83% of the study area, the basal diluvial surface is the Precambrian/Phanerozoic unconformity. For the rifts, it is the base of rift fill. If they are Flood features, these two rifts must have come very early because they formed, were filled, and were eroded prior to the arrival of the post-rift transgressive marine sediments (Figure 8).

Volume of the Midcontinent Rift

The total volume of the Midcontinent Rift has been estimated between 1,000,000–2,000,000 km^3 (Green, 1983;

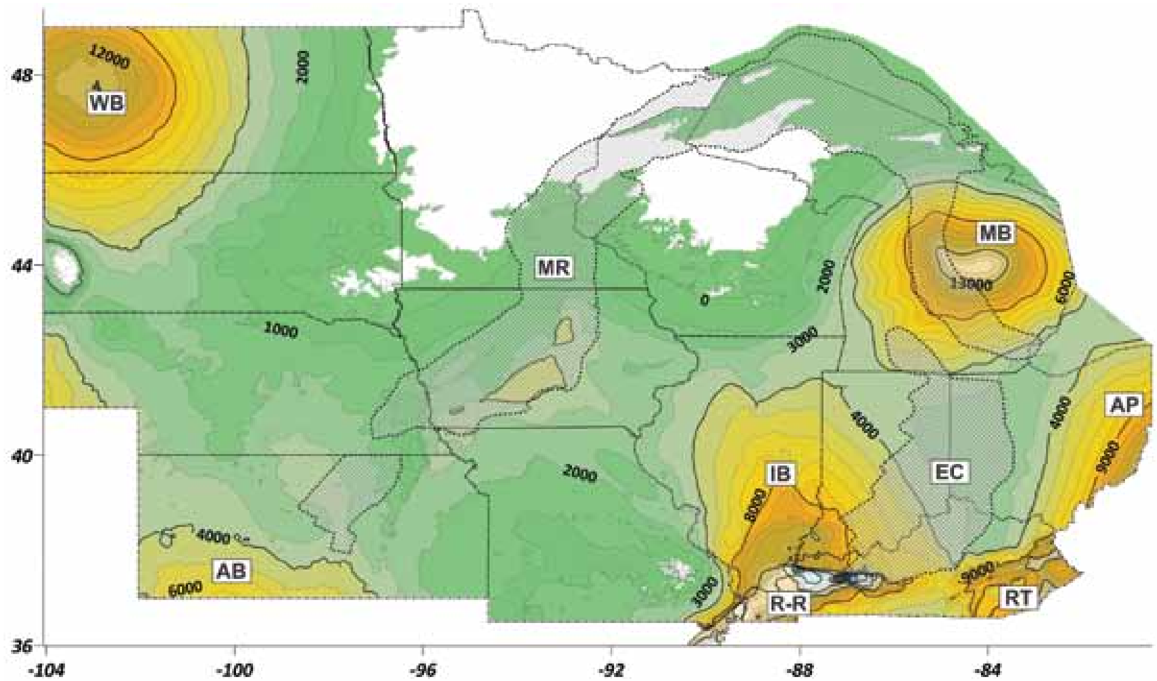

Figure 8 *(above)*. **Isopach map of the Phanerozoic for the upper midcontinent region in feet. The contour interval is 1,000 feet. This does not include rift or basin fill in the Midcontinent Rift (MR) and East Continent Basin (EC). Note how the cratonic basins and southern rifts stand out as depocenters.**

Figure 9 *(below)*. **Isopach map from the ground surface to the diluvial basement in the study area in feet. The contour interval = 5,000 ft. The Midcontinent Rift (MR) dwarfs the later cratonic basins and other rifts; the Williston (WB), Illinois (IB), Michigan (MB), and Appalachian Basins (AP), as well as the other rifts; the East Continent Basin (EC) and the Reelfoot/Rough Creek/Rome (RR) Rifts.**

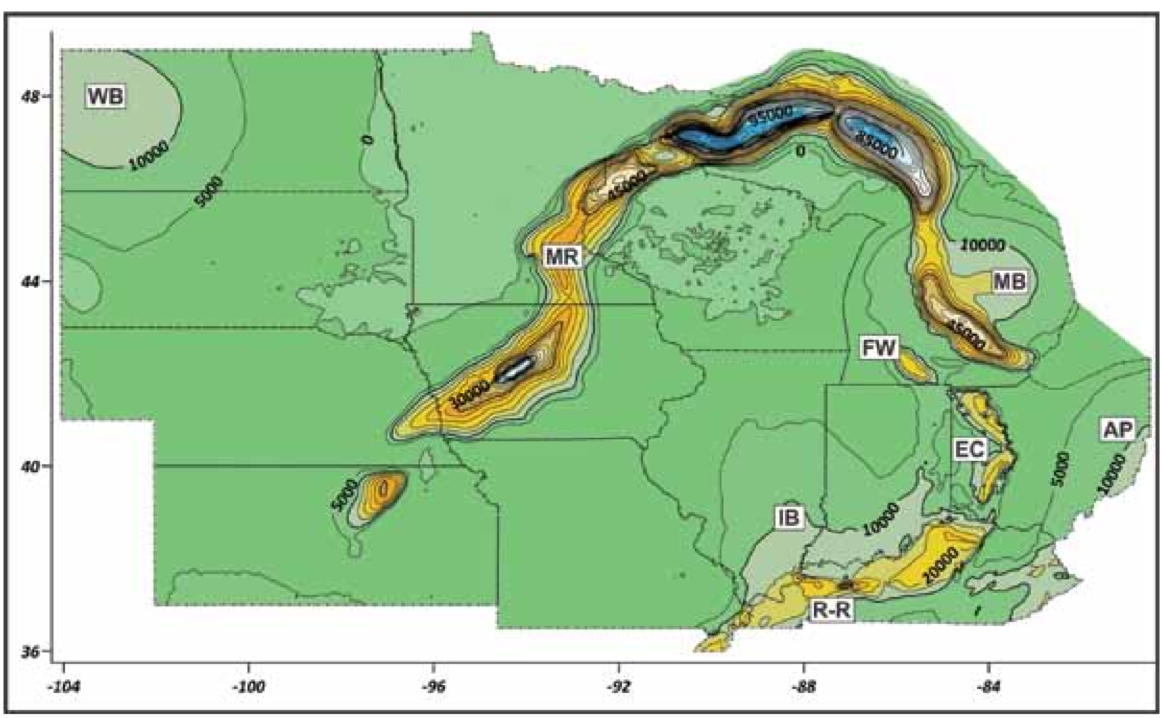

Table I. Volume and average thickness of Midcontinent Rift by state. There is a slight discrepancy between the totals shown here and those from calculating the total rift boundary.

STATE	AREA (km^2)	VOLUME (km^3)	AVG THICK (m)	AVG THICK (ft.)
Kansas	21,684	60,478	2,789	9,150
Nebraska	10,541	36,788	3,490	11,450
Iowa	63,241	383,754	6,068	19,908
Minnesota	41,213	220,854	5,359	17,581
Wisconsin	27,794	269,197	9,684	31,772
Michigan	101,639	1,158,806	11,401	37,405
Ontario	24,456	127,852	5,228	17,151
TOTAL	291,348	2,258,057	7,750	25,427

Hutchinson et al., 1990; Ojakangas et al., 1997). Stein et al. (2015) calculated 2,100,000 km^3. Our calculated volume is slightly larger, 2,311,378 km^3, but supported by maps of the base and the top of the rift. This volume came from subtracting the gridded surface of the base of the rift (Figure 6) from the basal marine diluvial surface (Figure 4), which is the erosional unconformity underlying widespread marine diluvial sedimentation.

The 13-state study area covers 2,295,682 km^2. The Midcontinent Rift occupies a surface expression of 295,965 km^2, or 12.9% of the total study area. The rift's total volume of 2,311,378 km^3 yields an average thickness of 25,631 ft. (7,812 m), with maximum depths exceeding 100,000 ft. (30,480 m)—*or 19 miles*—in the Lake Superior Basin! Thus, an area that occupies less than 13% of the study area holds 48% of the study area's total volume (4,837,013 km^3) of diluvial and Ice Age rocks (Table I, Figure 9). The greatest thicknesses occur in the Lake Superior Basin, as shown by Table I (Michigan and Wisconsin).

Volume of the East Continent Basin

Much smaller than the Midcontinent Rift, the East Continent Basin is not as well understood. We recognize uncertainties in mapping its base and use the boundary of Moecher et al. (2018). Doing so yields a surface expression of 100,757 km^2, a little more than a third of the Midcontinent Rift and 4.39% of the study area. This is slightly larger than the boundary of Drahovzal et al. (1992), with less area in the south and more to the northwest, following the gravity anomaly reflecting the Fort Wayne Rift. We calculated that the total volume of the East Continent Basin is 238,435 km^3. This is a little more than 10% of the volume of the Midcontinent Rift and nearly 11% of the volume of the marine diluvial sediment in the study area. The average thickness of the basin is 7,764 ft. (2,366 m).

Together, the Midcontinent Rift and East Continent Basin total a little more than 2.5 million km^3 and exceed the volume of the total overlying marine post-rift diluvial and Ice Age sediments in the study area (Figure 10). This can be readily visualized in Figure 9. If the volumes of the Reelfoot Rift-Rough Creek Graben and Rome Trough were subtracted from the marine post-rift diluvial package and their volume combined with the northern rifts, the total *rift* volume for the study area would significantly exceed that of the overlying sedimentary record. When their areal extent is compared to the entire study area, their volumes suggest high energy levels very early in the Flood, with greater volumes of basalt emplaced in the northern rifts.

Midcontinent Rift Volcanics and Sediments

The Midcontinent Rift is an immense structure, infilled with volcanics—primarily basalt—and sediments. Estimating their relative volumes is difficult. Although the rift as a whole has been mapped, there are many uncertainties regarding the deep morphology of its sedimentary basins. There are also unknown volumes of sediment interbedded between basalt flows, varying fault angles between the volcanic horsts and the flanking sedimentary basins, and a lack of knowledge of the configuration of sedimentary basins in Michigan, if any. But like mapping the base of the rift to approximate the total volume of the rift fill, this helps constrain the volcanic/sediment ratio.

Two locations, illustrating different styles of sedimentation, can help. The first is the western Lake Superior Basin, where Oronto and Bayfield Group sediments overlie basalt flows. The second is in the Iowa/Nebraska segment, where Anderson (1990) reported volumes for sedimentary basins. Dickas and Mudrey (1999) mapped the base

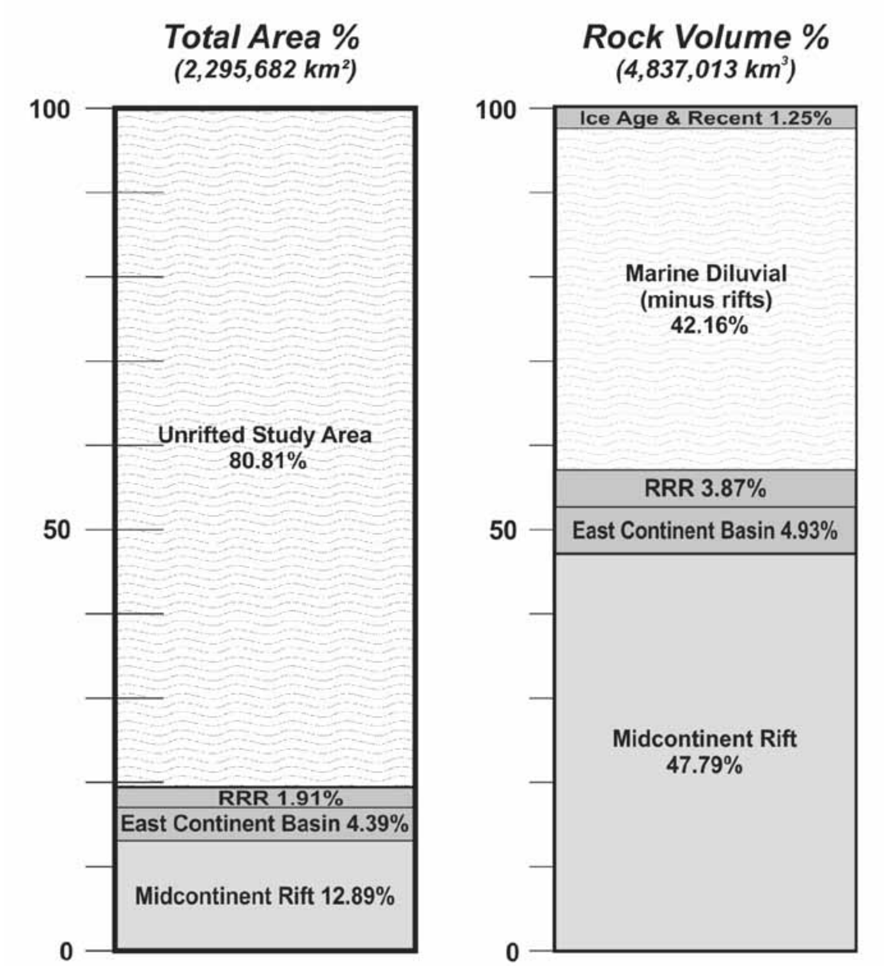

Figure 10. Area vs. volume of rifts in the Midcontinent study area. RRR means Reelfoot/Rough Creek/Rome rifts. Though the rifts occupy less than 20% of the study area, they comprise over 56% of its total rock volume.

of the Oronto Group in the western Lake Superior Basin. Using their map, a surface was gridded and a boundary drawn (Figure 11). The volume from the base of the Oronto Group to the sediment surface (this would include glacial and lake deposits) within this boundary is 144,084 km^3. Ice Age sediments make up 8,752 km^3 of that volume, leaving 135,332 km^3 of rift sediments. The volume of the underlying volcanics is 299,118 km^3. The Oronto and Bayfield sediments here are thus 31.15% of the total volume within the bounded area of the Lake Superior Basin (Figure 11).

In Iowa, Anderson (1990) calculated areas and volumes for the flanking and horst-top basins. He estimated a total of 49,500 km^3 for the western flanking basins, 99,700 km^3 for the eastern flanking basins, and 18,200 km^3 in the horst top basins, totaling 167,400 km^3. We compared this number to our total rift fill of the same segment, which is 423,750 km^3, and based on that comparison, sediment is 39.5% of the total fill. Based on our mapping (Figure 8), the volume for the flanking basins is 165,497 km^3, which is 11% greater than Anderson's (1990) number. Adding Anderson's (1990) number for the horst-top basins, the sediment in this segment totals 185,600 km^3 (24% greater than Anderson's total). This suggests that sediments could be as much as 48% of the rift fill (Figure 11). If these two locations are representative for the entire Midcontinent Rift, sedimentary facies comprise somewhere between a third and a half of the total volume of the rift.

Although imprecise, it is clear that the volume of Midcontinent Rift sedimentary rock is quite large. If even a third of the total fill is sedimentary, that would total over 824,000 km^3. That would be nearly 36% of the total Phanerozoic volume in the entire study area. The Midcontinent Rift occupies less than 13% of that area. Nor does this account for the volume of sediment (and basalt) eroded before the arrival of the post-rift sediments. In any case, the volume of sedimentary rock in the Midcontinent Rift is staggering.

Table II. Volume and average thickness of the study area rifts. See Figure 9.

RIFT BASIN	AREA (km^2)	VOLUME (km^3)	AVG THICK (m)	AVG THICK (ft.)
Midcontinent Rift	295,865	2,311,378	7,812	25,631
East Continent Basin	100,757	238,435	2,366	7,764
Reelfoot_Rough Creek	23,419	128,213	5,475	17,962
Rome Trough	20,171	59,166	2,933	9,623
TOTAL	440,212	2,737,192	6,218	20,400

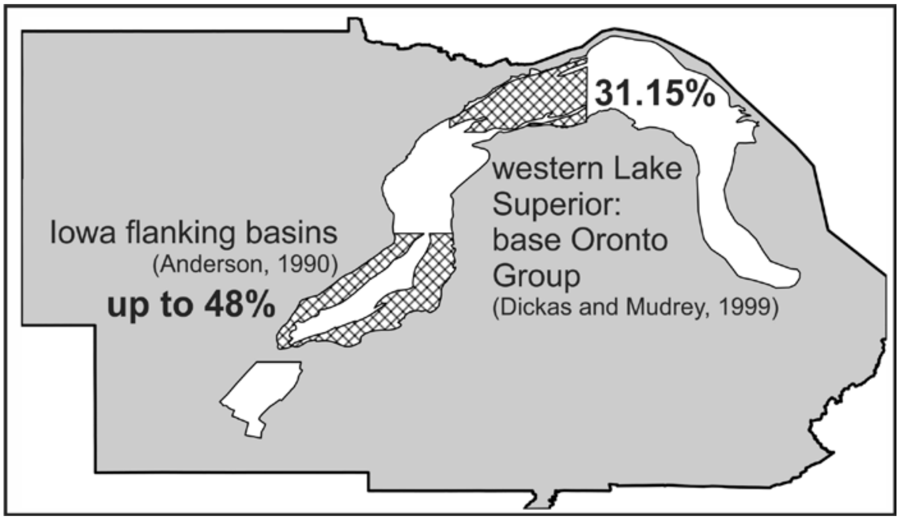

Figure 11. Two areas of the Midcontinent Rift allowed estimates of the sediment-to-volcanic rift fill ratio. In western Lake Superior, sediments of the Oronto and Bayfield groups overlying volcanics occupy nearly a third of the total volume there. In the flanking (and horst top) basins of Iowa, the sediments approach half the total volume.

Sudbury Impact and the Midcontinent Rift

Another interesting aspect of the Midcontinent Rift is its proximity to the Sudbury impact crater, located about 200 km from its present boundary. The Sudbury impact structure was controversial for a long time, but has since been accepted as an impact crater, meeting stringent criteria for identifying impacts. The crater has been greatly eroded (see below), which added to the problem of identifying it as an impact. Geologists think its original diameter was between 200 and 250 km (Huber et al., 2020). Adding a 200 km buffer to the present impact site slightly intersects the present Midcontinent Rift boundary (Figure 12) but they would overlap noticeably if the original rift boundary and the impact crater were both larger.

Based on Green et al. (1987) report that feeder dikes for the rift occur as much as 200 km out from its present location, it is reasonable to see the original rift as much larger. Recognizing that any pre-erosion boundary would not be a uniform distance from the present boundaries along the entire rift, we created a conservative uniform buffer 100 km from the present boundary. That increased the area covered significantly, to 821,691 km^2, or to nearly 36% of the total study area. However, the pre-eroded *volume* of the rift would probably not be proportionately greater since the greatest depths are found in the rift axis. Every 1,000 m of fill eroded from the buffer zone would represent nearly a half-million km^3 of volume.

Erosion at the nearby Sudbury feature is estimated at approximately 5,000 m (16,404 ft.) (Senft and Stewart, 2009). If erosion at the Midcontinent Rift was similar, the eroded thickness of 5,000 m multiplied by the ~800,000 km^2 would have been more than 4,000,000 km^3. Compare that to the current volume of the rift of less than 2,500,000 km^3. That would mean that over 60% of the original rift volume was eroded. This represents a vast sediment source for clastic rocks across central North America early in the Flood. The 4 million km^3 would represent a much greater volume of sediment than is found in the entire Phanerozoic record in the study area. Sourcing sediment for Flood deposits appears to have been no problem, given the energy of its erosion possibly reflected here.

Is there a link between the impact and rifting? Uniformitarians see the location as coincidental because they date Sudbury 700 million years before the rift. But to diluvialists, both could be related to the onset of the Flood. It is difficult to see one of the world's largest impact features in direct proximity to a massive rift and not think they were related. We could only speculate on the mechanics. Some very powerful force caused the rift, and the Sudbury impact was powerful. If they are connected, the 700-million-year error in dating is another indication that skepticism is warranted for the geological ages.

Precambrian Geology and the Base of the Flood

A century ago, the Precambrian was simply the doorway from a well-understood sedimentary record into a misty, speculative realm that inconveniently contained nearly 90% of deep time. That has changed. Precambrian geology has seen dramatic changes in two generations, as more data combined with mature narratives like plate tectonics have created a more complete Earth history extending far deeper into the uniformitarian past (e.g., Whitmire and Karlstrom, 2007; Miall, 2019).

Diluvialists have argued for some time over the basal diluvial boundary. Hunter (2022) has argued that it is the 660-km mantle seismic discontinuity (aka the 660-km phase transition).

Others place it at various stratigraphic markers. Austin and Wise (1994), among others, believe that the basal diluvial boundary is just below the Precambrian/Cambrian contact in the Grand Canyon and well below the contact in the Mojave Desert. Dickens and Hutchinson (2021) place the lower diluvial boundary at the Mesoproterozoic/Neoproterozoic boundary. We suggest that most, if not all Precambrian sedimentary rocks are from the early Flood (Oard et al., 2023). Most today believe we must look past at least one cycle of plate tectonics (Snelling, 2009). But a common factor is the mantle's geological work during the Flood. The midcontinent rifts and their relationships to the large sedimentary basins provide an empirical test of these ideas.

What was the depth and nature of crustal erosion and tectonism at the beginning of the Flood? With regard to tectonism, CPT, HPT, and the Impact model (Oard, 2024) all picture an immediate catastrophic onset with upper-mantle involvement. Erosion is not specified. Perhaps it is more important to define criteria for setting a lower diluvial boundary. We suggest three Biblical ones: (1) an abrupt, clear, destructive signature in the rock record; (2) a significant and widespread erosional unconformity separating crystalline basement (which we assume to be antediluvian crust) from the sedimentary record; and (3) a global record of marine transgression and regression. Deeper crustal faulting, metamorphism, and intrusion are expected as a matter of course, but discovering those details is a forensic exercise, not a Biblical one.

For the central North American rifts described above, the first criterion certainly applies. The second is found at the Proterozoic/Phanerozoic unconformity outside of the Midcontinent Rift and East Continent Basin. Within those rifts, rapid sedimentation associated with the basalt flows certainly speaks to volcanism, erosion, and deposition at a scale achievable only during the Flood. The third is seen in the sedimentary sequence atop that unconformity, both outside and across the two rifts. Significant regional erosion is seen in the estimates of crustal removal from the nearby Sudbury impact crater, from the likely original size of the Midcontinent Rift, and in the ubiquitous presence of erosion of the surrounding crystalline basement, including erosional remnants in areas where sufficient well control exists to delineate them (Reed et al., 2024).

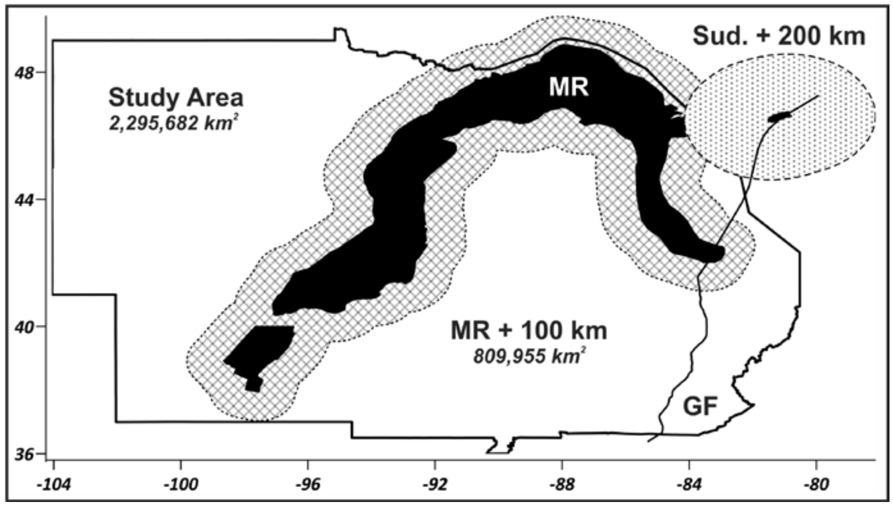

Figure 12. The relationship of the present Midcontinent Rift (black) to the present Sudbury Impact erosional remnant (also black). The Grenville Front (GF) also intersects the center of the Sudbury impact crater. A 200 km buffer of the Sudbury crater (stippled area) and a conservative 100 km buffer (hatched) of the Midcontinent Rift show the original impact zone would intersect with the eastern Lake Superior Basin part of the rift.

An Early Rifting Episode

The northern midcontinent of the United States is dominated by rifting (Figure 9). If gravity signatures farther south accurately outline rifts in Tennessee and Alabama (Stein et al., 2015), the area between the Appalachians and Rocky Mountains saw significant rifting prior to or coinciding with widespread post-rift marine sedimentation of the Flood Given the cross-cutting relationship with the crystalline basement, we speculate that the rifts in the subsurface are relicts of widespread and large-scale crustal disruption, probably marking the onset of the Flood. Most geologists attribute these rifts to plate tectonic episodes operating over millions of years. They are separated on the time scale by approximately a half-billion years. However, if rifting was an expression of crustal disruption during the early Flood, we would start with the assumption that all of the rifts are of similar ages, and that time is not the key factor in explaining differences in size, orientation, style, and fill. It is instead differences in local geological processes that must account for differences in size, orientation, style, and fill.

The Midcontinent Rift exhibits extensive vertical and lateral motion in its faults and the relative positions of its volcanics and sediments. Motion was initially extensional but the rift axis was inverted with compression afterwards, but prior to Flood post-rift marine sedimentation. This is more marked in the western arm of the rift than in the Lake Superior Basin. Reverse faulting occurred in the Lake Superior Basin, but its thicker sediments were preserved across the entire basin, not just in flanking and horst-top basins, as seen farther south. Little is known about the rift segment in Michigan.

What were the mechanics of rifting? On Earth's surface, the relationship between vertical motion and lateral separation or compression is geometrically equal to pi (ratio of circumference to radius). This is vastly complicated by the ability of rocks to deform locally by faulting or folding. Faulting may compensate for extension or compression, while folding will only accommodate compression. In general, compression of rocks results in relatively minor volume changes in the rock itself, and thermal expansion or contraction is of similar magnitude. However, mineral transformations at depth due to temperature or pressure changes can produce significant volume changes. For rough estimates such as described here, the ratio of pi is a good starting point. For every km of uplift, the crust will compensate by roughly 3 km of lateral separation, and the same for downwarping and compression. The Midcontinent Rift could have originally affected a region up to 500 km across, given the width of the present Lake Superior Basin and the estimate of Green et al. (1987) of its original extent.

Courtillot (1999) estimated 2 km of crustal uplift over a 1,000 km area prior to rifting. This is not enough to explain the lateral motion at the rift, which was estimated by Stein et al. (2015, their Figure 5) as 32 km at GLIMPCE Line A and 23 km at GLIMPCE Line C (both beneath Lake Superior). This would require a vertical uplift of nearly 10 km or another component of regional lateral motion. Rift dimensions are smaller in the southern arms (Figure 8), so the Lake Superior Basin probably represents the maximum disruption.

Basalt flooding was almost instantaneous with deformation (Reed, 2000) since the single largest constraint on the duration and volume of basalt emplacement is vent width. There was a smaller volume of basalt flows in the East Continent Basin and much less in the Reelfoot-Rough Creek-Rome complex. This may speak to crustal thickness or localized mantle activity. The volume of basalt in the rifts suggests an episode of severe decompression melting of the uppermost mantle. Basalt is concentrated in the rift axis, although it looks like a plateau basalt away from the center (Stein et al., 2015). There is also significant underplating of the crust along the rift (Reed, 2000).

Faults show that early extension was followed by compression, with up to 8 km of reverse motion (Reed, 2000) recorded at the major faults along the central basalt horst. So early Flood events included: crustal disruption with large normal faulting; flood basalt eruptions concentrated in a central axis; emplacement of intrusive bodies (e.g., the adjacent Duluth and Mellon complexes) with underplating of the crust at the rift axis; and then erosion and sedimentation, perhaps concurrent with the inversion of a solid horst. Reed (2000) argued that they were concurrent and that the relative volumes during the formation of the rift do not necessarily reflect changing sedimentation rates as much as they show rapid rifting and volcanism temporarily overwhelming erosion and sedimentation. This synchronicity, expected in the timeframe of the Flood, is evidenced by thin sediments beneath and between flows. Sedimentation continued well after, leaving up to 10 km in the Lake Superior Basin. Lower clastics were sourced from local erosion of volcanics and the surrounding granitic crust; later clastics appear to be sourced more from the granitic crust.

Differences and Similarities Between Rifts

The rifts in the study area share both similarities and differences. These include the northern rifts—the Midcontinent Rift and East Continent Basin—and the southern rifts—the Reelfoot Rift (or Mississippi Graben), the Rough Creek Graben, and the Rome Trough. In scale, the Midcontinent Rift dwarfs the others (Figure 7), both in size and depth. The orientations and stress vectors also vary. The Midcontinent Rift trends south/southwest in Kansas and arcs north/northeast to Lake Superior, where it bends under the lake, then pushes south through Michigan before turning southeast and terminating at either the Grenville Front or a little beyond. The Fort Wayne Rift parallels that segment. The East Continent Basin ranges roughly north-south. The Reelfoot Rift bends northeast at the southern boundary of the study area before curving east into the Rough Creek Graben. The Rome Trough runs east/northeast out of the study area, where it bends more north/northeast through West Virginia and Pennsylvania. These suggest a complex variety of lateral kinematic forces not easily explained. If these rifts formed concurrently, these differences are not easily explained by present models.

Uniformitarians attribute these differences to time. The Midcontinent Rift is dated at ~1.1 Ga, the East Continent Basin is thought to be approximately the same age, although the Middle Run litharenite has been dated at ~1.0 Ga (Moecher et al., 2018), leading them to see the East Continent Basin as a rift which evolved into a foreland basin dominated by Grenville thrusting. However, the Reelfoot-Rough Creek-

Rome rifts are dated as early Cambrian (Hickman, 2013). We think instead that the rifts are very similar in age.

The Lake Superior Basin shows two major types of sediment: (1) lithically and texturally immature volcanogenic clastics of the Oronto and Solor Church formations conformably overlying volcanic flows in the rift axis, and (2) more mature, more quartz-rich sediments of the Bayfield Group and Jacobsville Sandstone (and their equivalents) spreading out laterally. The Oronto Group reaches 5,500 m (18,044 ft.) in thickness and the nature of seismic reflectors suggests interbedded basalt flows and sediments at its base (Canon et al., 1989); there is not a profound erosional unconformity between them in the Lake Superior Basin. They are interpreted as having been deposited in alluvial fans and by braided streams. The relatively mature clastics of the Bayfield Group show more quartz and fewer volcanic clasts; these overlie the Oronto Group in the Lake Superior Basin and reach 5,000 m (16,404 ft.) in thickness. Both groups are unfossiliferous, with inversion of the volcanic horst occurring during Bayfield deposition along the original normal faults.

There is little data in Michigan but there are good descriptions of the flanking basin sediments in Iowa and Minnesota. The "red clastics" of Anderson (1990) are immature sandstones, siltstones, and shale. He divided them into a lower and upper unit, though they do not reflect the composition of the Lake Superior Basin sediments. In Kansas, similar sediments were called "arkose," "red clastics," and "granite wash" before Scott (1966) coined the term, "Rice Formation." These also appear unfossiliferous, and their base has not been penetrated. The Texaco Noel Poersch well encountered basalt flows over immature subarkose sediments, confirming reverse faulting there.

The East Continent Basin forms a shallower rift in western Ohio, eastern Indiana, and Kentucky. Drahovzal et al. (1992) posited a southern boundary into northern Tennessee. However, Moecher et al. (2018) terminated it at the Rough Creek Graben. Based on seismic data, Baranowski et al. (2009) extended the sedimentary basin west as far as Illinois. Basin fill, based on cores, drill samples, and geophysics is similar to the Midcontinent Rift, with bimodal volcanics dominated by continental flood basalts at its base and fewer felsic volcanics. These are overlain by unfossiliferous arkosic and lithic red-to-gray arenites of the Middle Run Formation. Cores and geophysics confirmed the presence of gabbro, flood basalt, felsic volcanics, and volcanic-to-feldspathic, lithic arenites (Shrake, 1991).

Based on radiometric dating of detrital zircons, Moecher et al. (2018) posit a two-stage basin formation: rifting as a southern extension of the Midcontinent Rift, followed by thrusting at the Grenville Front, resulting in a foreland basin receiving additional similar sediment from eroding orthogneissic basement, east of the Grenville Front. Drahovzal et al. (1992, p. 6) described the Middle Run Formation from the Ohio Geological Survey well No. 2627, which penetrated an 1800-foot (549 m) section of the Middle Run Formation, as "remarkably homogeneous, consisting of red to gray, fine- to medium-grained, thickly bedded lithic sandstones. It is estimated to contain less than 10 percent siltstones and shales." This reinforces the high-energy levels seen in sedimentation in the Lake Superior Basin. Those sediments are unconformably overlain by marine Cambrian Mount Simon sandstones.

The Fort Wayne Rift, a suspected northern extension of the East Continent Basin through northeast Indiana, and possibly extending as far as Lake Michigan, has been defined geophysically (Stein et al., 2018), but no wells have tested the extents of the rift, and we could find no description of its fill. Inference suggest basalts and sediments of the Middle Run Formation or its equivalent.

The southern rifts are distinct in their fill. Rifting coincides with sedimentation and much less basalt volcanism. Drahovzal (1997) described ultramafic intrusions which pointed to rifting. Hickman (2013) described the sedimentary sequence from the early Cambrian Reelfoot Arkose up through the Eau Claire Group, and the Knox Supergroup. By this point, the greatest thickness of rift sediment had been deposited, showing that these rifts were structurally most active early in the Flood. These were overlain by Lower Paleozoic strata through the Devonian New Albany Shale, and a few thousand feet of Mississippian through Permian sediment. The Gulf Coastal Plain extends up through western Kentucky with those strata onlapping over the rift fill.

Finally, if large-scale rifting represents a style of deformation associated with the onset of the Flood, then the rifts in the study area offer a problem for the geologic timescale. These rifts span 600 million years for uniformitarians, but would be, at most, forming within a few weeks of each other. If the relative dates of the chronostratigraphic time scale are accurate, then diluvialists need to explain why such similar features in the cratonic interior happened at such diverse times.

Erosion of the Basement

The basement in the northern study area was subjected to three episodes of erosion: (1) the top of the rift fill, (2) the late Flood regression after deposition of the Phanerozoic, marine sediments, and (3) the post-Flood, Ice Age glaciation. Basement erosional remnants in Minnesota and Wisconsin may reflect glaciation but the erosional remnants in Kansas, covered by thousands of feet of Flood sediments, show that erosion early in the Flood was significant.

Often, the identification of remnants is a function of well density. Contours are smooth in places where well control is sparse, but less so where well control is abundant. In the northern study area, this is especially seen in Minnesota and Wisconsin and on the Sioux Ridge (Reed et al., 2024). In the southern study area, it is seen most clearly in Kansas (see Figure A-4 in Part I). Cole (1976) mapped many pinnacles in the Kansas basement; some hundreds of feet high. It is hard to avoid the conclusion that these are erosional remnants from the early Flood, similar to those described by geomorphologists today that occurred during Late Flood regression (Oard, 2013).

Conclusion and Summary

If rifting across the study area occurred early in the Flood, then the scale of geological processes speaks to extremely high energy levels. One indicator of this energy would be the volume and distribution of the rift fill. We created a map of the base of the rifts in the study area and found that the sediment volume in the Midcontinent Rift alone was nearly half of that of the total Phanerozoic in the study area, even though the Midcontinent Rift occupies less than 13% of that area. An isopach map of the total diluvial rock record in the study area illustrates its importance and the significance of the other rifts and rift basins.

This mapping completes the necessary surfaces in the study area to define the volume and distribution of Ice Age and recent sediments, diluvial sediments deposited during and after the passage of the marine diluvial sediments, and diluvial sediments deposited as rift fill. As shown in Reed et al. (202x), marine diluvial sediments accumulated in cratonic basins, such as the Williston, Illinois, Michigan, Anadarko, and Appalachian Basins. But their volumes are easily exceeded by those of the rifts. The origin of the rifting is not known, but we find the congruence of the restored boundaries of the Midcontinent Rift and Sudbury Impact to be interesting and worthy of further investigation.

This paper summarizes a significant amount of regional data worth careful consideration by diluvialists. If the rifts represent the onset of the Flood, what mechanism(s) caused the rifting? Was the Midcontinent Rift related to the Sudbury impact? Is the estimated 5 km of erosion at Sudbury more widely applicable to the region? If so, what caused that erosion and where did the resulting sediment go? Why are the rift sedimentary basins different in the Lake Superior Basin and southern segments of the Midcontinent Rift? Why is the East Continent Basin more similar to the Lake Superior Basin than those southern limbs? Why were the southern rifts infilled by marine Phanerozoic sediments, as opposed to the Midcontinent Rift and East Continent Basin? How did the large cratonic basins, such as the Michigan, Williston, Illinois, and Anadarko form? What were their sediment sources and transport pathways? What volume of sediment and basalt was eroded from the Midcontinent Rift and East Continent Basin before the deposition of more widespread marine facies? With the volumes and distributions of the rift and basin fill presented in this study, diluvialists now have a more solid base of

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