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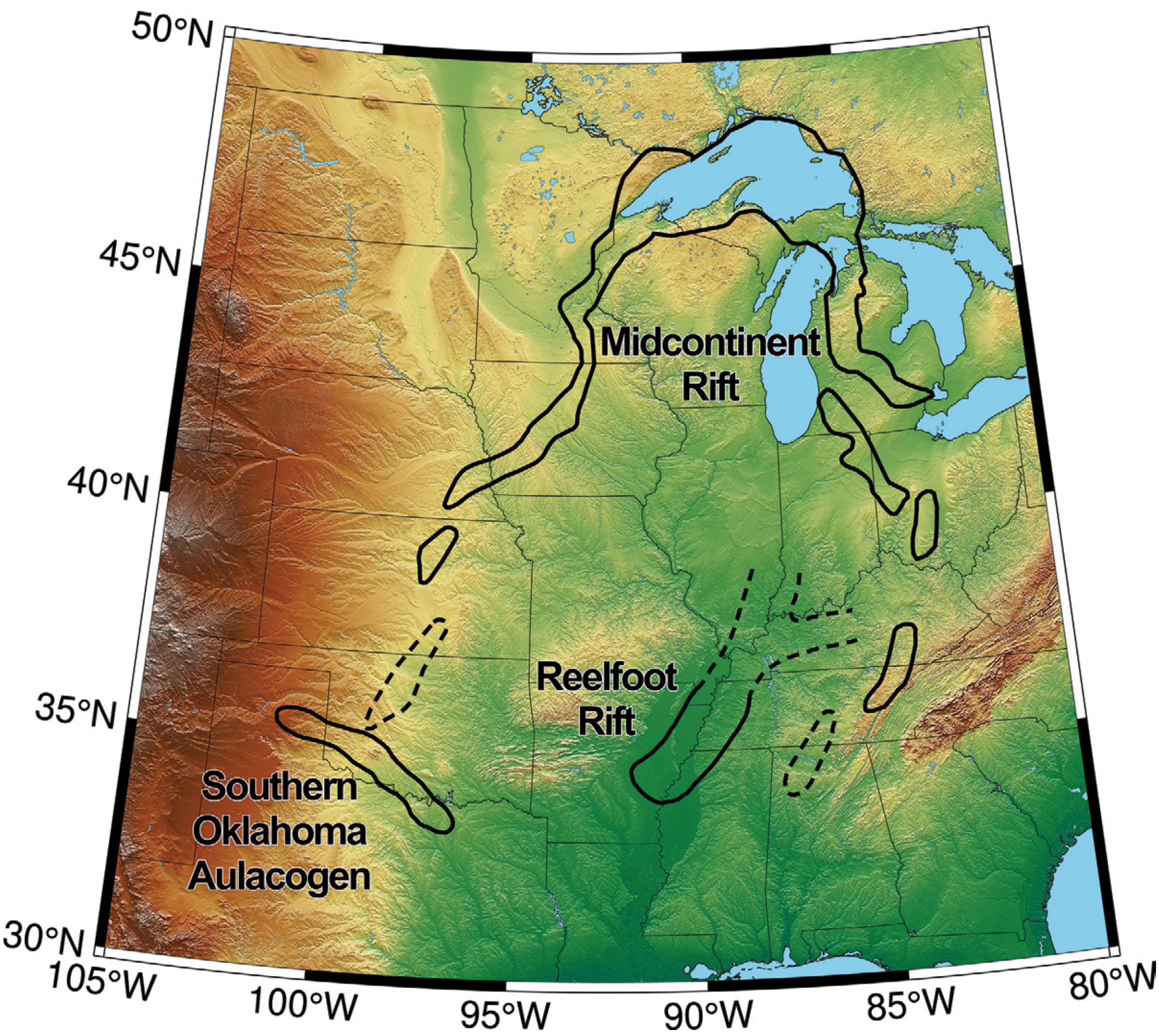

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Three Major Failed Rifts in Central North America: Similarities and Differences

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ABSTRACT

The North American craton preserves nearly two billion years of geologic history, including three major rifts that failed rather than evolving to continental breakup and seafloor spreading. The Midcontinent Rift (MCR) and Southern Oklahoma Aulacogen (SOA) show prominent gravity anomalies due to large volumes of igneous rift-filling rock. The Reelfoot Rift (RR), though obscure in gravity data, is of interest due to its seismicity. The ca. 1.1 Ga MCR records aspects of the assembly of Rodinia, whereas the ca. 560 Ma SOA and RR initiated during the later breakup of Rodinia and were inverted during the assembly of Pangea. Comparative study of these rifts using geophysical and geological data shows intriguing similarities and differences. The rifts formed in similar tectonic settings and followed similar evolutionary paths of extension, magmatism, subsidence, and inversion by later compression, leading to similar width and architecture. Differences between the rifts reflect the extent to which these processes occurred. Further study of failed rifts would give additional insight into the final stages of continental rifting and early stages of seafloor spreading.

INTRODUCTION

Plate tectonics shapes the evolution of the continents and oceans via the Wilson cycle, in which continents rift to form new oceans. Many rifts evolve to passive continental margins. However, some rifts fail before continental breakup and remain as fossil features within continents, which are largely buried beneath the surface and studied primarily with gravity and seismic surveys. Failed rifts preserve a snapshot of the rifting process before the beginning of seafloor spreading and thus give insight into late stages of continental rifting and formation of passive continental margins (S. Stein et al., 2018; Stein et al., 2022).

North America contains multiple impressive, failed rifts (Fig. 1), preserving important aspects of the fabric of nearly two billion years of geologic history in Laurentia, its Precambrian core (Whitmeyer and Karlstrom, 2007; Marshak and van der Pluijm, 2021). We focus on three major failed rifts, covering ~10% of central North America (defined for these purposes as the area shown in Fig. 1A). One, the Midcontinent Rift (MCR), is a prominent feature in geophysical maps of the region. Due to its size and the availability of geophysical and geological data, the MCR has been the focus of many studies giving insight into its evolution, role in the assembly of Rodinia, and processes of rifting and passive margin evolution (e.g., Green et al., 1989; C. Stein et al., 2018; Swanson-Hysell et al., 2019). Two other failed rifts, the Southern Oklahoma Aulacogen (SOA) and Reelfoot Rift (RR), have also been subjects of much interest. Parts of the SOA lie within the basement near and below the Anadarko Basin, a major oil- and gas-producing basin. Thus, its oil-bearing upper crust is well studied (Brewer et al., 1983; Keller and Stephenson, 2007; Hanson et al., 2013), but the deeper structures in the lower crust and uppermost mantle are rarely the primary target of study. The RR and its northern extensions, on the other hand, have little interest for the energy industry but are of interest due to their active seismicity (Hildenbrand and Hendricks, 1995; Calais et al., 2010).

These three failed rifts are grossly similar, with similar tectonic origins and structural features, but with interesting differences highlighting aspects of their evolution. These are shown by gravity data that are uniformly sampled across the central U.S. (Fig. 1). In contrast, other data available differ from area to area. In particular, high-quality seismic reflection data giving detailed structure at depth that allows modeling of the rift's evolution are available only across the part of the MCR below Lake Superior. Conversely, EarthScope local seismic array data showing structure beneath the rift are available only across parts of the MCR's west arm and the RR.

Using gravity data from the PACES (Keller et al., 2006) and TOPEX data sets (Sandwell et al., 2013), we extracted profiles 150 km long and ~50 km apart across each rift (Fig. 1B). Figure 1C shows each rift's mean Bouguer anomaly and standard deviation. The mean profiles show differences between rifts, reflecting their tectonic origin and subsurface structure. The MCR's west arm shows large gravity highs (~80 mGal) bounded by ~20 mGal lows on either side of the rift basin. In contrast, the MCR's east arm has a positive anomaly half that of the west arm and lacks bounding lows. The Southern Oklahoma Aulacogen has an ~60 mGal positive anomaly, similar to the MCR, whereas the RR shows only a minor (~10–15 mGal) positive anomaly despite forming about the same time as the SOA.

The profiles are generally similar in width and form, but differ in amplitude, suggesting general similarities in crustal and uppermost mantle structure between the rifts. We use the mean gravity profiles augmented with seismic and other data, combined with results from earlier studies, to model the rifts' general subsurface structures. We start with the hypothesis that the rifts are similar, and so when needed use inferences from one rift to gain insight into the others, to the extent that the data permit. Although models from gravity data alone are non-unique, augmenting them with information from seismic, aeromagnetic, surface mapping, and drill-hole data lets us characterize average structure along the rifts and illustrate similarities and differences between them. The similarities and differences reflect the combined effects of a

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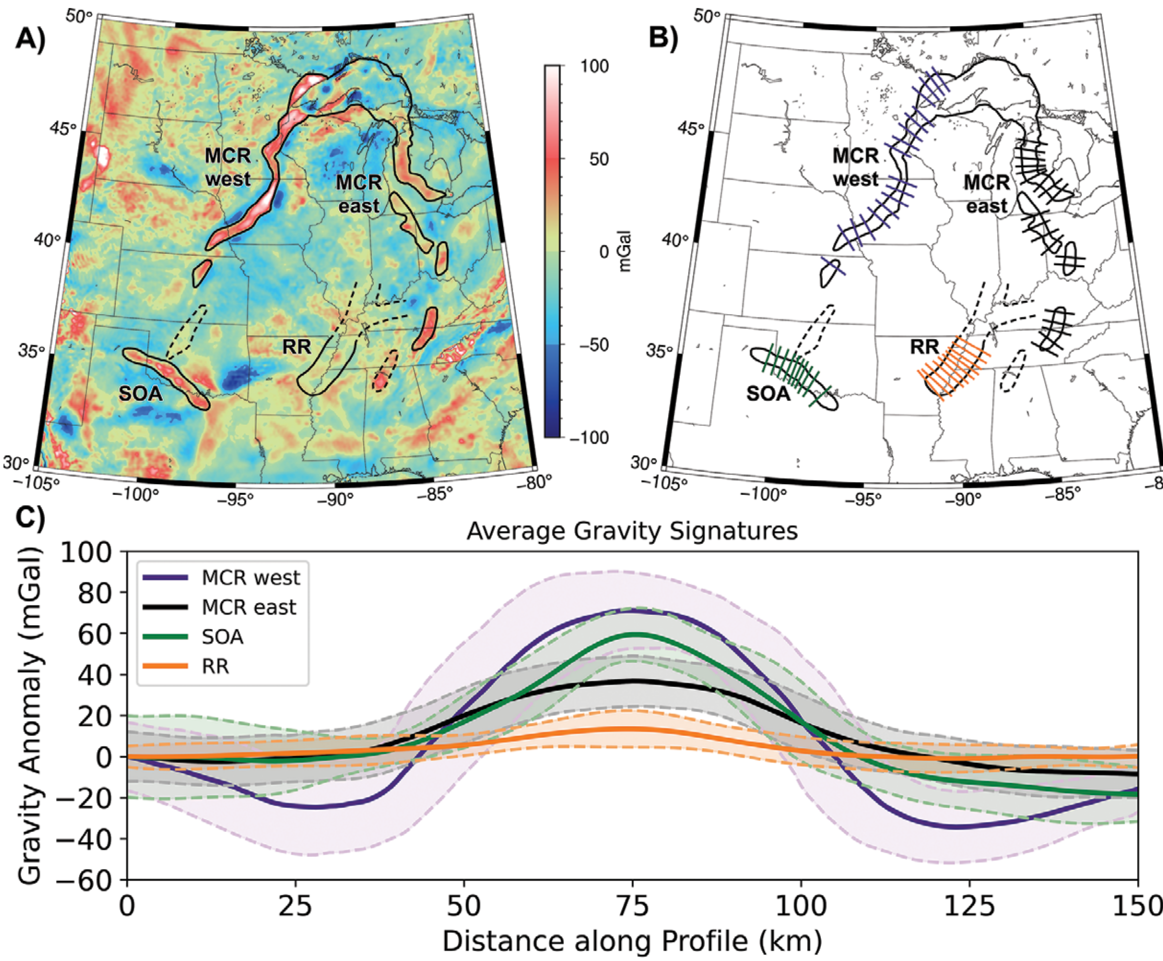

Figure 1. (A) Bouguer gravity anomaly map for central North America. Anomalies related to the Midcontinent Rift (MCR), Southern Oklahoma Aulacogen (SOA), and Reelfoot Rift (RR) are outlined. Dashed lines outline possible extensions of rift arms not included in analysis. (B) Profiles used in calculating the average gravity anomalies. (C) Mean anomalies and standard deviations for rifts.

sequence of rifting, volcanism, sedimentation, subsidence, compression, erosion, and later effects (Stein et al., 2015; Elling et al., 2020). They give insight into how rifts evolve and are useful when studying other failed or active rifts elsewhere.

MIDCONTINENT RIFT

The Midcontinent Rift (MCR), a 3000-km-long band of more than 2 million km^3 of buried igneous and sedimentary rocks that outcrop near Lake Superior, has been extensively studied, as reviewed by Ojakangas et al. (2001) and S. Stein et al. (2018). To the south, it is buried by younger sediments, but easily traced because the rift-filling volcanic rocks are dense and highly magnetized. The western arm extends southward to Oklahoma, as shown by positive gravity anomalies and similar-age diffuse volcanism (Bright et al., 2014). The eastern arm extends southward to Alabama (Keller et al., 1983; C. Stein et al., 2014, 2018; S. Stein et al., 2018; Elling et al., 2020). The MCR likely formed as part of rifting of the Amazonia craton (now in northeastern South America) from Laurentia, the Precambrian core of North America at 1.1 Ga, after the Elzeverian and Shawinigan orogenies and before the Grenville Orogeny (C. Stein et al., 2014, 2018; S. Stein et al., 2018). Surface exposures, seismic data, and gravity data delineate rift basins filled by thick basalt layers and sediments, underlain by thinned crust and an underplate unit, presumably the dense residuum from the magma extraction (Vervoort et al., 2007; S. Stein et al., 2018). The rift was later massively inverted by regional compression, uplifting the volcanic rocks so that some are exposed at the surface today. The MCR has little seismicity along most of its length, but portions in Kansas and Oklahoma experienced seismicity and Phanerozoic deformation (Burberry et al., 2015; Levandowski et al., 2017).

We developed models for each arm (Figs. 2A and 2B), following Elling et al. (2020), because the west arm's larger gravity anomaly indicates differences in magma volume and tectonic evolution. For simplicity, the models use average densities of the sediment, igneous rift fill, underlying crust, underplate, and mantle. We began with GLIMPCE seismic reflection profiles across Lake Superior that give the best available image of structure at depth in the MCR (Green et al., 1989) and permit detailed modeling of its evolution (Stein et al., 2015). We also considered prior gravity models across parts of the MCR (Mayhew et al., 1982; Shay and Trehu, 1993). EarthScope data (Zhang et al., 2016) provided values for the depth and thickness of the volcanics and underplate along the west arm that were used to update the models. These data showed that structure below the west arm resembles that below Lake Superior, suggesting that the structure along the entire MCR is similar. On either side of the central rift basin, basins ~5 km thick resulting from post-rift sedimentation

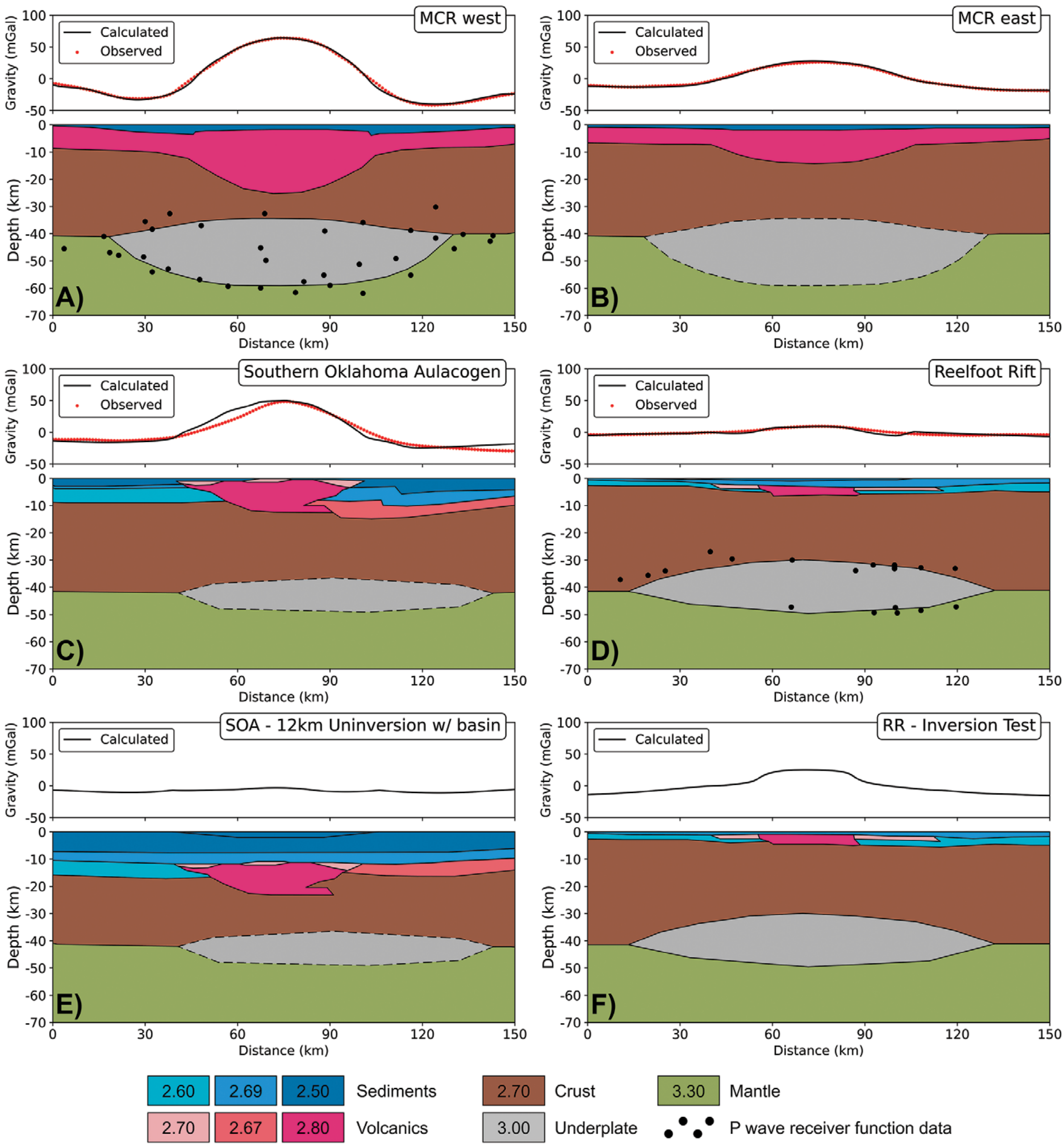

Figure 2. Gravity data and rift models. (A) West Midcontinent Rift (MCR) arm, with underplate based on receiver function data (dots). (B) East MCR arm, modeled with underplate like the west arm's, dashed given its uncertainty. (C) Southern Oklahoma Aulacogen (SOA), with proposed underplate dashed given its uncertainty. (D) Reelfoot Rift (RR), with underplate based on receiver function data (dots). (E) Model for the SOA if it had not been inverted, eliminating the positive anomaly. (F) Model for the RR if it had been inverted, producing a positive anomaly. Densities in g/cm³.

produce bounding gravity lows. The sediments are much thinner over the central basin as a result of inversion, uplift, and erosion after rift failure.

We model the east arm as similar to the west. Because the east arm does not show bounding gravity lows, the model does not include bounding basins. We include an underplate like that below the west arm, although seismic data needed to resolve it are lacking, because such underplates are also seen below the RR, have been proposed below the SOA, are common in rifts worldwide (Thybo and Artemieva, 2013; Rooney et al., 2017), and are expected given the igneous rift fill (Vervoort et al., 2007). The largest difference between the models is the thickness of rift-filling volcanics; the west arm contains 20–25 km of volcanics, whereas the east arm contains 10–15 km. The dense igneous rocks affect the gravity anomaly much more than the underplate, so the geometry of the volcanics in the east arm was adjusted to match the gravity profiles.

SOUTHERN OKLAHOMA AULACOGEN

The Southern Oklahoma Aulacogen (SOA) (Walper, 1977) is a linear alignment of extensively inverted rift structures perpendicular to the southern tip of the MCR's west arm. Its main structures are the Wichita uplift (and associated igneous provinces) and Anadarko Basin. Both the SOA and RR (discussed shortly) initiated as the Cuyania block, also known as the Argentine Precordillera, rifted away from Laurentia (Thomas, 2011; Whitmeyer and Karlstrom, 2007). Rifting is thought to have begun in latest Precambrian, but the oldest dates come from SOA igneous rocks dated at ca. 540 Ma (Wall et al., 2021).

The SOA's geologic and tectonic history has three major phases. The first involved emplacement of the Wichita Igneous Province during development of a rift beginning in the Ediacaran to mid-Cambrian (Brewer et al., 1983; Perry, 1989; Wall et al., 2021). Extensional and transtensional tectonism within the SOA developed during the latest Precambrian–Cambrian opening of the southern Iapetus Ocean as part of Rodinia's breakup (Robert et al., 2021). Following rift failure, thermal subsidence allowed deposition of thick sedimentary sequences, marking the onset of the Anadarko Basin formation (Perry, 1989; Johnson, 2008). Finally, Late Mississippian through Pennsylvanian compression inverted the SOA and formed a NE-trending fold-thrust belt containing the Wichita and Arbuckle Mountains (Keller and Stephenson, 2007). The compression is believed to be related to North America's collision with Africa and South America during the Alleghenian Orogeny (Kluth and Coney, 1981) or tectonic activity along North America's western and southwestern margins (Lawton et al., 2017; Leary et al., 2017). The SOA exposes only a fraction of its extent in the Wichita Mountains and contains more than 210,000 km^3 of buried mafic rocks up to 10 km thick along the entire rift (Hanson et al., 2013), along with a large volume of felsic igneous rocks, including granitic intrusions and interbedded rhyolites. Emplacement and subsequent inversion of the igneous rocks yielded a positive gravity anomaly of ~60 mGal, similar to the average of the MCR arms.

Our SOA model is modified from Keller and Stephenson's (2007) model based on gravity, seismic, aeromagnetic, surface mapping, and drilling data. Seismic reflection data were used to constrain the location and thicknesses of the gabbroic and felsic intrusions producing the large positive anomaly. We simplified their model for comparison with the other rifts. Sedimentary basin rocks were averaged into a few units, and bodies within the gabbroic intrusion that increased in density with depth in the original model were averaged to a single density. Keller and Baldridge (1995) proposed the presence of an underplate, which is consistent with the gravity data and included in our model, though seismic data adequate to confirm (or disprove) its presence are not available.

REELFOOT RIFT

The Reelfoot Rift (RR) underlies the Upper Mississippi Embayment, a broad trough with a complex history of rifting and subsidence (Catchings, 1999). The NE-trending graben of the RR is 70 km wide and more than 300 km long. Reflection profiles and mafic alkalic plutons suggest several episodes of faulting and intrusive activity (Mooney et al., 1983). The RR is believed to have experienced multiple phases of subsidence (Ervin and McGinnis, 1975), with the earliest rifting in the Ediacaran associated with widespread rifting along North America's margins during the breakup of Rodinia. The rift basin primarily developed during this Cambrian event. Later subsidence, perhaps as late as the Cretaceous, is associated with emplacement of mafic igneous intrusives inside the rift and deposition of several kilometers of sediments that bury them (Hildenbrand and Hendricks, 1995; Cox and Van Arsdale, 2002). Relative to the MCR and SOA, the RR experienced significantly less volcanic activity during rifting, and its subsidence influenced the sedimentation and subsequent development of the drainage basins of major rivers, such as the Mississippi. Climate-controlled erosion and unloading of sediments that fill the rift basin have been proposed to have triggered the present seismicity (New Madrid seismic zone) on faults remaining from the rifting (Calais et al., 2010).

We developed our model by modifying one by Liu et al. (2017) based on their work and earlier models constrained by seismic refraction, gravity, and magnetic data (Mooney et al., 1983; Braile et al., 1986; Nelson and Zhang, 1991). Earlier studies identified an underplate, or "rift pillow," whose location is constrained by Liu et al.'s (2017) results. An underplate has also been observed along the RR's northeastern extension (Aziz Zanjani et al., 2019). A feature of our model, required to replicate the lack of a large gravity anomaly, is that the RR contains far less high-density volcanics than the other rifts, perhaps because it extended less. Low-density Quaternary sediments of the Mississippi River basin overlying the rift rocks also contribute to the minimal anomaly.

SIMILARITIES AND DIFFERENCES

Comparing the three rifts' average gravity profiles and subsurface structures inferred in part from them illustrates similarities and differences between the rifts.

Tectonic Setting

All three formed during rifting associated with Laurentia's interactions within the supercontinent of Rodinia. The MCR formed after the Elzeverian and Shawinigan orogenies and before the Grenville Orogeny that assembled Rodinia (e.g., Hynes and Rivers, 2010). Its formation was likely associated with rifting between Laurentia and Amazonia during a plate boundary reorganization (S. Stein et al., 2014, 2018) (Fig. 3A), although details of Amazonia's location and motion are not well constrained at this time because of limited paleomagnetic data (Tohver et al., 2006; Li et al., 2008).

Additional evidence for this view comes from a change in Laurentia's absolute plate motion around the time of the formation of the MCR. A global plate model (Scotese and Elling, 2017), updated with a global compilation of paleomagnetic poles (McElhinny and Lock, 1996; Torsvik et al., 2008, 2012; Merdith et al., 2017; Scotese and Van der Voo, 2017; Veikkolainen et al., 2017), was inverted to generate synthetic apparent polar wander (APW) paths that match the plate model. Comparison with global mean poles (GMP) revealed these synthetic APW paths produce a good fit within the α95 error of the GMPs. Laurentia's APW path has a major cusp, called the Logan Loop, recorded in part by the MCR's volcanic rocks (Fig. 3C). Cusps in APW paths have been observed elsewhere when continents rift apart (Gordon et al., 1984). A similar cusp appears ca. 600 Ma in this model (Fig. 3C), during opening of the Iapetus Ocean as the Argentine Precordillera microcontinent rifted from the Wichita embayment on Laurentia's SE margin (Whitmeyer and Karlstrom, 2007; Thomas, 2011). Both the SOA and RR

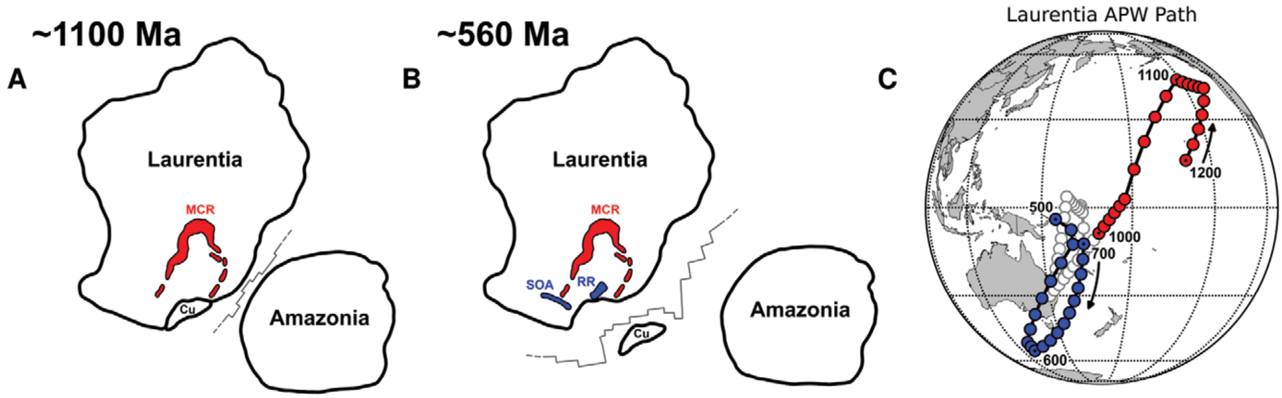

Figure 3. (A) Schematic reconstruction of plate positions relative to Laurentia ca. 1100 Ma during formation of Rodinia. After the Elzeverian and Shawinigan orogenies, but before the Grenville orogeny, spreading likely initiated between the major plates. Following failure of the Midcontinent Rift (MCR), Amazonia shifted north along the margin before recolliding. (B) Similar reconstruction at ca. 560 Ma as Rodinia was breaking up. Cuyania (Cu) block rifted off Laurentia, leaving the Southern Oklahoma Aulacogen (SOA) and Reelfoot Rift (RR) as failed arms. (C) Apparent polar wander (APW) path of Laurentia, plotted in present-day coordinates, at 10-m.y. increments. Red cusp (1200–1000 Ma) is related to formation of the MCR, and blue cusp (700–500 Ma) is related to initial rifting of the SOA and RR. Path between these events plotted in gray.

opened as arms of this triple junction but ultimately failed (Fig. 3B).

Spatial Scale and Architecture

The three rifts have similar spatial scales and structures that seem to characterize failed rifts. Their central grabens, filled with volcanic and sedimentary rocks, are bounded by faults that presumably had normal fault motion during extension. Despite structural differences, all three rifts are ~60–80 km wide, suggesting that failed rifts are consistent with observations that presently spreading rifts had initial widths controlled by crustal thickness rather than the extension history (Allemand and Brun, 1991).

For the MCR and SOA, the rifting faults were reactivated as reverse faults during subsequent inversion. The SOA's gravity high reflects structural inversion of basaltic and gabbroic material in the Wichita Mountains, but significant amounts of rift-fill remain buried beneath the Anadarko Basin (Keller and Stephenson, 2007). Although the RR looks similar overall, it was not significantly reactivated by later inversion. This left its rift-filling volcanics deeper in the subsurface, causing the absence of a positive gravity anomaly. This effect is illustrated by a model showing the gravity anomaly at different stages in the MCR's evolution (Fig. 4), derived from cross-section–balanced reconstructions from GLIMPCE data (Stein et al., 2015). During rifting, dense volcanics near the surface would have caused a large positive anomaly. Subsequent deposition of low-density sediments and subsidence that depressed the volcanics would have caused a gravity low. Eventually, inversion of the rift and erosion and removal of low-density sediments brought the volcanics closer to the surface, causing today's gravity high. Without this inversion, a positive anomaly would not have developed.

We explored the hypothesis that inversion is crucial for producing a positive gravity anomaly using the SOA and RR. The SOA experienced up to 15 km of inversion in the late Paleozoic (Keller and Stephenson, 2007). "Uninverting" the rift by re-burying the gabbroic fill 12 km below a sedimentary basin eliminates the positive anomaly (Fig. 2E). Hence the SOA's gravity high largely reflects the inversion. Conversely, because the RR did not experience significant inversion, its rift basin is buried beneath low-density sediments. Inverting the RR by 3 km and removing sediments overlying the basin (Fig. 2F) produces a positive anomaly due to the high-density igneous rift fill being much nearer to the surface.

Igneous Rock Volumes

There are interesting differences in the volumes of rift volcanics. The MCR is ~3000 km long and contains more than 2 million km^3 of buried igneous rocks, while the SOA and RR are both roughly 1/10 the length of the MCR and contain significantly less volcanics. Although the SOA's volcanic package produces a large positive gravity anomaly, it contains only ~1/10 as much volcanics as the MCR (Hanson et al., 2013).

The differences appear in the cross sections. Volcanics in MCR's west and east arms have average cross-sectional areas of 1100 km^2 and 680 km^2, the SOA has an average cross-sectional area of 470 km^2, whereas the RR's cross-sectional area is much smaller (160 km^2). How these differences arose is unclear. The volumes of igneous rocks produced in rifting can reflect two effects. The first is passive rifting in which extension due to far-field forces causes lithospheric thinning and inflow of hot asthenosphere, such that greater extension produces more melt (Koptev et al., 2015). The second, active rifting, involves an upwelling thermal plume, such that melt is generated by elevated mantle temperatures beneath the lithosphere (Burov and Gerya, 2014). The relative roles of these and other possible rifting processes (King, 2007) are extensively debated but remain unclear (Foulger, 2010). Both active and passive rifting have been invoked to explain the volumes of volcanic rocks at rifted continental margins (White and McKenzie, 1989; Richards et al., 1989; van Wijk et al., 2001). Gallahue et al. (2020) find evidence for both processes on continental margins, with passive rifting having a stronger effect.

A plume contribution for the MCR has been inferred from petrologic and geochemical data (Nicholson et al., 1997; White, 1997; Davis et al., 2021), consistent with the enormous volume of volcanic rocks making it a Large Igneous Province (Green, 1983; Stein et al., 2015). The large volume of MCR rocks also likely reflects Precambrian mantle temperatures higher than today's (Korenaga, 2013). The difference between the west and east arms likely reflects a difference in the amount of extension during rifting (Merino et al., 2013; Elling et al., 2020). The smaller cross-sectional areas of volcanics in the SOA and RR probably do not require assuming a plume. Hence, in our view, the simplest

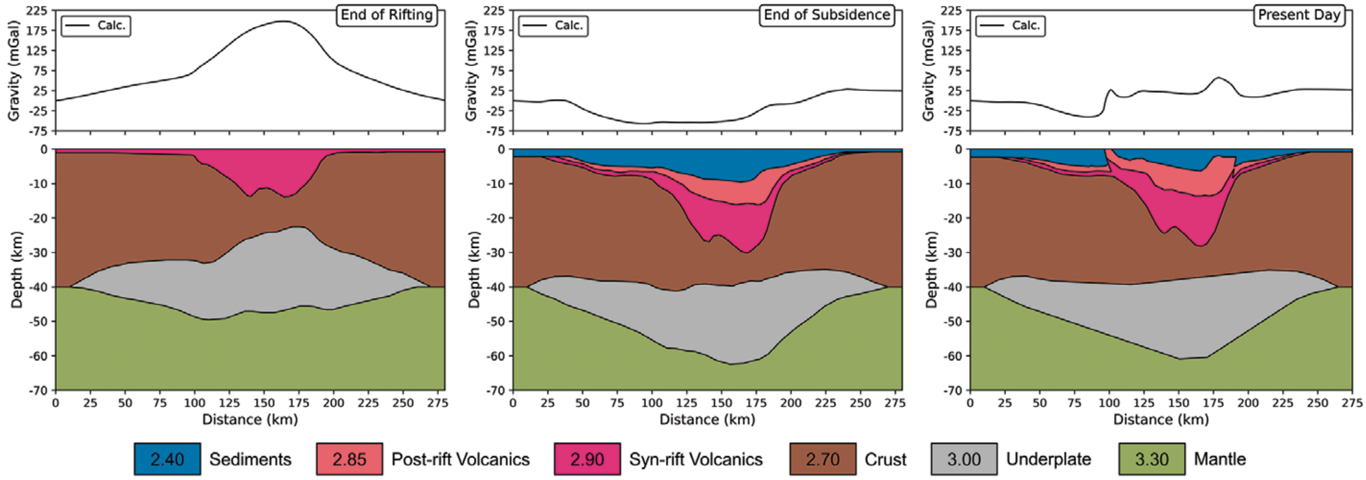

Figure 4. Gravity anomalies expected at various stages in rift evolution, based on model for the Midcontinent Rift under Lake Superior. During rifting, dense volcanics cause a large positive anomaly. Subsequent deposition of low-density sediments and associated subsidence cause a gravity low. Inversion of the rift and erosion of low-density sediments cause the high observed today. Densities in g/cm³. (After Elling et al., 2020.)

explanation of the differences between the SOA and RR, which formed about the same time in similar events, is that the RR had less extension and inversion.

Although models without underplates could fit the gravity data, we include underplates because seismic data both from the MCR (below Lake Superior and on its west arm) and RR show them, and underplates are typically observed at presently spreading rifts. Furthermore, underplates are thought to form from residual melt after extraction of low-density lavas and would be expected given the volume of volcanic material in these rifts. We expect their size to be proportional to the volume (cross-sectional area) of volcanics, as observed for rifted continental margins (Gallahue et al., 2020). Hence, the similar underplates beneath the western MCR and RR are surprising, given that the MCR has roughly ten times more volcanics in cross section. One possible explanation is that in addition to the volcanics in our RR model, another volcanic unit, a mafic high-density upper crustal layer, also exists. Liu et al. (2017, p. 4581) suggest this possibility while noting that such a layer is not required by the data and would be "rare, if not previously unrecognized, for continental rifts." Another possibility is that during the mid-Cretaceous, as the area passed over the Bermuda plume (Cox and Van Arsdale, 2002), plume-derived material may have augmented the underplate. An improved understanding of the relation between the volcanics and underplate would be helpful in understanding the transition between the final stages of continental rifting and early stages of seafloor spreading.

CONCLUSIONS

Traditionally, studies have considered the major failed rifts in central North America separately. However, it is useful to consider them as similar although not identical entities and to view them in the context of both failed and active rifts worldwide. Although they are grossly similar, with similar tectonic origins and structural features, interesting differences between them reflect the extent to which extension, magmatism, subsidence, and inversion by later compression occurred. Further study of these and other failed rifts would provide additional insight into how many rifts transition from the final stages of continental rifting to the early stages of seafloor spreading.

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