Was the Midcontinent Rift part of a successful seafloor-spreading episode?

Carol A. Stein1, Seth Stein2, Miguel Merino2, G. Randy Keller3, Lucy M. Flesch4, and Donna M. Jurdy2

1Department of Earth and Environmental Sciences, University of Illinois at Chicago, Chicago, Illinois, USA, 2Department of Earth and Planetary Sciences, Northwestern University, Evanston, Illinois, USA, 3School of Geology and Geophysics, University of Oklahoma, Norman, Oklahoma, USA, 4Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana, USA

Abstract The ~1.1 Ga Midcontinent Rift (MCR), the 3000 km long largely buried feature causing the largest gravity and magnetic anomaly within the North American craton, is traditionally considered a failed rift formed by isolated midplate volcanism and extension. We propose instead that the MCR formed as part of the rifting of Amazonia (Precambrian northeast South America) from Laurentia (Precambrian North America) and became inactive once seafloor spreading was established. A cusp in Laurentia's apparent polar wander path near the onset of MCR volcanism, recorded by the MCR's volcanic rocks, likely reflects the rifting. This scenario is suggested by analogy with younger rifts elsewhere and consistent with the MCR's extension to northwest Alabama along the East Continent Gravity High, southern Appalachian rocks having Amazonian affinities, and recent identification of contemporaneous large igneous provinces in Amazonia.

1. Introduction

One of the most prominent features on gravity and magnetic maps of North America is the Midcontinent Rift (MCR), a band of buried igneous rocks and associated sediments extending from Lake Superior (Figure 1). These rocks crop out from Minnesota through Wisconsin and the Upper Peninsula of Michigan. To the south, the rift is buried by younger sediments but easily traced because the igneous rocks are dense and strongly magnetized [Hinze et al., 1992; King and Zietz, 1971]. Its west arm extends at least to Oklahoma, and perhaps Texas and New Mexico, via similar-age diffuse volcanism [Adams and Keller, 1996]. The east arm goes through Michigan and extends southward along the Fort Wayne rift and East Continent Gravity High (ECGH) to Alabama [Keller et al., 1982], where gravity and magnetic anomalies are interpreted as indicating mafic rocks [Steltenpohl et al., 2013].

In what tectonic setting the MCR formed remains unclear, despite its prominence. It formed at about 1.109–1.085 Ga within Laurentia, the core of the North American continent assembled in the Precambrian, by volcanism [Davis and Green, 1997; Nicholson et al., 1997] and normal faulting followed by subsidence and sedimentation [Cannon, 1992]. Hence, it is commonly viewed as a type example of a failed rift that formed and died within a continental interior, far from its margins, and thus was not associated with a plate boundary or successful rifting/seafloor-spreading event.

2. Microplate Formation During Continental Rifting

A problem with this interpretation is that many, but not all, intracontinental rifts are associated with plate boundary reorganizations (Figure 2). Present-day continental extension in the East African Rift (EAR) and seafloor spreading in the Red Sea and Gulf of Aden form a classic three-arm rift geometry as Africa splits into Nubia, Somalia, and Arabia. GPS and earthquake data show that the opening involves several microplates between the large Nubian and Somalian plates [Saria et al., 2013]. If the EAR does not evolve to seafloor spreading and dies, in a billion years it would appear as an isolated intracontinental failed rift similar to the MCR.

Another analogy is the West Central African Rift (WCAR) system formed as part of the Mesozoic opening of the South Atlantic. Reconstructing the fit between Africa and South America without overlaps and gaps and matching magnetic anomalies requires microplate motion with extension within continents [Moulin et al., 2010; Seton et al., 2012]. These rifts failed when seafloor spreading initiated along the whole boundary between South America and Africa, illustrating that intracontinental extension can start as part of continental breakup and end when full seafloor spreading is established.
Although similar rift systems existed earlier in the geologic record, it is harder to identify them and establish their history because the plates involved are now widely separated and sometimes experienced subsequent continent-continent collisions that overrode the rifted continental margins. Moreover, the oceanic seafloor with its magnetic reversal record formed after the continents rifted has been lost to subduction.

Figure 1. Gravity map showing Midcontinent Rift (MCR), Fort Wayne Rift (FWR), and East Continent Gravity High (ECGH), computed by upward continuing complete Bouguer anomaly (CBA) data to 40 km and subtracting result from CBA (as shown in the supporting information). Grenville-age Appalachian inliers with Laurentia and Amazonia affinities are shown as light and dark grey regions. Grenville Front shown by solid line where observed and dashed lined where inferred.

Although similar rift systems existed earlier in the geologic record, it is harder to identify them and establish their history because the plates involved are now widely separated and sometimes experienced subsequent continent-continent collisions that overrode the rifted continental margins. Moreover, the oceanic seafloor with its magnetic reversal record formed after the continents rifted has been lost to subduction.

Figure 2. Microplate formation during continental rifting. (a) Present rifting of Africa into three major plates and three microplates, after Saria et al. [2013]. (b) Four-microplate geometry of the west central African rift system, formed during the Mesozoic opening of the South Atlantic, after Moulin et al. [2010].
As just discussed, some active continental rifts with similar lengths to the MCR form boundaries of microplates within the evolving boundary zone between major plates. Similarly, the MCR can be described as part of a microplate’s boundary [Chase and Gilmer, 1973]. Magma volumes inferred from gravity modeling [Merino et al., 2013] are consistent with the western arm opening mainly by extension and the eastern arm in Michigan as a leaky transform.

3. MCR Formation Linked to Laurentia/Amazonia Rifting

We hypothesize that the MCR’s formation and shutdown was part of the evolution of the plate boundary between Laurentia and neighboring plates. The location and timing of key events relevant to the MCR’s evolution fit the known history of plate interactions. Reconstructions based on paleomagnetic data provide a general view of this evolution.

3.1. Cusp in Apparent Polar Wander Path at MCR Initiation

The late Mesoproterozoic loop in Laurentia’s apparent polar wander (APW) path (Figure 3a), often referred to as the Logan Loop, has been interpreted in several ways. The loop was considered to be due to an irregularity in the earth’s magnetic field ~1.11 Ga (a reversal asymmetry or nondipolar field component) but is now thought to reflect a plate tectonic event [Irving, 1979; Halls and Pesonen, 1982]. Volcanic rocks of the MCR provide high-resolution paleomagnetic data for this period and show no asymmetry in the reversals [Swanson-Hysell et al., 2009]. We thus propose that the cusp in Laurentia’s APW path reflects plate motion changes due to rifting, in part involving the MCR. Cusps in APW paths have been observed when continents separate and a new ocean forms between the two fragments [e.g., Irving, 1979]. For example, cusps in North America’s path coincide with the rifting of Europe from North America and the rifting of Gondwana from Laurasia [Gordon et al., 1984].

We propose that the ~1.11 Ga cusp reflects rifting between Laurentia and Amazonia (Precambrian northeast South America). In some models, Amazonia was in contact with Laurentia ~1.2 Ga [Tohver et al., 2002] (Figure 3b), moved left-laterally until about 1.12 Ga [Tohver et al., 2006], and then separated. These interactions are recorded in the rock record. The absence of igneous rocks younger than ~1.23 Ga in the Llano uplift (Texas) area is interpreted to indicate the end of a subduction episode [Mosher et al., 2008]. By 1.2 Ga, intracontinental rifting in Amazonia is recorded in the Nova Brasilândia region [Teixeira et al., 2010]. Amazonia’s subsequent left lateral motion relative to Laurentia is recorded by deformation in the Ji-Paraná shear network from 1.18 to 1.12 Ga [Tohver et al., 2006]. The beginning of its separation from Laurentia is indicated by recently dated ~1.110 Ga mafic rocks in Rincón del Tigre and Huanchaca in the SW corner of the Amazon craton [Ernst et al., 2013] and renewed igneous activity in Nova Brasilândia [Teixeira et al., 2010; Tohver et al., 2006].

Because the MCR formed during Amazonia’s rifting from Laurentia, we argue that the rifting events are related. Mafic magmatism started north and west of Lake Superior ~1.15 Ga and continued for 40 m.y. [Heaman et al., 2007]. The huge volume of MCR volcanism started in the Lake Superior area at ~1.109 Ga [Davis and Green, 1997], approximately the same time as volcanism within the SW part of the Amazonian craton [Ernst et al., 2013].

3.2. Reconstructions Using Paleomagnetic Data

These events are also spatially related. Paleomagnetic reconstructions (Figure 3b) [D’Agrella-Filho et al., 2008] place SW Amazonia near the southern end of the East Continent Gravity High, an extension of the MCR’s eastern arm. Hence, the MCR probably connected to the extensional system that separated the two continents (Figure 3b). In this scenario, MCR extension and volcanism ended when motion was taken up by seafloor spreading between Laurentia and Amazonia, rather than ending due to a Grenville collision.

Subsequently, normal faults in the MCR region were reactivated as reverse faults ~1.06 ± 0.02 Ga [Cannon et al., 1993]. This shortening is assumed to be associated with collisional tectonics during the Grenville orogeny [Sooﬁ and King, 2002], the ~1.3–0.98 Ga assembly of Amazonia and other continents into the supercontinent of Rodinia [Dalziel et al., 2000; Hoffman, 1991; McLelland et al., 2010].
4. Discussion

Our scenario is consistent with the recent recognition that the central and south Appalachians were not part of Laurentia before the Grenville orogeny [Fisher et al., 2010; Loewy et al., 2003; McLelland et al., 2010]. Although Grenville-age Appalachian inlier rocks in the Adirondacks have affinities to Grenville rocks in Canada, most of those to the south are more similar to Amazonia. The latter lack a petrologic signature of the ~1.5–1.3 Ga Granite-Rhyolite province formed within Laurentia, suggesting that they were not part of Laurentia before the Grenville orogeny. The location of Laurentia's eastern margin is obscured by subsequent collisions and thick sedimentation, but we expect that the SE margin would have been south of the southern end of the ECGH.
Our scenario addresses events 1.1 billion years ago, when the geologic record is limited and sparse because many areas are deeply buried, have been eroded, or have been subsequently deformed. Because many aspects of Laurentia-Amazonia rifting and Rodinia’s subsequent assembly during the Grenville orogeny remain unresolved, our scenario is schematic. We attribute MCR formation to Laurentia-Amazonia rifting, which—depending on unresolved issues in reconstruction—also may be related to contemporaneous large igneous provinces and possible rifting in the Indian, Congo, and Kalahari cratons [Ernst et al., 2013] recorded by APW path cusps [Gose et al., 2013]. The key feature of our scenario is the relation between the MCR and continental rifting, which neither requires nor excludes rifting being started by a mantle plume [Nicholson et al., 1997].

In our model, rifting does not result from Grenville collisional events, as sometimes proposed [Gordon and Hempton, 1986]. Instead, the MCR results from rifting during the Grenville at a time when shortening was absent or occurred elsewhere. Probably because of lack of exposure, it is commonly assumed that Grenville-atectonism along the present U.S. to Mexico margin was similar to that recorded by Grenville-age rocks exposed in Canada. However, this need has not been the case. This margin’s length is comparable to that from Turkey to Gibraltar, along which tectonism varied with space and time during the Cenozoic. Similarly, events associated with the formation of the Paleoozoic Appalachian-Caledonian mountains differed along the length of the system.

In summary, rather than viewing the largest gravity and magnetic anomaly in the North American craton as an “exotic” feature, we view the MCR’s formation and evolution in a plate tectonic context, consistent with what is known of plate motions then and analogous rifting events. Additional data can test this scenario. One promising source is the EarthScope program, which is acquiring new data about lithospheric structure below the MCR [Shen et al., 2013; Stein et al., 2011]. Data across its possible extensions to the south and the Grenville Front will show more about these structures and possible relations between them. Our model suggests that the East Continent Gravity High should appear similar to the MCR and that there may be additional evidence of the rifting margin between Amazonia and Laurentia.

Acknowledgments
This work was supported by NSF grants EAR-1148086 and EAR-0952345. C. Stein and S. Stein thank J. Kley and D. Hindle for hospitality at the Georg-August-Universität Göttingen, where much of the writing was done. S. Stein thanks the Alexander von Humboldt Foundation for supporting his stay. We thank Stephen Gao and John Geissman for helpful reviews. Some figures were made using the GMT and GPlates software.

The Editor thanks Stephen Gao and John Geissman for their assistance in evaluating this paper.

References


Gordon, R. G., A. Cox, and S. O’Hare (1984), Paleomagnetic Euler poles and the apparent polar wander and absolute motion of North America since the Carboniferous, Tectonics, 3, 499–537.


