1   **Was the Mid-Continent Rift part of a successful seafloor-spreading episode?**
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23   **Abstract:**

24   The ~1.1 Ga Mid-Continent Rift (MCR), the 3000-km long largely-buried

25   feature causing the largest gravity and magnetic anomaly within the North American

26   craton, is traditionally considered a failed rift formed by isolated midplate volcanism

27   and extension. We propose instead that the MCR formed as part of the rifting of

28   Amazonia (Precambrian northeast South America) from Laurentia (Precambrian

29   North America) and became inactive once seafloor spreading was established. A cusp

30   in Laurentia's apparent polar wander path near the onset of MCR volcanism, recorded

31   by the MCR's volcanic rocks, likely reflects the rifting. This scenario is suggested by

32   analogy with younger rifts elsewhere and consistent with the MCR's extension to

33   southwest Alabama along the East Continent Gravity High, southern Appalachian

34   rocks having Amazonian affinities, and recent identification of contemporaneous

35   large igneous provinces in Amazonia.

36   **1. Introduction**

37   One of the most prominent features on gravity and magnetic maps of North

38   America is the Mid-Continent Rift (MCR), a band of buried igneous rocks and

39   associated sediments extending from Lake Superior (Figure 1). These rocks crop out

40   from Minnesota through Wisconsin and the Upper Peninsula of Michigan. To the

41   south the rift is buried by younger sediments, but easily traced because the igneous

42   rocks are dense and strongly magnetized [*Hinze et al.*, 1992; *King and Zietz*, 1971].

43   Its west arm extends at least to Oklahoma, and perhaps Texas and New Mexico, via

44   similar-age diffuse volcanism [*Adams and Keller*, 1996]. The east arm goes through

45   Michigan and extends southward along the Fort Wayne rift and East Continent

46   Gravity High (ECGH) to Alabama [*Keller et al.*, 1982], where gravity and magnetic

47   anomalies are interpreted as indicating mafic rocks [*Steltenpohl et al.,* 2013].

48   In what tectonic setting the MCR formed remains unclear, despite its

49   prominence. It formed at about 1.109-1.085 Ga within Laurentia, the core of the

50   North American continent assembled in the Precambrian, by volcanism [*Davis and*

51   *Green*, 1997*; Nicholson et al.*, 1997] and normal faulting followed by subsidence and

52   sedimentation [*Cannon*, 1992]. Hence it is commonly viewed as a type example of a

53   failed rift that formed and died within a continental interior, far from its margins, and

54   thus was not associated with a plate boundary or successful rifting/seafloor-spreading

55   event.

56   **2. Microplate formation during continental rifting**

57   A problem with this interpretation is that many, but not all, intracontinental

58   rifts are associated with plate boundary reorganizations (Figure 2). Present-day

59   continental extension in the East African Rift (EAR) and seafloor spreading in the

60   Red Sea and Gulf of Aden form a classic three-arm rift geometry as Africa splits into

61   Nubia, Somalia, and Arabia. GPS and earthquake data show that the opening involves

62   several microplates between the large Nubian and Somalian plates [*Saria et al.*,

63   2013]. If the EAR does not evolve to seafloor spreading and dies, in a billion years it

64   would appear as an isolated intracontinental failed rift similar to the MCR.

65   Another analogy is the West Central African Rift (WCAR) system formed as

66   part of the Mesozoic opening of the South Atlantic. Reconstructing the fit between

67   Africa and South America without overlaps and gaps and matching magnetic

68   anomalies requires microplate motion with up to 95 km extension within continents

69   [*Moulin et al.*, 2010; *Seton et al.*, 2012]. These rifts failed when seafloor spreading

70   initiated along the whole boundary between South America and Africa, illustrating

71   that intracontinental extension can start as part of continental breakup and end when

72   full seafloor spreading is established.

73   Although similar rift systems existed earlier in the geologic record, it is harder

74   to identify them and establish their history because the plates involved are now widely

75   separated and sometimes experienced subsequent continent-continent collisions that

76   overrode the rifted continental margins. Moreover, the oceanic seafloor with its

77   magnetic reversal record formed after the continents rifted has been lost to

78   subduction.

79   As just discussed, some active continental rifts with similar lengths to the

80   MCR form boundaries of microplates within the evolving boundary zone between

81   major plates. Similarly, the MCR can be described as part of a microplate's boundary

82   [*Chase and Gilmer*, 1973]. Magma volumes inferred from gravity modeling [*Merino

83   et al.*, 2013] are consistent with the western arm opening mainly by extension and the

84   eastern arm in Michigan as a leaky transform.

85   **3. MCR formation linked to Laurentia/Amazonia Rifting**

86   We hypothesize that the MCR's formation and shutdown was part of the

87   evolution of the plate boundary between Laurentia and neighboring plates. The

88   location and timing of key events relevant to the MCR's evolution fit the known

89   history of plate interactions. Reconstructions based on paleomagnetic data provide a

90   general view of this evolution.

91   **3.1 Cusp in apparent polar wander path at MCR initiation**

92   The late Mesoproterozoic loop in Laurentia's apparent polar wander (APW)

93   path (Figure 3a), often referred to as the Logan Loop, has been interpreted in several

94   ways. The loop was considered to be due to an irregularity in the earth's magnetic

95   field ~1.11 Ga (a reversal asymmetry or non-dipolar field component), but is now

96   thought to reflect a plate tectonic event [*Irving,* 1979; *Halls and Pesonen*, 1982].

97   Volcanic rocks of the MCR provide high-resolution paleomagnetic data for this

98   period and show no asymmetry in the reversals [*Swanson-Hysell et al.*, 2009]. We

99   thus propose that the cusp in Laurentia's APW path reflects plate motion changes due

100   to rifting, in part involving the MCR. Cusps in APW paths have been observed when

101   continents separate and a new ocean forms between the two fragments [e.g. *Irving,*

102   1979]. For example, cusps in North America's path coincide with the rifting of

103   Europe from North America and the rifting of Gondwana from Laurasia [*Gordon et*

104   *al.*, 1984].

105   We propose that the ~1.11 Ga cusp reflects rifting between Laurentia and

106   Amazonia (Precambrian northeast South America). In some models, Amazonia was in

107   contact with Laurentia ~1.2 Ga [*Tohver et al.*, 2002] (Figure 3b), moved left-laterally

108   until about 1.12 Ga [*Tohver et al.,* 2006], and then separated. These interactions are

109   recorded in the rock record. The absence of igneous rocks younger than ~1.23 Ga in

110   the Llano uplift (Texas) area is interpreted to indicate the end of a subduction episode

111   [*Mosher et al.*, 2008]. By 1.2 Ga, intracontinental rifting in Amazonia is recorded in

112   the Nova Brasilândia region [*Teixeira et al.*, 2010]. Amazonia's subsequent left

113   lateral motion relative to Laurentia is recorded by deformation in the Ji-Paraná shear

114   network from 1.18-1.12 Ga [*Tohver et al.*, 2006]. The beginning of its separation

115   from Laurentia is indicated by recently dated ~1.110 Ga mafic rocks in Rincón del

116   Tigre and Huanchaca in the SW corner of the Amazon craton [*Ernst et al.*, 2013] and

117   renewed igneous activity in Nova Brasilândia [*Teixeira et al.*, 2010; *Tohver et al.*,

118   2006].

119   Because the MCR formed during Amazonia's rifting from Laurentia, we argue

120   that the rifting events are related. Mafic magmatism started north and west of Lake

121   Superior ~1.15 Ga and continued for 40 my [*Heaman et al.*, 2007]. The huge volume

122   of MCR volcanism started in the Lake Superior area at ~1.109 Ga [*Davis and Green*,

123   1997], approximately the same time as volcanism within the SW part of the

124   Amazonian craton [*Ernst et al.*, 2013].

125   **3.2 Reconstructions using paleomagnetic data**

126   These events are also spatially related. Paleomagnetic reconstructions (Figure

127   3b) [*D'Agrella-Filho et al.*, 2008] place SW Amazonia near the southern end of the

128   East Continent Gravity High, an extension of the MCR's eastern arm. Hence the

129   MCR probably connected to the extensional system that separated the two continents

130   (Figure 3b). In this scenario, MCR extension and volcanism ended when motion was

131   taken up by seafloor spreading between Laurentia and Amazonia, rather than ending

132   due to a Grenville collision.

133   Subsequently,, normal faults in the MCR region were reactivated as reverse

134   faults ~1.06±0.02 Ga [*Cannon et al., 1993*]. This shortening is assumed to be

135   associated with collisional tectonics during the Grenville orogeny [*Soofi and King*,

136   2002], the ~1.3-0.98 Ga assembly of Amazonia and other continents into the

137   supercontinent of Rodinia [*Dalziel et al.*, 2000*; Hoffman*, 1991; *McLelland et al.*,

138   2010].

139

140   **4. Discussion**

141   Our scenario is consistent with the recent recognition that the central and

142   south Appalachians were not part of Laurentia before the Grenville orogeny [*Fisher et*

143   *al.*, 2010*; Loewy et al*., 2003; *McLelland et al*., 2010]. Although Grenville-age

144   Appalachian inlier rocks in the Adirondacks have affinities to Grenville rocks in

145   Canada, most of those to the south are more similar to Amazonia. The latter lack a

146   petrologic signature of the ~1.5-1.3 Ga Granite-Rhyolite province formed within

147   Laurentia, suggesting that they were not part of Laurentia before the Grenville

148   orogeny. The location of Laurentia's eastern margin is obscured by subsequent

149   collisions and thick sedimentation, but we expect that the SE margin would have been

150   south of the southern end of the ECGH.

151   Our scenario addresses events 1.1 billion years ago, when the geologic record

152   is limited and sparse because many areas are deeply buried, have been eroded, or have

153   been subsequently deformed. Because many aspects of Laurentia – Amazonia rifting

154   and Rodina's subsequent assembly during the Greenville orogeny remain unresolved,

155   our scenario is schematic. We attribute MCR formation to Laurentia – Amazonia

156   rifting, which – depending on unresolved issues in reconstruction - also may be

157   related to contemporaneous large igneous provinces and possible rifting in the Indian,

158   Congo, and Kalahari cratons [*Ernst et al.*, 2013] recorded by APW path cusps [*Gose*

159   *et al*., 2013]. The key feature of our scenario is the relation between the MCR and

160   continental rifting, which neither requires nor excludes rifting being started by a

161   mantle plume [*Nicholson et al.*, 1997].

162   In our model, rifting does not result from Grenville collisional events, as

163   sometimes proposed [*Gordon and Hempton*, 1986]. Instead, the MCR results from

164   rifting during the Grenville at a time when shortening was absent or occurred

165   elsewhere. Probably because of lack of exposure, it is commonly assumed that

166   Grenville-age tectonism along the present U.S. to Mexico margin was similar to that

167   recorded by Grenville-age rocks exposed in Canada. However, this need not have

168   been the case. This margin's length is comparable to that from Turkey to Gibraltar,

169   along which tectonism varied with space and time during the Cenozoic. Similarly,

170   events associated with the formation of the Paleozoic Appalachian-Caledonian

171   mountains differed along the length of the system.

172   In summary, rather than viewing the largest gravity and magnetic anomaly in

173   the North American craton as an "exotic" feature, we view the MCR's formation and

174   evolution in a plate tectonic context, consistent with what is known of plate motions

175   then and analogous rifting events. Additional data can test this scenario. One

176   promising source is the EarthScope program, which is acquiring new data about

177   lithospheric structure below the MCR [*Shen et al.*, 2013; *Stein et al.*, 2011]. Data

178   across its possible extensions to the south and the Grenville Front will show more

179   about these structures and possible relations between them. Our model suggests that

180   the East Continent Gravity High should appear similar to the MCR, and that there

181   may be additional evidence of the rifted margin between Amazonia and Laurentia.

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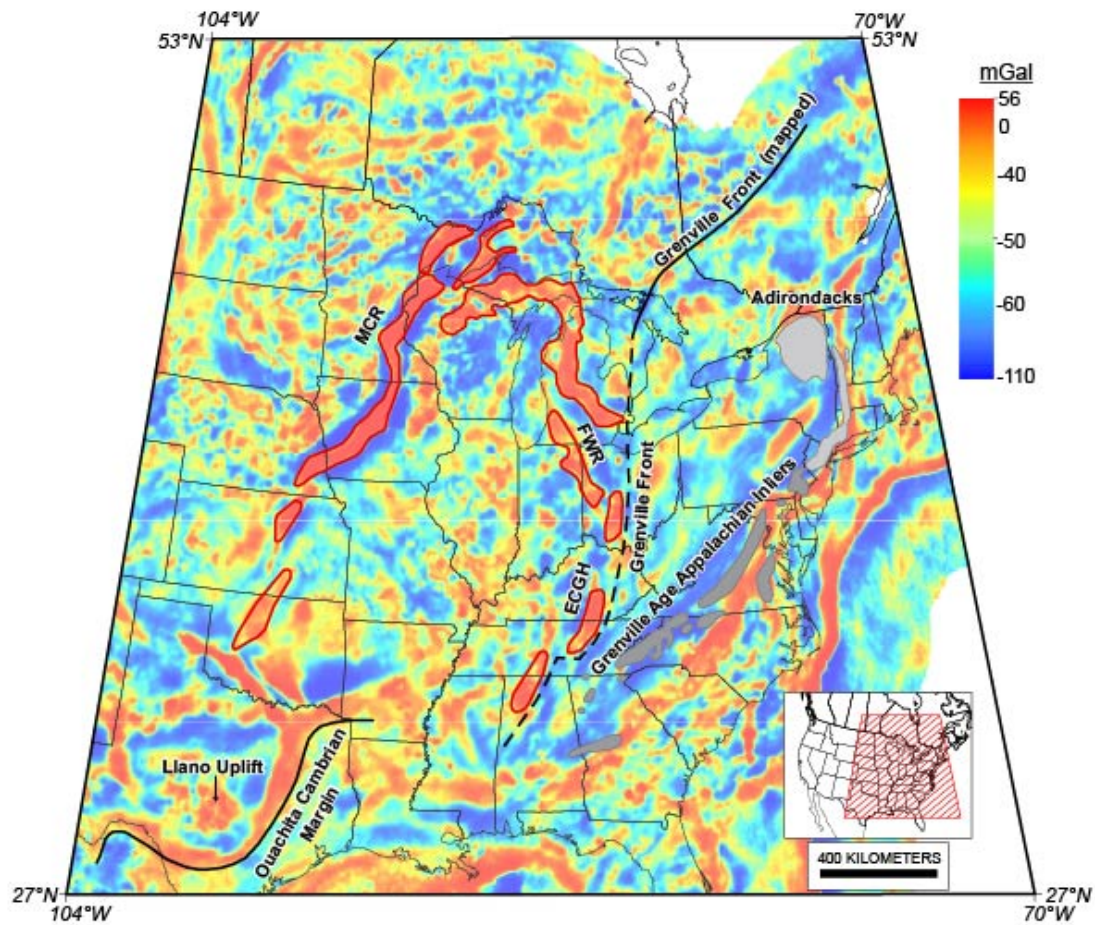
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343   Figure 1. Gravity map showing Midcontinent Rift (MCR), Fort Wayne Rift (FWR),

344   and East Continent Gravity High (ECGH), computed by upward continuing complete

345   Bouguer anomaly (CBA) data to 40 km and subtracting result from CBA (as shown in

346   the supplemental material). Grenville-age Appalachian inliers with Laurentia and

347   Amazonia affinities are shown as light and dark grey regions. Grenville Front shown

348   by solid line where observed and dashed lined where inferred.

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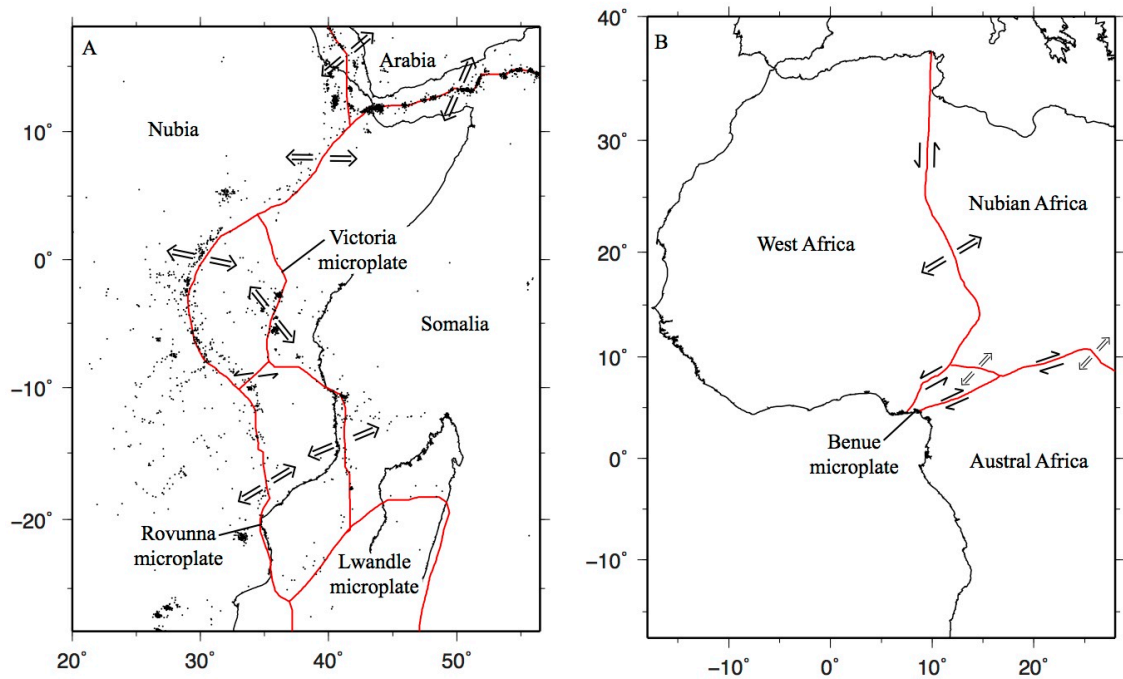
351 Figure 2. Microplate formation during continental rifting. (a) Present rifting of Africa

352 into three major plates and three microplates, after *Saria et al.* [2013]. (b) Four-

353 microplate geometry of the west central African rift system, formed during the

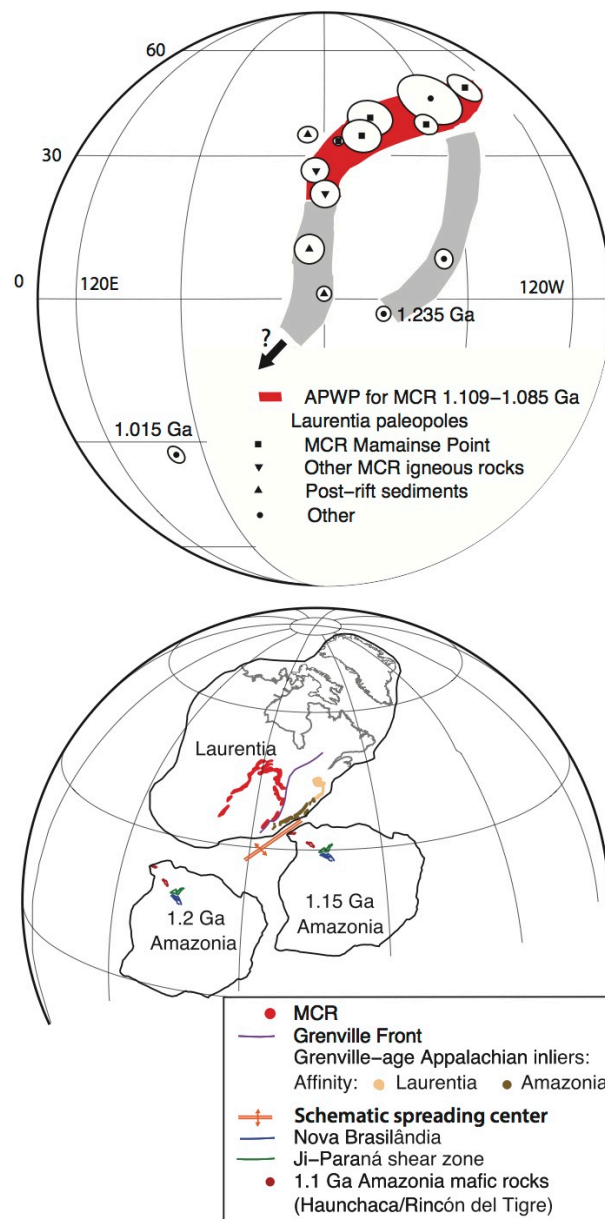354 Mesozoic opening of the South Atlantic, after *Moulin et al.* [2010].

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358   Figure 3. (a) Apparent polar wander path for Laurentia, showing cusp approximately

359   at onset of MCR volcanism (1.109 Ga) that likely reflects the rifting. MCR volcanism

360   interval is shown in red. Poles from *Elming et al.* [2009] and *Swanson-Hysell et al.*

361   [2009]. (b) Reconstruction of plate positions before Laurentia-Amazonia separation,

362   after [*D'Agrella-Filho et al.,* 2008; *Elming et al.,* 2009; *Tohver et al.,* 2002],

363   schematic spreading center geometry, and relevant features. Additional information

364   about the poles is in the supplemental material.

1 **Auxiliary material for:**

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3 **Was the Mid-Continent Rift part of a successful seafloor-spreading episode?**

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23 **1. Gravity Analysis**

24 The residual Bouguer anomaly gravity map in Figure 1 in the main text

25 (Figure S3 here) was calculated by upward continuing complete Bouguer anomaly

26 (CBA) data (Figure S1) to 40 km (Figure S2) and subtracting the result point-by-point

27 from the CBA grid. Upward continuation acts as a low pass filter that attenuates

28 shorter wavelength anomalies and so smoothes the data, as demonstrated in Figure S2

29 [Blakely, 1996]. The gravity highs associated with the Mid-Continent Rift (MCR),

30 Fort Wayne Rift (FWR), and East Continent Gravity High (ECGH) still appear

31 strongly, trending in the same directions as in the CBA map. Subtracting the upward

32 continuation result removes the long wavelength anomalies and hence emphasizes

33 shallower features (Figure S3). The gravity lows associated with the flanking rift are

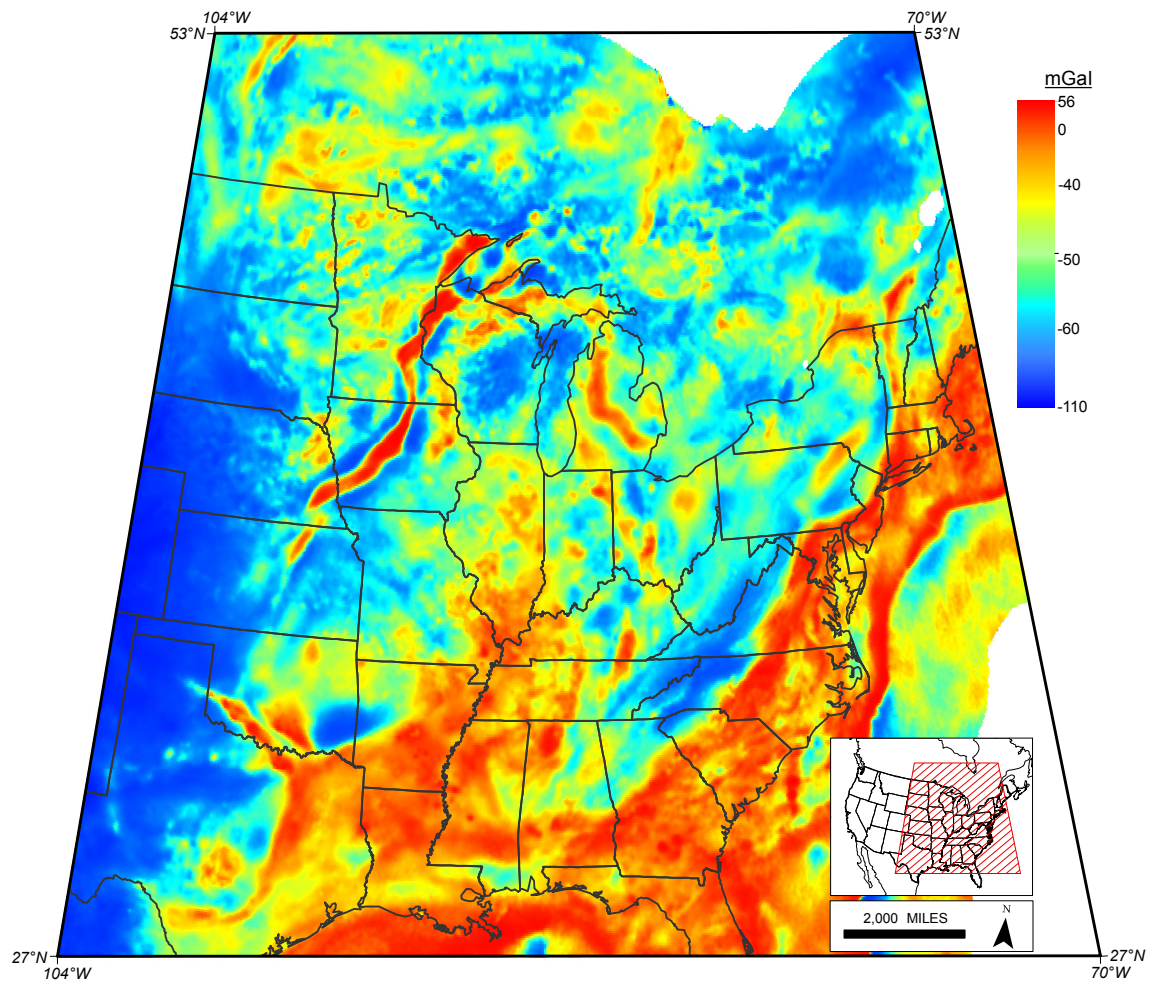34 more pronounced, particularly in Michigan [*Buening*, 2013].

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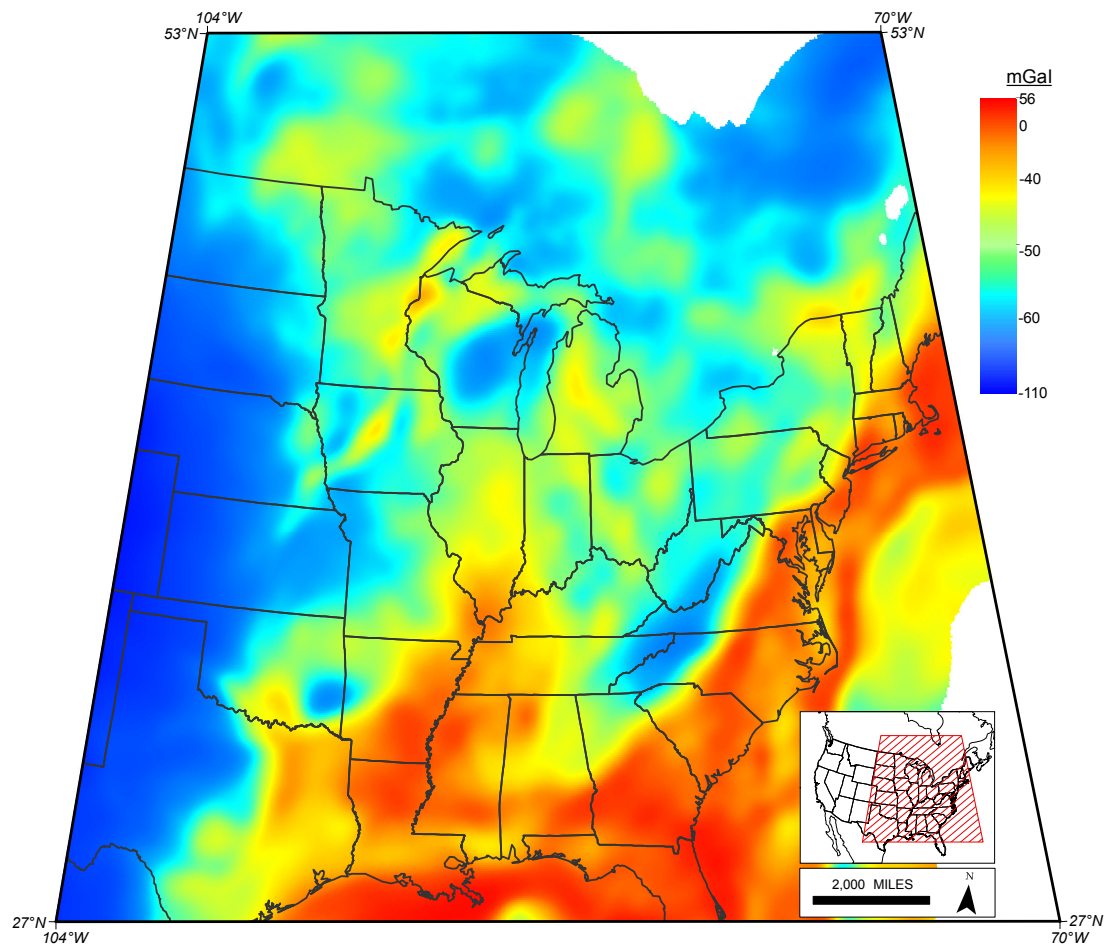Figure S1. Complete Bouguer gravity anomaly (CBA) for eastern United States.

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43   Figure S2. Gravity anomaly upward continued to 40 km.
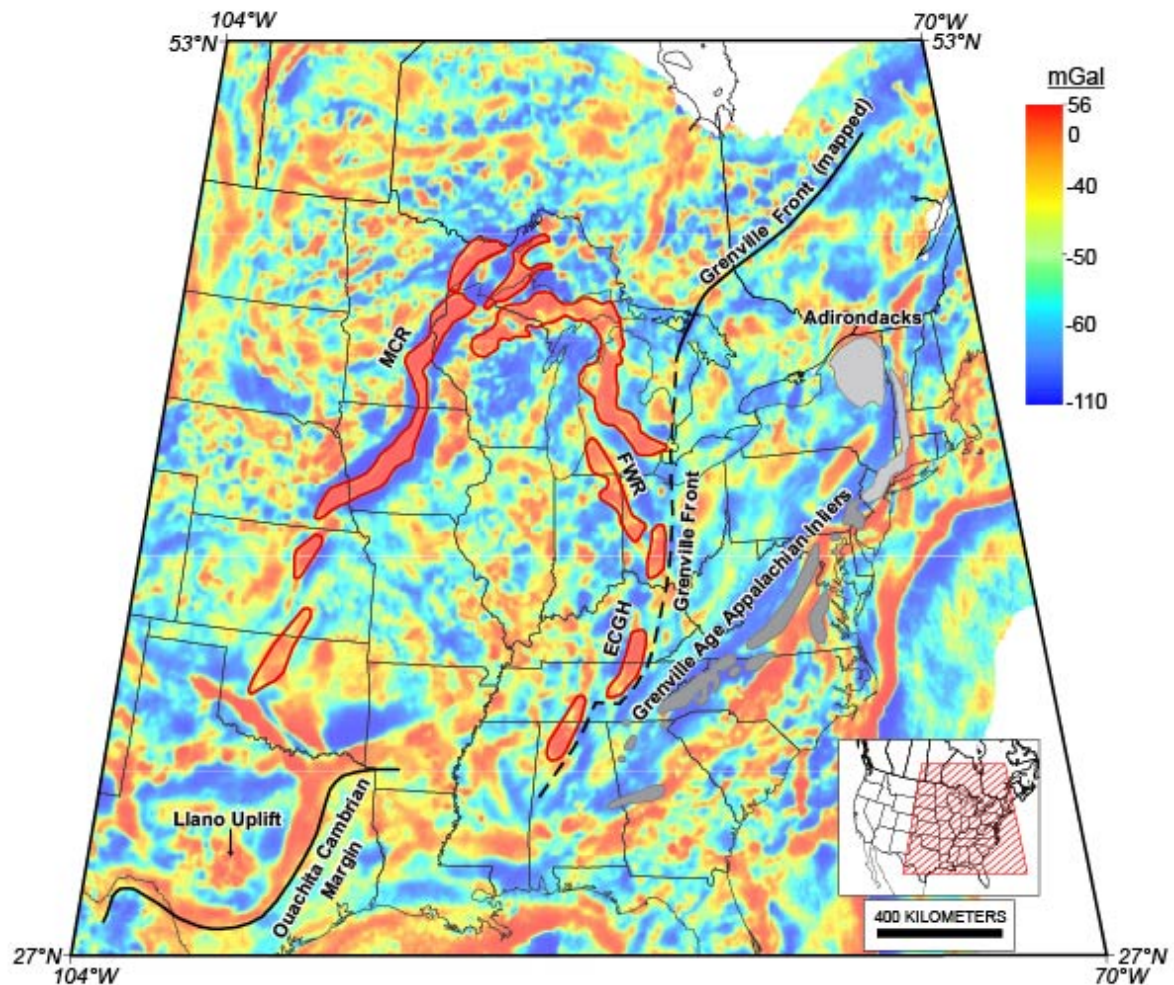44
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48   Figure S3. Residual anomaly map (same as Figure 1 in paper) computed by

49   subtracting the 40 km upward continued grid (Figure S2) from the Complete Bouguer

50   Anomaly grid (Figure S1). This process shows features that have a strong expression

51   in the upper crust. Large features appear sharper and smaller scale features are more

52   pronounced. The gap in the ECGH in the northern part of Kentucky at about 38°N is

53   due to the overprinting by the much younger (Cambrian) Rome Trough, an

54   extensional feature [*Gao et al.,* 2000]. Labeled features include the Midcontinent Rift

55   (MCR), Fort Wayne Rift (FWR), and East Continent Gravity High (ECGH),

56   Grenville-age Appalachian inliers with Laurentia and Amazonia affinities are shown

57   as light and dark grey regions. Grenville Front shown by solid line where observed

58   and dashed lined where inferred.

59 **2. Apparent Polar Wander Path**

60   The apparent polar wander path for Laurentia in Figure 3a contains

61 paleomagnetic poles from *Elming et al.* [2009] *and Swanson-Hysell et al.* [2009].

62 Prior to the formation of the Mid-Continent Rift (MCR) we use the 1.235 Ga pole for

63 the Sudbury Dykes (1, blue), 1.204 Ga Upper Bylot (2, blue), and 1.141 Ga pole for

64 the Abitibi Dykes (3, blue). For the MCR, we primarily use the best-dated sites, those

65 from Mamainse Point (4-8, red) determined by *Swanson-Hysell et al.* [2009]. These

66 dates [*http://www.swanson-hysell.org/research/keweenawan/*] range from about

67 1.109-1.094 Ga with the exception of one somewhat younger paleopole. We also use

68 two somewhat younger paleopoles from *Swanson-Hysell et al.* [2009] for the ~1.095

69 Ga Portage Lake Lavas (9, red) and the ~1.087 Ga Lake Shore Traps (10, red).

70   For the post-rift sediments of the MCR [*Ojakangas et al.*, 2001] we use only

71 those from the Oronto Group (Copper Harbor Conglomerate (oldest, 11 green),

72 Nonesuch Shale (12, green) and Freda Sandstone (youngest, 13 green)). The Copper

73 Harbor Conglomerate pole plots near the igneous MCR path, unlike the two younger

74 formations. *Halls and Palmer* [1981] note that the direction of magnetization of the

75 Copper Harbor sediments is "virtually indistinguishable" from the Portage Lake

76 volcanics and thus may have been reset due to the interlayering volcanic intrusions

77 and/or are of similar age. Thus these sediments may have been deposited during the

78 rift's opening. Because the Bayfield Group near the MCR may be significantly

79 younger than the Oronto Group, we do not use its paleomagnetic pole. The youngest

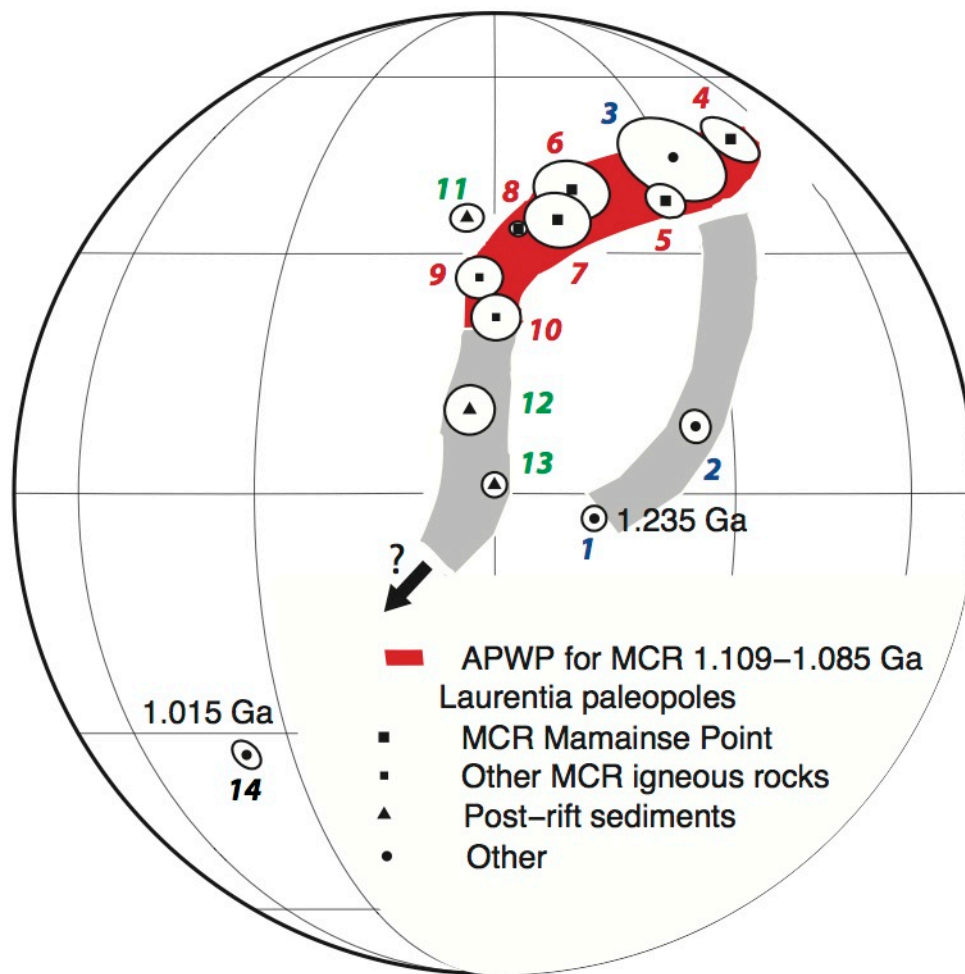80 pole shown is for the 1.015 Ga Halliburton Intrusions (14, black).

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Figure S4- Figure 3a from text with additional information. Apparent polar wander path for Laurentia, showing cusp approximately at onset of MCR volcanism (1.109 Ga) that likely reflects the rifting. Poles from *Elming et al.* [2009] and *Swanson-Hysell et al.* [2009]. 1-3 (blue) before MCR volcanism; 4-10 (red) MCR volcanics, 11-13 (green) mostly post-volcanic MCR sediments, 14 (black) post MCR data. The paleopole for the Copper Harbor Conglomerates (11) most likely reflects syn-rift deposition.

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