Tectonic implications of the gravity signatures of the Midcontinent Rift and Grenville Front

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Abstract

North America's Midcontinent Rift (MCR) and Grenville Front (GF) jointly record aspects of the complex history of the assembly of Rodinia. The \~1100 Ma MCR, remaining from a failed major rifting event, is exposed along Lake Superior and well defined by gravity, magnetic, and seismic data. The GF, which results from collisions between Laurentia and Amazonia \~1300-980 Ma, is exposed in and identified by seismic and potential field data in Canada. In the eastern U.S., lineated gravity highs extending southward from Michigan to Alabama, along the trend of the front in Canada, have been interpreted either as a buried Grenville Front or as part of the MCR's east arm. We explore this issue by examining the gravity signatures of the MCR and GF. Both the MCR's arms have pronounced gravity highs, with the west arm's greater than the east arm's. Combining the gravity observations with seismic data suggests that the west arm contains 20-25 km thickness of volcanics, whereas the east arm contains 10-15 km of volcanics. Along the Grenville Front in Canada, thickened crust along the northern portion causes a broad gravity low, whereas the stacked thrusts along the southern portion cause essentially no gravity signature. Hence the lineated gravity highs in the eastern U.S. appear similar to those along the remainder of the MCR, and unlike those on either portion of the GF. These data favor the gravity anomalies traditionally interpreted as the Grenville Front in the eastern U.S. instead being part of the MCR's east arm. A thrust sheet structure like that of the southern Canadian Grenville Front - which would have essentially no gravity effect - could also be present along the MCR's east arm, as implied by recent EarthScope seismic data.
Introduction

Two prominent Precambrian features of central North America (Fig. 1) record opposite ends of the Wilson cycle. One, the Midcontinent Rift (MCR), is a 3000-km long horseshoe-shaped band of buried igneous and sedimentary rocks that outcrop near Lake Superior (Ojakangas et al., 2001; Stein et al., 2018a). To the south, it is buried by younger sediments, but easily traced because the rift-filling volcanic rocks are dense and highly magnetized (Merino et al., 2013). The western arm extends at least through Oklahoma, and perhaps Texas and New Mexico, as evidenced by similar-age diffuse volcanism (Adams and Keller, 1994, 1996; Bright et al., 2014). The eastern arm extends southward through lower Michigan and probably to Alabama (Lyons, 1970; Keller et al., 1982; Dickas et al., 1992; Stein et al., 2014). The MCR likely formed as part of the rifting of the Amazonia craton (now in northeastern South America) from Laurentia, the Precambrian core of North America (Stein et al., 2014, 2016).

The second major feature, east of the MCR, is the Grenville Front (GF). The front is the observed continentward boundary of deformation from the Grenville orogeny, the sequence of orogenic events from ~ 1300- 980 Ga culminating in the assembly of the supercontinent of Rodinia from blocks including Amazonia and Laurentia (Li et al., 2008). Studies in SE Canada, where Grenville rocks are exposed, find that the orogeny involved discrete contractional phases, notably the Shawinigan from ~ 1200-1140 Ma, Ottawan from ~ 1090-1030 Ma, and Rigolet from ~ 1010-980 Ma (Rivers, 2012; McLelland et al., 2013). In SE Canada from ~54°N to Lake Ontario, erosion has exposed deformed rocks from these orogenic events.

The orogeny’s phases presumably reflect a series of continental blocks and arcs colliding with and accreting to Laurentia at various locations along its eastern margin. However, the specifics of the plate interactions remain unresolved because the limited paleomagnetic data allow a range of possible scenarios. A common aspect of many reconstructions during this time period is that Amazonia collided, rifted, and re-collided with Laurentia during multiple phases (Tohver et al., 2002, 2006), but the inferred southern extent of this collision varies between reconstructions (Li et al., 2008, 2013; Cawood and Pisarevsky, 2017; Merdith et al., 2017). The MCR likely formed between...
compressional phases of the Grenville Orogeny, involving the rifting of Amazonia from Laurentia, where it was left behind as a failed rift, with extension ending in ~ 1096 Ma (Stein et al., 2014, 2015).

The locations of the Grenville Front in Canada and of the MCR's east arm from Lake Superior to southern Michigan are generally accepted. However, questions remain as to their locations further south in the eastern U.S. Lineated gravity highs (Fig. 1b), known as the East Continent Gravity High (ECGH) and Fort Wayne Rift (FWR), extend southward from Michigan to Alabama. Based on the similarity of their trend to that of the Grenville Front in Canada, these have been interpreted as indicating a southward extension of the Front (Zietz et al., 1966; Hoffman, 1991; Whitmeyer and Karlstrom, 2007; Baranoski et al., 2009; Bartholomew and Hatcher, 2010). Alternatively, based on the anomalies' similarities to those along the MCR, they have been interpreted as part of the MCR's eastern arm (Lyons, 1970; Keller et al., 1982; Dickas et al., 1992; Stein et al., 2014; 2018b). The traditionally assumed Front's location near southeast Michigan implies that the MCR's east arm ended there, presumably because propagation of the rift extension and volcanism were stopped by the preexisting Front (Cannon et al., 1989). However, it now appears that the MCR formed before the presently observed Grenville Front (Malone et al., 2016; Stein et al., 2018a).

In this paper, we explore this issue by examining the gravity signatures of the MCR and GF away from the disputed area in the eastern U.S. The two features have quite different gravity signatures, owing to their different tectonic natures. We then find that the lineated gravity highs in the eastern U.S. appear similar to those along the remainder of the MCR, and unlike those on either portion of the GF, favoring the gravity anomalies reflecting a southward part of the MCR's east arm. In addition, a thrust sheet structure like that of the southern Canadian Grenville Front - which would have a minimal gravity signature - could also be present along the MCR's east arm, as implied by recent EarthScope seismic data (Long et al., 2019).

Comparison of gravity data for the Rift and Front
We analyzed gravity data to compare and contrast the differences between four features; the west and east arms of the MCR and the northern and southern portions of the Grenville Front in Canada. We grouped profiles into MCR west, MCR east, GF south, and GF north. Using a combination of the PACES gravity database jointly developed by the University of Texas at El Paso and the U. S. Geological Survey (Keller et al., 2006) and the TOPEX satellite gravity data (Sandwell et al., 2013) (to fill in gaps in PACES), profiles 150 km long and approximately 50 km apart were extracted (Fig. 2a). We calculated a mean gravity profile and its standard deviation for each feature (Fig. 2b).

The mean profiles show differences between the features, reflecting their structure and origin. The Grenville Front in Canada exhibits two decidedly different gravity signatures. Along its northern portion, the Front appears as a broad negative anomaly of ~40 mGal. Along the front’s southern section, it exhibits essentially no anomaly, positive or negative. Hence the two portions of the Front differ, with one showing a low and the other showing essentially no anomaly.

In contrast, the rift appears as a large positive anomaly along its entire length. This anomaly, which has has been used to map the MCR, reflects the fact that the MCR combines the geometry of a rift and the huge igneous rock volume of a Large Igneous Province (Green, 1983; Stein et al., 2015). Some differences appear between the east and west arms of the MCR. The west arm is characterized by large gravity highs (~80 mGal) bounded by ~20 mGal lows on either side of the rift basin. The east arm has smaller (~40 mGal) gravity highs and lacks the bounding lows. Thus the anomalies over the two arms are generally similar, in that both are highs, but with differing amplitudes. These differ noticeably from the anomalies over the Grenville Front.

We divided the profiles across the east arm into nine crossing the traditionally mapped east arm in Michigan and eleven crossing its proposed southward extension (Fig. 2c). As shown, the mean profiles of the two sets are almost identical in shape and overlap in amplitude. Hence this larger dataset supports Stein et al.’s (2018b) analysis, based on individual profiles, that the gravity anomalies of the East Continent Gravity
High and Fort Wayne Rift, traditionally interpreted as a southward extension of the Grenville Front are instead part of the MCR's east arm.

**Midcontinent Rift Models**

The gravity signatures of the features reflect their different subsurface structures. The Midcontinent Rift's present structure results from the combined effects of a sequence of rifting, volcanism, sedimentation, subsidence, compression, and any later effects (Stein et al., 2015; 2018a). The large positive gravity anomalies along the MCR primarily reflect the large volume of high-density igneous rocks filling the rift basins. Modeling this for each arm provides a useful comparison of the effects of magma volume and position. Merino et al. (2013) produced a generalized model, inspired by a COCORP reflection line in Kansas (Serpa et al., 1984; Woelk and Hinze, 1991), in which the intrusions were modeled simply as trapezoids of uniform density. Here, we developed more detailed models for the average structure along each arm (Fig. 3). We began with structural results from the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) seismic reflection profiles of the rift across Lake Superior (Green et al., 1989). We also considered other 2-D gravity models across the MCR (Mayhew et al., 1982; Hinze et al., 1992; Van Schmus and Hinze, 1985; Chandler et al., 1989; Shay and Trehu, 1993), and new seismic data from the Superior Province Rifting EarthScope Experiment (SPREE) (Zhang et al., 2016). The SPREE data show structure below the west arm similar to that below Lake Superior, suggesting that the structure along the entire MCR is similar.

Hence in our models, the rift arms have similar structures. The largest difference between the arms is the thickness of the rift-filling volcanics. Based on the SPREE seismic data, the west arm model has 20-25 km of volcanics filling the rift basin, producing an 80 mGal positive anomaly that closely matches the actual data. On either side of the rift basin, sedimentary basins roughly 5 km thick resulting from post-rift sedimentation produce the bounding gravity lows. The sediments are much thinner over the basin as a result of inversion, uplift, and erosion after rifting ended. This stripped off much of the overlying sediments, leaving only the bounding basins. The east arm's
comparatively moderate gravity high, however, is modeled assuming significantly less
(10-15 km) volcanics. Because the data do not show bounding gravity lows, the model
does not include bounding sedimentary basins. The models for both arms assume
similar Moho depth and underplating, presumably the dense lower residuum from the
magma extraction (Vervoort et al., 2007; Stein et al., 2018a).

The models are schematic, in that they are seek to characterize an average
structure of the two arms. Nonetheless, they show clear differences between the MCR
and Grenville Front, discussed next.

Grenville Front Models

COCORP and Lithoprobe seismic reflection studies have imaged the crustal
structure of the Grenville Front in Canada, showing southeast-dipping structures
throughout preserved sections of the orogen (Culotta et al., 1990; Ludden and Hynes,
2000; Hynes and Rivers, 2010). Using these, we modeled schematic subsurface
structures to fit the negative gravity anomaly in the northern section and the lack of a
gravity anomaly in the south (Fig. 4).

The northern section of the Front is characterized by a pronounced Bouguer
gravity low that likely reflects progressive thickening of the older and less dense
northwestern Laurentian crust with continued orogenic thrusting, consistent with studies
of analogous mountain-building events such as the Himalayan-Tibetan orogen
(Pilkington, 1990; Hynes, 1994; Hynes and Rivers, 2010). In our models, thickening of
the Laurentian crust by roughly 10 km at the front replicates the ~40 mGal gravity
anomaly.

In contrast, gravity data across the southern section show essentially no gravity
anomaly, positive or negative. This observation accords with the fact that seismic data
along the southern section show no crustal thickening (Culotta et al., 1990). Most of the
present-day preserved structure is likely related to the last major episode of orogeny in
this area, during which the shear zones soled (became subhorizontal) into the present-
day middle crust no deeper than 25 km (White et al., 2011). The thrust faulting has only
a minor gravity signature. In our model, denser younger crust to the southeast stacked against an older less dense Laurentian crust leads to a small anomaly that becomes more negative to the northwest.

Tectonic implications

The analysis here confirms our previous conclusion that the lineated positive gravity anomalies along the FWR and ECGH are consistent with their being due to igneous rocks filling part of the MCR's east arm. Moreover, these positive gravity anomalies are unlike those on either portion of the Grenville Front in Canada.

Given that the gravity highs likely reflect the MCR's east arm, the question remains whether a Grenville-Front type structure could also exist nearby. Because the northern Grenville Front in Canada has a pronounced negative anomaly associated with crustal thickening, it seems implausible that such a structure could exist along the MCR's east arm. However, the gravity data do not exclude GF South-type structures, in which thrust faulting produces only a minor gravity anomaly. Deformation interpreted as Grenville age has been identified in Ohio and Kentucky in seismic reflection data (Drahovzal, 1997; Baranoski et al., 2009). Recent seismic data support this possibility, showing southeast-dipping structures, similar to those along the GF in southern Canada, near the MCR's east arm (Long et al., 2019).

In summary, the gravity data favor the traditionally inferred position of the “Grenville Front” in the eastern U.S. being part of the MCR's east arm. However, a thrust sheet structure like that of the southern Canadian Grenville Front - which would have essentially no gravity effect - could also be present in the area. In our view, modern high-quality seismic reflection surveys combined with additional geological studies would be the best way to address this question.

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Fig. 1: (a) Reconstruction showing commonly assumed locations of major blocks and Grenville-age orogenic belts, in present-day orientation, associated with the accretion of the Amazonia and Rio de la Plata (RdP) blocks to Laurentia, the core of Precambrian North America (after Li et al., 2008). (b) Complete Bouguer anomaly gravity map, showing locations of the MCR, East Continent Gravity High (ECGH), Fort Wayne Rift (FWR), and the Grenville Front in Canada. Dashed segment shows the traditionally-assumed continuation of the GF in the eastern United States.
Fig. 2: (a) Locations of gravity profiles across each of the regions considered. Colors correspond to those for profiles. (b) Mean gravity anomalies for west and east arms of the MCR and south and north sections of the Grenville Front in Canada. Solid lines indicate average anomalies, and dashed lines indicate 1σ range from the mean. For graphic purposes, all four profiles are set to zero on the left side. (c) Mean gravity anomalies for the nine profiles across the traditionally mapped east arm in Michigan and the eleven other profiles across its extension south through Alabama. Solid lines are averages of all profiles, and dashed lines indicate 1σ range from the mean.
Fig. 3: Gravity models matching the mean anomalies across the west (a) and east (b) arms of the MCR.

**Fig. 4**: Gravity models matching the mean anomalies across the north (a) and south (b) sections of the Grenville Front in Canada. North model assumes strong crustal thickening of the Laurentian crust. South model assumes no crustal thickening, with the front expressed only as stacked thrusts. Densities, in g/cm³: Laurentian Crust – Dark Pink – 2.70, Grenvillian Crust – Light Pink – 2.75, Lower Crust – White – 2.85, Upper Mantle – Purple – 3.30.
References


