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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 with Laurentia, 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. as 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.

1. 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 more than 2 million km^3 of buried igneous and sedimentary rocks that outcrop near Lake Superior (Ojakangas et al., 2001; 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 (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). Surface exposures, seismic data, and gravity data delineate a rift basin filled by inward-dipping flood basalt layers, underlain by thinned and underplated crust. These features are suggestive of those at volcanic passive margins, which are characterized by thick sequences of volcanic rocks yielding magnetic anomalies landward of and sometimes larger than the oldest spreading anomalies. Seaward-dipping reflectors, packages of volcanic flows interbedded with volcanoclastic sediments and tuff, mostly occur on thinned continental crust landward of the oldest oceanic crust and are frequently underplated by high velocity lower crustal bodies (HVLC). That the MCR shows many features common to rifted volcanic margins suggests that it came close to continental breakup before it failed and illustrates how passive margins may form prior to breakup (S. Stein et al., 2018).

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

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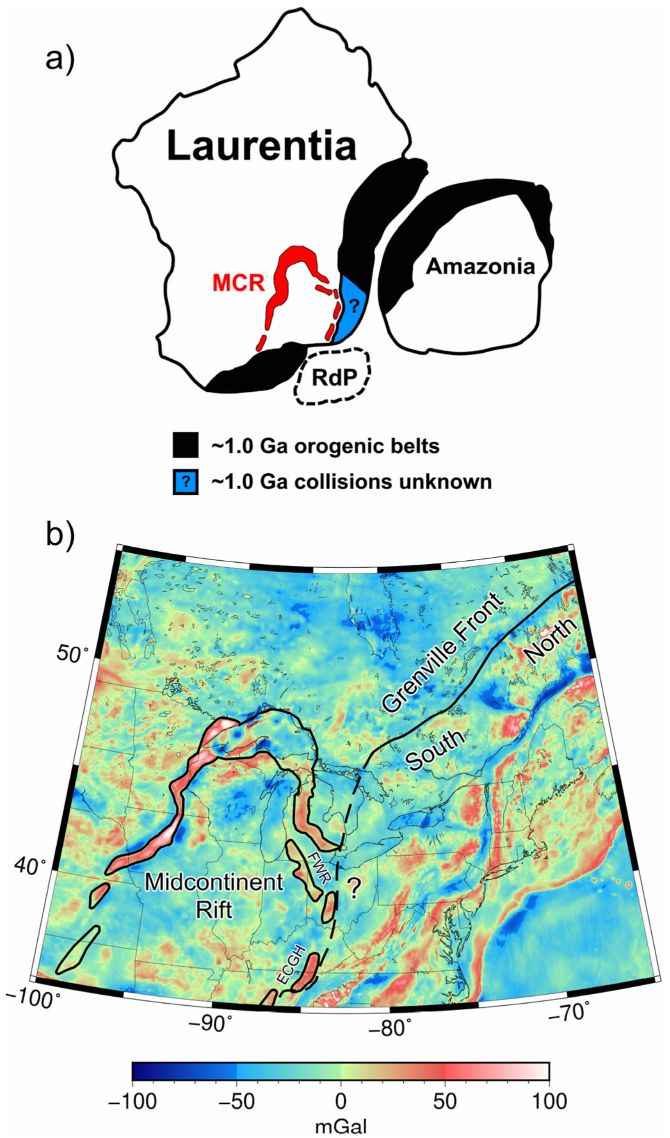

Fig. 1. (a) Reconstruction showing commonly assumed locations of major blocks and Grenville-age orogenic belts, in present-day orientation, associated with the accretion of the Amazonia and Rio de la Plata (RdP) blocks to Laurentia, the core of Precambrian North America (after Li et al., 2008). (b) Complete 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, adapted from Whitmeyer and Karlstrom (2007).

∼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, 1988; 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; C.A. Stein et al., 2014, 2018). 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; S. Stein et al., 2018).

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 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).

2. 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. Profiles were grouped 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-derived free-air gravity data (Sandwell et al., 2013) over the lakes, profiles 150 km long and approximately 50 km apart were extracted (Fig. 2a). The gravity anomalies used to derive the models in this paper reflect the complete Bouguer anomalies from the PACES database. These attempt to correct for the mass of the material between each gravity station and Earth's geoid, which if left uncorrected, would cause a variation of gravity with elevation. We then 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 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

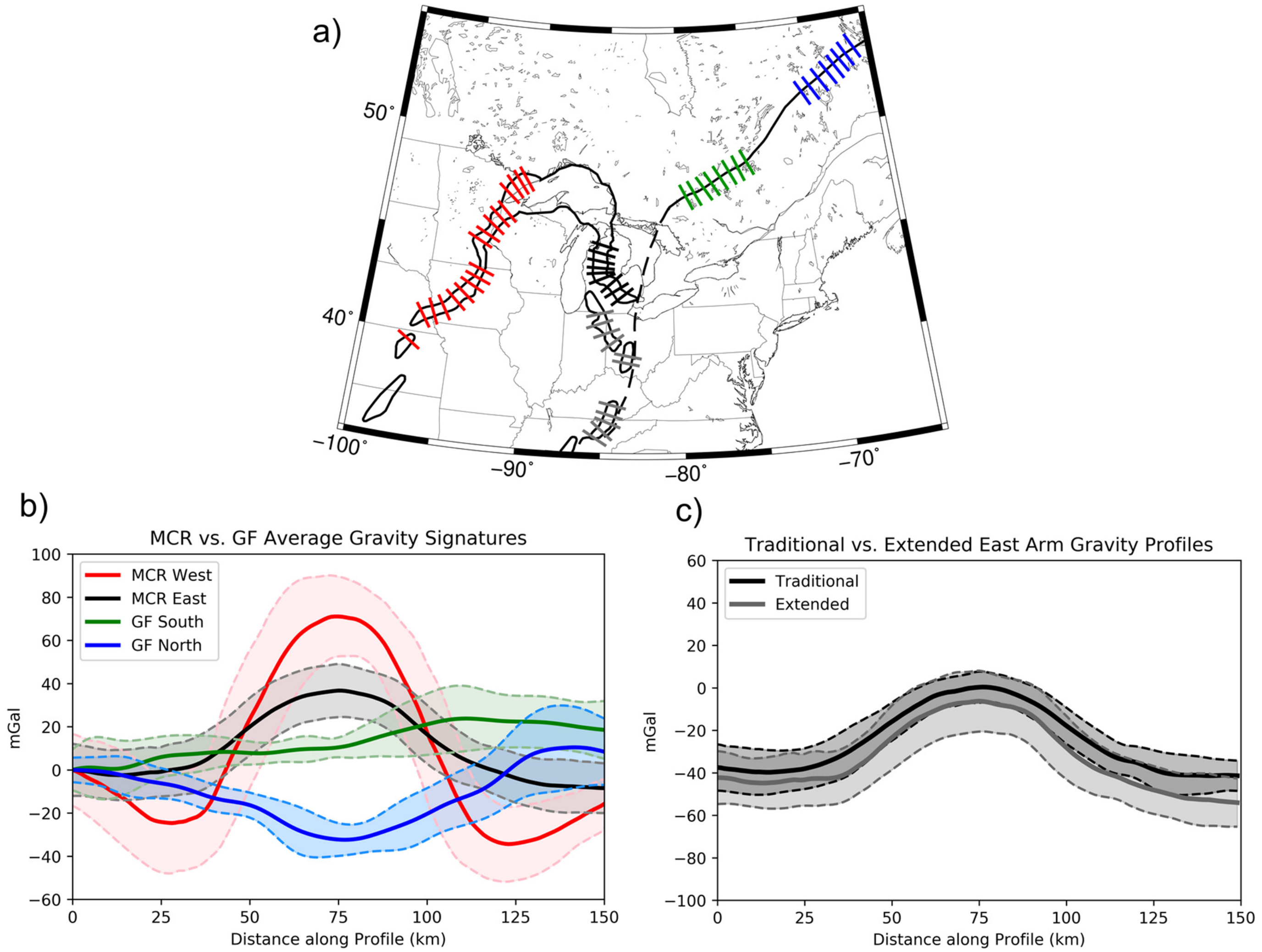

Fig. 2. (a) Locations of gravity profiles across each of the regions considered. Colors correspond to those for profiles in parts b and c, with black corresponding to the traditionally mapped east arm in Michigan (north of 42°N) and grey to its southward extension through Alabama (south of 42°N). (b) Mean gravity anomalies for west and east arms of the MCR and south and north sections of the Grenville Front in Canada. The mean for the MCR East anomaly includes both the black and grey plotted profiles. 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 are plotted in black and the eleven other profiles across its southward extension are plotted in grey, matching the profile map. Solid lines are averages and dashed lines indicate 1σ range from the mean.

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 C.A. Stein et al.'s (2018) 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.

3. 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, erosion, and any later effects (Stein et al., 2015; S. Stein et al., 2018). 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; Van Schmus and Hinze, 1985; Chandler et al., 1989; Hinze et al., 1992; Shay and Tréhu, 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

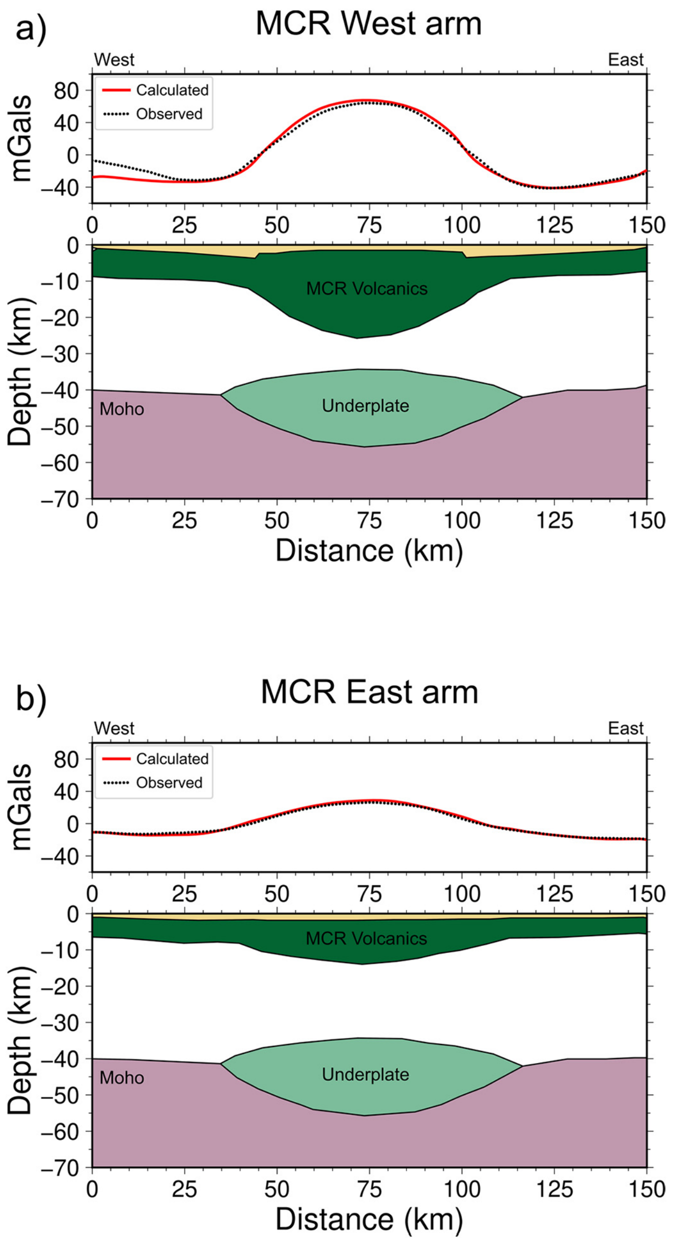

Fig. 3. Gravity models matching the mean anomalies across the west (a) and east (b) arms of the MCR. Densities, in g/cm^3: sediments – yellow – 2.45, Keweenawan Volcanics – dark green – 2.95, lower crust – white – 2.67, underplate – light green – 3.10, upper mantle – purple – 3.30. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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. These events 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; S. Stein et al., 2018). The ratio of the cross-sectional area of rift-filling volcanics to that of underplated material is 1.55 in the west arm of the MCR and 0.97 in the east arm.

We modeled the underplated bodies as similar in depth and volume for both arms, as seismic reflection data constraining its location have lower resolution at these depths, and gravity modeling alone cannot constrain its location well. Receiver function data from the SPREE profiles reveal a consistent Moho beneath regions away from the MCR (Zhang et al., 2016). However, its depth elsewhere along the rift remains less clear owing to the lack of detailed studies, which should improve as additional EarthScope data are analyzed. While exploring possible thicknesses of the rift-filling volcanics and underplated structures, it became clear that the volume of the highly dense igneous rocks which fill the rift basin affects the overall gravity anomaly much more than changing the depth or volume of the underplate. Hence, while the subsurface model of the west arm was largely constrained by the available seismic data, the geometry of the volcanics in the east arm was only adjusted within the rift basin itself to match the average gravity profiles.

Past modeling of seismic and gravity profiles has yielded estimates of the total magma volume within the MCR. Hutchinson et al. (1990) analyzed the available seismic data and calculated a total volume of more than 1.3×10^6 km^3. This estimation was based on the traditionally drawn MCR with a truncated east arm, leading to an estimate that likely did not capture the total extent of the rift. Using the new geometry to recalculate the values, Stein et al. (2015) estimated the total magma volume to be $\sim 2.1 \times 10^6$ km^3. Our new average models for the west and east arms of the MCR provide hopefully better estimates for the cross-sectional area of volcanics within the rift basin along both arms. Along the west arm, the average cross-sectional area is roughly 1200 km^2, while along the east arm it is 740 km^2. This adds up to $\sim 2.0 \times 10^6$ km^3 of magma in the arms alone. Accounting for the magma volumes inferred from the GLIMPCE surveys across Lake Superior (Cannon et al., 1989), the total magma volume estimated based on our new average models is increased to 2.6×10^6 km^3.

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

4. 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). Our model is consistent with Lithoprobe reflection and refraction lines along this section that show a relatively well-defined Moho at about 40 km which deepens slightly to about 45 km to the southeast (Ludden and Hynes, 2000; Rivers, 2014). 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 sub-horizontal) into the present-day middle crust no deeper than 25 km (White et al., 2011). The thrust faulting has only a

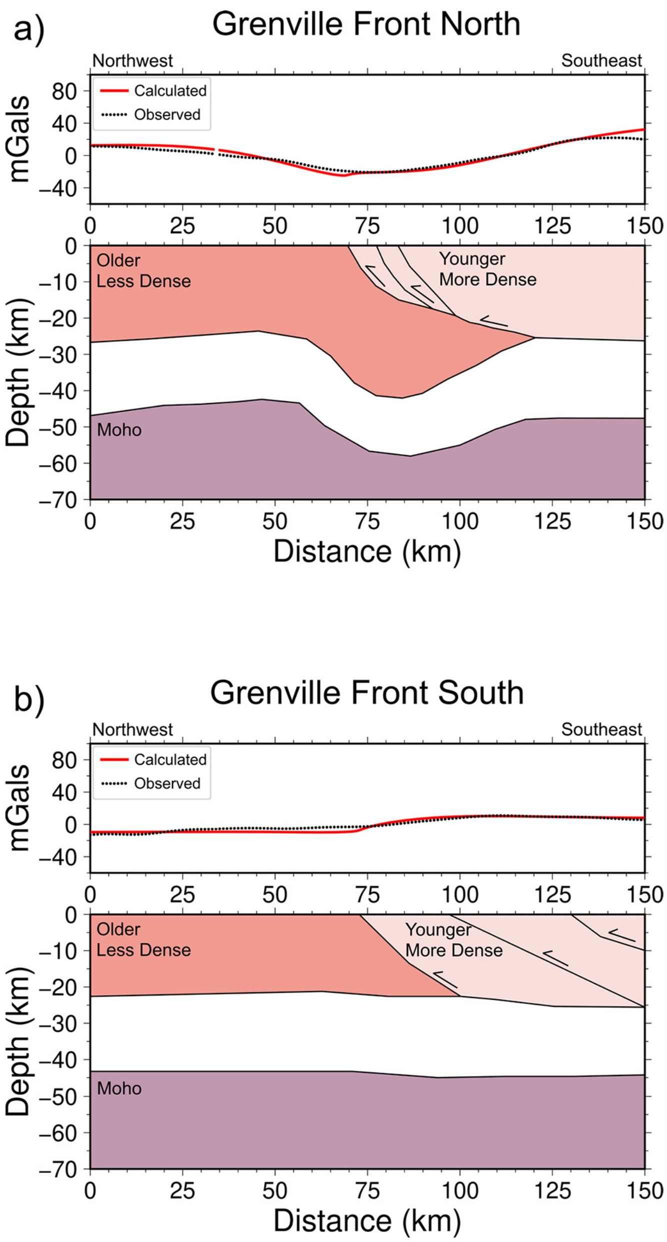

Fig. 4. Gravity models matching the mean anomalies across the north (a) and south (b) sections of the Grenville Front in Canada. North model assumes strong crustal thickening of the Laurentian crust. South model assumes no crustal thickening, with the front expressed only as stacked thrusts. Densities, in g/cm^3: Laurentian Crust – dark pink – 2.70, Grenvillian Crust – light pink – 2.75, lower crust – white – 2.85, upper mantle – purple – 3.30. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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.

5. 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 and geology (Drahovzal, 1997; Baranoski et al., 2009; Moecher et al., 2018). Recent seismic data support this possibility, as EarthScope projects in the last decade have provided us with a wealth of new data on crustal structure in the eastern United States. Schmandt et al. (2015) used multimode receiver function stacking and Rayleigh wave tomography data to investigate crustal thicknesses across the U.S. and revealed an overall thickened crust along segments of the MCR. P-to-S receiver function data for the Mid-Atlantic Geophysical Integrative Collaboration (MAGIC) array just north of the gravity high beneath central Ohio similarly imaged local crustal thicknesses ~100–200 km from the west end of the transect as high as ~58 km (Long et al., 2019). These observations are consistent with the base of the underplated high velocity lower crustal body in our models. They also imaged southeastward dipping structures extending to the east of the positive gravity lineaments that we associate with the east arm of the MCR. This has been interpreted as the main deformation front of the Grenville orogen in the eastern United States. We believe this interpretation to be consistent with the location of the MCR in this region. If stacked thrust sheets similar to those seen in the south GF continued southward into the United States, it makes sense that they should be found to the east of the positive gravity anomalies our models aim to match. This view is also consistent with the deformation related to the Grenville Front having occurred primarily in the upper ~30 km of the crust, rather than deeply seated near the Moho.

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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Authors' statement

All authors participated in all aspects of this work.

Declaration of competing interest

There are no interests to declare.

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