Flexural and thermal subsidence of the 1.1 Ga Midcontinent Rift

Luke Fairchild, EPS 108 Term Paper — 12/15/2015

Abstract

The Midcontinent Rift (MCR) is a failed rift system that formed within the interior craton of Laurentia (Mesoproterozoic North America) and was active from ∼1110 to 1085 Ma. A widely accepted timeline of MCR development has been inferred through seismic, geochemical, geochronologic and structural measurements (Cannon, 1989, 1992; White, 1997; Stein et al., 2015). The syn- and post-rift flexural and thermal subsidence of the MCR is the least constrained stage of rift development, as sediments are the primary lithological product of this period and do not yield reliable dates. Understanding MCR subsidence is critical for inferring past structure and rift duration from present observations. This study compiles and reviews the estimates of past investigations of MCR subsidence in the context of the MCR's broader developmental timeline. In doing so, I aim to give a comprehensive overview of the MCR system similar to that presented by Stein et al. (2015) but with a more detailed treatment of the MCR's subsidence history.

INTRODUCTION

The Mesoproterozoic Midcontinent Rift (MCR) is the most prominent feature on gravity and magnetic maps of North America. The MCR primarily consists of thick flood basalt successions confined to a narrow zone extending northward from the Midwestern United States into Lake Superior and looping back southward through Michigan, U.S. The origin of the MCR is an outstanding question in current investigations. While the volume of volcanic rock in the MCR ($\sim$1-2 $\times 10^6$ km^3; Hutchinson et al., 1990) necessitates a mantle plume origin ($\geq 10^5$ km^3 by the criterion of Ernst et al., 2013), it is unclear whether the plume had any role in the initiation of the rift itself. Recent studies suggest that the MCR formed in response to far-field tectonic stresses as Amazonia rifted from Laurentia, and ended once oceanic spreading between the two continents was successfully established (Stein et al., 2014). This hypothesis (of an already active rift encountering a mantle plume by chance) is consistent with the idea that the small temperature perturbations (∼100-150° C above normal mantle temperatures) of hotspots can dramatically amplify the decompression magmatism of rift zones (White and McKenzie, 1989). Constraining the geodynamic evolution of the MCR is critical for 1) evaluating such hypotheses, 2) understanding potential unique structural consequences of interaction between continental rifting and a mantle plume, and 3) constraining the dynamics of post-rift sedimentation.

Cannon and Hinze (1992) used seismic data across Lake Superior to map the structure of the MCR and infer discrete stages of faulting and volcanism. The results of this study are generally accepted as the timeline of the MCR's geodynamic evolution, which are outlined as follows. At ∼1110 Ma, rifting and incipient volcanism occurred, followed by an outburst of "main" stage flood basalts confined to the central graben until ∼1095 Ma. Continued "late" stage volcanism resulted in flexural subsidence and subsequent sedimentation. While it has been proposed that crustal thickening also occurred during this last stage of rifting (Stein et al., 2015), it is plausible that significant thermal subsidence would have been prevented or delayed by the elevated temperatures and forces of an upwelling mantle plume (White, 1997). Rifting ended at ∼1085 due to either far-field tectonic stresses (both compressional and extensional events have been proposed; Stein et al. (2014); Cannon (1994)) or the dissipation or relocation of the mantle plume source in the presence of fast plate tectonic rates (Swanson-Hysell et al., 2014). By this time, thermal subsidence would have certainly been underway. The cumulative post-rift subsidence in the MCR would have dramatically altered the surface long after the rifting had actually ceased, a factor that must be considered in interpretations of the rift's evolution and tectonic setting.

Constraining this post-rift stage of MCR development is paramount to a comprehensive understanding of this unique geologic feature. Additionally, in the absence of coherent age constraints on MCR sediments, quantifying expected subsidence and associated sedimentation in the MCR could allow a better understanding of syn- and post-rift sedimentary sequences and the timeframe and geologic context of their deposition. For example, recent detritial zircon dates from the post-rift Jacobsville sandstone suggest that this 3-4 km thick sedimentary infill was still being deposited at ∼900 Ma (Craddock et al., 2013), much later than the Grenville orogeny that presumably interrupted the development of the post-rift sedimentary basin. While this particular data is under immense scrutiny, it demonstrates how such findings cannot yet be robustly tested (or dismissed) due to an incomplete understanding of post-rift development.

LITHOSPHERIC LOADING AND FLEXURE

Previous Studies

Nyquist and Wang (1988) approximated the amount of flexural subsidence in the MCR using seismic data from the southwest limb of the MCR. They were able to satisfactorily describe flexure interpretted from seismic data using a thin-plate model deflected by a line load. Data were matched reasonably well with both broken and unbroken plate models, although each required a slightly different elastic thickness. Surface loading of post-rift sediments and extrusive volcanics were not sufficient to produce the observed flexure, so Nyquist and Wang (1988) hypothesized the presence of a large central volcanic plug emplaced during rifting that provided the most dramatic lithospheric loading.

Nyquist and Wang (1988) remain the most direct treatment of flexural subsidence in the MCR. However, their data is isolated to a small arm of the rift that has poor surface exposure and is (arguably) not entirely characterisitic of the rift as a whole. It would be preferable to conduct a similar study using developed seismic data (Behrendt et al., 1990) from what is considered to be the main rift basin across Lake Superior (also the region of best exposure of MCR volcanics).

Analysis and Future Studies

Using the parameters of Nyquist and Wang (1988) unchanged, I calculated lithospheric flexure in the MCR assuming a line load (Fig. 1). Nyquist and Wang (1988) used the

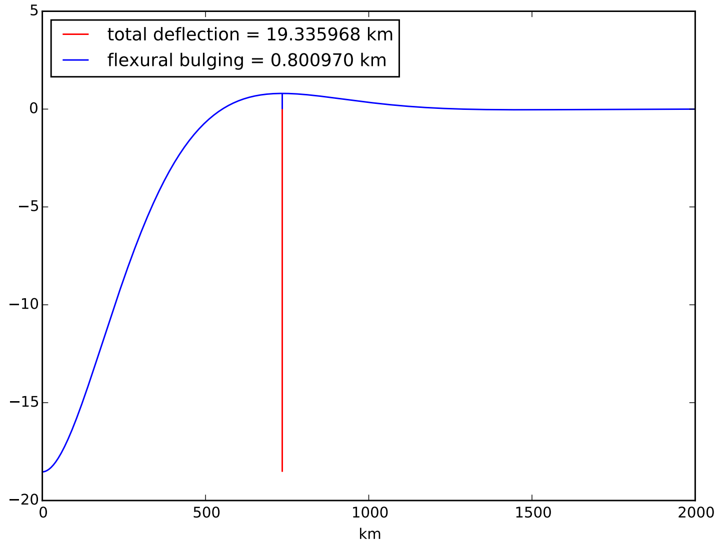

Figure 1: Flexural subsidence of the MCR assuming a line load equivalent to volcanic rock ~50 km thick. Other parameters are available in the Appendix.

maximum deflection observed in seismic data as the key boundary condition constraining their model, which does not account for the influence of thermal subsidence and therefore cannot successfully isolate the effects of lithospheric flexure. Attempting to improve upon the model of Nyquist and Wang (1988), I instead converted current estimates of volcanic volume to a concentrated force on the lithosphere. I take this to be a more accurate representation of MCR lithospheric flexure as it is not strictly based on seismically-observed deflection in the present day, which is the end result of combined flexural and thermal subsidence as well as a long-lived Grenvillian compressional event. Given the narrowness of the MCR structure (at least in comparison to other LIPs), a line load is probably a good appoximation. However, the MCR's present narrow structure might not be representative of its pre-Grenville extent, and future models should test the effects of longer wavelength and laterally variable loads.

My model also exhibits a flexural bulge approximately 1 km in height (Fig. 1). Future analysis should test for potential correlation between this region of positive elevation – which would be more susceptible to erosion – with widespread unconformities in the MCR stratigraphy that are currently explained by a "latent" stage of quiescent rift volcanism.

THERMAL SUBSIDENCE

Previous Studies and Implications

The thermal subsidence of the MCR is highly dependent on mantle temperature since it is essentially a feature of conductive cooling of sublithospheric mantle. As significant cooling and subisidence in the region would likely have required the shutoff of tensional stresses or the relocation of the underlying mantle plume, thermal subsidence in the

MCR is considered to be largely confined to the later stages of the rift. Using REE inversion techniques to estimate the changing melting depths and temperatures of distinct volcanic sequences in the MCR, White (1997) estimated the degree of lithospheric thinning at discrete intervals of rifting and suggested the plume source had disappeared by 1094 Ma. In accordance with the thermal subsidence model of McKenzie (1978), White (1997) estimated a β stretching factor of 6 in the MCR and elevated mantle temperatures of 1550°C during the main stage of rift volcanism. This β value reconciles the observed subsidence from seismic data with the volcanic volume of the MCR determined by the plume temperature anomaly (Fig. 2).

The duration and degree of thermal subsidence in the MCR is of particular importance because of the lack of current constraints on post-rift sedimentation. Ojakangas et al. (2001) estimated ∼6-10 km of post-rift sedimentation between the Oronto and Bayfield Groups (including highly variable estimates of the Jacobsville Sandstone). The total thickness and provenance of sediment atop MCR volcanics is a much more complicated function than simple thermal subsidence and post-rift sedimentation: the Grenville orogeny was underway during or shortly after the end of rift volcanism (Halls et al., 2015), reversing motion along syn-rift normal faults and interrupting thermal subsidence in the MCR. No comprehensive effort has been made to fully characterize sedimentary sequences in the MCR, and it would be somewhat difficult considering the lack of age constraints on these deposits (as well as the Grenville orogeny) and the largely interpretive aspect of deriving post-rift sediment thickness from seismic data. A comprehensive model of MCR thermal subsidence and the resulting sedimentary basin, when reconciled with future age constraints and seismic data, could largely benefit and clarify this discussion. Do current estimates of sediment thickness exceed what is expected from a thermal subsidence model? Could such discrepancies be explained by the sudden onset of a Grenville compressional regime?

Analysis

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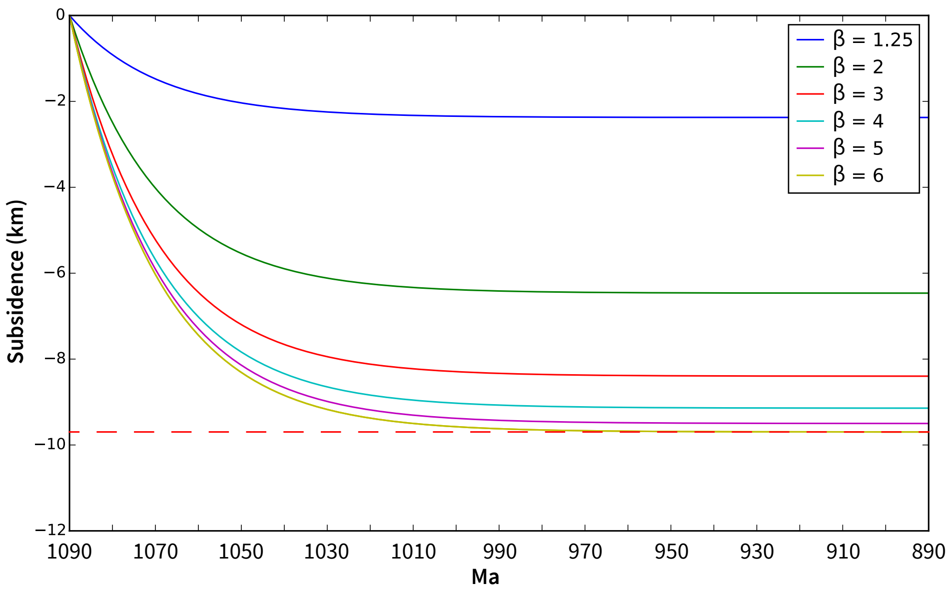

Figure 2: Thermal subsidence curves shown for a range of β stretching factors. White (1997) determined that a β factor of 6 was most consistent with both the observed subsidence and the volcanic output of the MCR. The diagram above is based on the McKenzie (1978) stretching model but does not take into account crustal uplift from an upwelling mantle plume as the model of White (1997) does. The model above therefore illustrates the importance of initial uplift, as it requires at least 2 km to put the final subsidence value in the range estimated from seismic data (4-8 km).

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