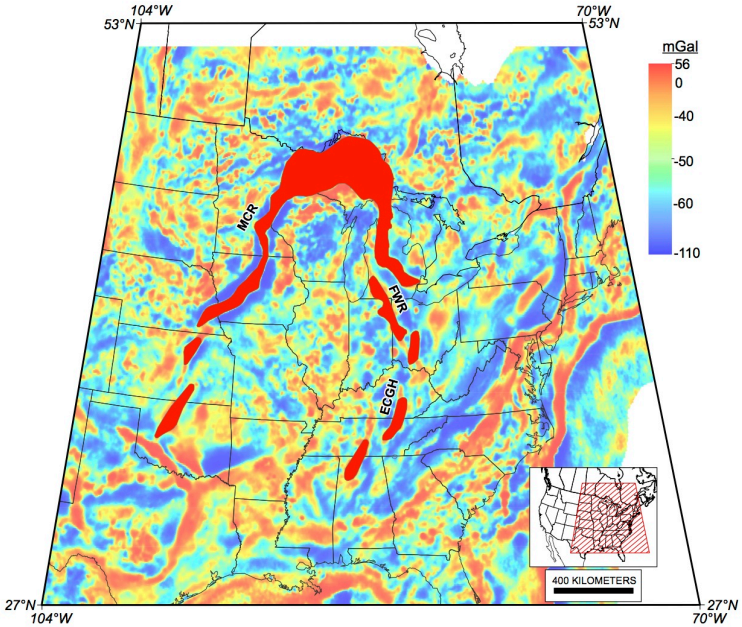
North America's Midcontinent Rift: When Rift Met LIP



Seth Stein[1], Carol Stein[2], Jonas Kley[3], Randy Keller[4], Trevor Bollman[1], Emily Wolin[1], Hao Zhang[1], Andrew Frederiksen[5], Kunle Ola[5], Michael Wysession[6], Douglas Wiens[6], Ghassan Al-Equabi[6], Greg Waite[7], Eunice Blavascunas[8], Carol Engelmann[7], Lucy Flesch[9], Jake Crane[9], Tyrone Rooney[10], Robert Moucha[11], Eric Brown[12]

[1]Northwestern Univ., [2]Univ. of Illinois at Chicago, [3]Georg-August-Universität Göttingen, [4]Univ. of Oklahoma, [5]Univ. of Manitoba, [6]Washington Univ., [7]Michigan Tech, [8]Whitman College, [9]Purdue Univ., [10]Michigan State Univ., [11]Syracuse Univ., [12]Aarhus Univ.

EarthScope is catalyzing a new generation of studies of North American geology

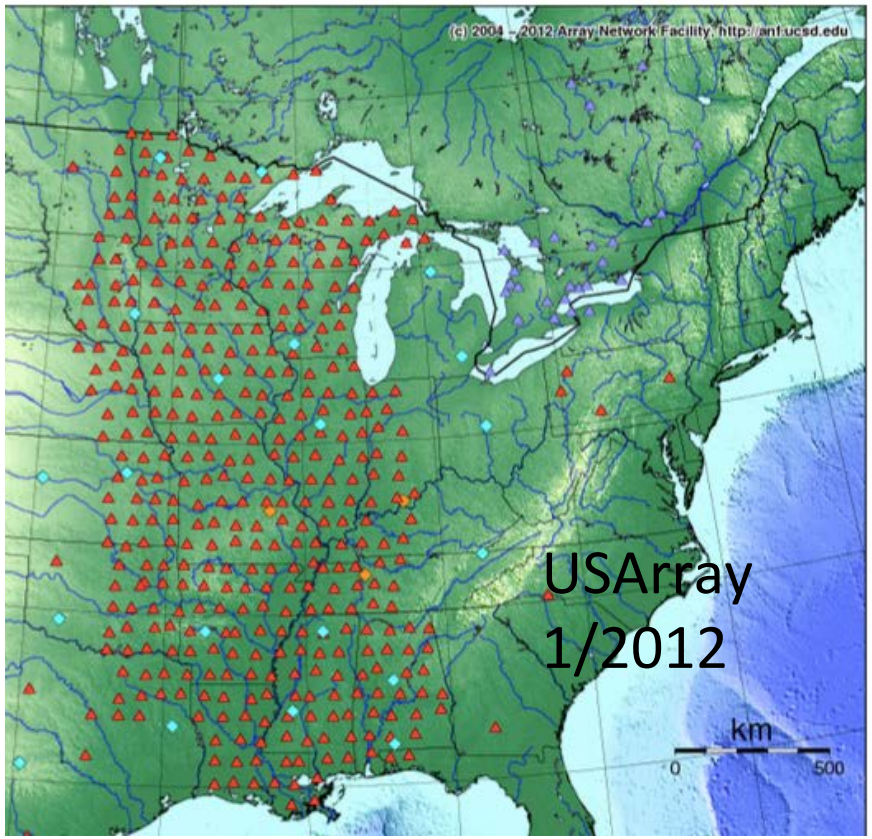
Its large-scale nature encourages a synoptic view

EUS targets are large buried structures formed in distant past

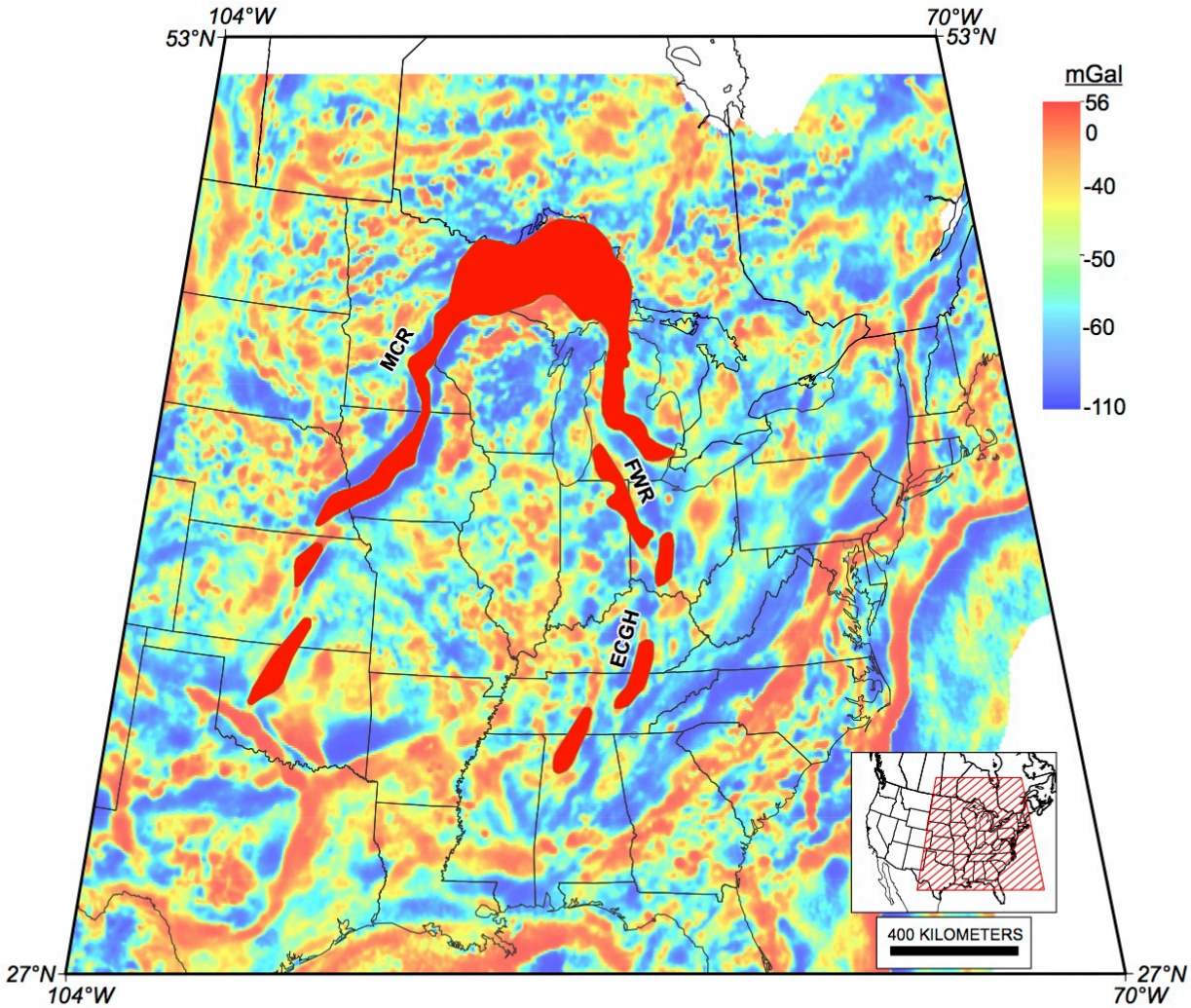
How & why did they form?

Combine new & existing geophysical data with insights from analogous younger & better understood structures elsewhere

Integrate with geological, petrological/geochemical data; kinematic & dynamic models



Midcontinent Rift (MCR)



Prominent on gravity & magnetic anomaly maps

Long arms of buried dense & highly magnetized 1.1 Ga igneous rocks
~ 3000 km long
~ 2 x 10^6 km^3 magma

Outcrops near Lake Superior

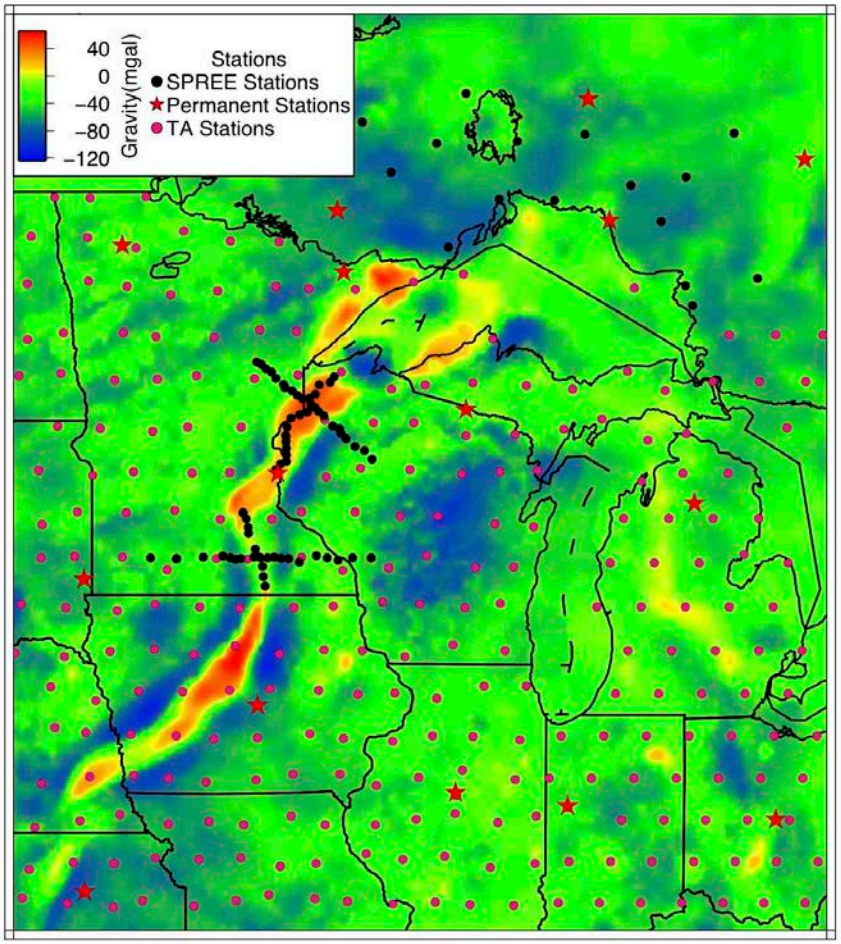
Broader Impact: MCR gave rise to Lake Superior, the basis of the surrounding area's water-based history and economy, copper and building stone deposits that shaped the area's settlement and growth, and today's tourism (place–based E&O opportunity).

Pictured Rocks National Lakeshore, MI

Apostle Islands National Lakeshore, WI

Learning from failure: The SPREE Mid-Continent Rift Experiment

Seth Stein*, Suzan van der Lee, Donna Jurdy, *Earth and Planetary Sciences, Northwestern University, Evanston, Illinois 60208, USA;* **Carol Stein,** *Earth and Environmental Sciences, University of Illinois, Chicago, Illinois 60607-7059, USA;* **Douglas Wiens, Michael Wysession,** *Earth and Planetary Sciences, Washington University, St. Louis, Missouri 63130, USA;* **Justin Revenaugh,** *Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota 55455, USA;* **Andrew Frederiksen,** *Geological Sciences, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada;* **Fiona Darbyshire,** *GEOTOP, University of Québec, Montreal, Québec H3C3P8, Canada;* **Trevor Bollmann, Jessica Lodewyk, Emily Wolin, Miguel Merino,** *and* **Karen Tekverk,** *Earth and Planetary Sciences, Northwestern University, Evanston, Illinois 60208, USA*



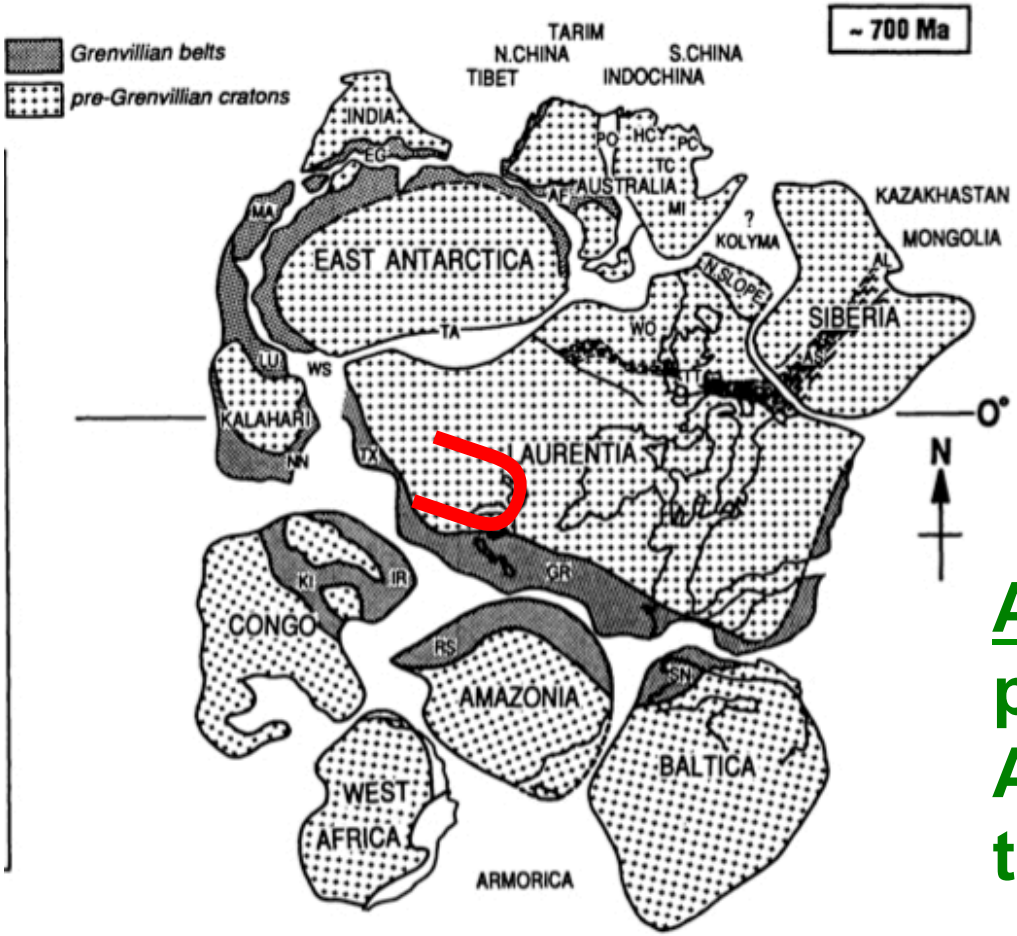
- How did the MCR start?
- How did the MCR evolve?
- How did the MCR fail?

GSA TODAY, SEPTEMBER 2011

How did the MCR form?

Flood basalts, Isle Royale National Park

Formation of MCR occurred ~1.1 Ga during the Grenville orogeny (1.3-0.98 Ga) associated with the assembly of supercontinent Rodinia

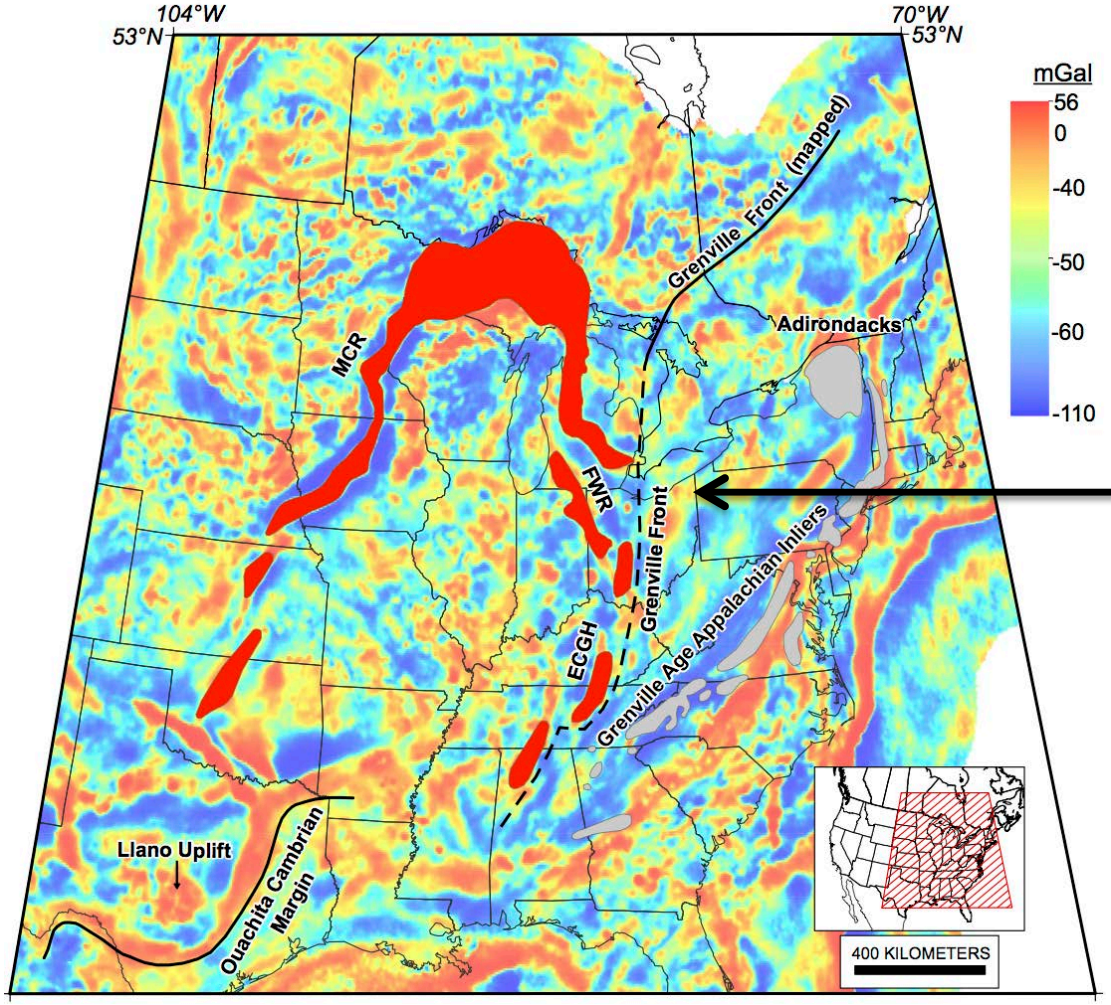


Hoffman, 1991

Laurentia- contiguous part of North America assembled in the Precambrian

Amazonia- contiguous part of NE South America assembled in the Precambrian

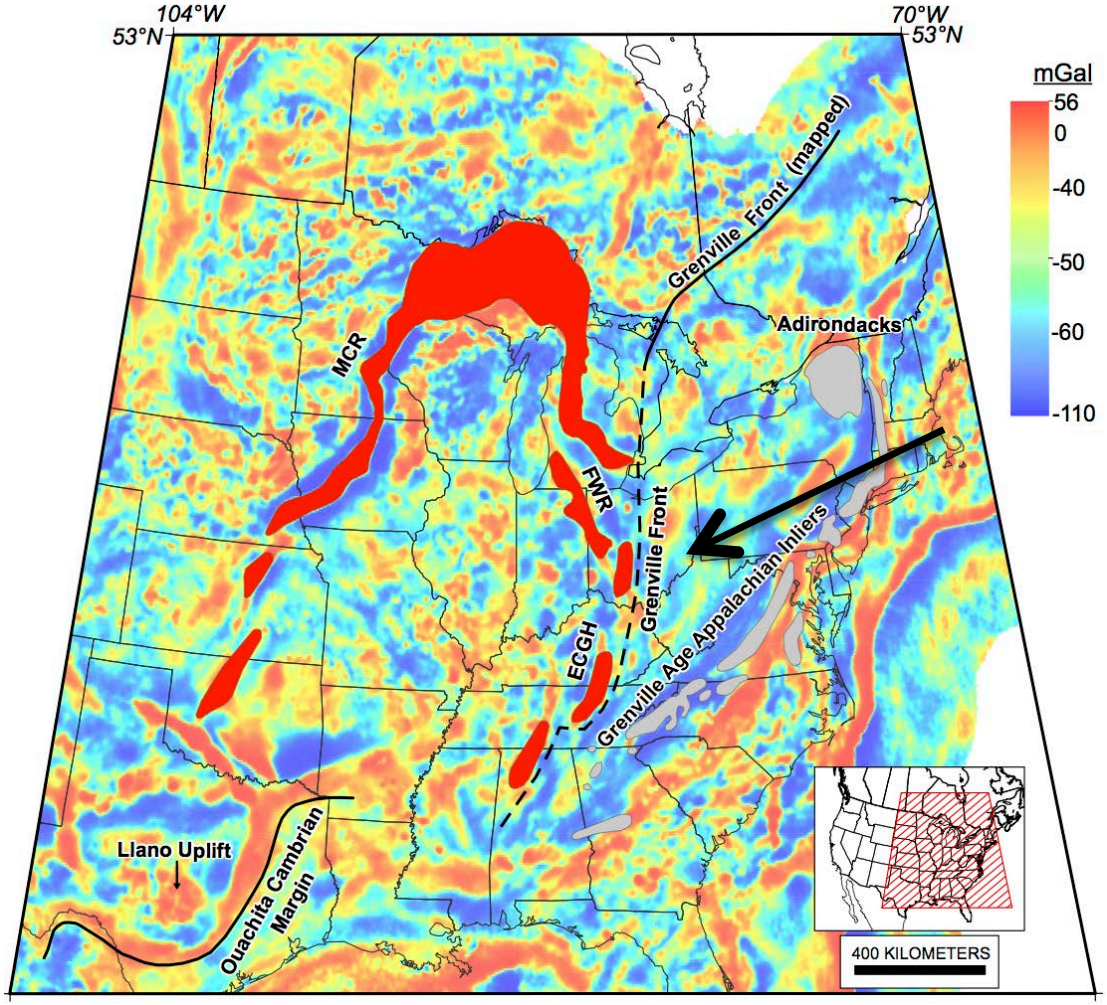
MCR traditionally viewed as a failed rift formed by isolated volcanism and extension within a continental interior, far from its margins…



Stein et al., 2014

- Not associated with successful rifting/ seafloor spreading event
- Assumed to end in Michigan at the Grenville Front (westernmost deformation associated with the Grenville orogeny)

New analysis of gravity data shows MCR continues along East Continent Gravity High (ECGH) to rifted margin from Amazonia-Laurentia separation ~1.1 Ga, indicating a relationship



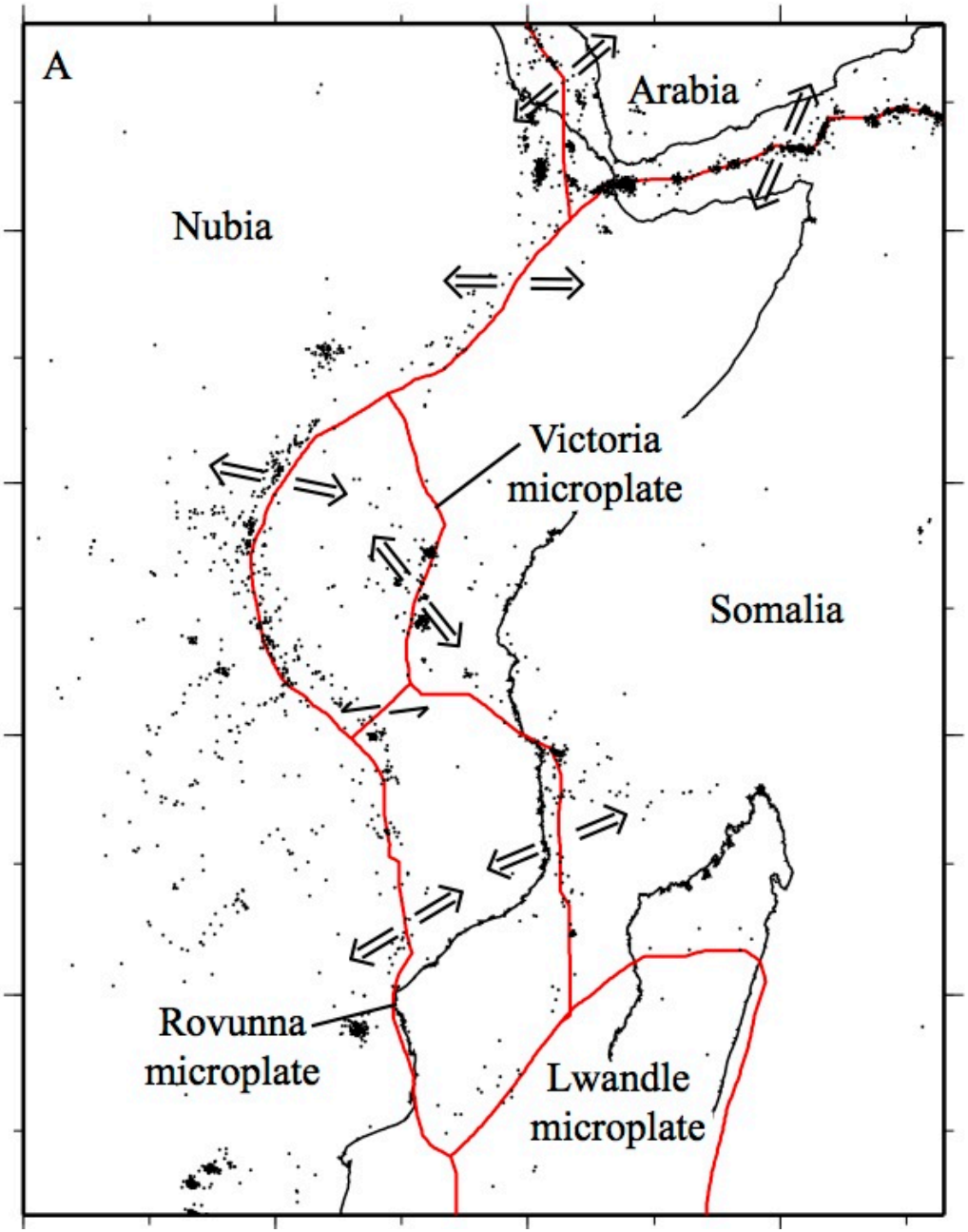
Stein et al., 2014

Seek plate tectonic explanation using insights from younger large rifts formed in interior of continent in association with new plate boundaries

East African Rift

Africa rifting into 3 major plates & 3 microplates (Saria et al., 2013)

If the EAR does not evolve to seafloor spreading & dies, in a billion years & additional continental collisions it would look like an isolated intracontinental failed rift - like the MCR.

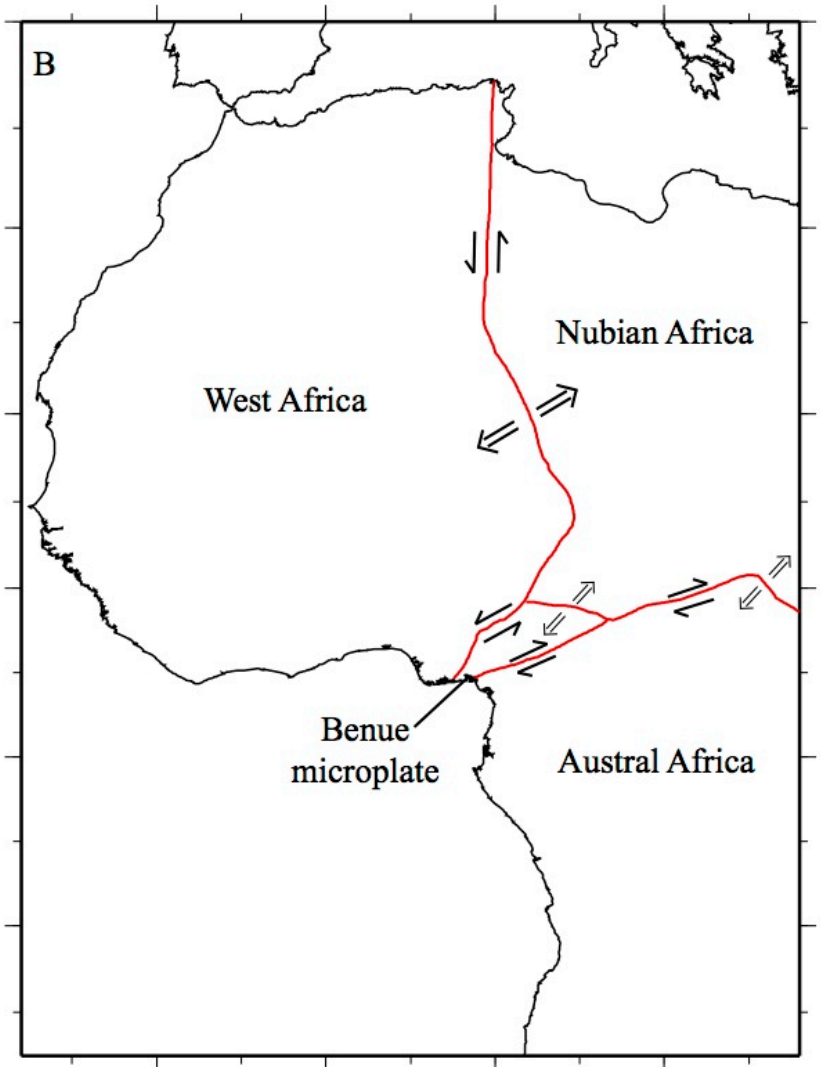


Stein et al., GRL, 2014

West Central African Rift System

- Formed as part of Mesozoic opening of the South Atlantic
- Microplate motion indicated by matching magnetic anomalies to avoid overlaps & gaps in reconstruction (Moulin et al., 2010)
- Intracontinental rifts failed when full seafloor spreading reached

Intracontinental extension can start as part of continental breakup and end when full seafloor spreading is established.

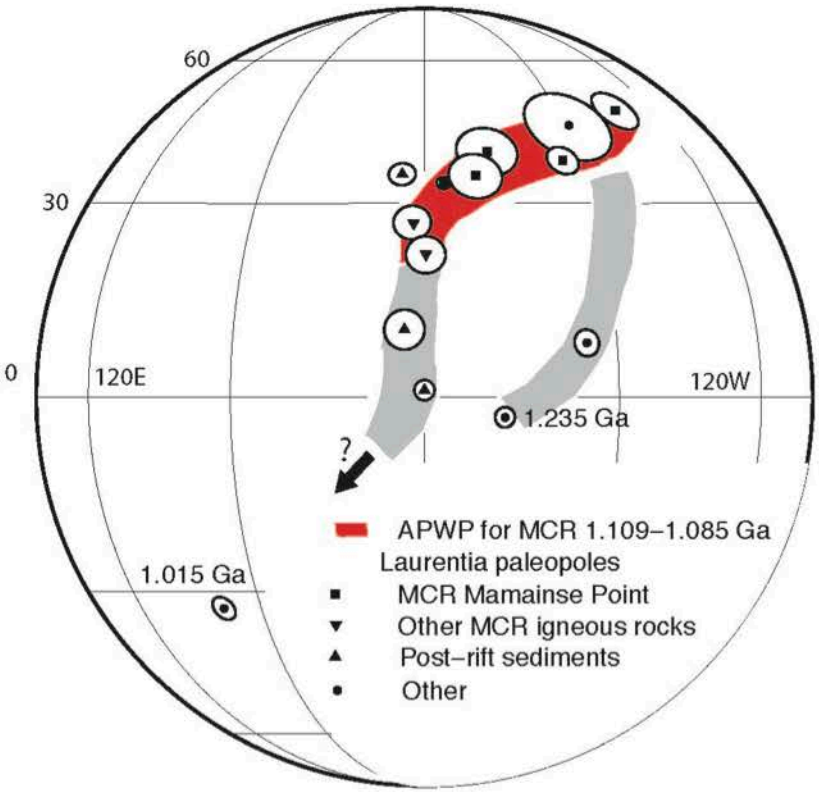


Stein et al., GRL, 2014

Laurentia's apparent polar wander path (APWP) has abrupt cusp at ~1.15 Ga before major MCR igneous activity starts

Cusps indicate change in direction (different pole of rotation)

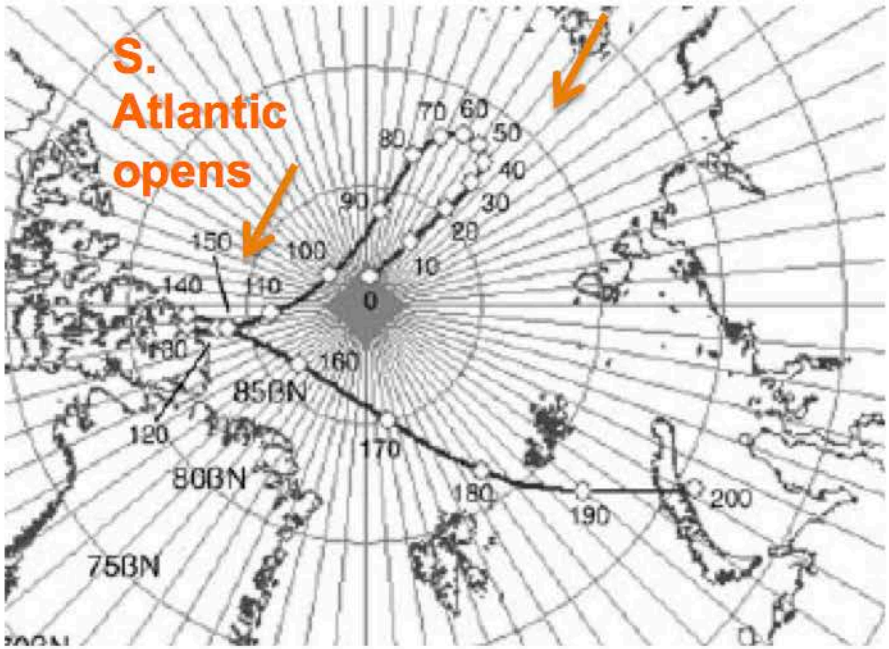
APWP for Laurentia poles



Stein et al., 2014

Smoothed APWP of South America since 200 Ma

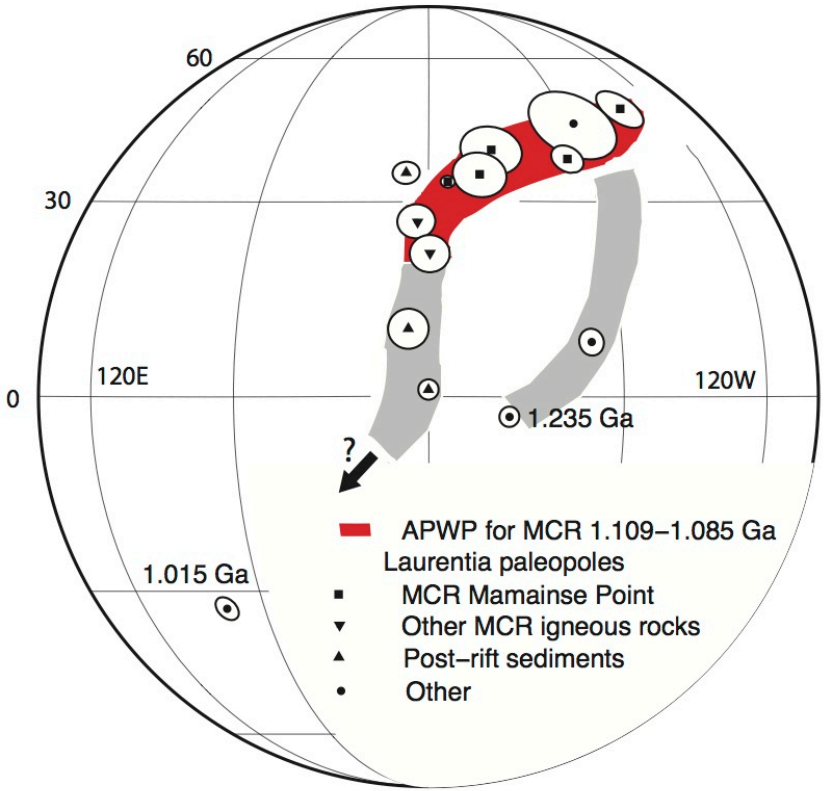
Rifting from Antarctica

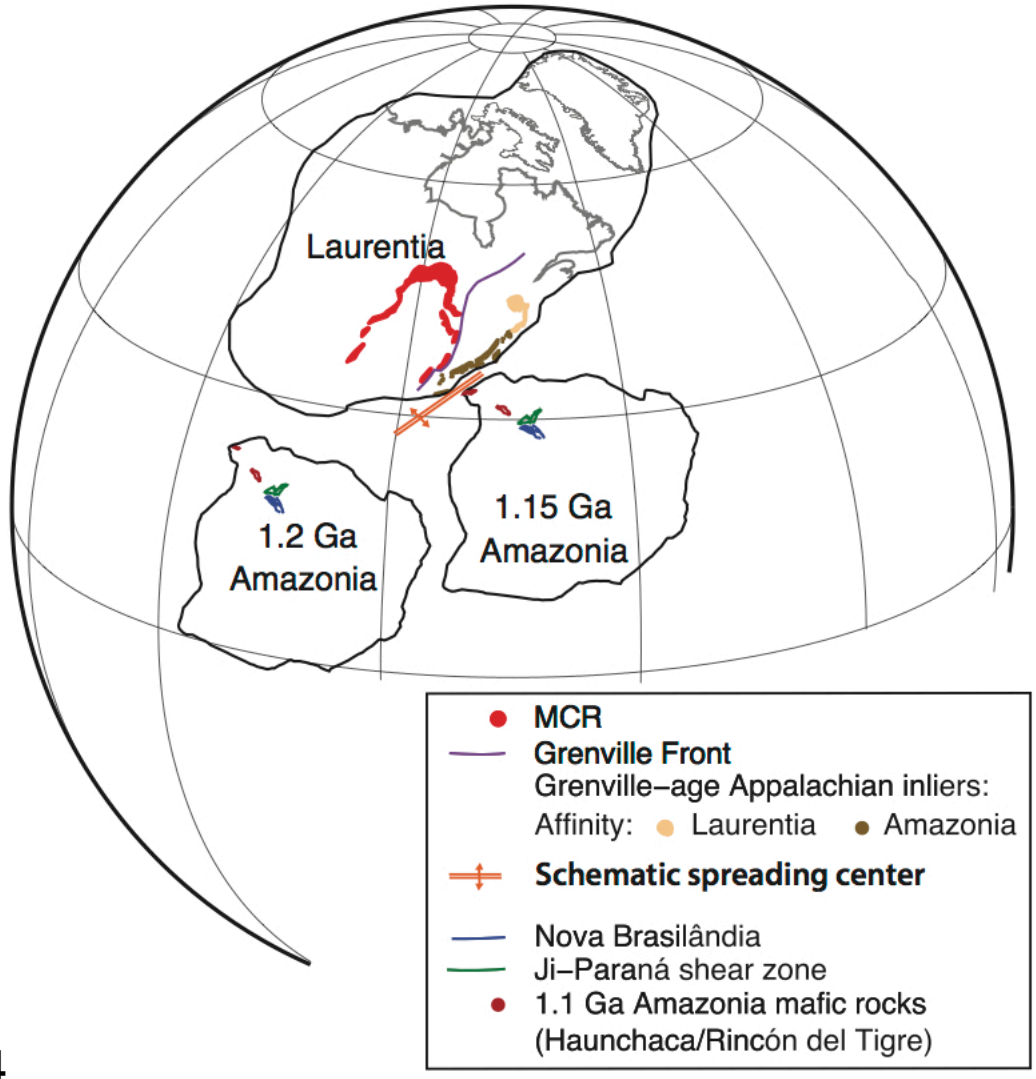


Schettino and Scotese, 2005

MCR likely formed as part of the rifting of Amazonia from Laurentia, recorded by APWP cusp & became inactive once seafloor spreading was established

APWP for Laurentia poles





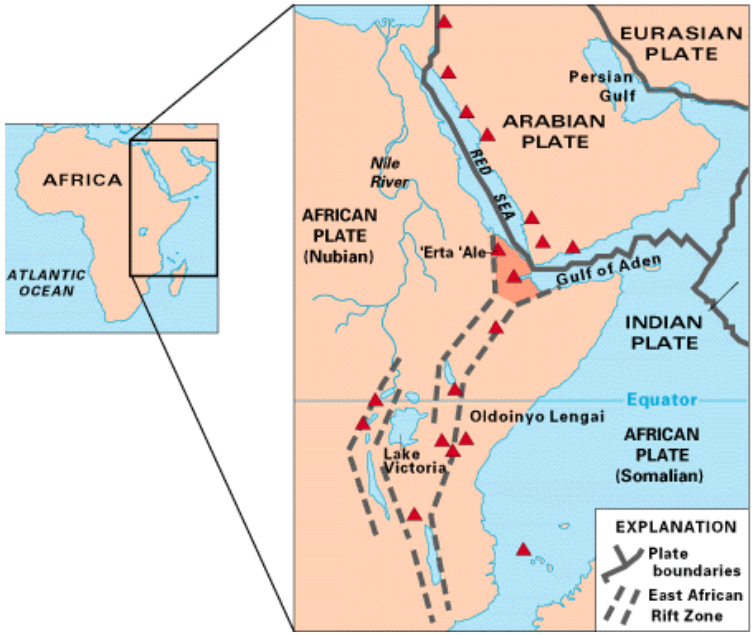
Stein et al., 2014

How did the MCR evolve?

Keweenaw Fault, Keweenaw peninsula, Michigan
MCR educators program (see Waite poster #33)

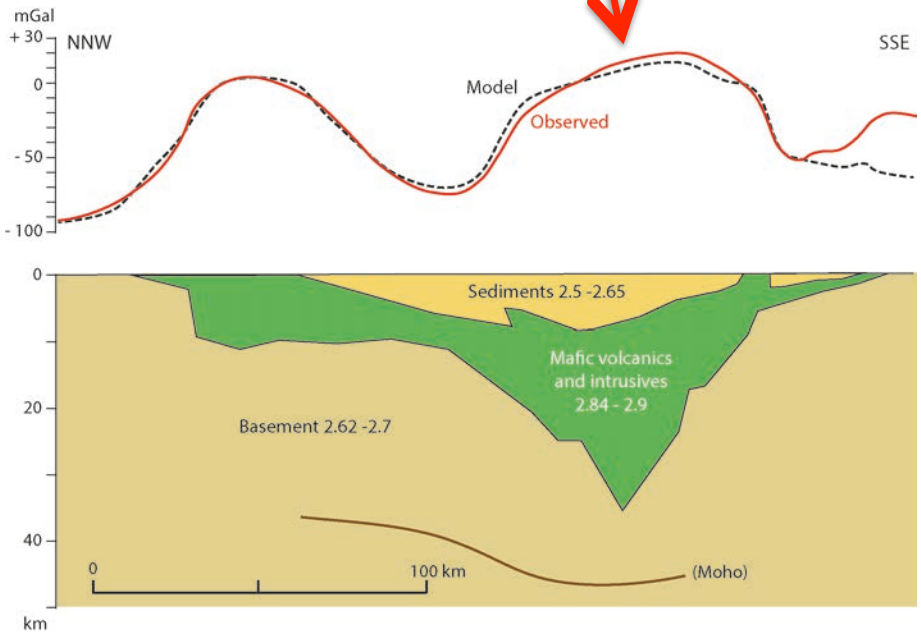
Rift and LIP

The MCR has aspects both of a *continental rift* - a segmented linear depression filled with sedimentary and igneous rocks that form by extension and often evolve into plate boundaries and a *large igneous province (LIP)* - huge volume of flood basalts.



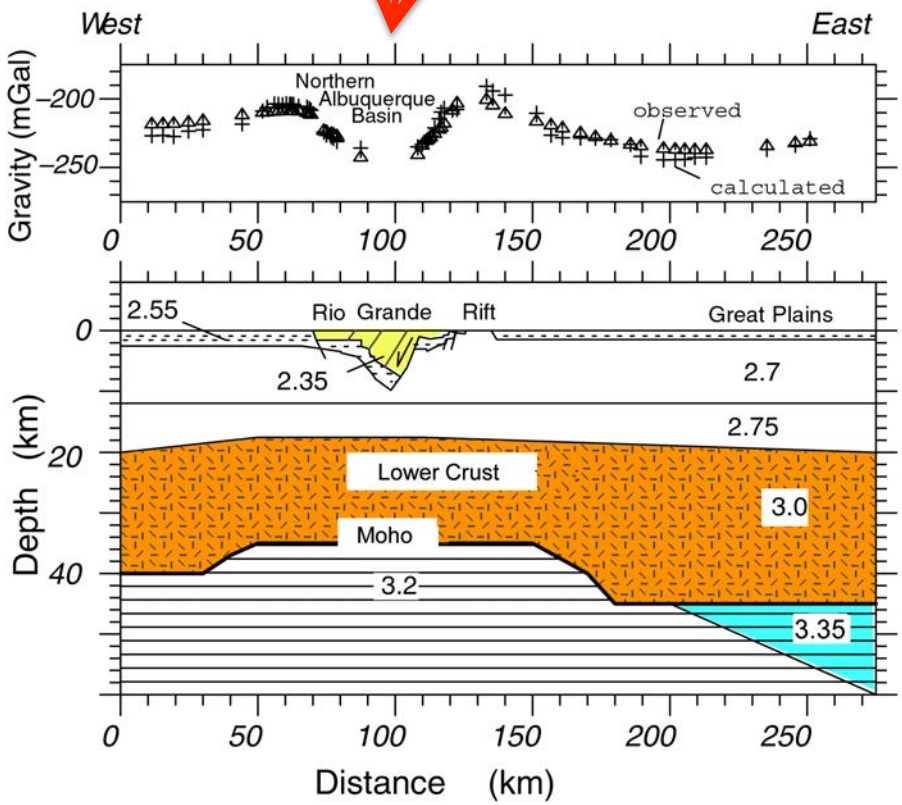
How did this combination arise?

MCR unusual – gravity high due to filling by igneous rocks below thick sediments



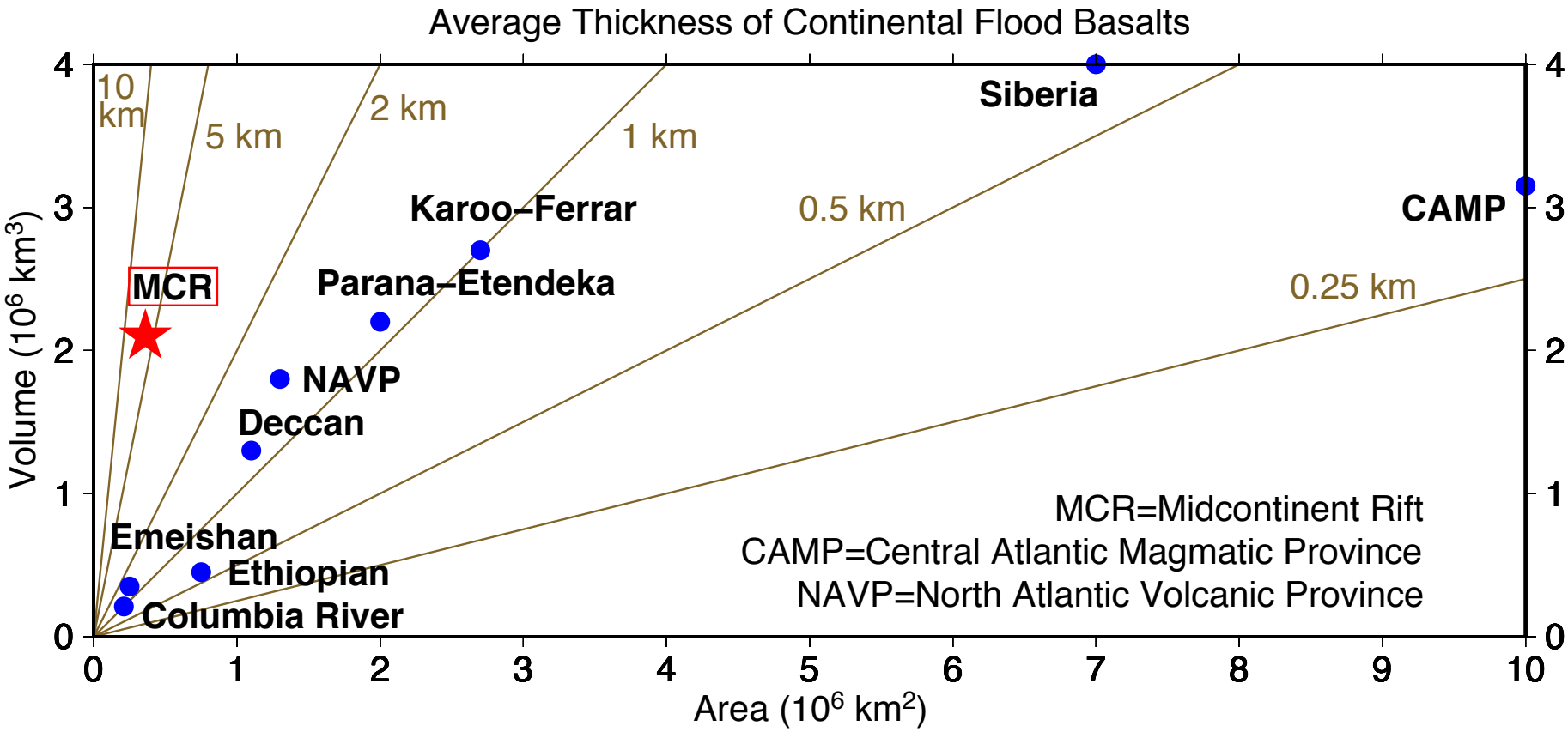
Thomas and Teskey, 1994

More usual – gravity low due to filling by sediment



Grauch, Gillespie & Keller, 1999

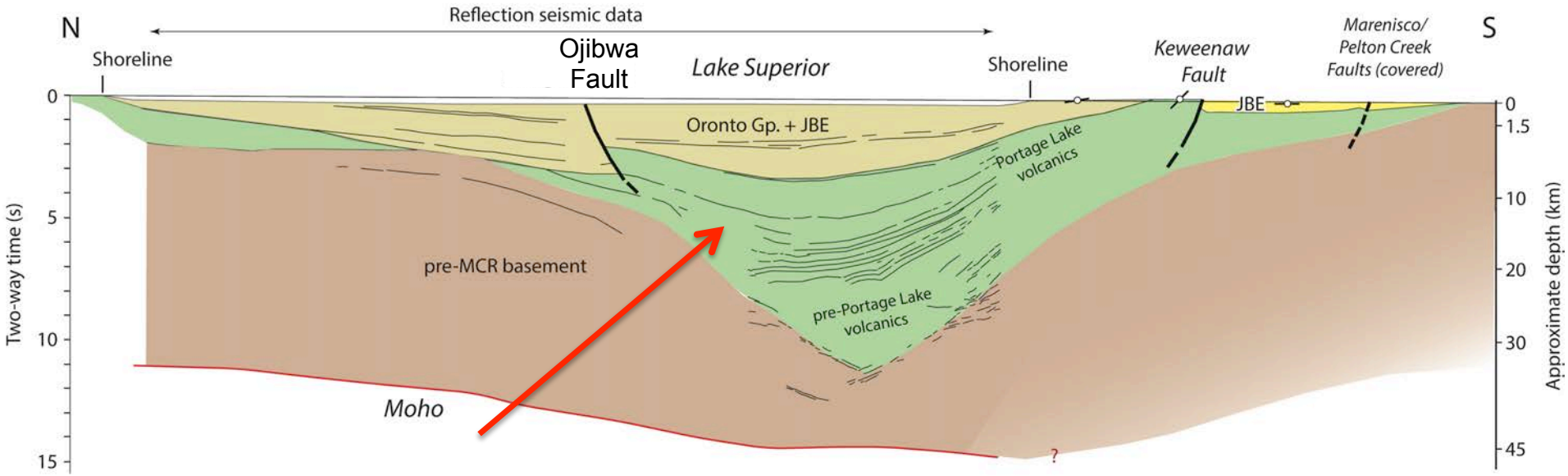
MCR volcanic rocks are much thicker than other LIPs



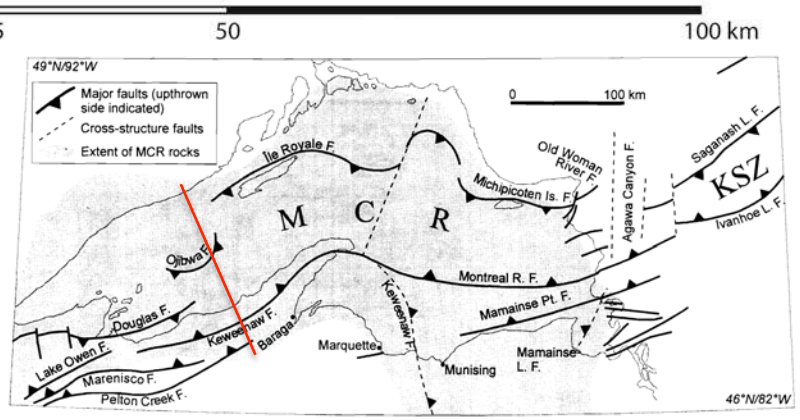
MCR volcanic rocks deposited in subsiding basin

Stein et al., 2015

Reexamine seismic line across Lake Superior



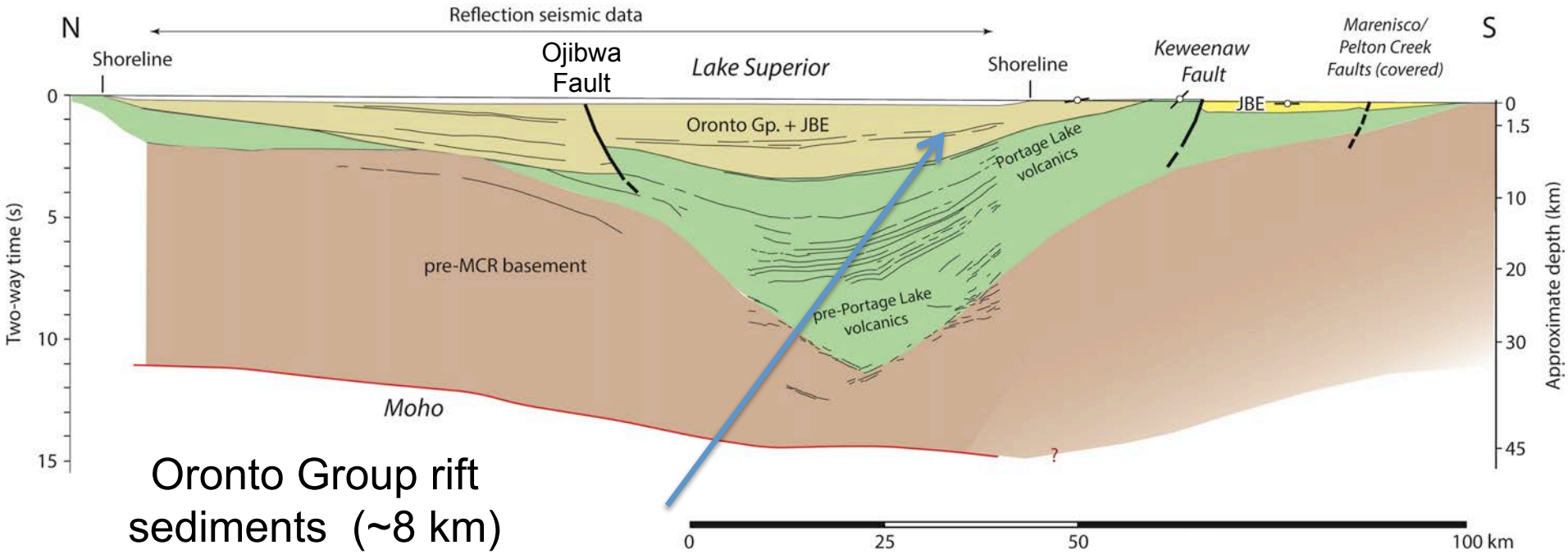
Up to 20 km igneous rocks



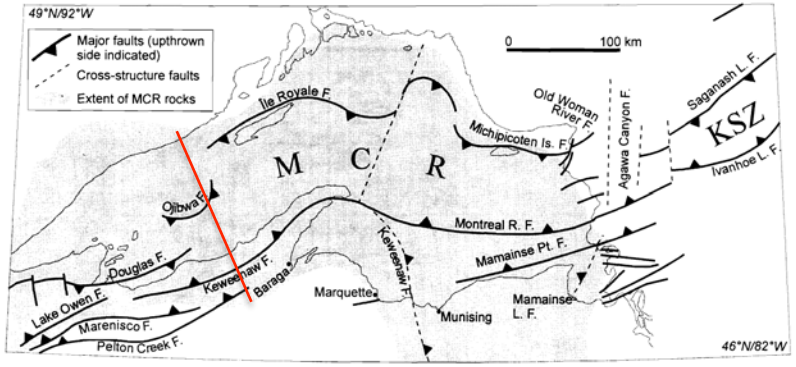
[Manson and Halls, 1997]

Profile after GLIMPCE line C
[Green et al., 1989]

Reexamine seismic line across Lake Superior



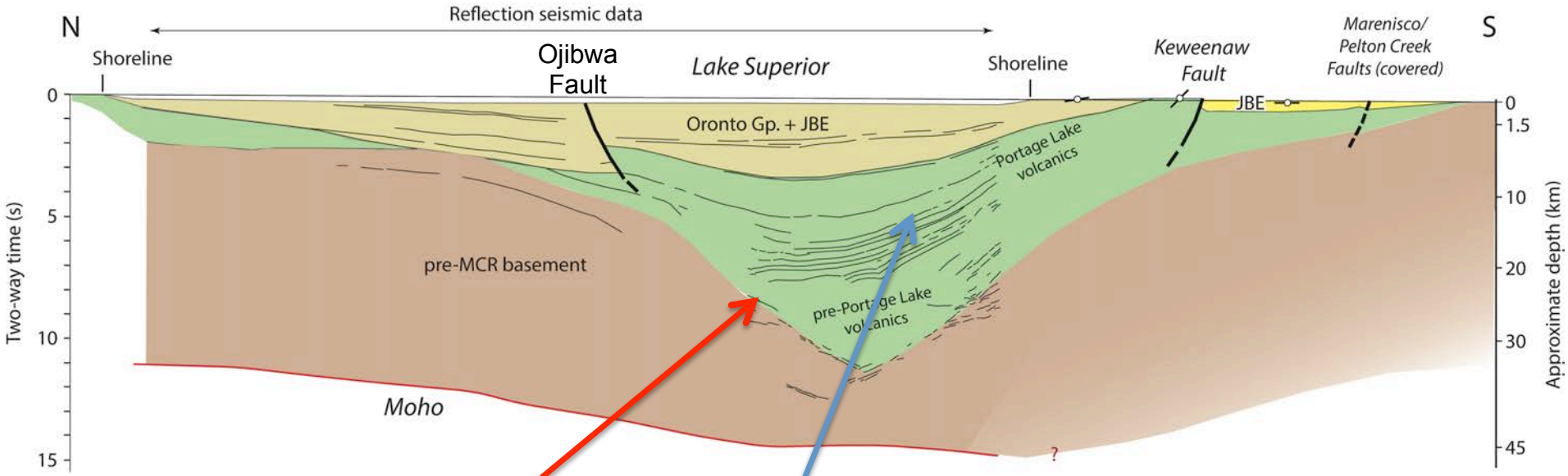
Oronto Group rift sediments (~8 km)



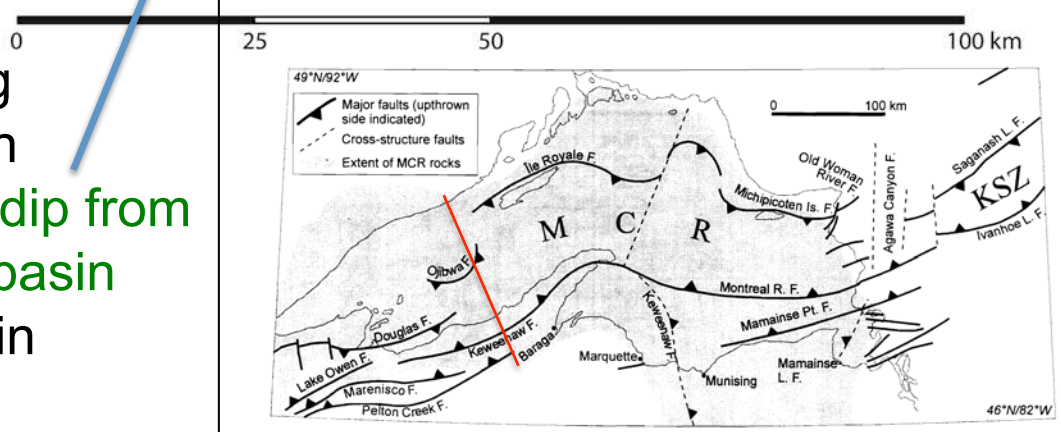
[Manson and Halls, 1997]

Profile after GLIMPCE line C
[Green et al., 1989]

Volcanics and Oronto sediments fill basin



- Lower volcanics truncate toward basin edge, indicating deposition during fault motion
- Upper volcanics and Oronto dip from both sides & thicken toward basin center, indicating deposition in subsiding basin



[Manson and Halls, 1997]

Synclinal structure arose from basin subsidence, not later compression

Profile after GLIMPCE line C
[Green et al., 1989]

RIFT/LIP HYBRID

Resolves paradox that tectonics favor continental breakup, e.g. “passive” rifting, whereas petrology & geochemistry of volcanic rocks favor “active” rifting over a mantle plume (*Nicholson et al*., 1997; *White*, 1997).

Seismic data demonstrate “active/passive” scenario combining both effects, including:

1) Mantle plume impinged upon rifting continent (*Courtillot et al.*, 1999), *Burov and Gerya*, 2014).

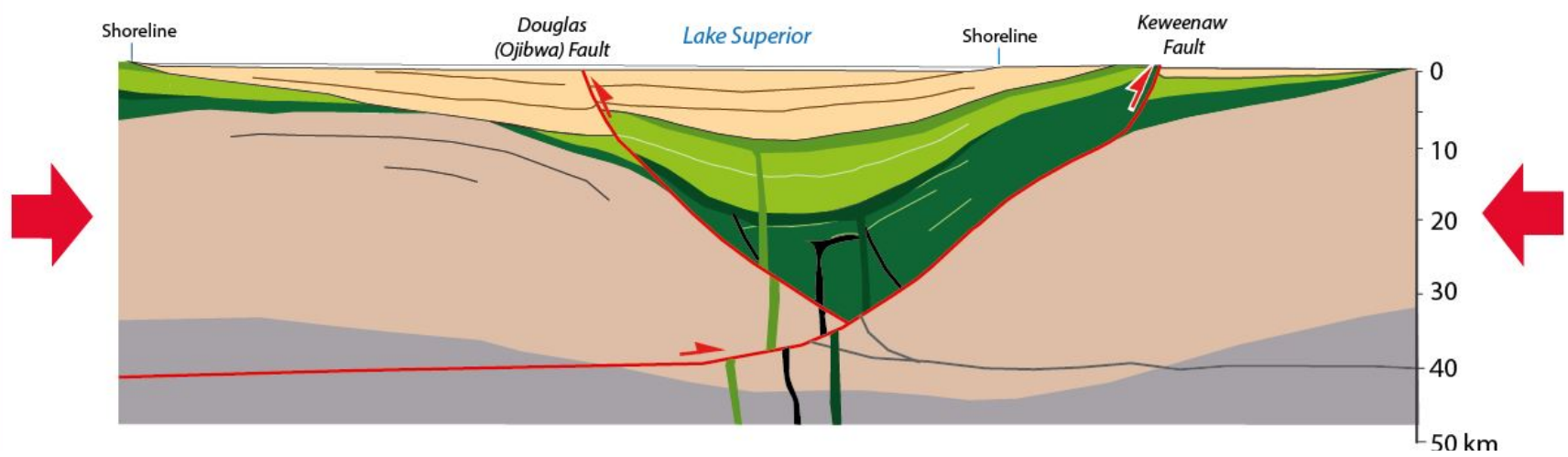
2) Rifting continent by chance overrode a shallow region of anomalously hot or fertile upper mantle (*Silver et al.*, 2006).

How did the MCR end?

Jacobsville sandstone, Keweenaw peninsula, Michigan
MCR educators program (see Waite poster #33)

Previous conventional wisdom

The MCR's "failure" - ending of volcanism and extension and thus its failure to develop into a new ocean basin - has been attributed to later compression & reverse faulting (basin inversion) during the Grenville orogeny



Stein et al., 2015

New view of sequence and timing of events shows MCR failed before basin inversion

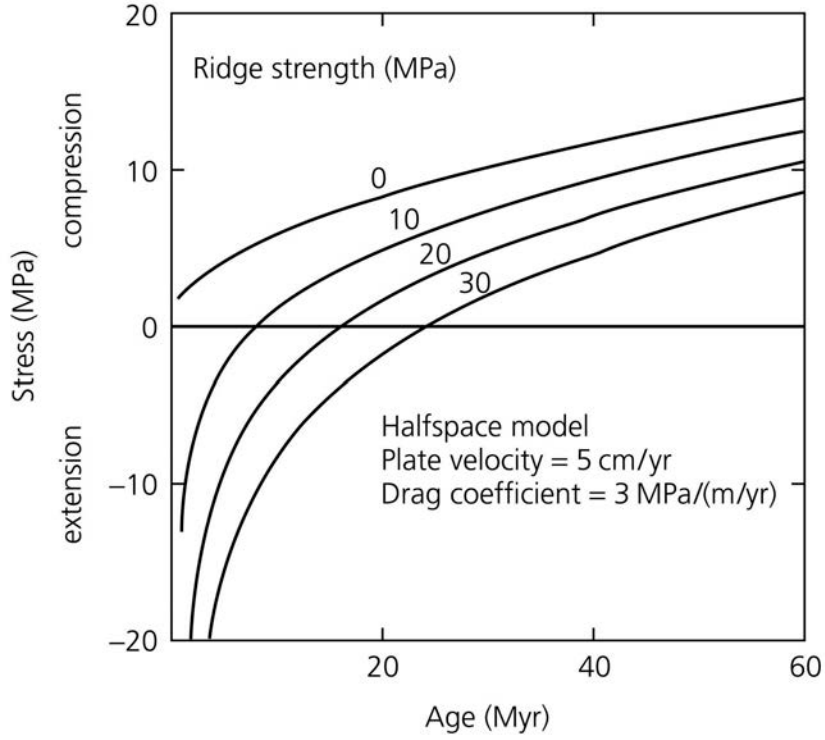
New analysis shows MCR rifting ended once seafloor spreading was established, long before regional compression event. How?

Oceanic lithosphere older than a few Ma is typically in compression

Within a few Myr, new oceanic lithosphere and thus adjacent continent are in compression

Successful rift makes remaining arms fail

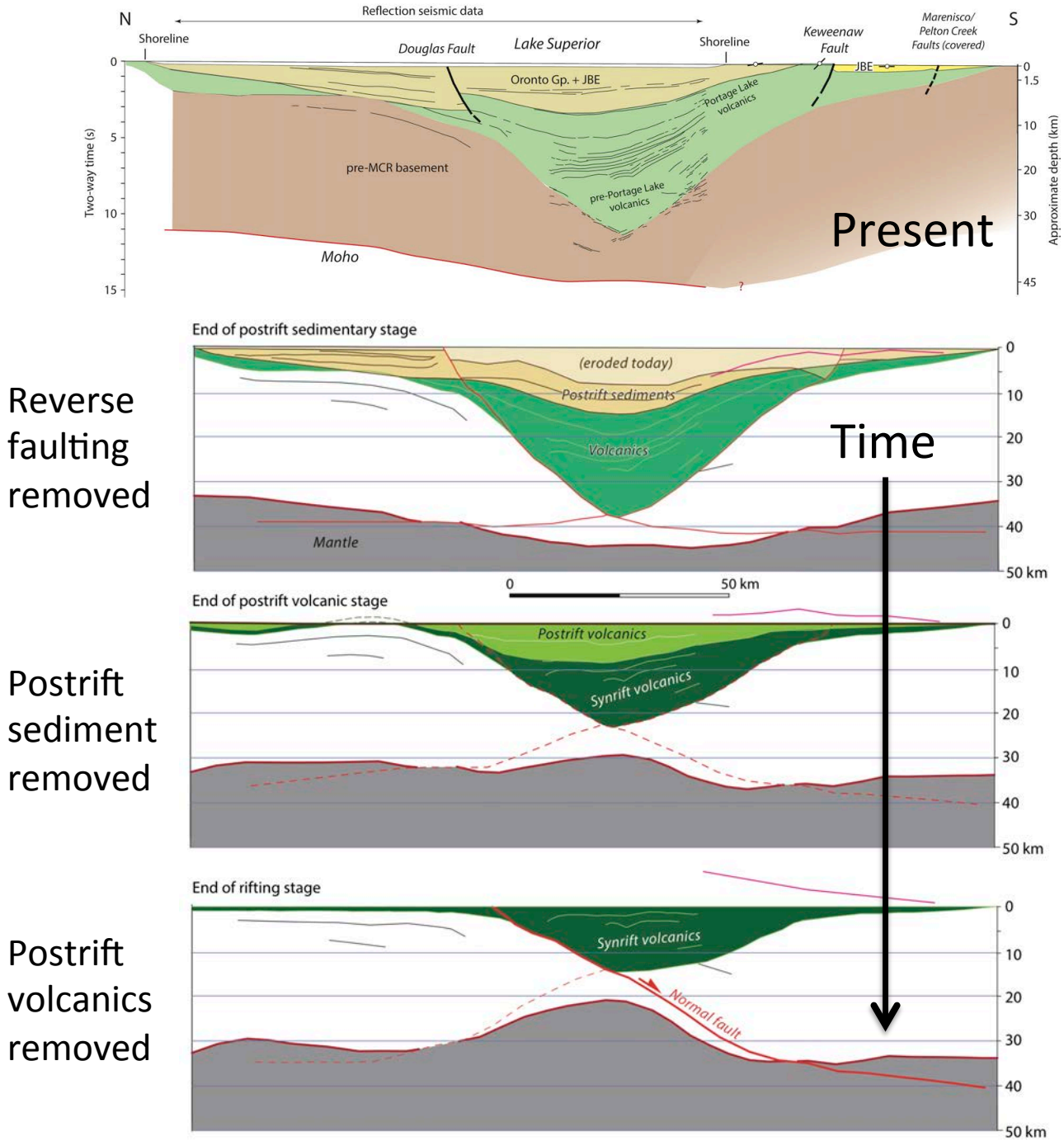
No special external event required for failure



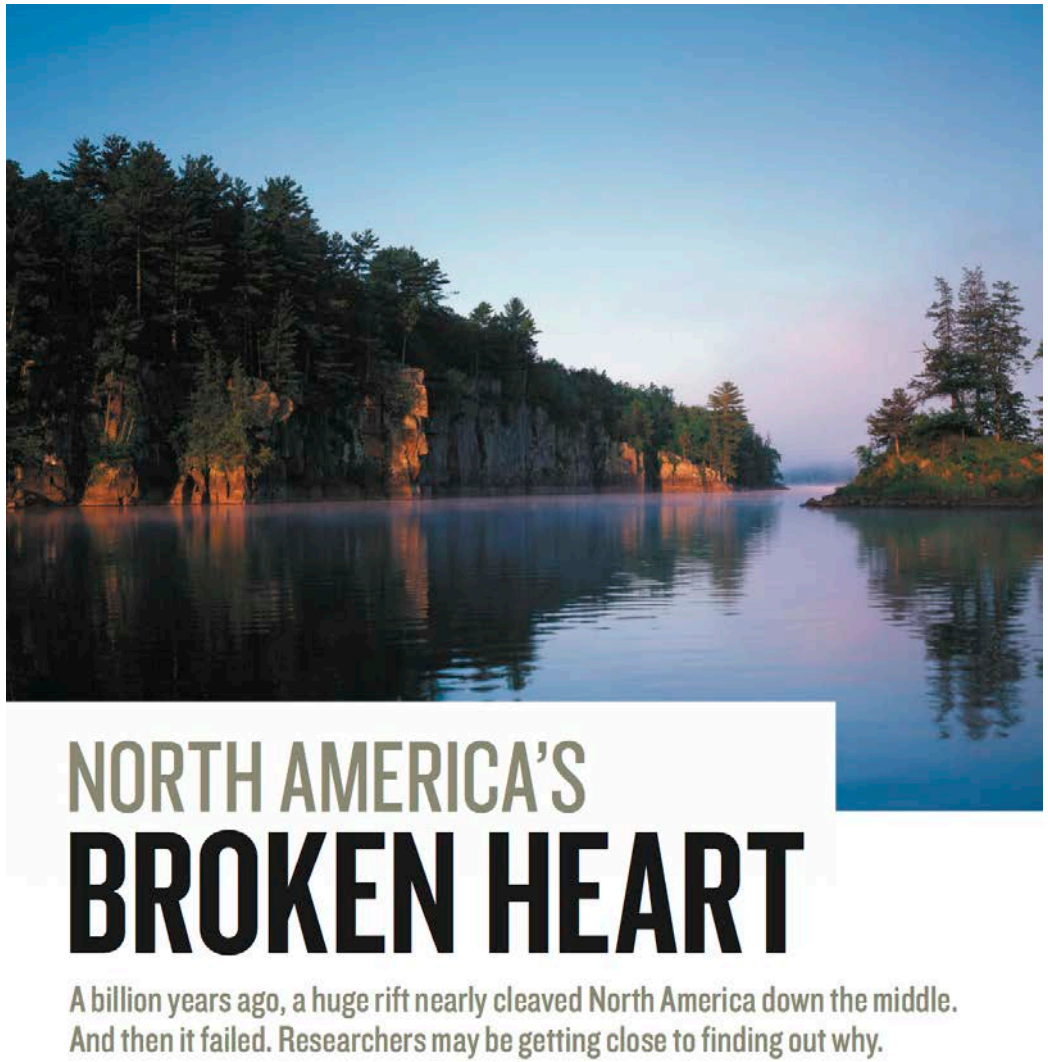
Wiens & Stein, 1984

MCR HISTORY RECONSTRUCTION

We model this history via numerical stepwise structural restoration of cross-sections working back from present geometry. This yields estimates of extension (~2 mm/yr), shortening, and crustal thickening.

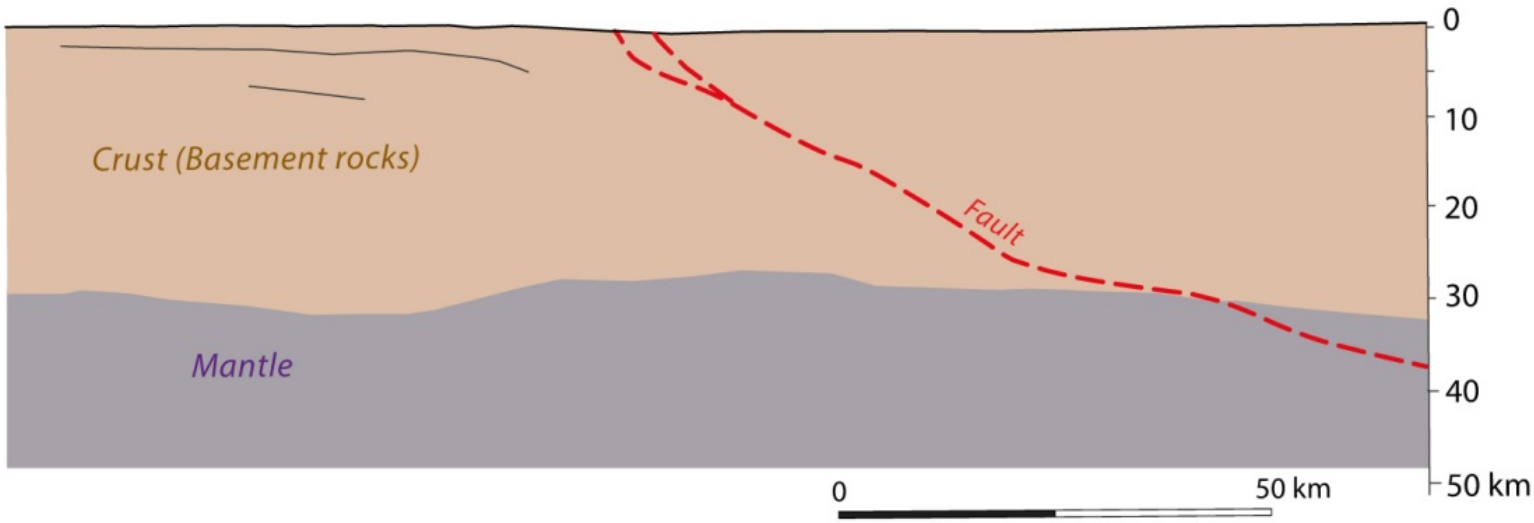


When Rift Met LIP



Rift/LIP model for MCR evolution

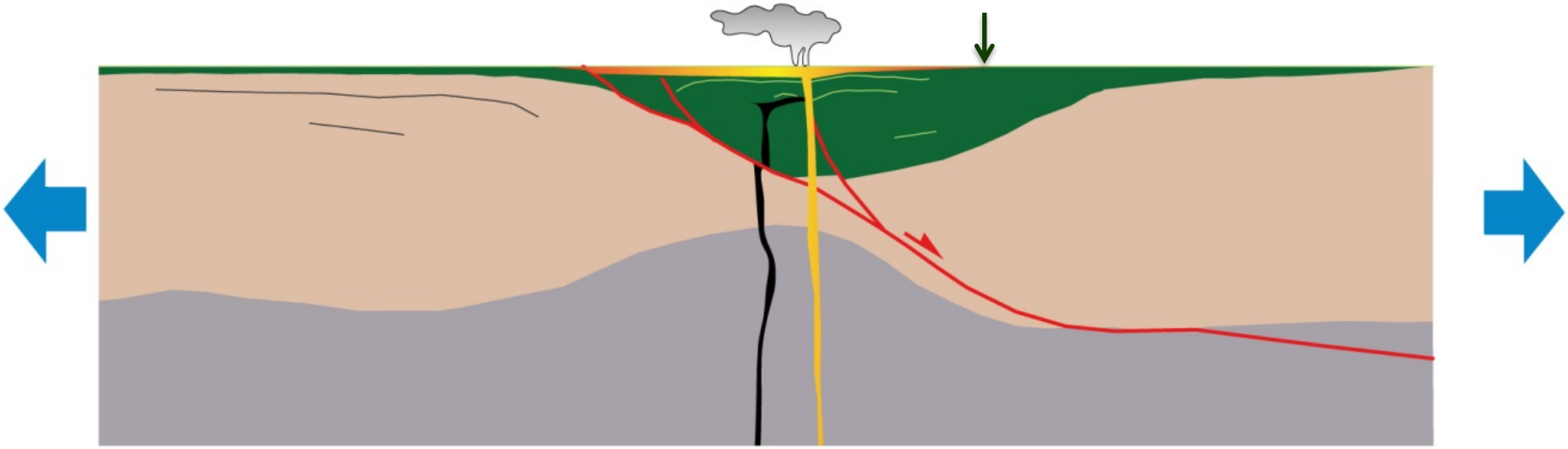
Rifting (extension) begins



NNW **About 1120-1109 Ma** SSE

Rift/LIP model for MCR evolution

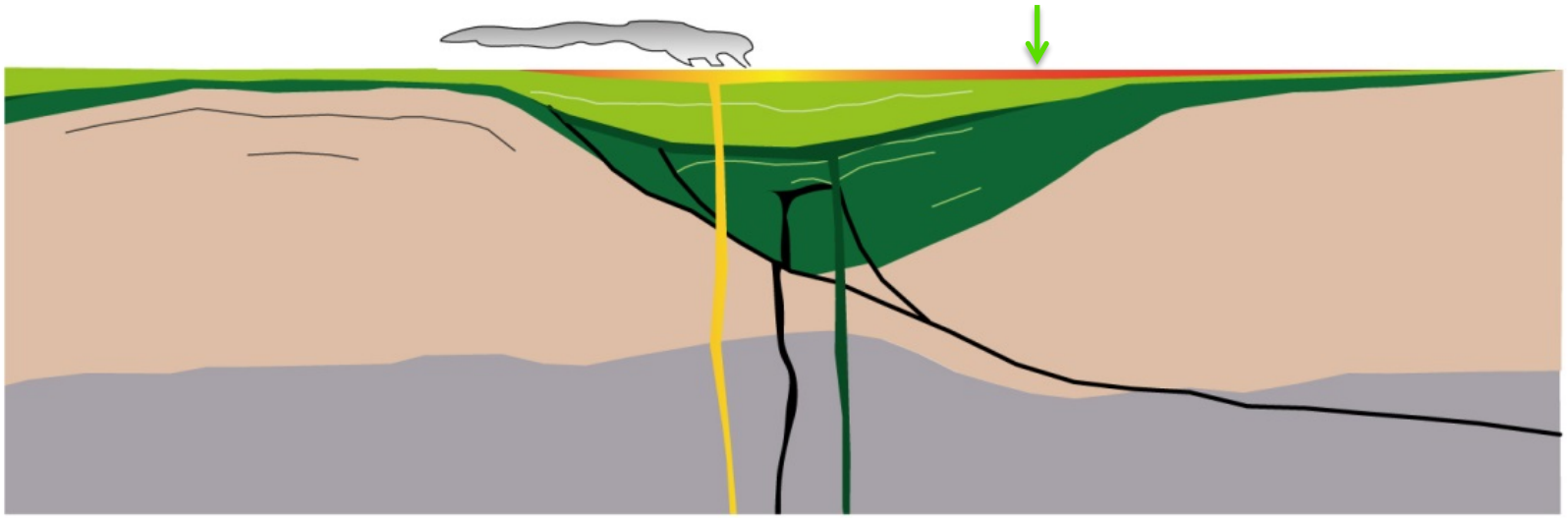
Rifting and volcanism, crustal thinning
Pre-Portage Lake volcanics



About 1109-1096 Ma

Rift/LIP model for MCR evolution

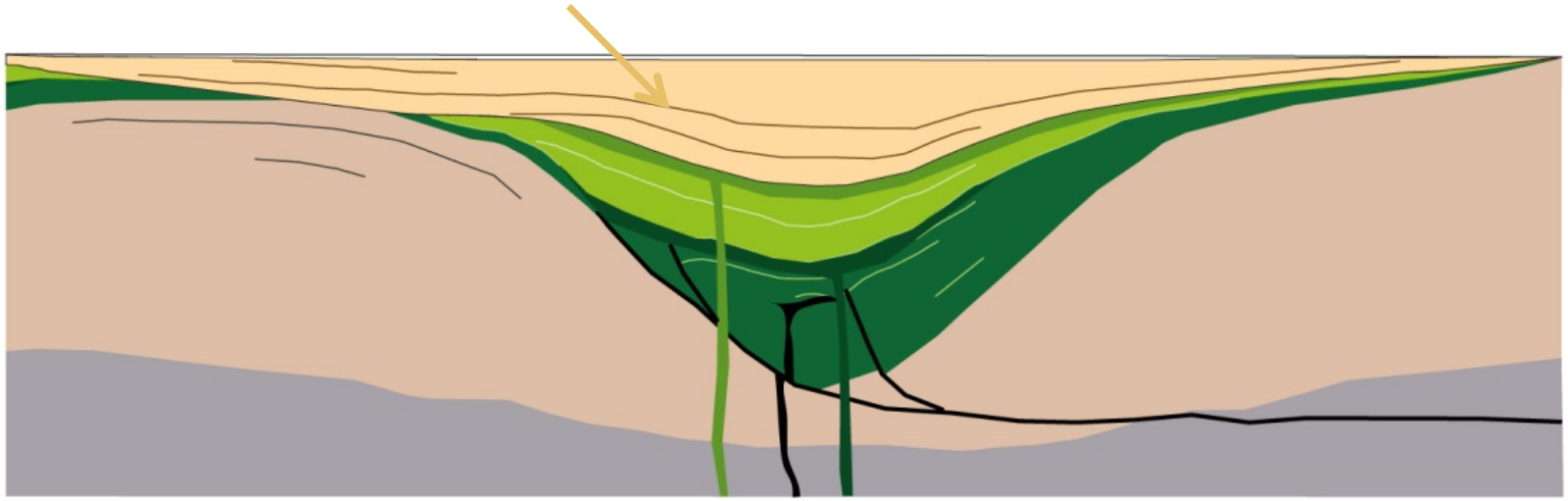
Faults inactive, volcanism and subsidence, Portage Lake volcanics, crustal thickening



About 1096-1086 Ma

Rift/LIP model for MCR evolution

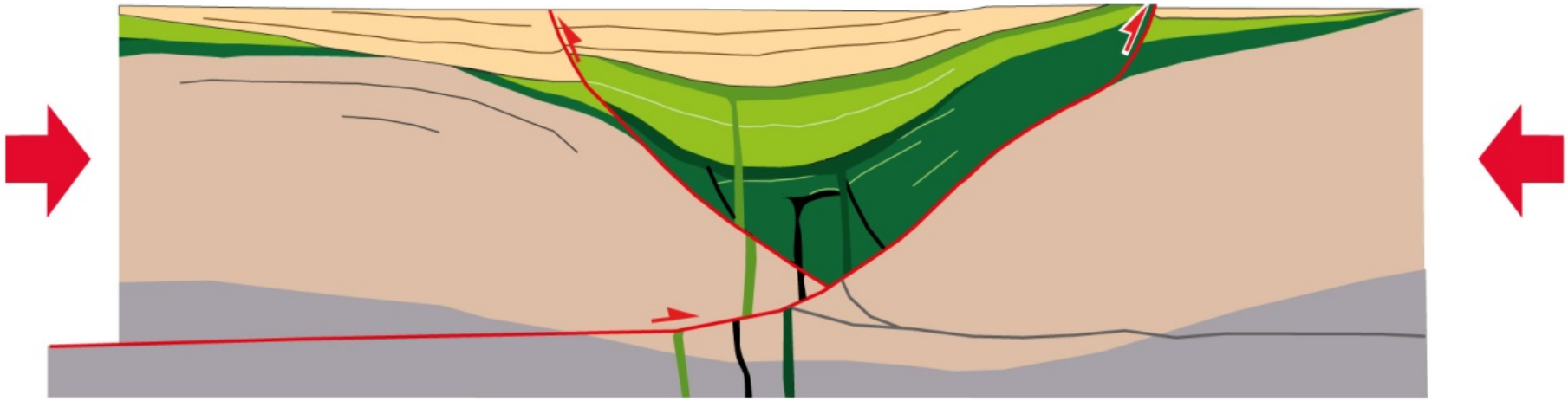
Faults inactive, volcanism ended
Subsidence & sedimentation, crustal thickening



About 1086-? Ma

Rift/LIP model for MCR evolution

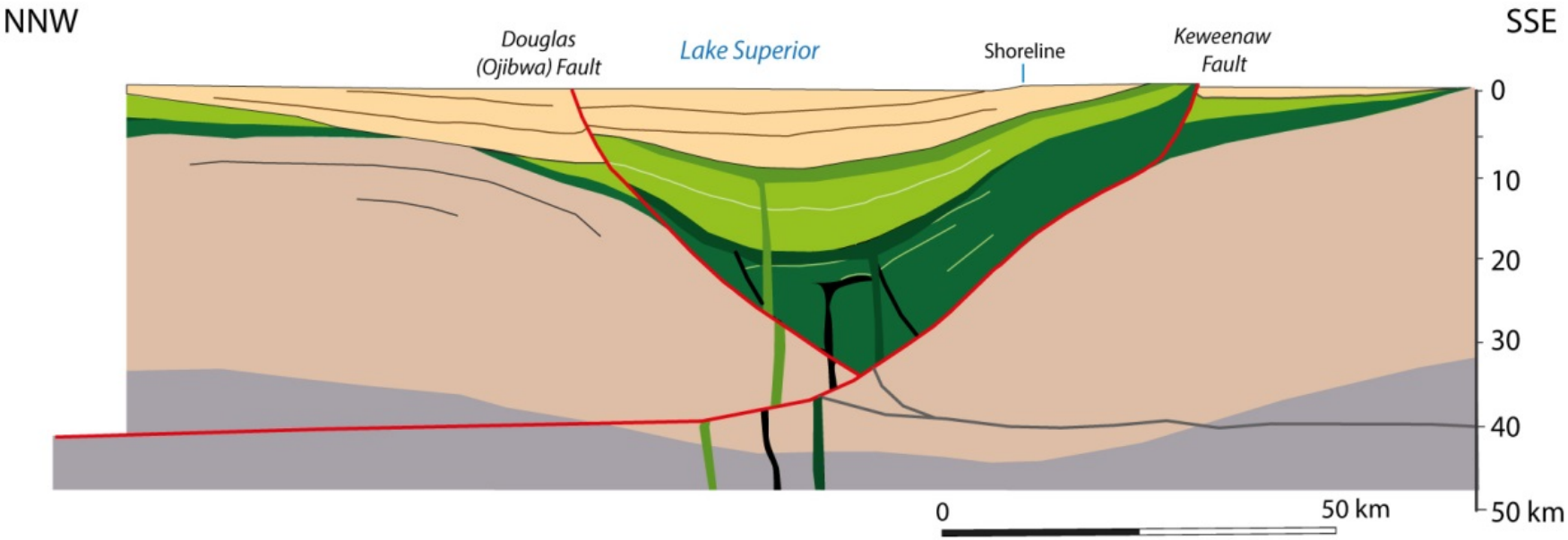
Reverse faulting and uplift
Additional crustal thickening



Much later

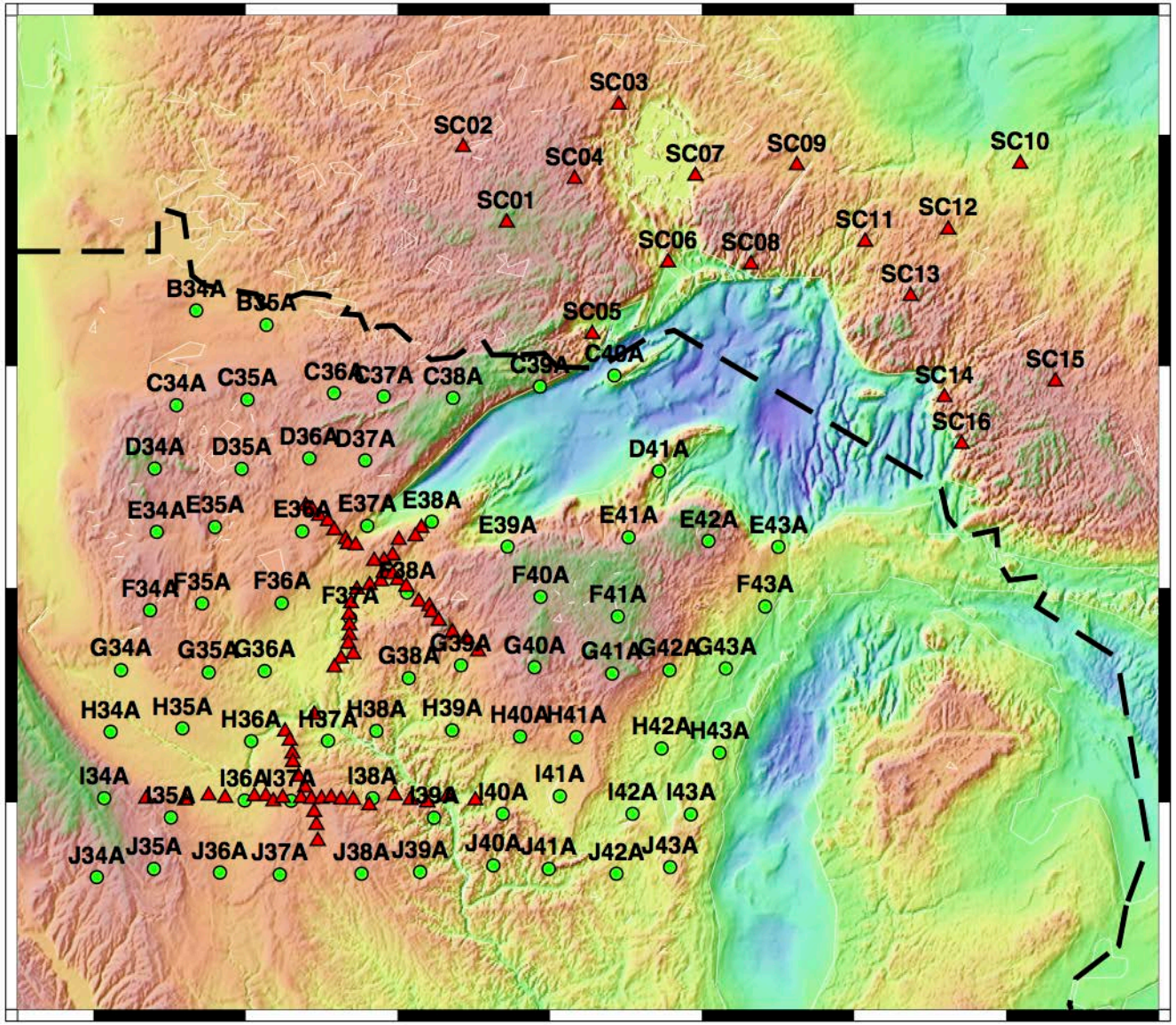
Rift/LIP model for MCR evolution

Net crustal thickening



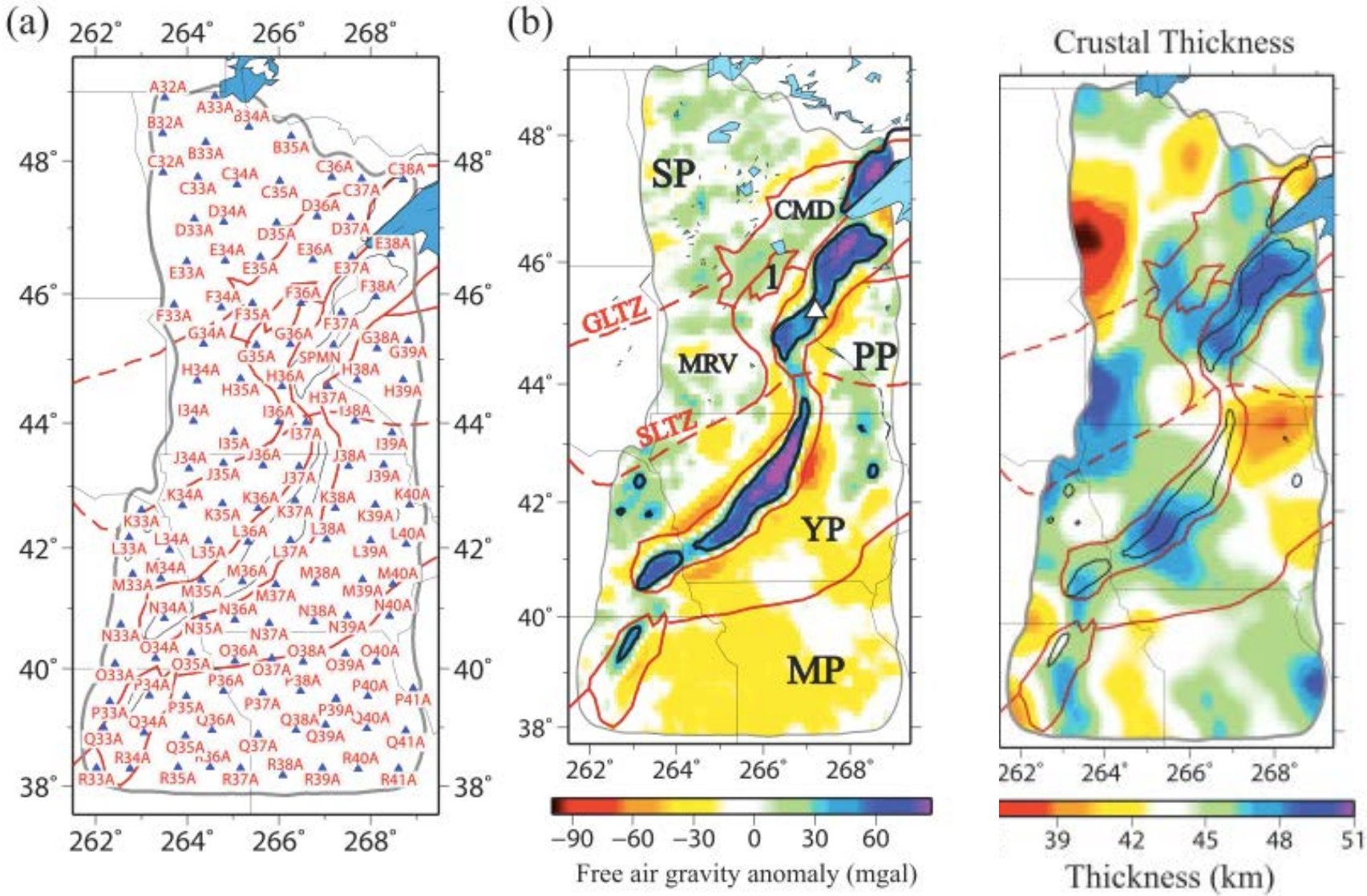
Present

New insight coming from SPREE / TA results



Crustal thickening observed along west arm

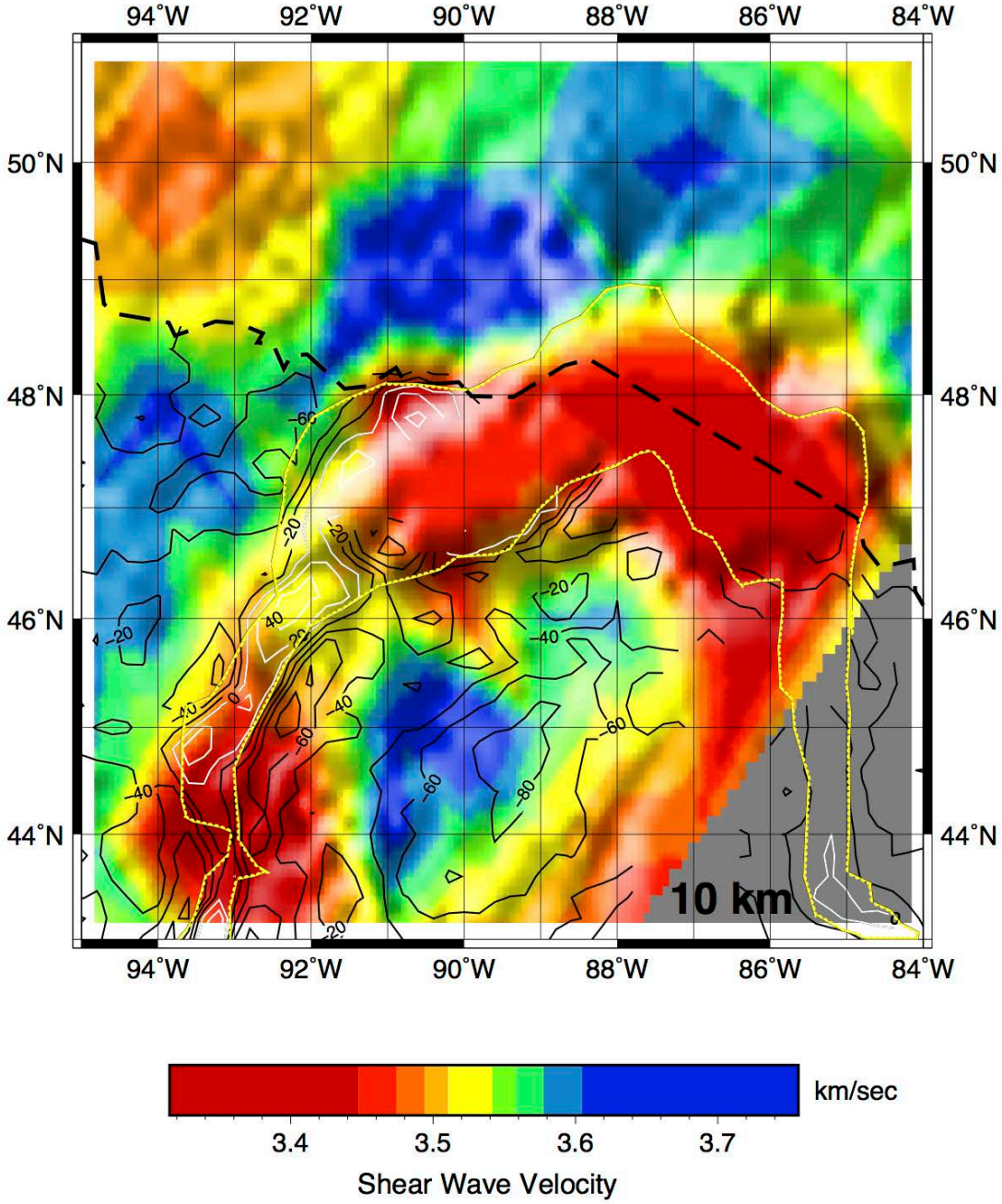
SHEN ET AL.: A 3-D MODEL OF THE MIDCONTINENT RIFT JGR, 2013



Crustal structure from ambient noise and earthquake surface wave analysis shows MCR nicely

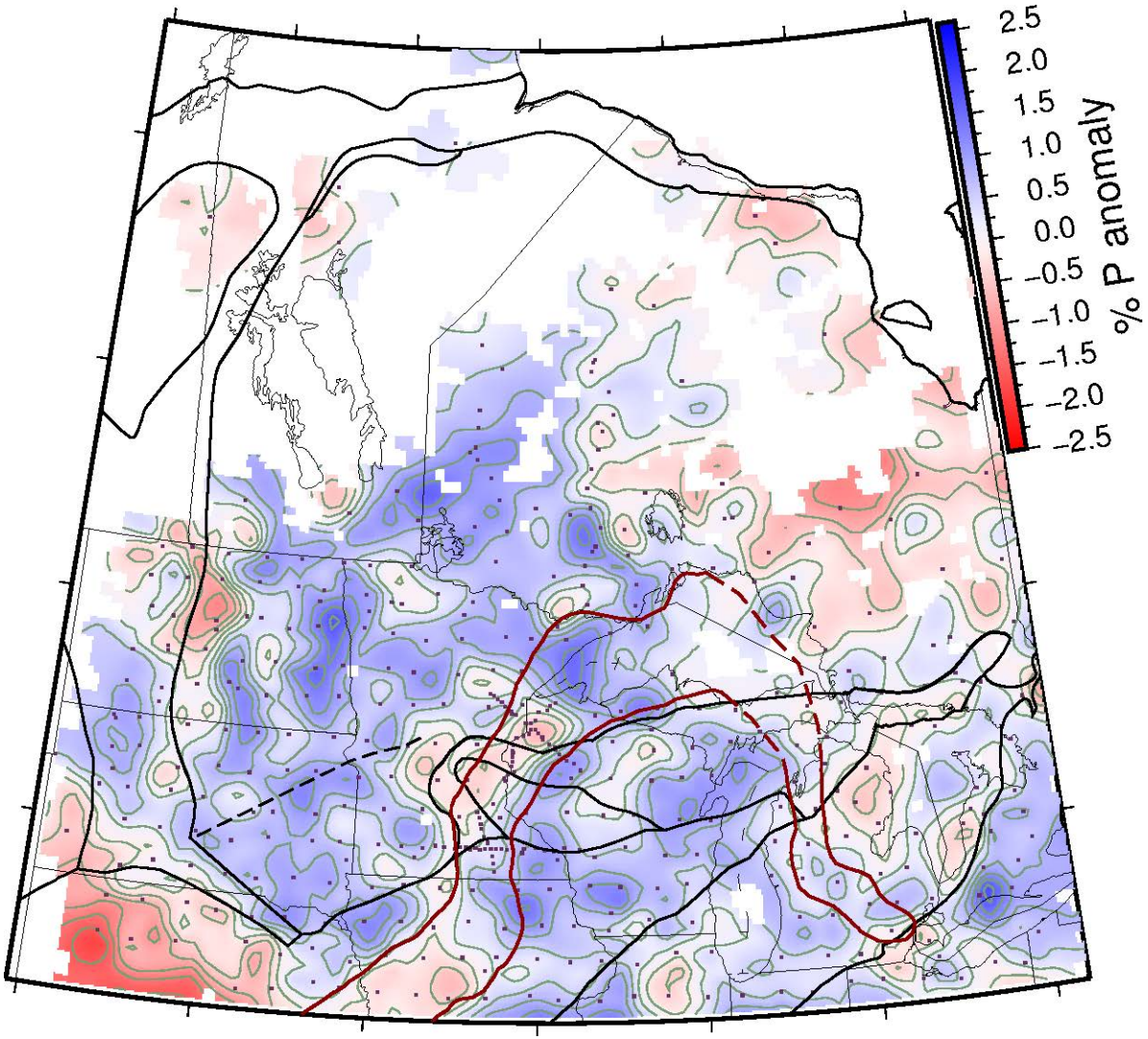
Low velocity of rift sediments

Al-Eqabi, Wiens, Wysession et al.



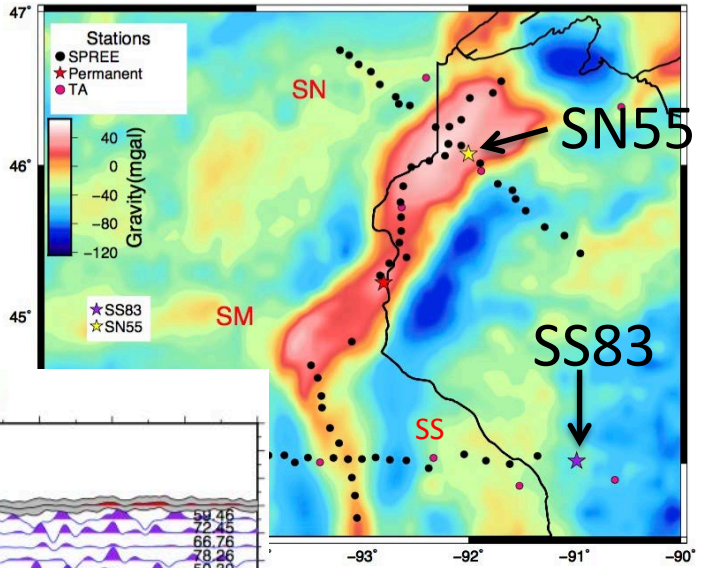
P-wave Teleseismic Tomography @ 100 km Depth

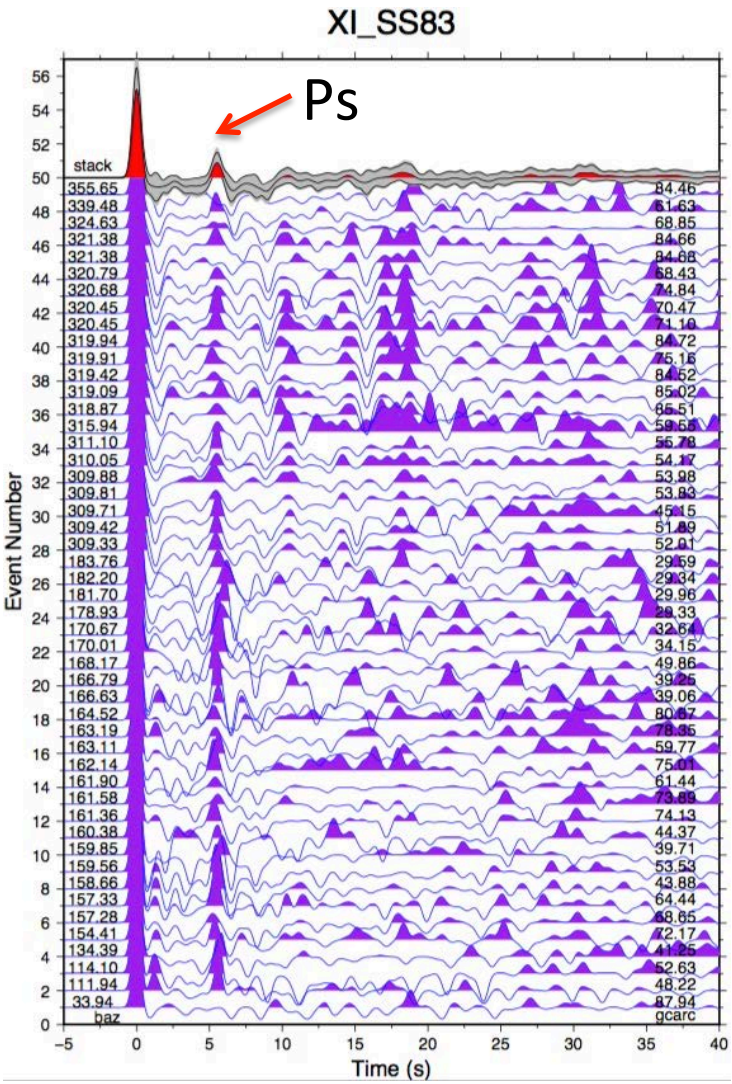
For further results and any questions, drop by Trevor Bollmann's poster (#4)

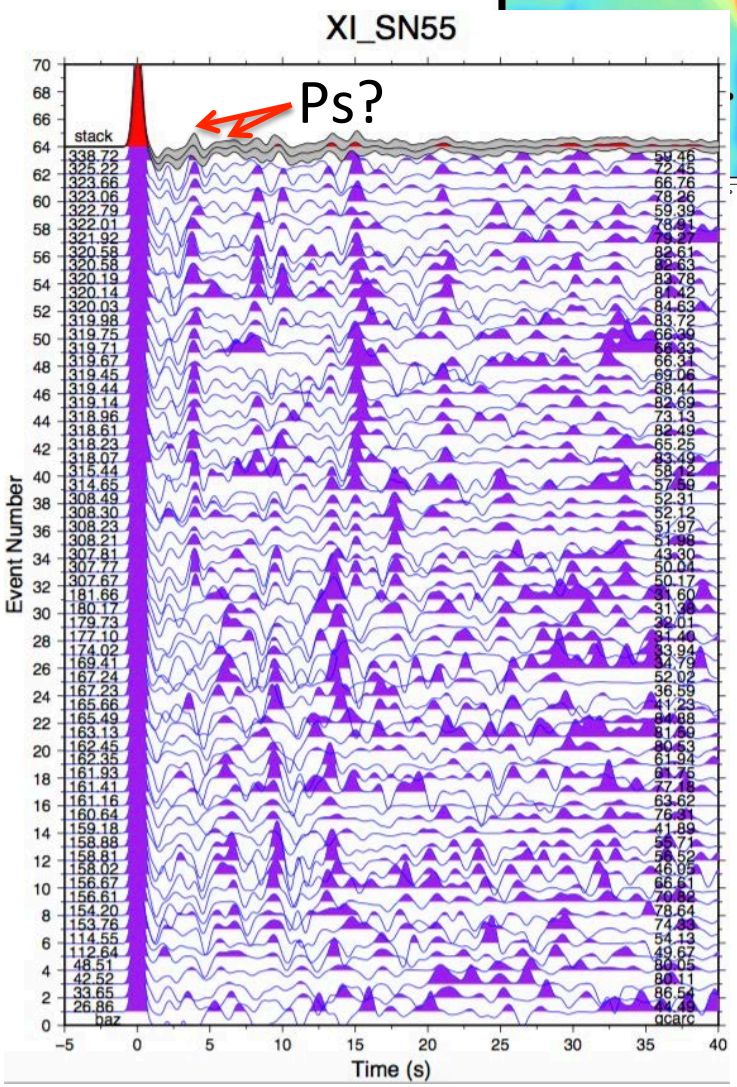


A linear feature of slightly lower velocity in the lithosphere beneath the surface expression of the MCR. This anomaly disappears at depths below 250 km.

P-wave receiver functions inside and outside of the Mid-Continent Rift System





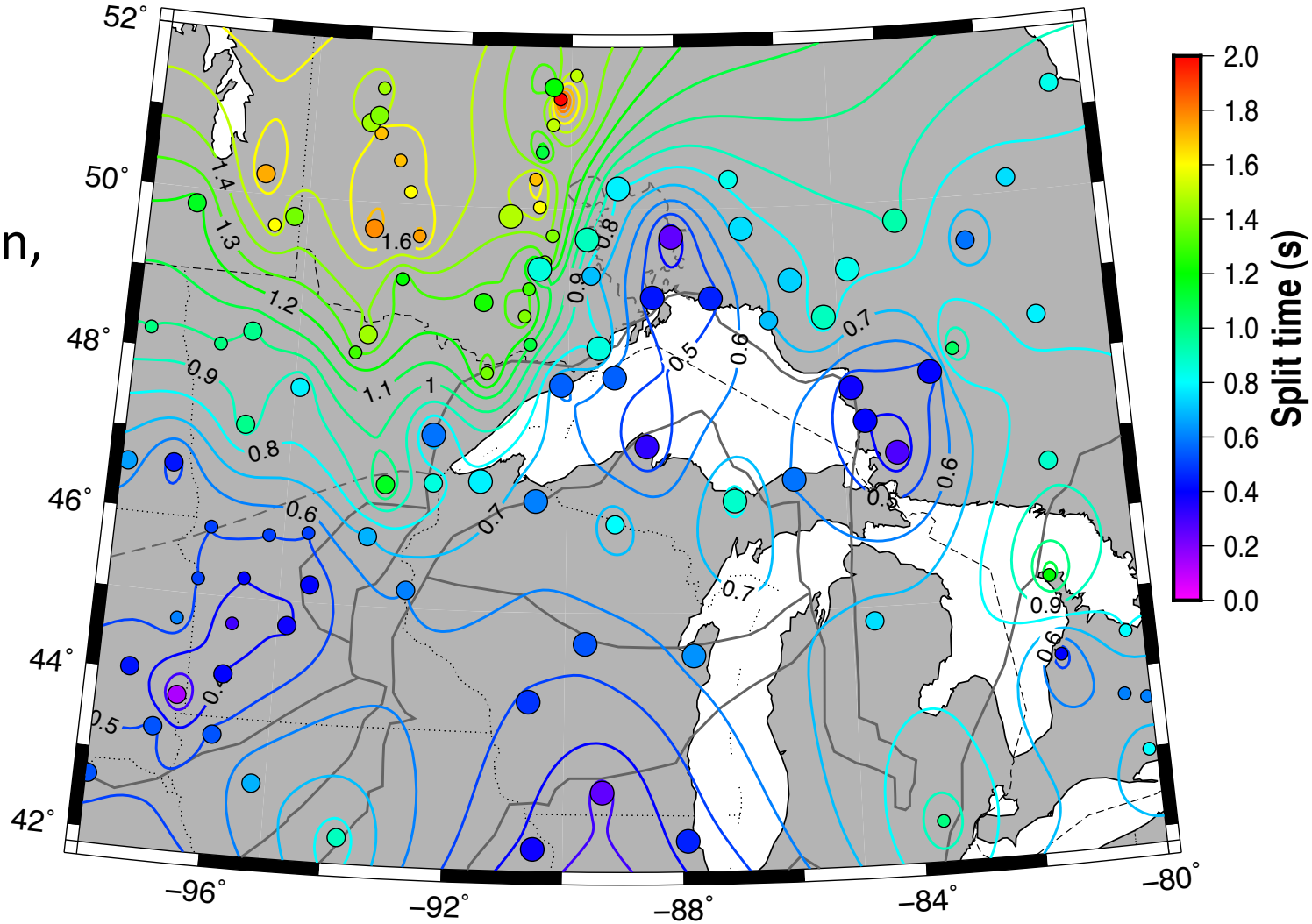


RFs inside the MRS are more complex.

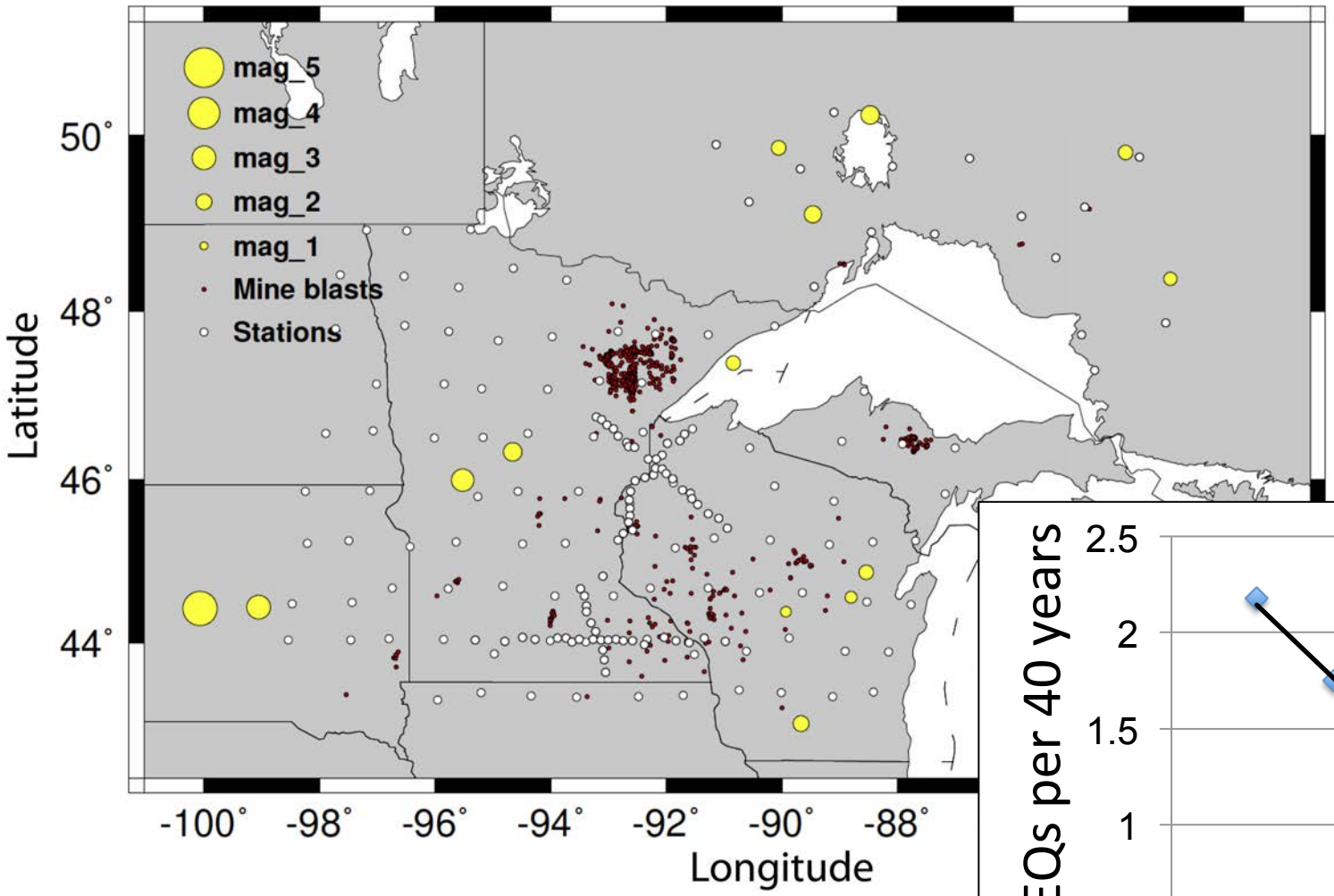
Zhang, van der Lee, et al.

Shear wave splitting shows significant change across the MCR, implying that the Superior province to the north was so thick and strong that the MCR did not break into it

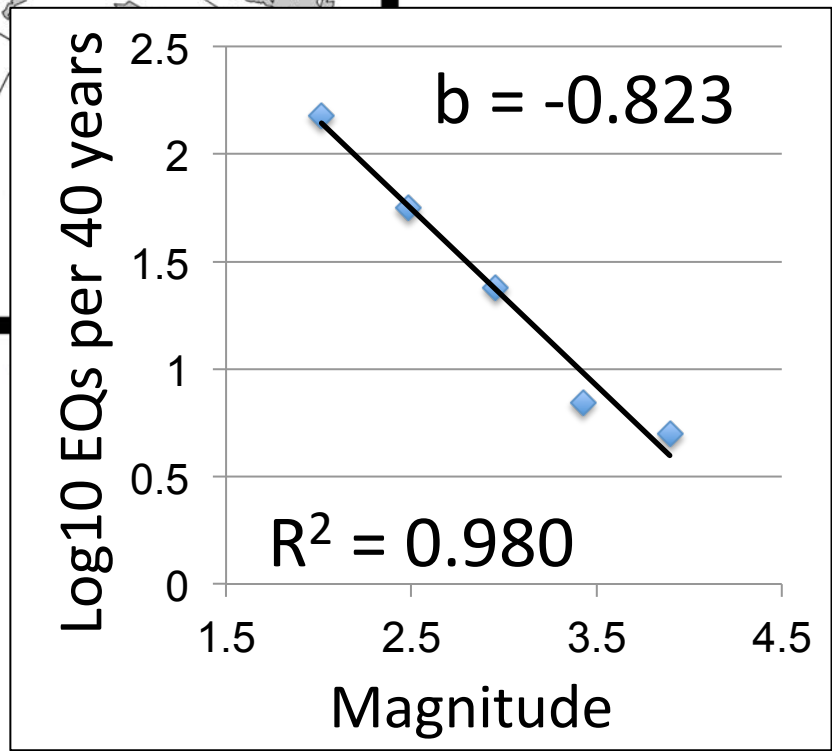
Ola, Frederiksen, et al.



14 Local Intraplate Earthquakes Located During SPREE Deployment

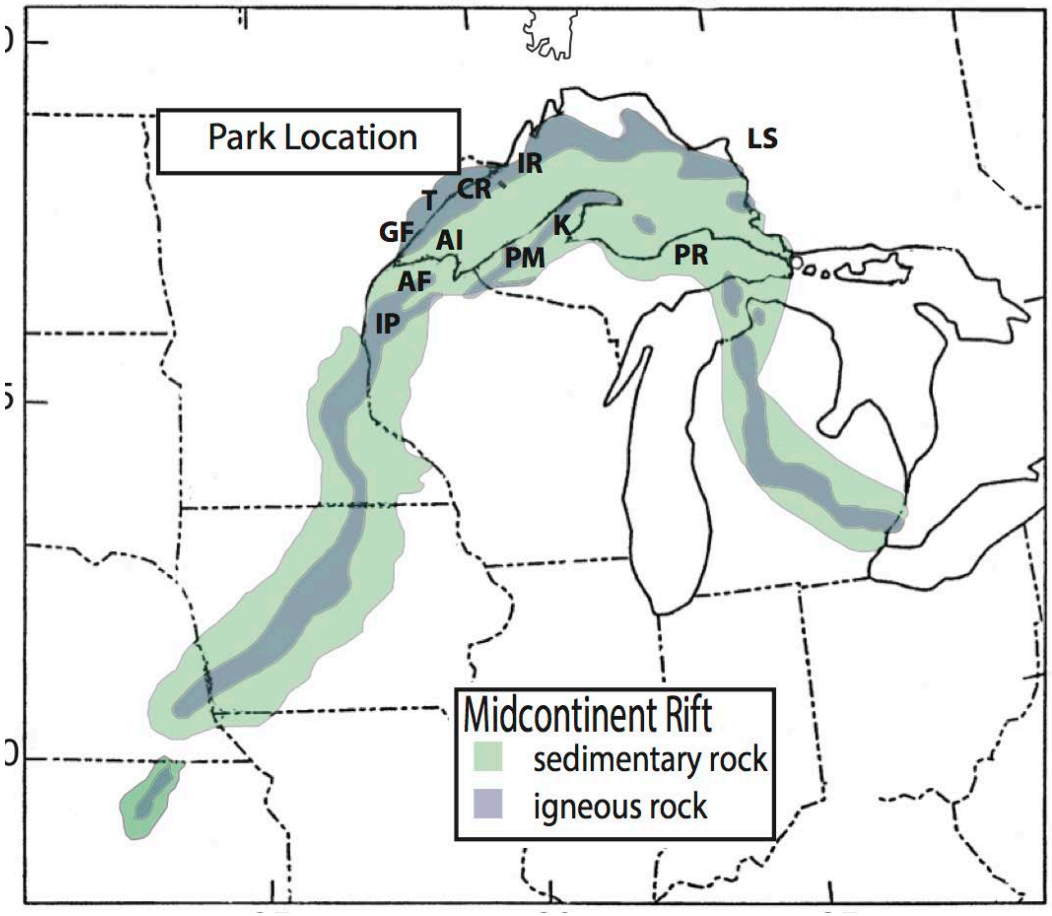


Bartz, Wysession, Wiens, Al-Eqabi, Shore, et al.



This part of MCR largely inactive

The MCR is an enormous but underutilized opportunity for park interpreters and educators



MCR gives rise to spectacular scenery, often in national, state, or provincial parks.

Many parks' interpretation describe only local and sometimes only recent geology, rather than explaining how they are parts of a huge ancient structure.

At Interstate Park, where a huge stack of volcanic flows are exposed, the visitor center explains only glacial geology.

Keweenaw National Historical Park, which explains how copper mining shaped the area's growth, does not explain that the copper deposits result from the MCR's volcanic rocks.

Interpretive Primer

Using Lake Superior parks to explain the Midcontinent Rift

By Seth Stein, Carol A. Stein, Eunice Blavascunas, and Jonas Kley

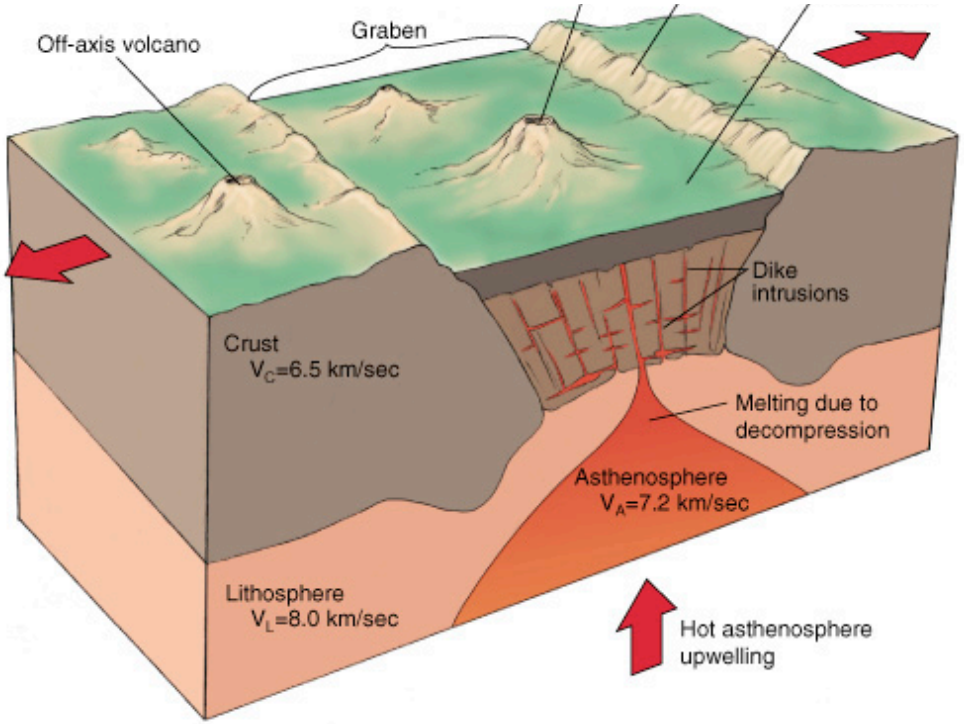
Summary sentence

Explaining the spectacular scenery around Lake Superior resulting from the 1.1 billion year old Midcontinent Rift System gives park interpreters an opportunity to discuss some of the most important processes that shape our planet and influenced the region's settlement and growth.

Details in poster #31

NPS Park Science, in press

From “MCR for interpreters”



How rifts work

The East African Rift shows how part of a continent starts to be pulled apart. This involves heating from below, but we still don’t know exactly why and how. The granite crust stretches like taffy and starts to break along newly formed faults, causing earthquakes and forming what’s called a rift valley, while the material below flows.

It’s like what happens if you pull both ends of a Mars candy bar – the top chocolate layer breaks and the inside stretches.

If the rift keeps opening, hot material from the mantle rises under the rift and causes volcanoes where basalt magma erupts.

From “MCR for interpreters”

Rift/LIP hybrid yields native copper

Native copper and basalt flow, MTU

The MCR has the world's largest deposit of native copper (copper not bounded to other elements) and major copper sulphide deposits like those found elsewhere.

From “MCR for interpreters”

Rift/LIP hybrid yields native copper

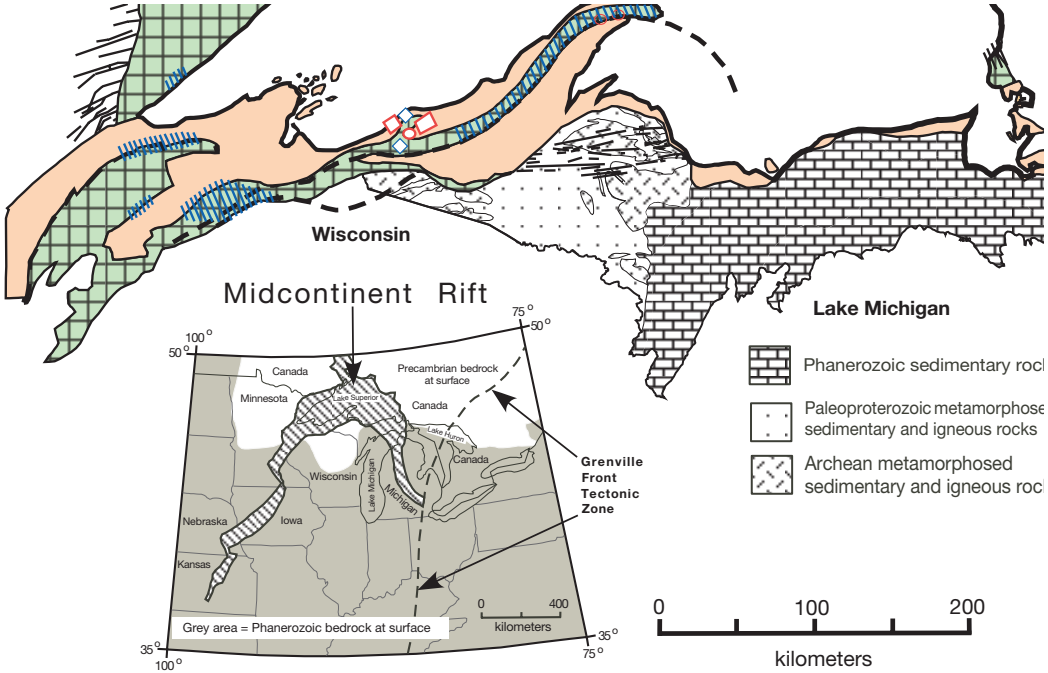


FIG. 1. Generalized bedrock geologic map of the Midcontinent rift of the Lake Superior region and the Upper Peninsula of Michigan showing locations of copper deposits and occurrences.

information with similar deposits, and propose a genetic model.

History

Sedimentary rock-hosted stratiform copper mineralization at the base of the Nonesuch Formation was first recognized in the 1850s near the White Pine mine (Ensign et al., 1968). From 1915 to 1921, native Cu was economically extracted from the White Pine fault (Mauk et al., 1992a). Beginning in 1937, exploration eventually led to the production, in 1953, of Cu from primarily chalcocite-bearing, sheetlike, tabular orebodies hosted by sedimentary rocks at Whit Copper Range Company. Production continue interruptions, until its closure in 1996.

From 1948 to 1954, the U.S. Geological Surv a major study of the Nonesuch Formation a Pine mine and surrounding area (White and V Table 1). Despite the lack of exposures of min White and Wright (1954, p. 690) concluded tha the Nonesuch Formation had potential to host area many times larger than that of the White deposit itself.” Soon after this publication, Ch

This arose because the MCR's rift/LIP combination gave rise to unusually thick basalts buried under thick sediments that kept the basalt at high temperatures, allowing extraction of large amounts of copper.

Native Americans mined copper, and the discovery of commercially viable copper deposits during the 1840s led to a mining boom that shaped the area’s economy.

Bornhorst and Williams, 2011

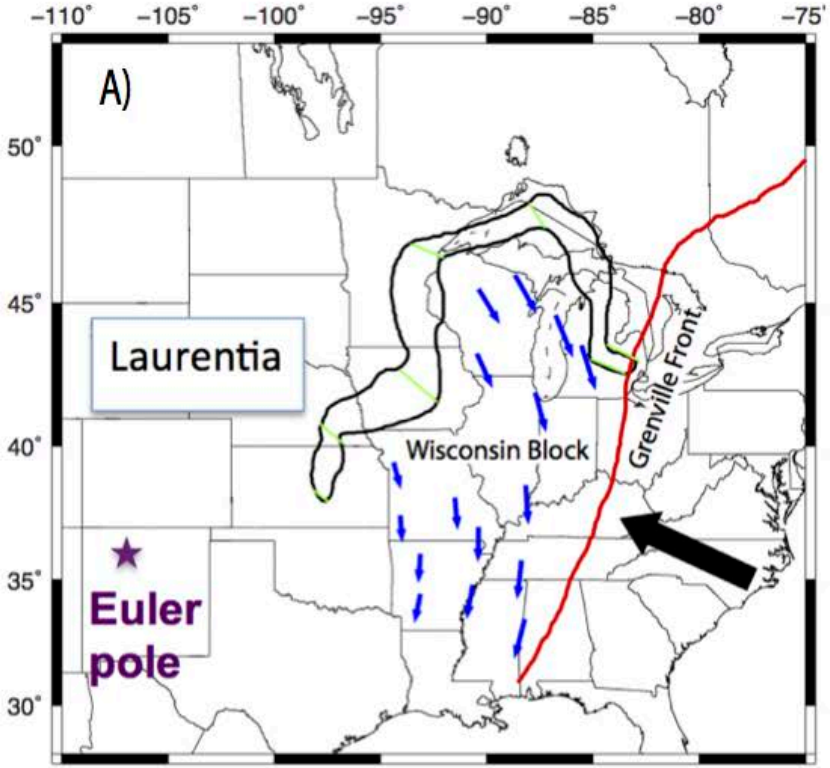
Next, learn more about:

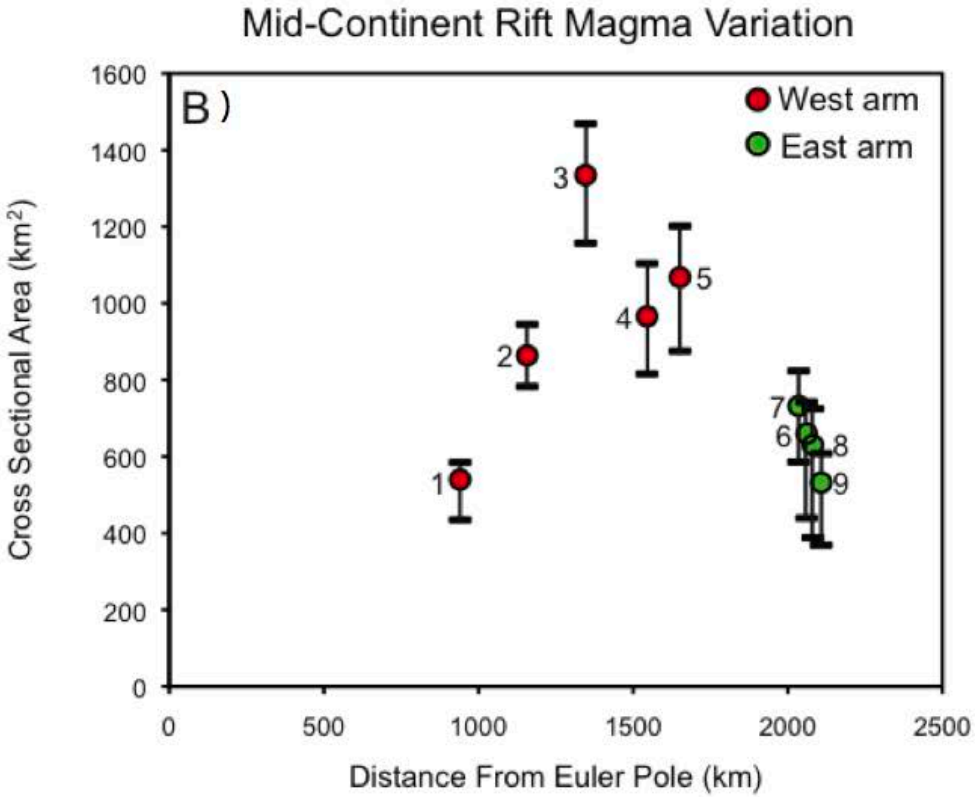
How did rifting initiate, develop, and stop; did it differ from typical continent rifting; and how did it vary along the MCR?

Does the MCR's unusual nature reflect typical continental rifting by chance encountering a plume, or was there something unusual about one, the other, or both?

How did magmatism evolve over time? How did it continue for 21 Ma, much longer than other LIPs, especially given Laurentia's rapid plate motion?

Refine spreading estimates, and thus microplate kinematics, with better gravity models constrained by SPREE data

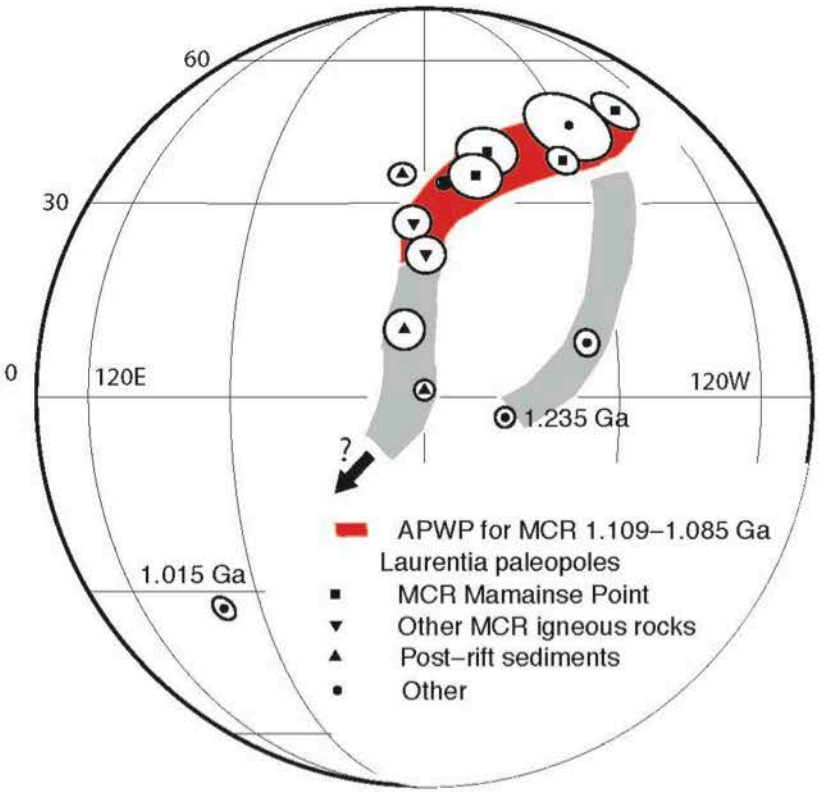




Merino et al., 2013

Model cusp evolution for both younger events & MCR to learn more about how cusps reflect rifting history

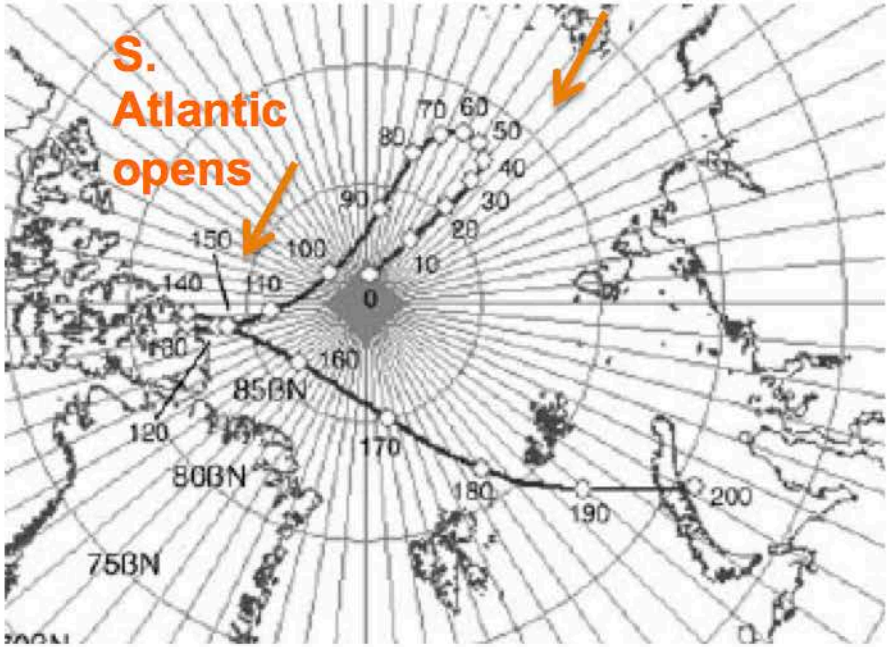
APWP for Laurentia poles



Stein et al., 2014

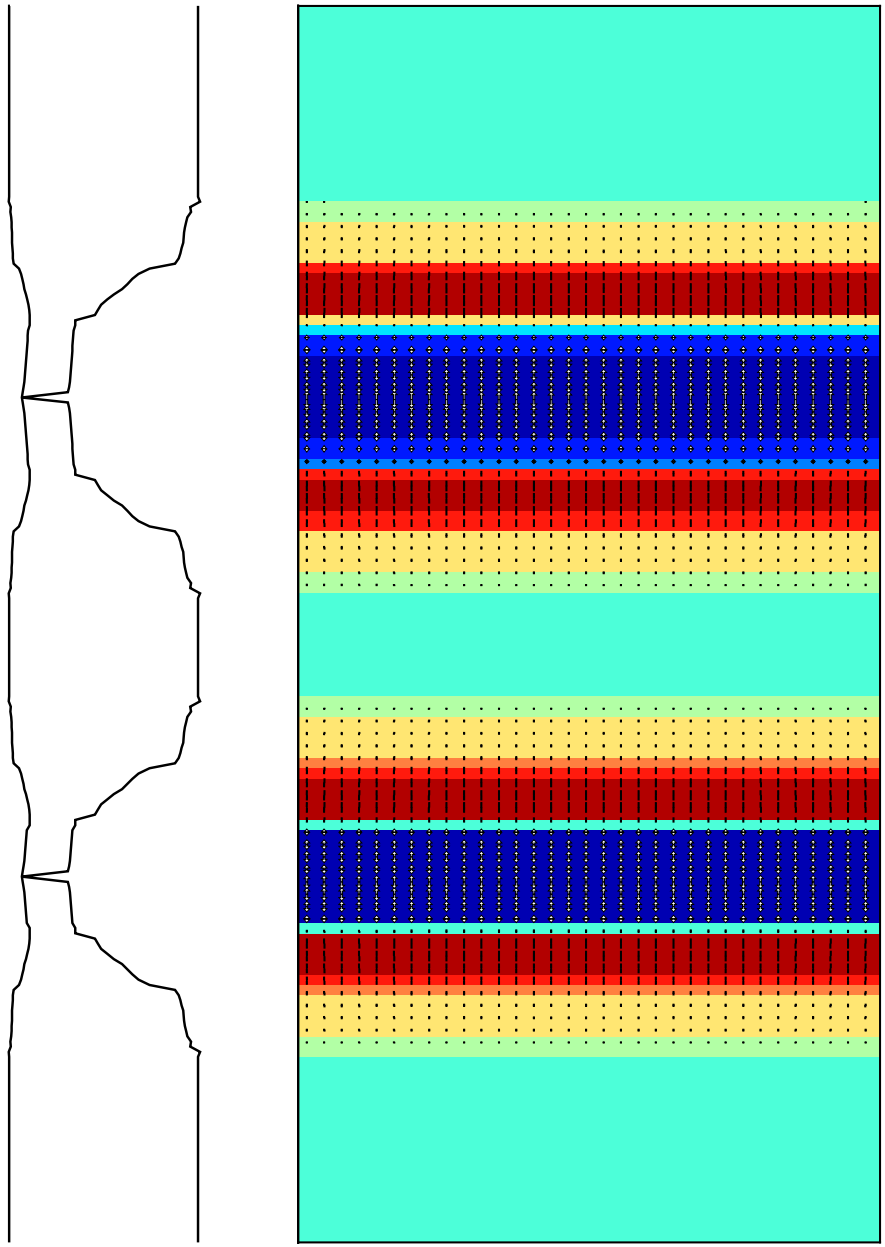
Smoothed APWP of South America since 200 Ma

Rifting from Antarctica



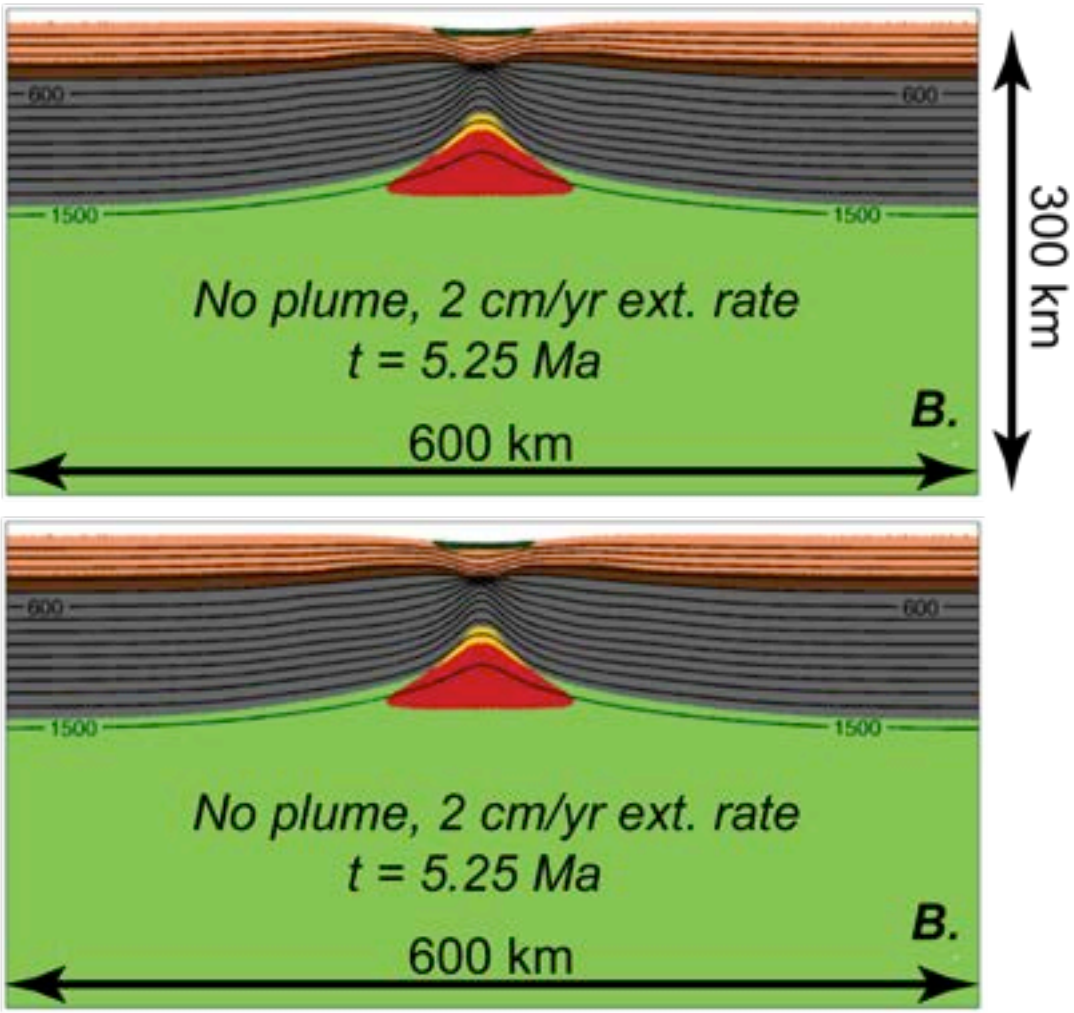
Schettino and Scotese, 2005

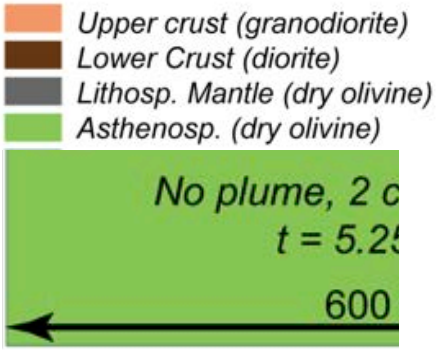
Model stress within continent to explore how transition to successful seafloor spreading changes stress on remaining arms from extension to compression, making them fail

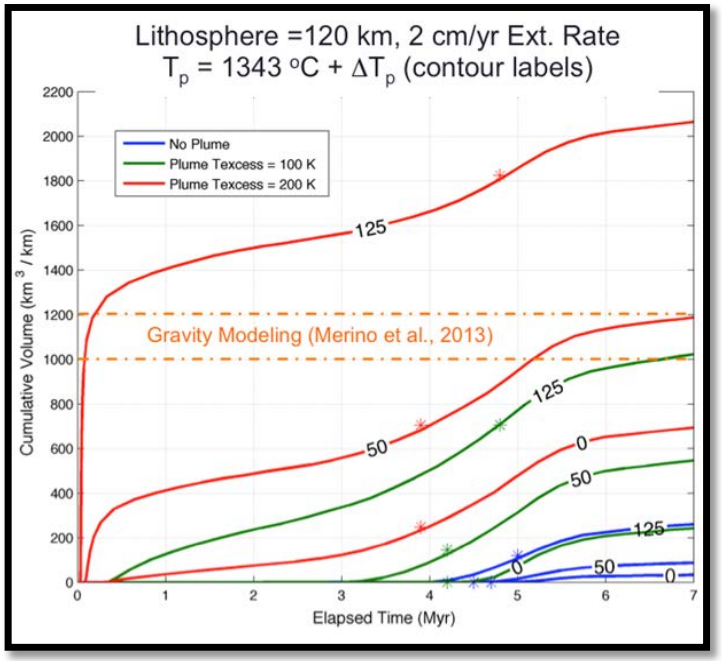


Flesch, Crane, Stein & Stein

Model rift/LIP system to determine P/T conditions allowing generation of such large volumes of magma under Precambrian conditions

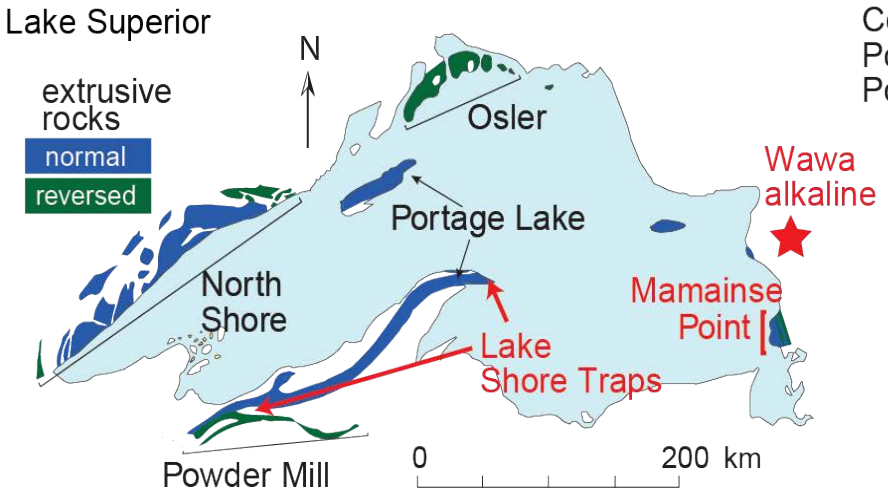




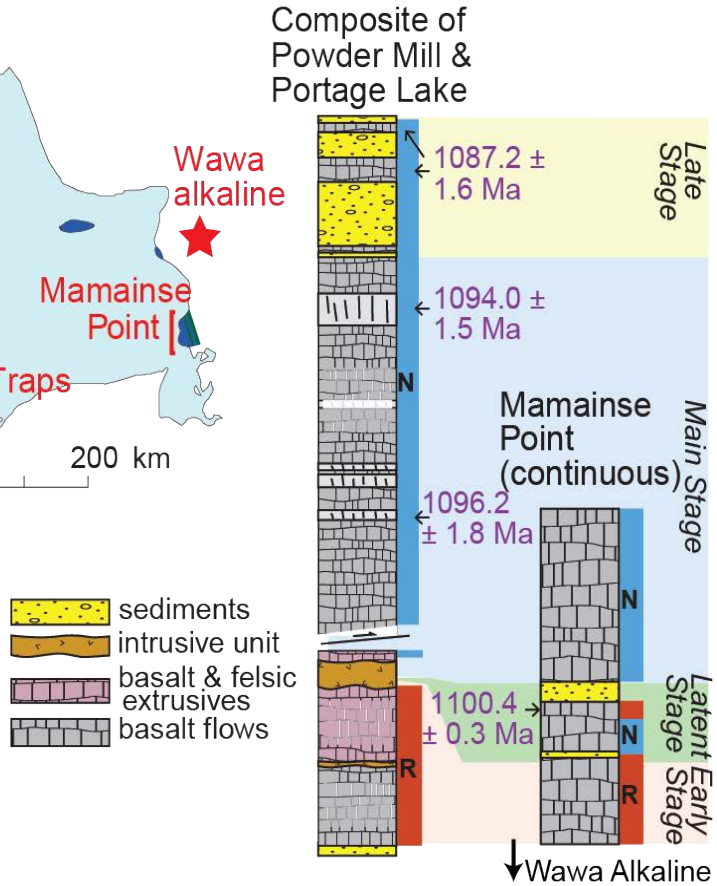


Mocha, Brown, Rooney, Stein & Stein

Geochemical & petrologic studies to learn more about how magmatism evolved during rift/LIP sequence



Swanson-Hysell et al., 2014



Rooney, Brown, Mocha, Stein & Stein

There's still a long way to go, and lots more will be forthcoming