How plate tectonics drives the geological carbon cycle

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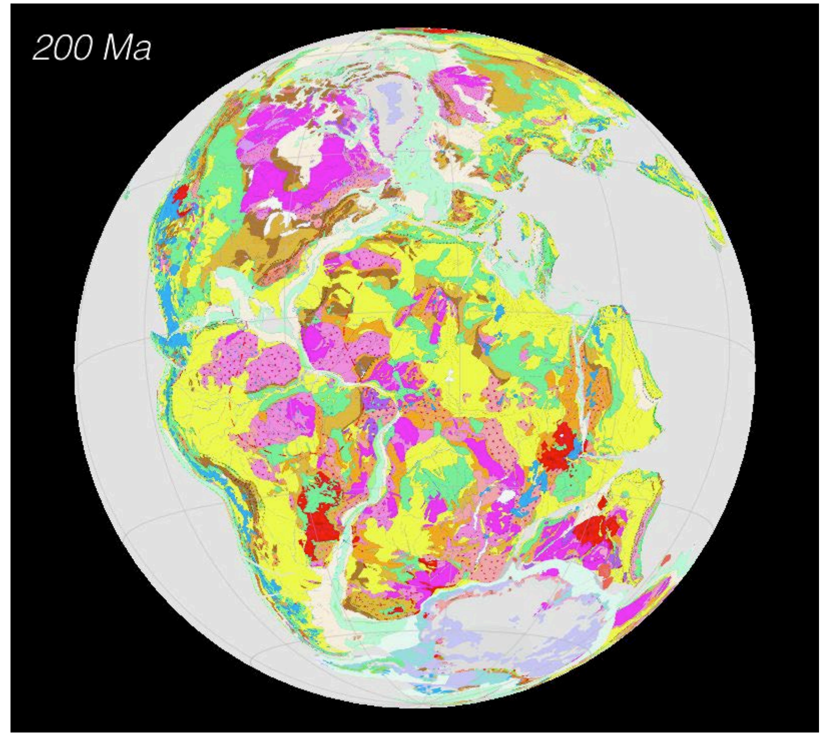
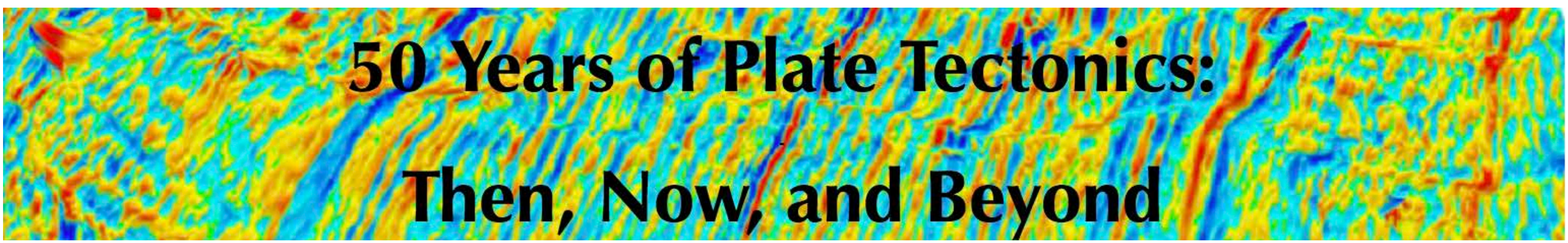
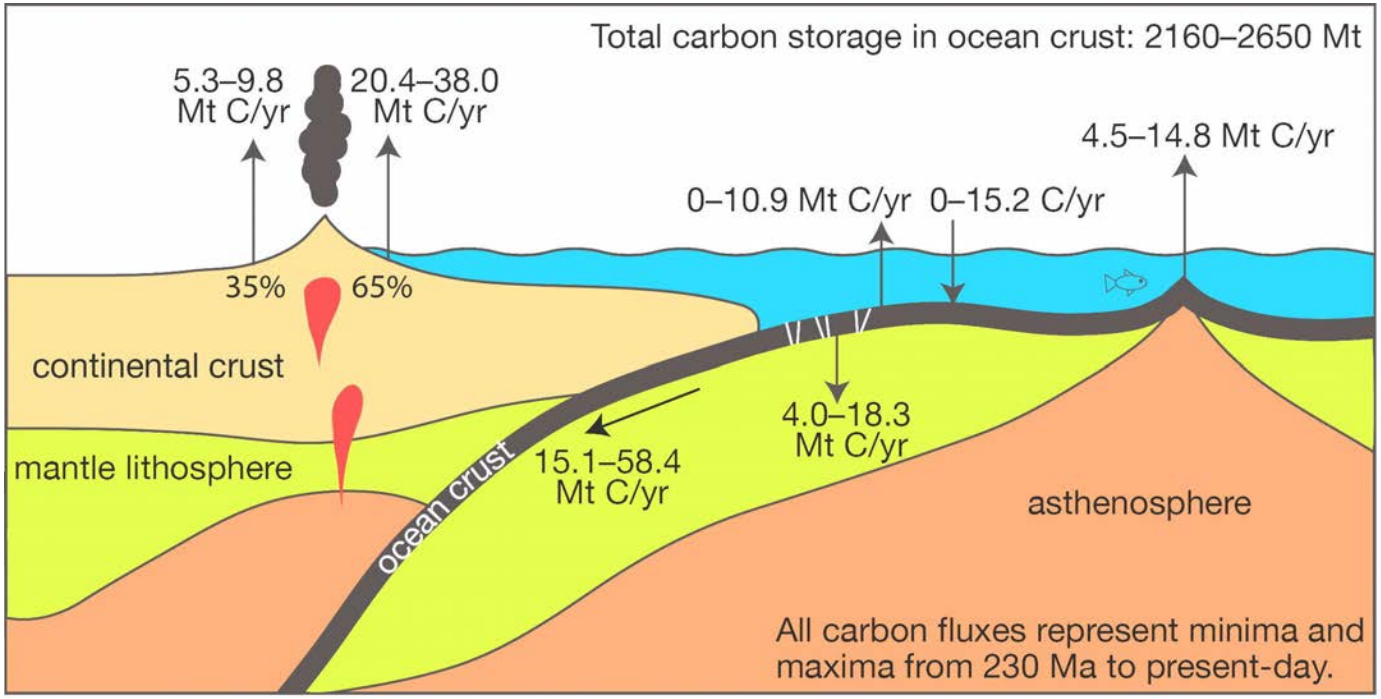
The University of Sydney



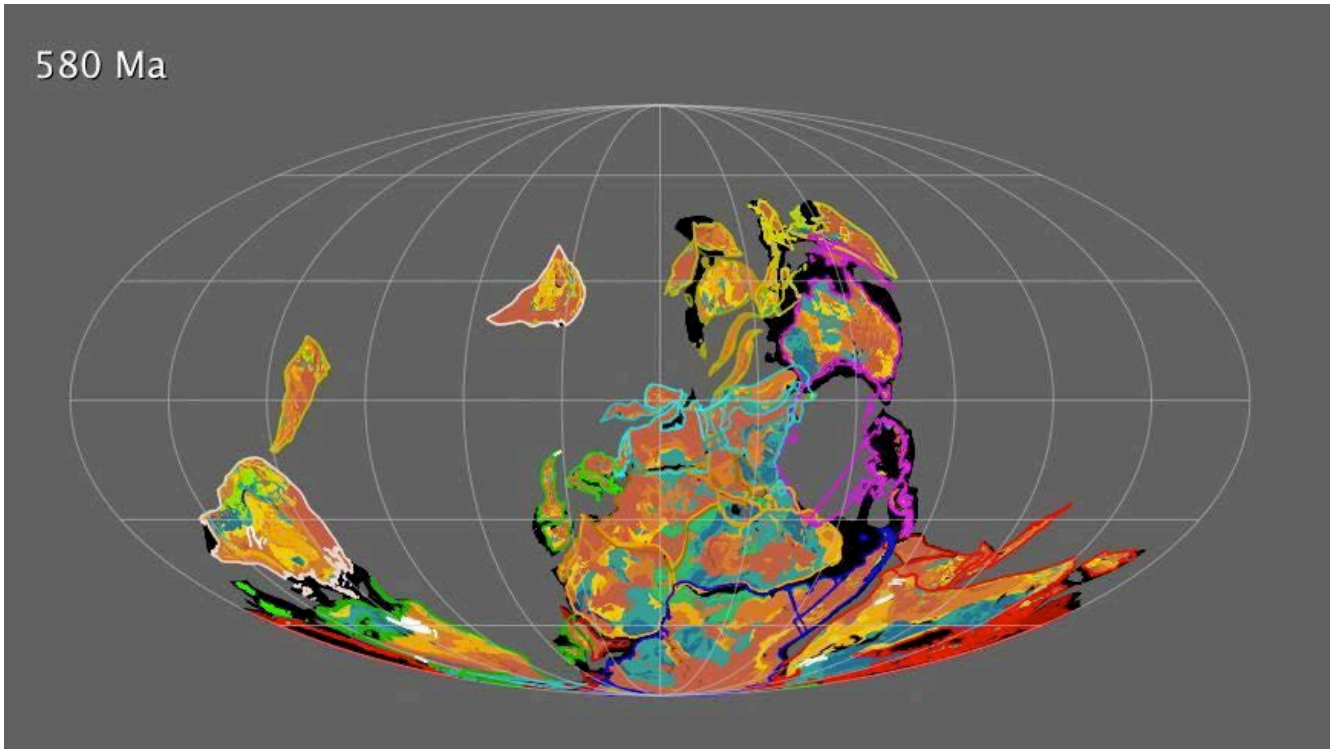


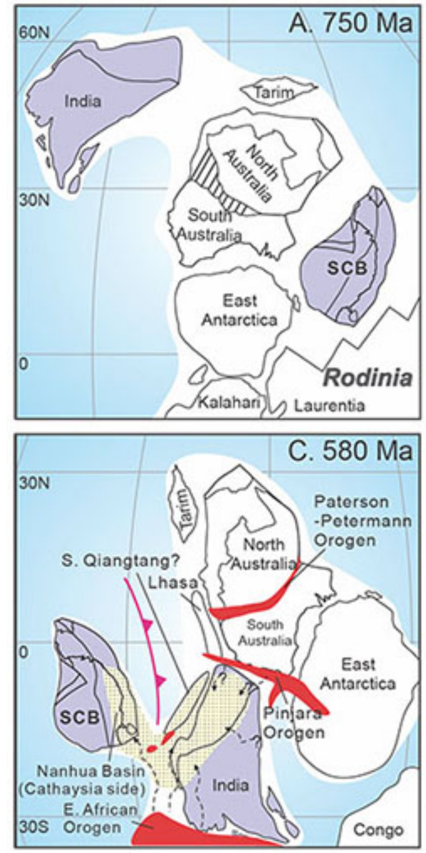
The long-term carbon cycle in a tectonic context



- Through a series of chemical reactions and tectonic activity, carbon takes up to 100-200 million years to move between the deep Earth, ocean, and atmosphere in the slow carbon cycle.
- On average, 10–100 million metric tons of carbon move through the slow carbon cycle every year. In comparison, human emissions of carbon to the atmosphere are on the order of 1 billion tons per year.
- Earth's degassing is driven by tectonics and volcanism. Can tectonic models help constrain the slow carbon cycle?

Traditional vs. next generation plate models



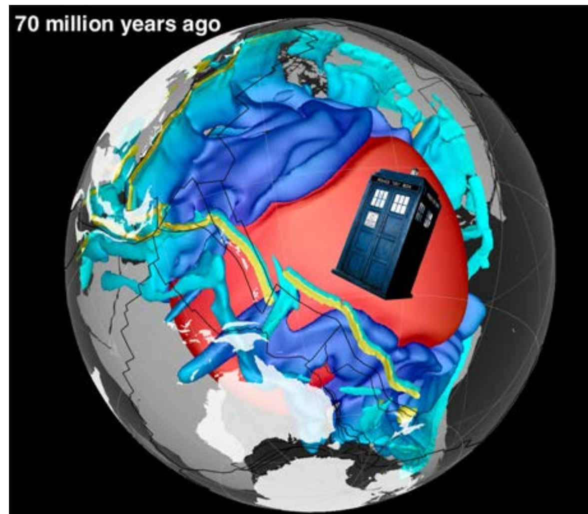


Traditional global plate tectonic models often reflect "motorboat tectonics", with continents floating on a mantle sea like boats on a lake, without plate boundaries

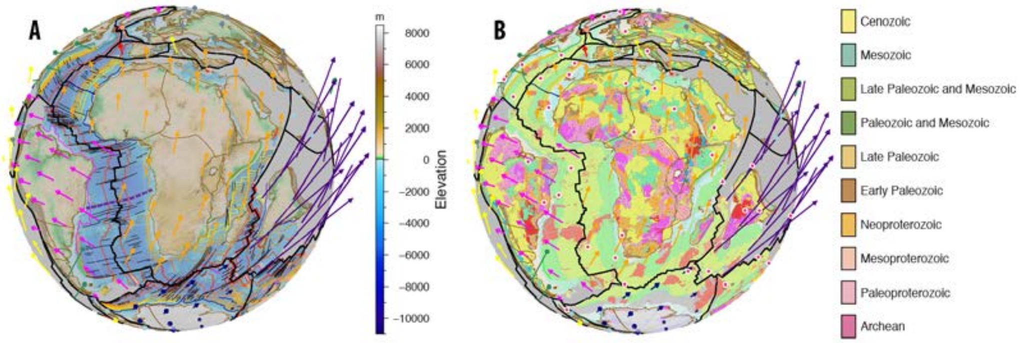
GPlates software as enabling research infrastructure

SAM AuScope
simulation, analysis, modelling

- Deep-time Geographic Information System platform
- Modeling: plate tectonics and plate deformation with continuously closing plate boundaries
- Visualization: surface and deep Earth in 4D – seismic tomography, geodynamic model outputs



AGU100 ADVANCING EARTH AND SPACE SCIENCE



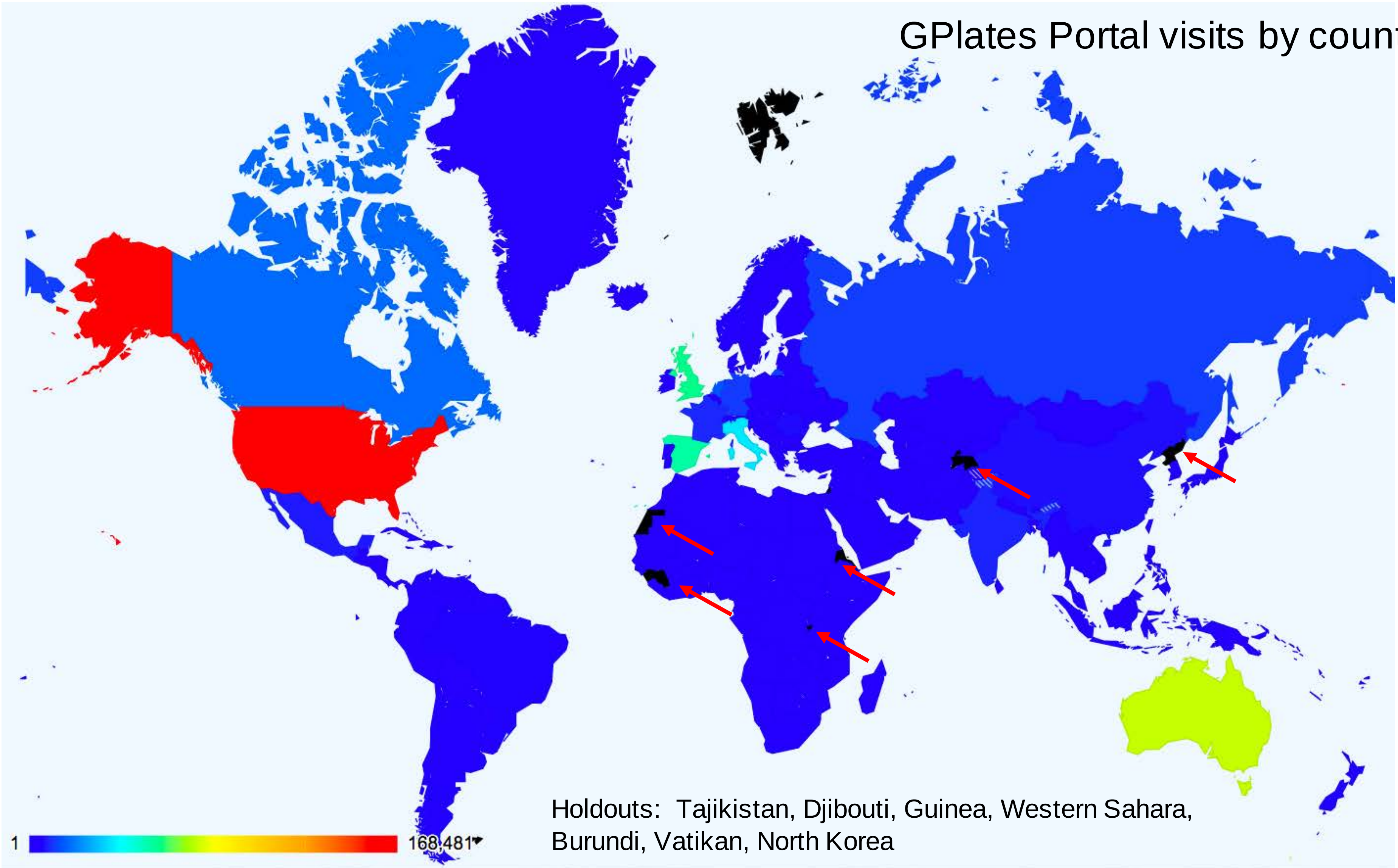
G³ | Geochemistry, Geophysics, Geosystems
AN AGU JOURNAL

Technical Reports: Methods | Full Access

GPlates – Building a Virtual Earth Through Deep Time

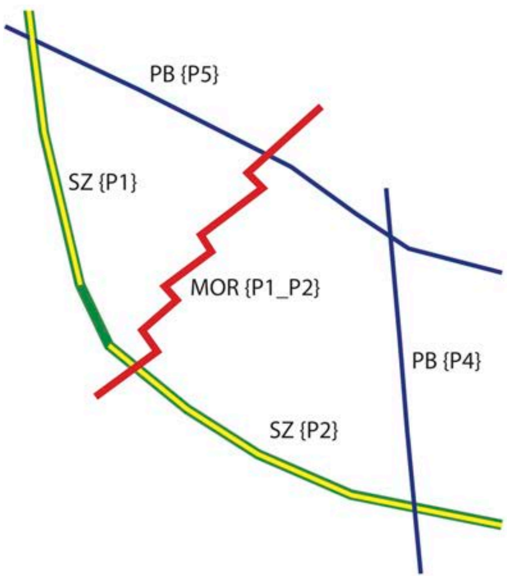
R. Dietmar Müller, John Cannon, Xiaodong Qin, Robin J. Watson, Michael Gurnis, Simon Williams, Tobias Pfaffelmoser, Maria Seton, Samuel H. J. Russell, Sabin Zahirovic

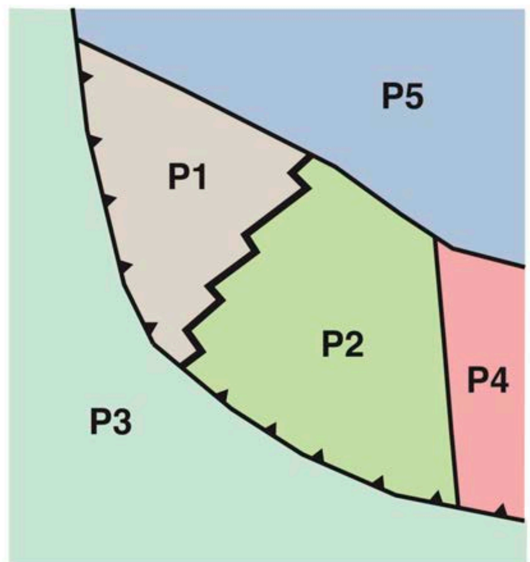
First published: 21 June 2018 | https://doi.org/10.1029/2018GC007584

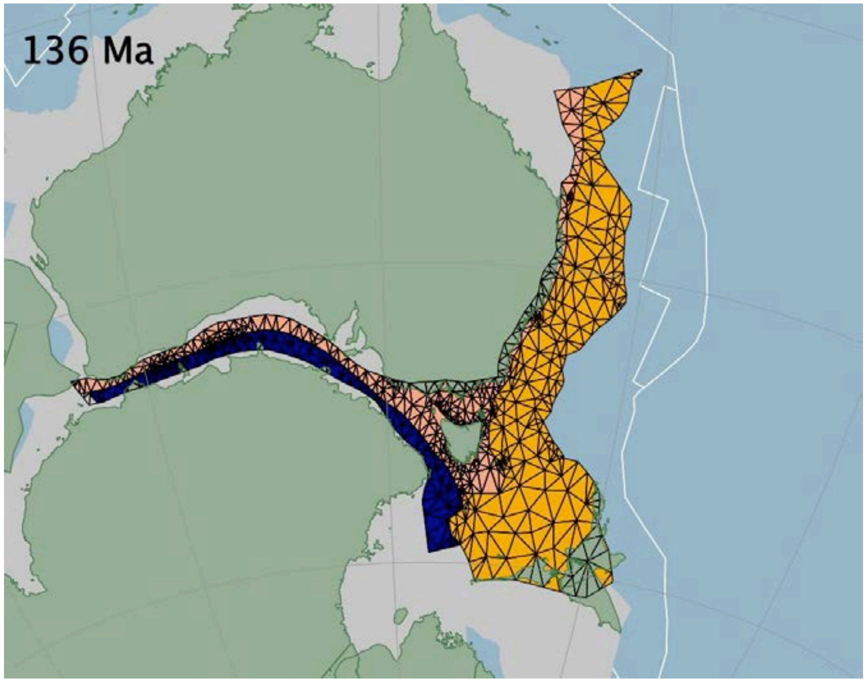

GPlates Portal visits by country
Holdouts: Tajikistan, Djibouti, Guinea, Western Sahara,
Burundi, Vatikan, North Korea
1
168,481

Evolving plate topologies in GPlates

- Plate tectonics requires connected network of plate boundaries globally
- In GPlates they are called Continuously Closing Plate Polygons (CCP)

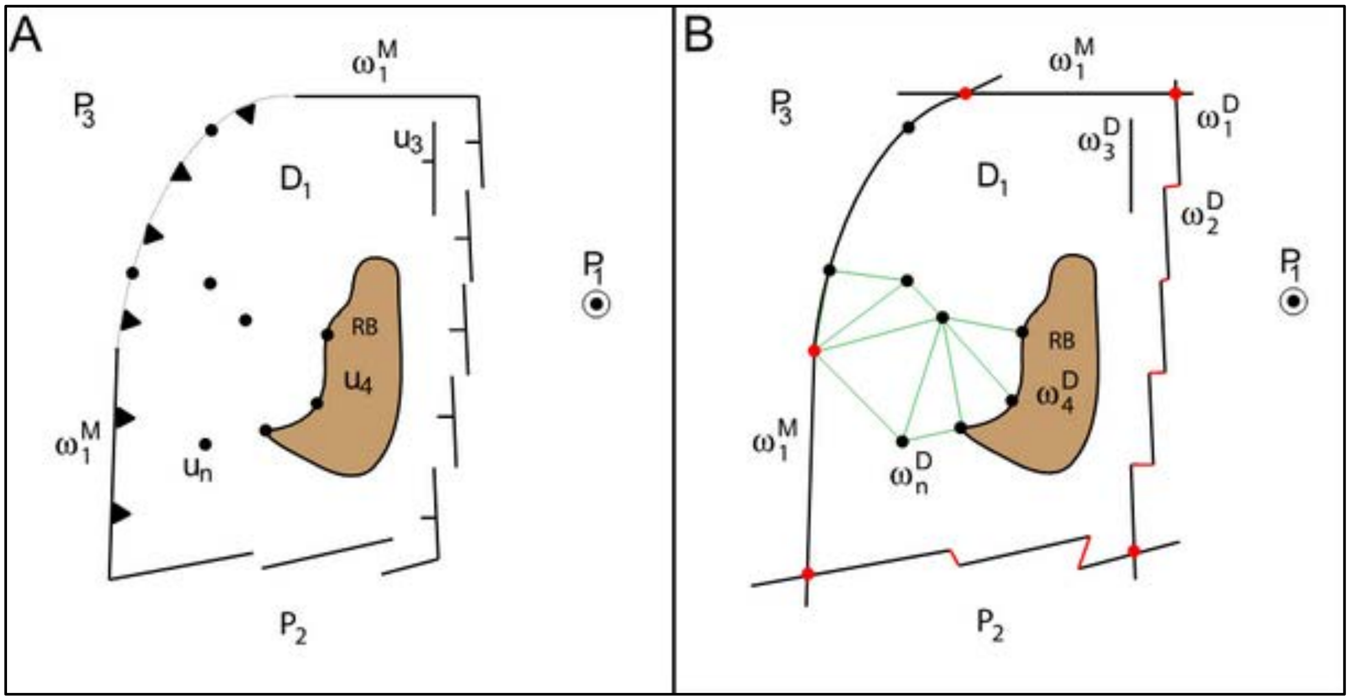






Gurnis et al. Comp. Geosci (2012, 2018); Müller et al. AREPS (2016)

How to build deforming meshes in GPlates embedded in plate boundary topologies



Gurnis et al. (Comp. Geosci., 2018)

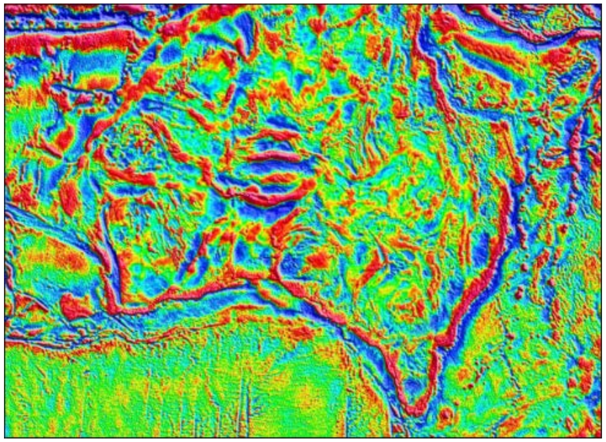
Red dots represent dynamically computed intersections between plate boundaries. Black dots are deformation points, RB=rigid block, D1=deforming region 1, P1=plate 1. A) Geological data and concepts used in the reconstruction B) Computer representation of this information.

Implementation of the deforming region must be consistent with the concepts of a continuously closed plate. The continuous deformation is represented by a triangular mesh, formed by Delaunay triangulation algorithms..

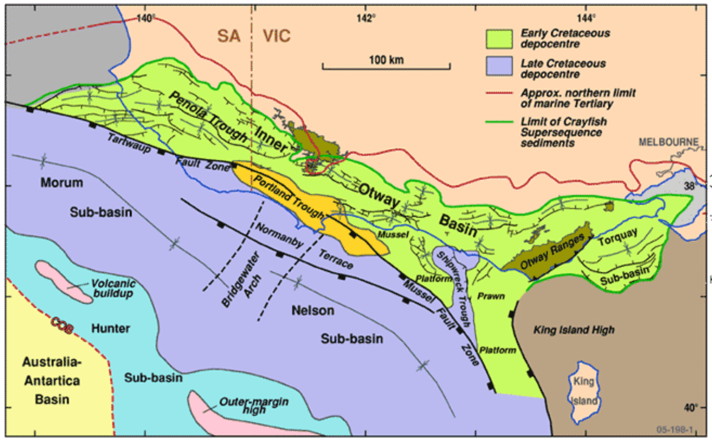
Defining the extent of the deforming region: outer boundary, inner boundary

We define the extent of the deforming regions from combining geophysics and geology

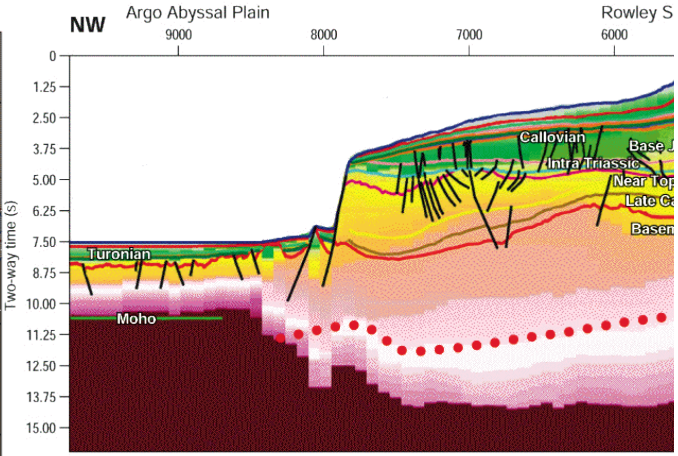
Magnetic and gravity anomalies



Stratigraphy

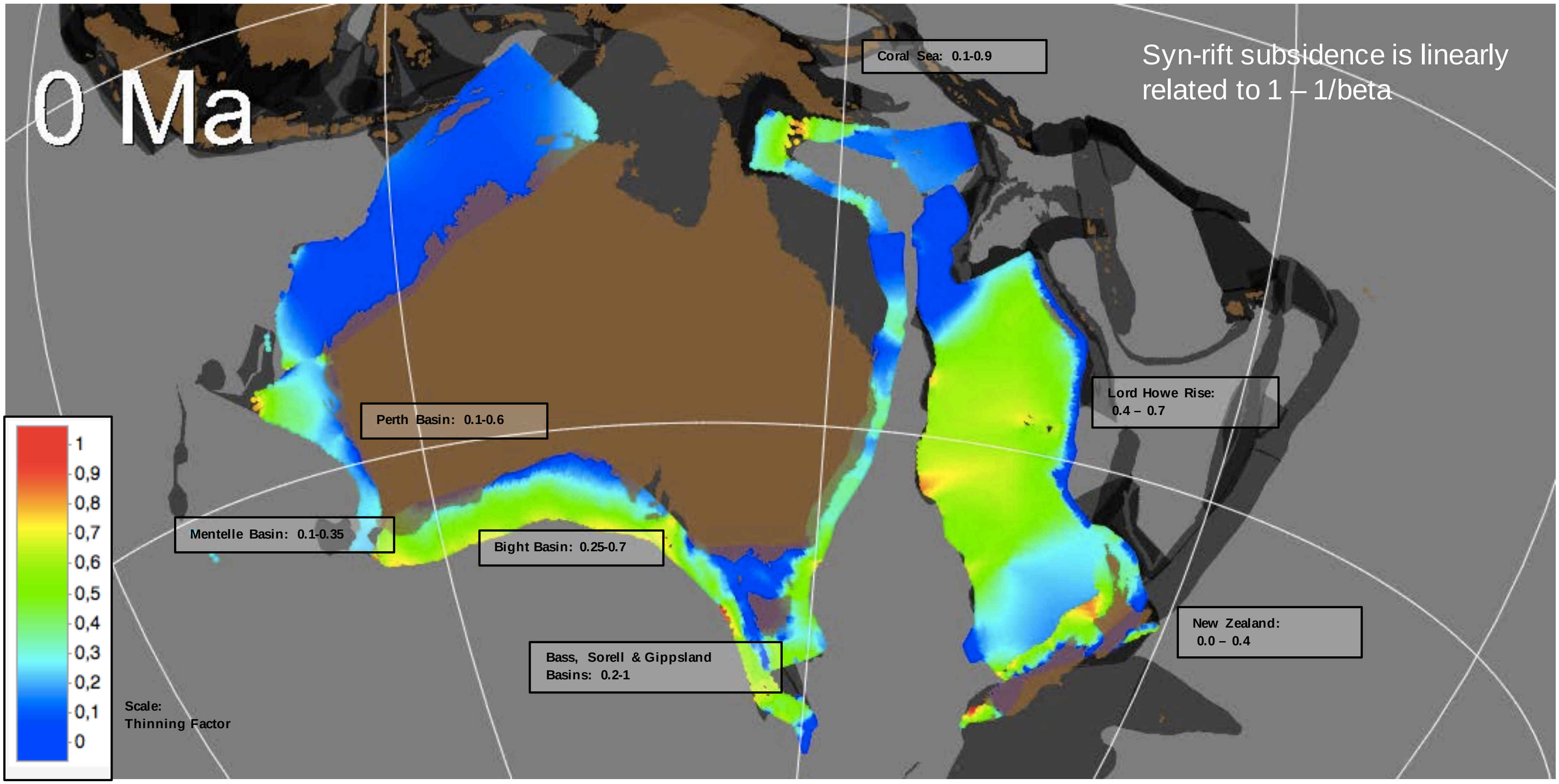


Seismic data

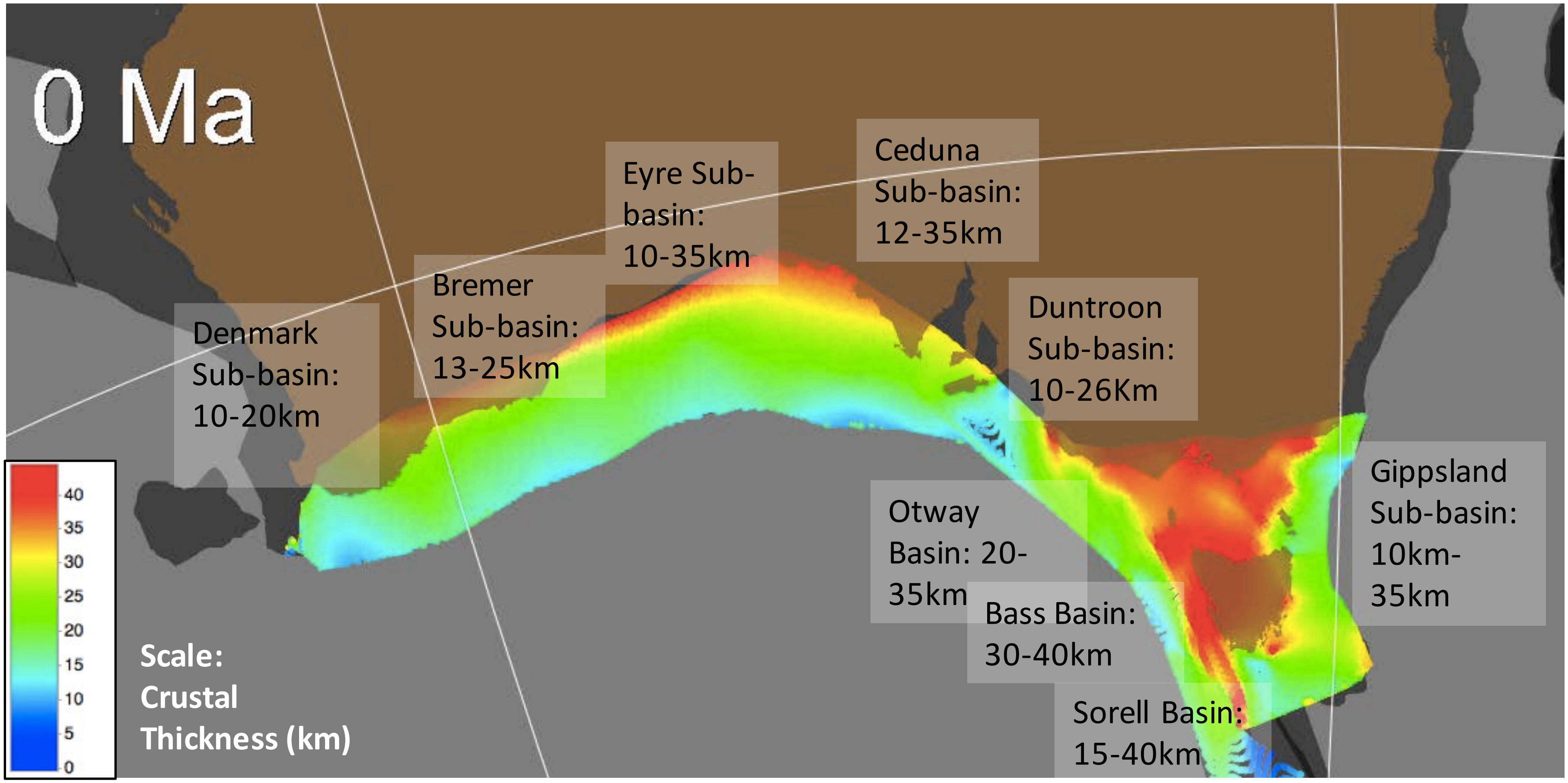


Define age range of deformation from geological data (stratigraphy, thermochronology)

Crustal thinning factors (1 – 1/beta)

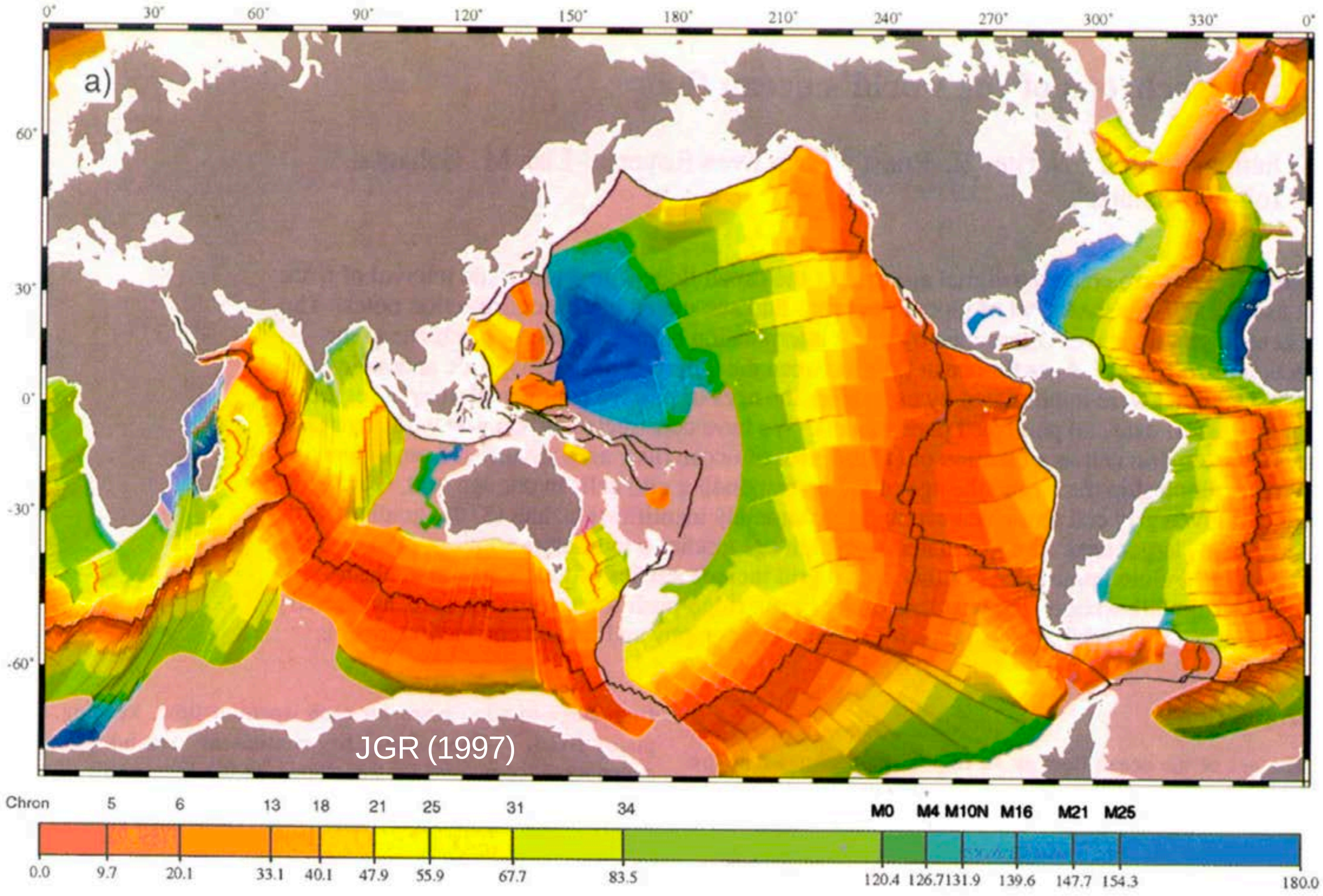


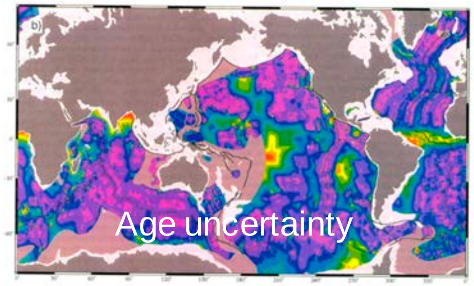
Modelled present-day crustal thickness of Australia's Southern Margin

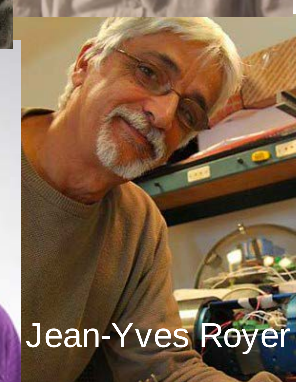


Based on an initial crust thickness of 40 km

Age of the ocean crust

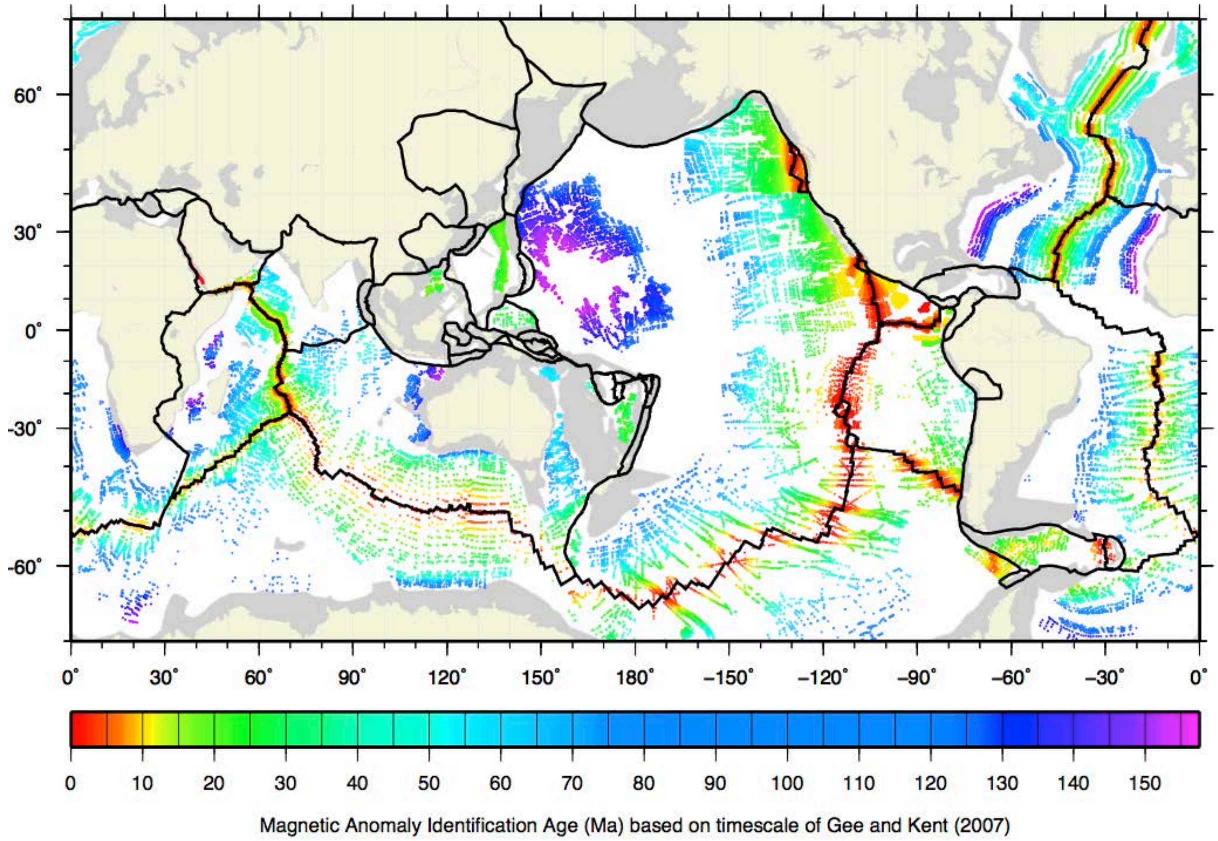






Magnetic Anomaly Identifications

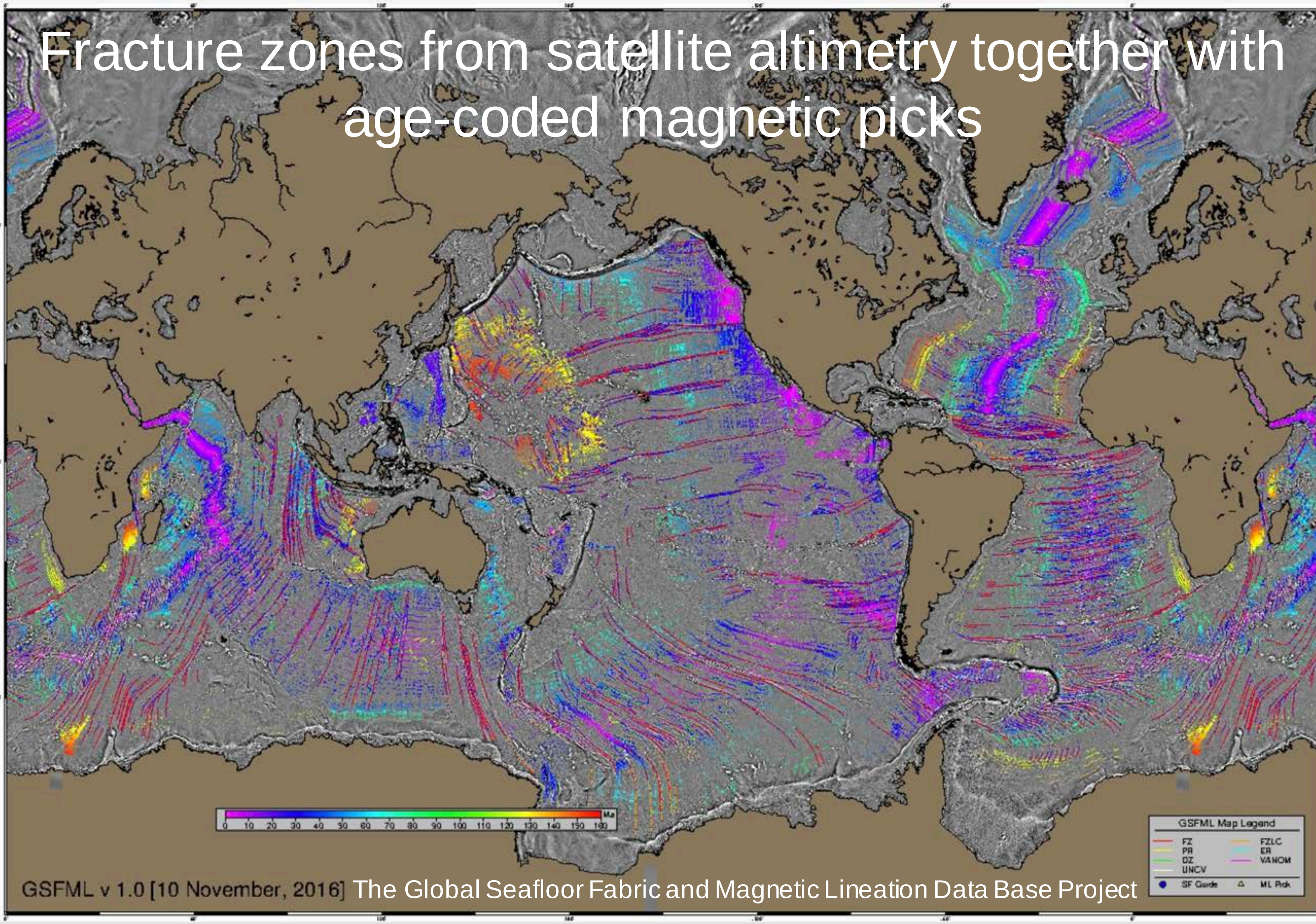
>100,000 magnetic anomaly identifications in public repository, Seton et al. (G-cubed, 2014)

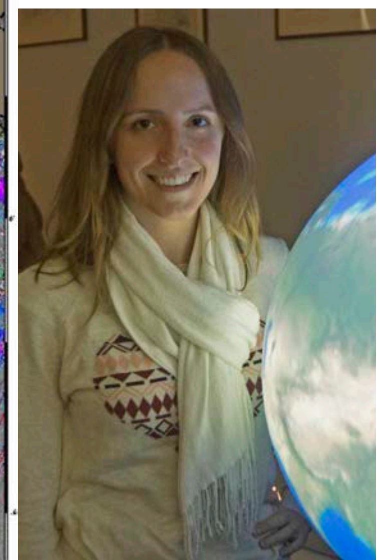


The Global Seafloor Fabric and Magnetic Lineation Data Base Project

http://www.soest.hawaii.edu/PT/GSFML/

Fracture zones from satellite altimetry together with age-coded magnetic picks



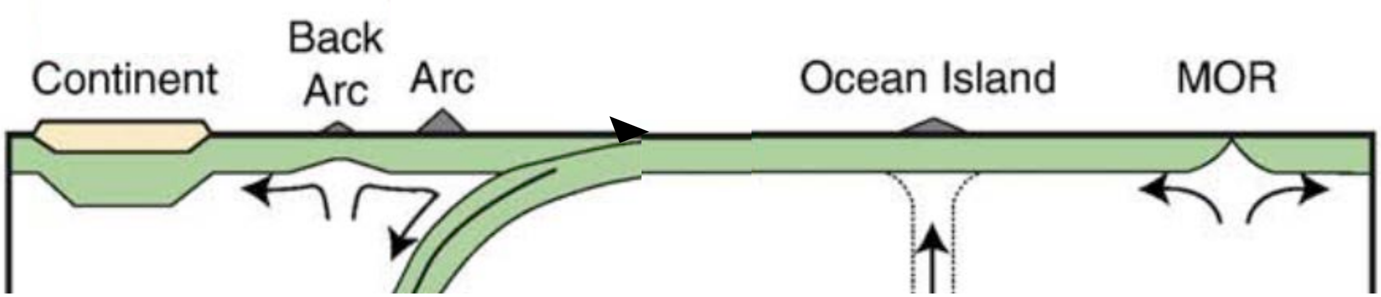


Kara Matthews

Wessel et al. (G-cubed, 2015); Matthews et al. (JGR, 2011)

Constraining the slow carbon cycle with plate tectonic models

- Degassing along rifts (Brune et al., 2017)
- Degassing and weathering of large igneous provinces (Kent and Muttoni, 2013; Johansson et al., 2018)
- Degassing at subduction zones (van der Meer et al. 2014; Lee et al. 2013; Pall et al., 2018)
- Degassing at mid-ocean ridges (Keller et al. 2016)
- Seafloor weathering (Gillis and Coogan, 2011; Müller and Dutkiewicz, 2018)

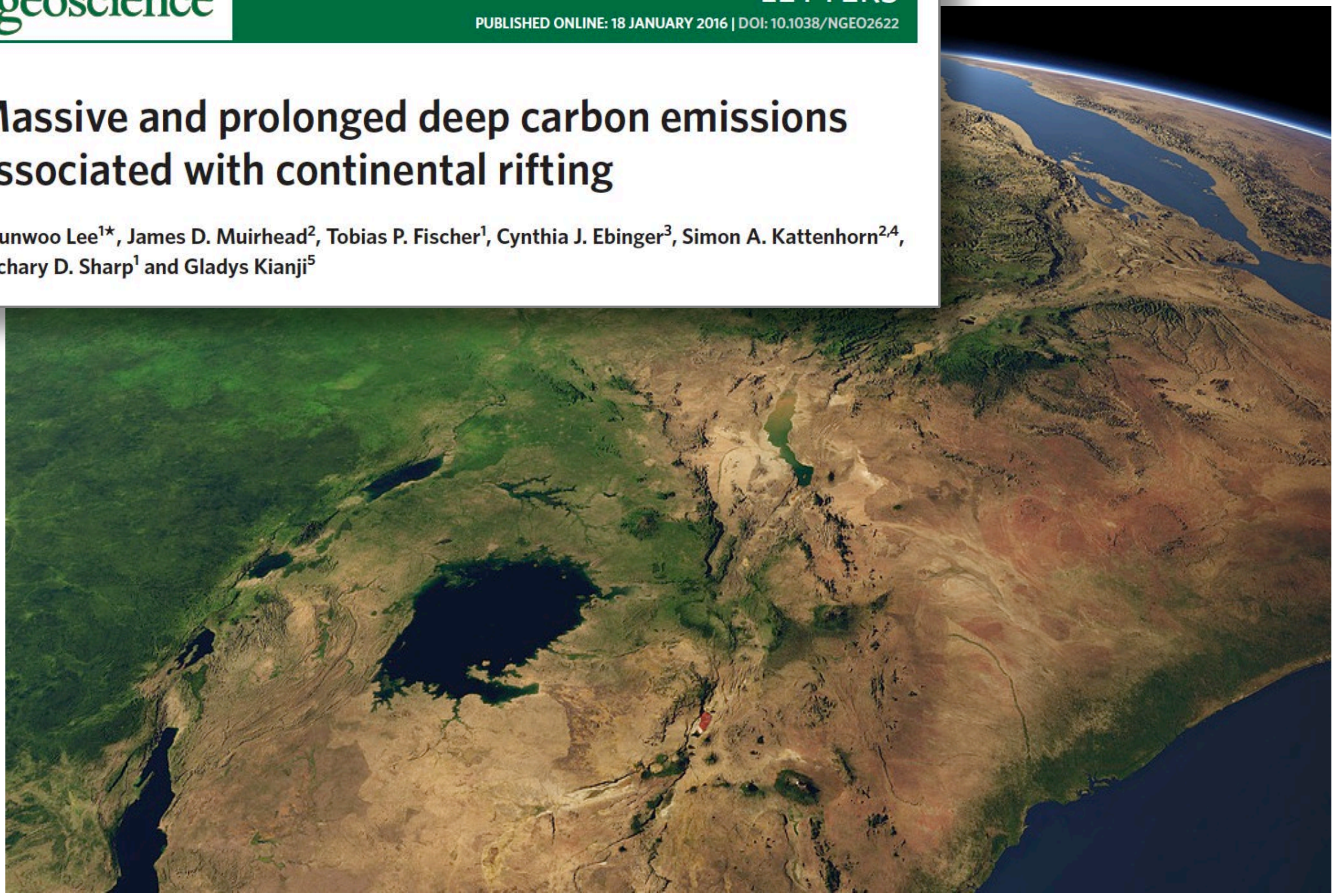


Dasgupta & Hirschmann (2010)

nature geoscience
LETTERS
PUBLISHED ONLINE: 18 JANUARY 2016 | DOI: 10.1038/NGEO2622

Massive and prolonged deep carbon emissions associated with continental rifting

Hyunwoo Lee[1*], James D. Muirhead[2], Tobias P. Fischer[1], Cynthia J. Ebinger[3], Simon A. Kattenhorn[2,4], Zachary D. Sharp[1] and Gladys Kianji[5]



(http://earth.imagico.de)

Slow carbon release from rifts well documented, but long-term variations unknown

East African Rift
- Eastern Branch (Hutchison et al., 2016)
- Western Branch (Lindenfeld et al., 2012)

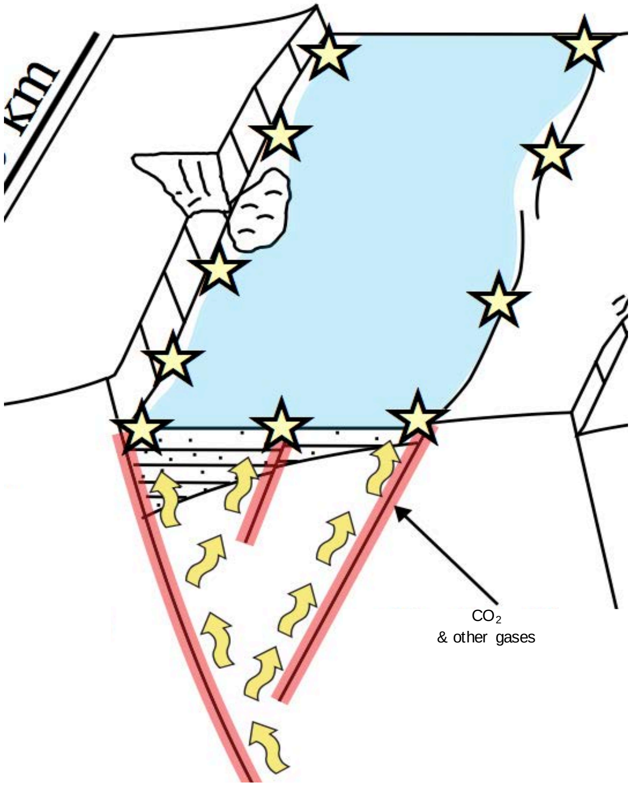
Basin and Range (Jolie et al., 2016)

Eger Rift (Weinlich et al., 1999)

Rio Grande Rift (Smith, 2016)

Central Italy (Chiodini et al., 2008)

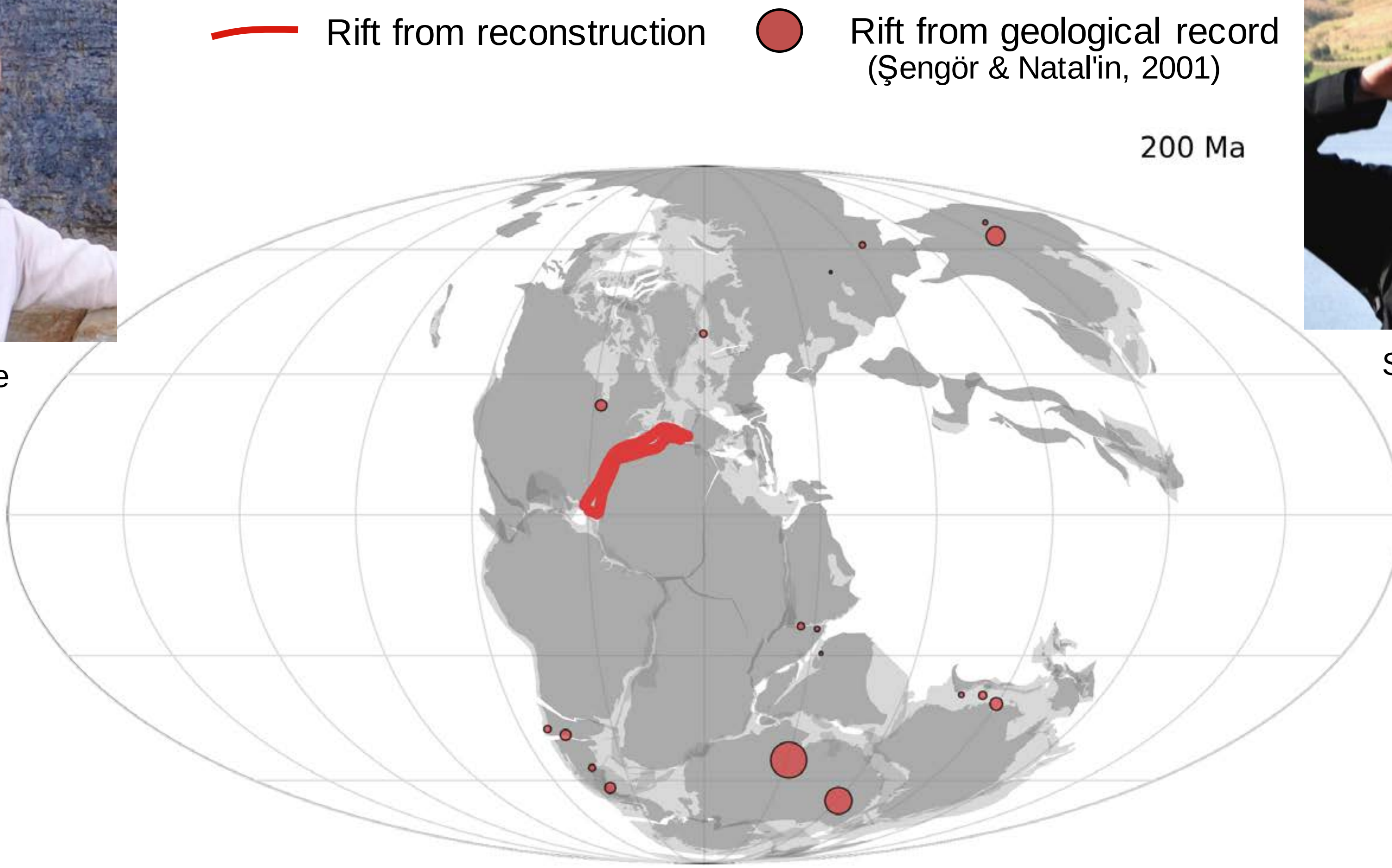
New Zealand (Seward and Kerrick, 1996)



High CO_2 flux along rift faults

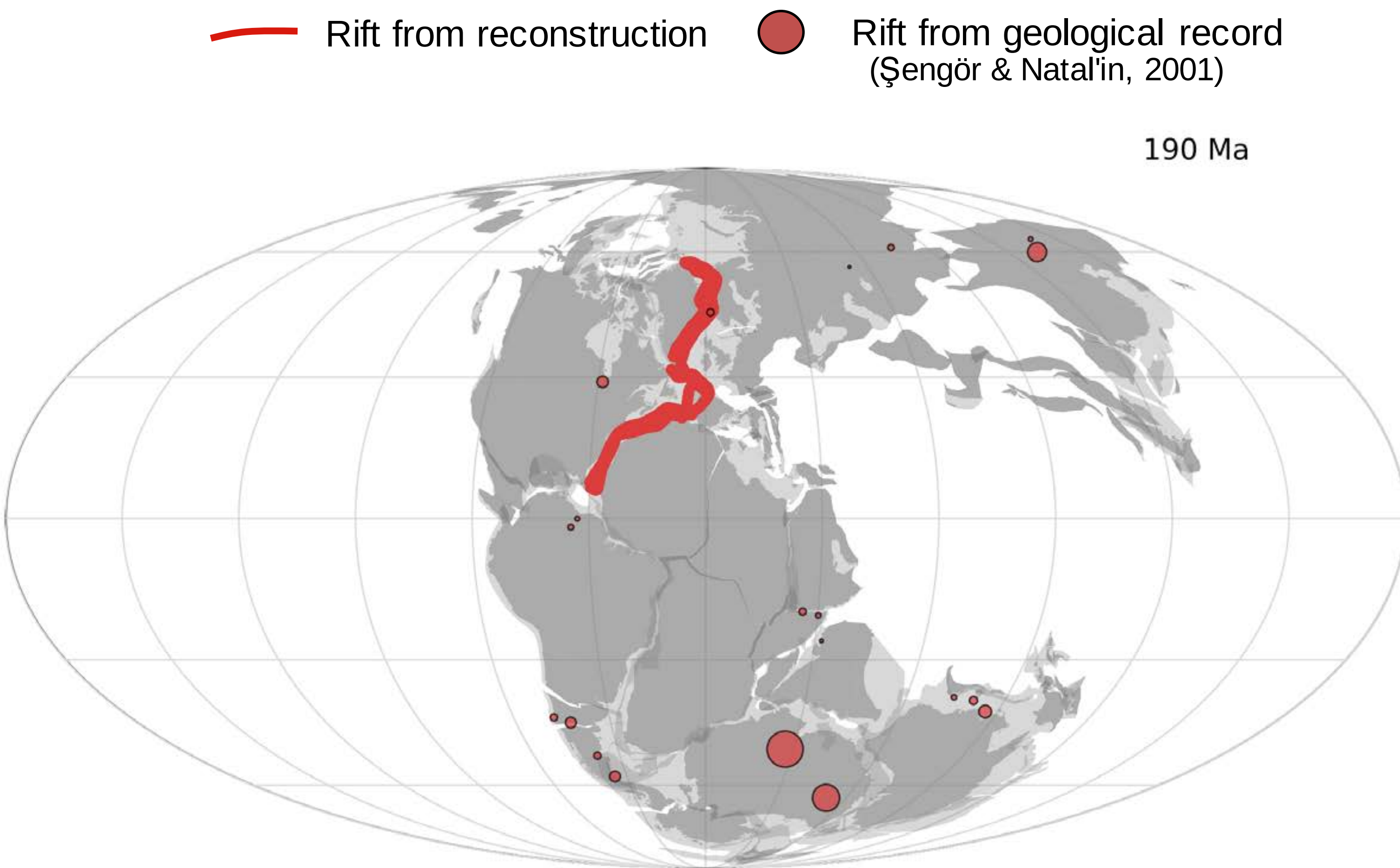
Muirhead et al. (2016)

Sascha Brune



Simon Williams

Brune, Williams, Müller
(Nature Geoscience, 2017)



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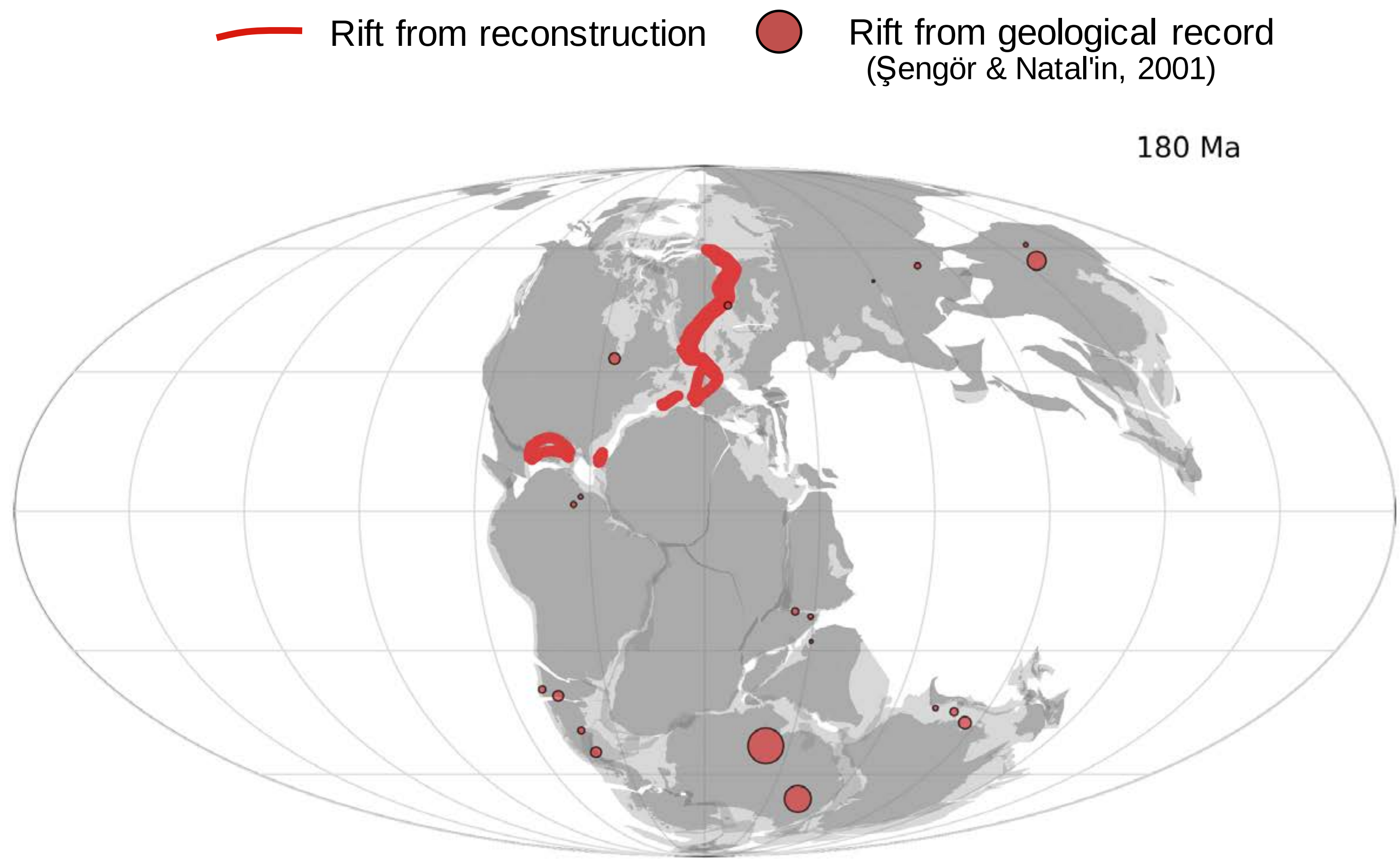

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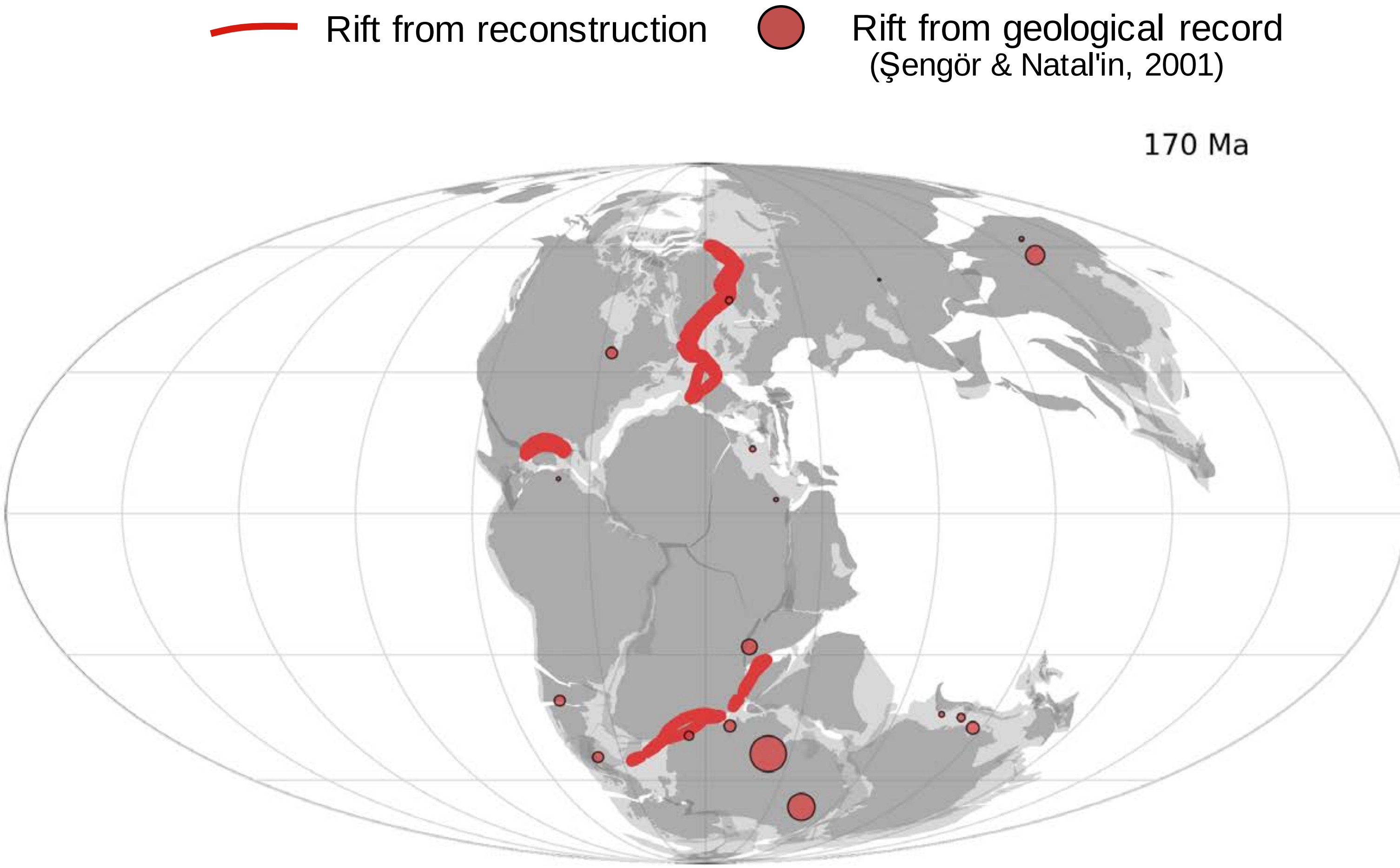

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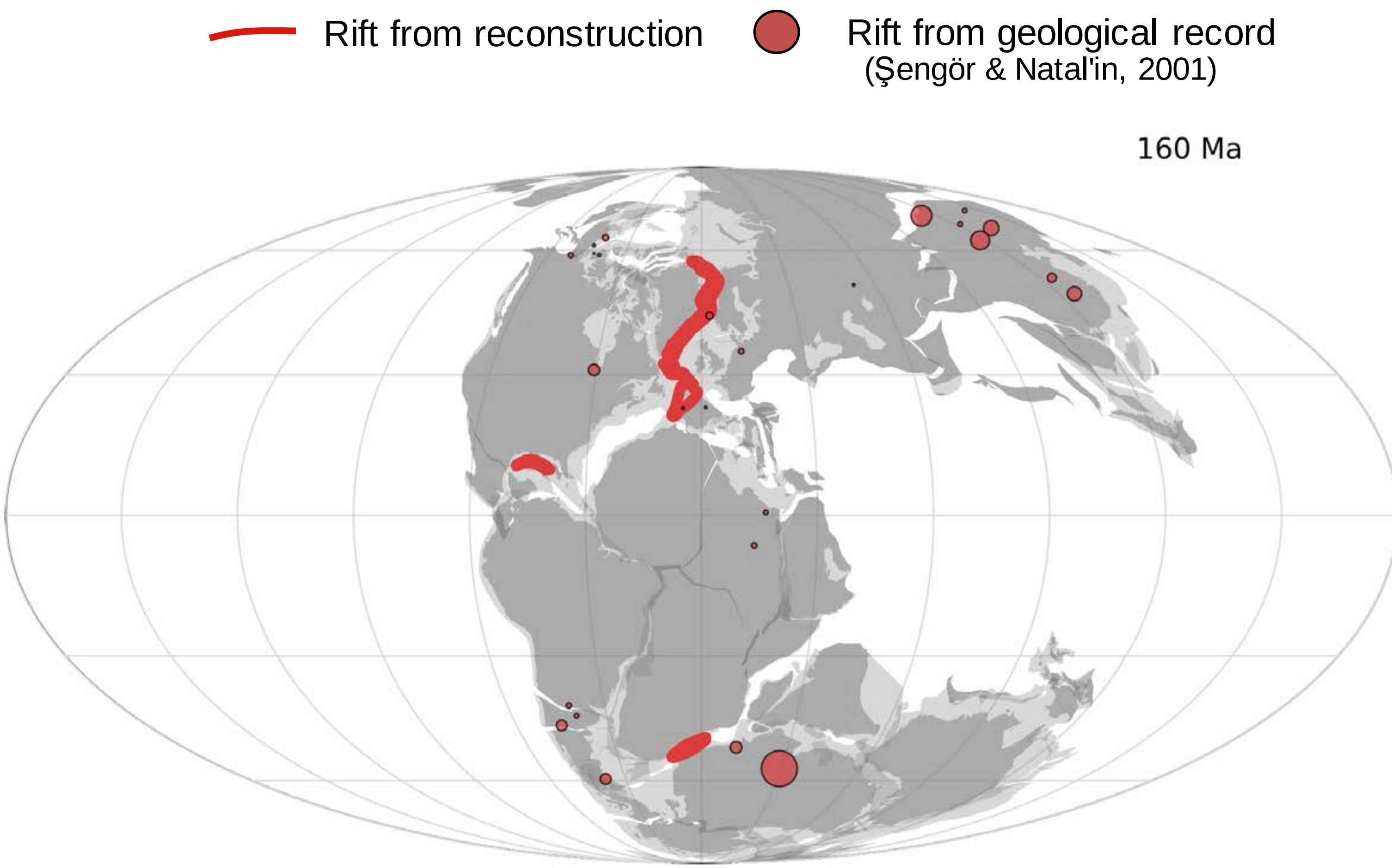

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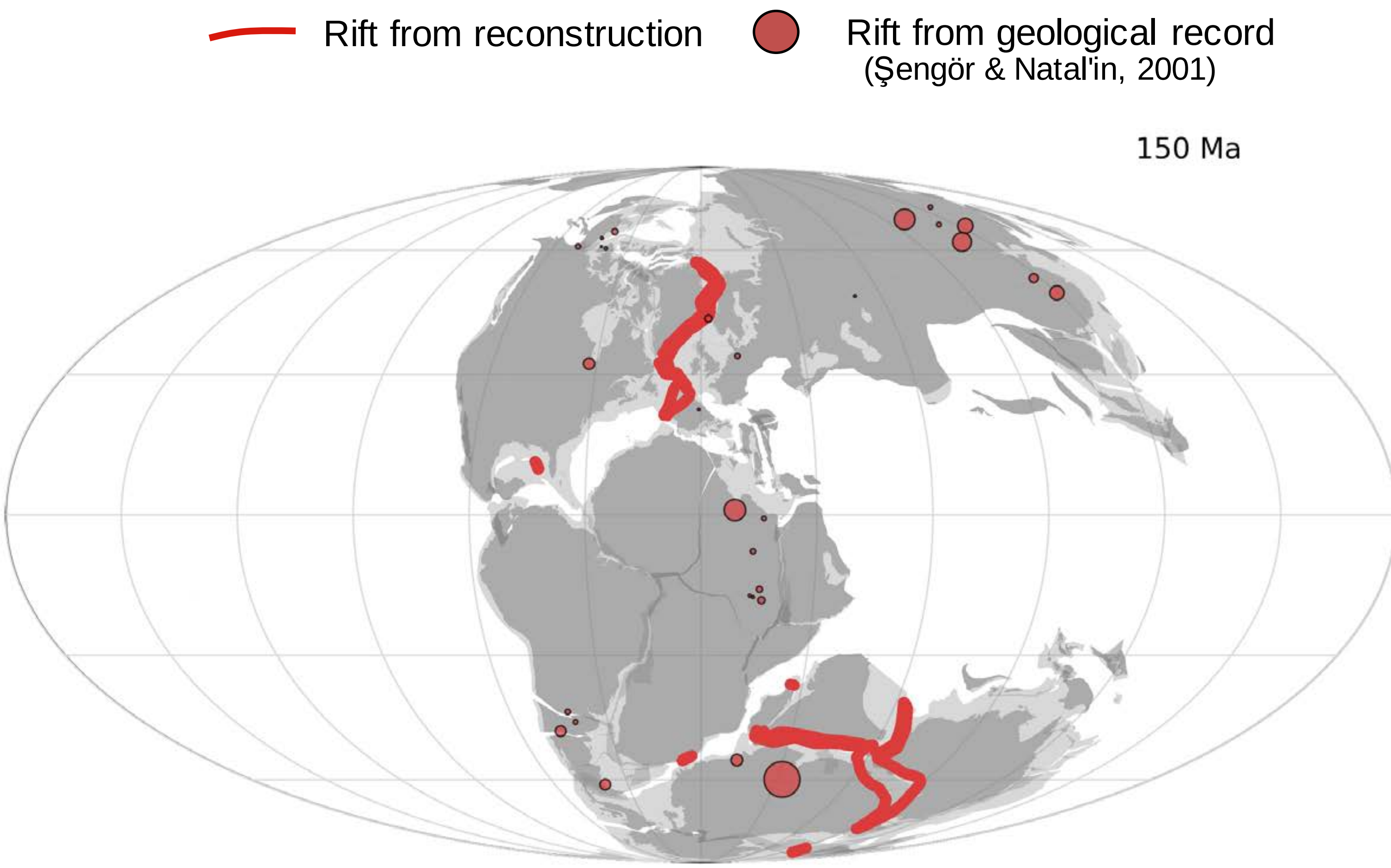
(Nature Geoscience, 2017)



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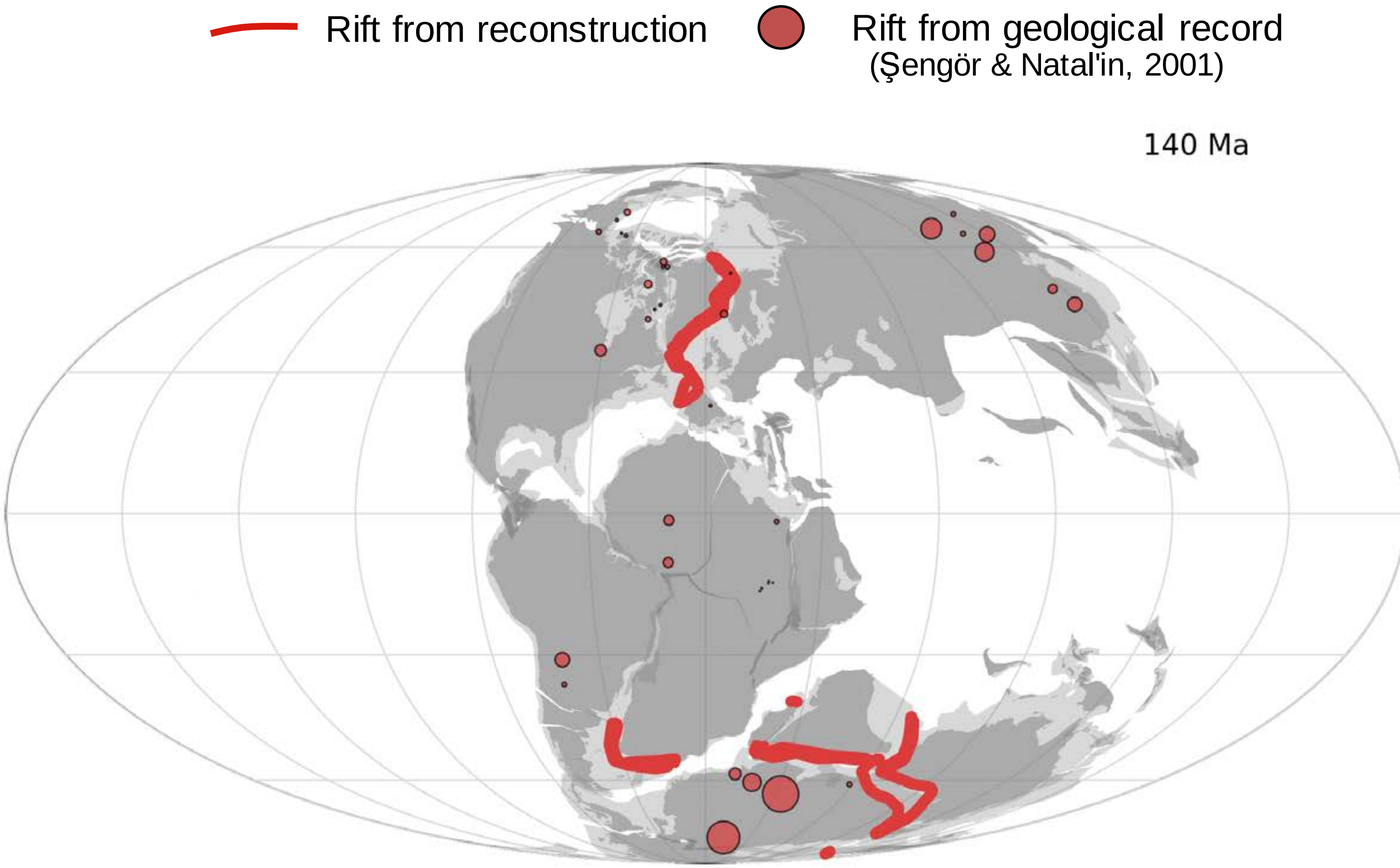

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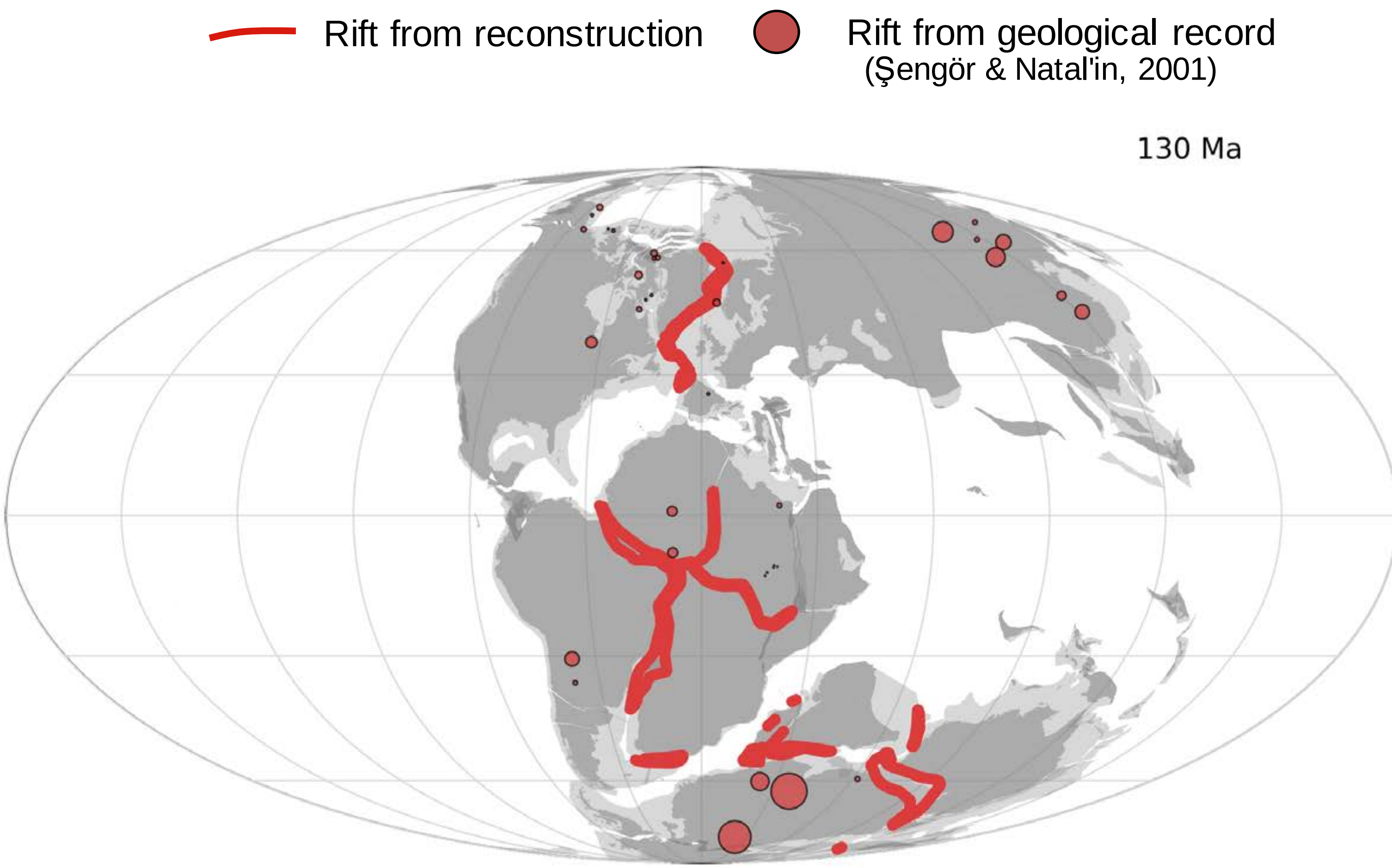
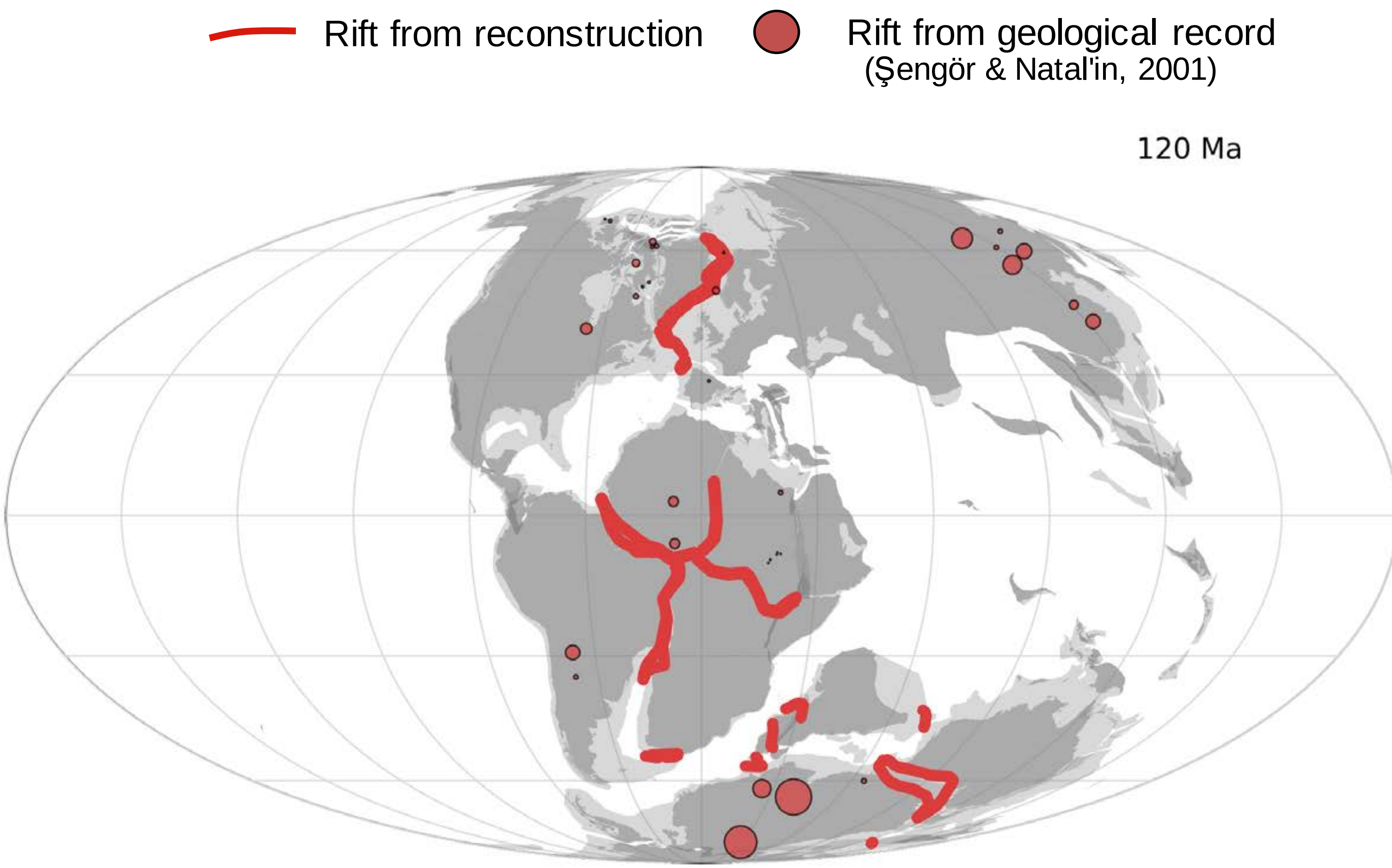
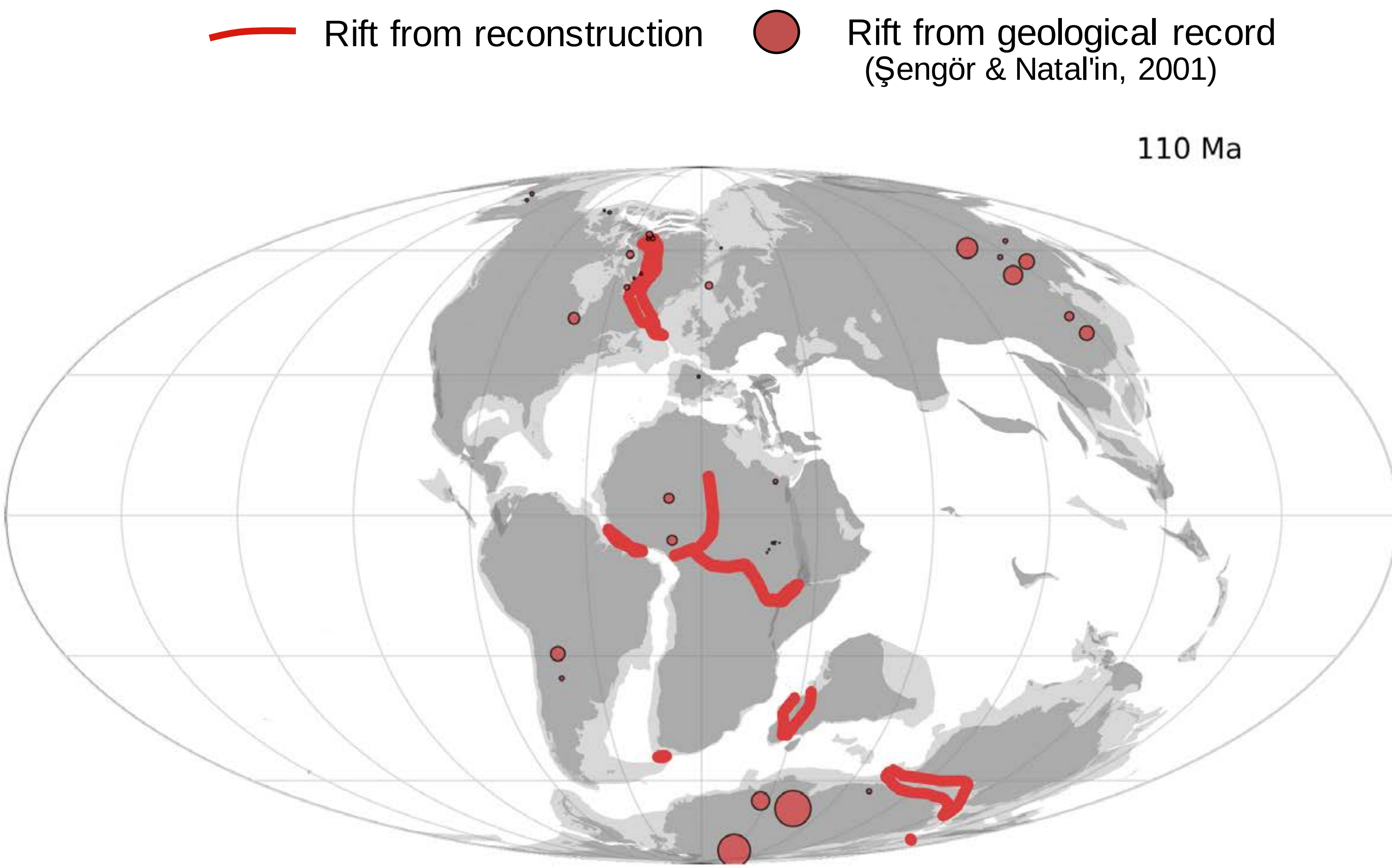


Brune, Williams, Müller
(Nature Geoscience, 2017)



Brune, Williams, Müller
(Nature Geoscience, 2017)



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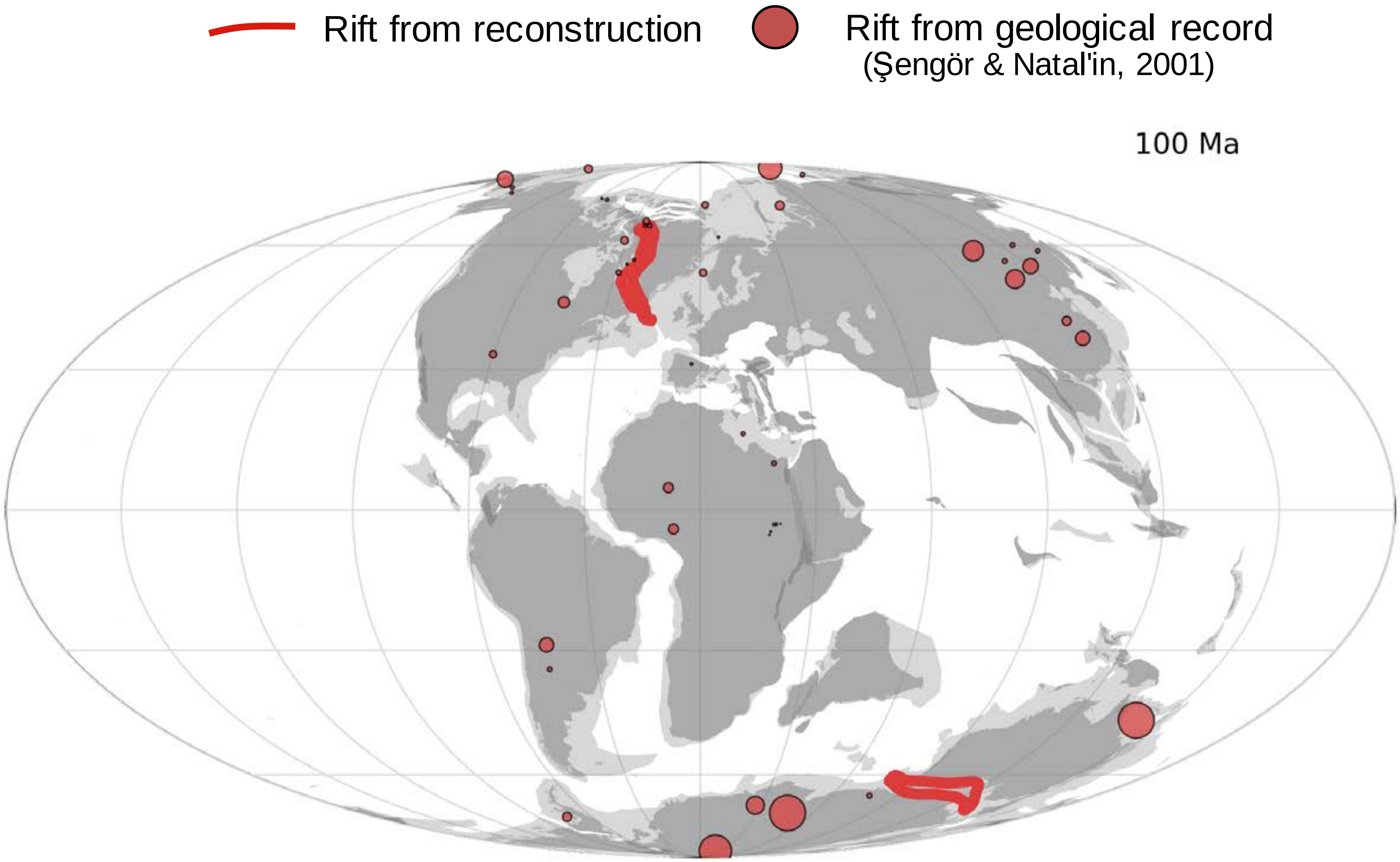

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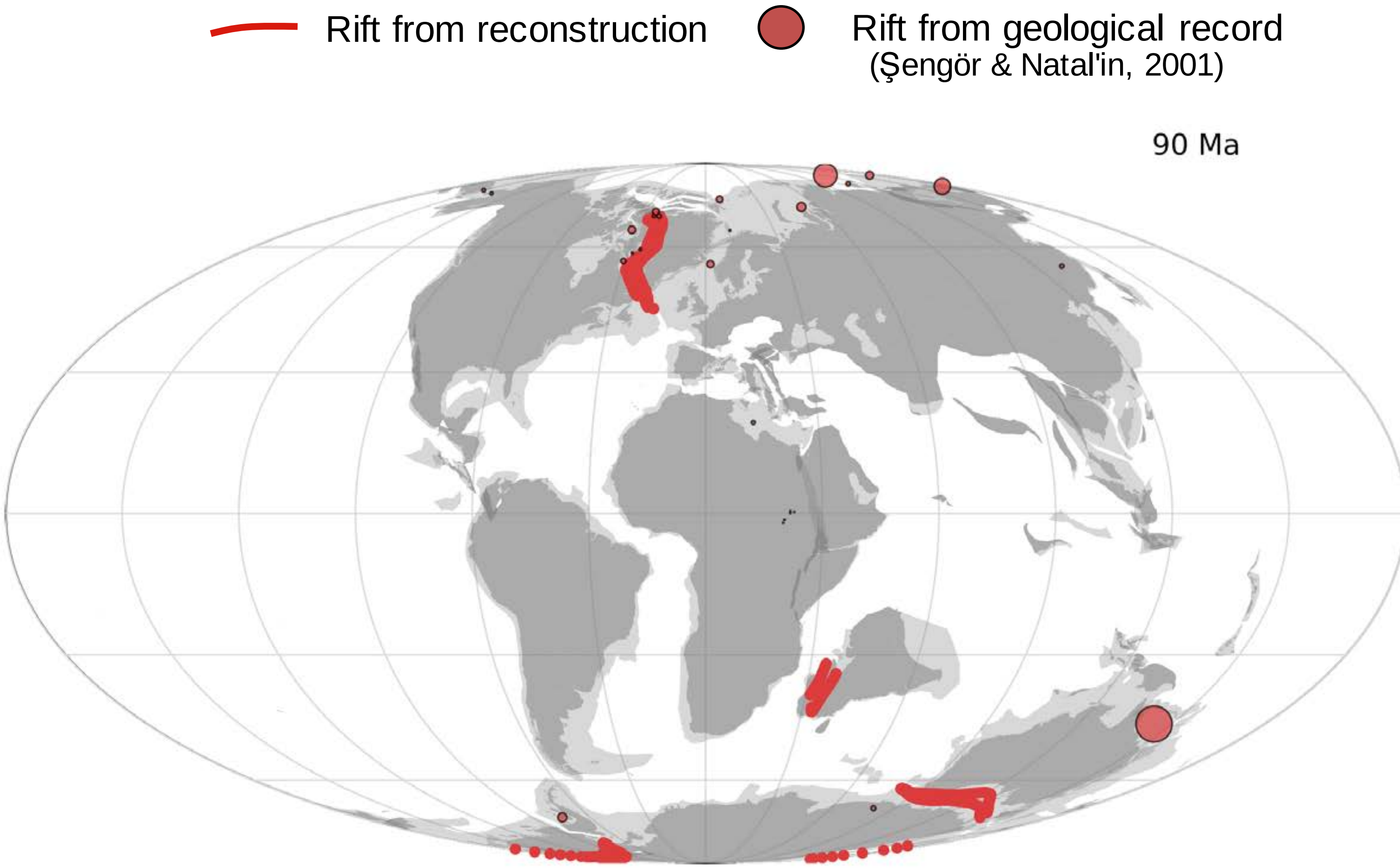

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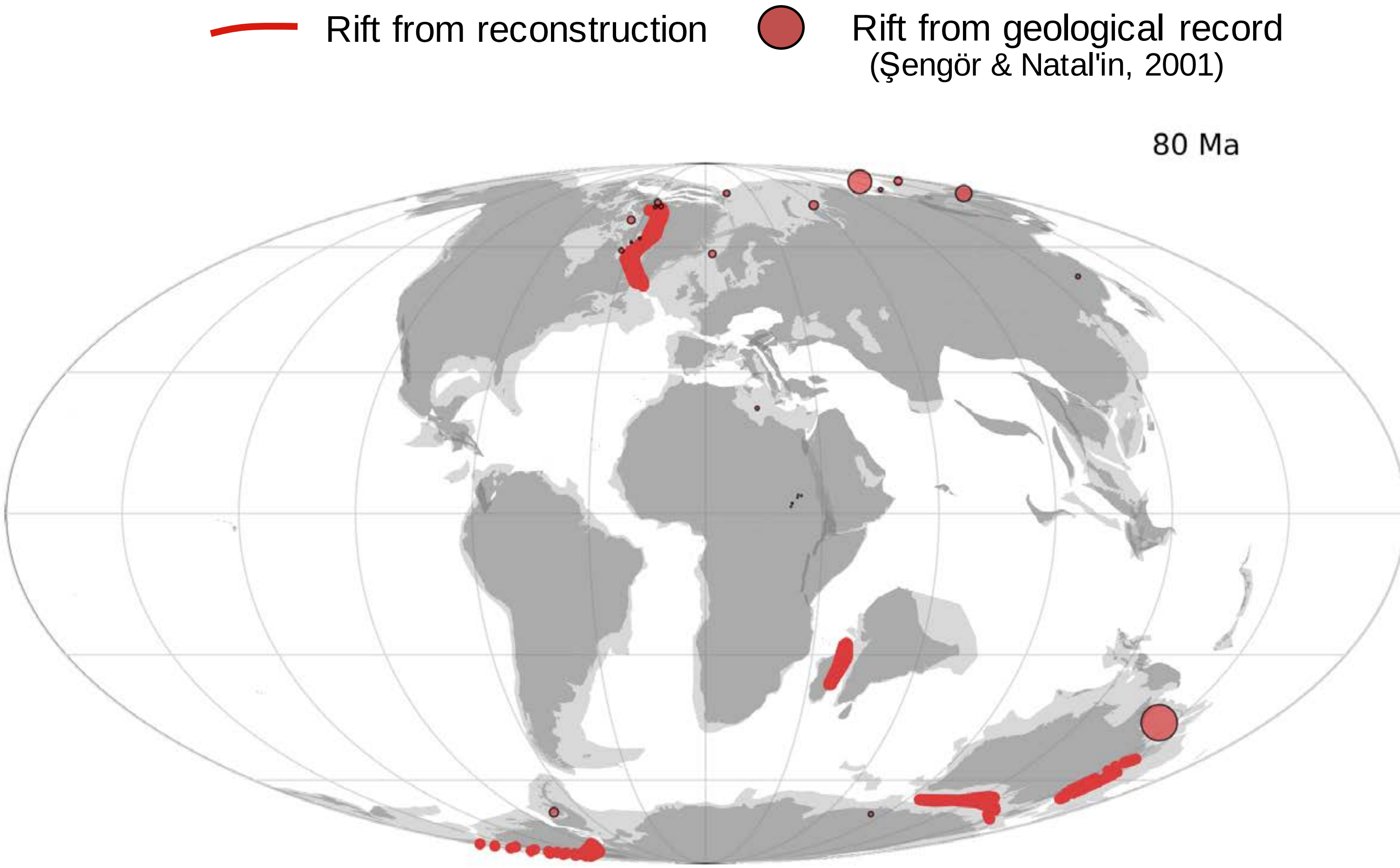

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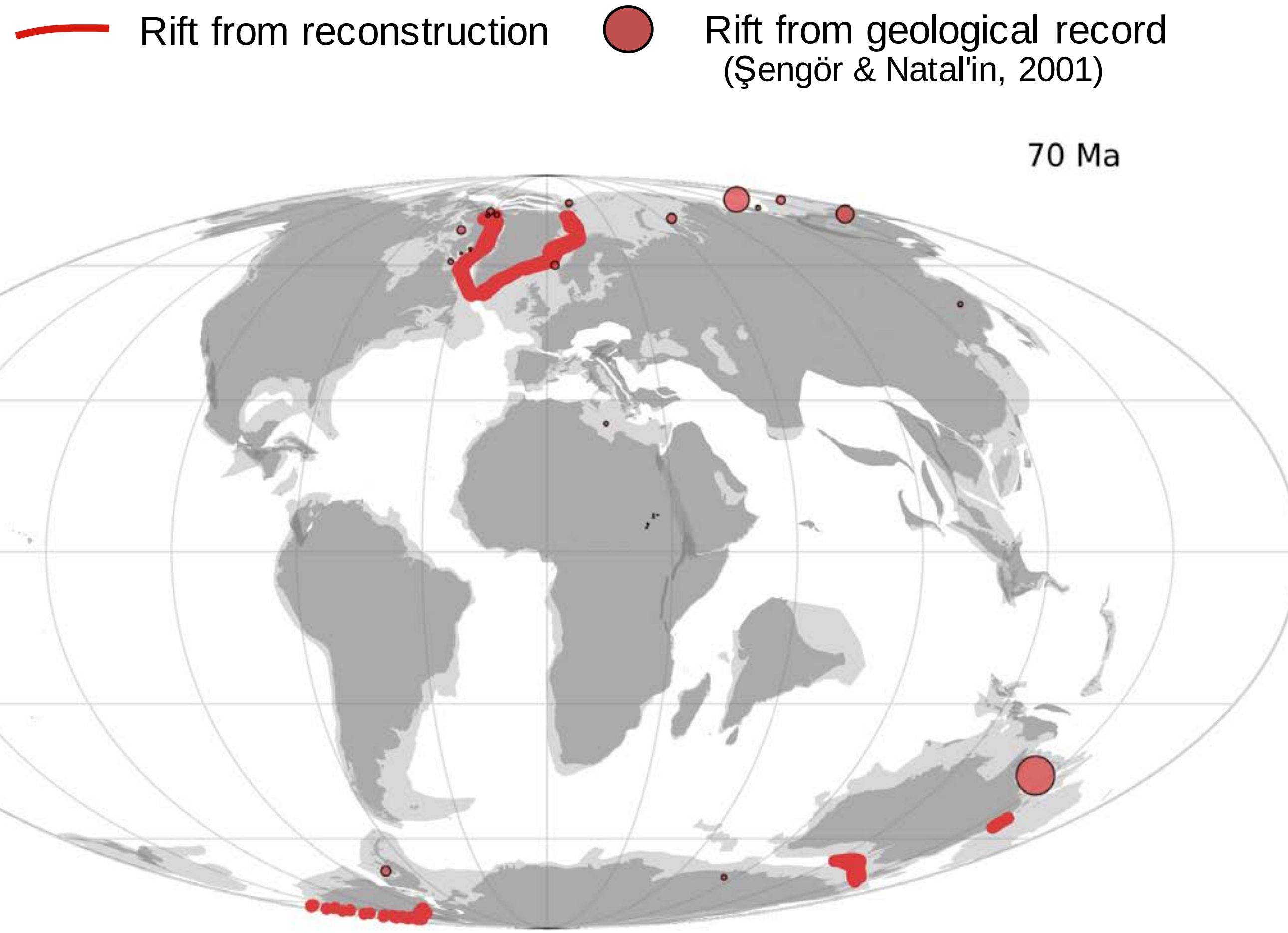

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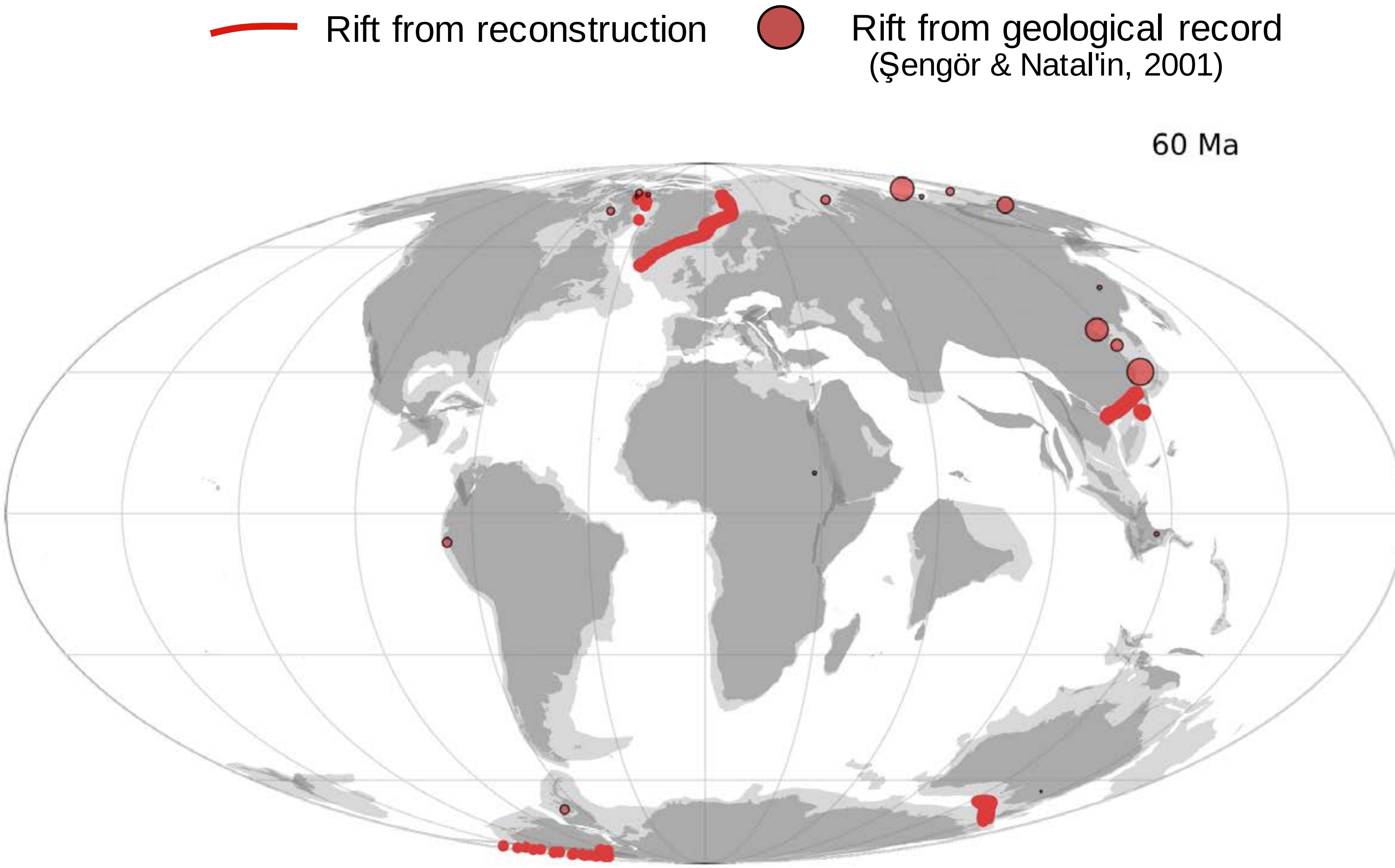

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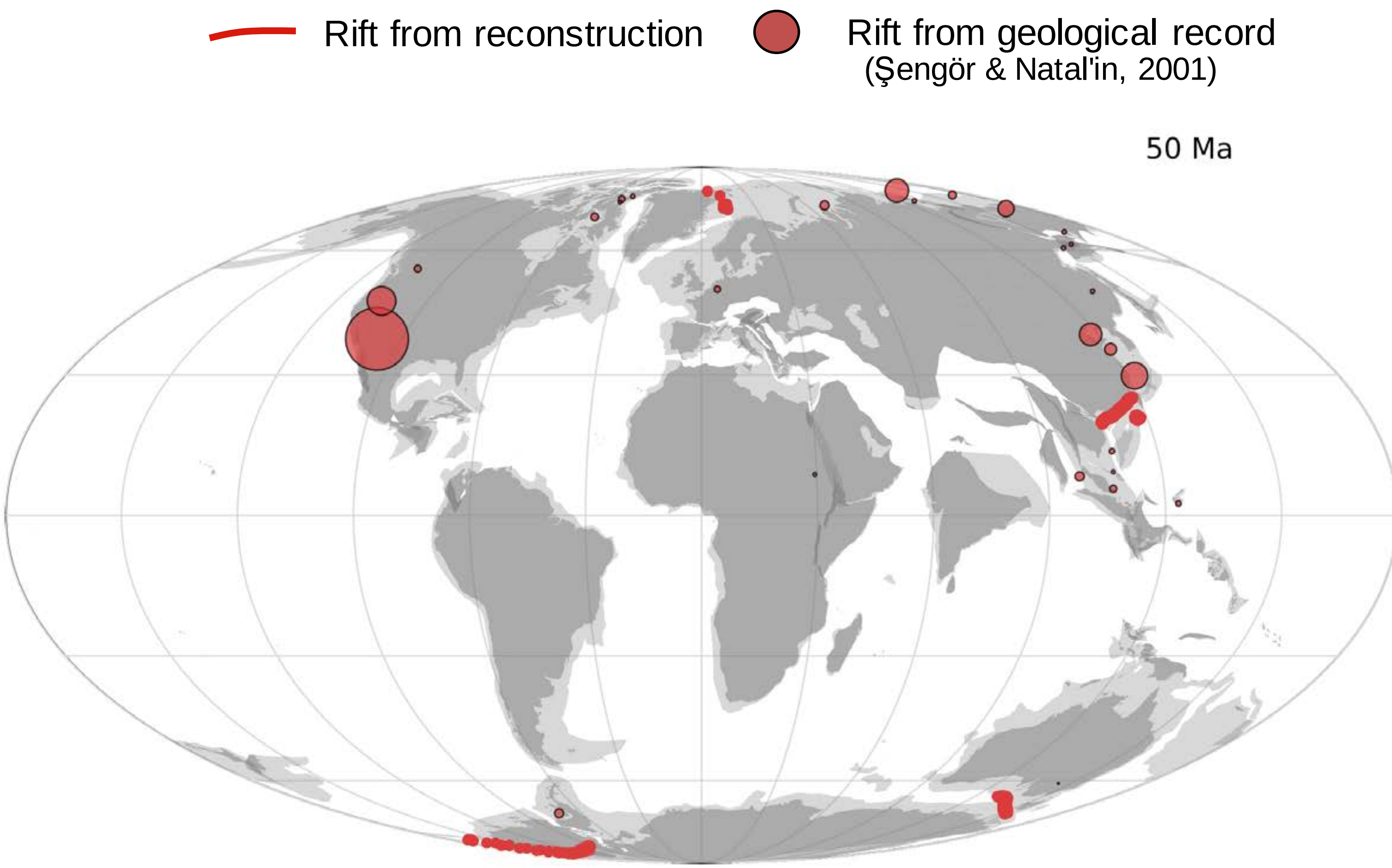

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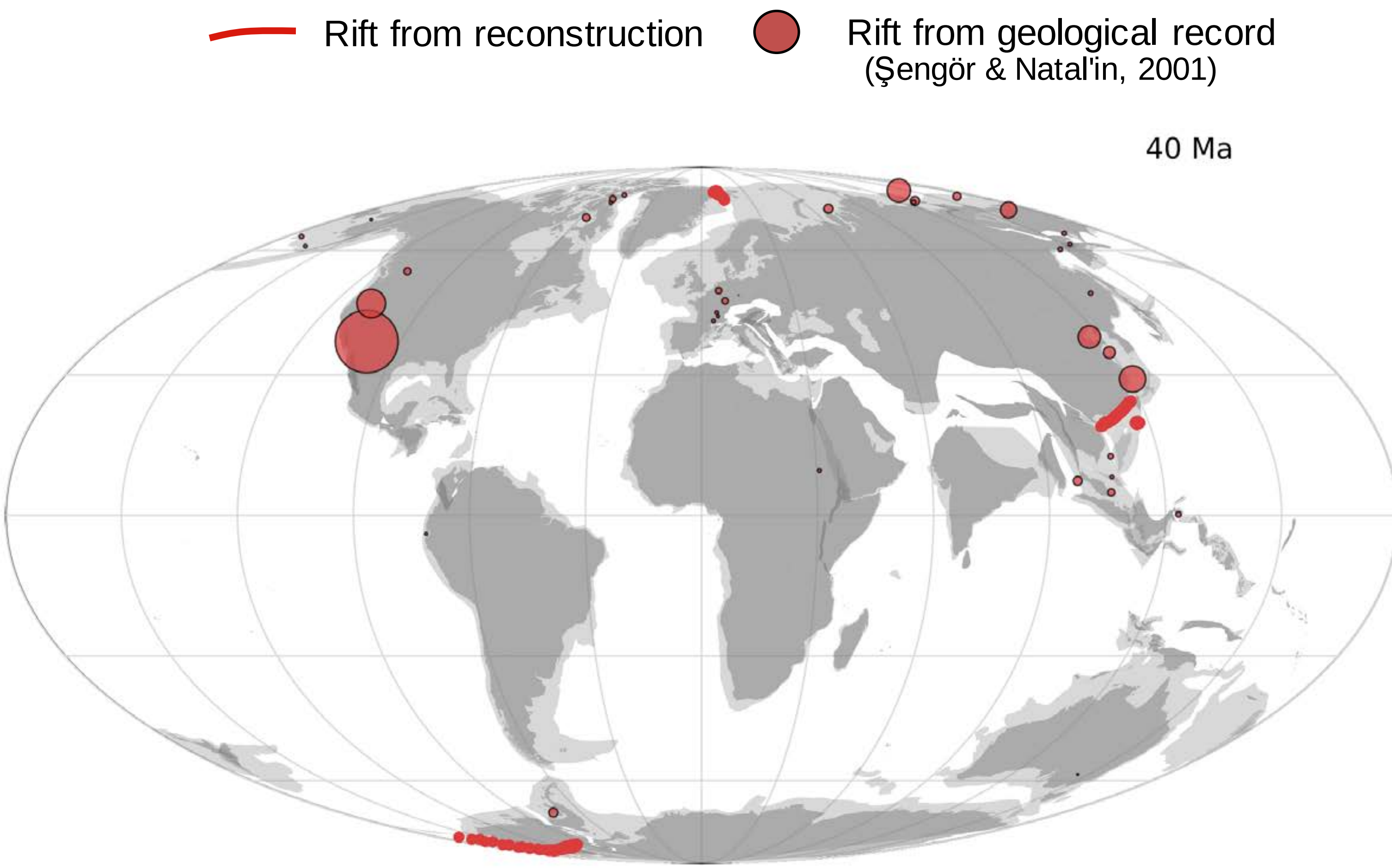

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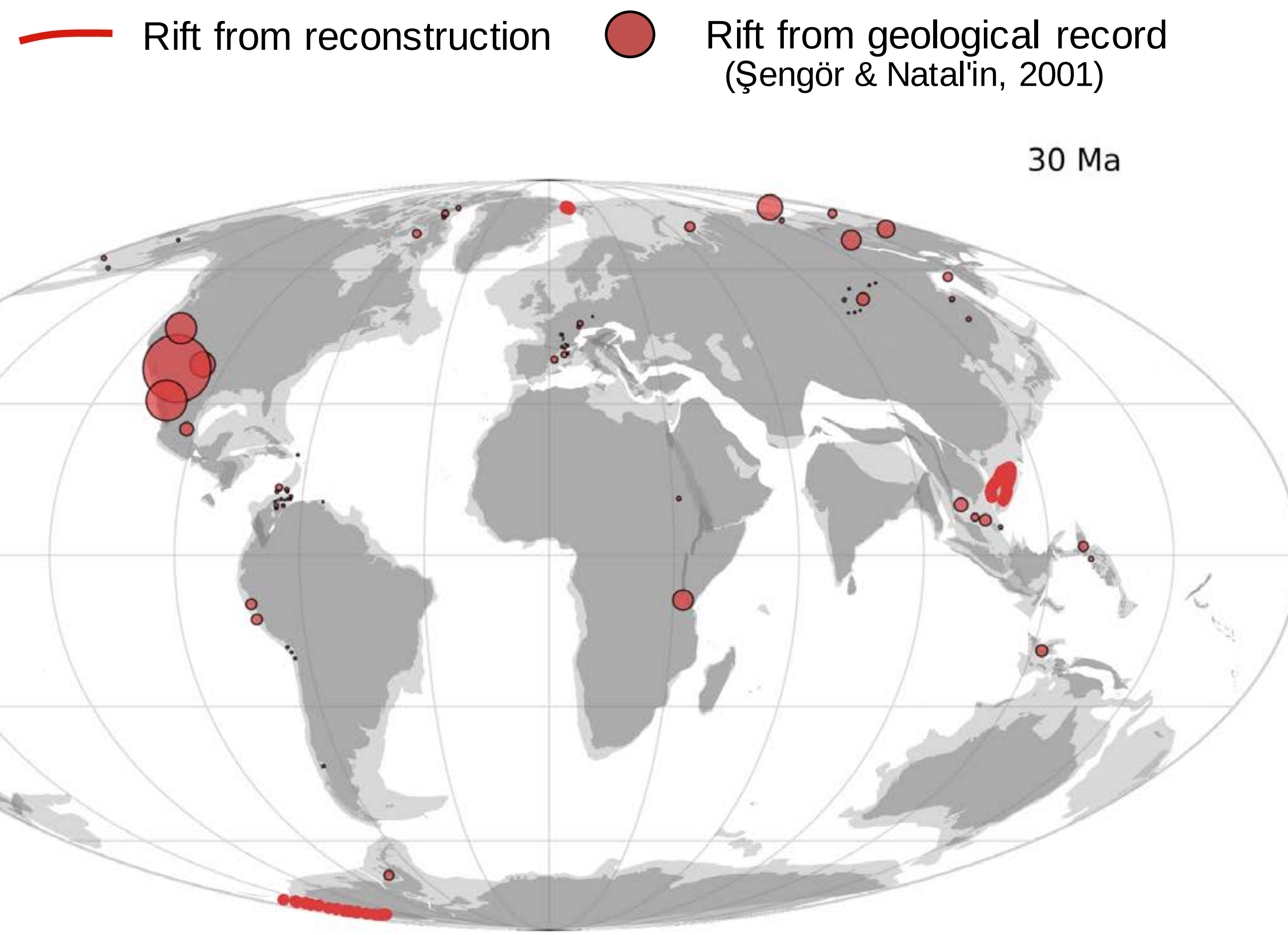

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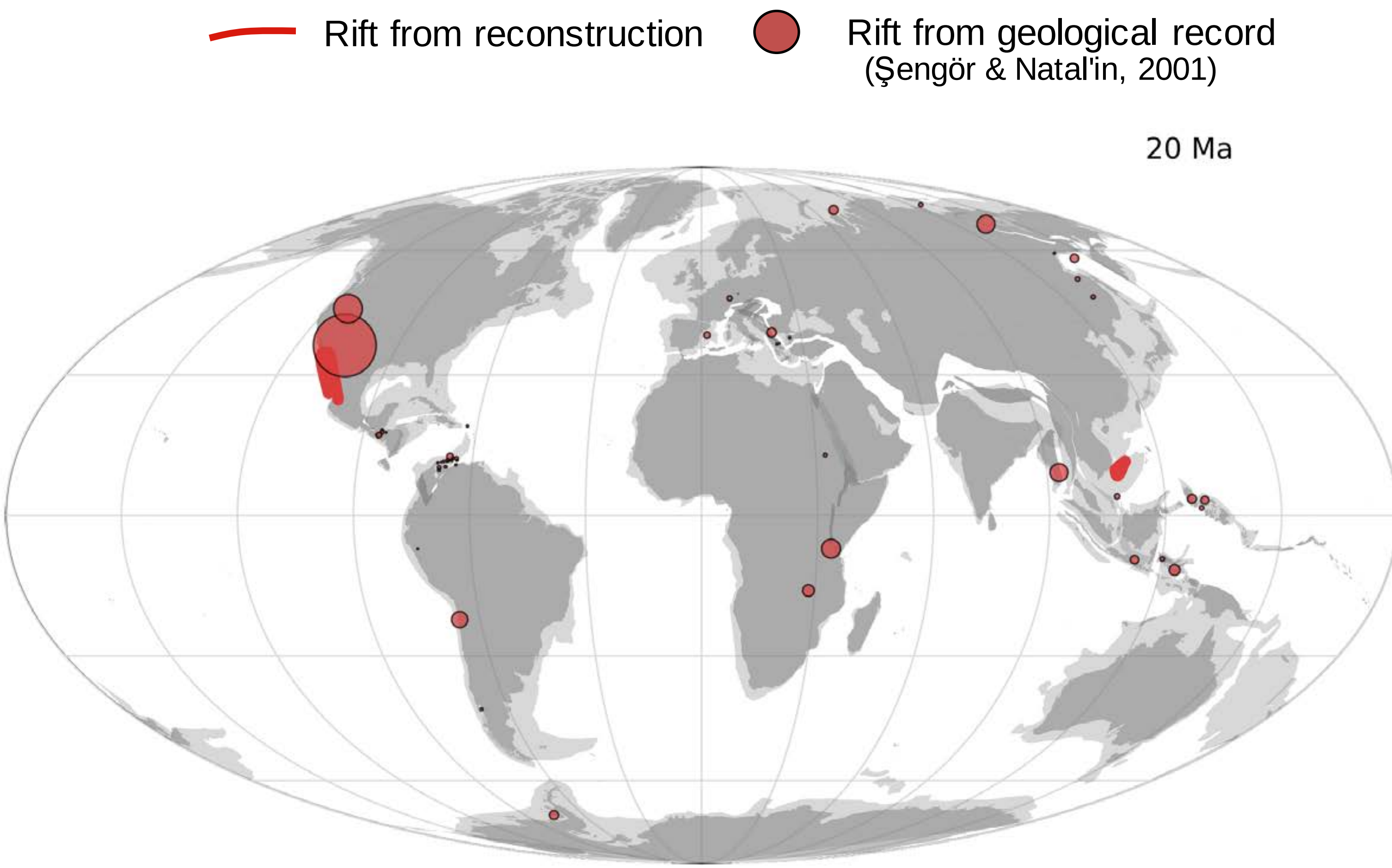

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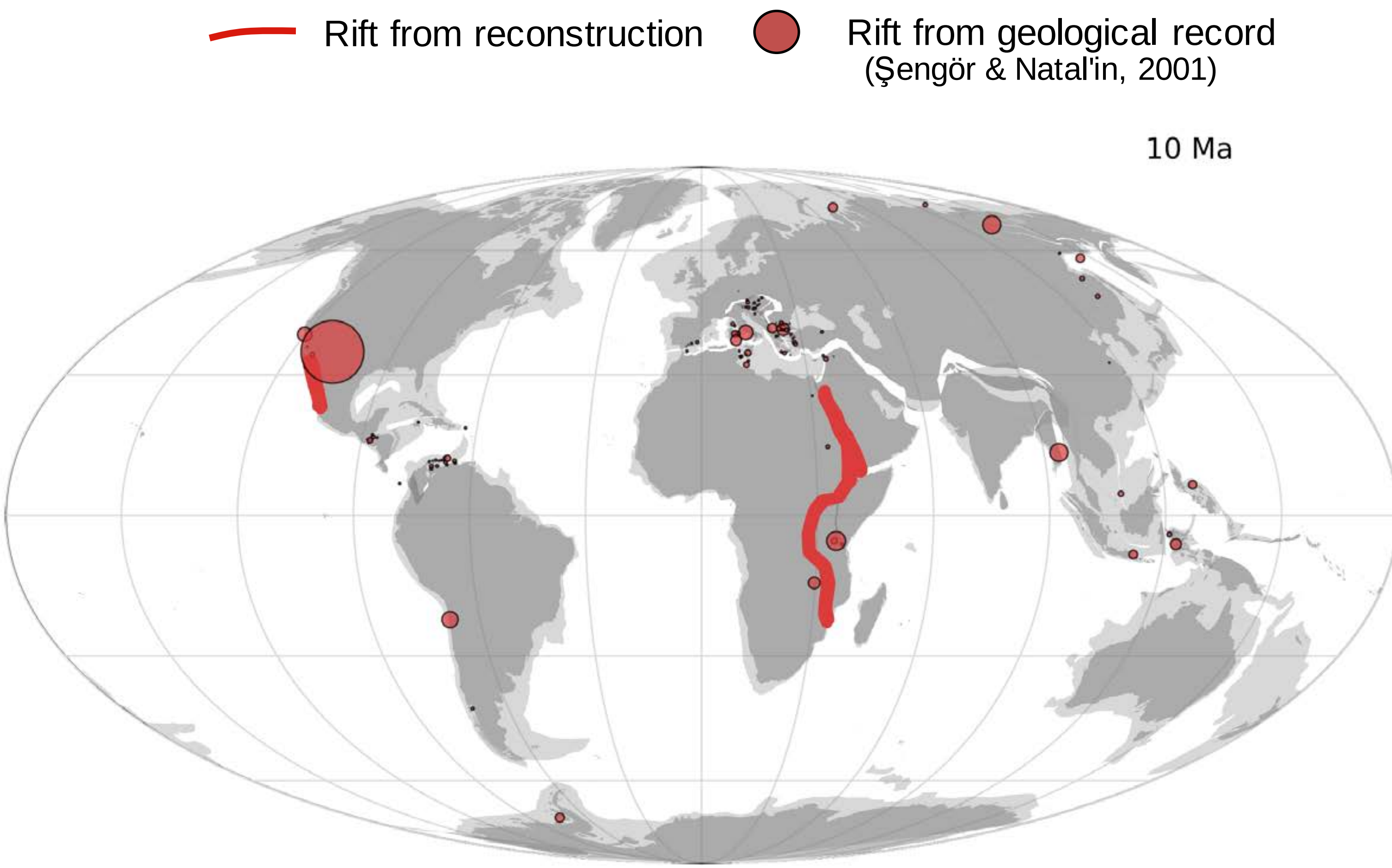

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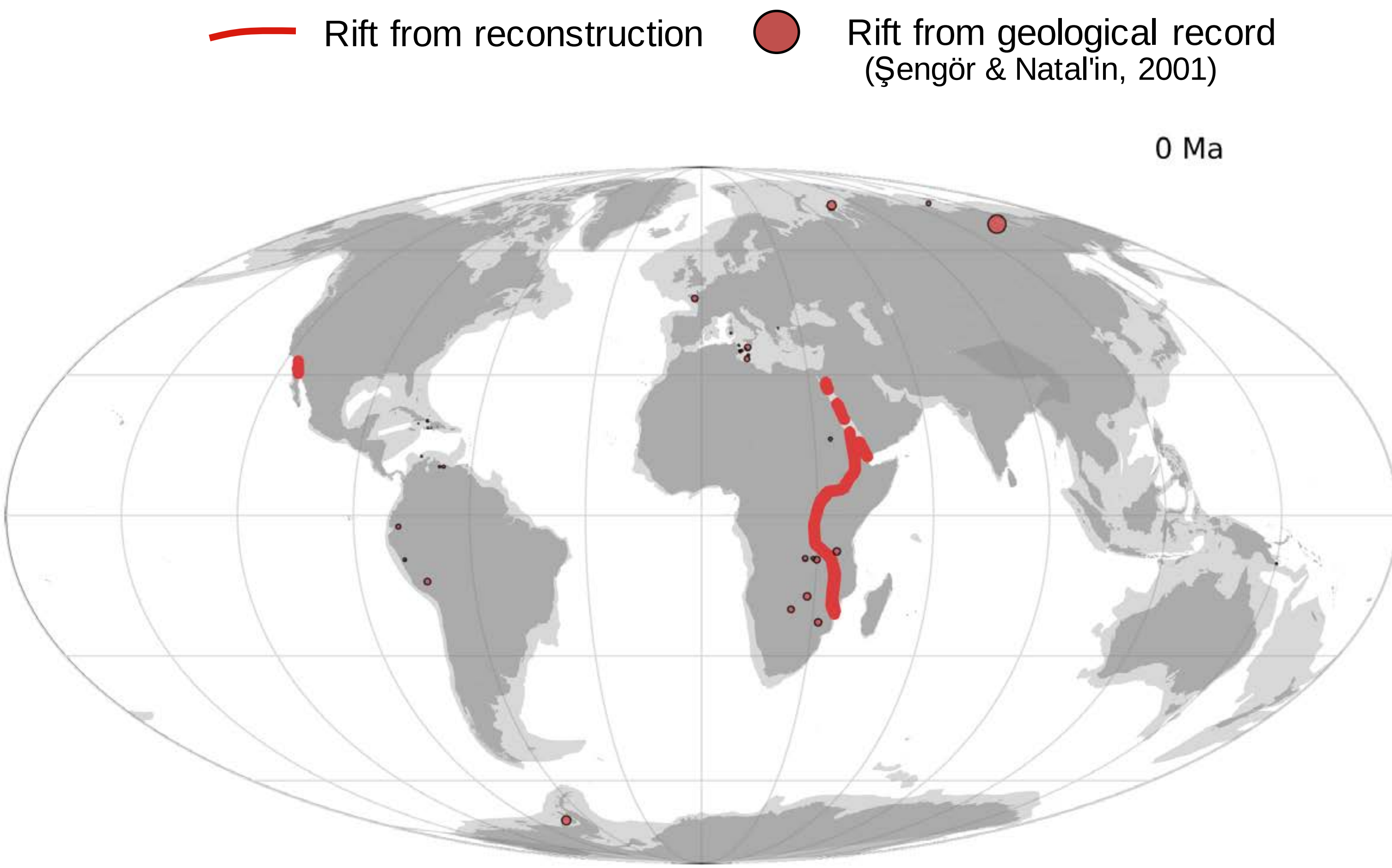

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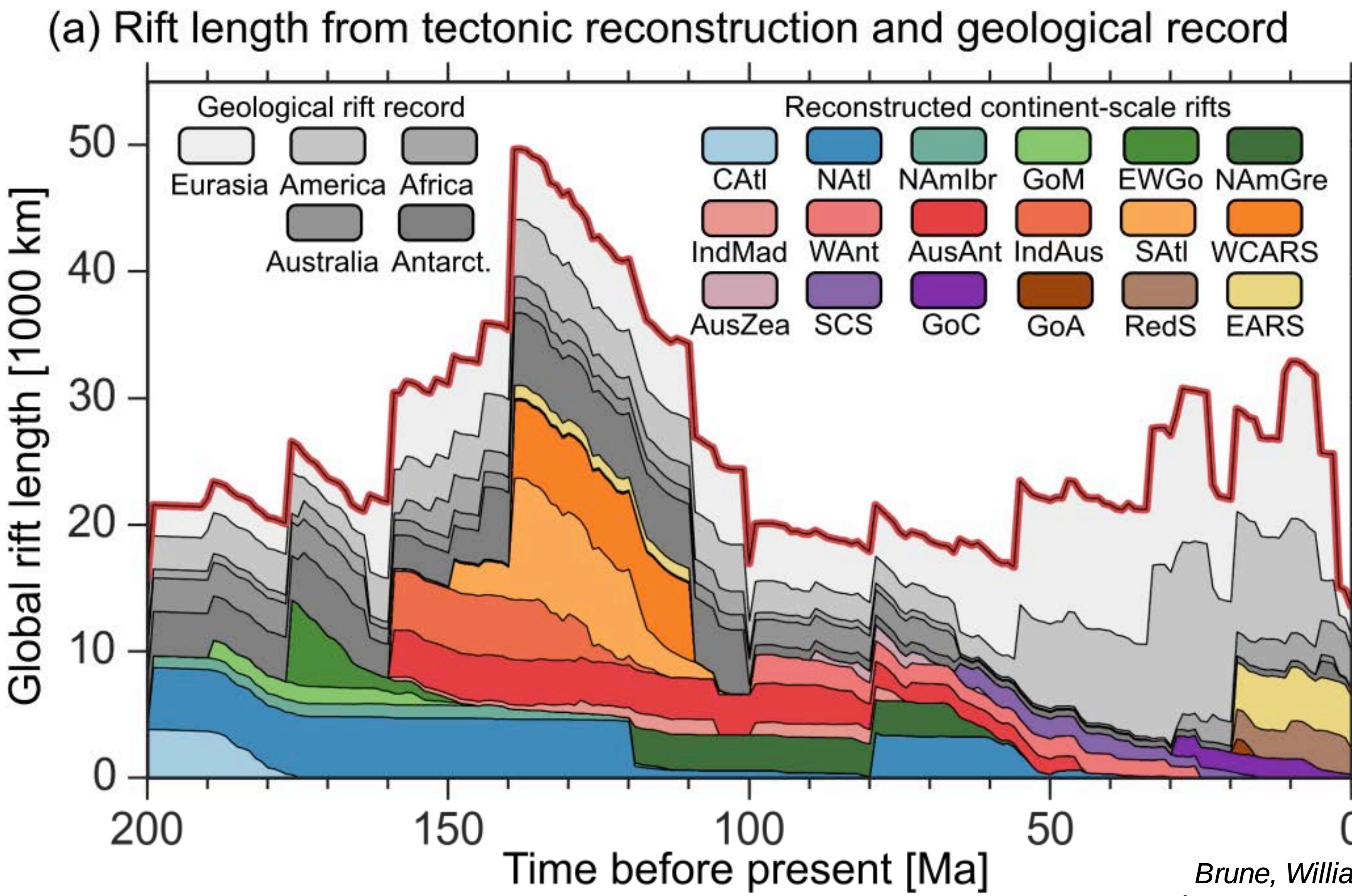
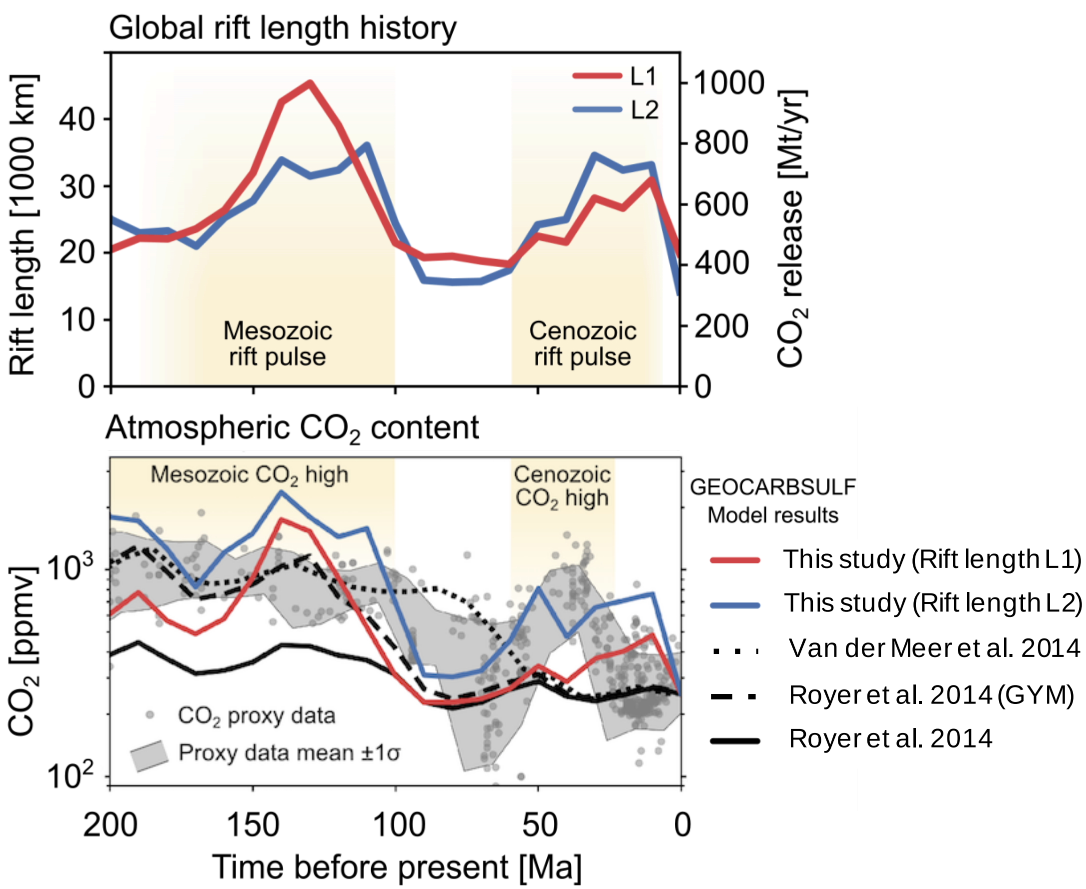


Brune, Williams, Müller (Nature Geoscience, 2017)

Rift length and atmospheric CO_2



Tectonic CO_2 release rates through time show that rift-related CO_2 degassing rates reached more than 300% of present-day values

Two prominent periods of enhanced rifting 160 to 100 million years ago and after 55 million years ago coincided with greenhouse climate episodes, with elevated atmospheric CO_2 concentrations

Continental fragmentation and long-term climate change may be causally linked via massive CO_2 degassing in rift systems

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER

10.1029/2017GL076691

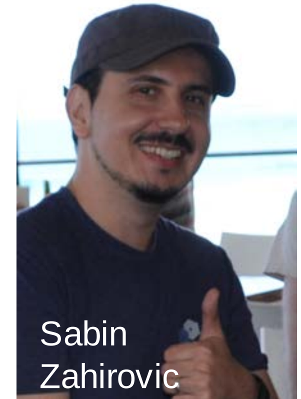
The Interplay Between the Eruption and Weathering of Large Igneous Provinces and the Deep-Time Carbon Cycle

Louis Johansson[1], Sabin Zahirovic[1], and R. Dietmar Müller[1,2]

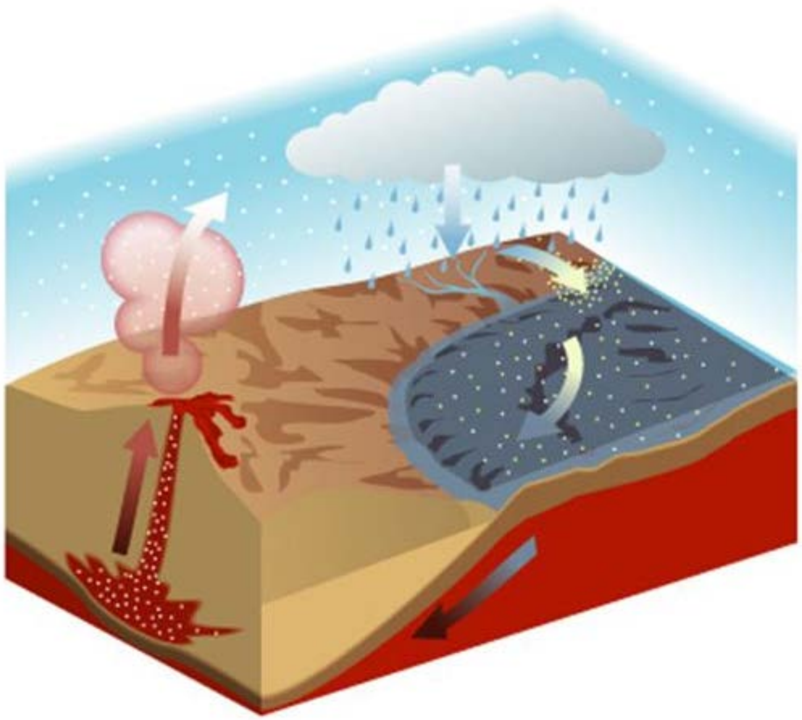
[1]EarthByte Group, School of Geosciences, University of Sydney, Camperdown, New South Wales, Australia, [2]Sydney Informatics Hub, University of Sydney, Darlington, New South Wales, Australia

Key Points:

- We investigated the global eruption and subsequent movement of continental Large Igneous Provinces in and out of latitudinal bands with

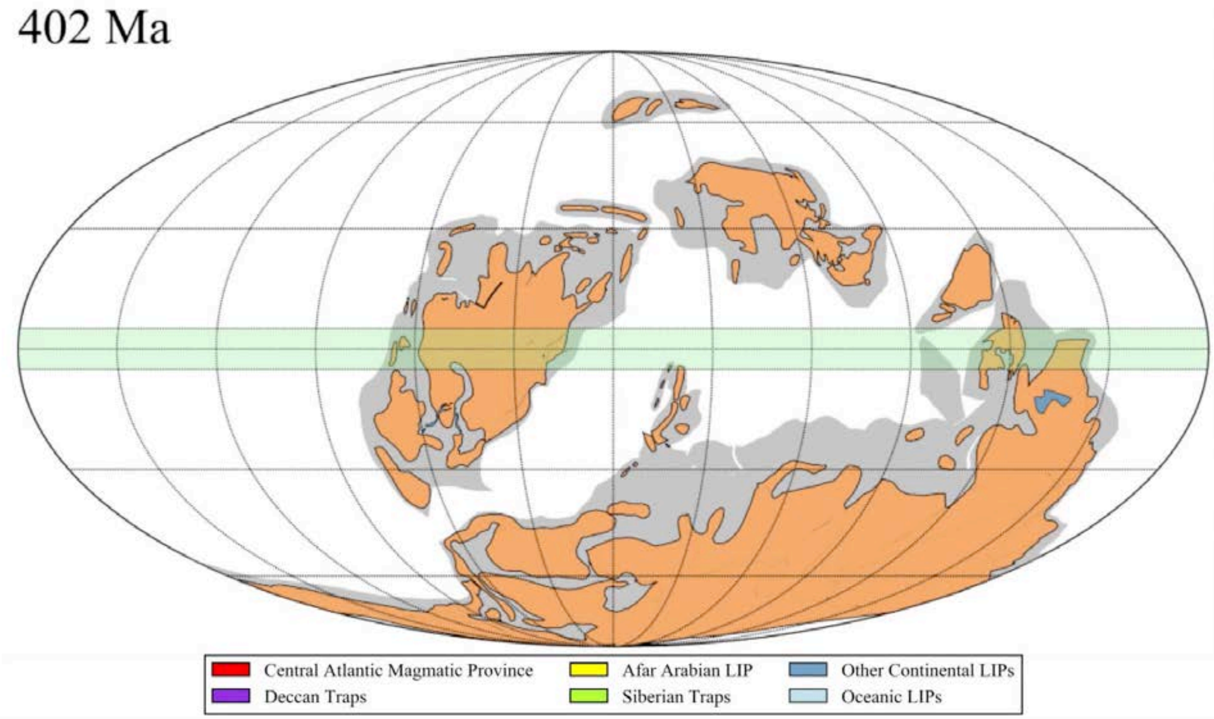


Silicate weathering



- CO_2 dissolved in rainwater reacts with silicate minerals, forming new minerals, consuming CO_2
- $CaSiO_3 + 2CO_2 + 3H_2O = Ca^{2+} + 2HCO_3^- + H_4SiO_2$
- The increased flux of sediments into the oceans during mafic rock weathering enhances carbon burial, sequestering CO_2 via biogenic processes involving various creatures making their shells or skeletons from calcium carbonate
- $Ca^{2+} + 2HCO_3^- = CaCO_3 + CO_2 + H_2O$

Distribution of LIPs reconstructed using the Matthews et al. (GPC, 2016) plate reconstruction based on a pure paleomagnetic reference frame (no hotspot tracks used) and the paleogeographies of Cao et al. (Biogeosciences, 2017)

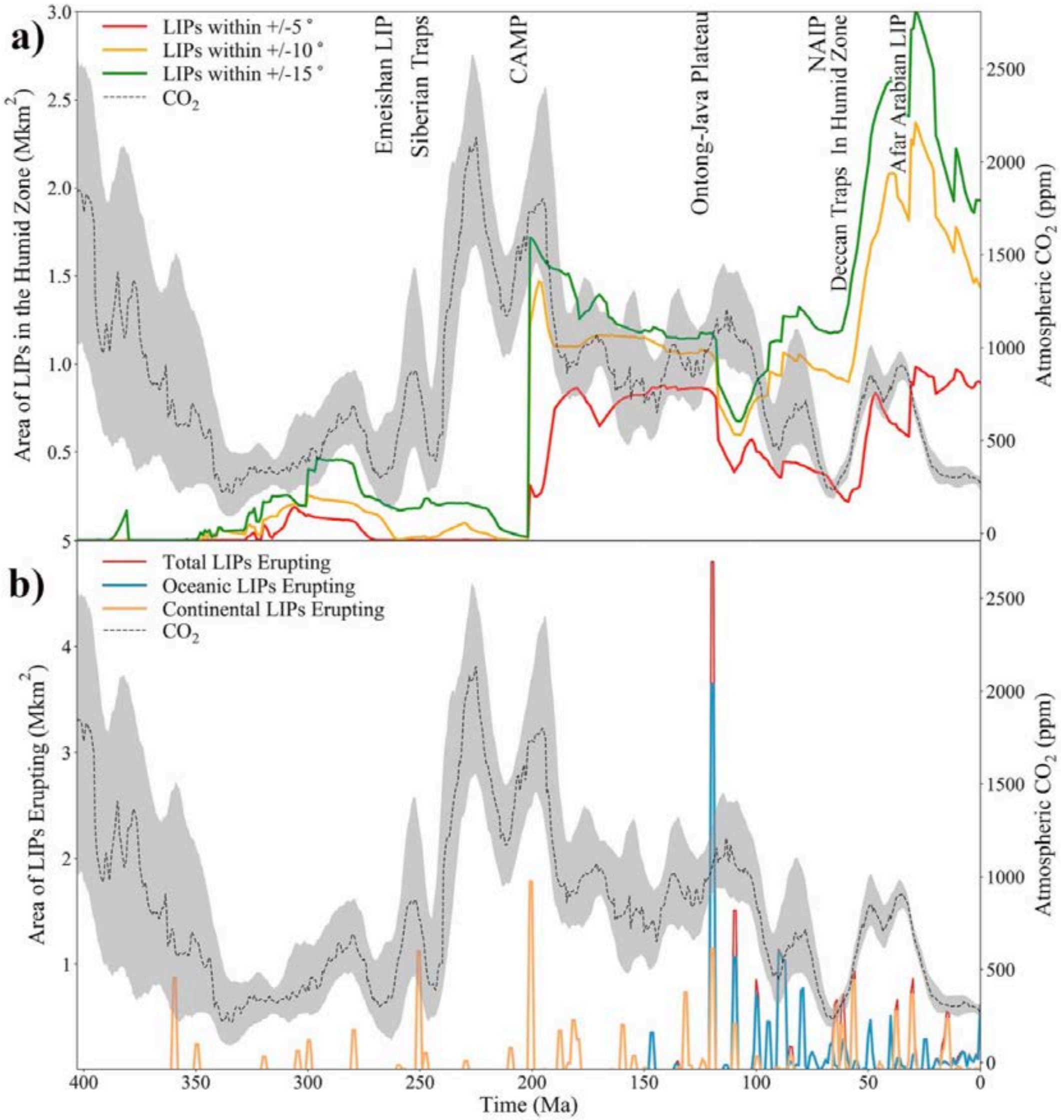


Light green: equatorial humid zone

Initial effect of LIP emplacement is CO_2 degassing

Wavelet analysis reveals significant correlations between the eruption of the Emeishan LIP (259 Ma), the Siberian Traps (251 Ma), the Central Atlantic Magmatic Province (CAMP) (201 Ma), the High Arctic LIP (130 Ma), the Deccan Traps (65 Ma) and the North Atlantic Igneous Province (55 Ma) withshort-term perturbations in atmospheric CO_2.

https://www.youtube.com/watch?v=m9MDIb8V7S8



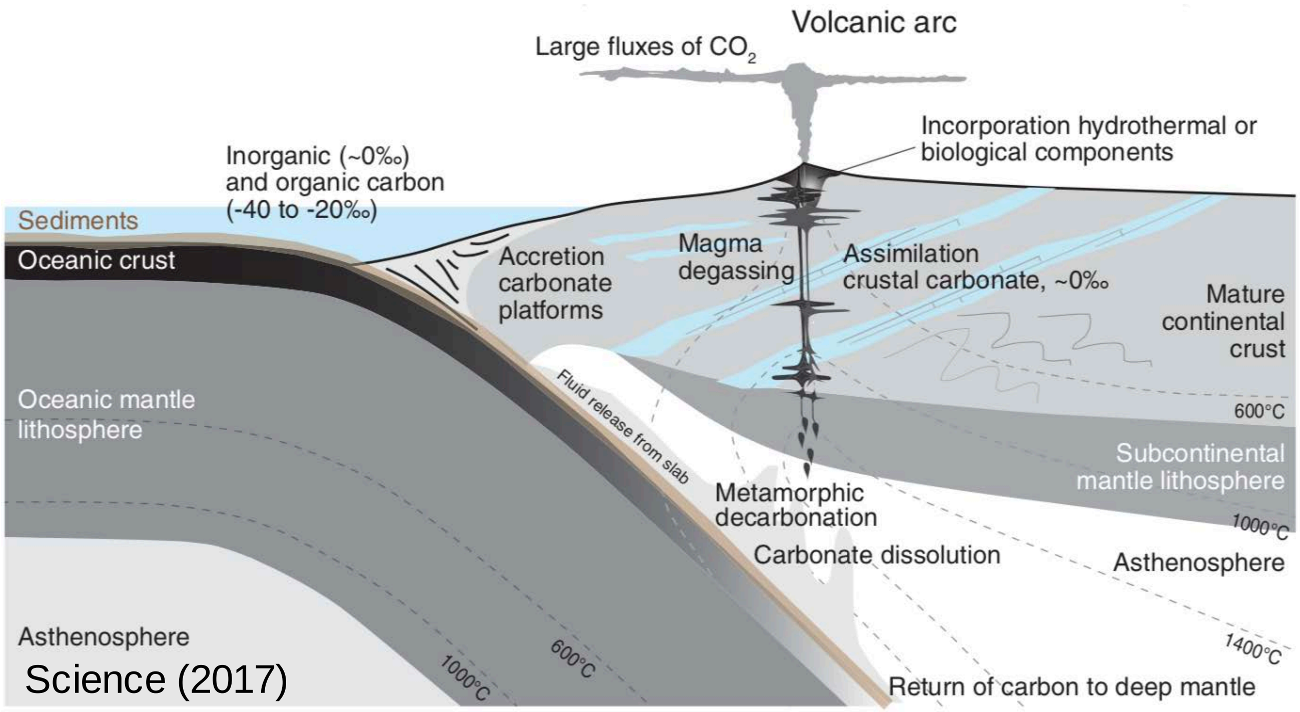
Top: Area of subaerial LIPs within the equatorial humid zone (5°N to 5°S, 10°N to 10°S, and 15°N to 15°S)

Bottom: area of erupting oceanic (blue), continental (orange), and all LIPs (red)

A cross-wavelet analysis reveals a relationship between the **weathering of the Central Atlantic Magmatic Province (CAMP) (~200–100 Ma), the Deccan Traps (50-35 Ma) and the Afar Arabian LIP (30–0 Ma)** and atmospheric CO_2 drawdown.

Remobilization of crustal carbon may dominate volcanic arc emissions

Emily Mason, Marie Edmonds,* Alexandra V. Turchyn



Carbon may be remobilized from the slab by metamorphic decarbonation or by dissolution into ionic supercritical fluids or may be returned to the deep mantle.

On ascent through the crust, magmas may interact with crustal carbonate incorporated into the crust e.g. by accretion of limestone platforms or switching of a passive to an active margin, assimilating CO_2-rich fluids, which then outgas during ascent and eruption at the surface.

Clim. Past, 14, 857–870, 2018
https://doi.org/10.5194/cp-14-857-2018

Climate of the Past
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The influence of carbonate platform interactions with subduction zone volcanism on palaeo-atmospheric CO_2 since the Devonian

Jodie Pall[1], Sabin Zahirovic[1], Sebastiano Doss[1], Rakib Hassan[1,2], Kara J. Matthews[1,3], John Cannon[1], Michael Gurnis[4], Louis Moresi[5], Adrian Lenardic[6], and R. Dietmar Müller[1]

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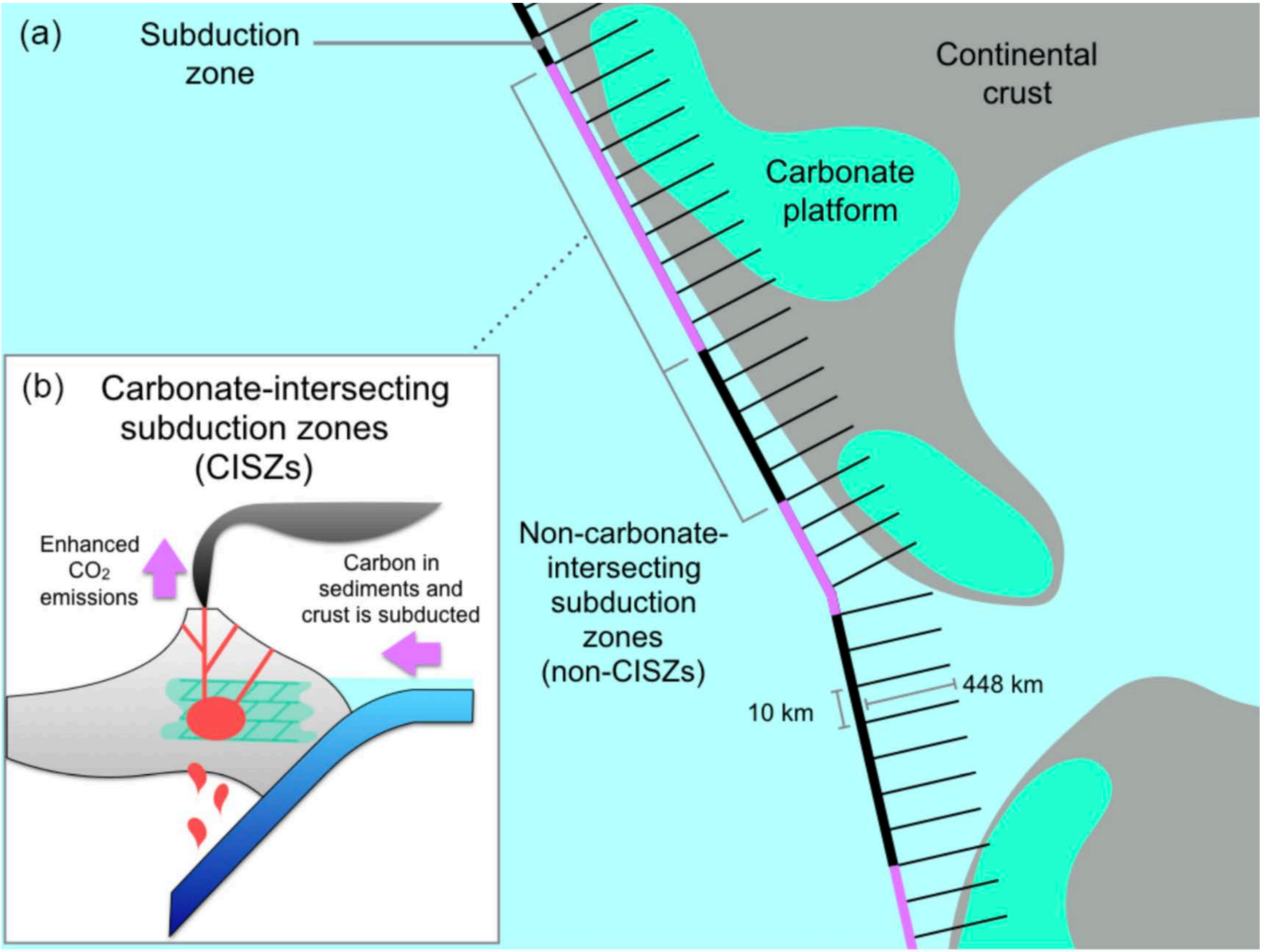
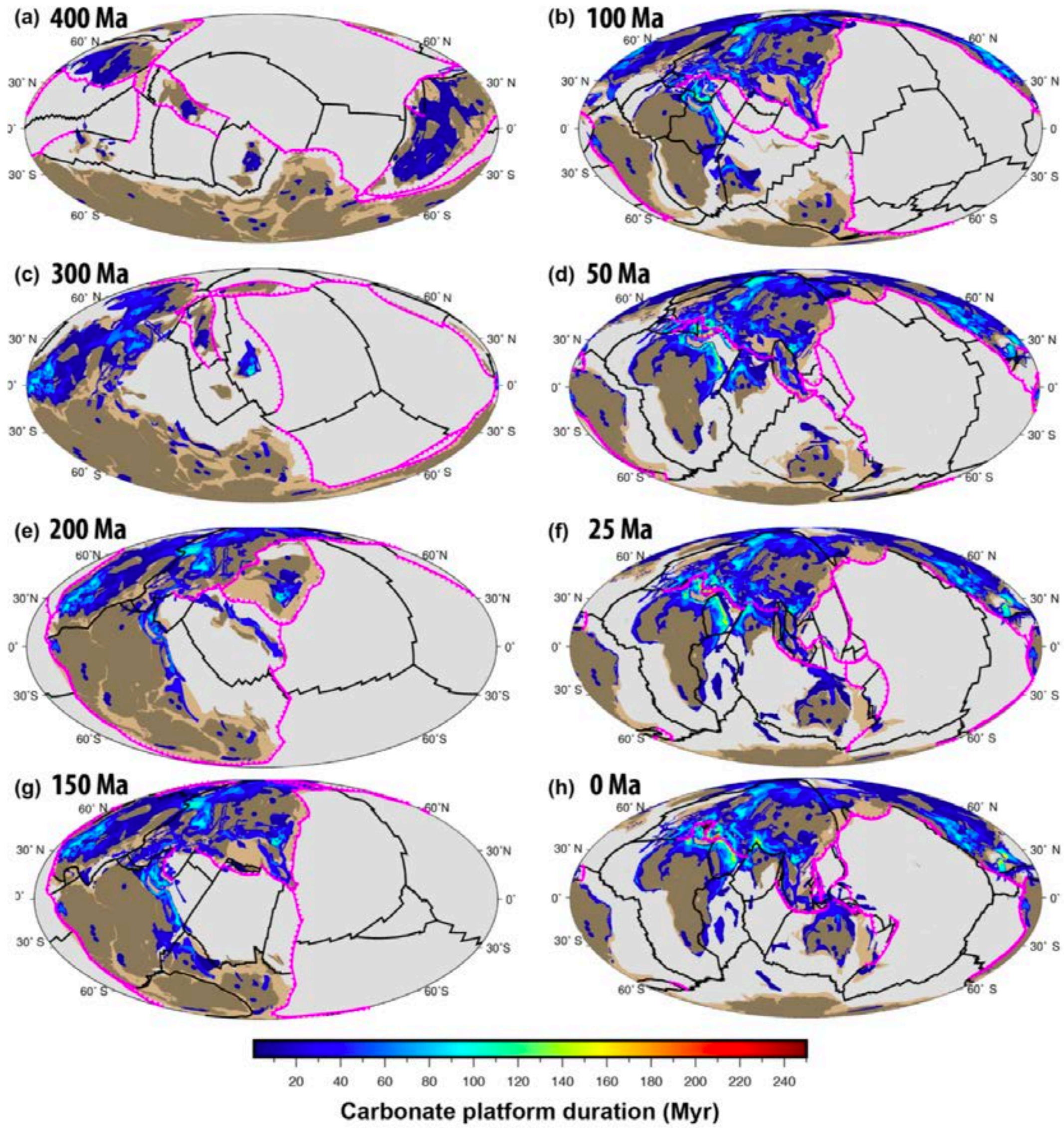
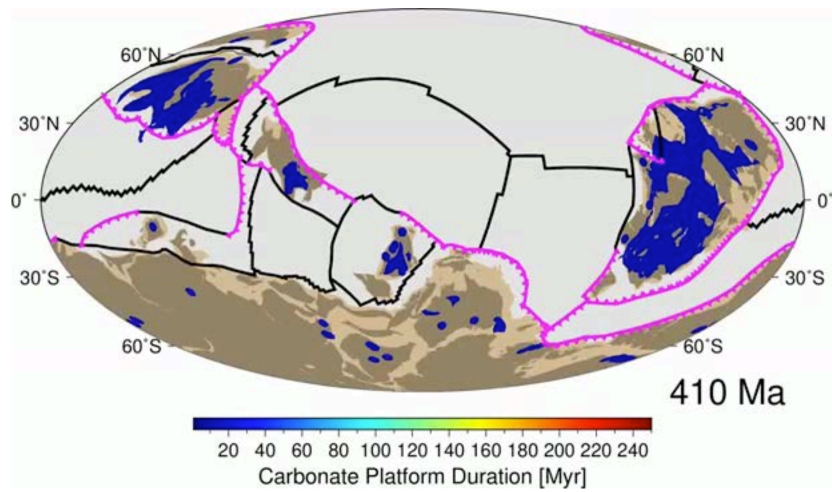


Jodie Pall

Digitise carbonate platforms through time from Kiessling et al. (2003)

Compute intersections between subduction zones and carbonate platforms on overriding plate since 410 Ma.



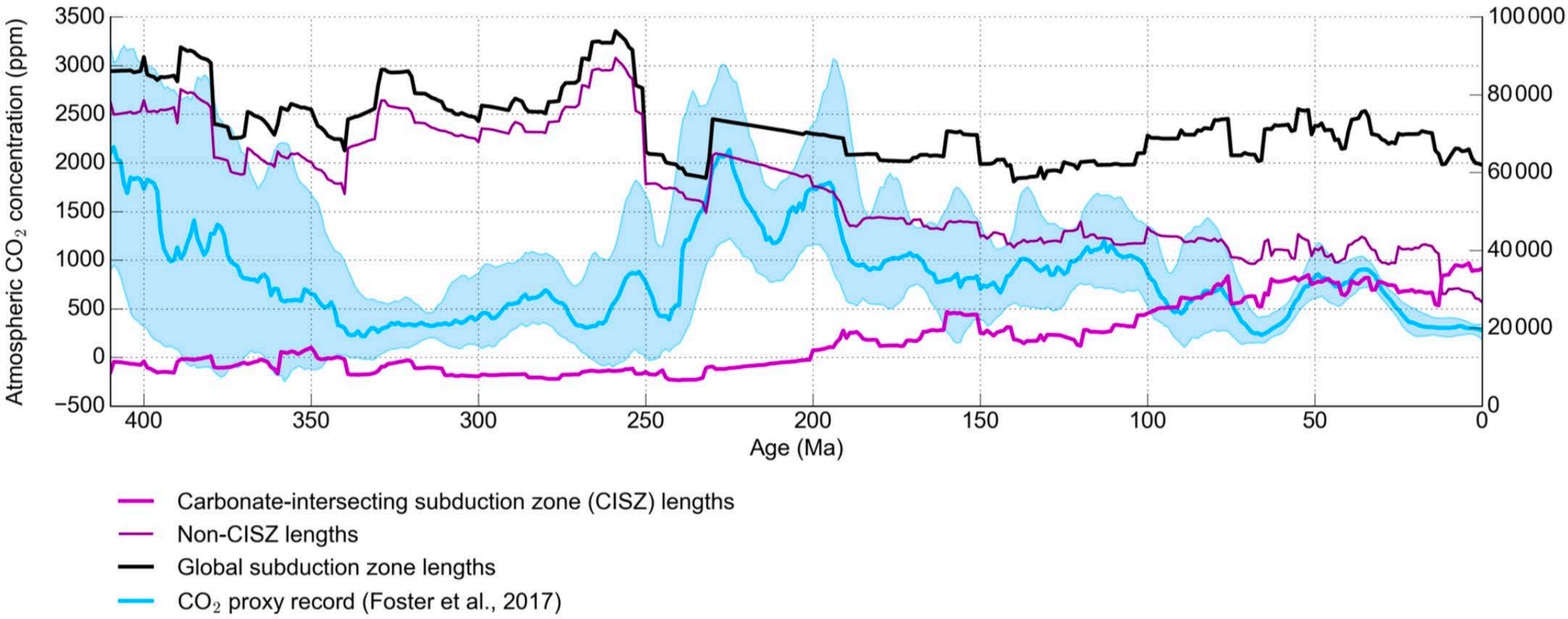


https://www.youtube.com/watch?v=8JeSHiPrCCA&t=4s

Plate reconstructions with plate boundaries (black), subduction zones (purple) and distributions of carbonate platforms, colour-coded by the duration of carbonate platform activity.

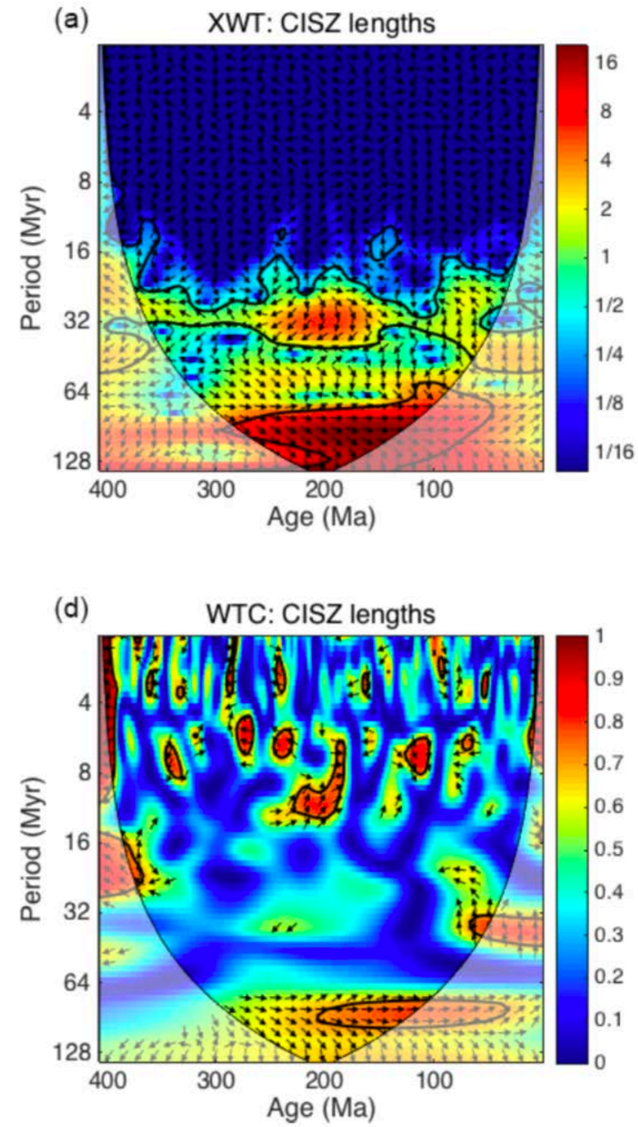
We set Precambrian and early Phanerozoic carbonate occurrences to appear at the beginning of the model at 400 Ma.

Subduction zone – carbonate platform intersections



Wavelet analysis

- Cross-wavelet transform (XWT; top) and wavelet transform coherence (WTC; bottom)
- WTC indicates significance level of cross-spectral power (XWT) between atmospheric CO_2 and subduction zone intersecting carbonate platforms
- Generally poor correlation, with the exception of Paleogene (~60-40 Ma)
- Possible connection to Eocene hothouse climate, but increased CO_2 emissions from rifting dominant
- Main signal is a long-term increase in subduction zone intersecting carbonate platforms after the breakup of Pangea, explaining Mason et al.'s (2017) observations



Conclusions

- Plate tectonic reconstructions can be used to constrain time-dependent models of rift degassing, LIP volcanic degassing and weathering, and subduction fluxes of carbon
- Seafloor weathering can also be constrained (see our recent paper in Science Advances)

RESEARCH ARTICLE | GEOCHEMISTRY

Oceanic crustal carbon cycle drives 26-million-year atmospheric carbon dioxide periodicities

R. Dietmar Müller[1,2,*] and Adriana Dutkiewicz[1]
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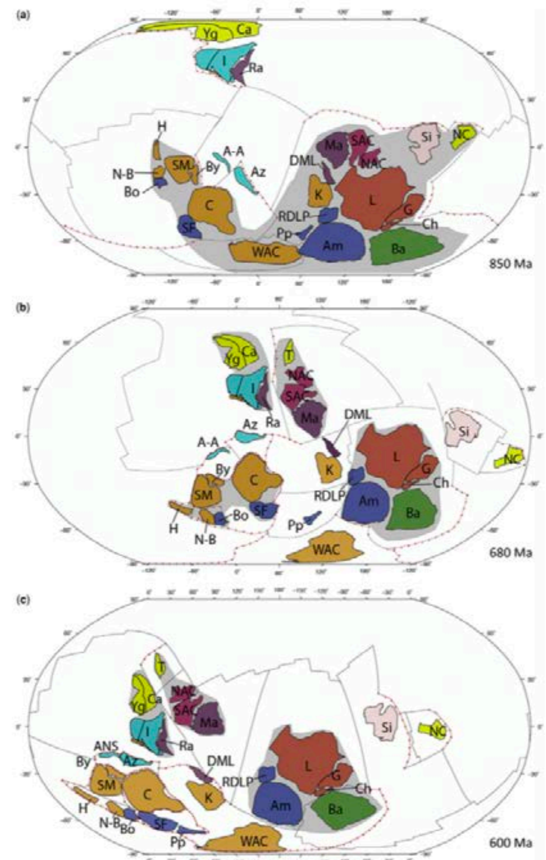
Science Advances 14 Feb 2018:
Vol. 4, no. 2, eaaq0500
DOI: 10.1126/sciadv.aaq0500

GR focus review

A full-plate global reconstruction of the Neoproterozoic

2017

Andrew S. Merdith [a,b,*], Alan S. Collins [c], Simon E. Williams [a], Sergei Pisarevsky [d,e], John D. Foden [c], Donnelly B. Archibald [c,f], Morgan L. Blades [c], Brandon L. Alessio [c], Sheree Armistead [c], Diana Plavsa [c], Chris Clark [g], R. Dietmar Müller [a]



Resources to build a virtual planet

- EarthByte Group: www.earthbyte.org (published plate models and data downloadable)
- GPlates and pyGPlates software: www.gplates.org
- GPlates Portal for interactive virtual globes: portal.gplates.org