Evolution of Large-Scale Topography and River Drainage Direction from Mantle Flow Models*

Nicolas Flament[1], R. Dietmar Müller[1], Michael Gurnis[2], Sabin Zahirovic[1], Grace E. Shephard[3], Dan J. Bower[2], Maria Seton[1], Simon Williams[1], and Jakob Skogseid[4]

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[1]School of Geosciences, The University of Sydney, Sydney, NSW, Australia (dietmar.muller@sydney.edu.au)
[2]Seismological Laboratory, California Institute of Technology, Pasadena, CA, United States
[3]Department of Geosciences, University of Oslo, Oslo, Norway
[4]Statoil ASA, Fornebu, Norway

Abstract

Flow within the mantle imposes a deformation of the Earth's surface called dynamic topography. However, quantifying this topography in space and time remains a challenge. Over the last few years, we have developed dynamic Earth models that progressively assimilate cutting-edge tectonic reconstructions with continuously closing plates and plate deformation. These models read-in plate velocities and subduction zone location and geometry defined in million-year increments for the last 230 Myr. The approach allows us to simultaneously model global mantle flow and large-scale lithospheric deformation, and in turn estimate the evolution of both dynamic and isostatic topography back to the Jurassic. In the South Atlantic domain, we show that long-wavelength topographic features, including the anomalously high elevations of southern Africa and East Brazil, could result from whole mantle flow, rather than asthenospheric flow, as previously suggested. Comparing model tectonic subsidence along the South American passive margin with that estimated from boreholes, we attribute the post-rift subsidence of the East Brazil Rift System since the Eocene to the motion of South America over ancient subducted slabs. This interplay between plate motion and mantle flow, combined with the development of flat slab subduction in Peru, also explains the reversal of the drainage direction of the Amazon River and the drying of the Pebas System since the Miocene. On a smaller scale, we show that deformation within the Central Andes imposes an inboard migration of the subduction zone relative to the South American plate that could have resulted in the migration of the depocenter of the Bolivian Chaco foreland basin and associated drainage reorganization. In South East Asia, we use simpler models without lithospheric deformation to attribute missing sedimentary sections of latest Cretaceous to Paleocene age across Sundaland to dynamic uplift resulting from a ~10 Myr subduction hiatus along the Sunda active margin. In the Arctic, we show that subduction-driven dynamic topography can explain the rapid Middle to Late Jurassic subsidence of the Slave Craton and North Slope of Alaska and the vertical motions of the Barents Sea region, characterized by subsidence between ~170–50 Ma followed by uplift since 50 Ma. Together, these results illustrate the important role of mantle flow on the evolution of large-scale topography, making dynamic Earth models powerful for frontier hydrocarbon exploration.

Selected References

Arriagada, C., P. Roperch, C. Mpodozis, and P. Cobbold, 2008, Paleogene building of the Bolivian orocline: Tectonic restoration of the central Andes in 2-D map view: Tectonics, v. 27/6, Article #TC6014. Website accessed January 21, 2016, http://onlinelibrary.wiley.com/doi/10.1029/2008TC002269/full.

Artemieva, I. M., 2006, Global 1 x 1 thermal model TC1 for the continental lithosphere: implications for lithosphere secular evolution: Tectonophysics, v. 416/1, p. 245–277.

Bower, D.J., M. Gurnis, and N. Flament, 2015, Assimilating lithosphere and slab his-tory in 4-D Earth models: Physics of the Earth and Planetary Interiors, v. 238, p. 8–22. Website accessed January 21, 2016, http://dx.doi.org/10.1016/j.pepi.2014.10.013..

Burgess, P.M., M. Gurnis, and L. Moresi, 1997, Formation of sequences in the cratonic interior of North America by interaction between mantle, eustatic and stratigraphic processes: Geological Society of America Bulletin, v. 108, p. 1515–1535.

Burgess, P.M., and L. Moresi, 1999, Modelling rates and distribution of subsidence due to dynamic topography over subducting slabs: Is it possible to identify dynamic topography from ancient strata?: Basin Research, v. Basin Research, v. 11, p. 305-314.

Chang, H. K., R.O. Kowsmann, AM.F. Figueiredo, and A. Bender,1992, Tectonics and stratigraphy of the East Brazil Rift system: An overview: Tectonophysics, v. 213/1, p. 97–138.

Clements, B., P.M. Burgess, R. Hall, and M.A. Cottam, 2011, Subsidence and uplift by slab related mantle dynamics: A driving mechanism for the Late Cretaceous and Cenozoic evolution of continental SE Asia, *in* R. Hall, M.E. Wilson, and M.A. Cottam, editors, The SE Asian Gateway: History and Tectonics of Australia–Asia Collision. Geological Society, London, Special Publications, no. 355, p. 37–51.

Flament, N., M. Gurnis, and R.D. Müller, 2013, A review of observations and models of dynamic topography: Lithosphere, v. 5, p. 189–210.

Flament, N., M. Gurnis, S. Williams, M. Seton, J. Skogseid, C. Heine,and R.D. Müller, 2014,Topographic asymmetry of the South Atlantic from global models of mantle flow and lithospheric stretching: Earth and Planetary Science Letters, v. 387, p. 107-119.

Flament, N., M. Gurnis, R.D. Müller, D.J.Bower, L. Husson, 2015, Influence of subduction history on South American topography: Earth and Planetary Science Letters, v. 430, p. 9-18. Website accessed January 21, 2016, http://www.earthbyte.org/influence-of-subduction-history-on-south-american-topography/.

Golonka, J., 2007, Phanerozoic paleoenvironment and paleolithofacies maps: Mesozoic. Geologia/Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie, v. 33/2, p. 211-264.

Golonka, J., 2009a, Phanerozoic paleoenvironment and paleolithofacies maps. Cenozoic: Mapy paleośrodowiska i paleolitofacje fanerozoiku. Kenozoik: Kwartalnik AGH. Geologia (Geologia/Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie), v. 35/4, p. 507-587.

Golonka, J., 2009b, Phanerozoic paleoenvironment and paleolithofacies maps. Early Paleozoic. Mapy paleośrodowiska i paleolitofacje fanerozoiku. Wczesny paleozoik. Kwartalnik AGH. Geologia (Geologia/Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie), v. 35/ 4, p. 589-654.

Golonka, J., M.I. Ross and C.R. Scotese, 1994, Phanerozoic paleogeographic and paleoclimatic modeling maps, *in* A.F. Embry, B. Beauchamp, and D.J. Glass, editors, Pangea: Global Environment and Resources: Canadian Society of Petroleum Geologists Memoir 17, p. 1-47.

Gurnis, M., M. Turner, S. Zahirovic, L. DiCaprio, S. Spasojevic, R.D. Müller, J. Boyden, M. Seton, V.C. Manea, and D.J. Bower, 2012, Tectonic reconstructions with continuously closing plates: Computers and Geosciences, v. 38/1, p. 35-42.

Haq, B.U., J. Hardenbol, and P.R. Vail, 1987, Chronology of fluctuating sea levels since the Triassic (250 million years ago to present): Science, v. 235, p. 1156-1167.

Hoorn, C., and F.P. Wesselingh, editors, 2010, Amazonia: Landscape and Species Evolution, a Look into the Past: Wiley-Blackwell publications, UK, 447p.

Jones, S.M., N. White, P. Faulkner, and P. Bellingham, P., 2004, Animated models of extensional basins and passive margins. Geochemistry, Geophysics, Geosystems, v. 5/8. Website accessed January 21, 2016, http://bullard.esc.cam.ac.uk/~basin/pubs/jonesetal04.pdf.

Jordan, T.H., 1975, The continental tectosphere: Reviews of Geophysics, v. 13/3, p. 1–12.

Jordan, T.H., 1988, Structure and formation of the continental tectosphere: Journal of Petrology, v. 29, p. 11-37.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40/1, p. 25–32.

Ramos, V.A., and A. Folguera, 2009, Andean flat-slab subduction through time, *in* J.B. Murphy, J.D. Keppie, and A.J. Hynes, editors, Ancient Orogens and Modern Analogues: Geological Society, London, Special Publications, no. 327, p. 31–54.

Seton, M., R.D. Müller, S. Zahirovic, C. Gaina, T. Torsvik, G. Shephard, A. Talsma, M. Gurnis, M. Turner, and M. Chandler, 2012, Global continental and ocean basin reconstructions since 200 Ma. Earth- Science Reviews, v. 113, p. 212–270.

Shephard, G.,R.D. Müller, L. Liu, and M. Gurnis, 2010, Miocene drainage reversal of the Amazon River driven by plate-mantle interaction: Nature Geoscience, v. 3/12, p. 870–875.

Smith, A., D.G. Smith, and B.M. Furnell, 1994, Atlas of Mesozoic and Cenozoic Coastlines: Cambridge University Press, Cambridge, United Kingdom, 112 p.

Uba, C.E., C. Heubeck, and C. Hulka, 2006, Evolution of the Late Cenozoic Chaco foreland basin, Southern Bolivia: Basin Research, v. 18, p. 145–170.

Wesselingh, F.P., and M.I.F. Ramos, 2010, Amazonian aquatic invertebrate faunas (Mollusca, Ostracoda) in their development over the past 30 million years, *in* C. Hoorn and F.P. Wesselingh, editors, Amazonia: Landscape and Species Evolution, a Look into the Past: Wiley-Blackwell publications, UK , Chapter 18, p. 302-316.

Zhong, S., Zuber, M.T., Moresi, L., 2000, Role of temperature-dependent viscosity and surface plates in spherical shell models of mantle convection. Journal of Geophysical Research, v. 105, p. 11063–11082.

Websites

www.earthbyte.org/the-basin-genesis-hub/. Website accessed January 21, 2016.

www.andespictures.com. Website accessed January 21, 2016, but inaccessible February 1, 2015; http://edugeography.com/content/image.php?pic=../images/andes/andes-02.jpg, accessible February 1, 2016.

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Melbourne
September 2015

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[a] The University of Sydney – [b] California Institute of Technology
[c] University of Oslo – [d] Statoil ASA

THE UNIVERSITY OF SYDNEY

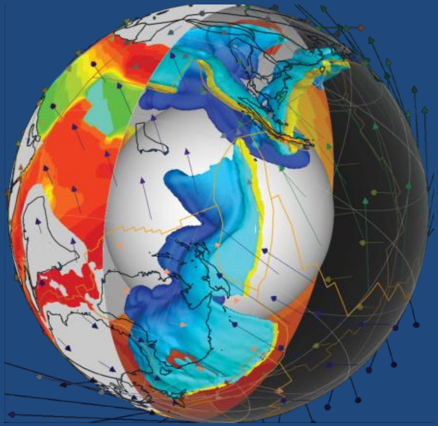
EarthBYTE

BGH

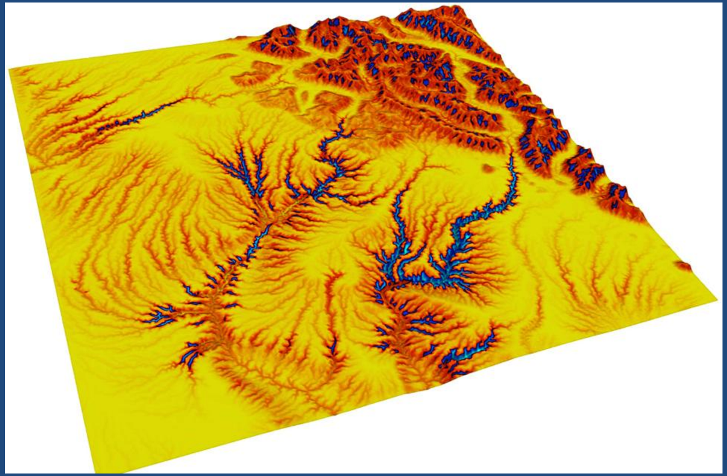
Basin GENESIS Hub

BGH

- 5-year industry linkage project with research focus on Australia, PNG and the Atlantic



Modelling effects of crustal- and mantle-scale processes on basin evolution

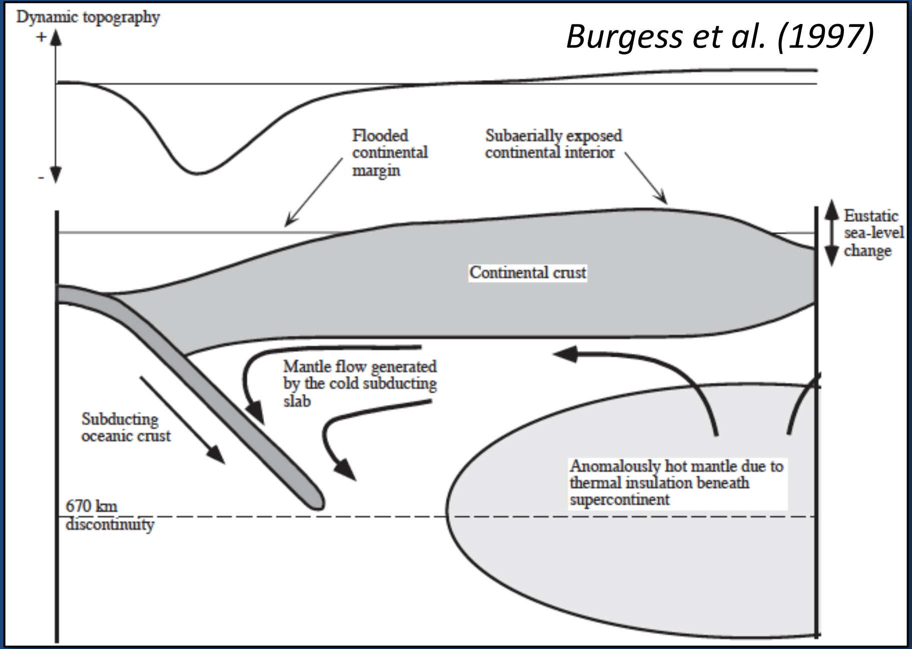


Modelling dynamics of surface topography, erosion, sedimentation

www.earthbyte.org/the-basin-genesis-hub/

Isostatic ("tectonic") and *dynamic* topography

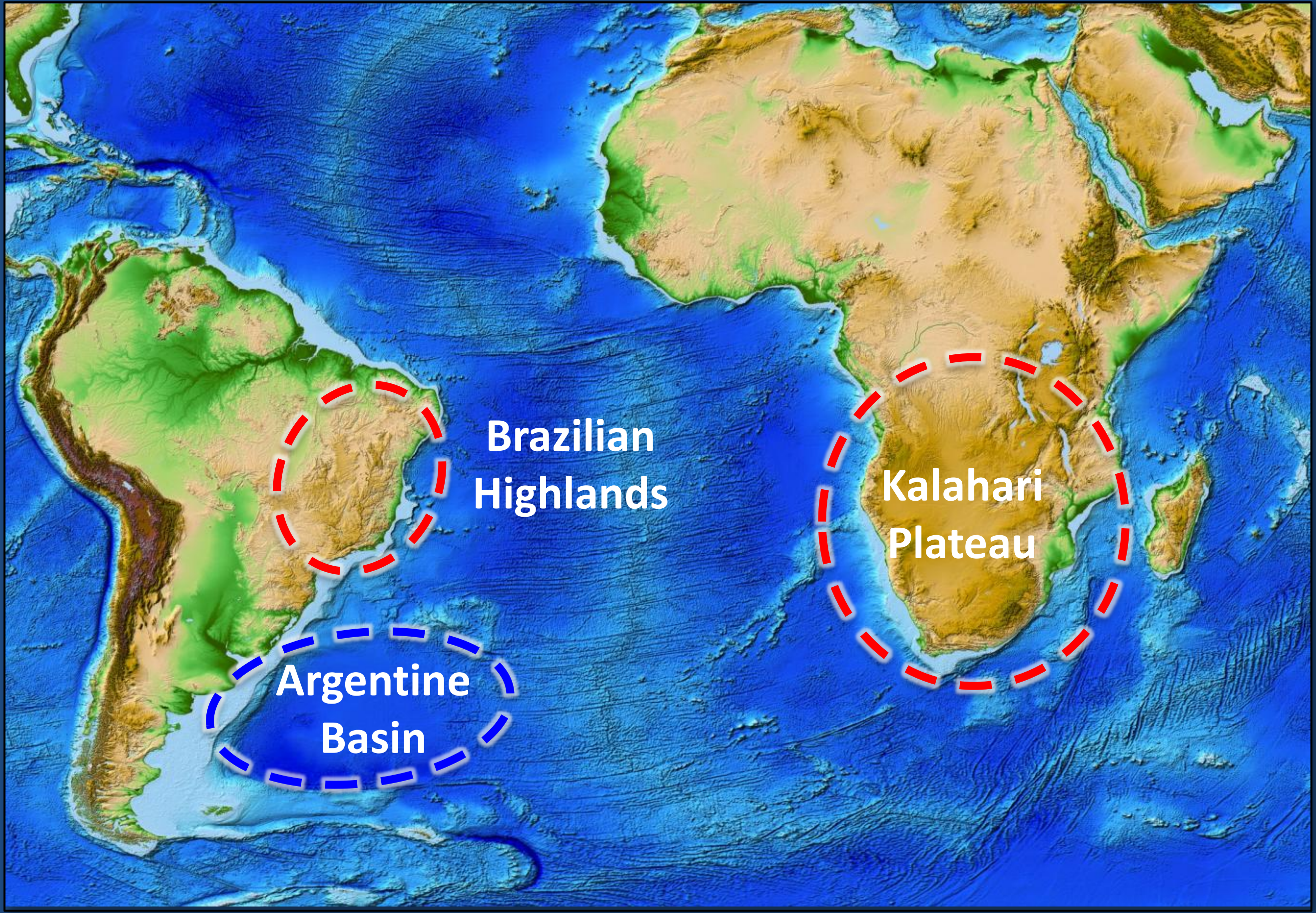
- Most of the topography at the Earth's surface is *isostatically compensated*
- This topography is related to the thickness of the continental crust and lithosphere



Many other processes affect topography, including:

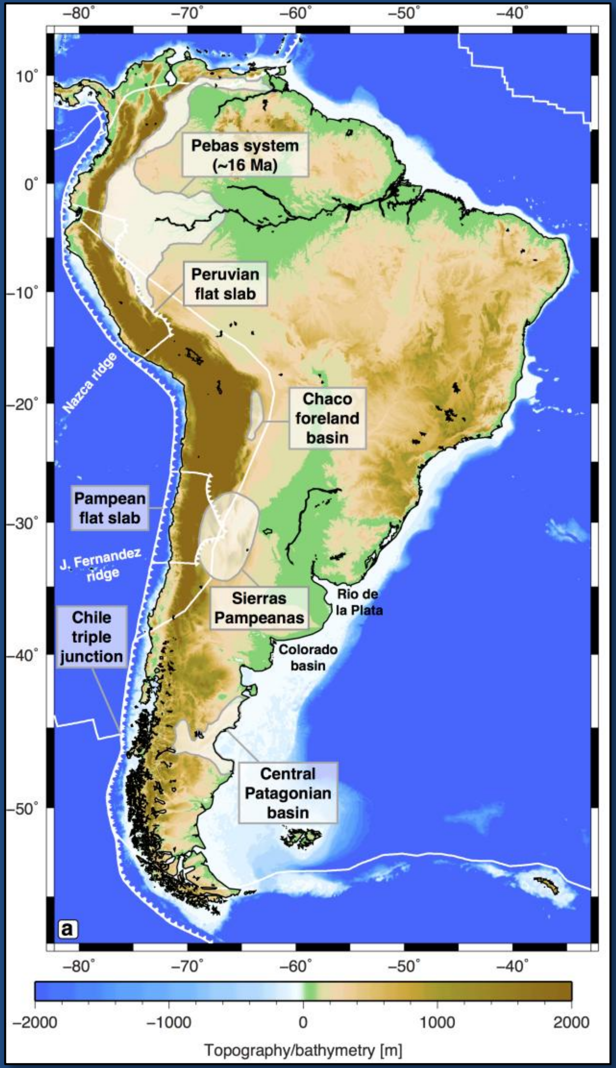
- Thermal diffusion that affects the thickness of the lithosphere
- Mantle flow

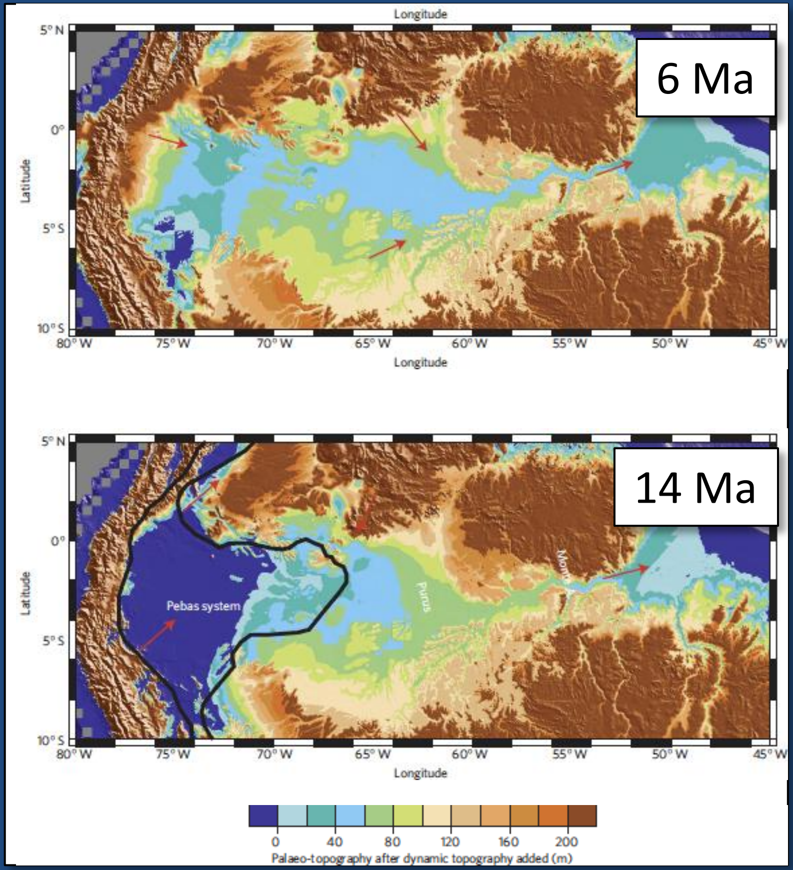
Topographic asymmetry of the South Atlantic domain



Anomalously
high
low
regions

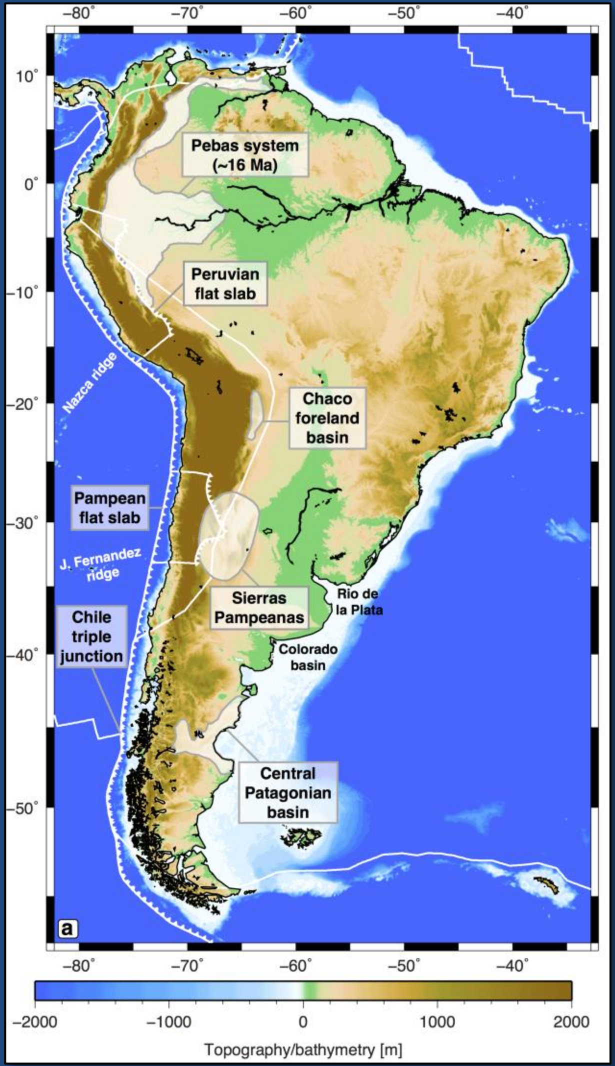
Pebas system and reversal of the drainage direction of the Amazon River

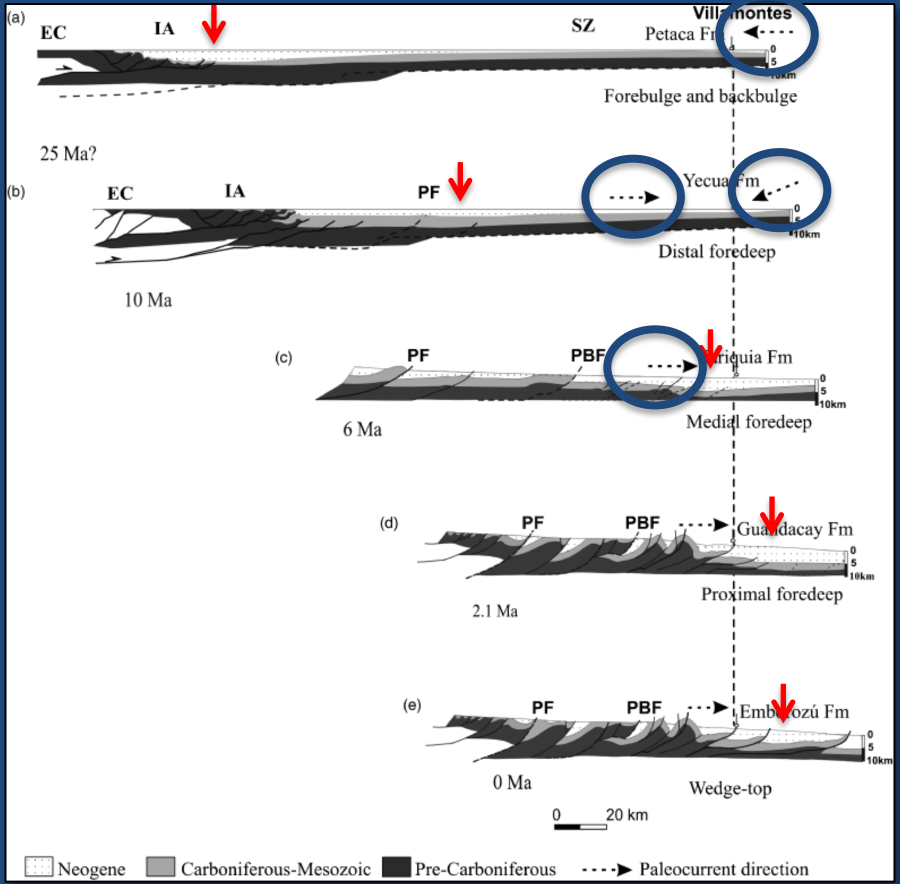




Shephard et al. (2010)

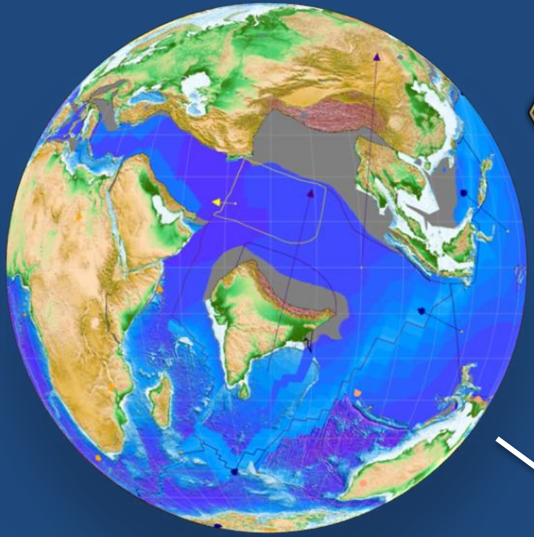
Migration of the depocentre of the Chaco Basin





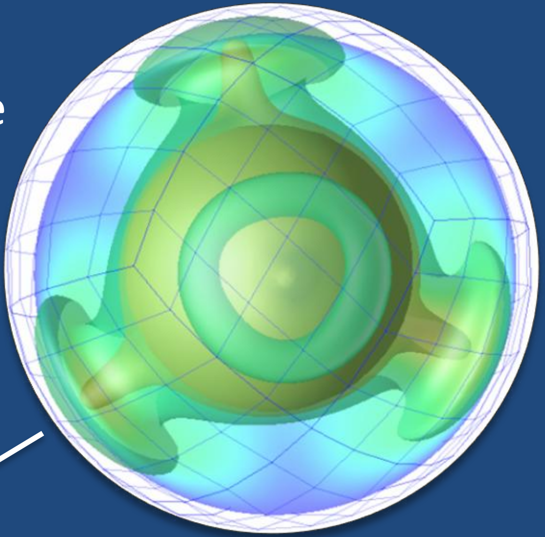
Uba et al. (2006)

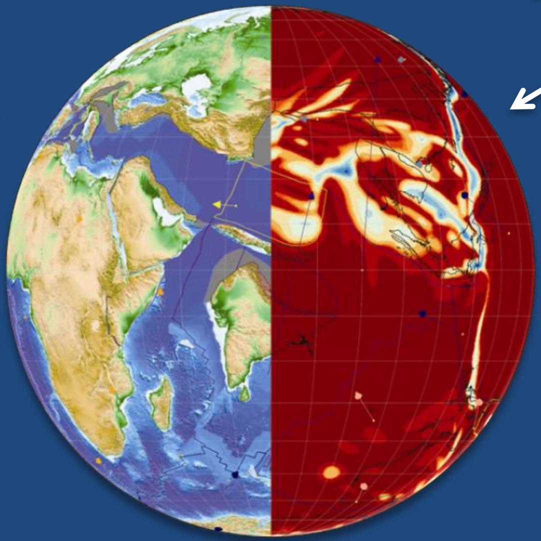
Forward global mantle flow models



CitcomS

- 3D spherical finite element mantle convection code
- Modified for data assimilation





GPlates

Global reconstructions back to 230 Ma with continuously closing plate polygons (velocities; plate boundaries)

13 x 10^6 points

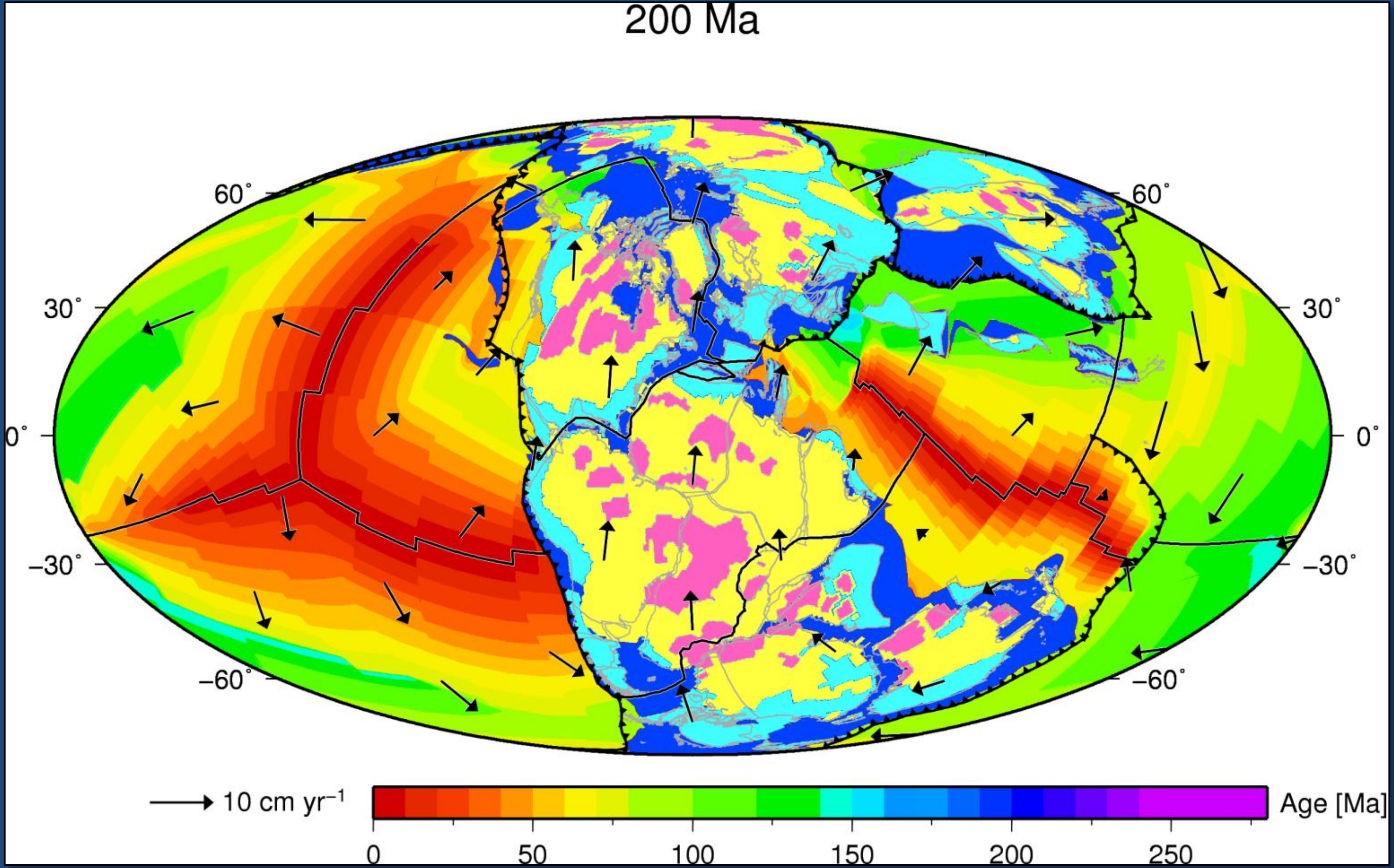
~ 40,000 CPU hours/model

Forward global mantle flow models

Seton et al. (2012)

Gurnis et al. (2012)

Artemieva (2006)



Forward global mantle flow models

Seton et al. (2012)

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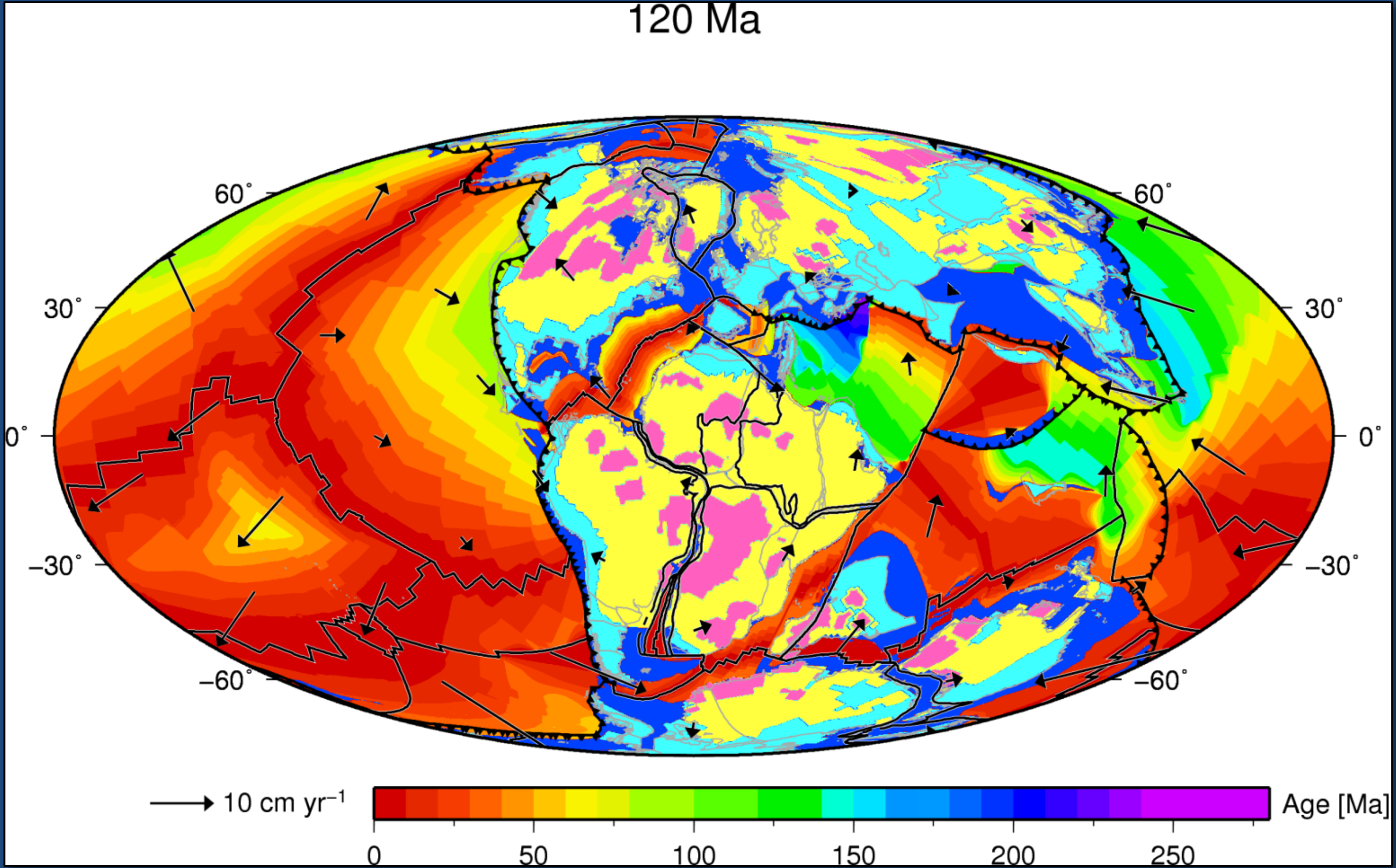
Artemieva (2006)

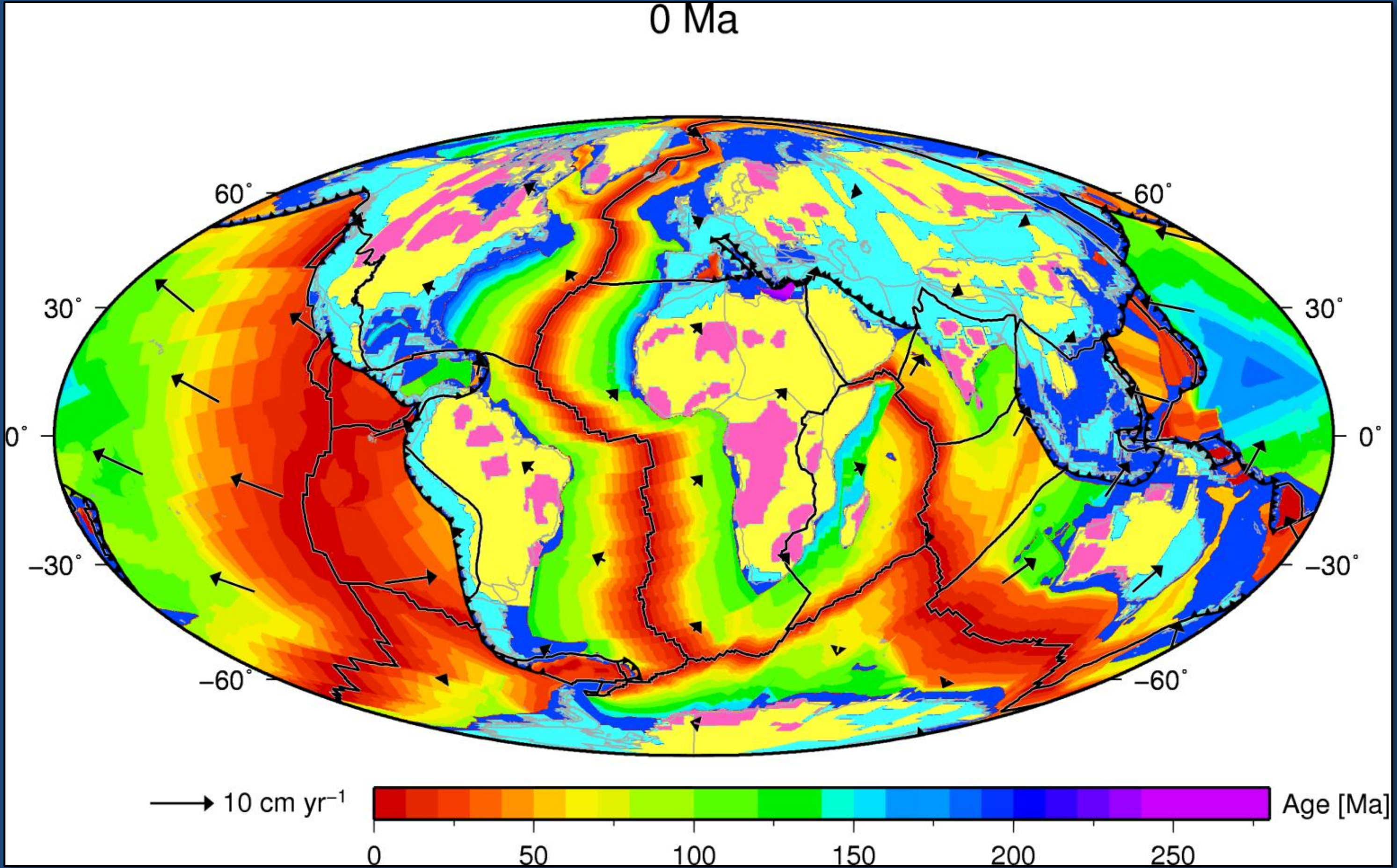


Forward global mantle flow models

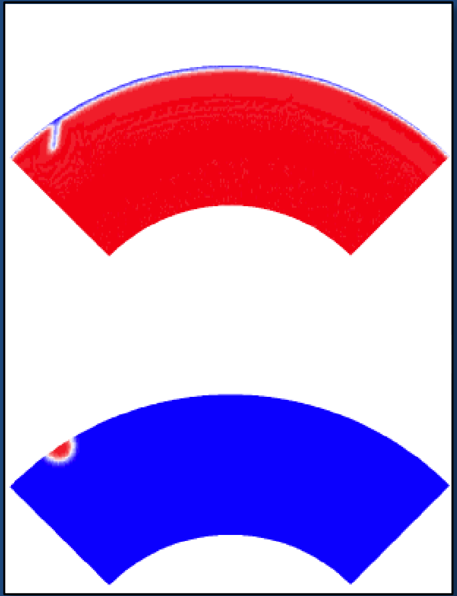
Seton et al. (2012)

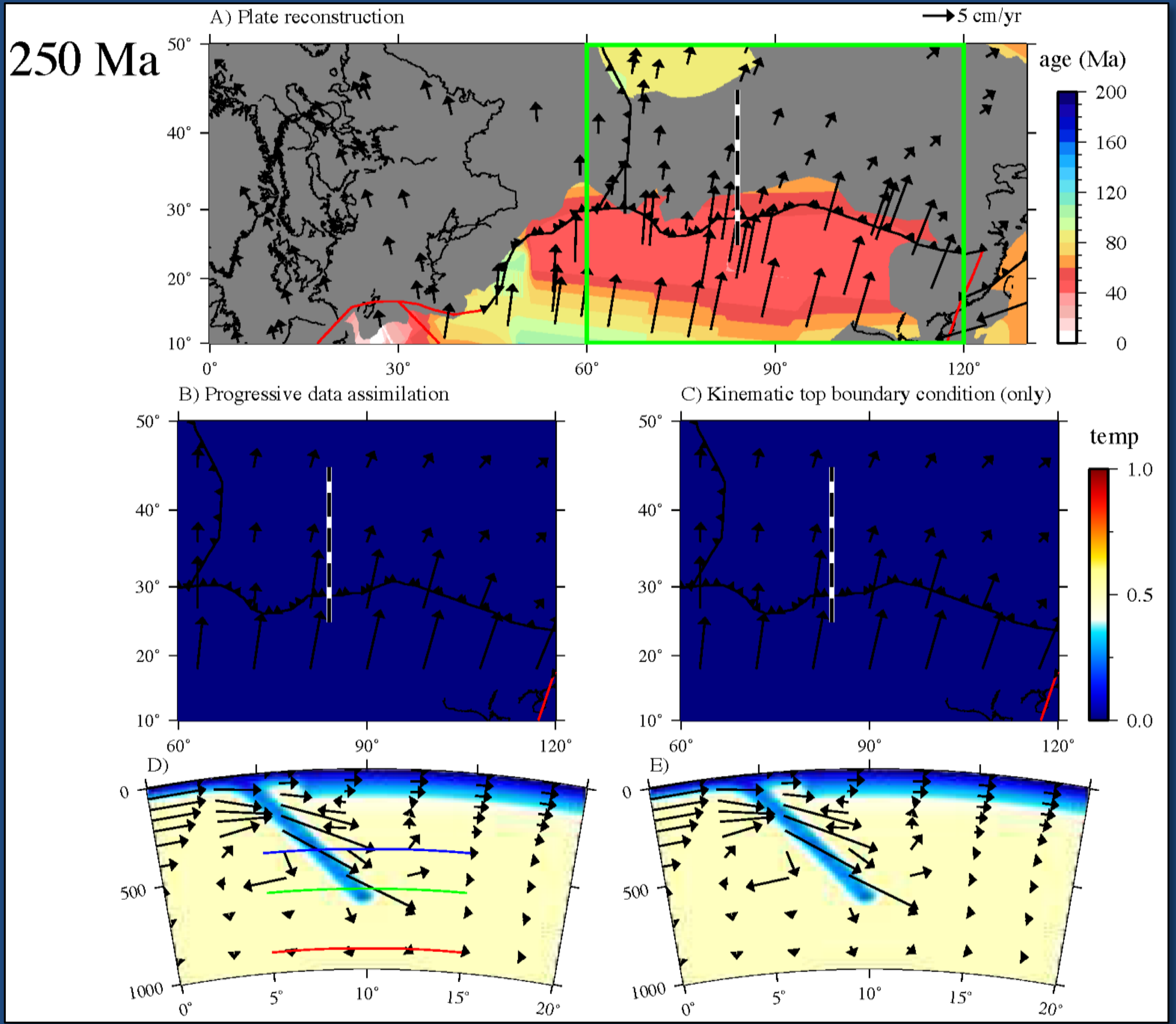
Gurnis et al. (2012)

Artemieva (2006)



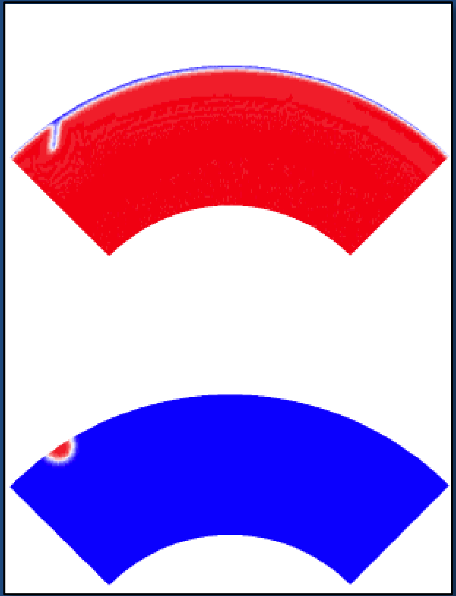
Progressive data assimilation



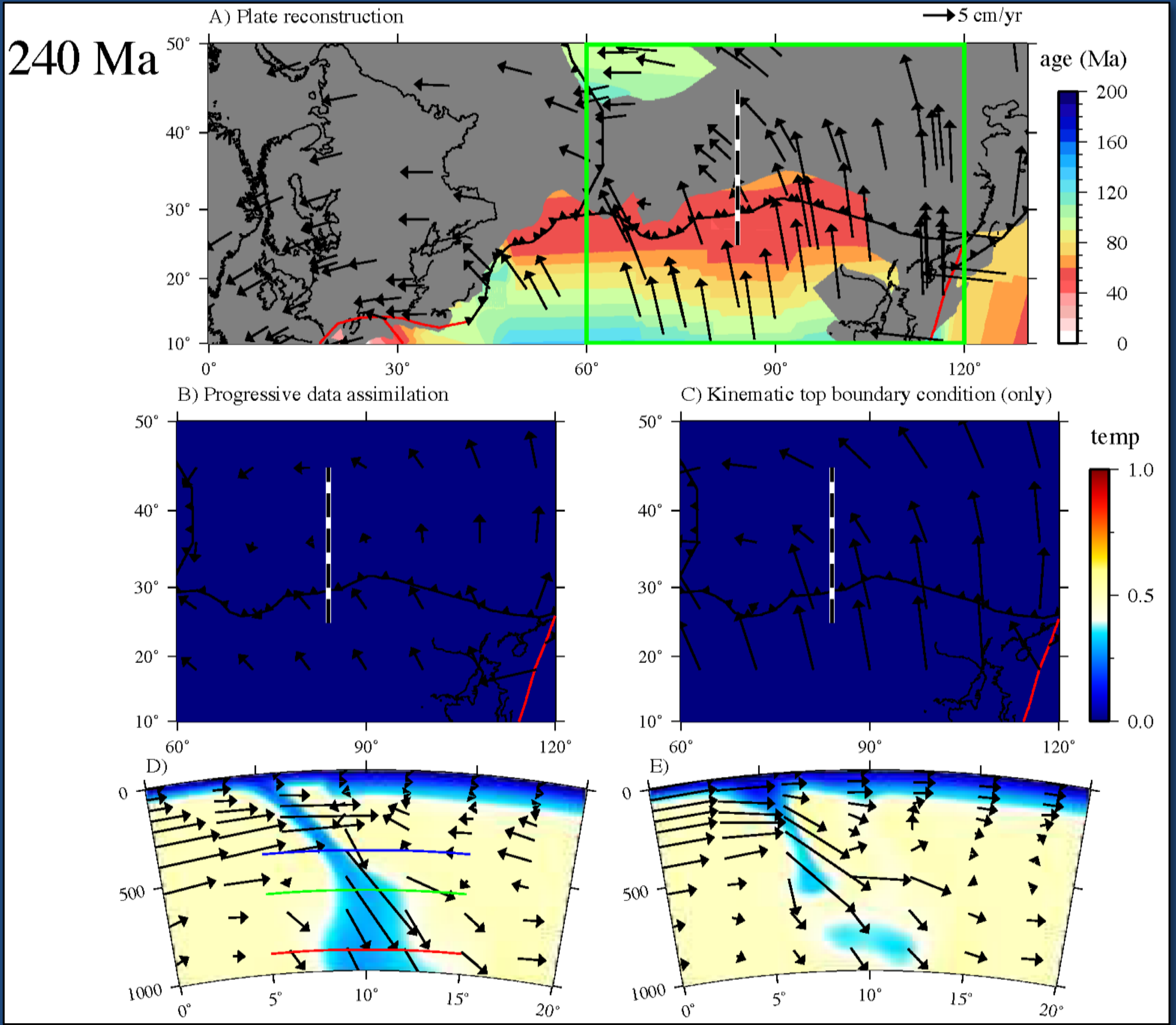


Bower et al. (2015)

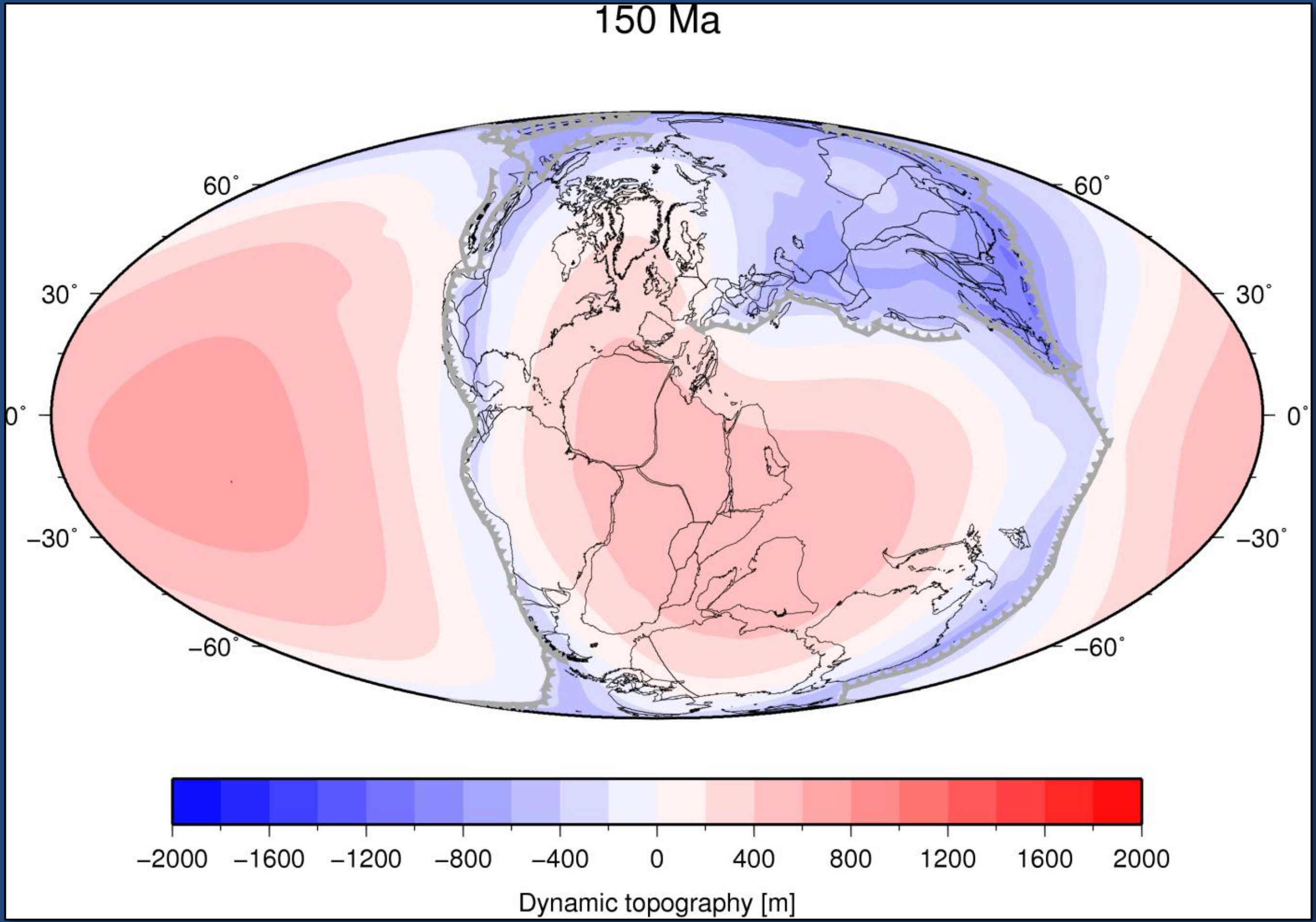
Progressive data assimilation



Bower et al. (2015)



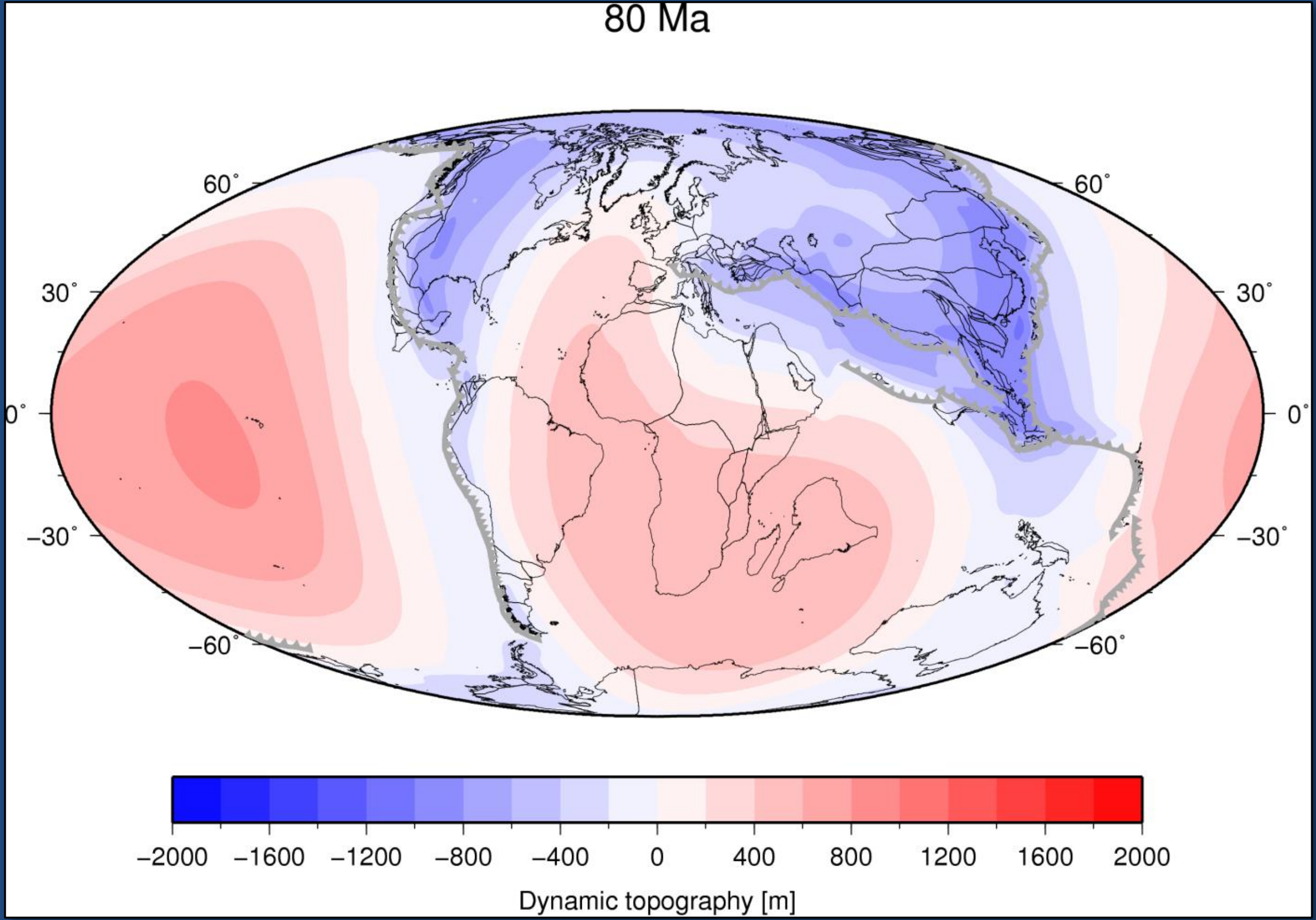
Evolution of global dynamic topography



Dynamic topography

- at the surface,
- from flow deeper than 350 km;
- free-slip boundary condition

Evolution of global dynamic topography



Dynamic topography

- at the surface,
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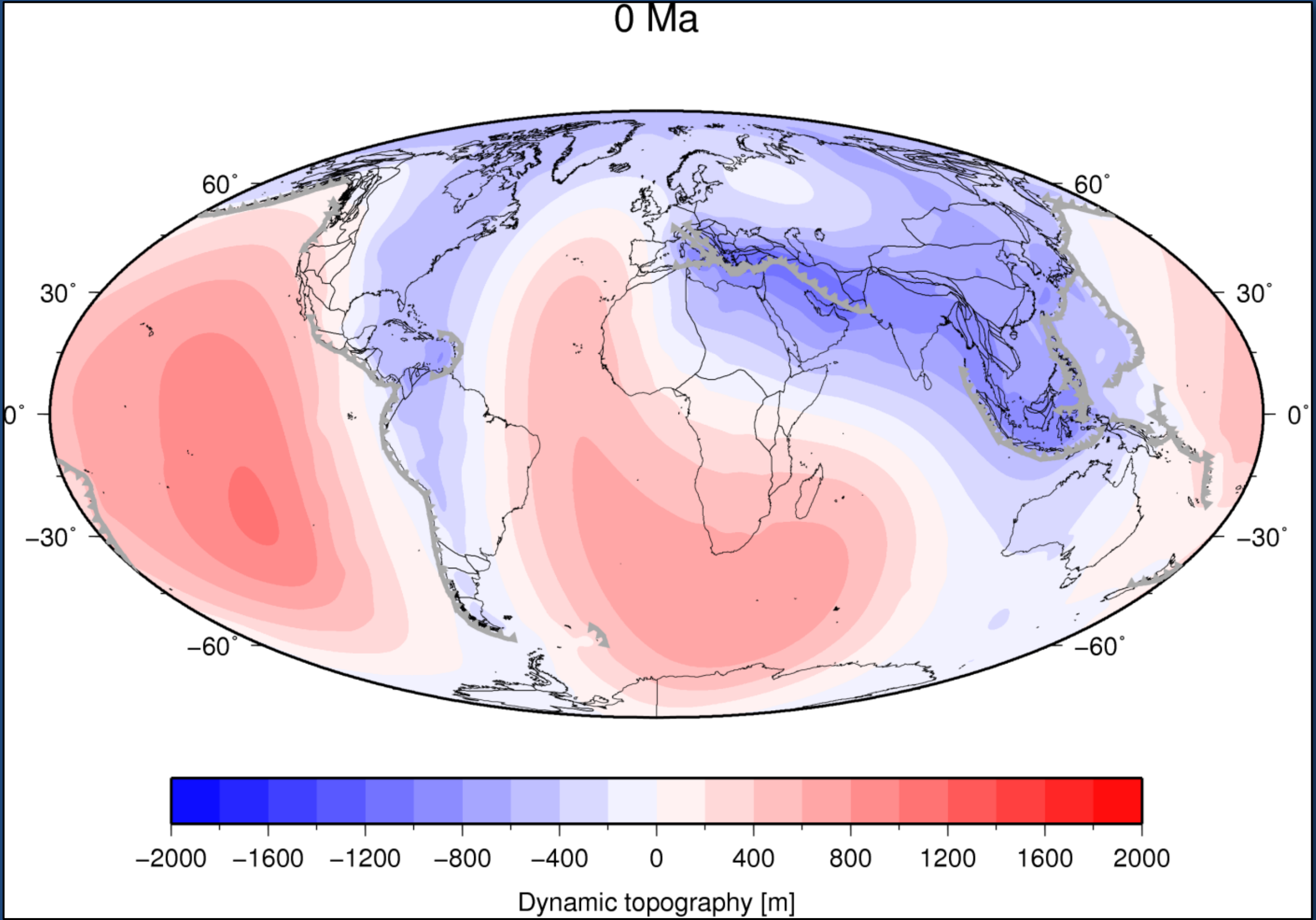
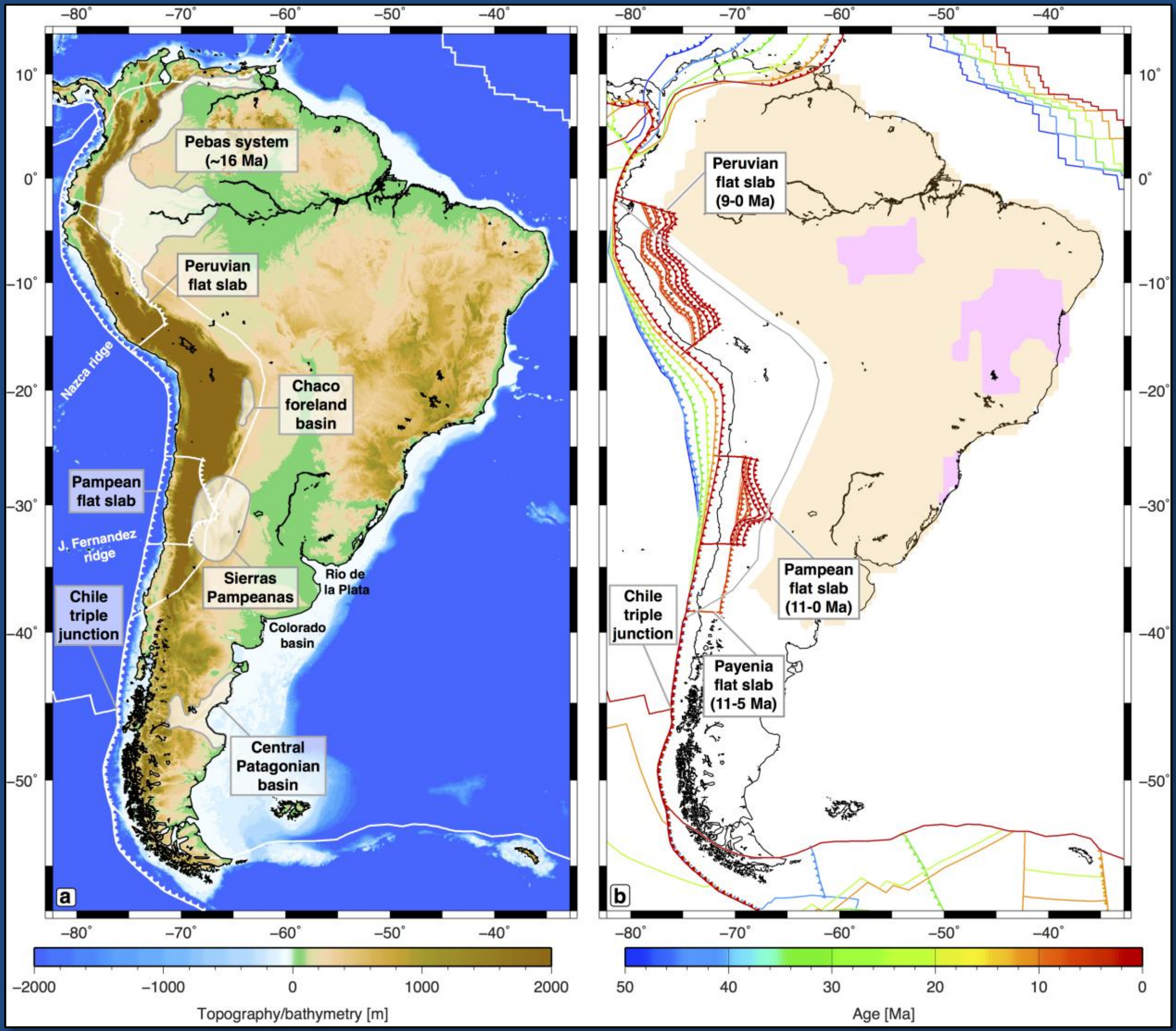
Evolution of global dynamic topography



Dynamic topography

- at the surface,
- from flow deeper than 350 km;
- free-slip boundary condition

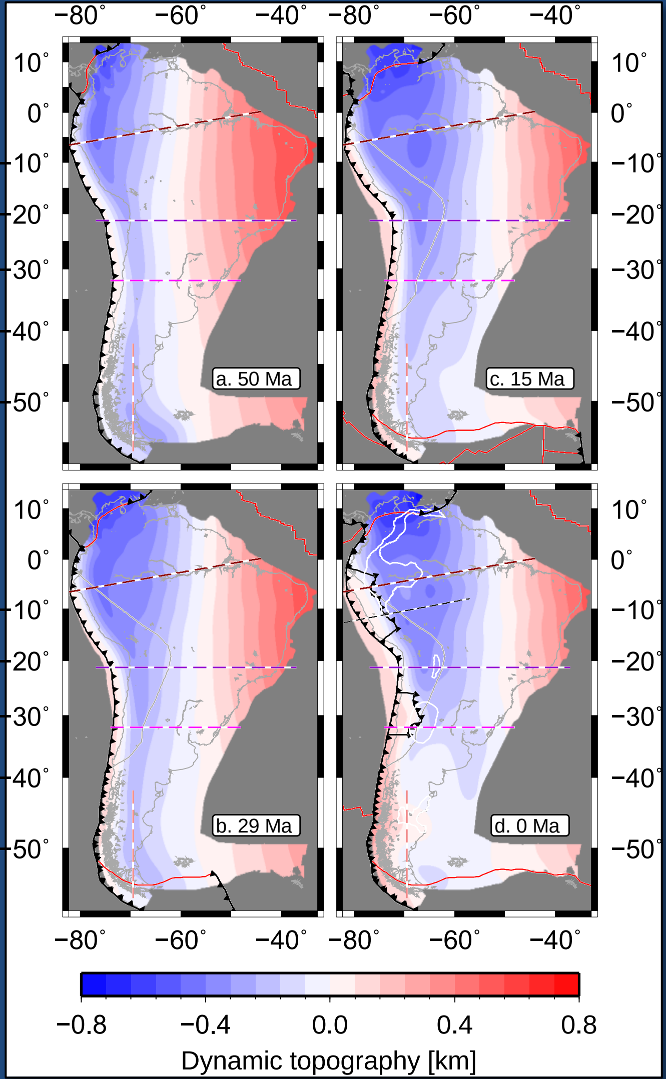
South American subduction history



- Andean deformation
  (Arriagada et al., 2008)
- Flat-slab subduction
  (e.g. Ramos & Folguera, 2009)

Flament et al. (2015)

Predicted South American dynamic topography



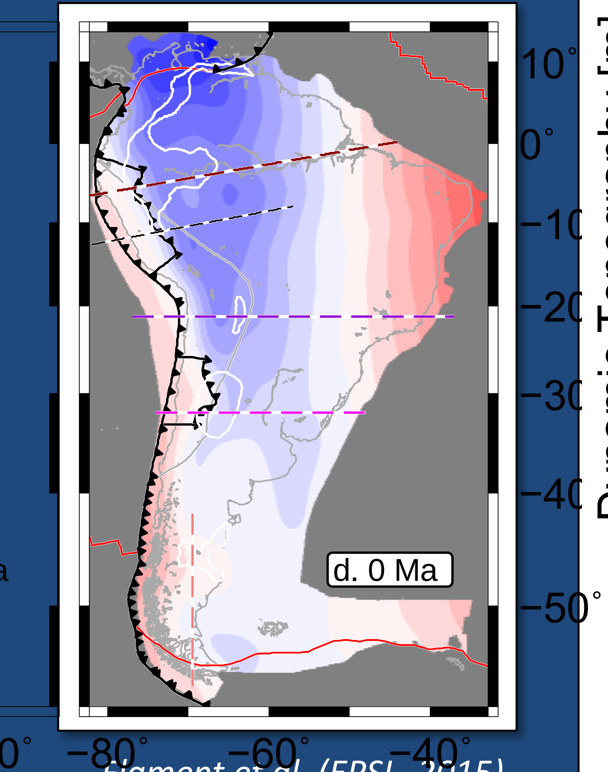
Eastward propagation of a dynamic topography low

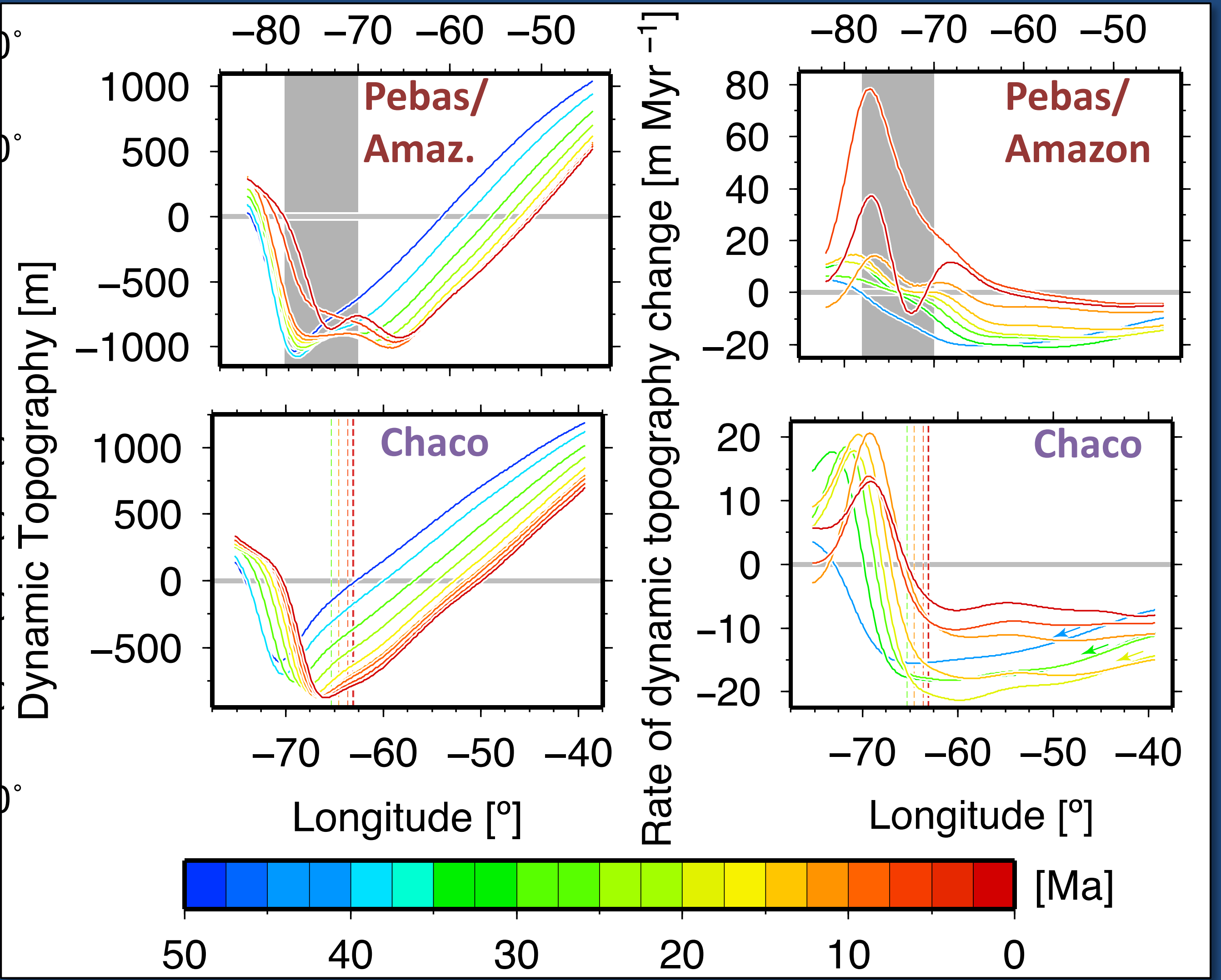
Effects of:

- Uplift associated with flat slabs
- Trench migration under the Central Andes

Flament et al. (EPSL, 2015)

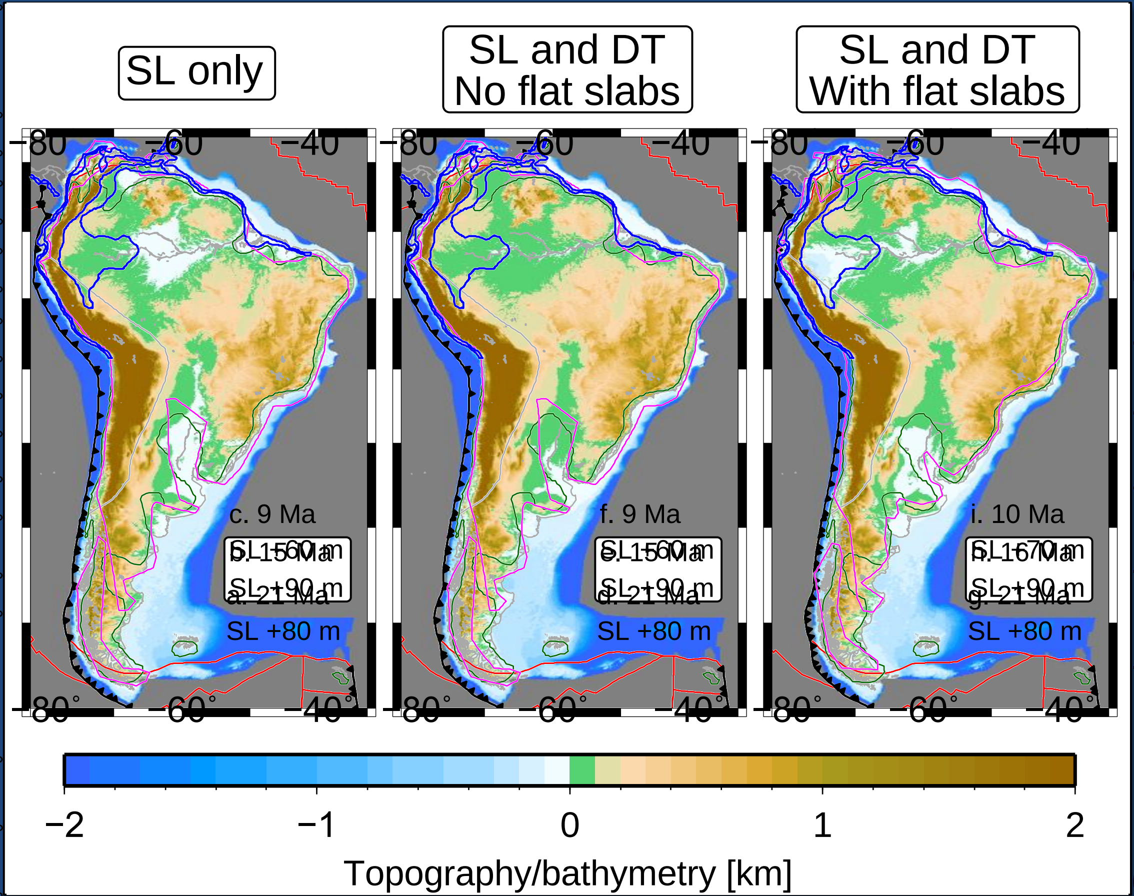
Predicted South American dynamic topography





Flament et al. (EPSL, 2015)

Predicted and "observed" Miocene South American flooding



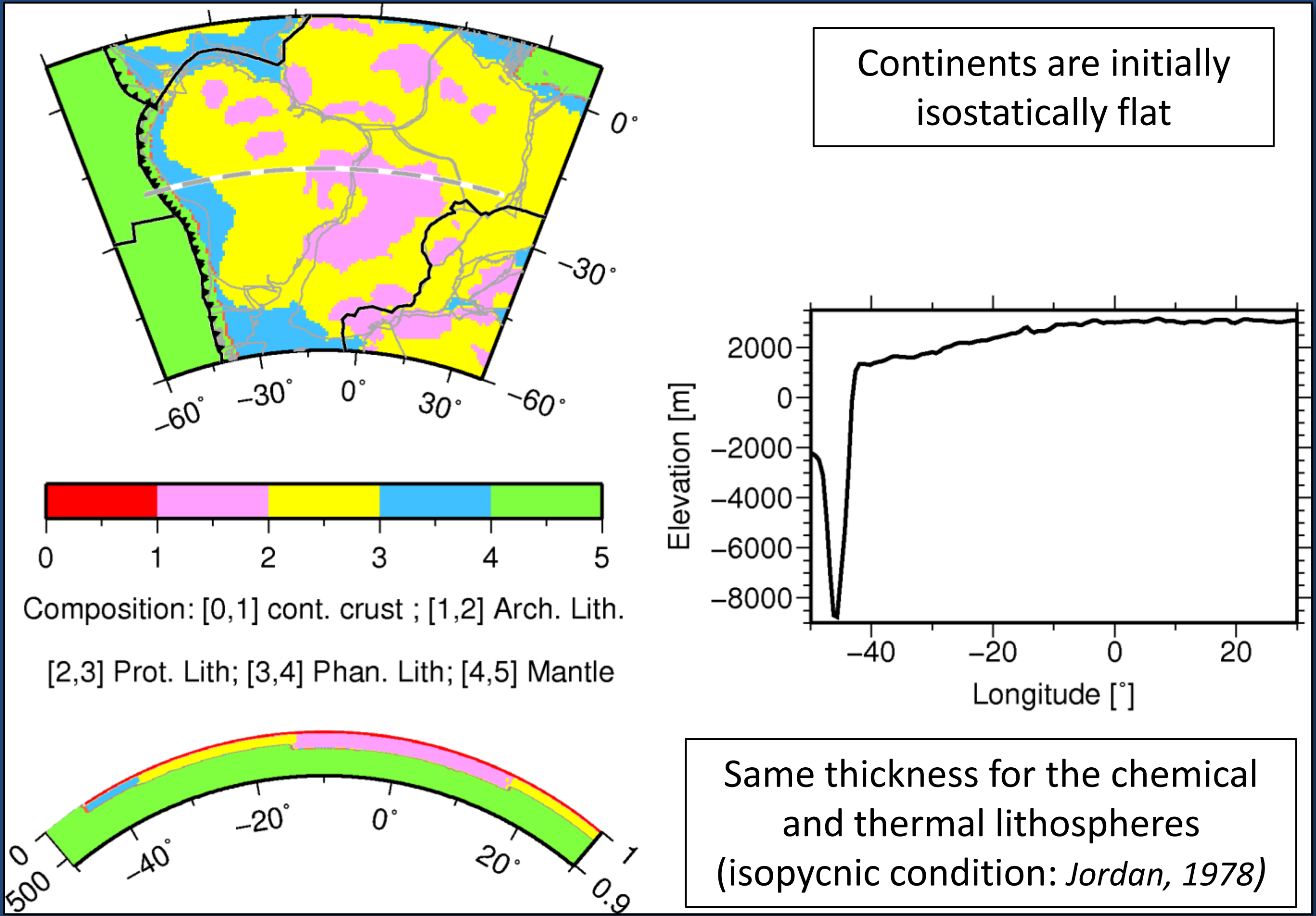
- Simple model paleogeography:
  - long-term sea level change *(Haq et al., 1987)*
  - changes in dynamic topography

- Paleoshorelines *(Smith et al., 2004; Golonka, 2009; Wesselingh et al., 2010)*

→ Both sea level change and flat slabs are required to match paleoshorelines

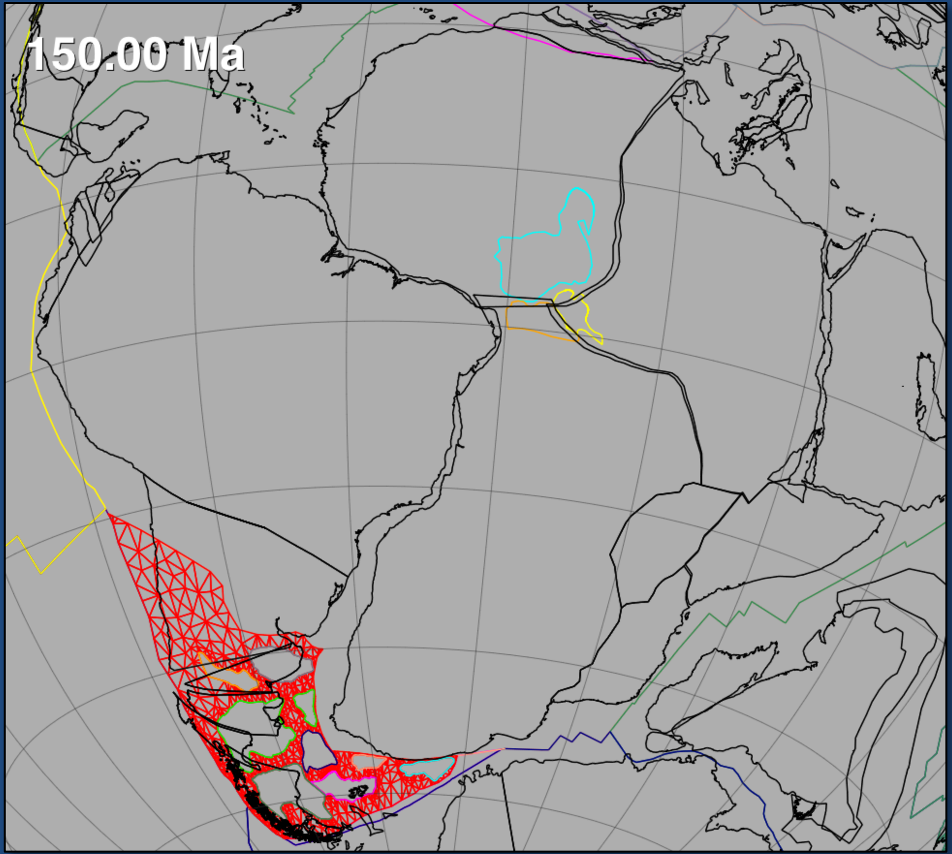
Flament et al. (EPSL, 2015)

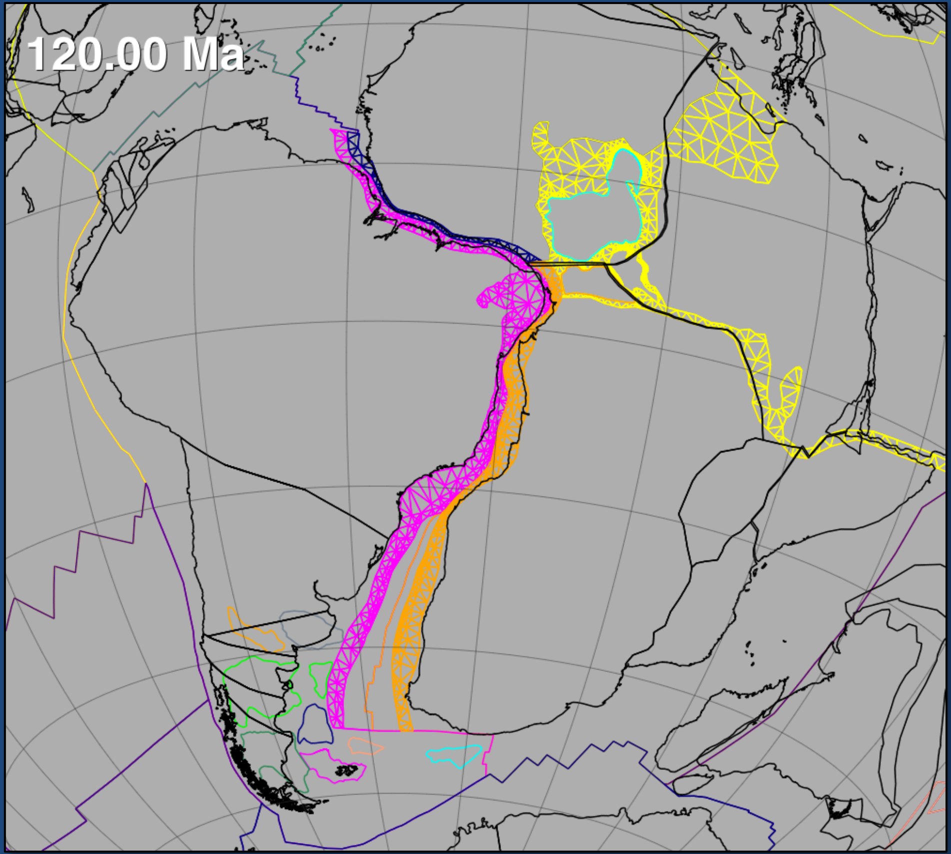
Modelling isostatic and dynamic topography



Flament et al. (2014)

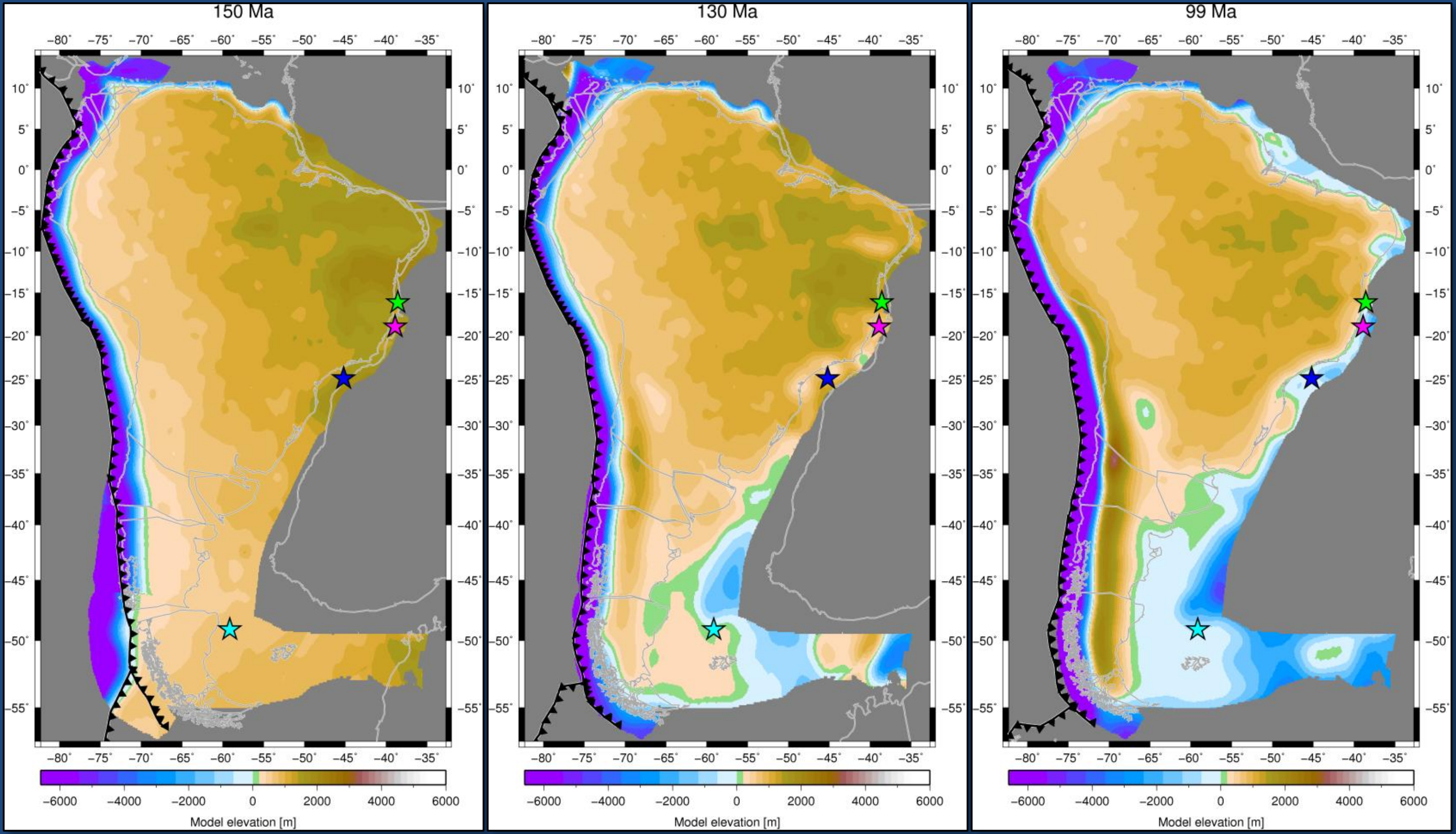
Reconstruction with deformation





Flament et al. (2014)

Evolution of South American *total model elevation*

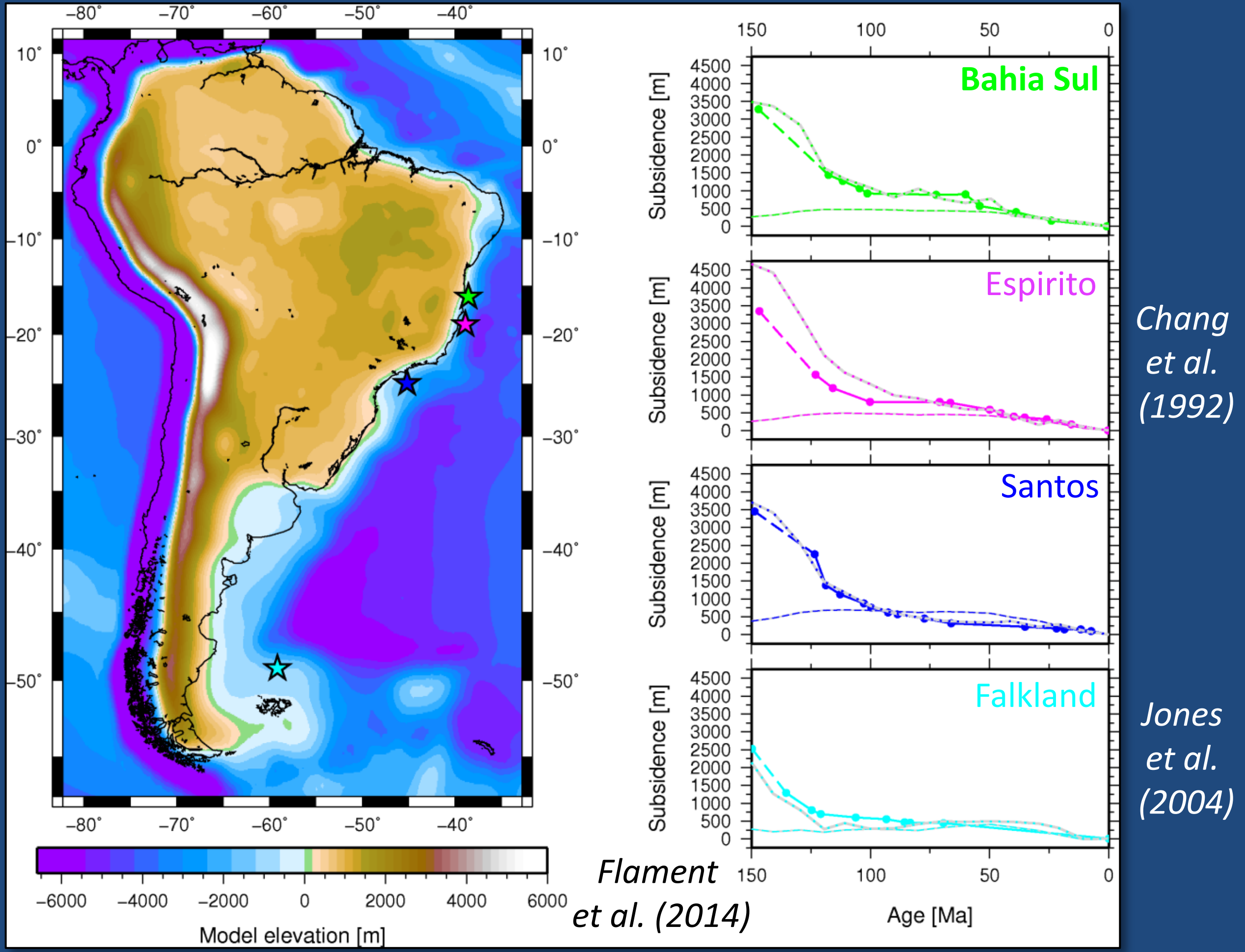


Bahia Sul Basin
Espirito Santo Basin
Santos Basin
Chang et al. (1992)

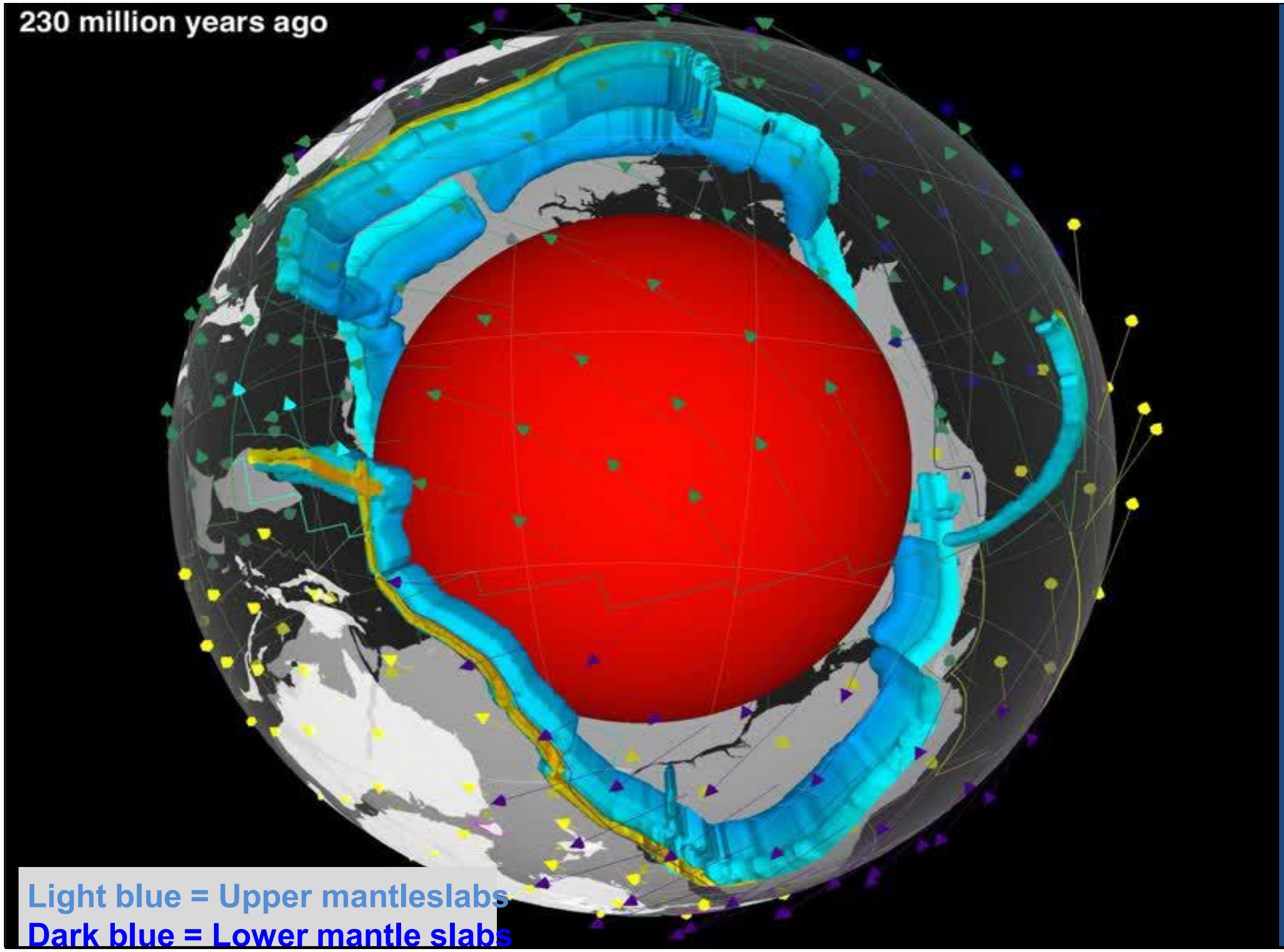
North Falkland Basin
Jones et al. (2004)

Flament et al. (2014)

Predicted and "observed" tectonic subsidence



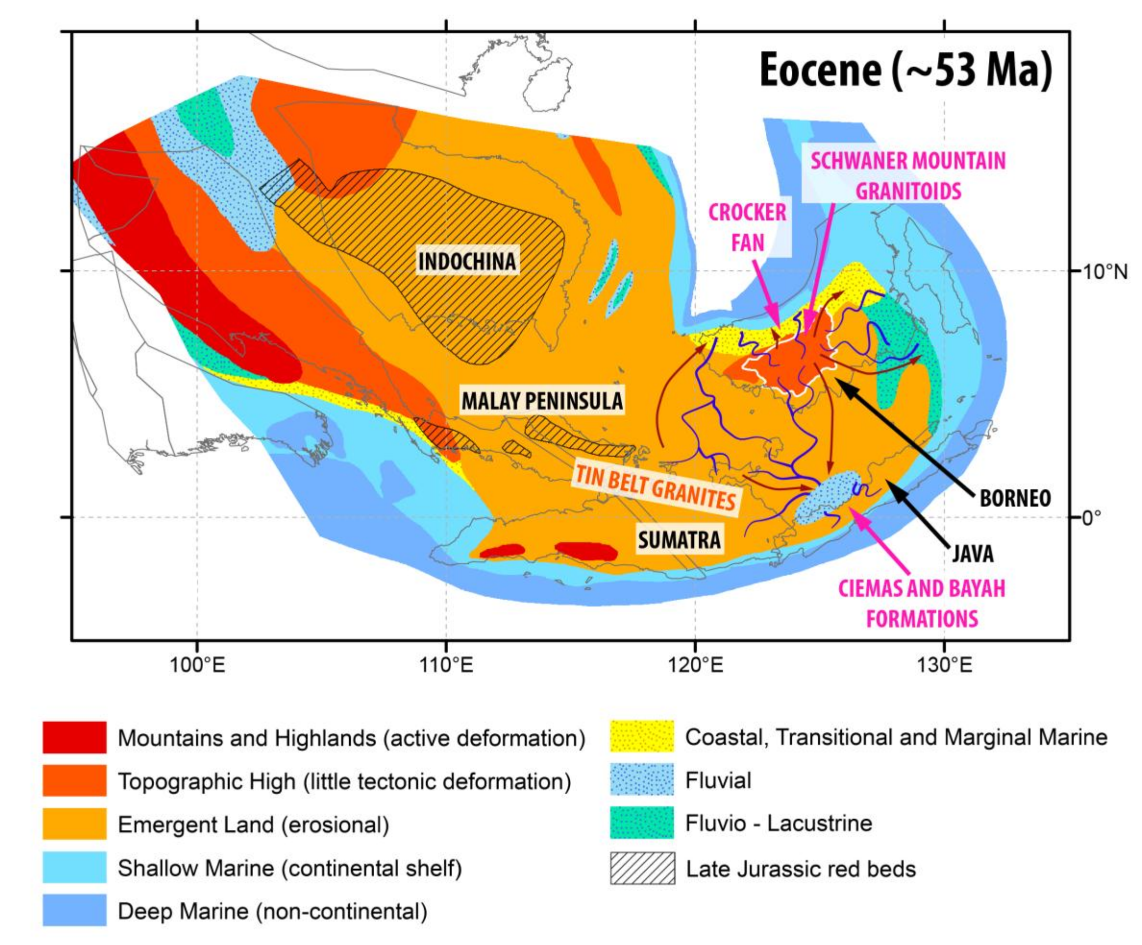
- Rift dynamics captured to first order: rift phase followed by thermal subsidence: essentially the model of *McKenzie (1978)* in 3D, time-dependent
- Accelerated tectonic subsidence since ~50 Ma corresponds to predicted dynamic subsidence



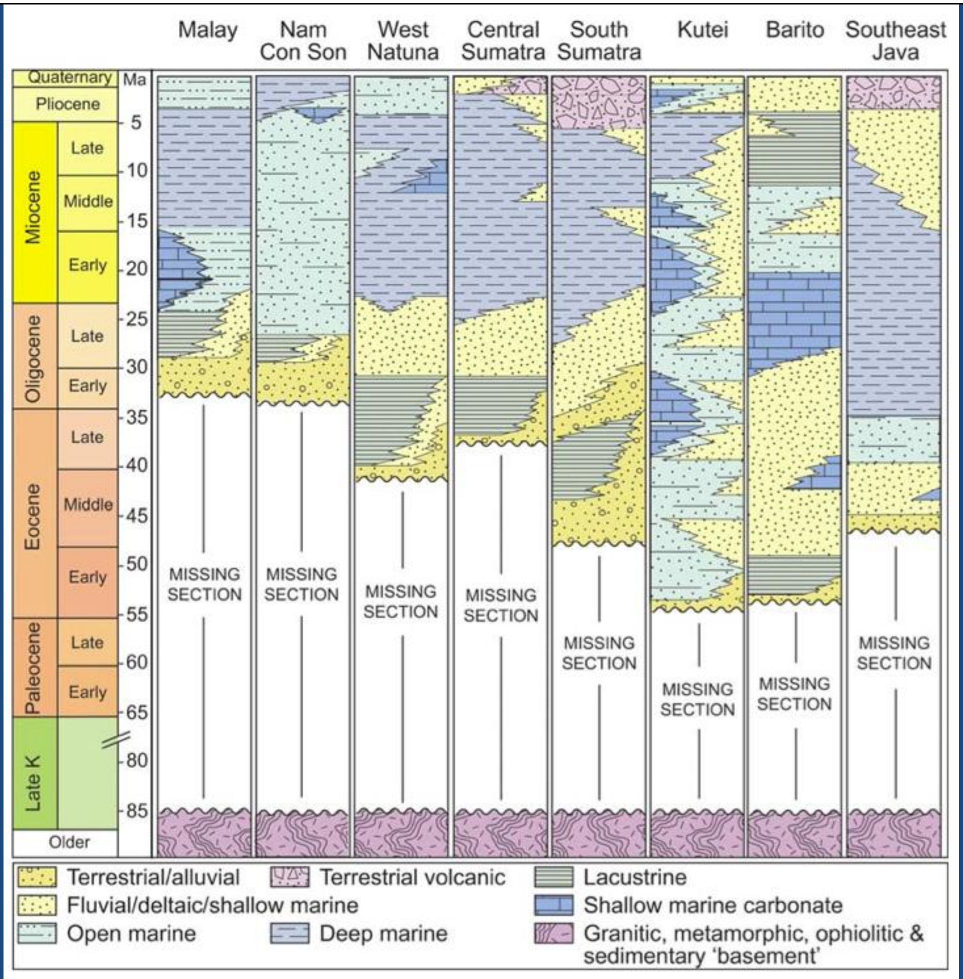
- Dynamic topography of SE Asia
- A complex, deforming region profoundly affected by subduction through time

Presenter's notes: Geodynamic simulation---We can then use these plate velocities to drive mantle convection in a global spherical mantle shell, allowing slabs to sink and interact in a more realistic manner. This allows us to track subducted material through time and then account for it at present day – as well as test alternative tectonic scenarios when the surface geology is vague. The first key here is the colours. Red represents upwelling hot mantle, and blue represents sinking slab material. Notice that New Guinea and SE Asia are overriding this 'slab burial ground', resulting in strong dynamic subsidence and flooding of these regions since ~30 Ma.

Late Cretaceous to Eocene Sundaland unconformity



- Missing sedimentary sections across wide region Late K to Eocene
- Regional unconformity
- Unlikely to be from “tectonic” topography or from flexure alone

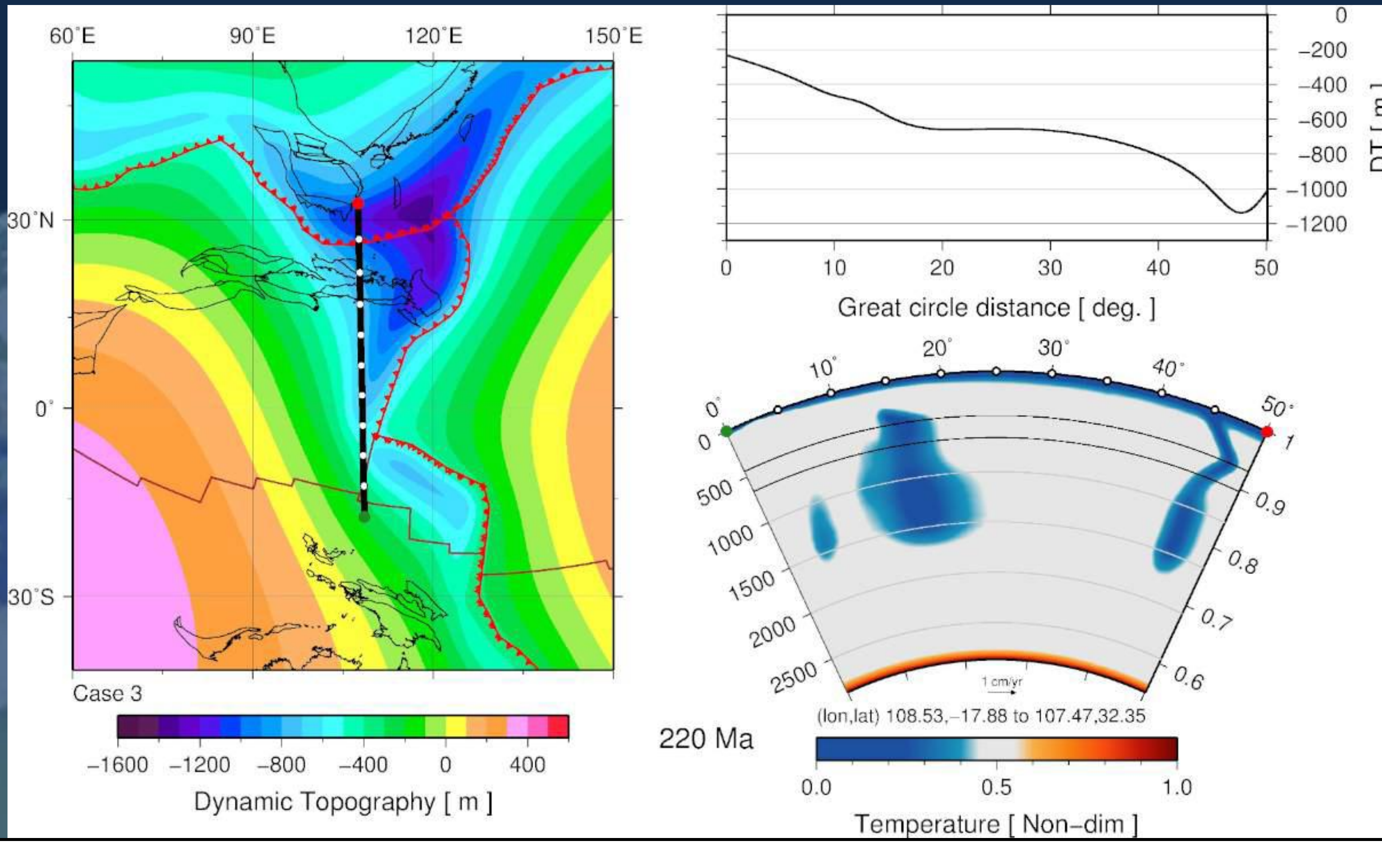


Regional unconformity, Clements et al. (2011)

Presenter's notes: Sundaland Case Study---Presented here is a case study of Sundaland emergence and subsequent flooding, which we argue is controlled largely by dynamic topography, which is topographic responses to mantle convection.

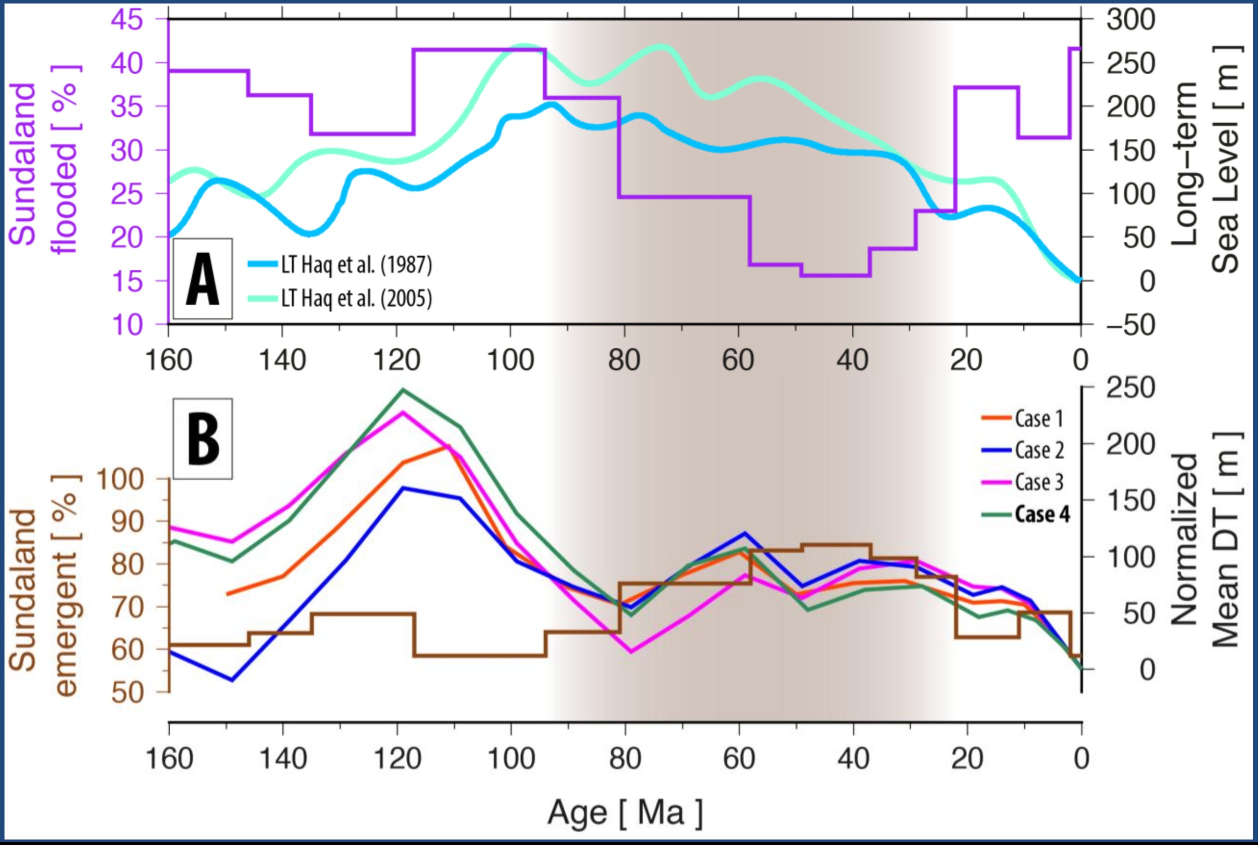
There is an enigmatic Late Cretaceous to Paleocene regional unconformity, and Clements et al. (2011) proposed that the accreted Gondwana fragments may have choked a subduction zone, resulting in dynamic uplift due to the absence of subduction. The emergence and flooding pattern is also supported by paleogeography.

Geodynamic model of dynamic topography



Presenter's notes: Dynamic Topography: We can then interrogate the geodynamic model, both vertical slices through the mantle, but also the surface dynamic topography. Here is a slice across Sumatra, showing the sinking slab material.

Dynamic topography and flooding/emergence



Presenter's notes: Results---What we find is that the eustatic sea level trends are anti-correlated to the flooding since ~30 Ma, where the falling sea level curve would suggest a tendency toward emergence. Instead, the pattern of emergence, resulting from a hiatus in subduction, and subsequent flooding since ~30 Ma from re-established subduction, suggests that dynamic topography had a dominant control on the flooding of Sundaland. We need to look at New Guinea in this context as well, as it seems it could provide the mechanism for widespread contemporaneous flooding and carbonate deposition since ~30 Ma (Oligocene times).

Conclusions

- Ability to jointly investigate mantle flow and crustal deformation over 100's and 1000's of km and 10's of Myr
- Direct comparison between predicted and observed tectonic subsidence/uplift
- **Exploration Geodynamics**: An emerging exploration tool

EarthByte | dietmar.muller@sydney.edu.au