Sea level and basin subsidence from global dynamic earth models

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In collaboration with
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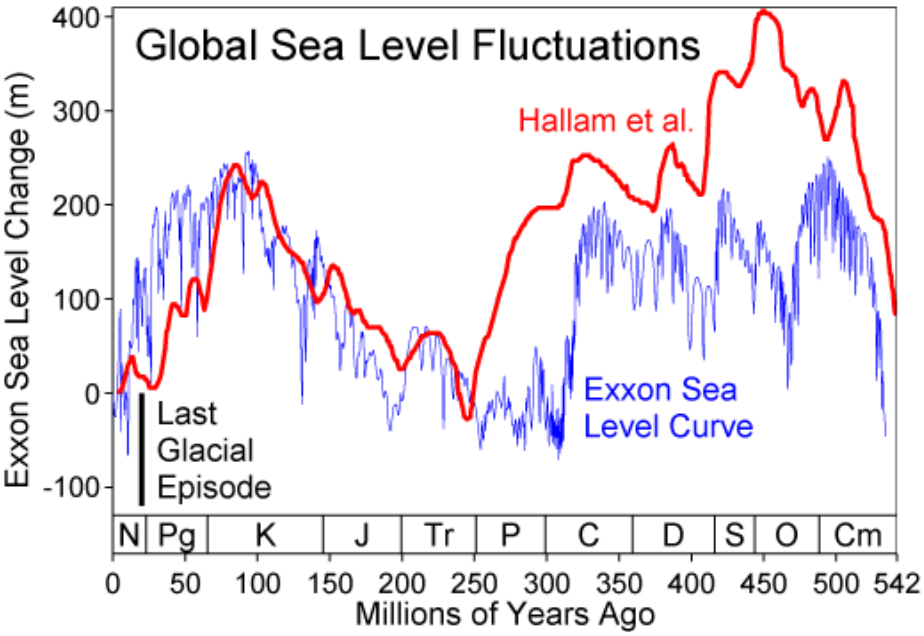
Mantle Convection Workshop, Aug., 2011

Note: Unpublished global models presented at meeting note in this slide pack.

Sea Level Change and Vertical Motions

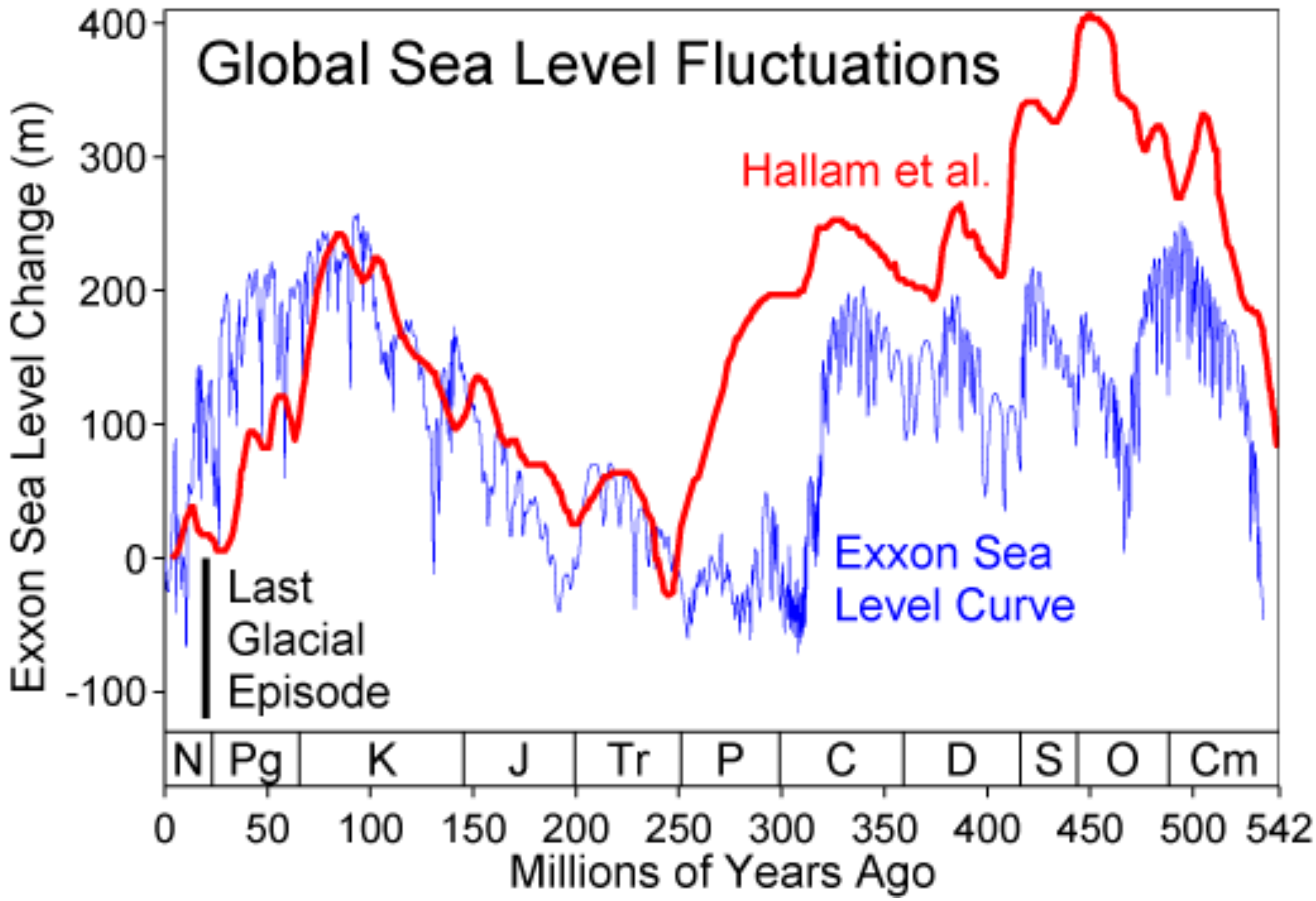
Western Interior Seaway: 80 Ma



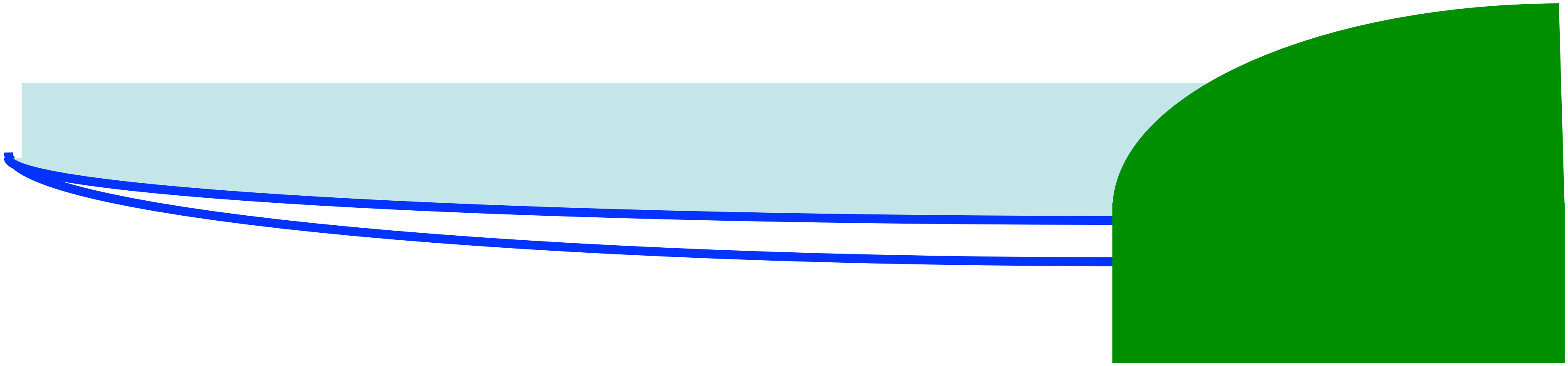
Outline

- Global Sea Level and general hypothesis
- Observational and theoretical limitations
- 4-D Dynamic earth models
- Regional applications
  - Australia
  - North America
  - Antarctica-New Zealand
- Simultaneous prediction of global and relative sea levels

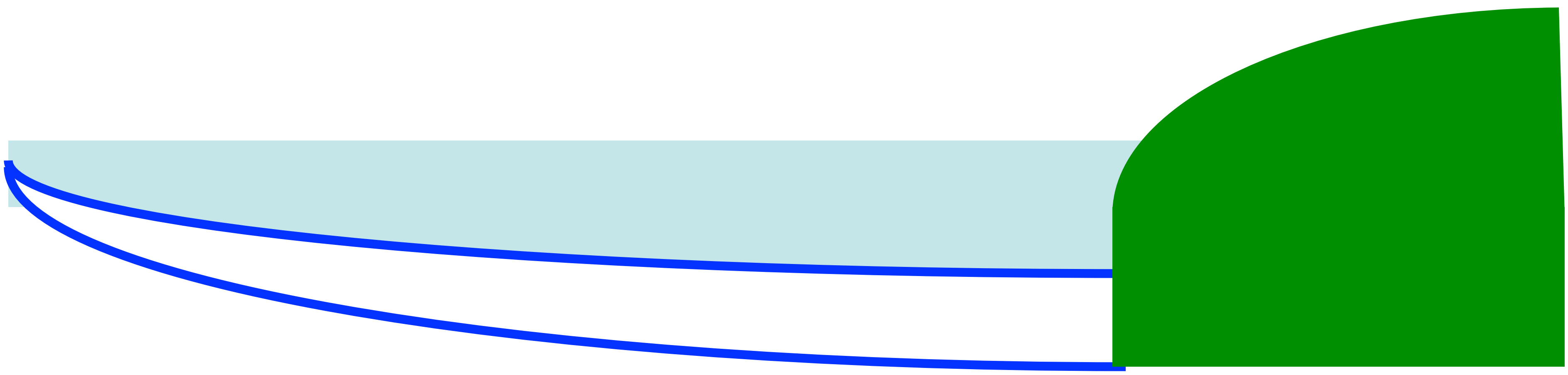
Sea Level Change and Vertical Motions



Carrying capacity of the ocean basins – ‘Pitman hypothesis’

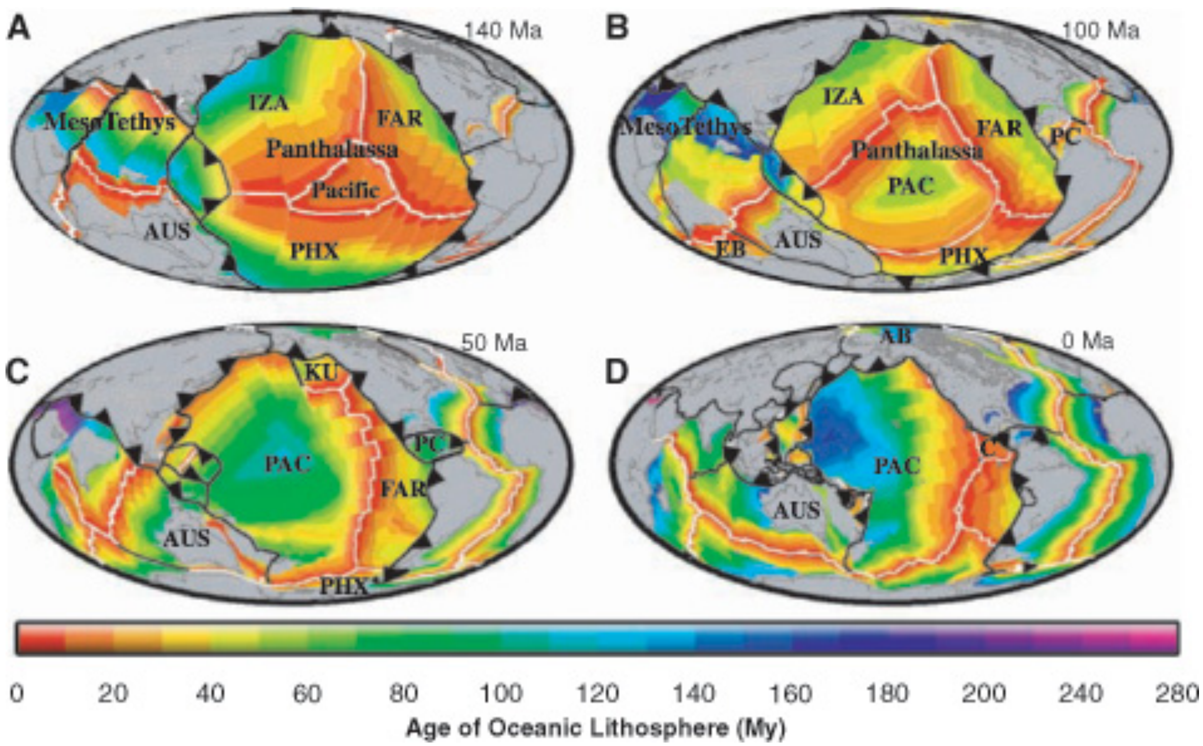


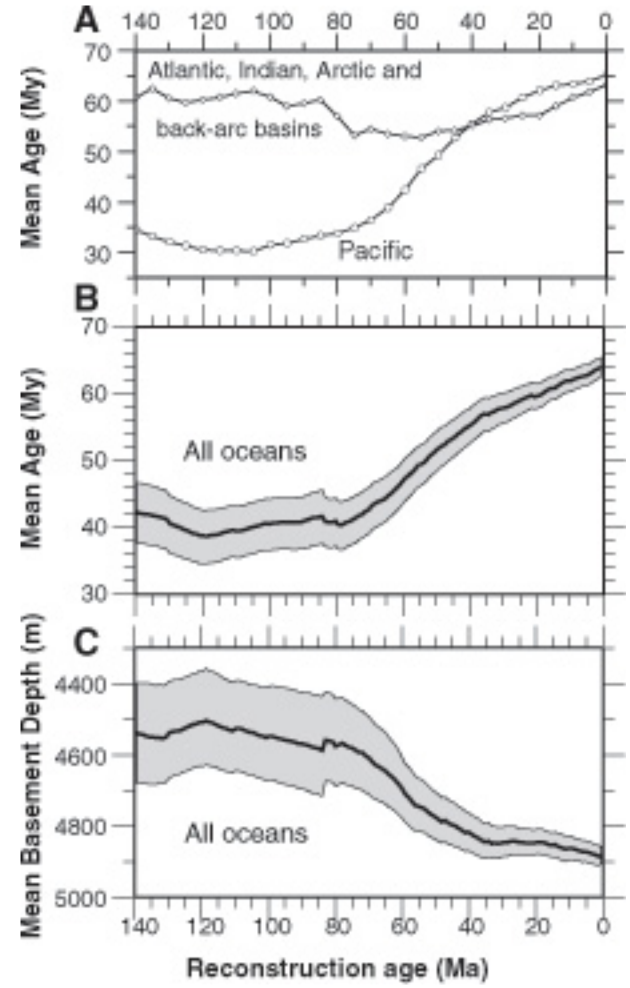
Carrying capacity of the ocean basins – ‘Pitman hypothesis’



- Change in spreading rates
- Change in length of ridges
- Formation of ‘Atlantic’ basin
- Change in the age distribution of the sea floor

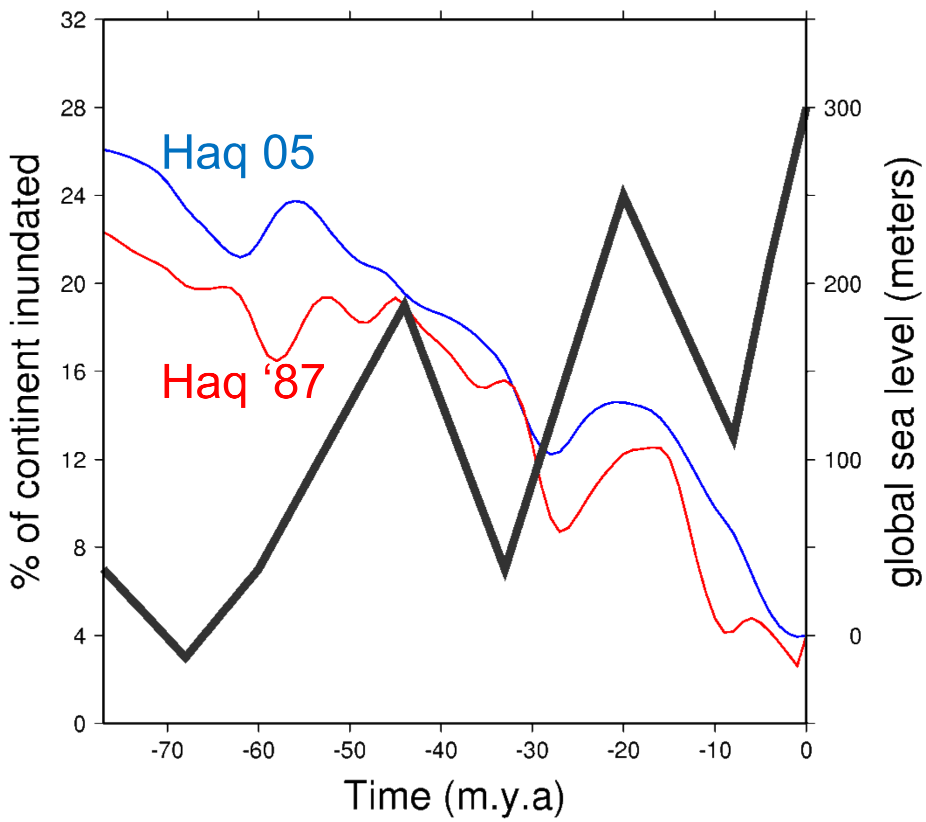
Changes in Ocean Basin Volume





Müller et al. [2008]

Sea level and Australian continental inundation

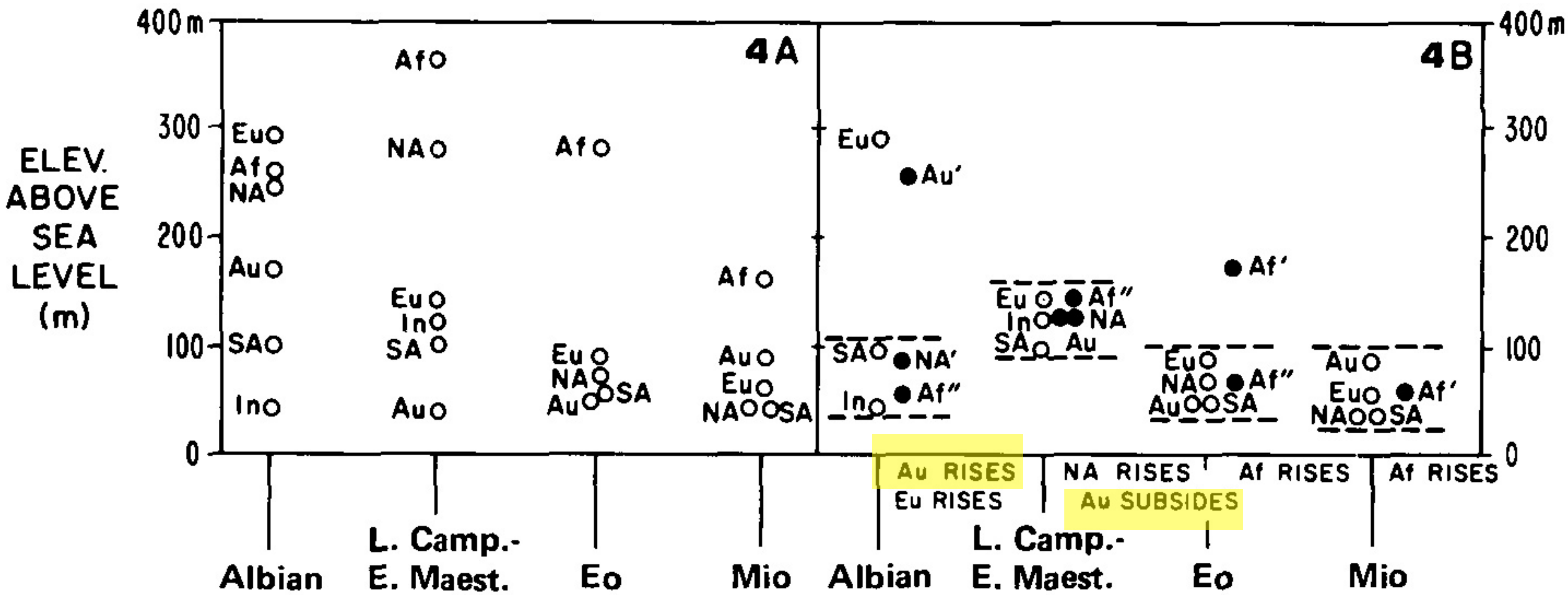


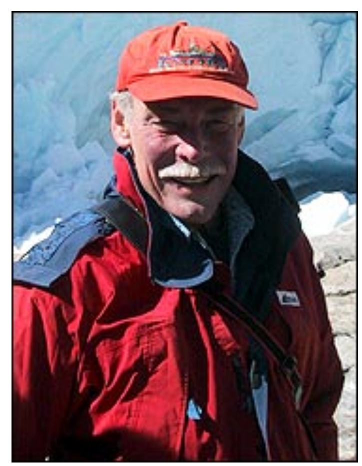
Signal

Global sea level decreases during and the since the Late Cretaceous.

The Australian continent becomes more inundated

Continental Epeirogeny and Eustasy

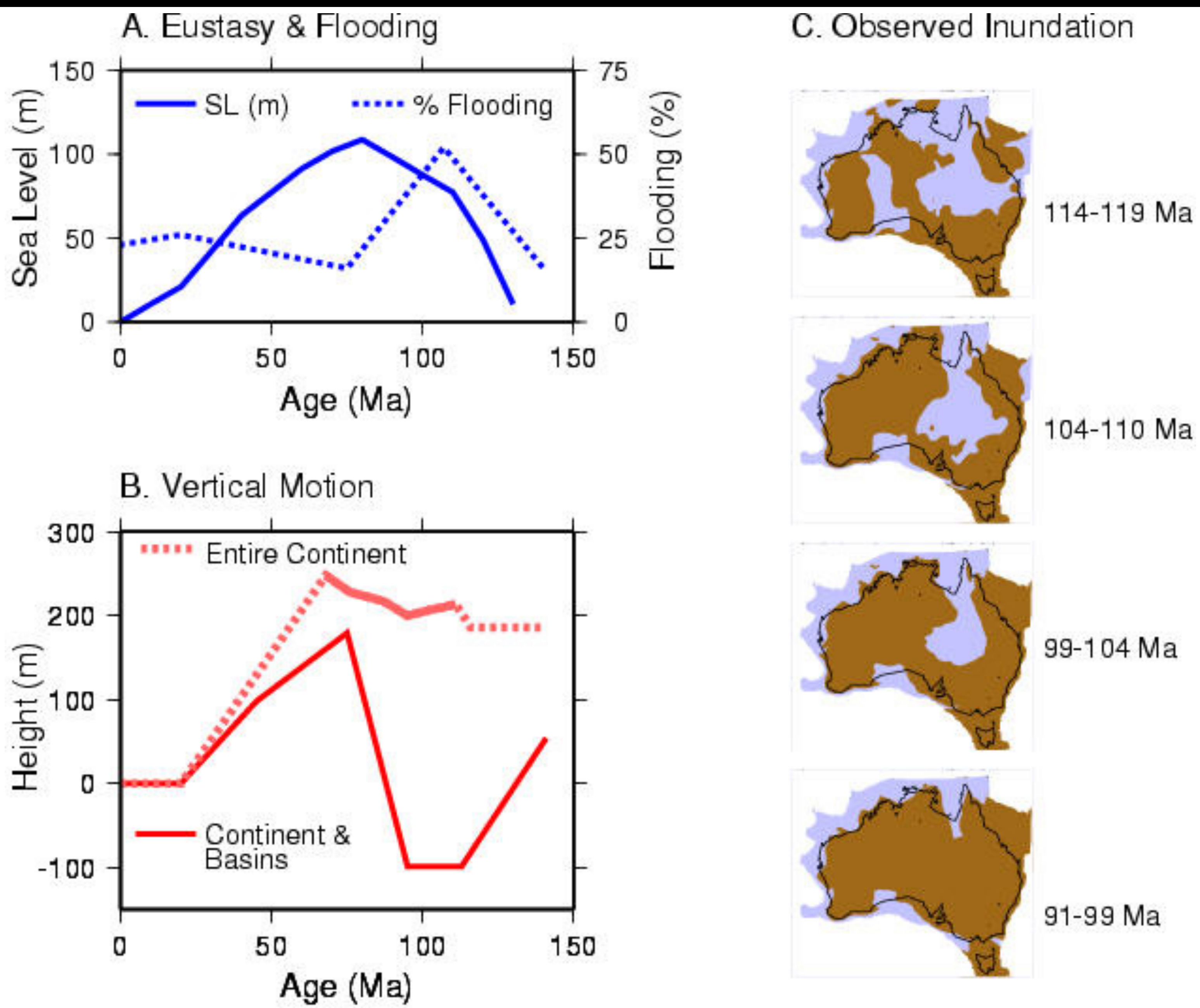




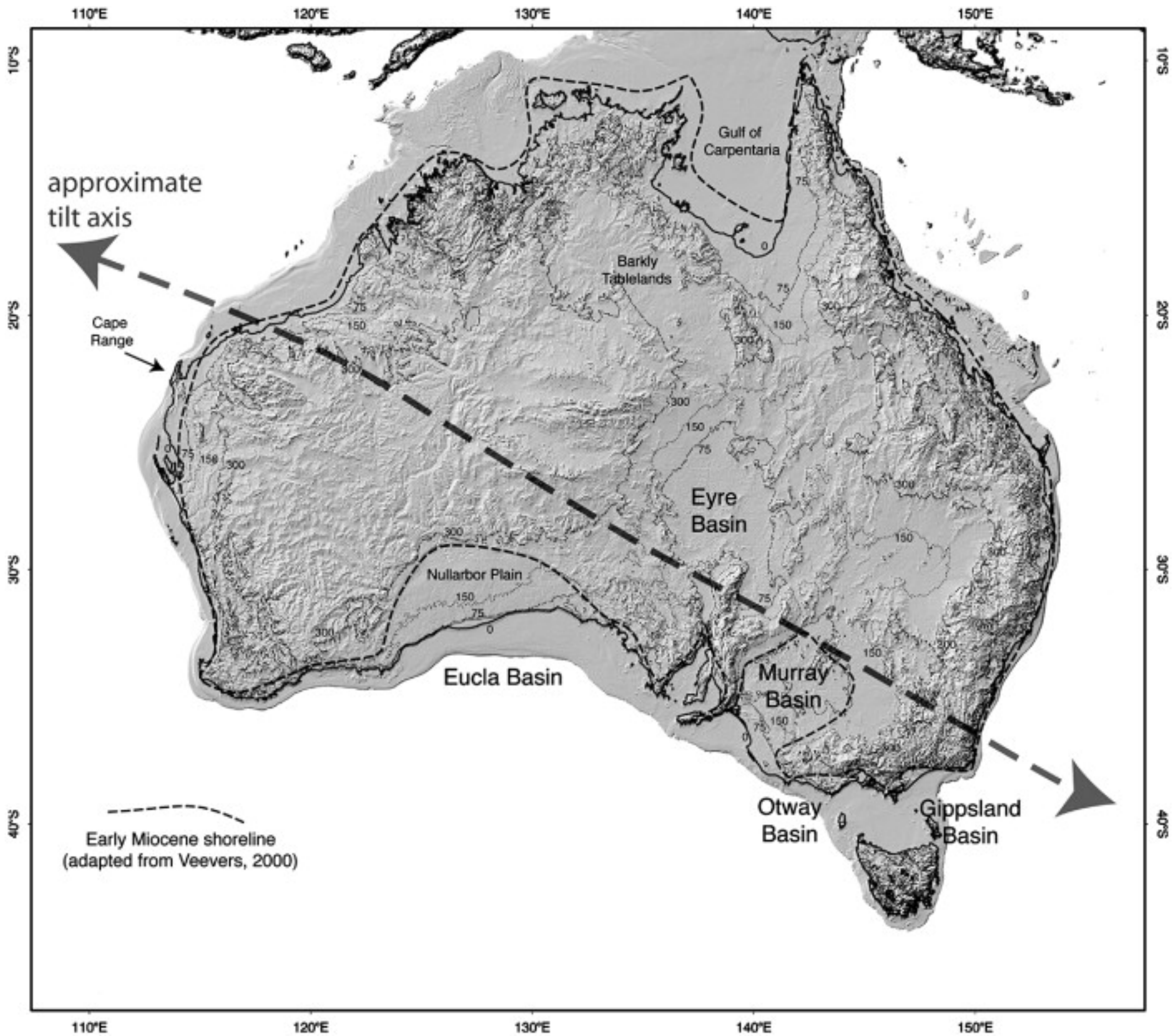
Gerard Bond, 1940-2005

Bond [1978]

Two scales of Australian Vertical Motions



Miocene Tilting



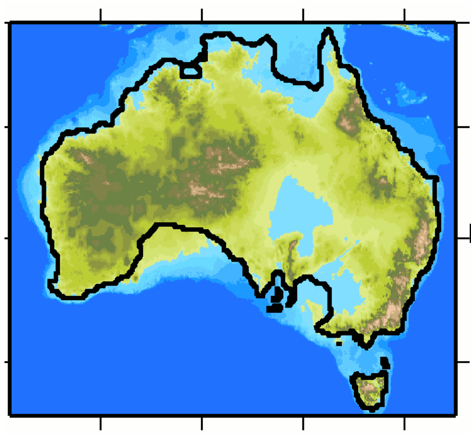
Sandiford [2007]

Best fitting tiltings

1. Remove sediment from the continent and then inundated with the global sea level.

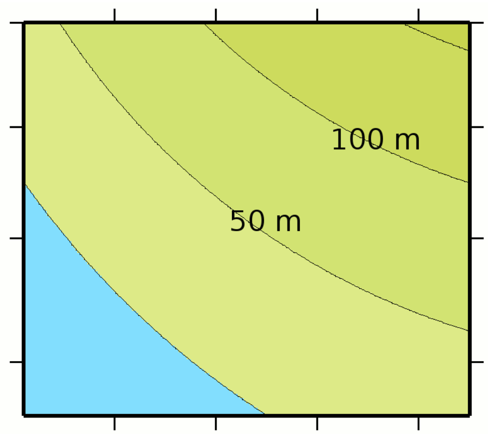
2. We reduce the mismatch between the expected coastline and the observed coastline by tilting the continent.

3. Adding the planar surface to the expected topography gives our resultant topography.



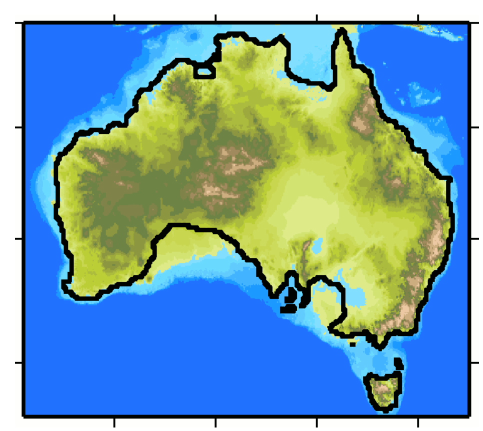
1. Expected Australian topography (Miocene)

+



2. Best fitting planar surface

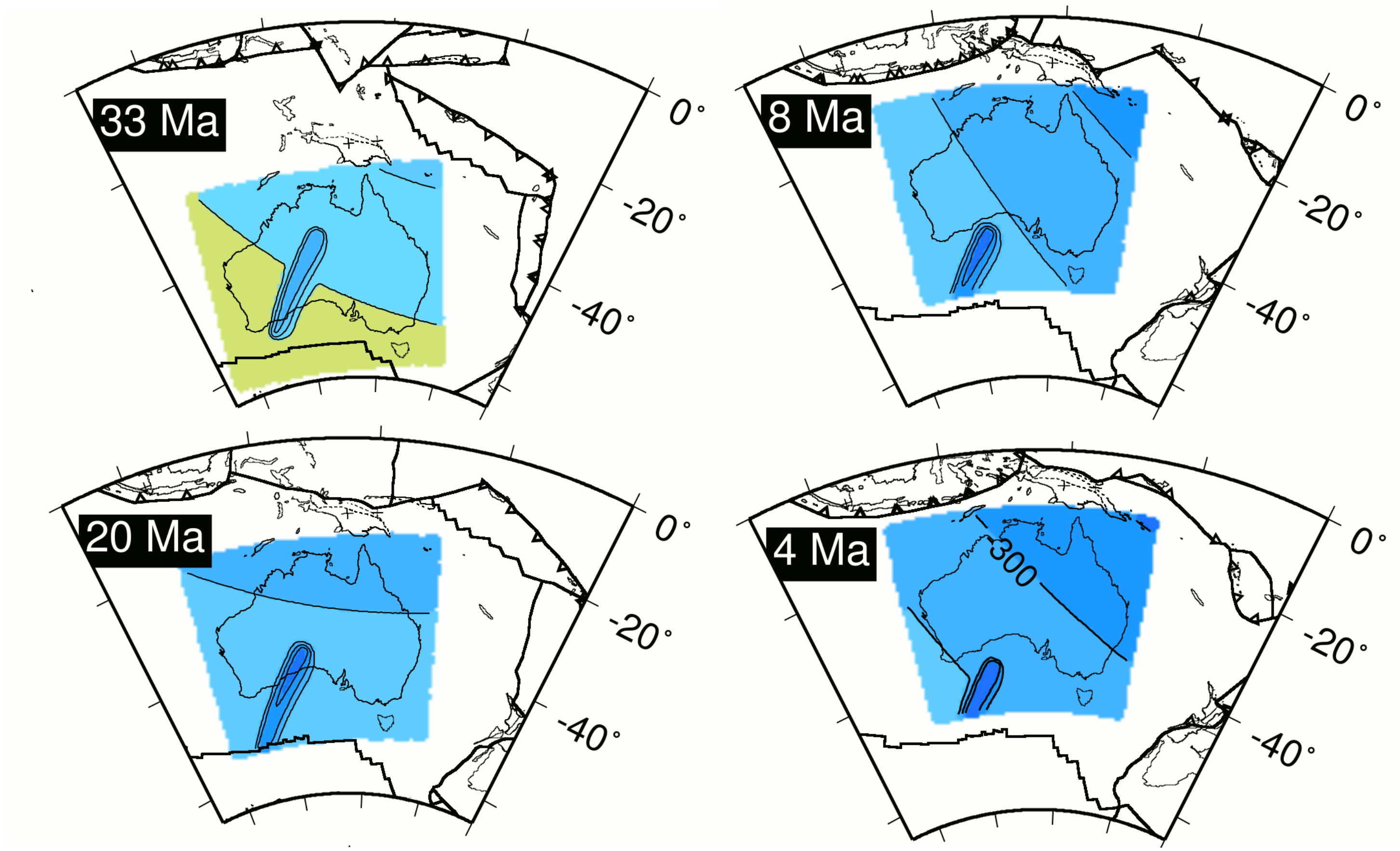
=



3. Resultant topography

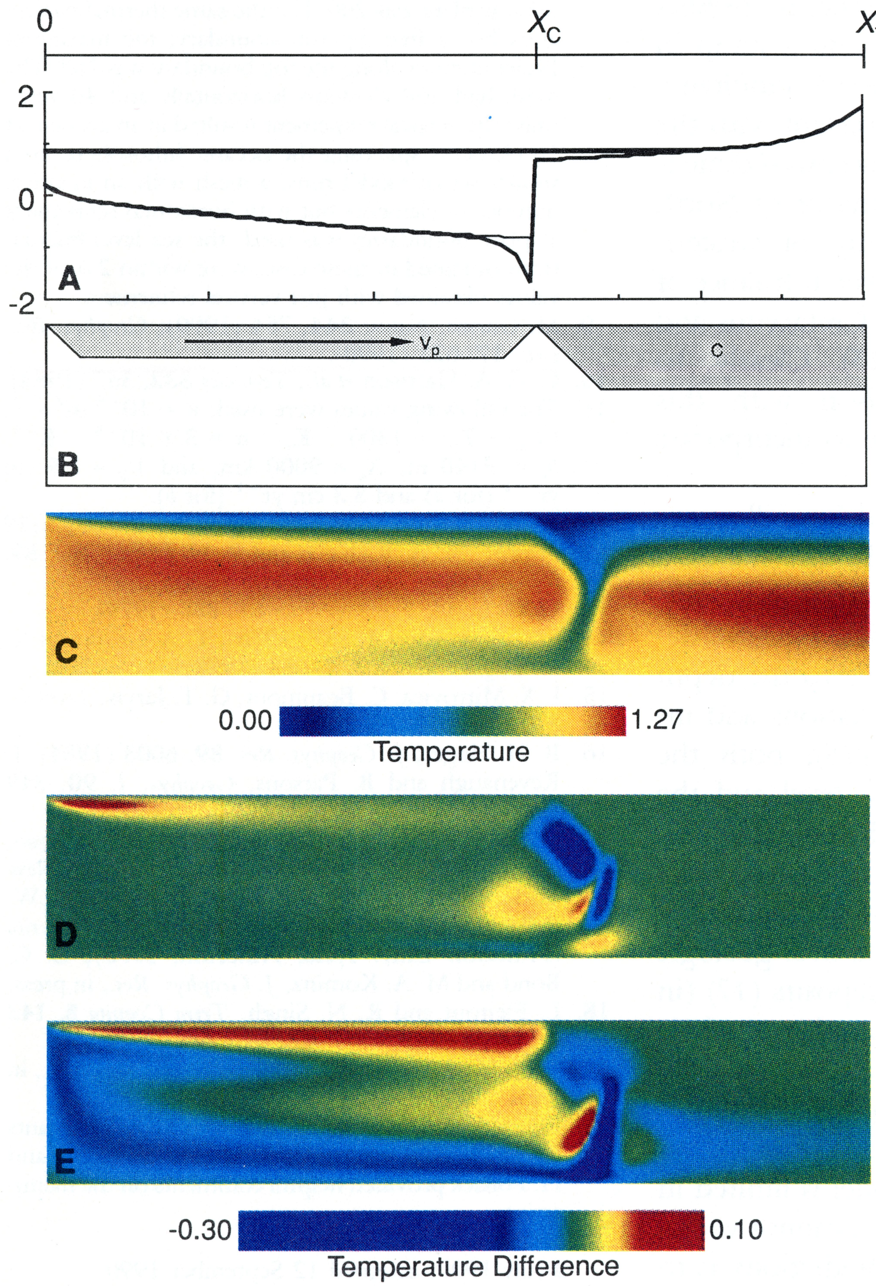
DiCaprio et al. [2009]

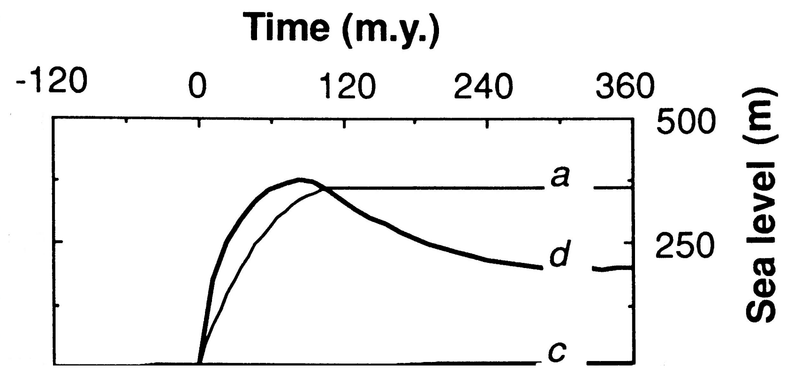
Long & short wavelength vertical motions



DiCaprio et al. [2009]

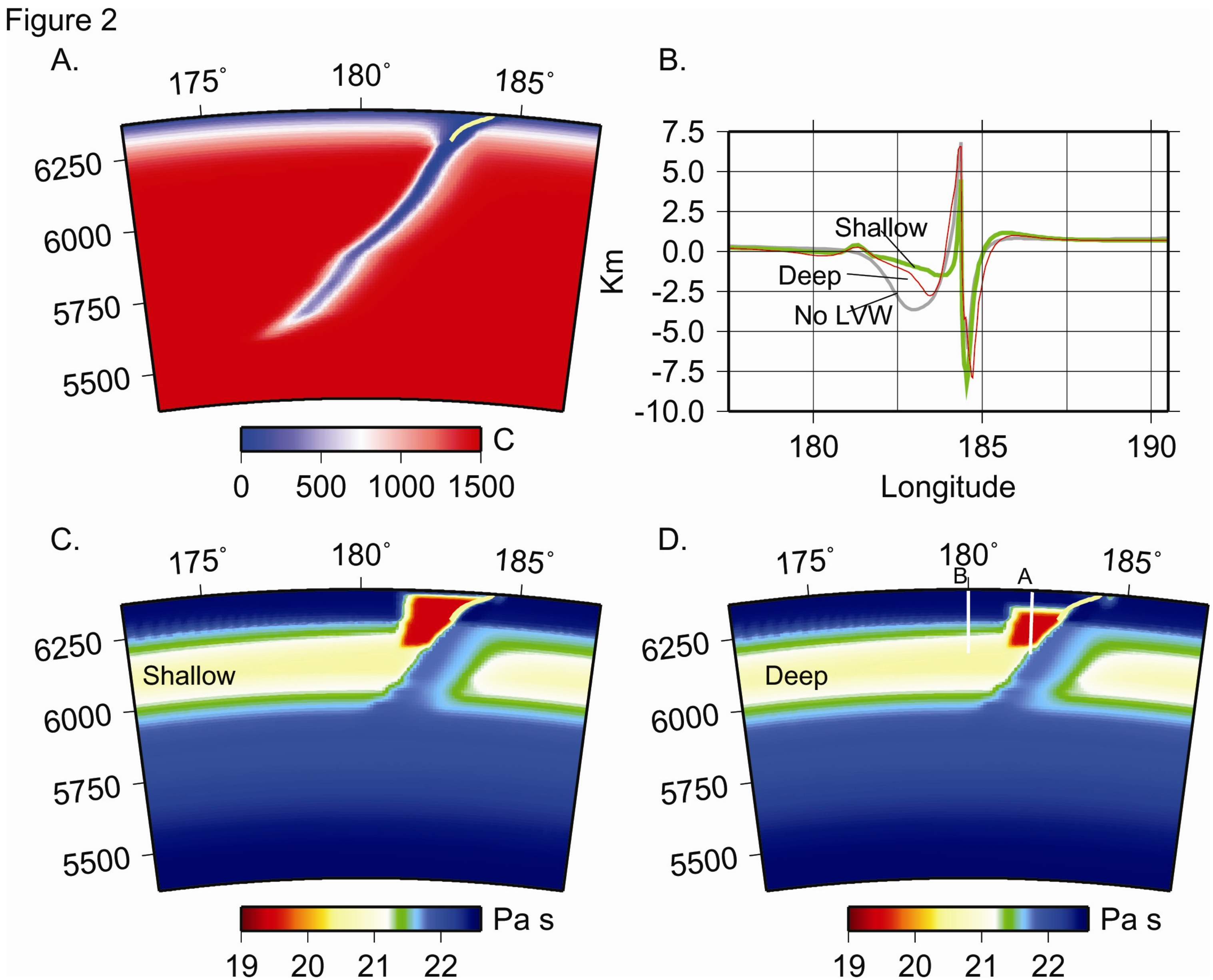
Sea level, ocean basins & conservation of mass





Gurnis [1990]

Lateral viscosity variations have a large effect on topography and geoid



Billen & Gurnis [2001]

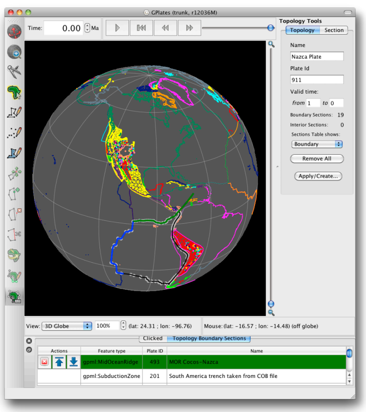
Software elements for 4D Dynamic Earth Models

Data Construction, Assimilation, and computation

Data Construction

Computation

'Paleogeography'



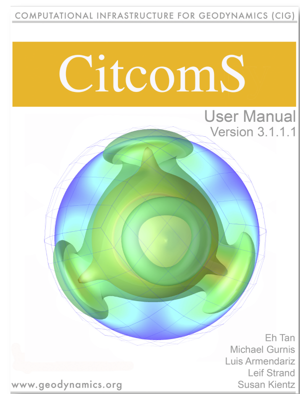
GPlates

Prep. For assimilation

```
gplates_citcoms_utils
```

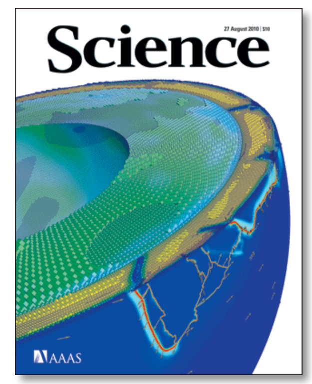
Python Framework

4-D Moderate resolution



CitcomS

3-D High resolution



Rhea

Equations of Mantle Convection and Plate Motions

$$\frac{\partial T}{\partial t} + u \cdot \nabla T - \nabla^2 T = \gamma$$

$$\nabla \cdot \left[\eta(T,p,u)\left(\nabla u + \nabla^T u\right) \right] - \nabla p = -RaTe_r$$

$$\nabla \cdot u = 0$$

Variables

T temperature

u velocity

p pressure

Parameters

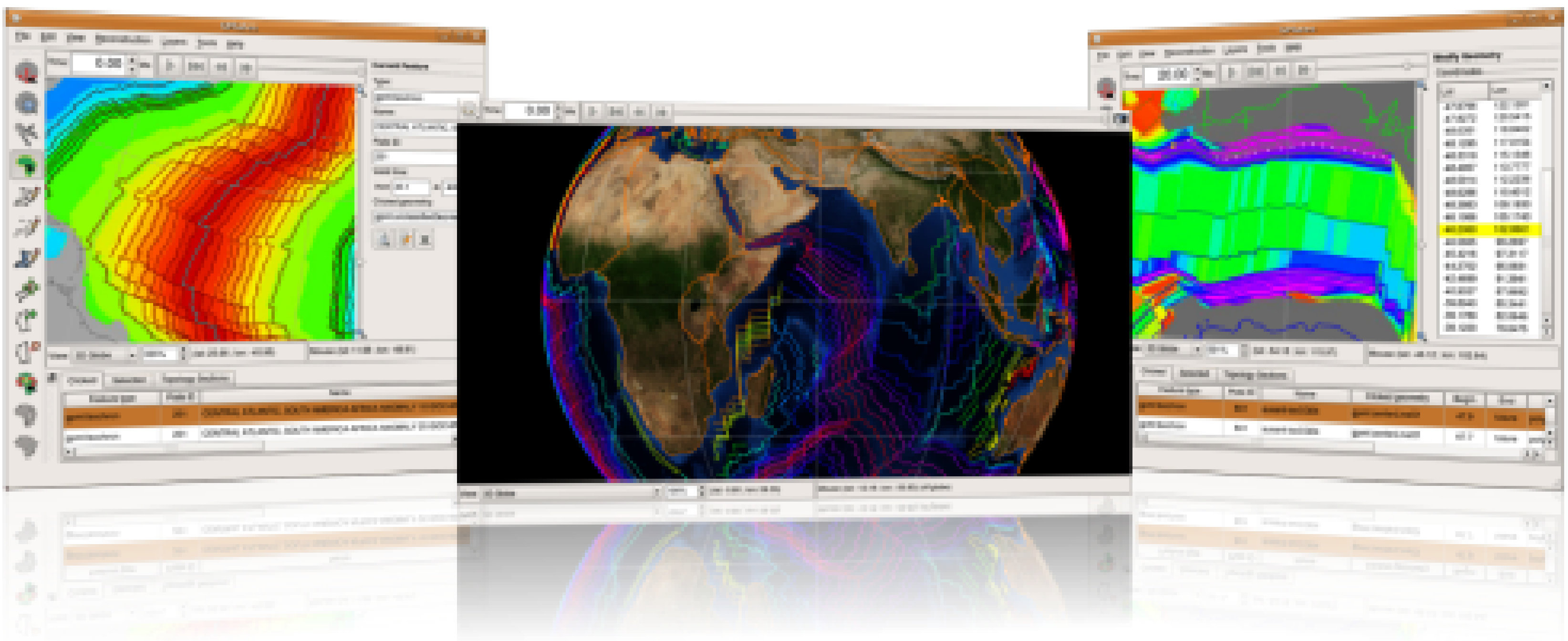
$Ra \sim 10^6 - 10^9$ Rayleigh number

γ heat productin rate

$\eta(T,p,u)$ viscosity (temperature - and pressure - dependent, non - linear)

e_r radial direction

GPlates



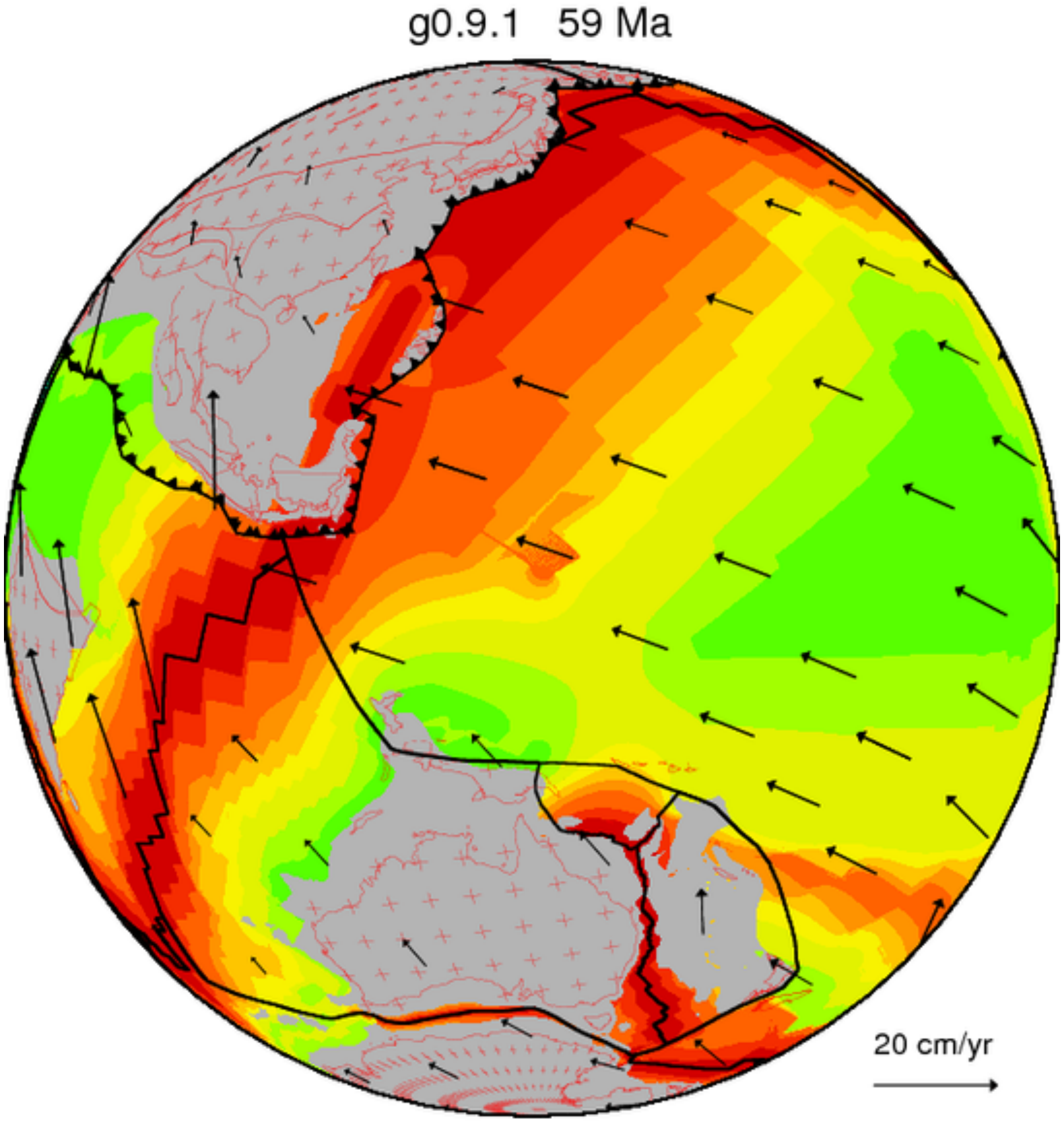
University of Sydney

Caltech

Norwegian Geological Survey/ University of Oslo

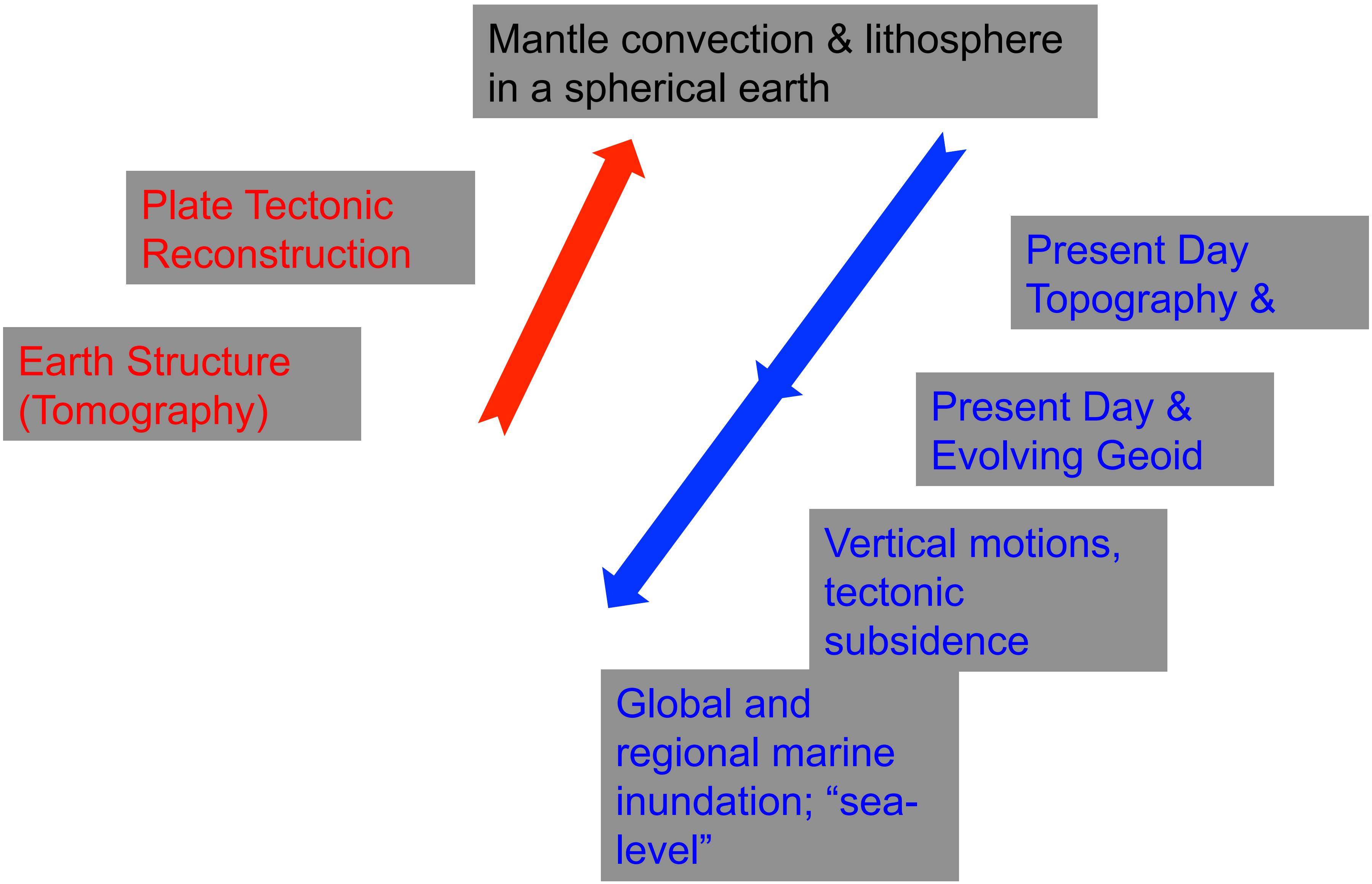
www.gplates.org

Continuously Closed Plate Polygons with Self-Consistent Motion Between Margins and Plates



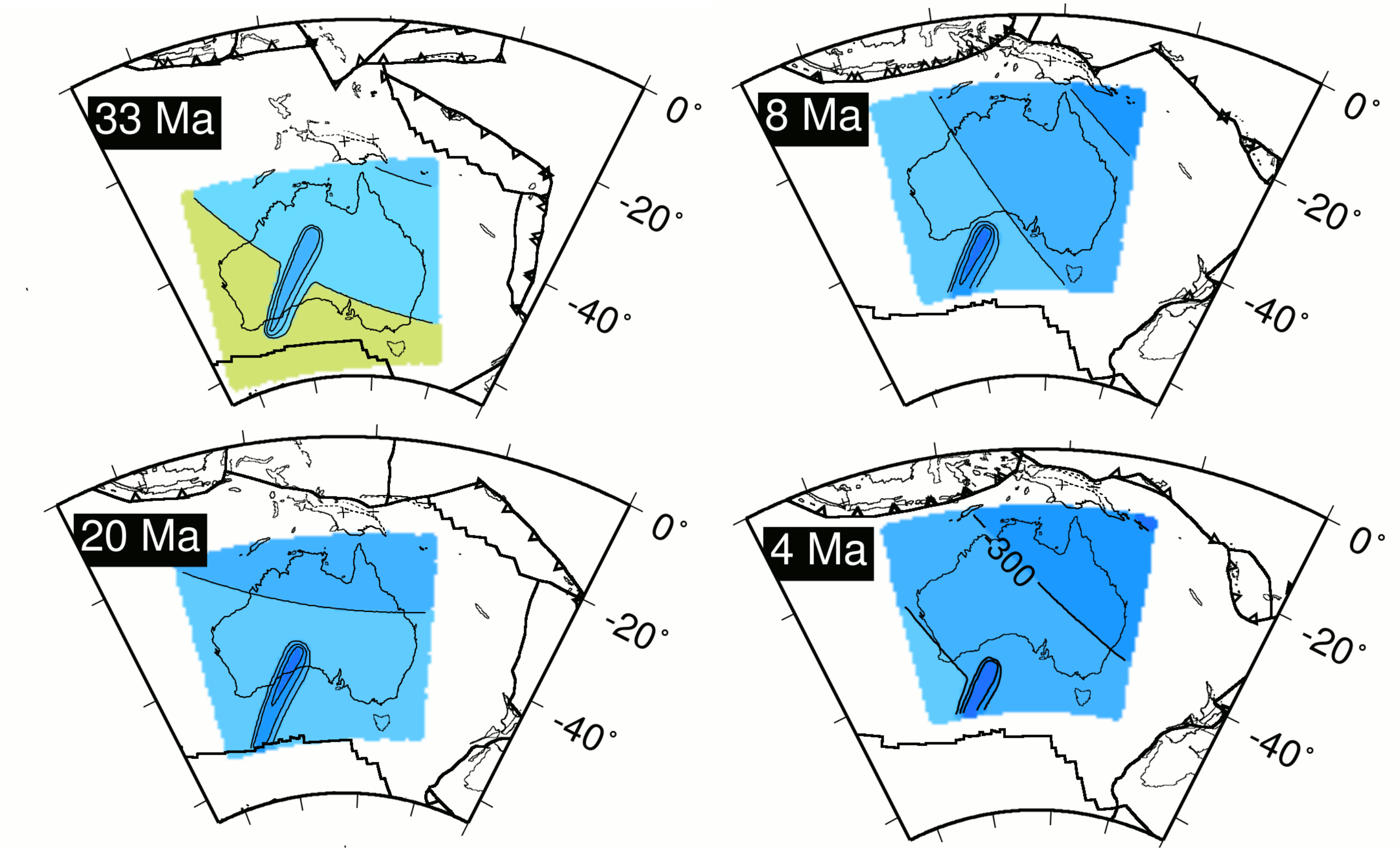
GPlates.org

Linking elements of 4-D earth models



Australia Since 50 Ma

Subsidence and tilting

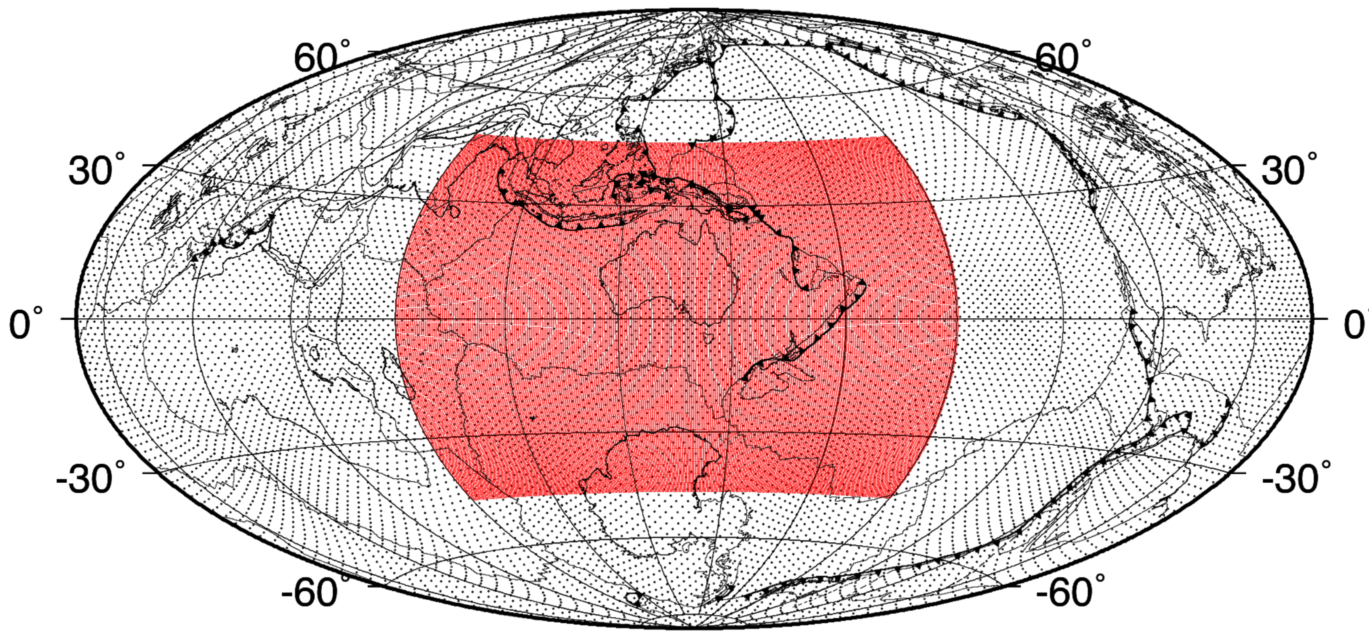


A kinematic analysis of paleoshorelines shows that Australia subsided and tilted downwards by about 300 meters over a continental-scale

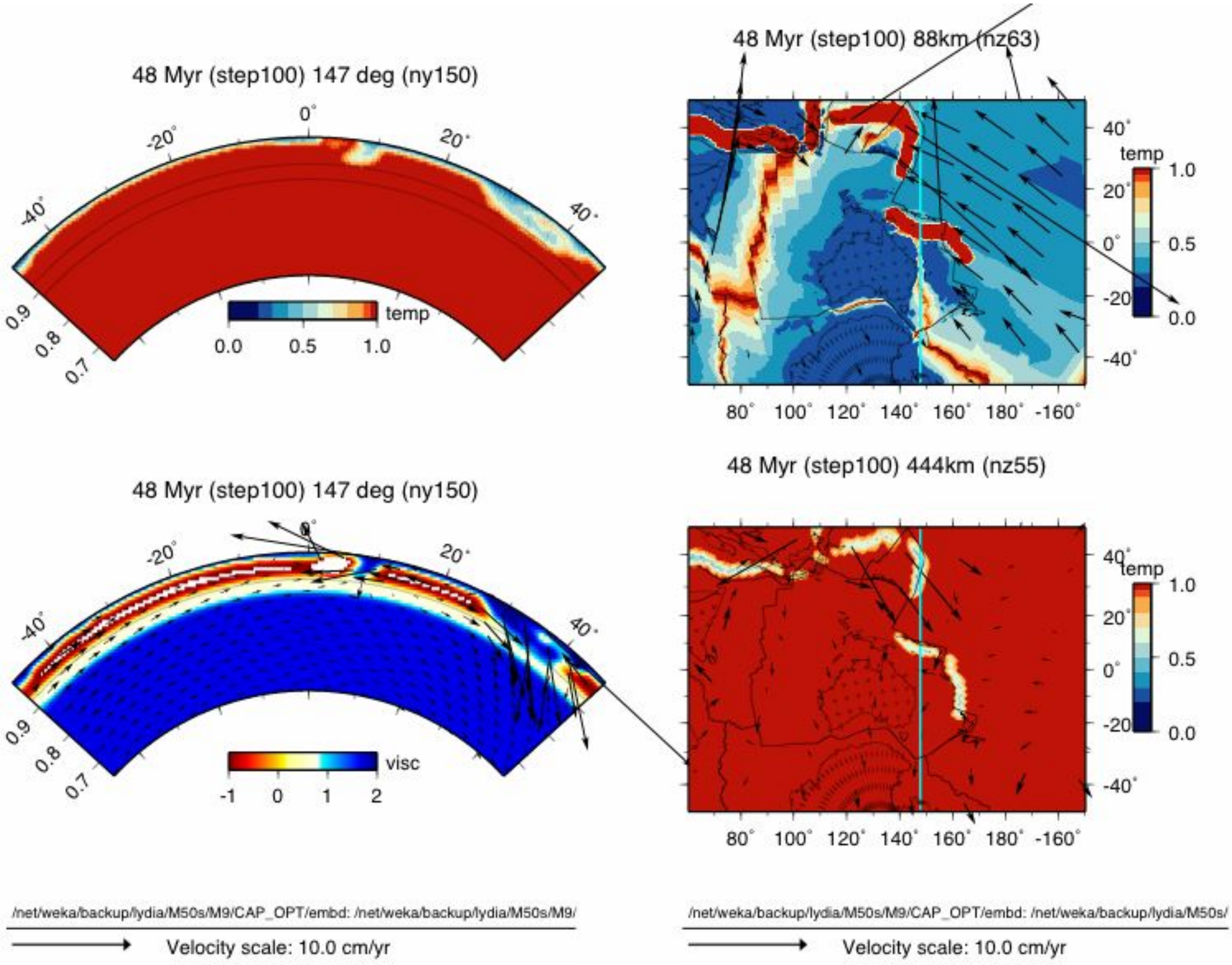
Since about 40 Ma

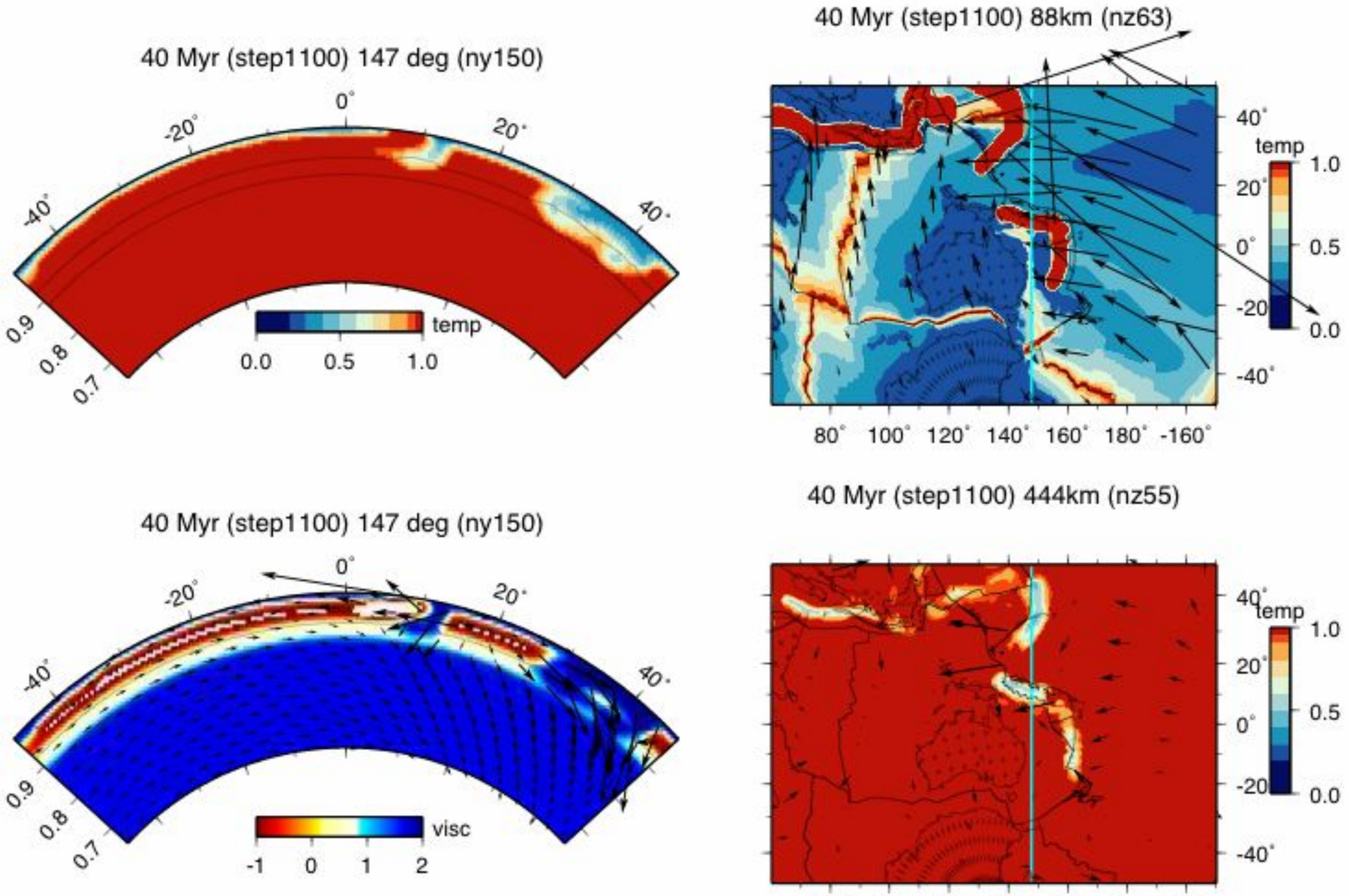
DiCaprio, et al. [2009]

Regional-Global Coupling



DiCaprio, Gurnis, Müller & Tan *[2011]*
Using the coupling approach of Tan et al. [2006]


48 Myr (step100) 147 deg (ny150)
temp
0.0
0.5
1.0
48 Myr (step100) 88km (nz63)
temp
48 Myr (step100) 147 deg (ny150)
visc
-1
0
1
2
48 Myr (step100) 444km (nz55)
temp
80°
100°
120°
140°
160°
180°
-160°
/net/weka/backup/lydia/M50s/M9/CAP_OPT/embd: /net/weka/backup/lydia/M50s/M9/
Velocity scale: 10.0 cm/yr
/net/weka/backup/lydia/M50s/M9/CAP_OPT/embd: /net/weka/backup/lydia/M50s/
Velocity scale: 10.0 cm/yr



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Velocity scale: 10.0 cm/yr

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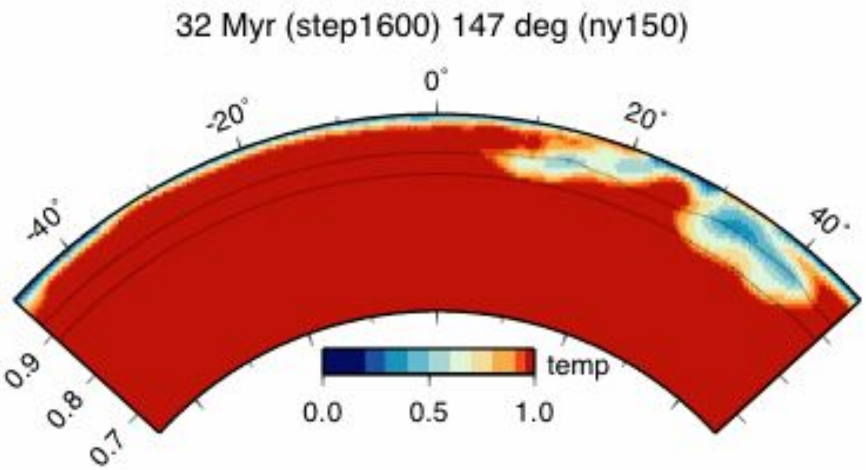
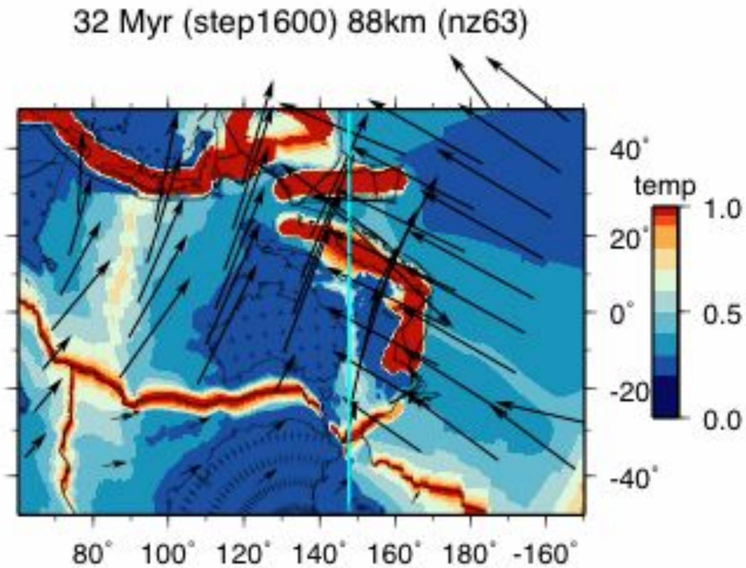
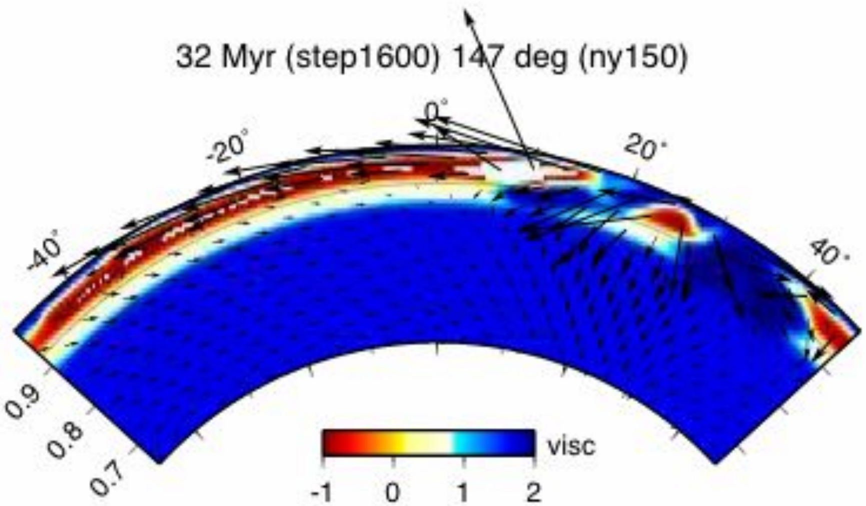
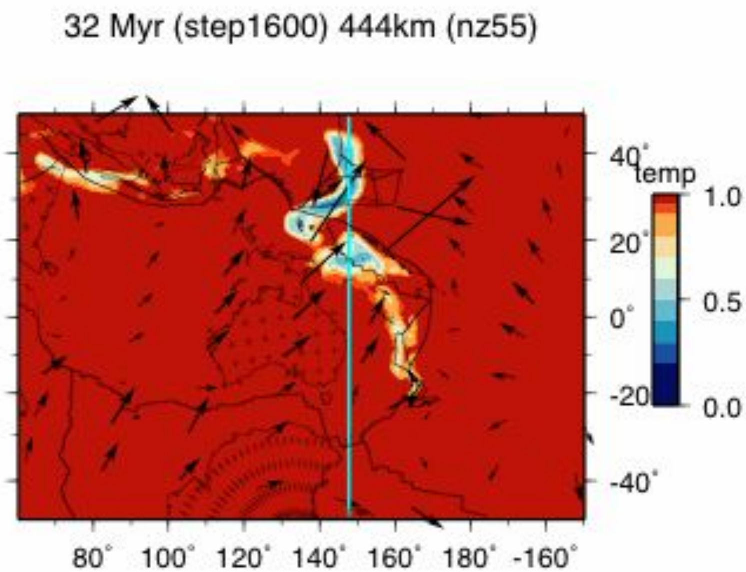
Velocity scale: 10.0 cm/yr









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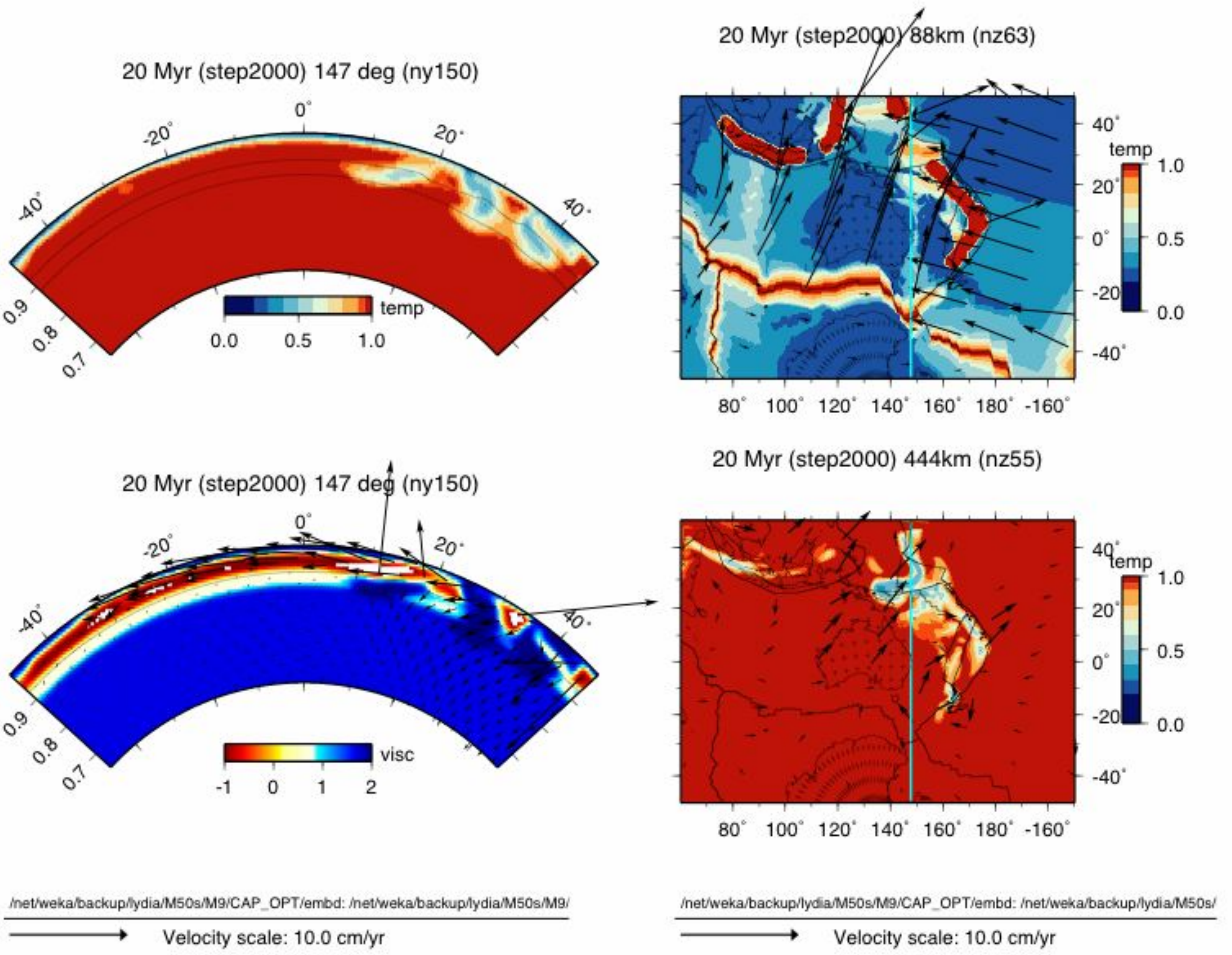
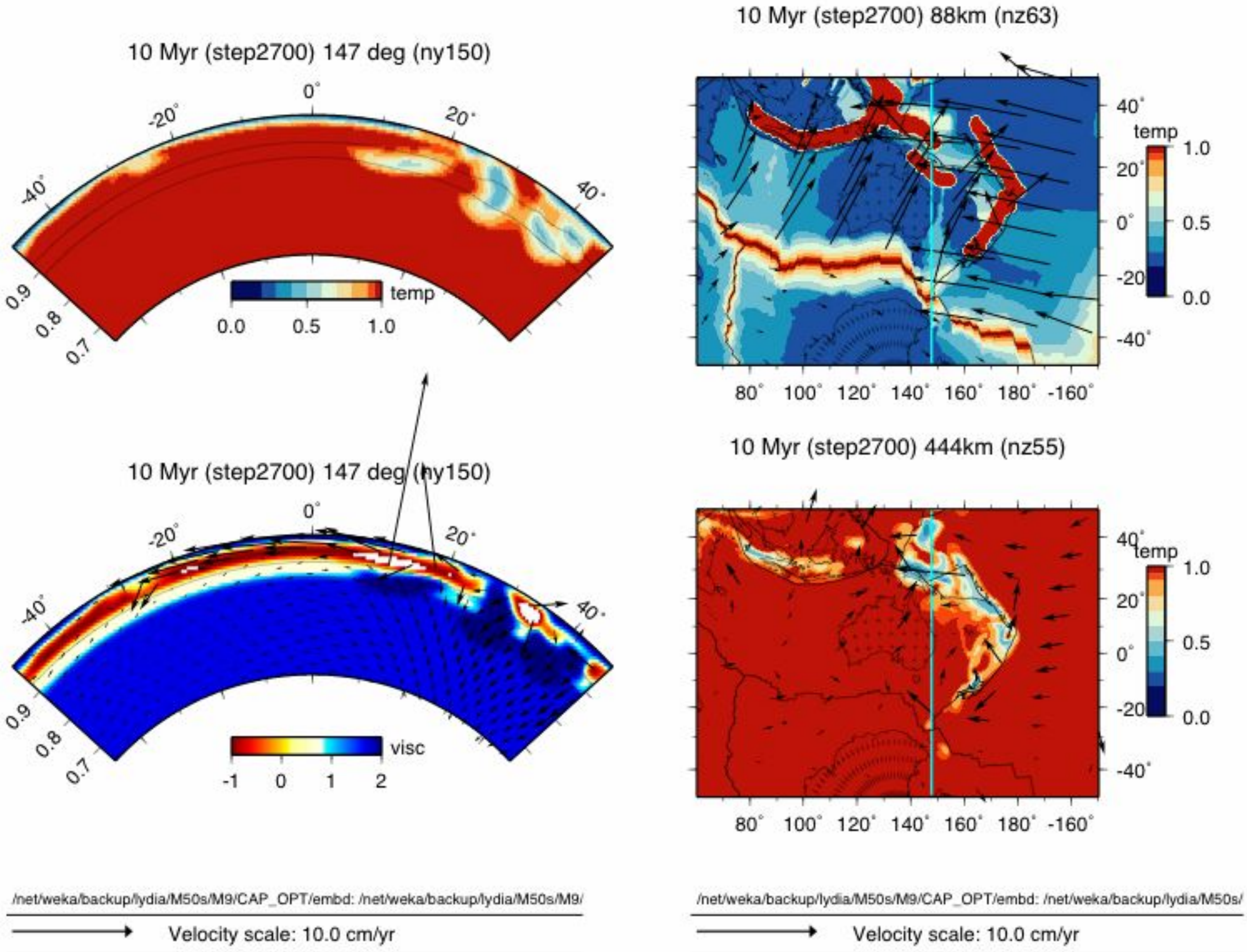
Velocity scale: 10.0 cm/yr

/net/weka/backup/lydia/M50s/M9/CAP_OPT/embd: /net/weka/backup/lydia/M50s/

Velocity scale: 10.0 cm/yr


20 Myr (step2000) 147 deg (ny150)
0° -20° 20° -40° 40°
0.9 0.8 0.7
temp
0.0 0.5 1.0
20 Myr (step2000) 88km (nz63)
40° 20° 0° -20 -40°
temp
1.0 0.5 0.0
80° 100° 120° 140° 160° 180° -160°
20 Myr (step2000) 147 deg (ny150)
0° -20° 20° -40° 40°
0.9 0.8 0.7
visc
-1 0 1 2
20 Myr (step2000) 444km (nz55)
40° 20° 0° -20 -40°
temp
1.0 0.5 0.0
80° 100° 120° 140° 160° 180° -160°
/net/weka/backup/lydia/M50s/M9/CAP_OPT/embd: /net/weka/backup/lydia/M50s/M9/
Velocity scale: 10.0 cm/yr
/net/weka/backup/lydia/M50s/M9/CAP_OPT/embd: /net/weka/backup/lydia/M50s/
Velocity scale: 10.0 cm/yr


10 Myr (step2700) 147 deg (ny150)
0°
-20°
20°
-40°
40°
0.9
0.8
0.7
temp
0.0
0.5
1.0
10 Myr (step2700) 88km (nz63)
40°
20°
0°
-20°
-40°
80°
100°
120°
140°
160°
180°
-160°
10 Myr (step2700) 147 deg (ny150)
visc
-1
0
1
2
10 Myr (step2700) 444km (nz55)
/net/weka/backup/lydia/M50s/M9/CAP_OPT/embd: /net/weka/backup/lydia/M50s/M9/
Velocity scale: 10.0 cm/yr
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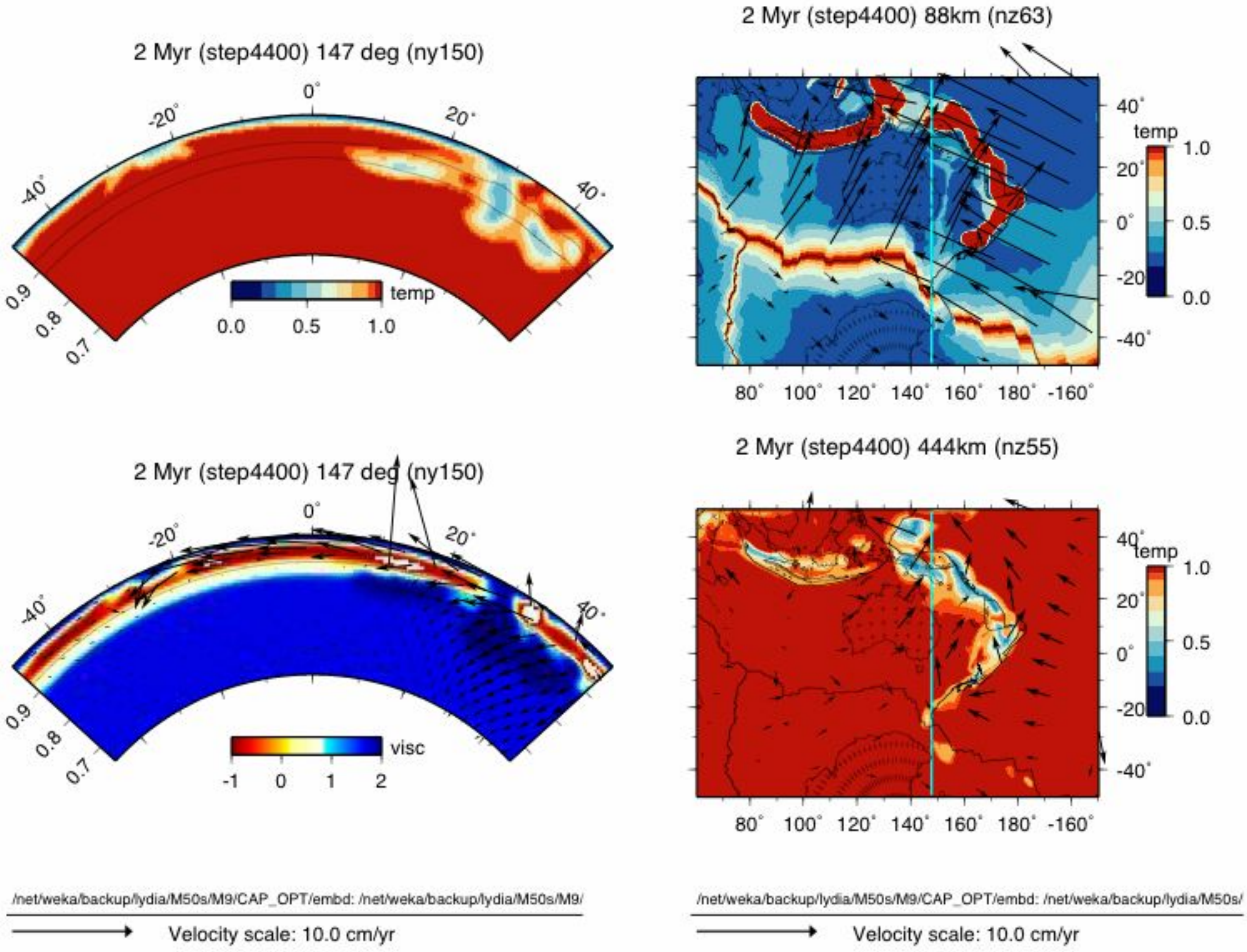
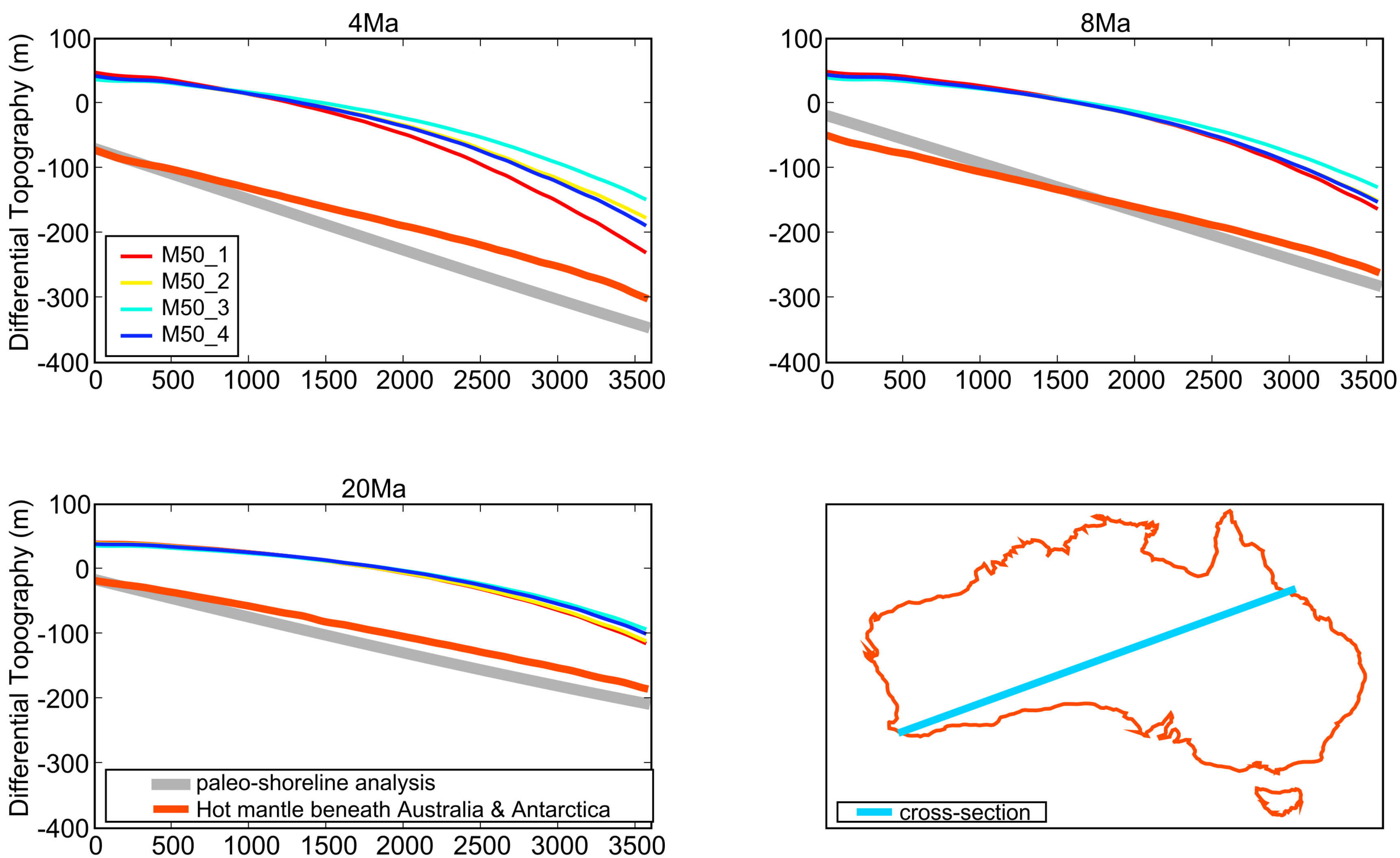
Velocity scale: 10.0 cm/yr



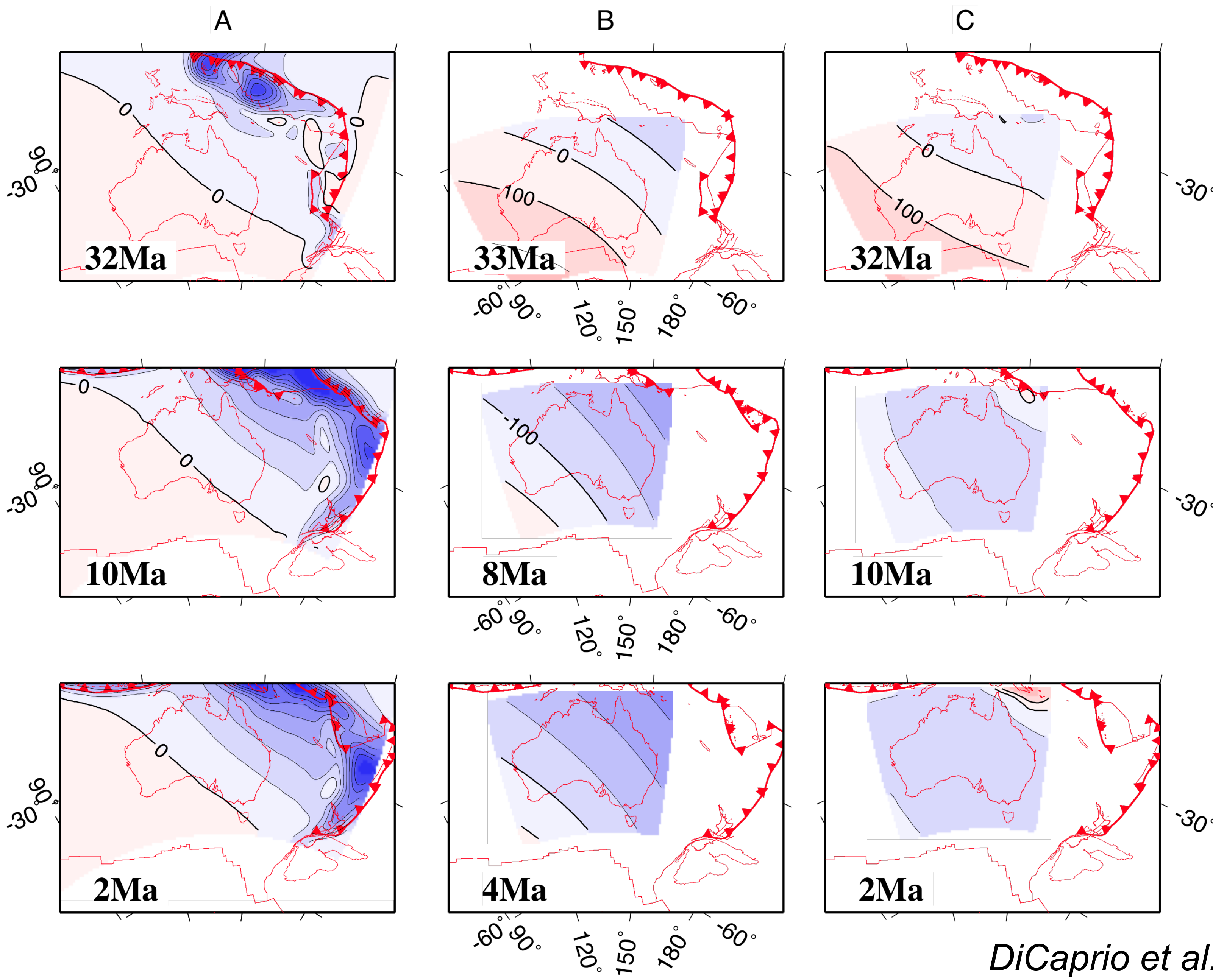
2 Myr (step4400) 147 deg (ny150)
temp
0.0 0.5 1.0
2 Myr (step4400) 88km (nz63)
temp
1.0
0.5
0.0
2 Myr (step4400) 147 deg (ny150)
visc
-1 0 1 2
2 Myr (step4400) 444km (nz55)
temp
80° 100° 120° 140° 160° 180° -160°
/net/weka/backup/lydia/M50s/M9/CAP_OPT/embd: /net/weka/backup/lydia/M50s/M9/
Velocity scale: 10.0 cm/yr
/net/weka/backup/lydia/M50s/M9/CAP_OPT/embd: /net/weka/backup/lydia/M50s/
Velocity scale: 10.0 cm/yr

Differential Motion since 50 Ma



DiCaprio et al. [2011]

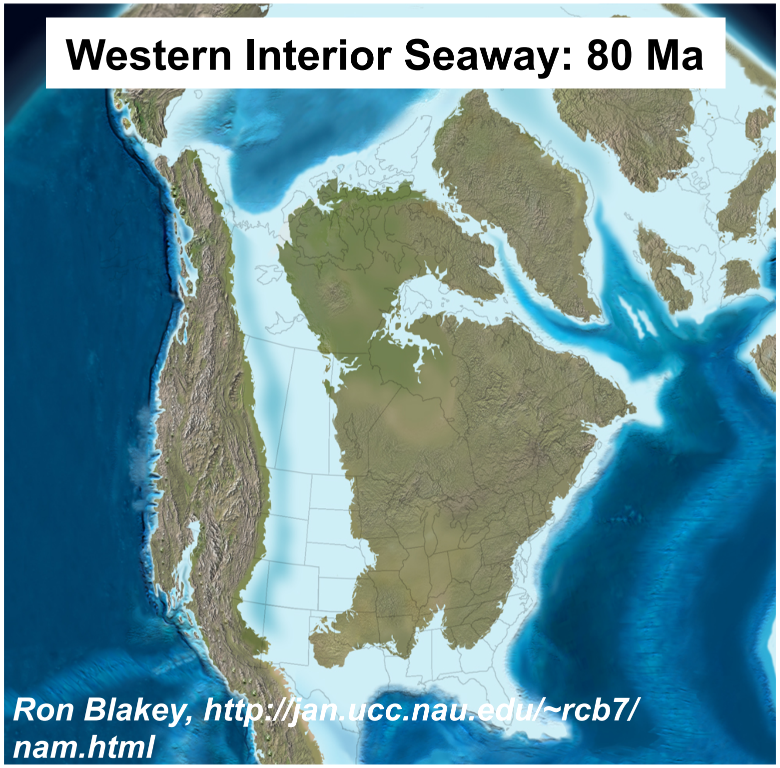
Differential motion w.r.t. topography at 44 Ma



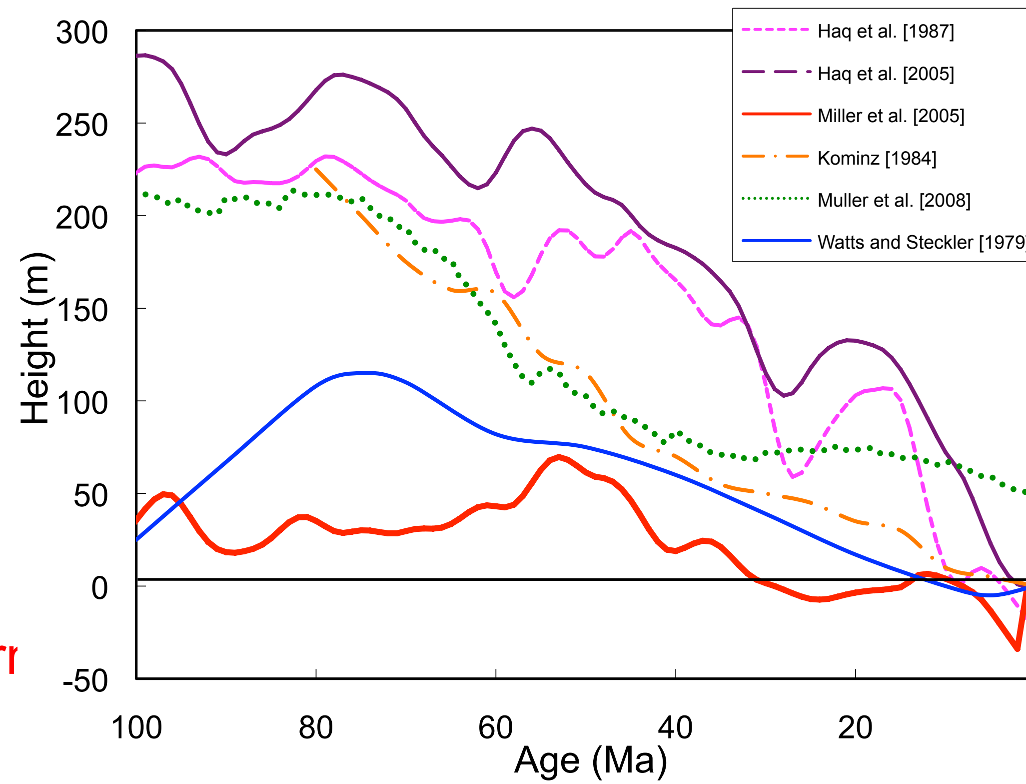
DiCaprio et al. [2011]

North America Since the Late Cretaceous

Motivation

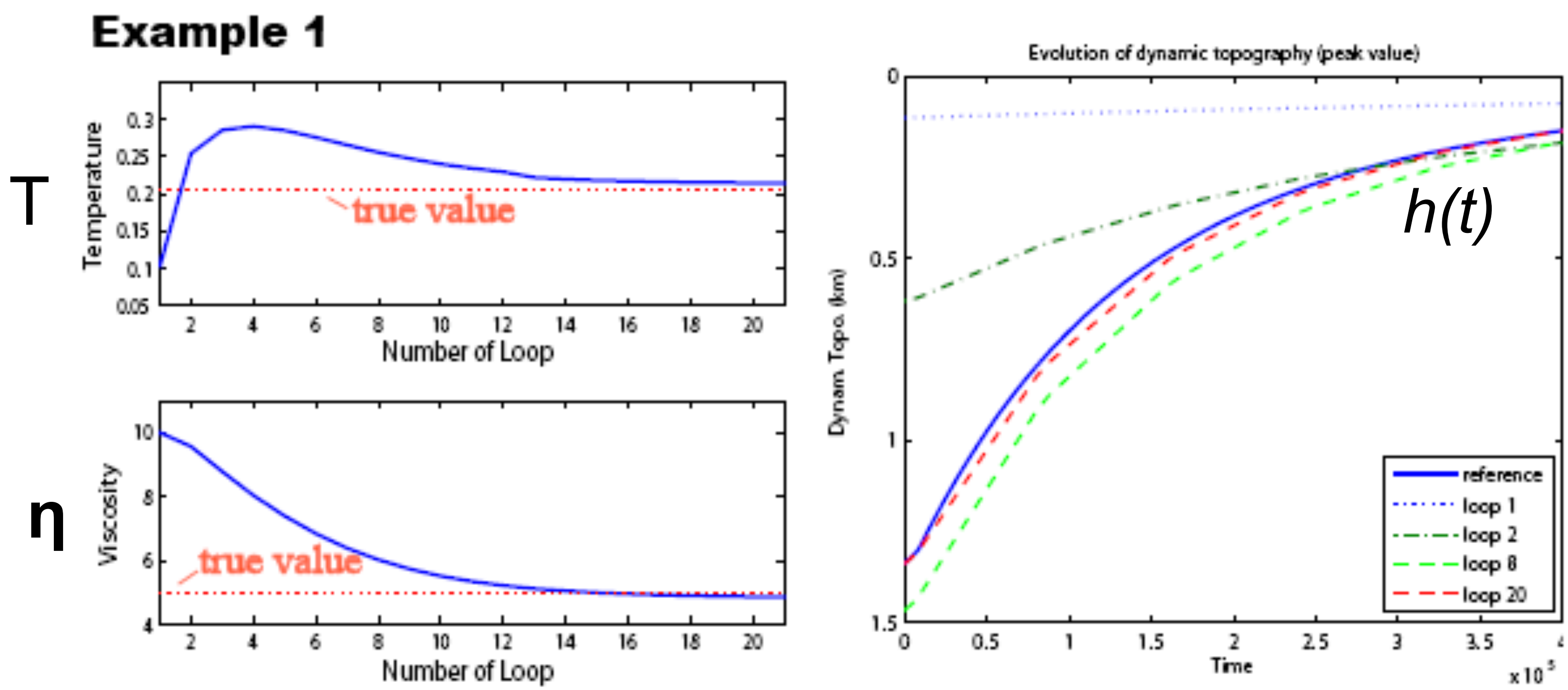


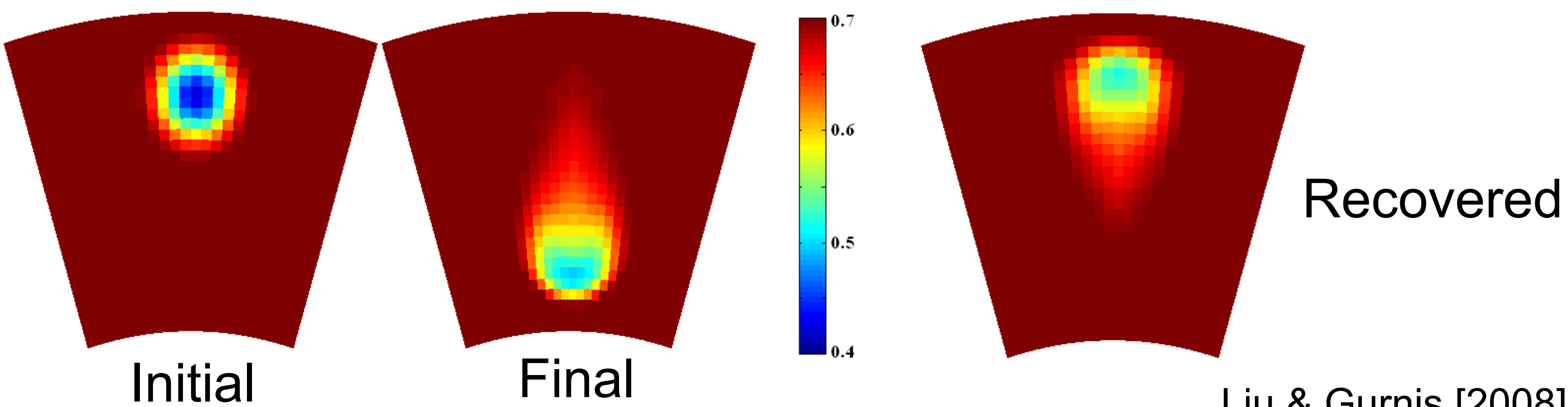
- Well documented flooding and dynamic subsidence in Western Interior Seaway [Cross & Pilger, 1978]
  - Interpreted to be related to change in Farallon slab dip (e.g. Mitrovica *et al.* [1989])
- Substantial discrepancy between New Jersey sea level (Miller *et al.*,2005) and other global sea-level curves



→ Develop a single geodynamic model that predicts Cretaceous subsidence, Tertiary uplift and putative subsidence in the eastern US.

Inverse Convection Model with 'Topographic Target'
Initial Ra off by 4X and both ΔT and η Incorrect





Liu & Gurnis [2008]

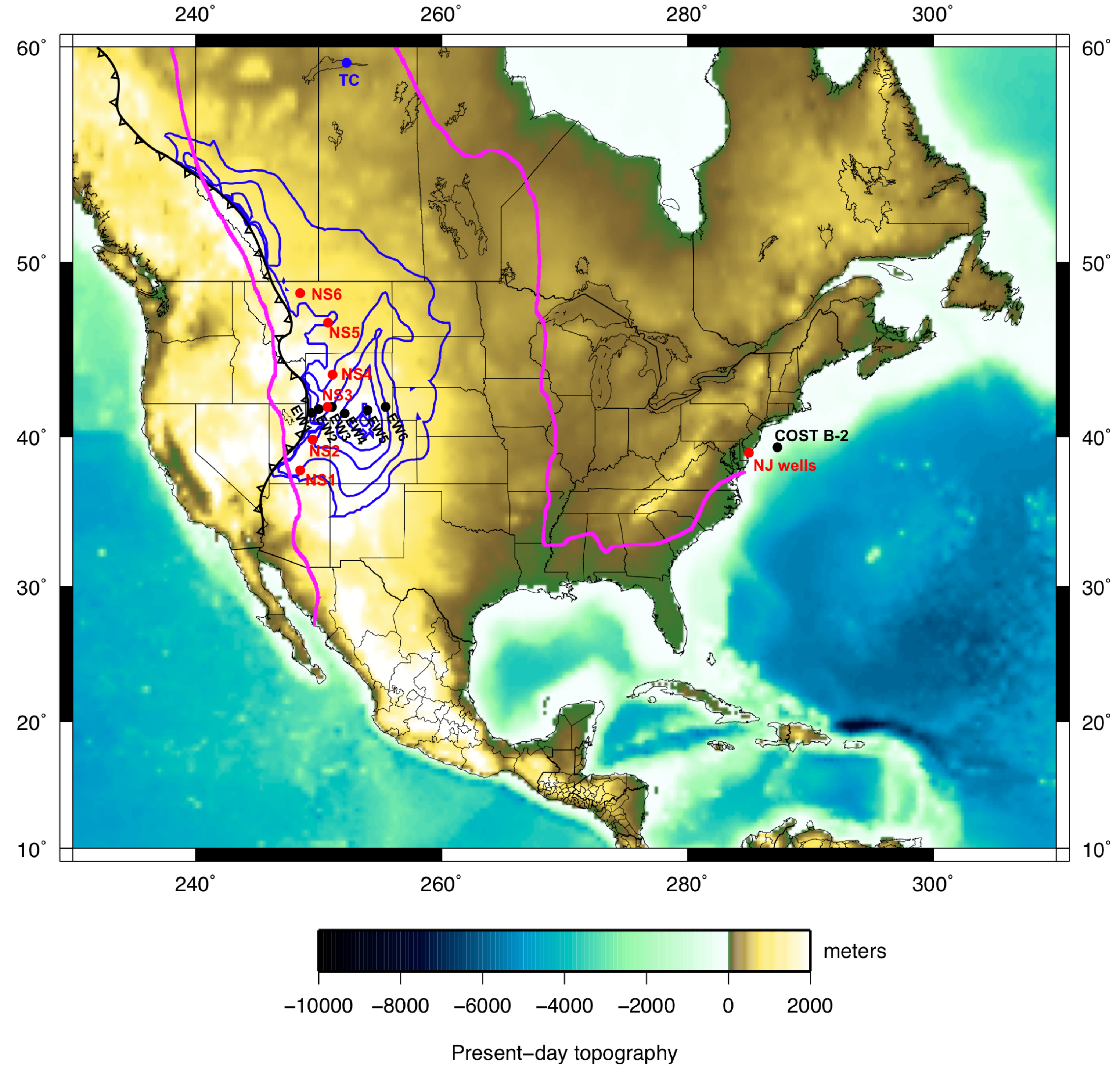
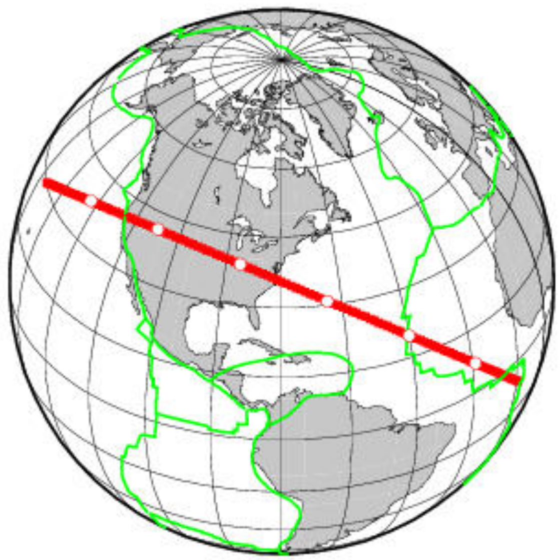
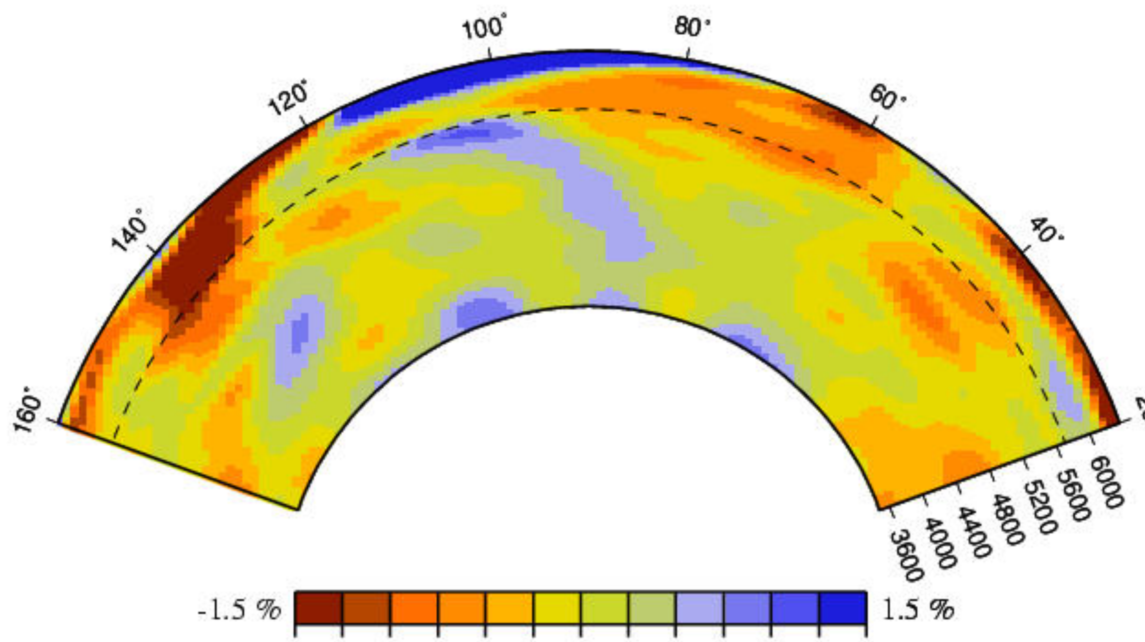

240°
260°
280°
300°
60°
50°
40°
30°
20°
10°
TC
NS6
NS5
NS4
NS3
NS2
NS1
EW1
EW2
EW3
EW4
EW5
EW6
COST B-2
NJ wells
meters
−10000
−8000
−6000
−4000
−2000
0
2000
Present−day topography

Figure 1

Farallon slab beneath North America

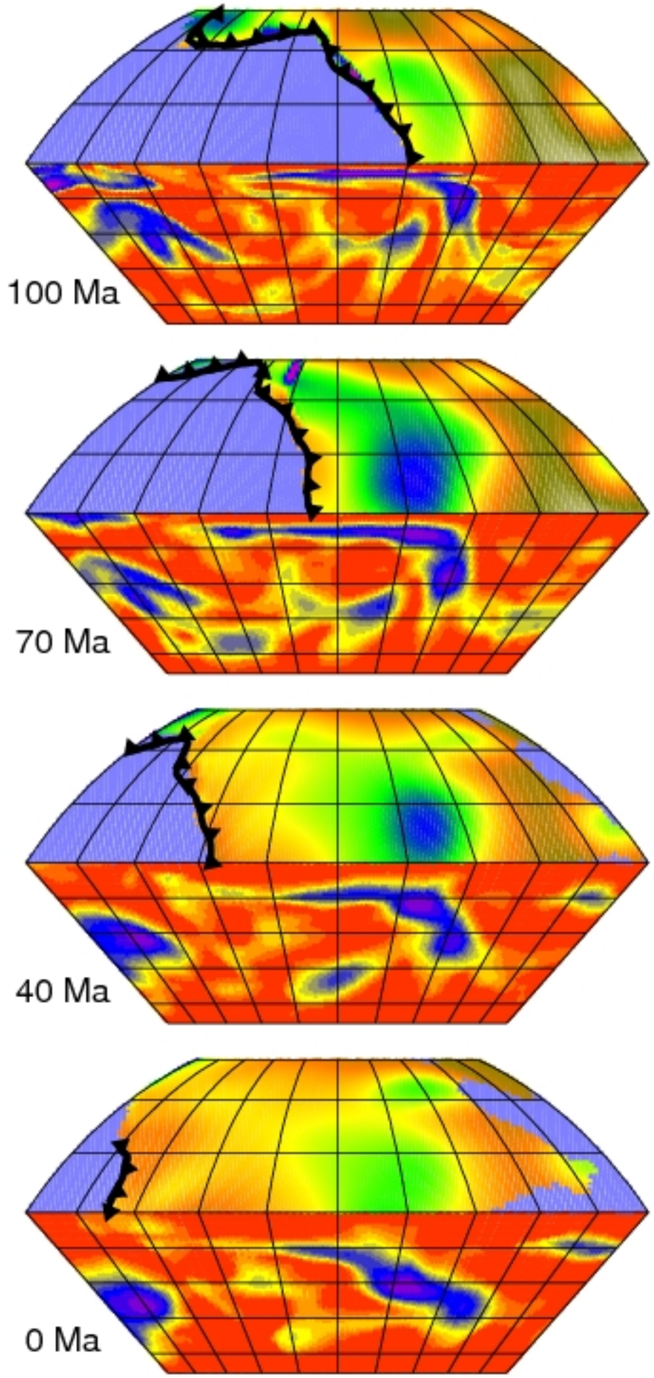


Shear wave tomography



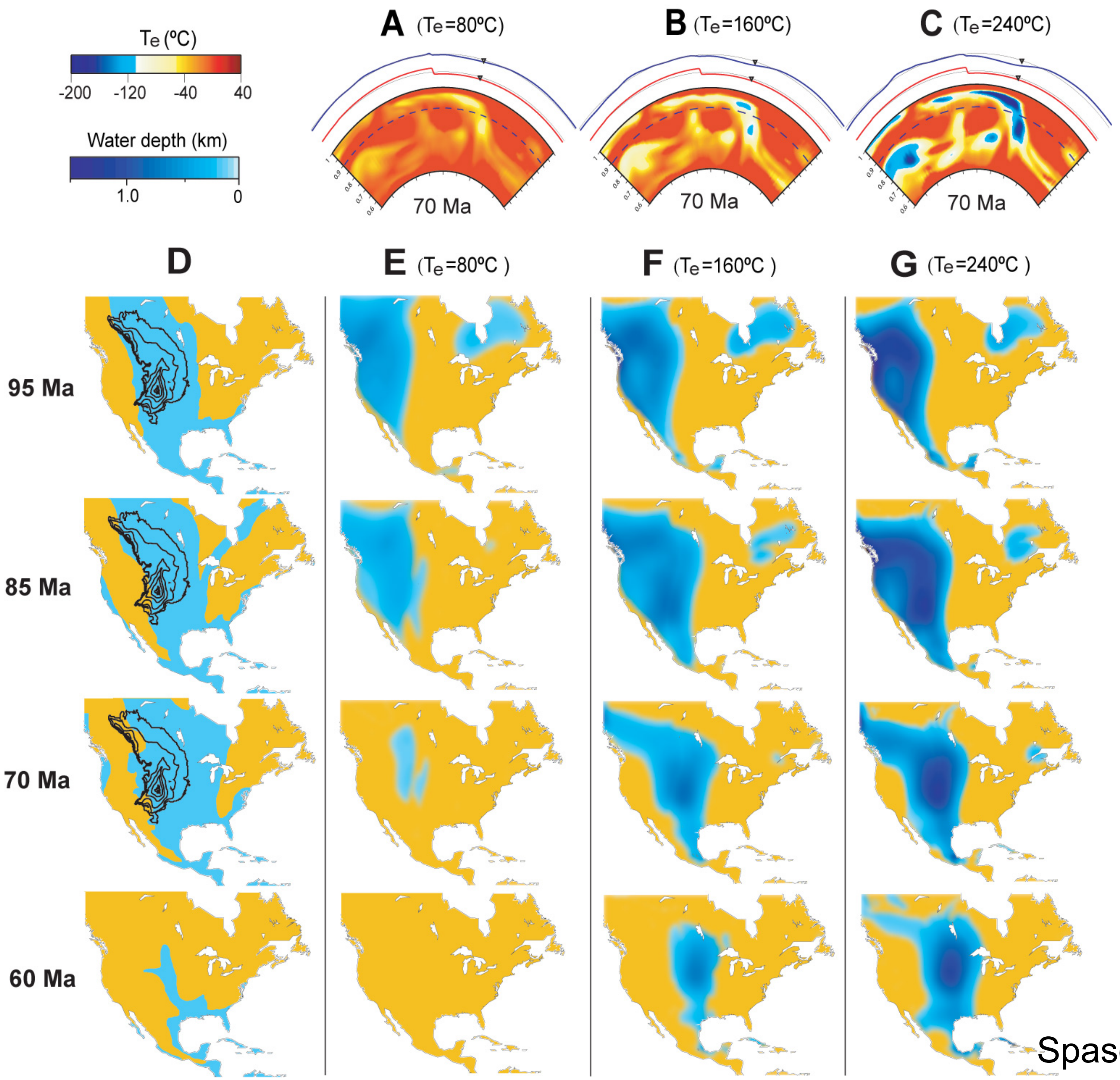
Ritsema et al

Bernhard Steinberger's Interpretation of the Liu et al. [2008] Inversion.



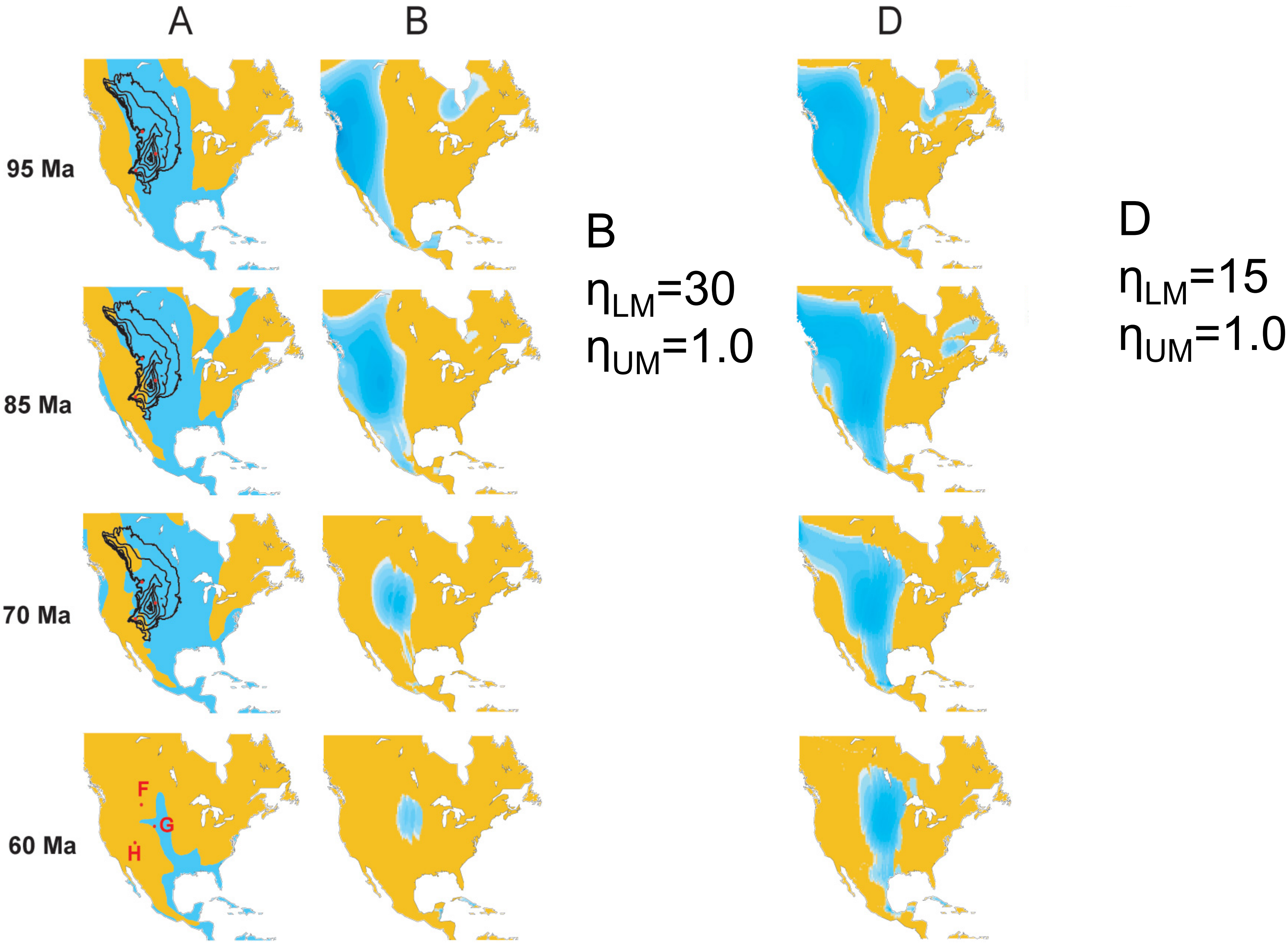
Cross section at 42 N through North America

Holding Ra constant

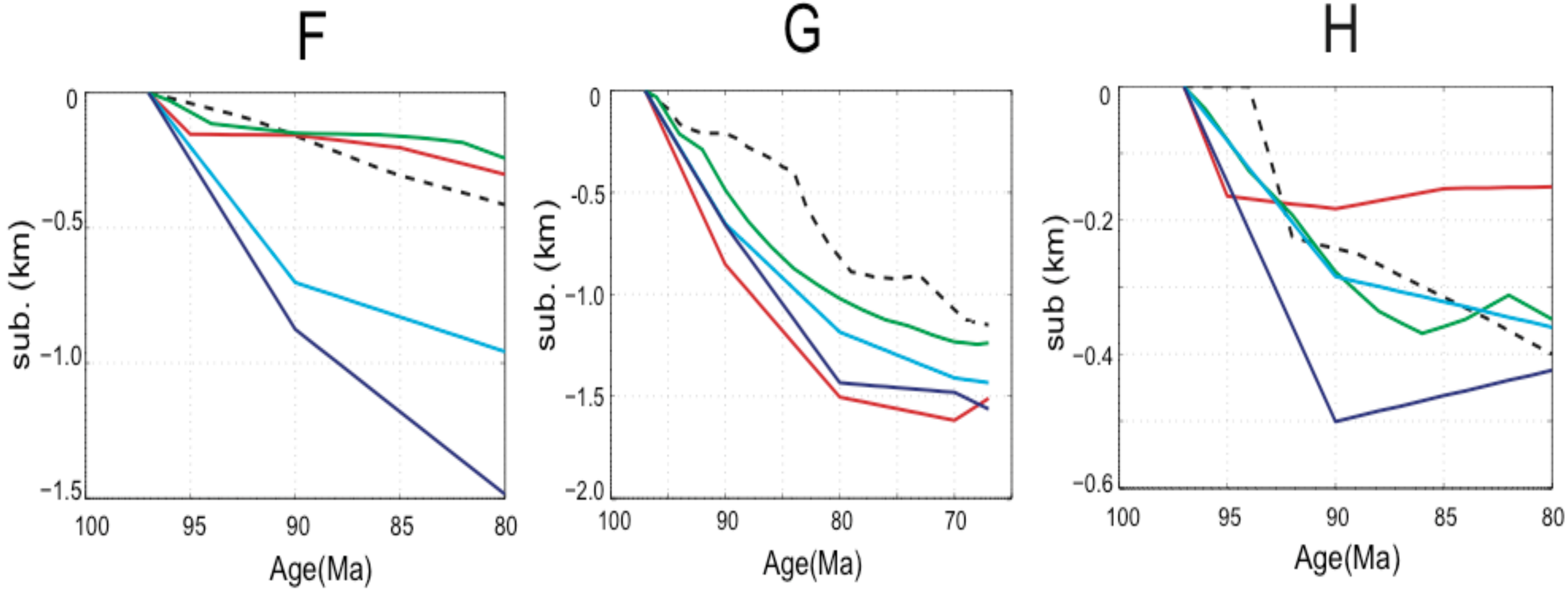


Spasojević, et al. [2009]

Prediction of flooding and vertical motions in the ‘plate frame’



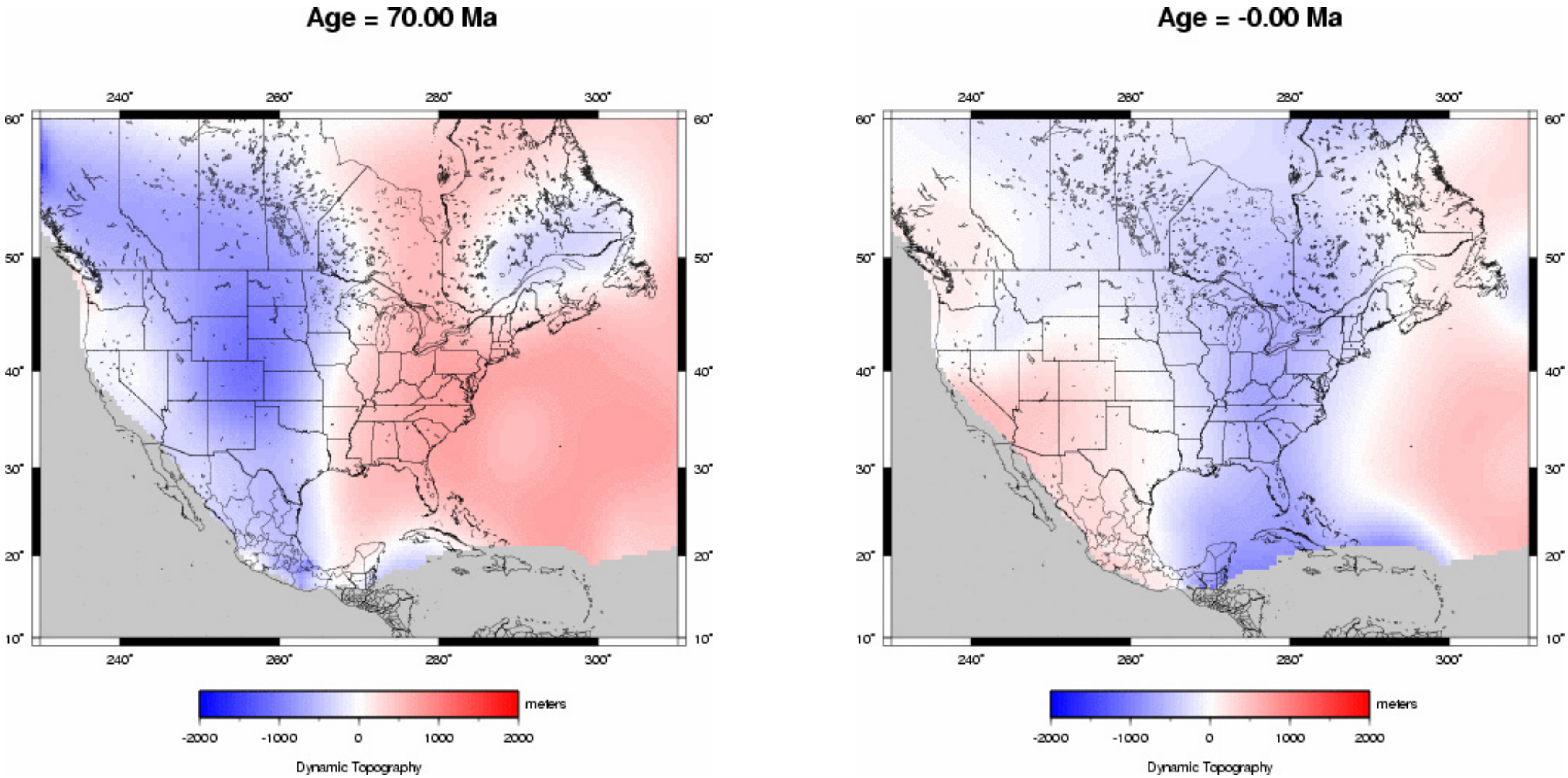
Prediction of borehole subsidence



- - - - - Observation
—— η_{LM}=30, η_{UM}=1.5, dT=0.6
—— η_{LM}=15, η_{UM}=1.0, dT=0.4
—— η_{LM}=15, η_{UM}=0.3, dT=0.4
—— η_{LM}=15, η_{UM}=0.1, dT=0.4

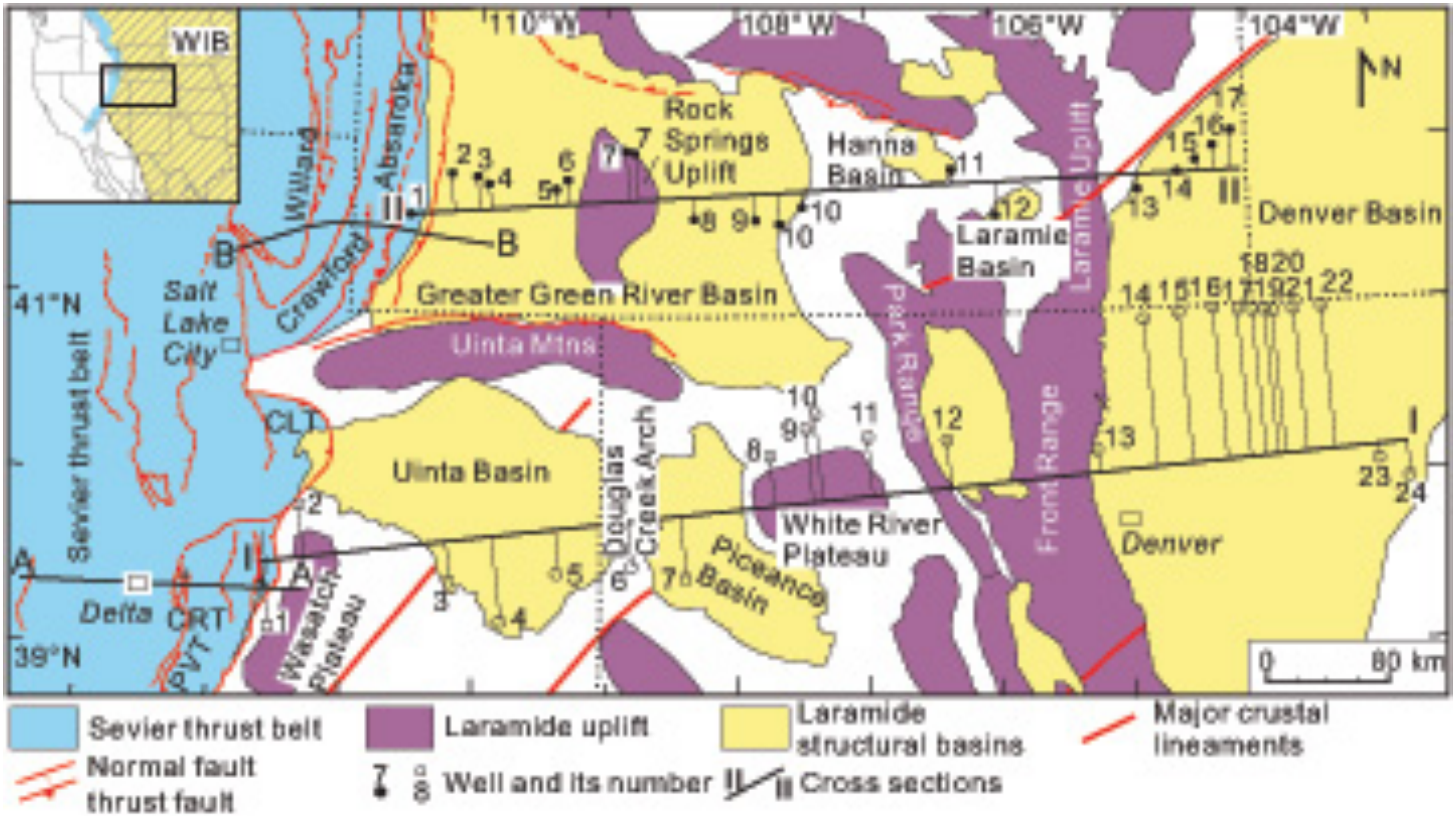
Liu et al., 2008

Dynamic topography migrates over North America



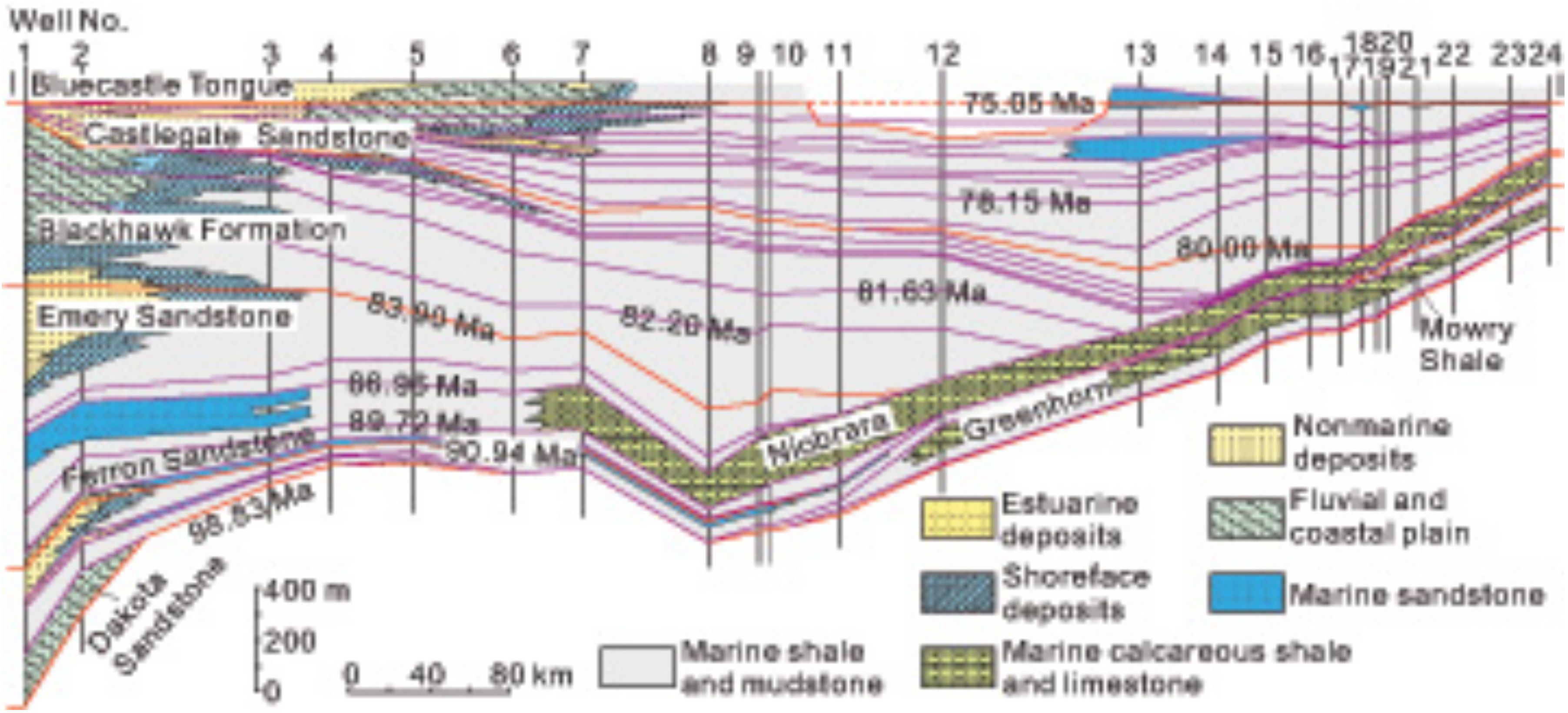
Liu, Spasojević. & Gurnis [2008]

The Cretaceous Seaway



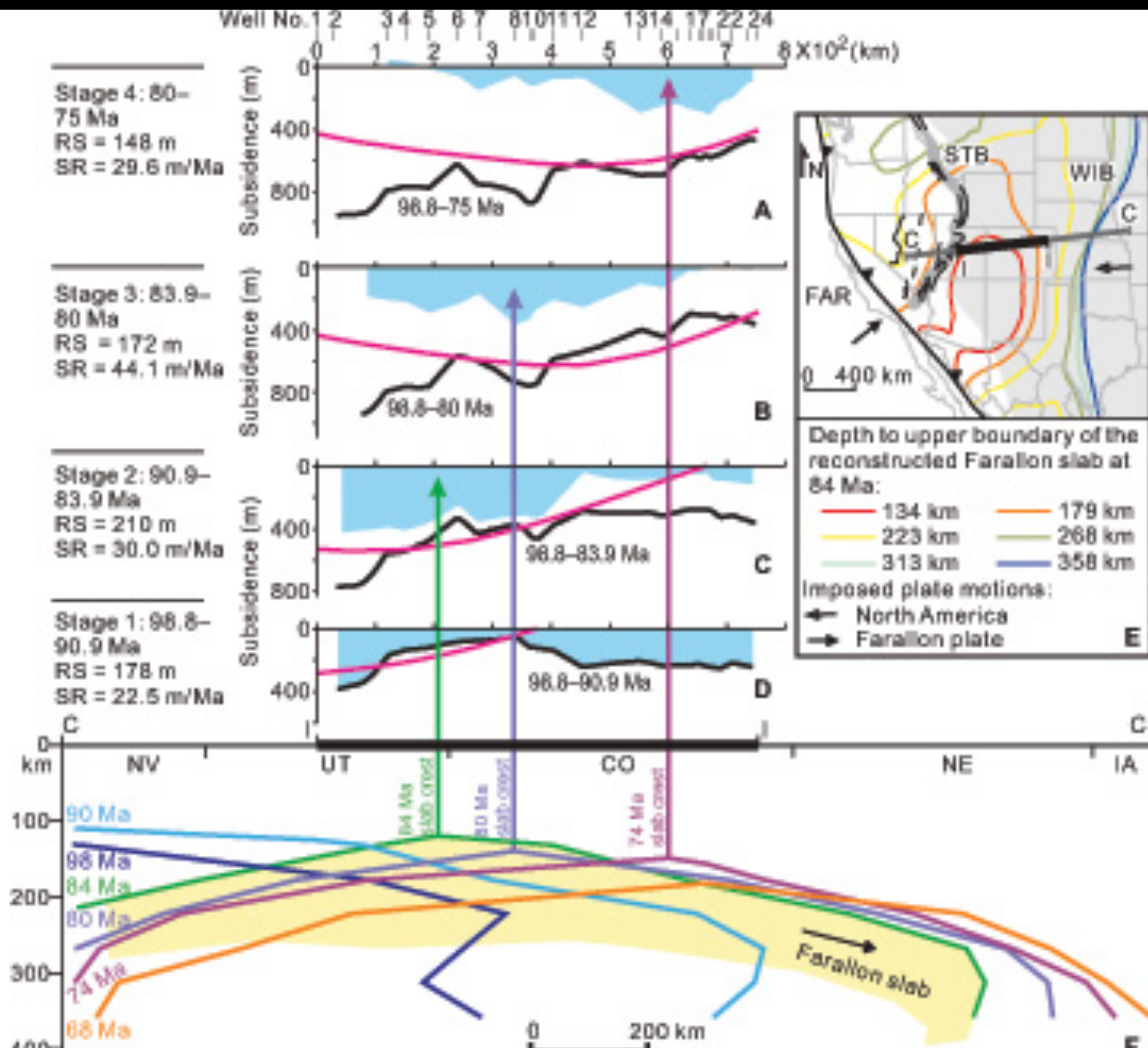
Shaofeng Liu et al. [2011]

Cretaceous Section



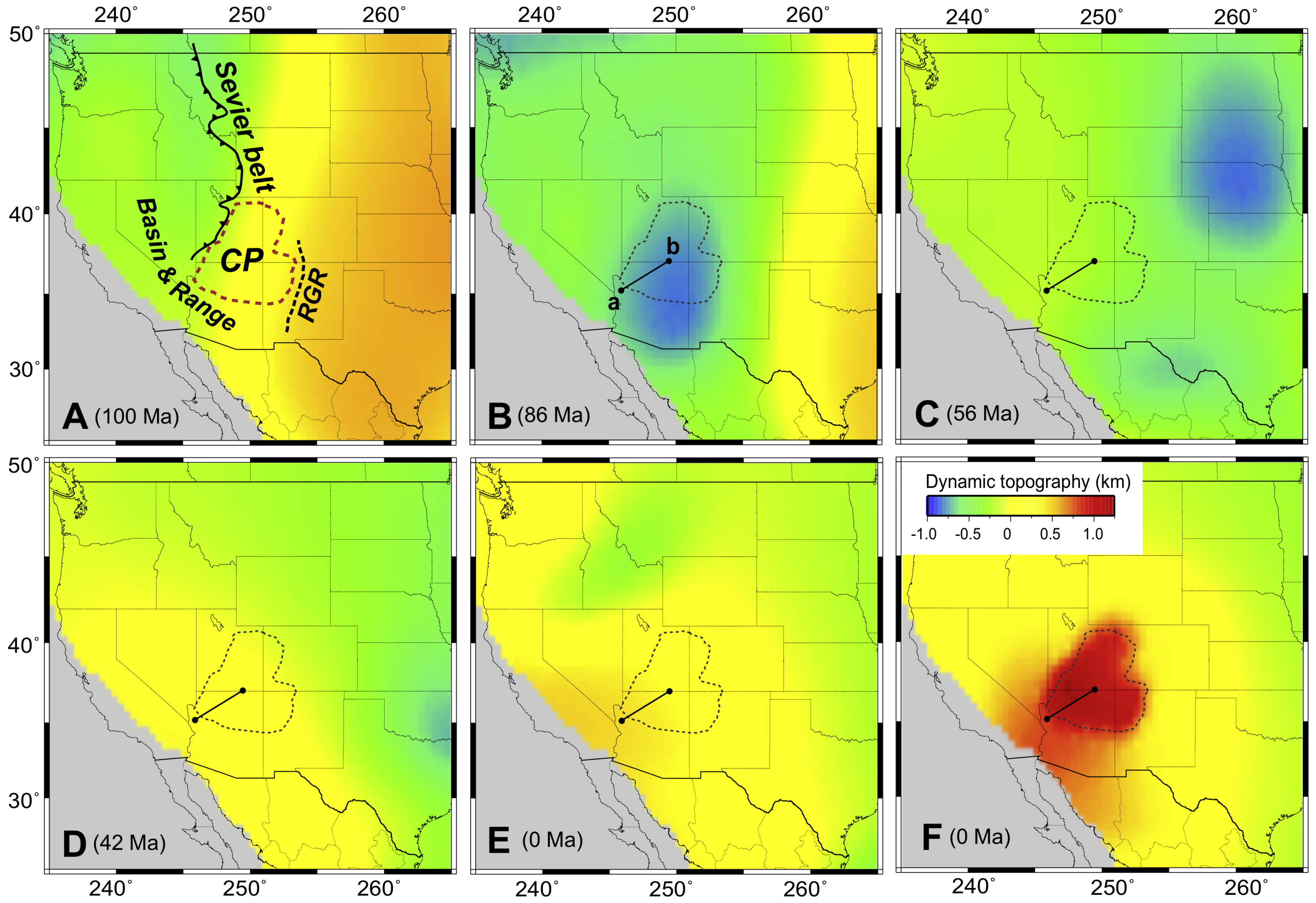
Shaofeng Liu et al. [2011]

A migrating depo-center versus simple E-W tilting



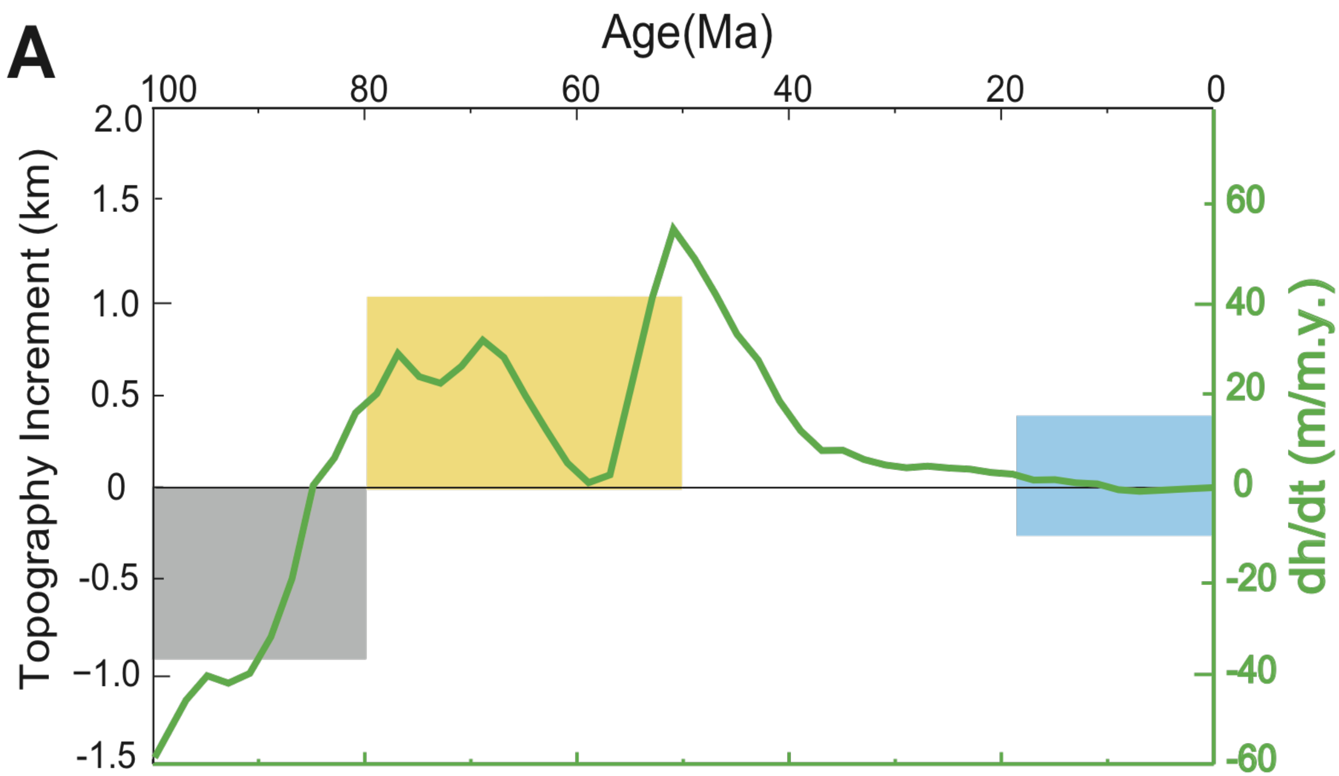
Liu et al. [2008]

Shaofeng Liu et al. [2011]



Liu & Gurnis [2010]

Uplift of the Colorado Plateau



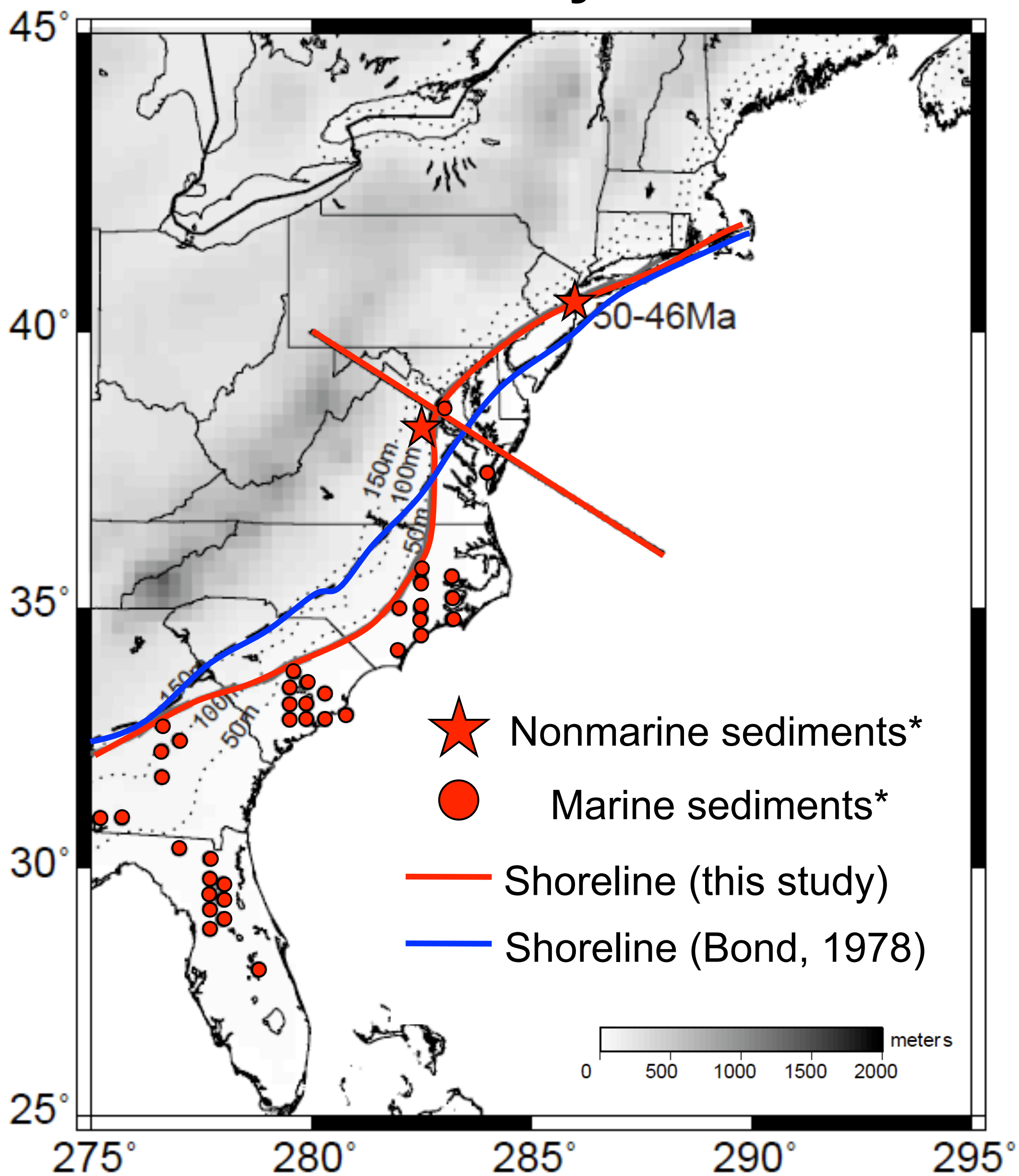
Model tuned for Cretaceous Western Interior Seaway

Clumped Carbon Isotopes on carbonates – Huntington, Wernicke, Eiler [2009]

Burial and unroofing of sediments with U-Th/He Flowers, Wernicke, Farley, 2008

Liu & Gurnis [2010]

Paleo shoreline analysis



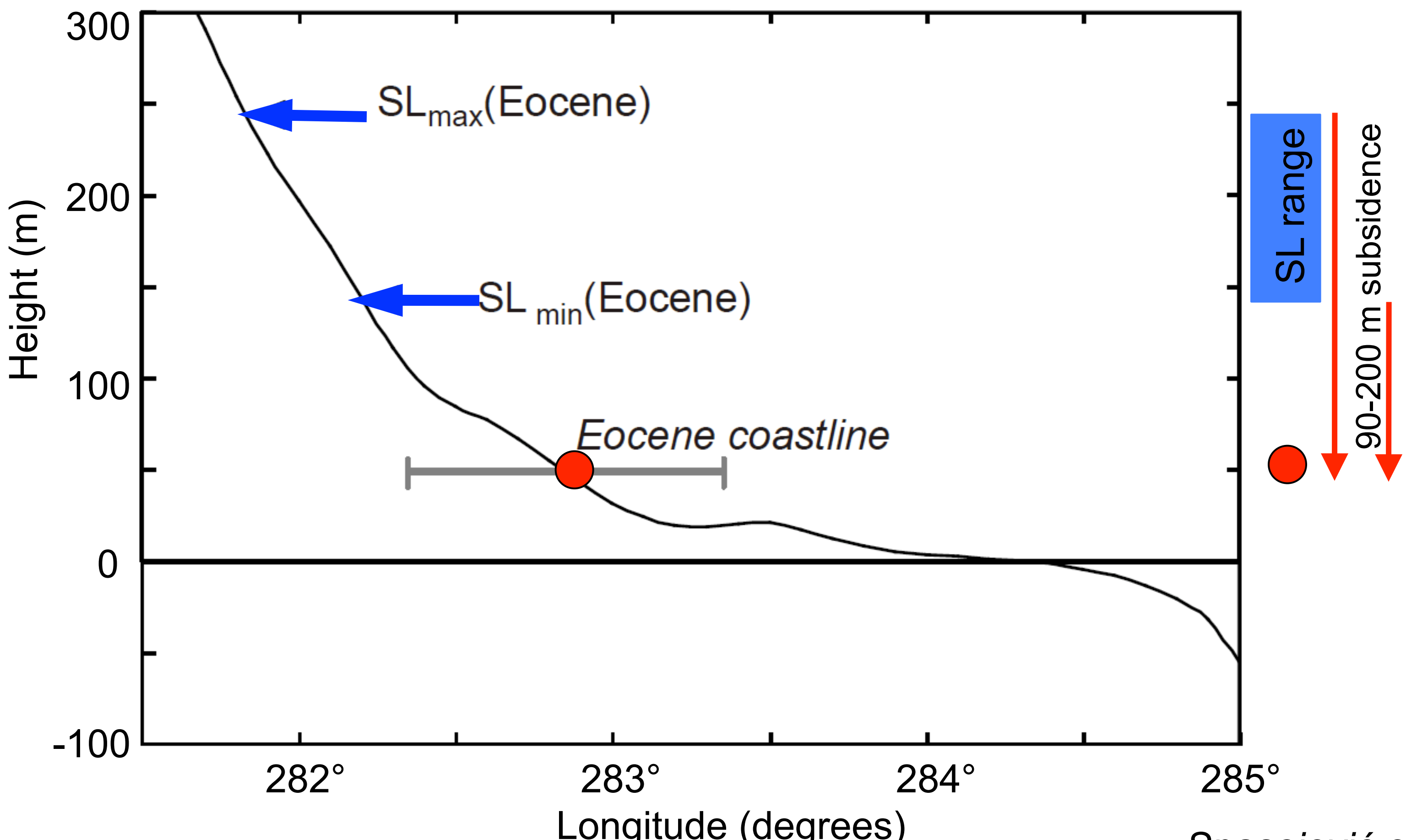
** PiP database, www.paleodb.org*

Paleo shoreline analysis

No subsidence/uplift: Elevation(Shoreline(T_1))$_{present}$=SeaLevel(T_1)

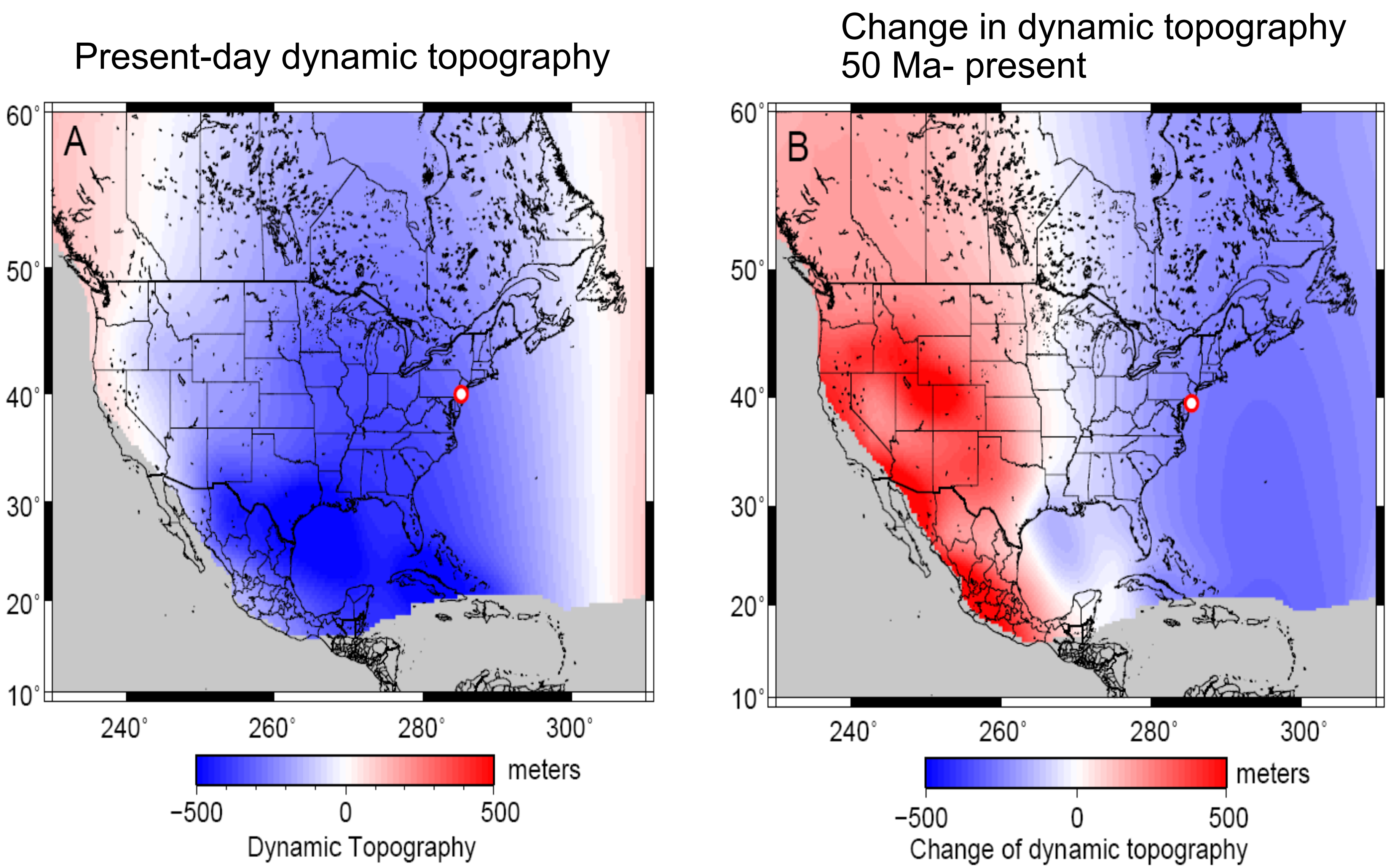
Land subsidence: Elevation(Shoreline(T_1))$_{present}$<SeaLevel(T_1)

Land uplift: Elevation(Shoreline(T))$_{sent}$>SeaLevel(T_1)



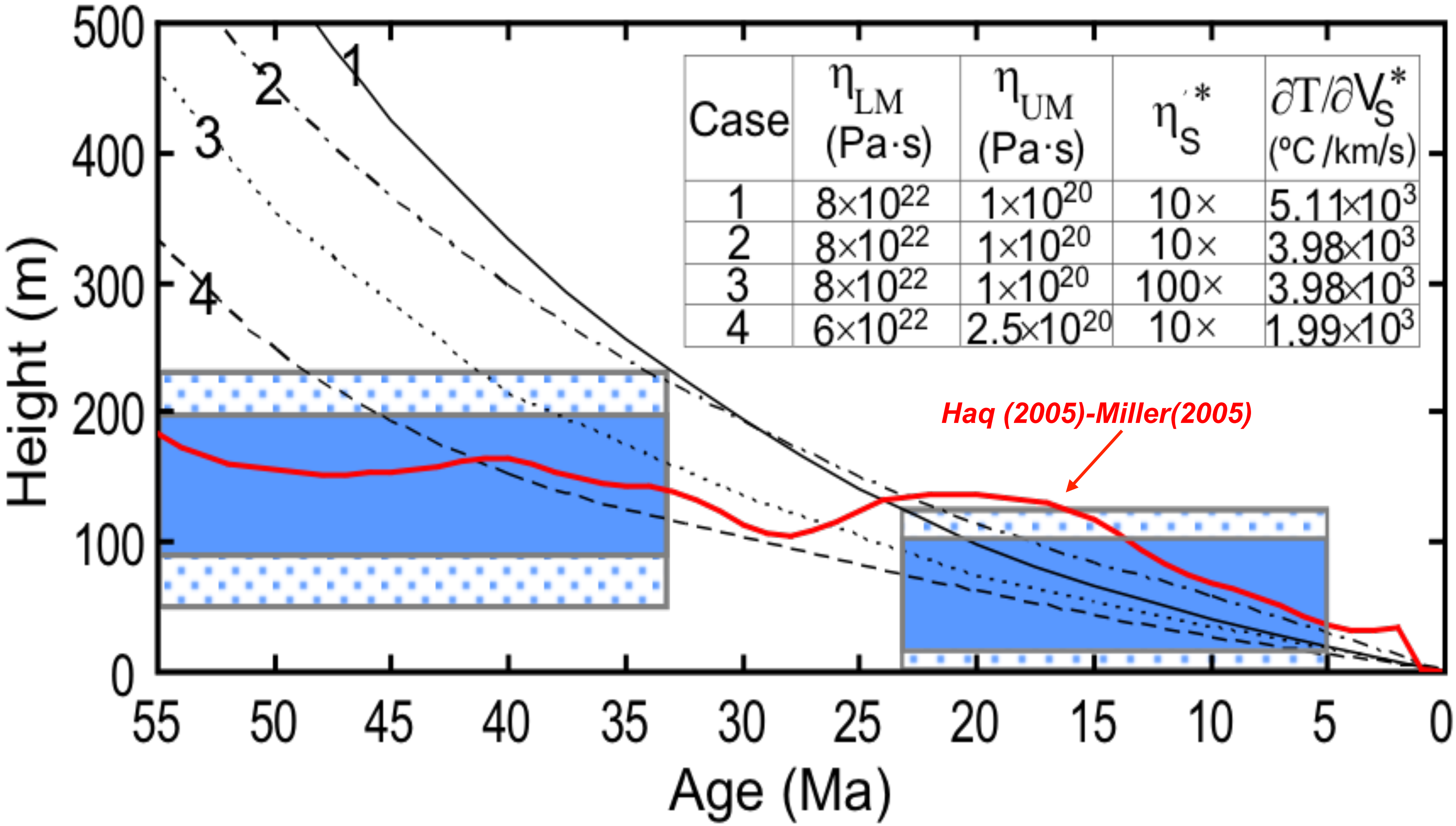
Spasojević et al., 2008

Dynamic topography predictions



Spasojević *et al., 2008*

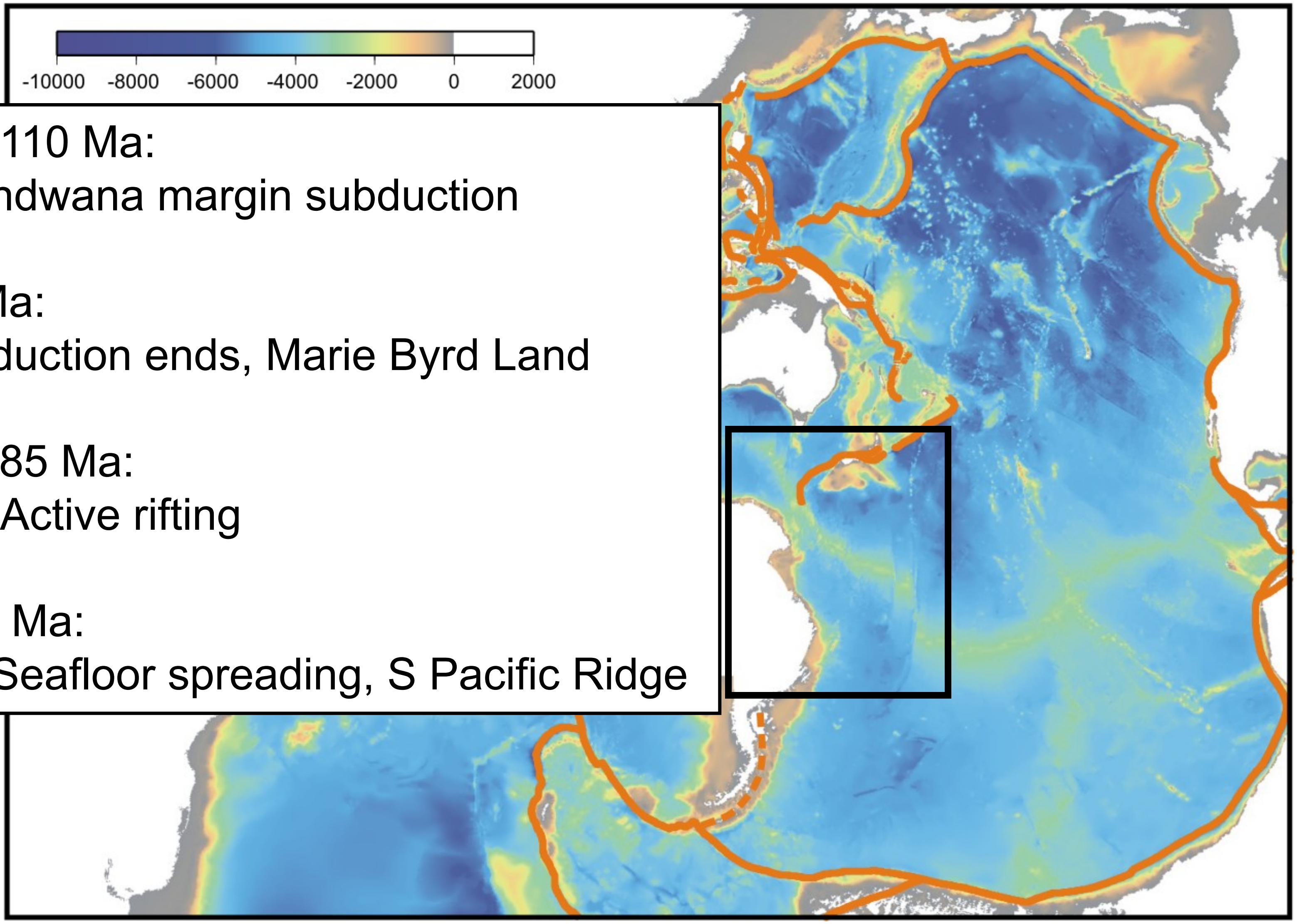
Dynamic subsidence of the US east coast



Spasojević et al., 2008

Mantle Upwelling in the SW Pacific?

Location and tectonic history



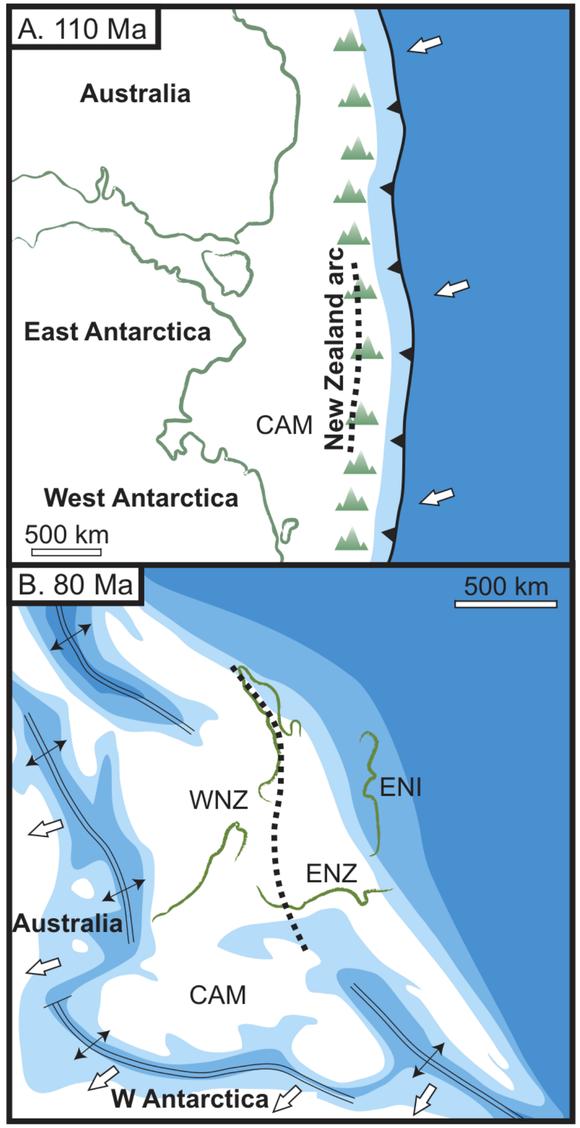
- 300-110 Ma:
  Gondwana margin subduction

- 95 Ma:
  Subduction ends, Marie Byrd Land

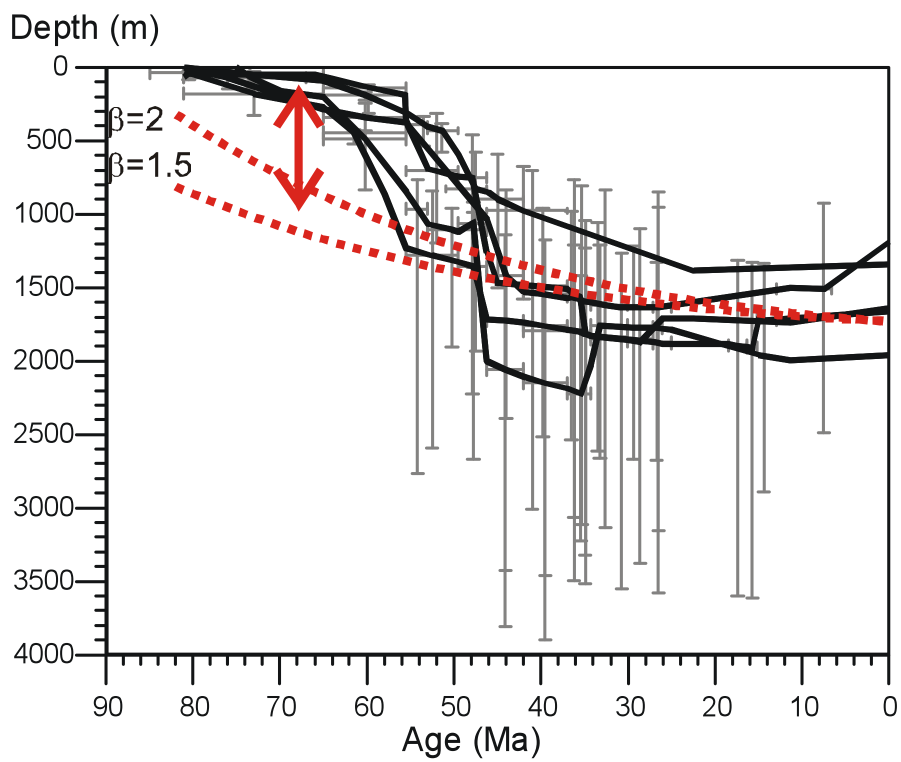
- 100-85 Ma:
  - Active rifting

- 85-0 Ma:
  - Seafloor spreading, S Pacific Ridge

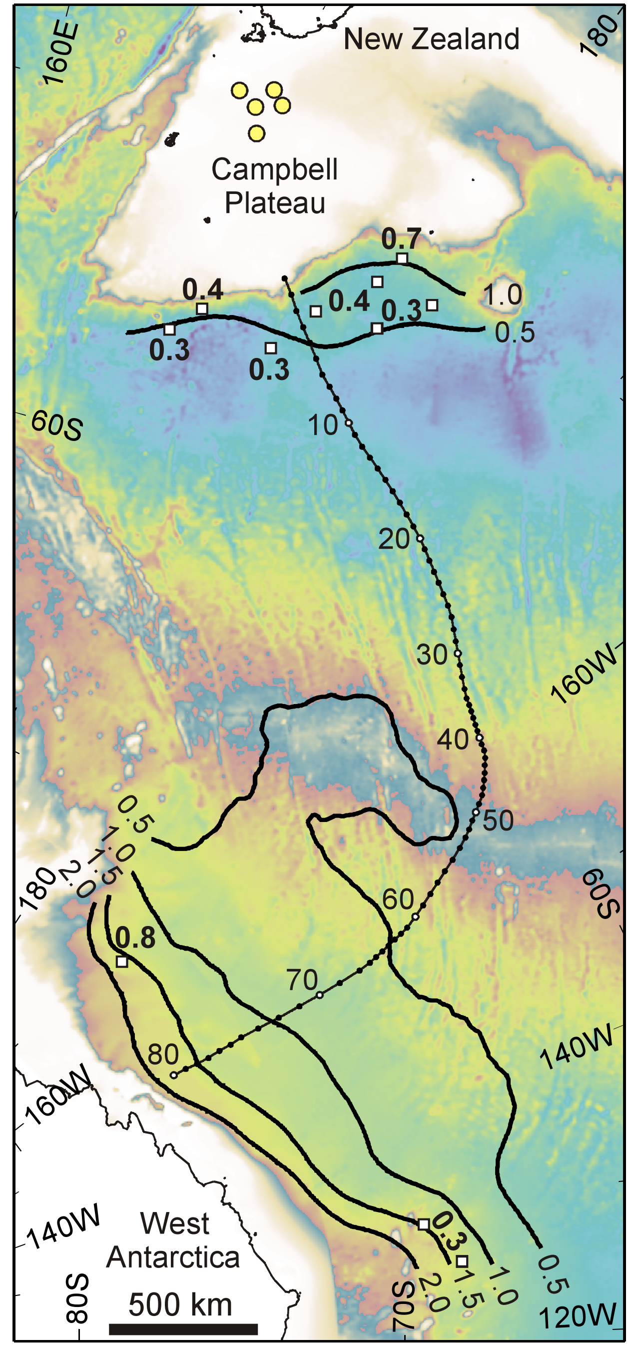
Cretaceous Paleogeography of the Ross Sea Region



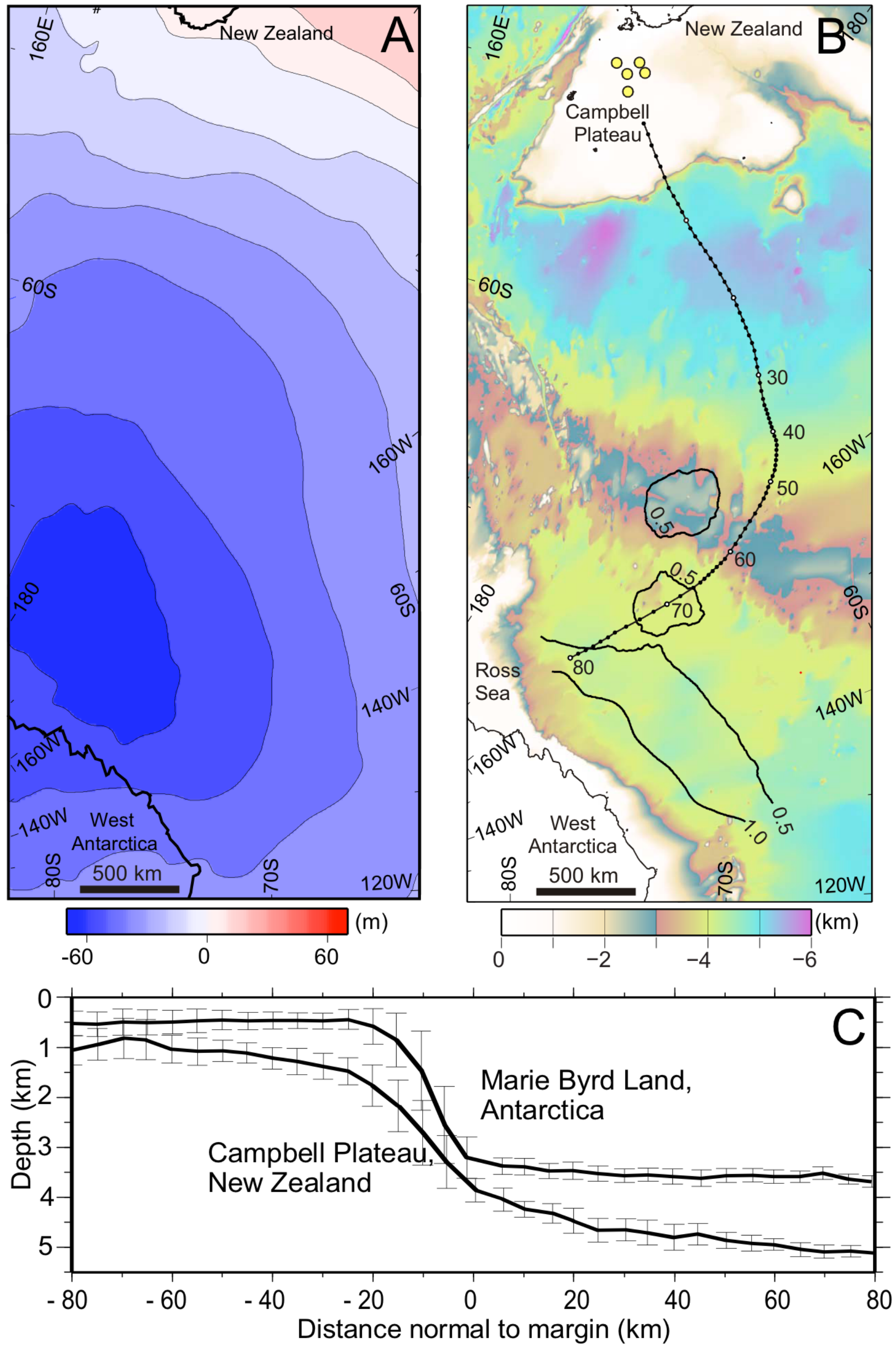
Campbell Plateau subsidence



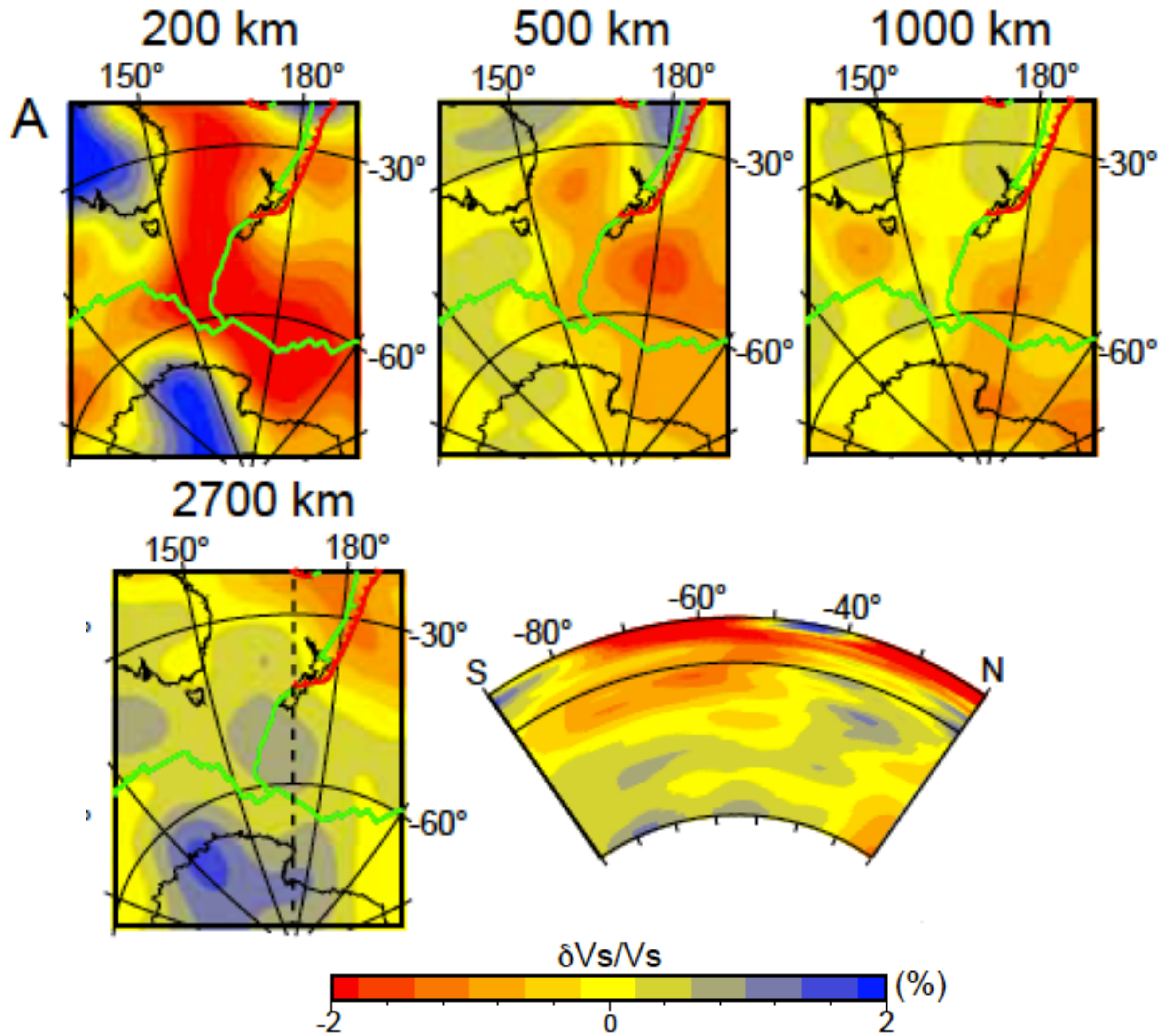
- Excess subsidence ~ 0.4-1.0 km
- Residual subsidence dies away 70-40 Ma



Sutherland et al. [2010]


A
New Zealand
160E
60S
160W
180
60S
140W
160W
140W
West
Antarctica
80S
500 km
70S
120W
(m)
-60
0
60
B
New Zealand
180
160E
Campbell
Plateau
60S
30
40
160W
50
0.5
60
0.5
70
180
60S
80
Ross
Sea
140W
160W
140W
West
Antarctica
0.5
1.0
80S
500 km
70S
120W
(km)
0
−2
−4
−6
C
Depth (km)
Marie Byrd Land,
Antarctica
Campbell Plateau,
New Zealand
Distance normal to margin (km)

Seismic tomography

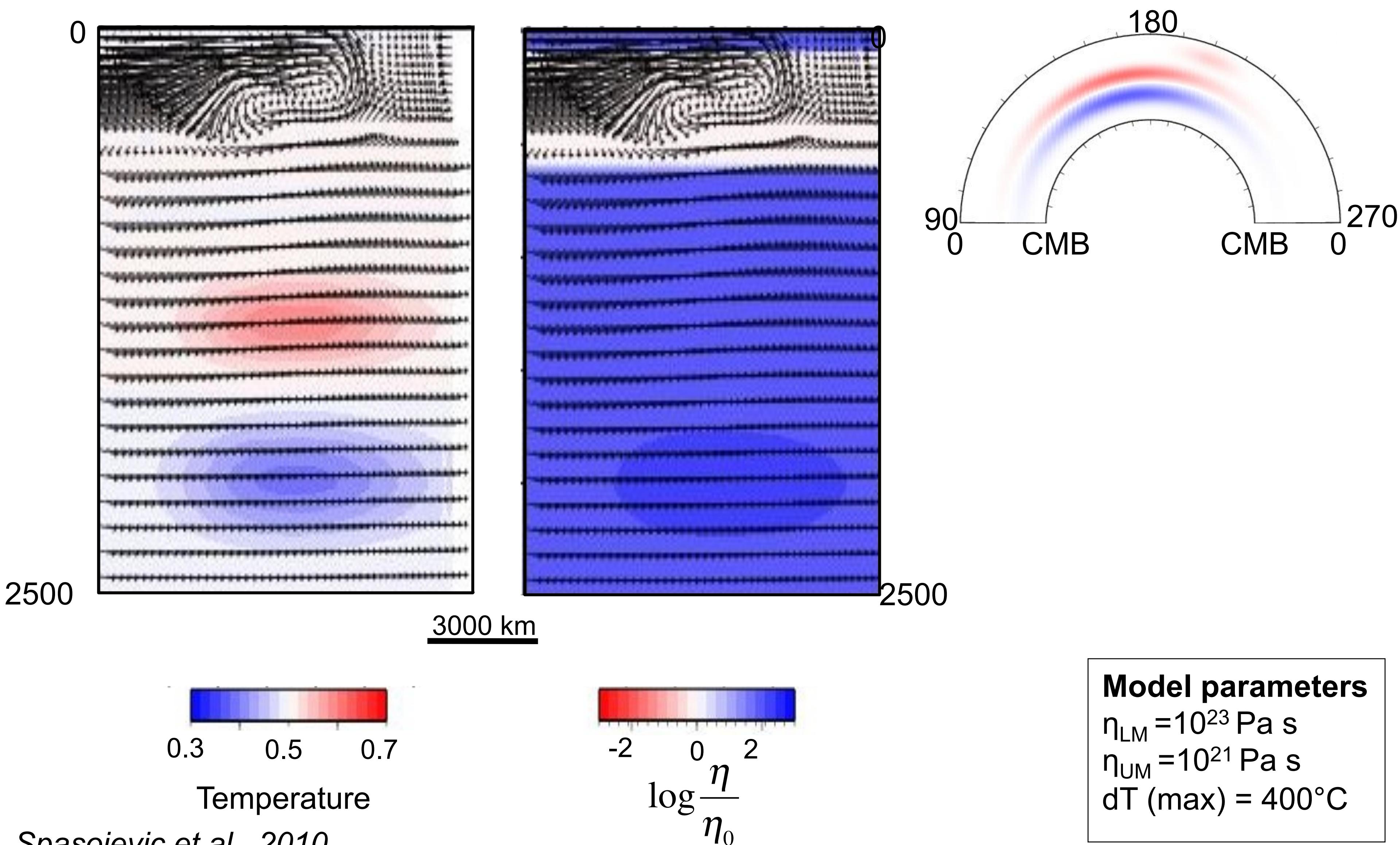


S20RTS tomography model

Motivation

- Can we simultaneously match in a single model
  - Time-evolution of dynamic topography (Campbell plateau)
  - Present-day observations of geoid, dynamic topography and seismic tomography?

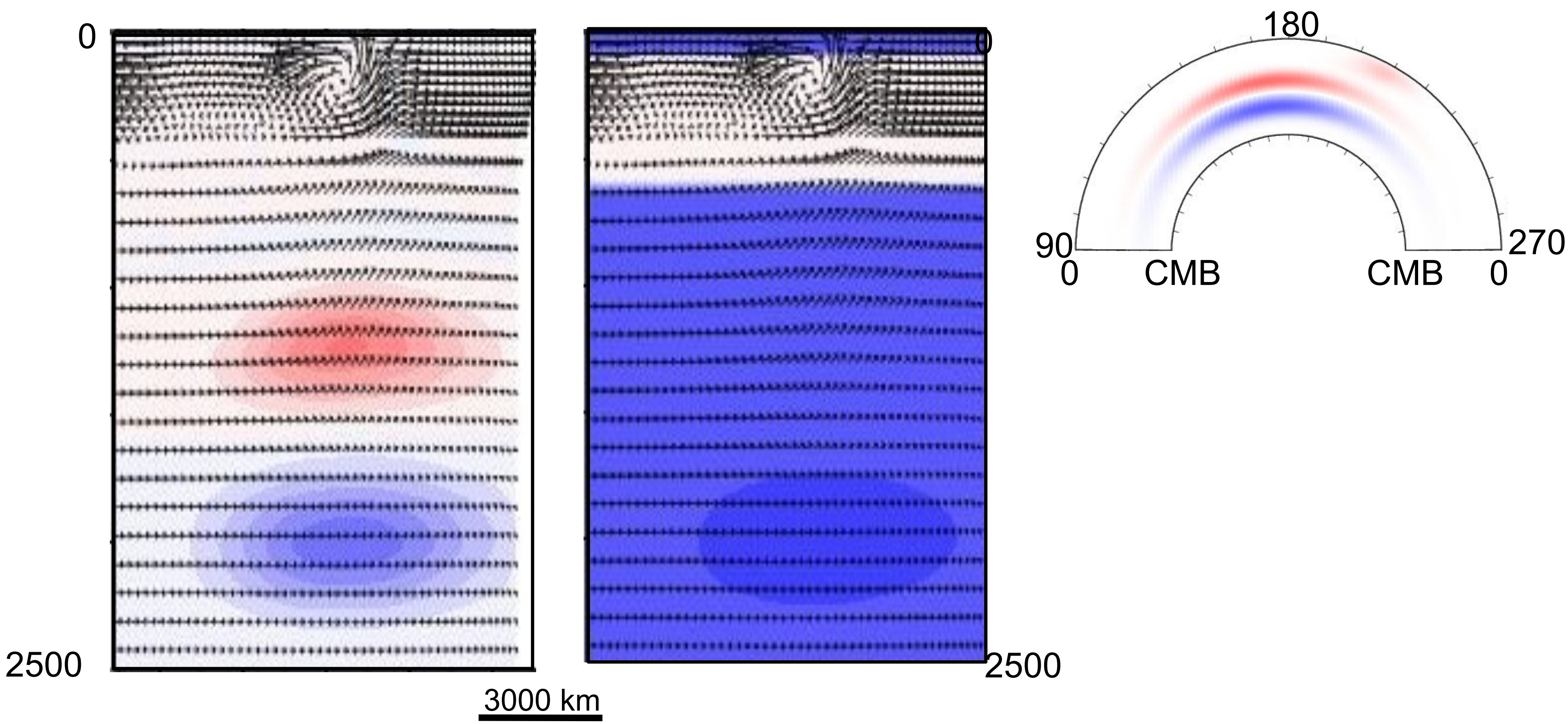
80 Ma



Model parameters
η_{LM} =10^{23} Pa s
η_{UM} =10^{21} Pa s
dT (max) = 400°C

Spasojevic et al., 2010

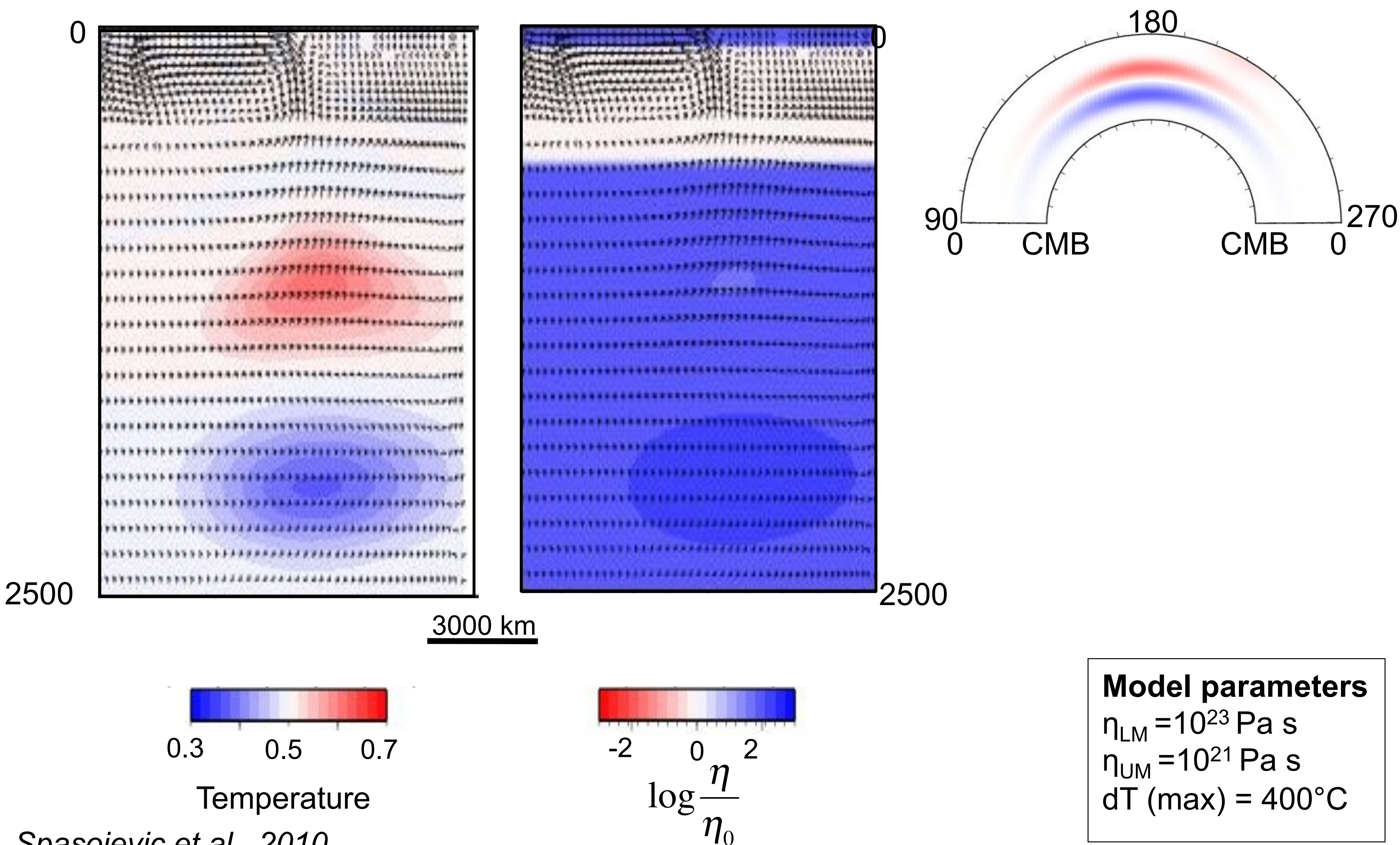
62 Ma



Model parameters
η_{LM} =10^{23} Pa s
η_{UM} =10^{21} Pa s
dT (max) = 400°C

Spasojevic et al., 2010

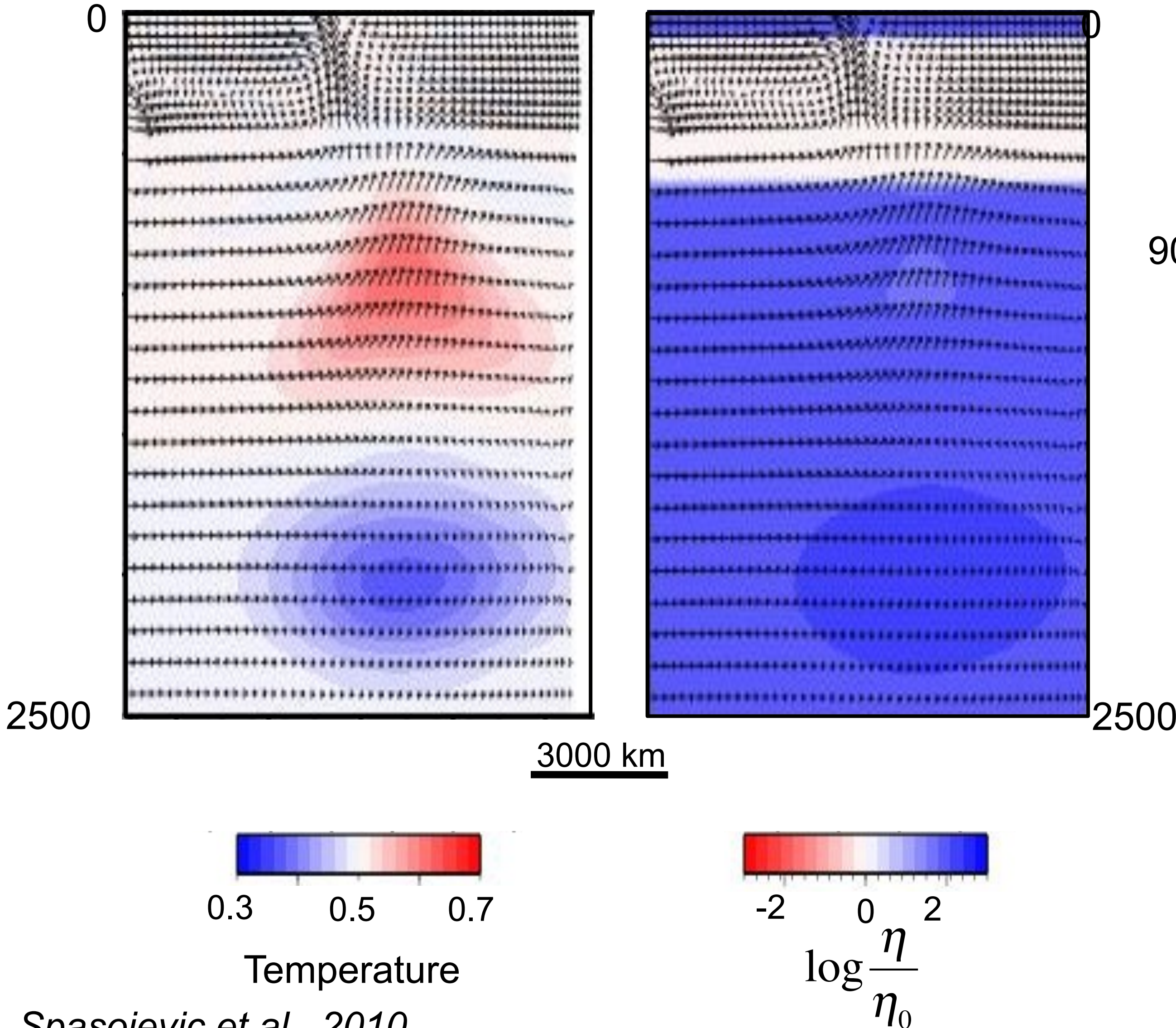
42 Ma

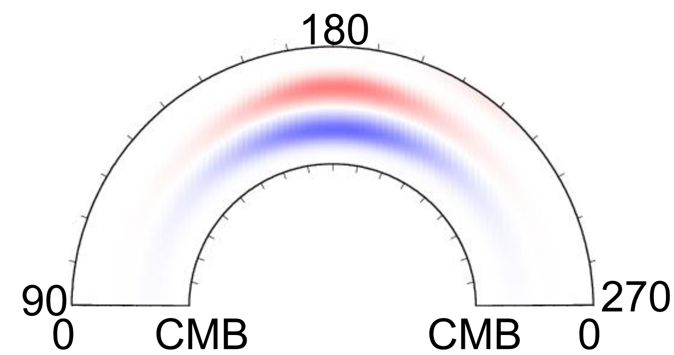


Spasojevic et al., 2010

Model parameters
η_{LM} =10^{23} Pa s
η_{UM} =10^{21} Pa s
dT (max) = 400°C

22 Ma

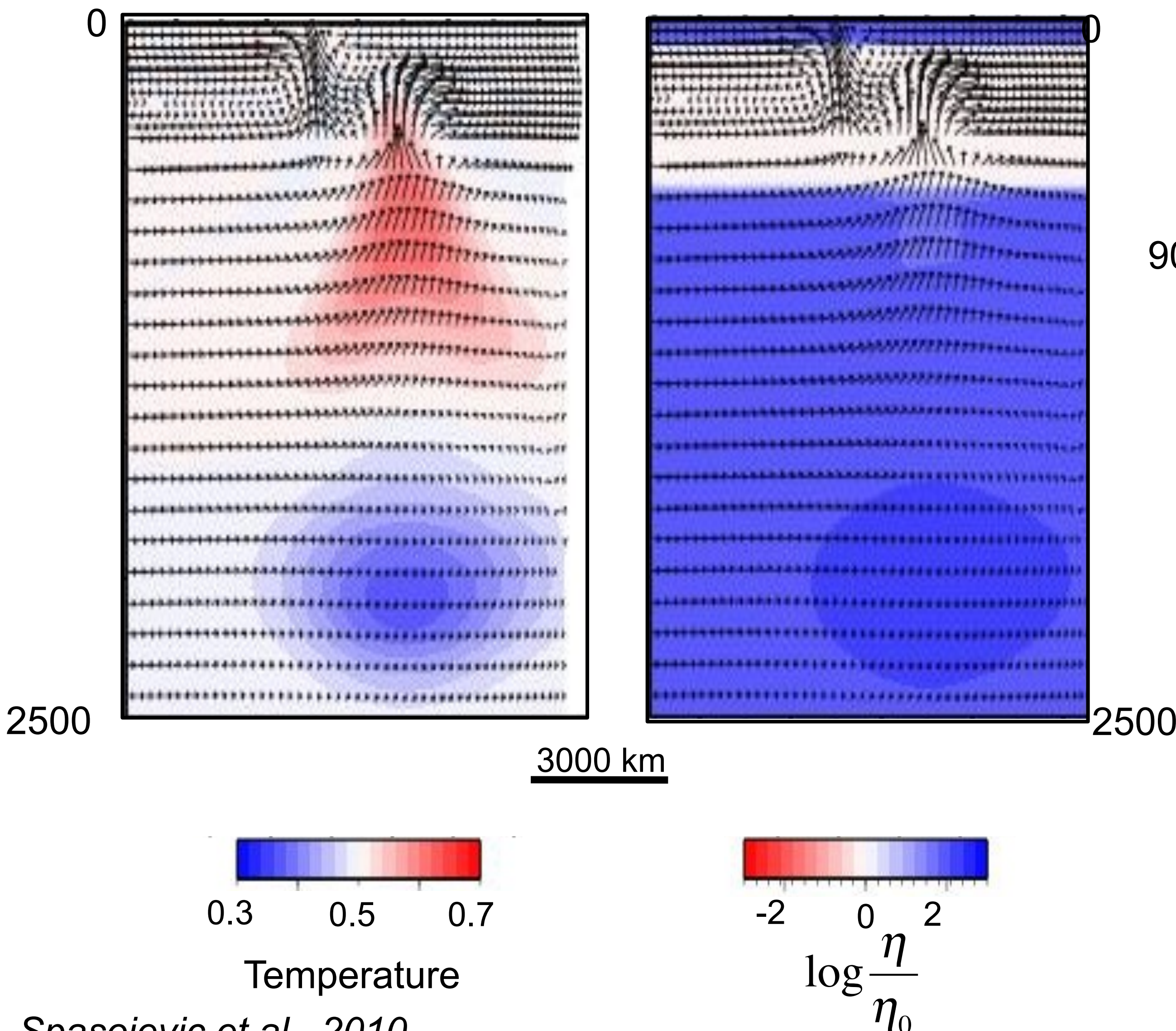


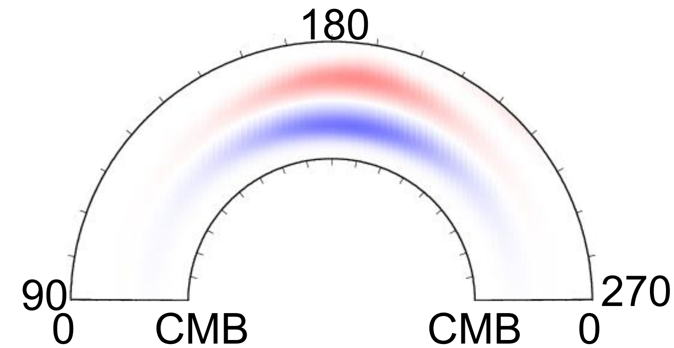


Model parameters
$\eta_{LM} = 10^{23}$ Pa s
$\eta_{UM} = 10^{21}$ Pa s
dT (max) = 400°C

Spasojevic et al., 2010

0 Ma

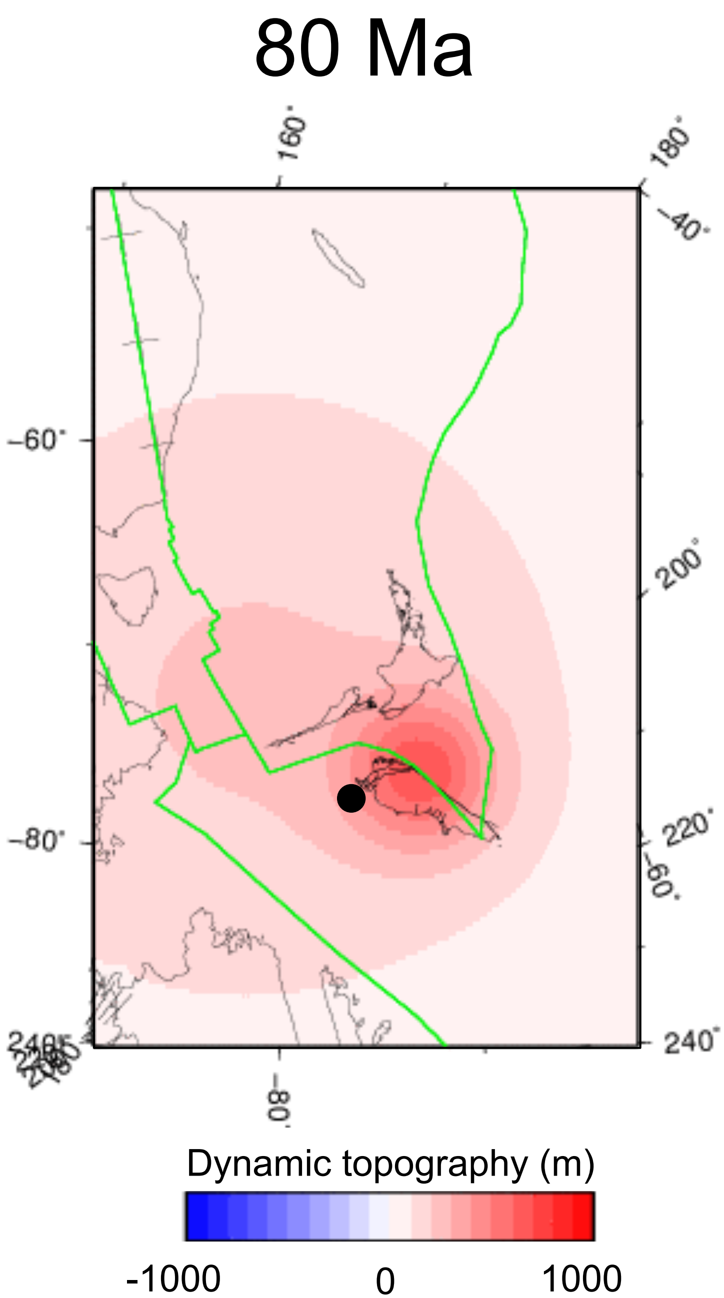




Model parameters
$\eta_{LM} = 10^{23}$ Pa s
$\eta_{UM} = 10^{21}$ Pa s
dT (max) = 400°C

Spasojevic et al., 2010

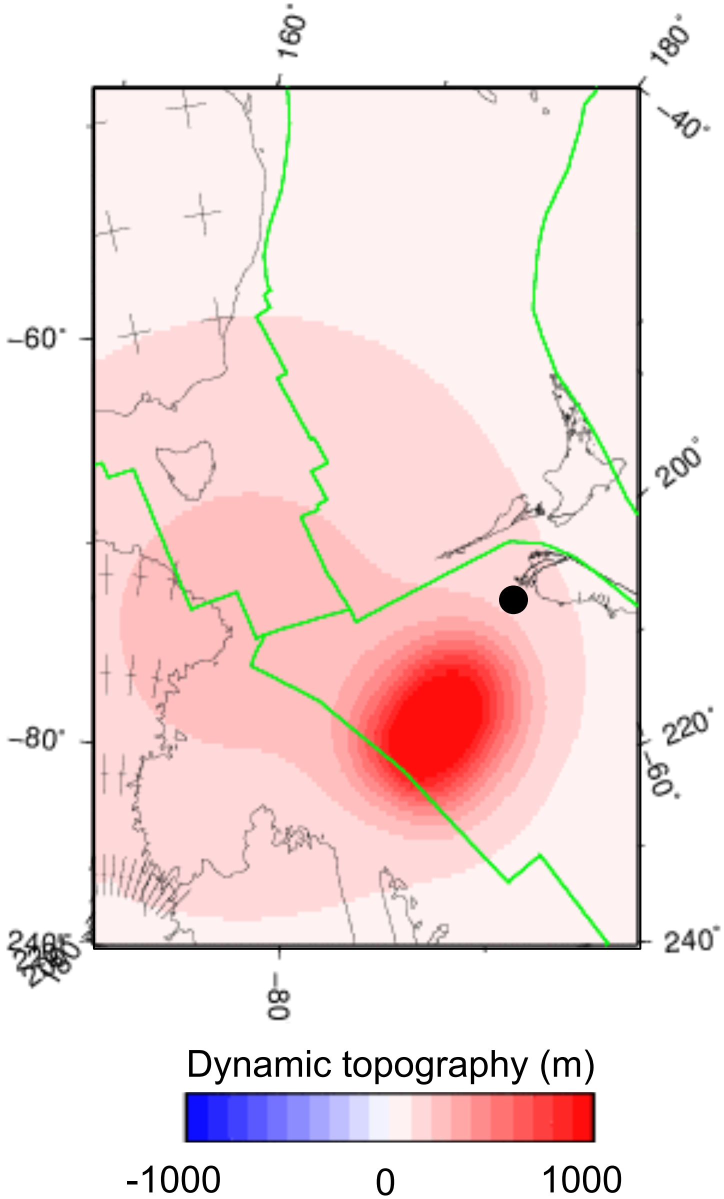
Campbell plateau subsidence



Spasojevic et al., 2010

Campbell plateau subsidence

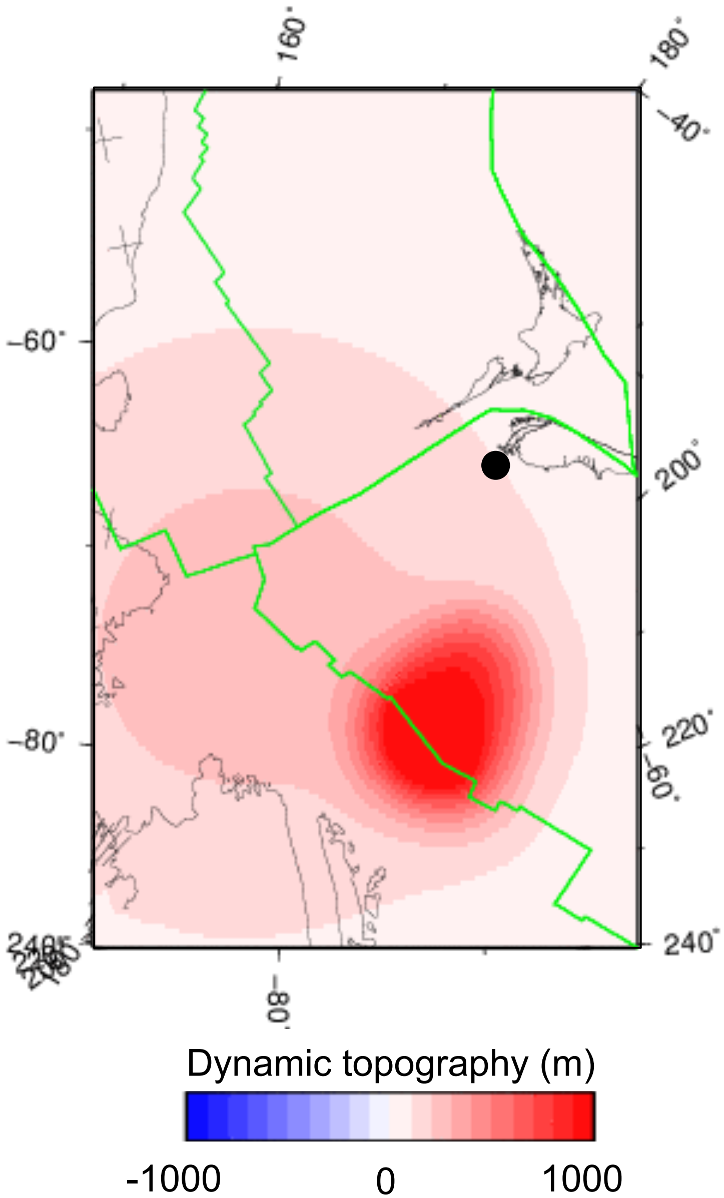
62 Ma



Spasojevic et al., 2010

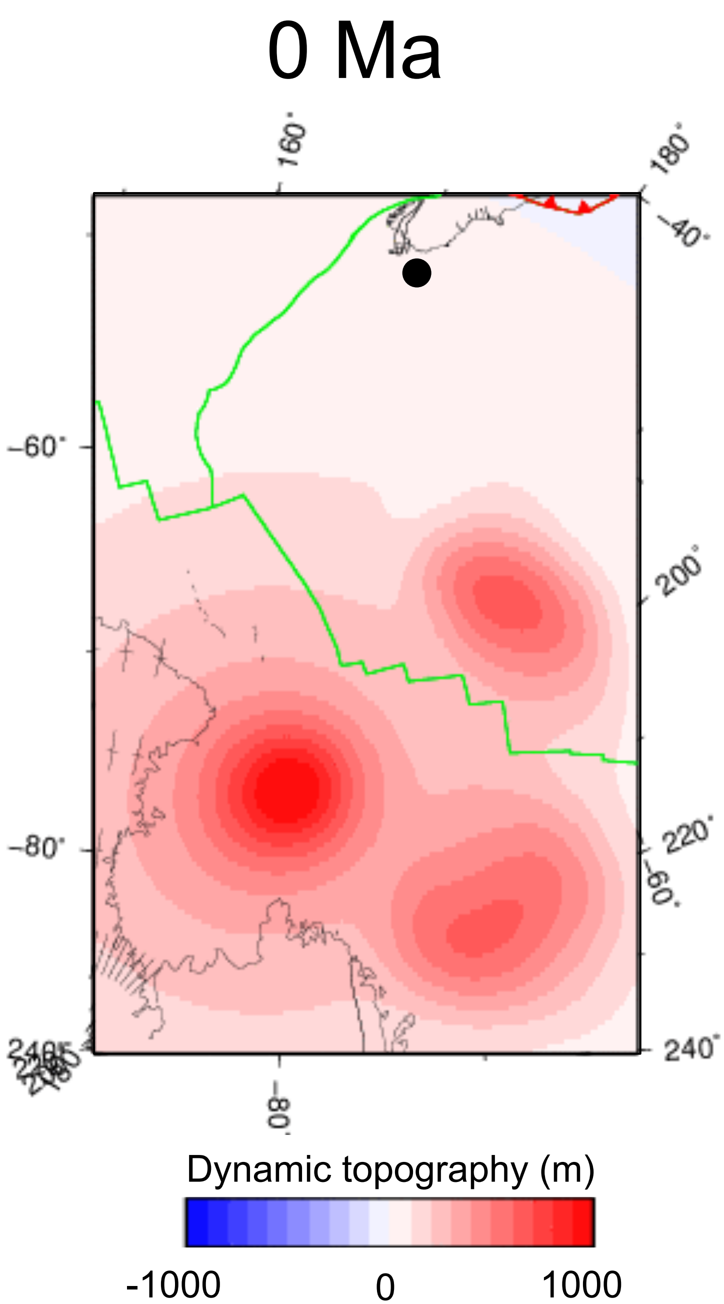
Campbell plateau subsidence

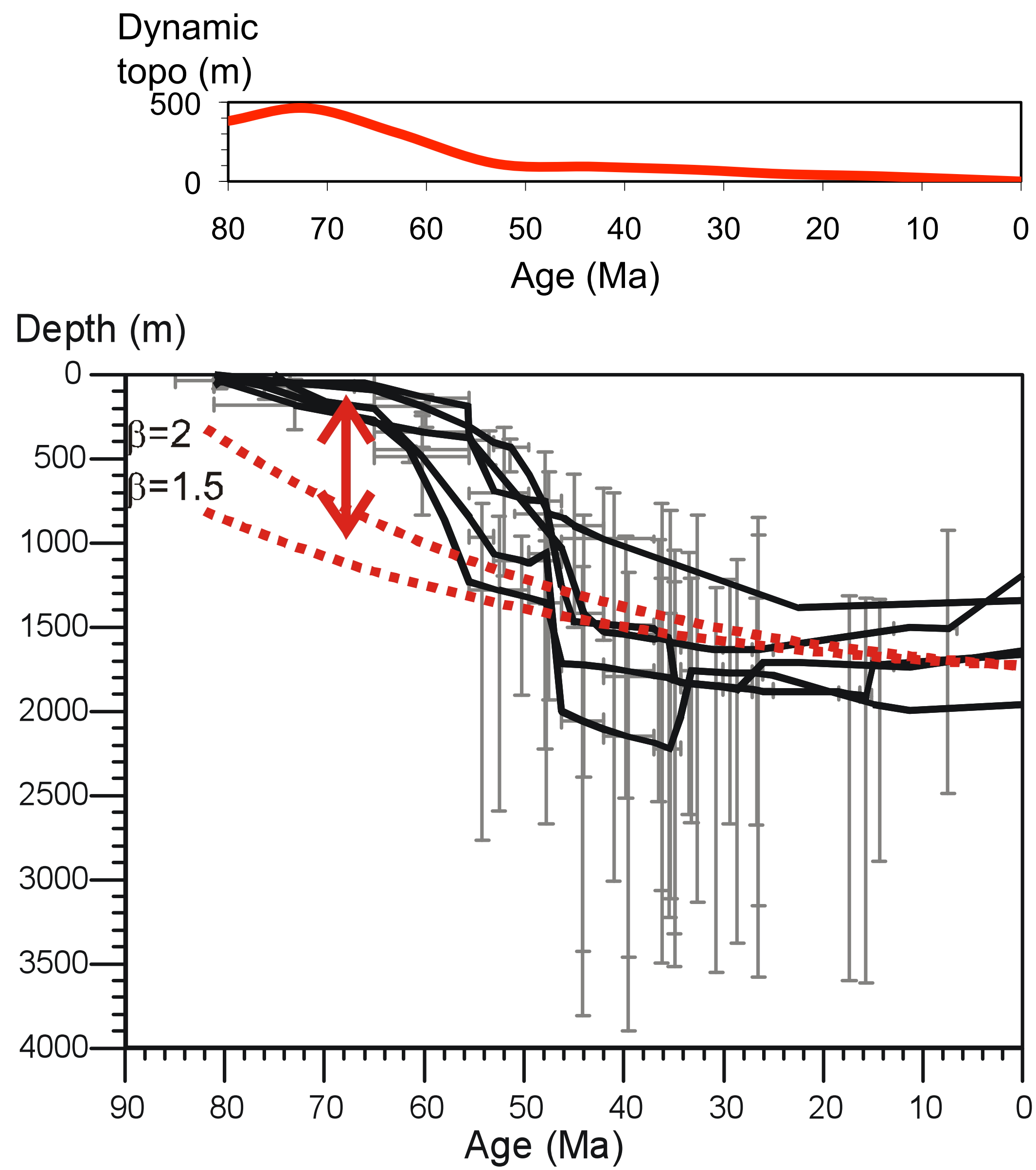
52 Ma

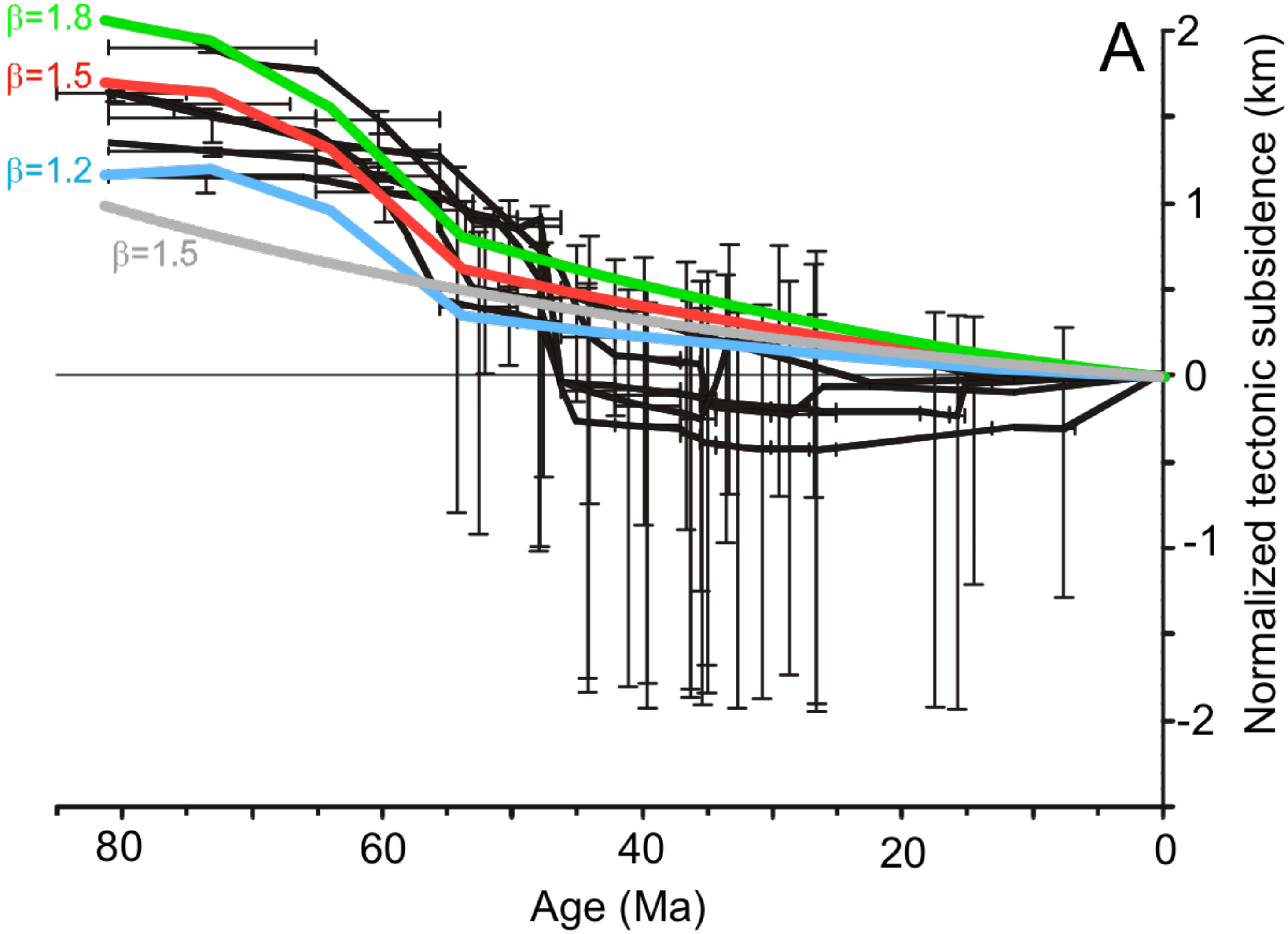


Spasojevic et al., 2010

Campbell plateau subsidence

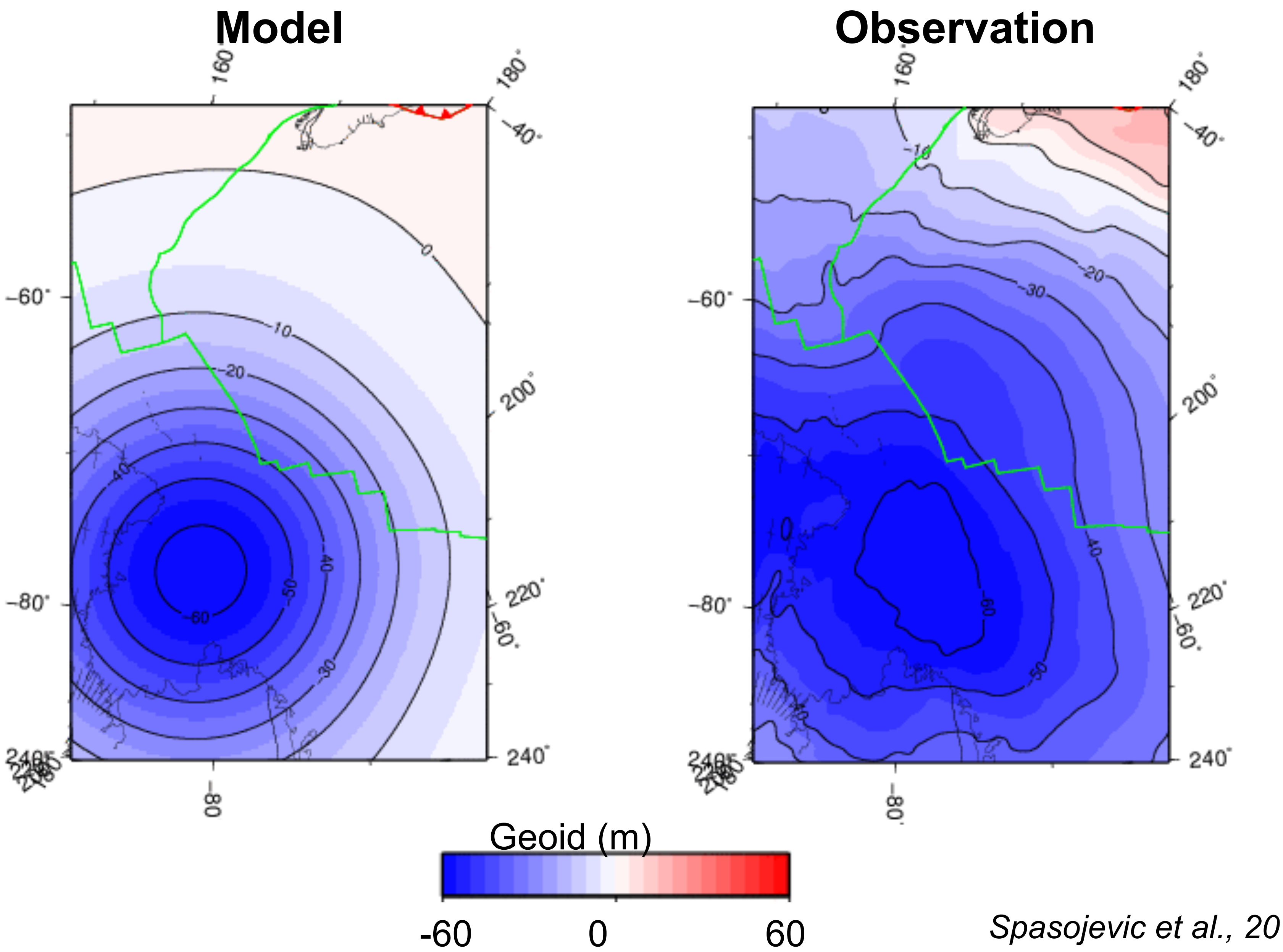





β=1.8
β=1.5
β=1.2
β=1.5
A
2
1
0
-1
-2
Normalized tectonic subsidence (km)
80
60
40
20
0
Age (Ma)

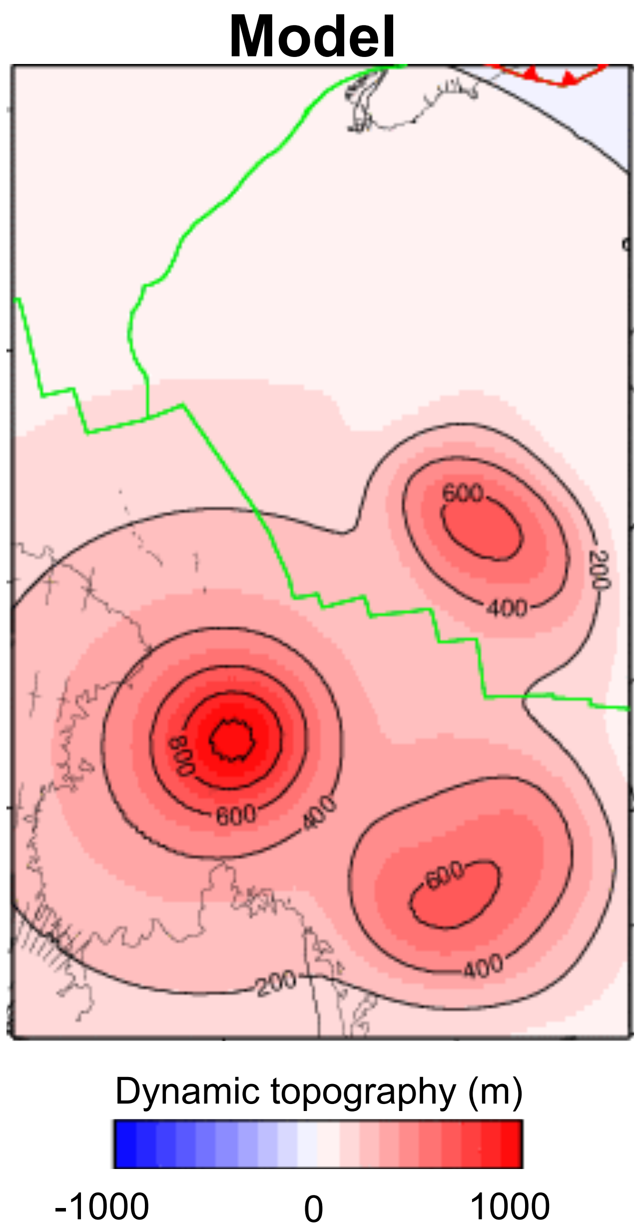

5
B
2

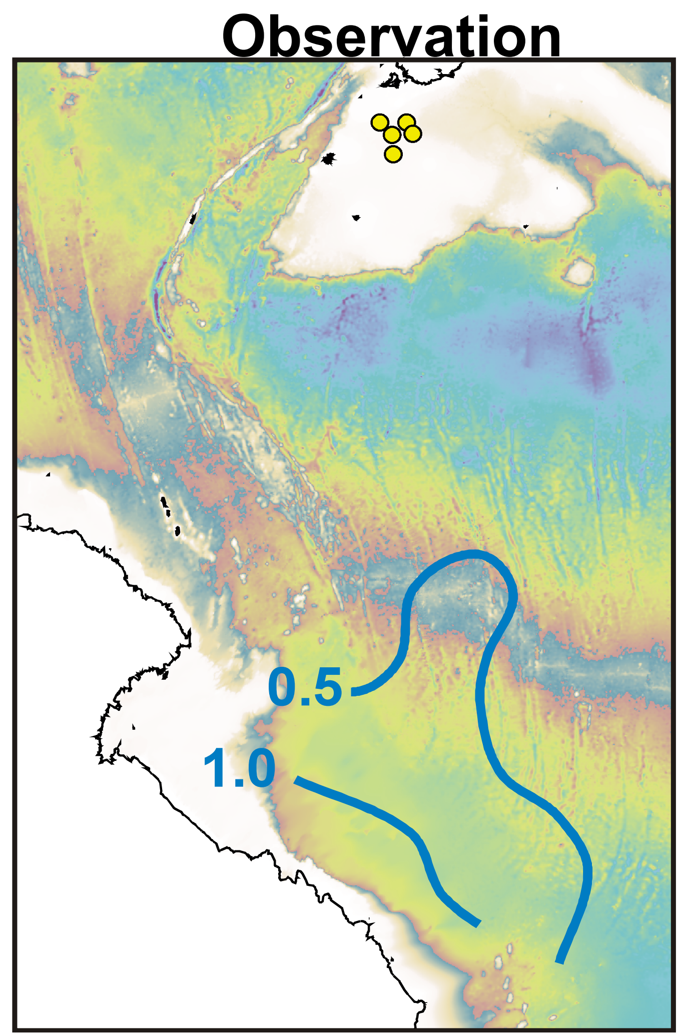
Geoid prediction



Spasojevic et al., 2010

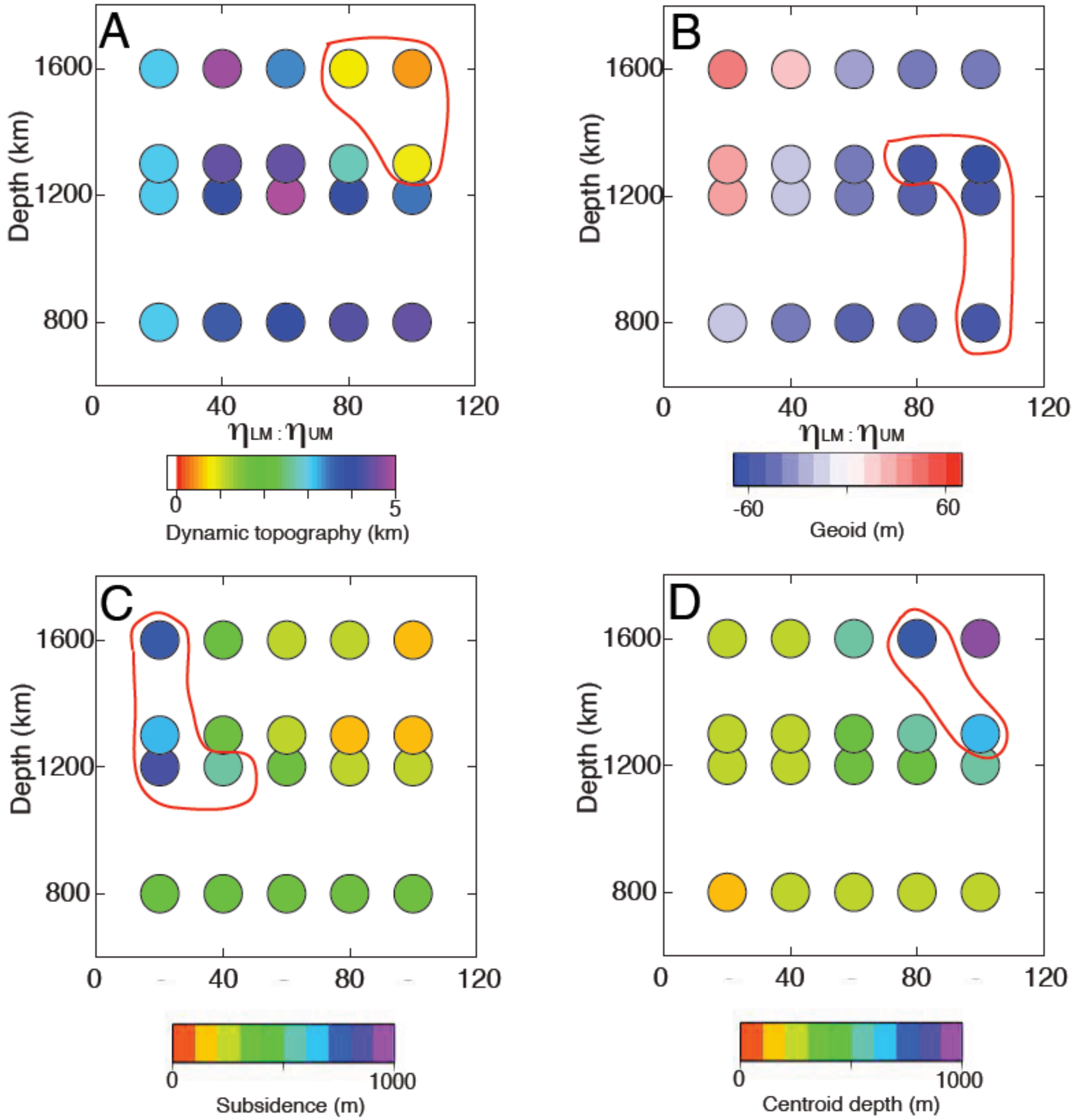
Topography prediction





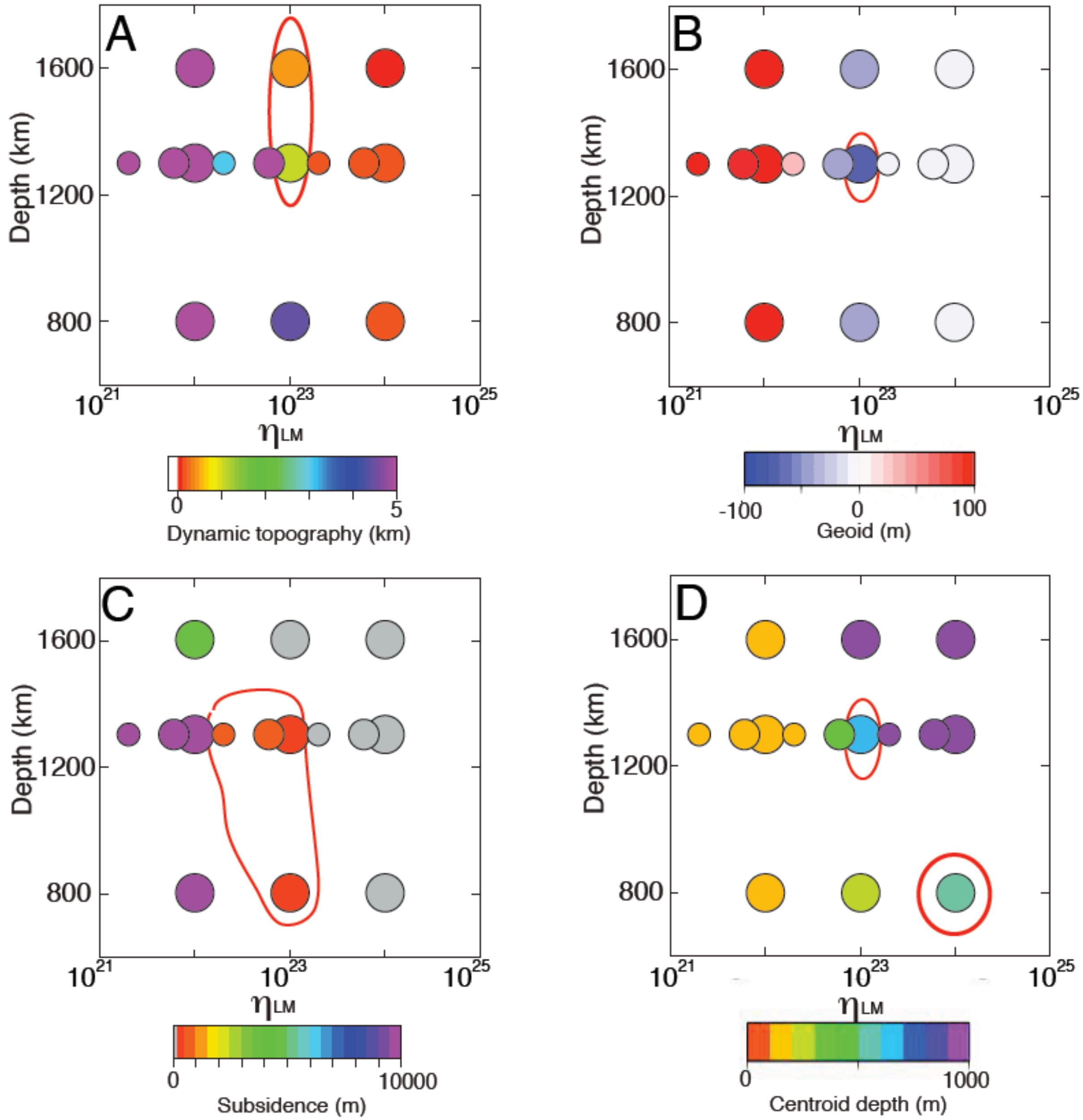
Spasojevic et al., 2010

Viscosity inferred: relative ratios



Spasojevic et al., 2010

Viscosity inferred: absolute value



Spasojevic et al., 2010

Take Away Message

- Time-dependent constraints on surface evolution provide constraints on earth dynamics when they are combined with present-day geophysical observations.
- Alone, neither tomography nor surface observations (such as vertical motions) provides us with a 4-D view of the earth's interior. But tomography, surface constraints, and plate motions, linked through a geodynamic model, does provide us with a 4-D framework of the interior.
- That framework provides not only a context to interpret observations, such as to pose new testable predictions in time and space, but it is also a vehicle to better understand earth dynamics.

Some Limits, controversies and upcoming developments

- Sharp and localized viscosity variations can have a significant impact on surface topography and geoid. As such, the short variations in topography (~200 km and less) can change significantly.
- There are no crustal thickness variations in the global sea level models (stay-tuned, the new *GPlates* and our present reconstructions have deforming plates).
- There are significant controversies regarding:
  - The plate reconstructions in the Pacific before 60 Ma. The reconstruction that we use has an age distribution with increasing ages since Cretaceous and this is the largest driver on the ‘average’ fall in global sea level.
  - The model predictions for the vertical motions on the U.S. east coast are slow dynamic subsidence. Other model arguments suggest that the region could be uplifting. Great opportunity for U.S. Array.