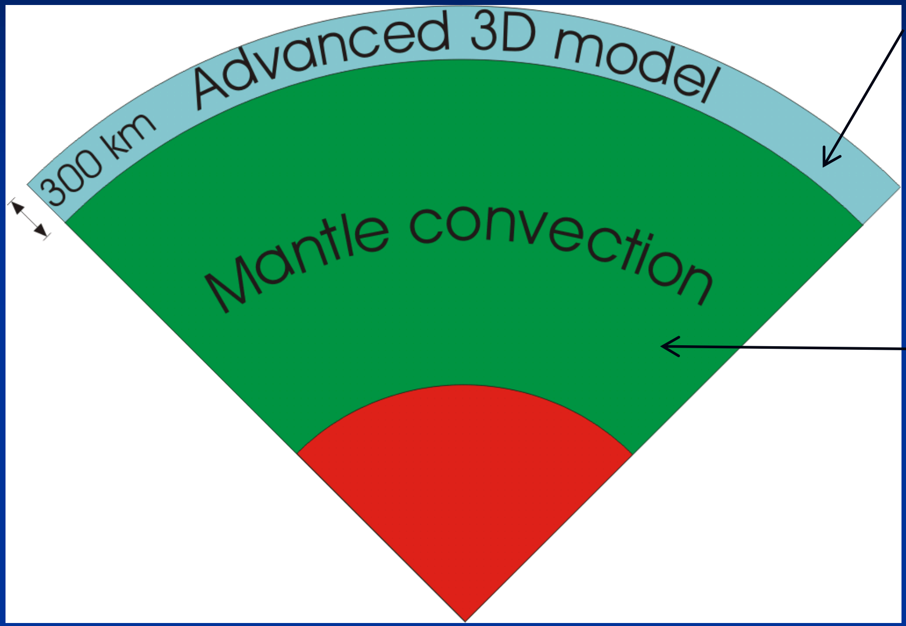
Remind from previous lectures

Coupling mantle convection and lithospheric deformation

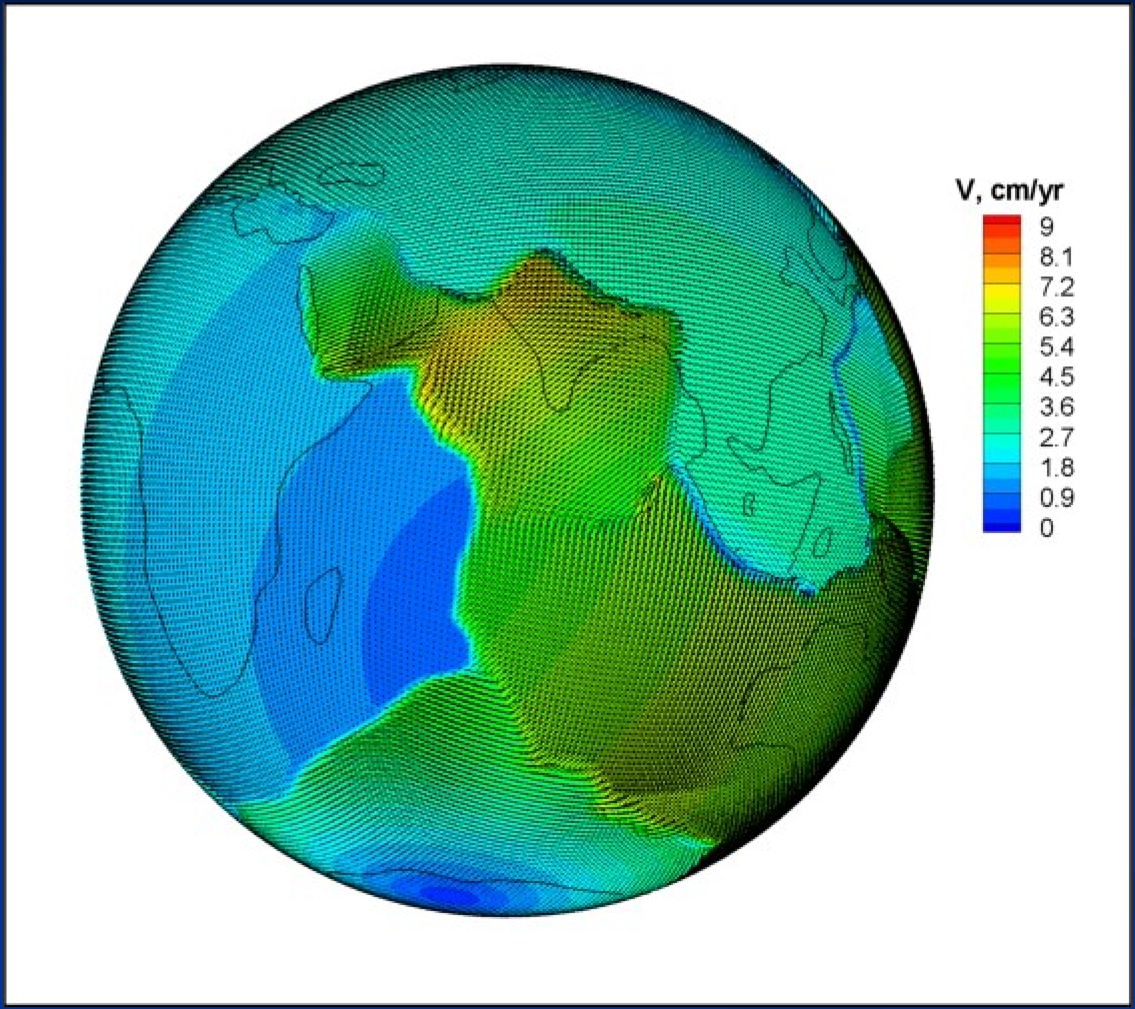


Lithospheric code (Finite Elements)

Mantle code (spectral or FEM)

Mantle and lithospheric codes are coupled through continuity of velocities and tractions at 300 km.

Friction at boundaries 0.02 (Smax= 30 MPa)



about right magnitudes of velocities

How to make friction so low?

$$\tau = c + \mu \cdot (\sigma_n - P_f)$$

$$\tau = c + \mu_{eff} \cdot \sigma_n$$

$$\mu_{eff} = \mu \cdot (1 - P_f / \sigma_n)$$

Assume μ = 0.6, P_f=0.95σ_n

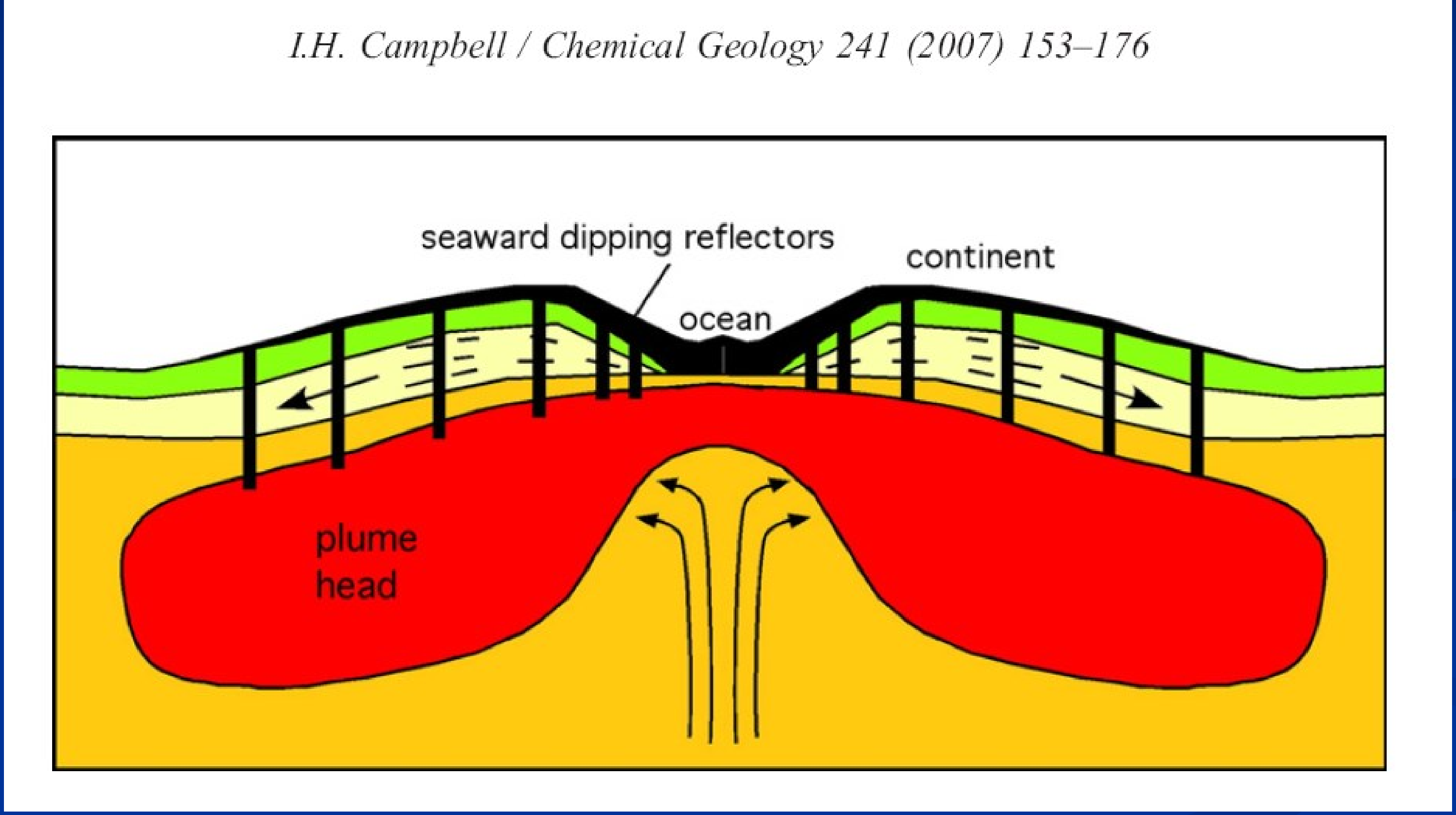
then μ_{eff} = 0.03

How to make friction so low?

then μ_{eff} = 0.03

Subducting slabs are aquaplaning deep into the mantle!

Problems of classical plume model

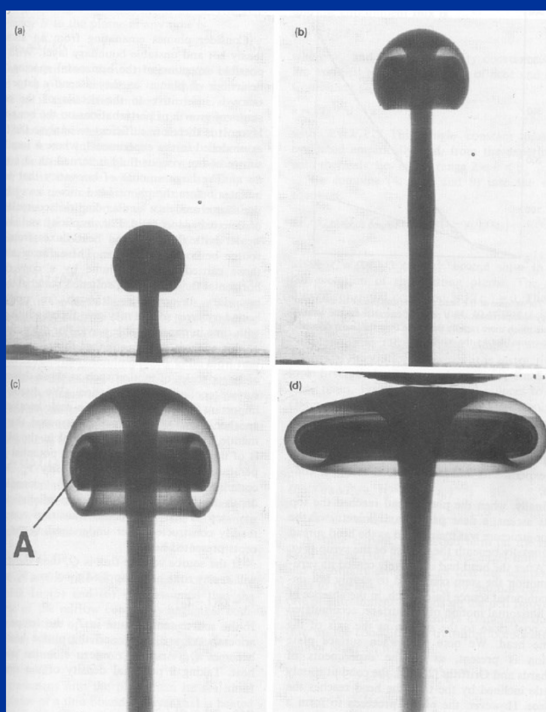


Prediction: Surface uplift = 0.7-1.0 km/100°, i.e. 1.4-3 km for DT= 200-300°

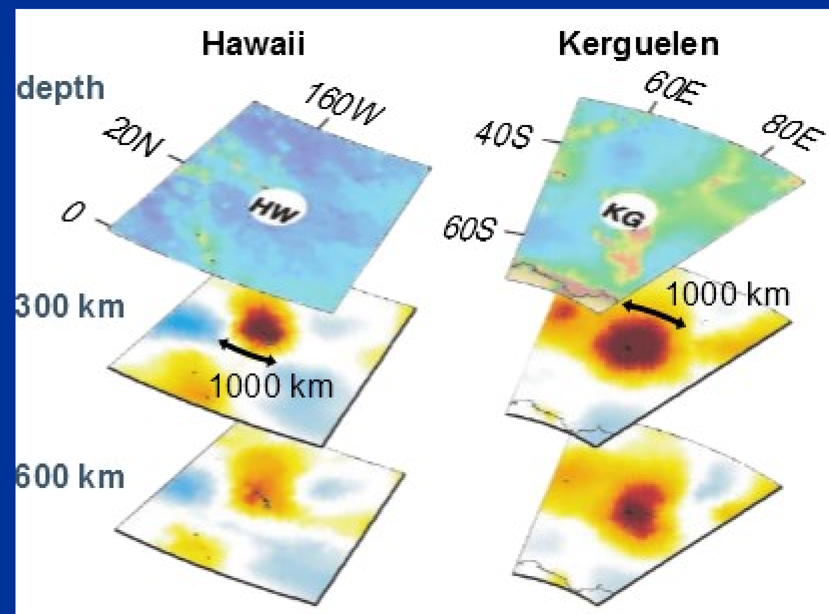
Observation: Often less than 1 km or even not detectable surface uplift

Problems of classical plume model

Prediction: narrow (R=100km) plume conduits (tails)



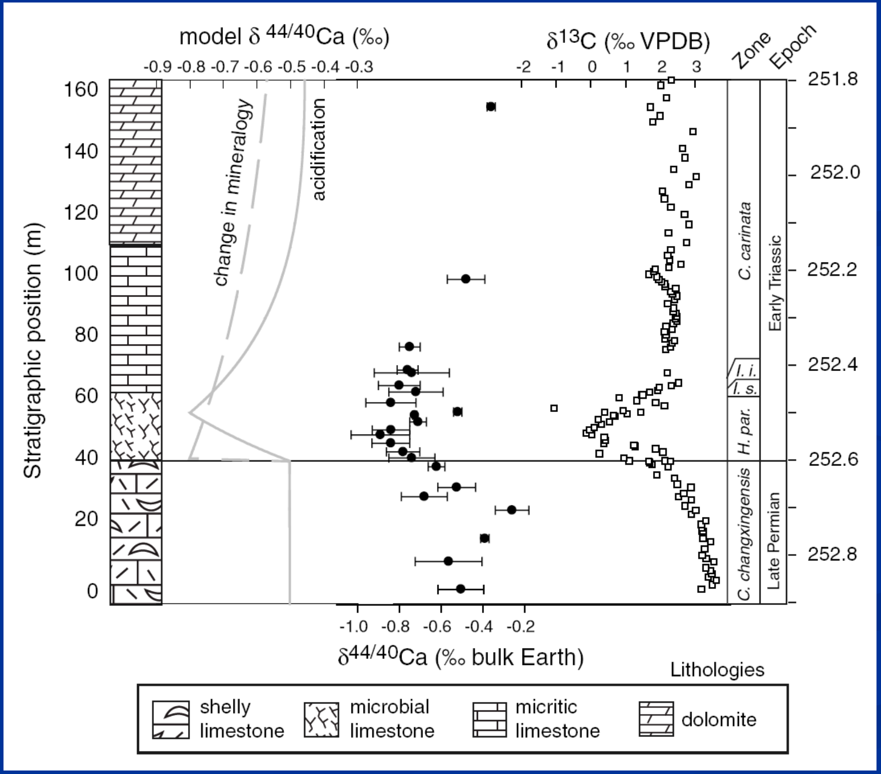
Seismic observations:
wide (R=500km) plumes



From Montelli et al., 2006

Problems of classical plume model

Volumes and isotopic composition of gases expected from eruptions above plume heads are not sufficient to explain observations for mass extinctions

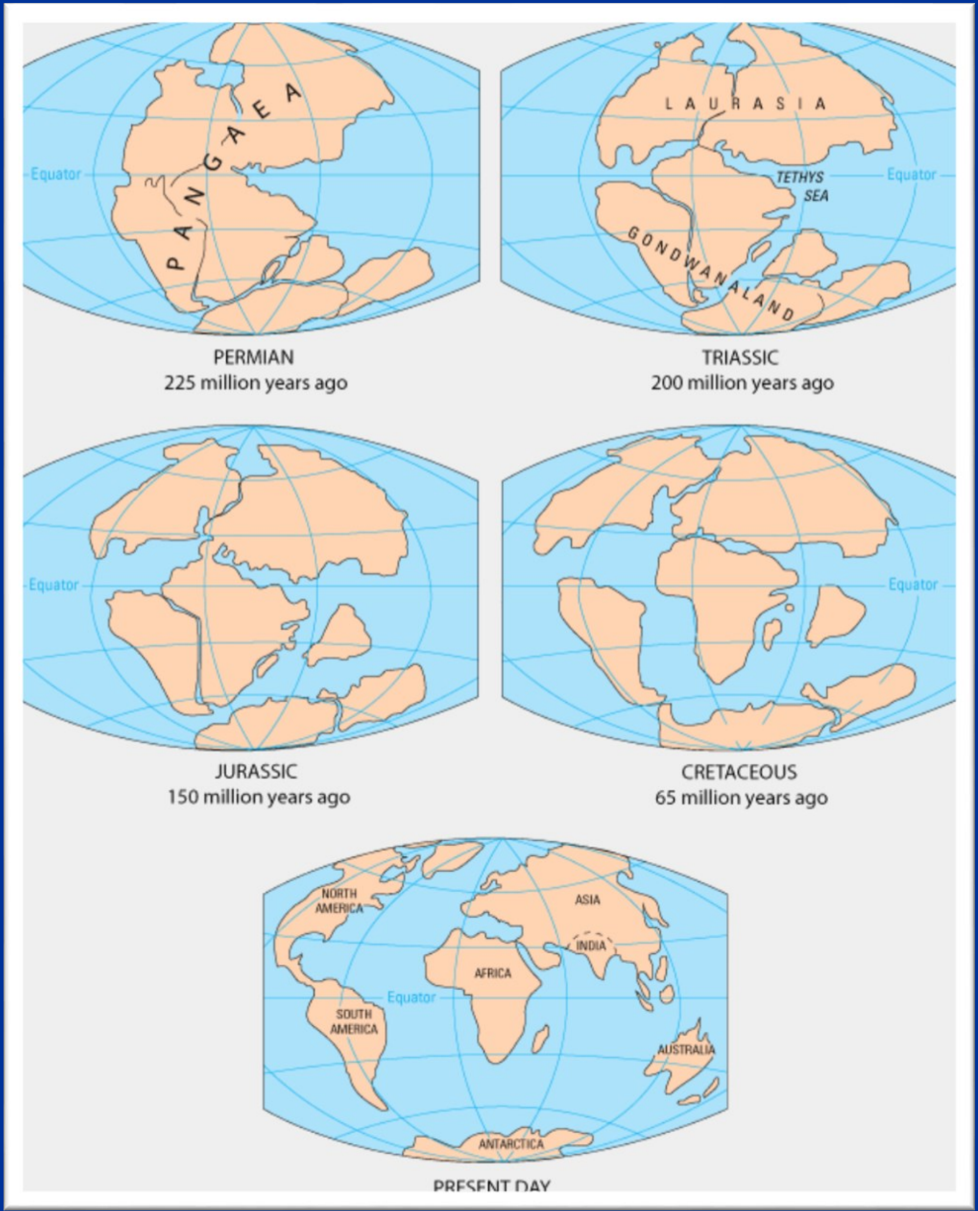


Lecture 5. Rifting, Continental break-up, Transform faults

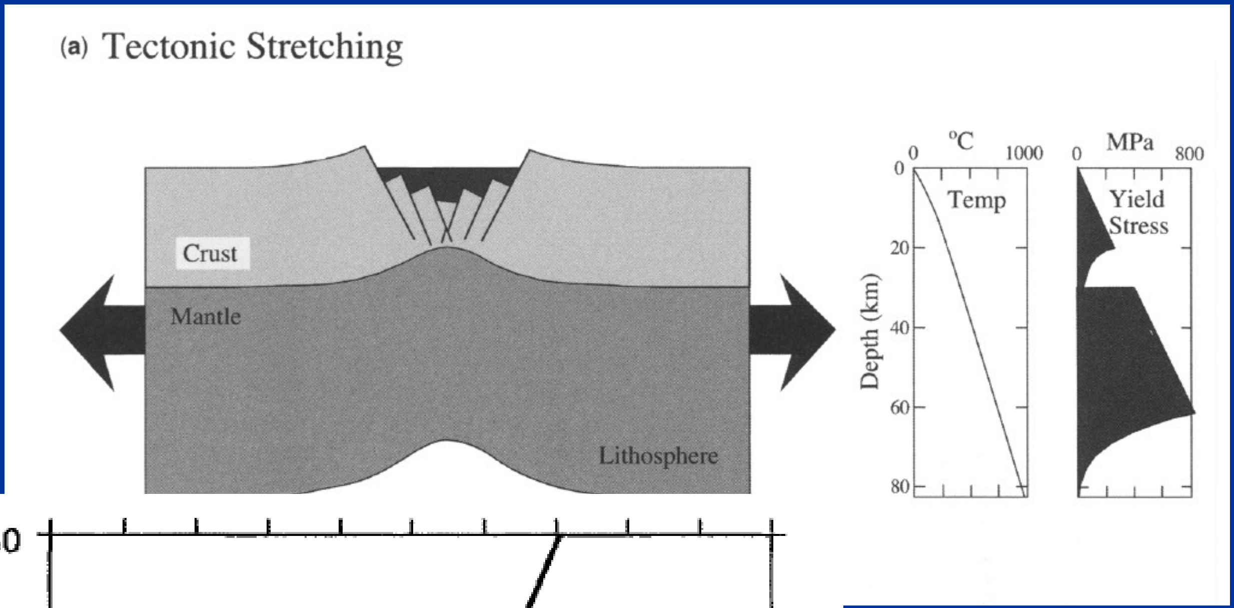
- How to break a continent?
  - Effect of magmas and Large Igneous Provinces
  - Effect of oblique rifting
- Continental transform faults
  - What caused Dead Sea transform?
  - San Andreas Fault System

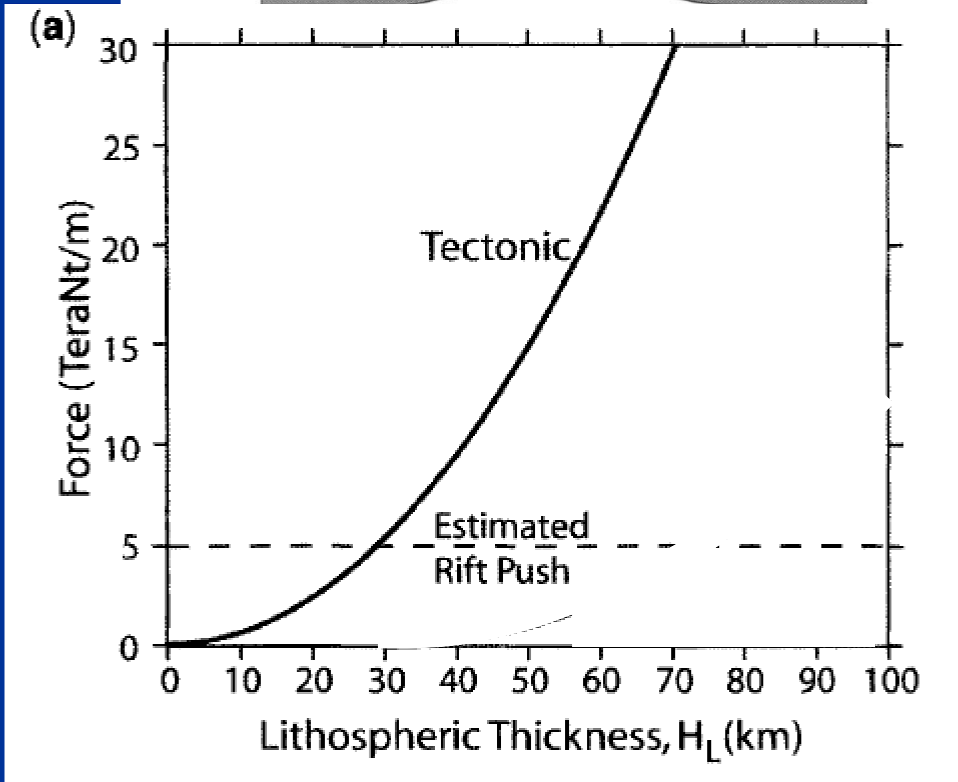
Continental break-up

Continental break-up



How to break continent?

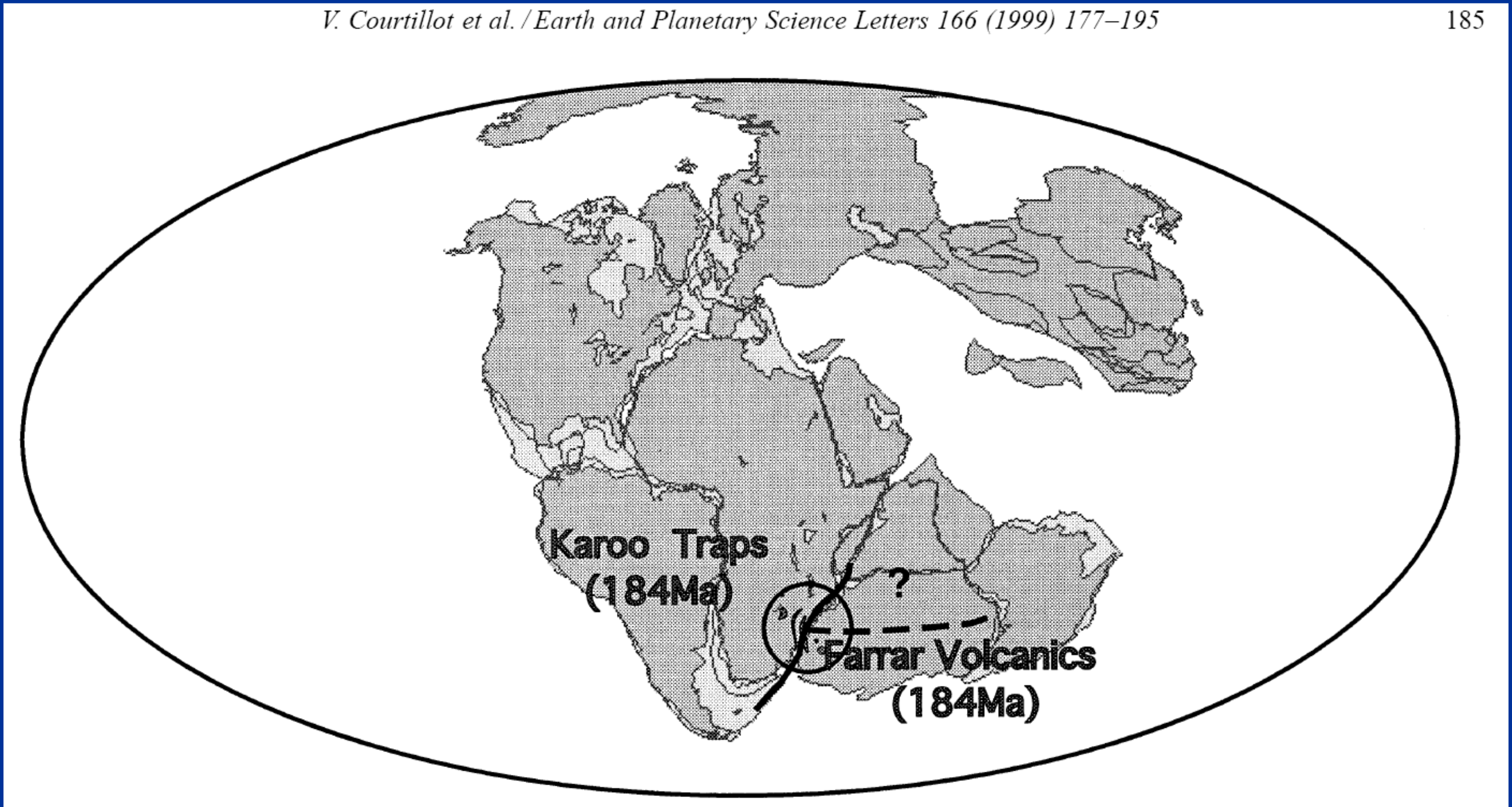




Cold lithosphere is too strong

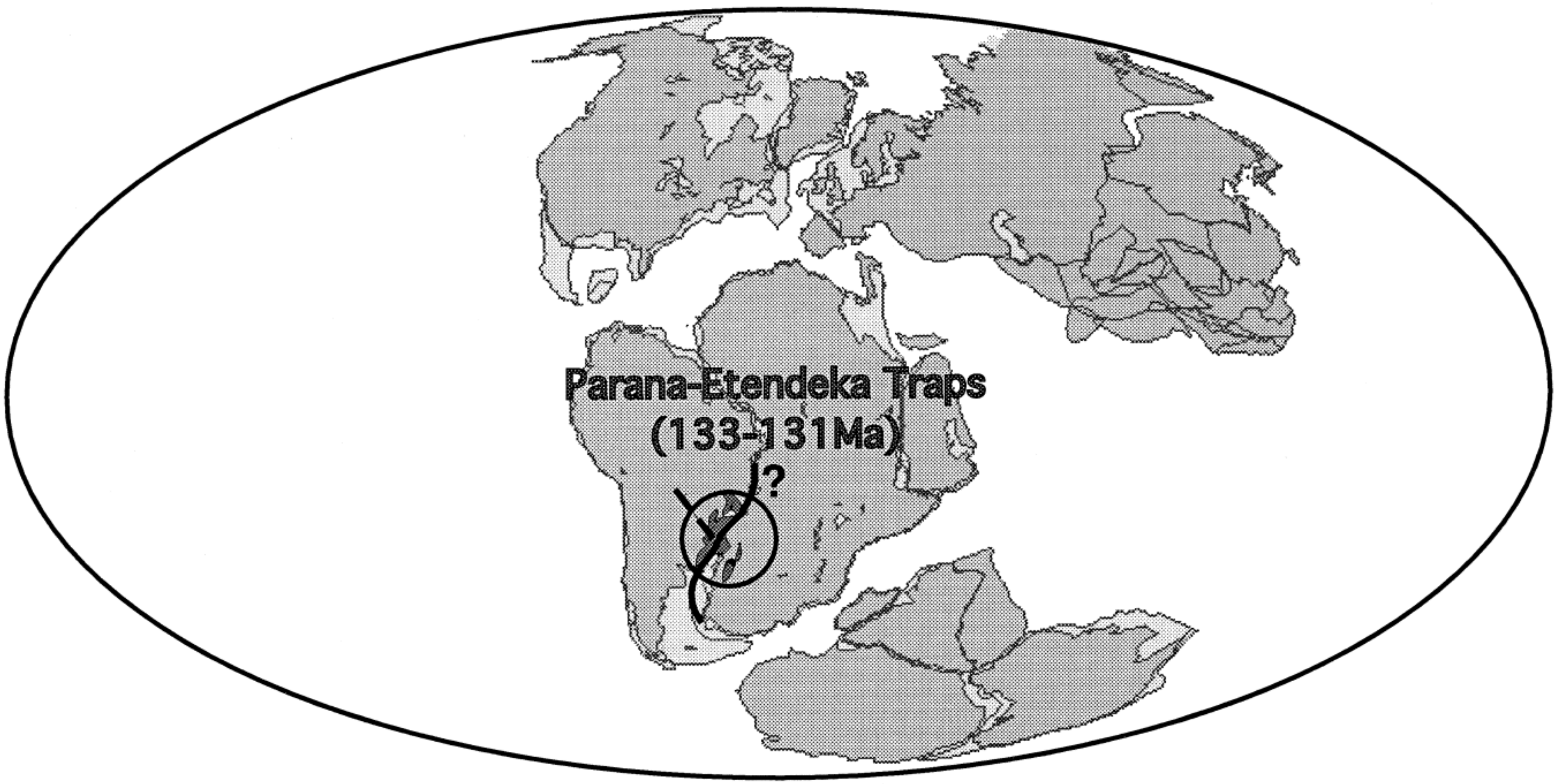
Buck (2006)

Continental break-up

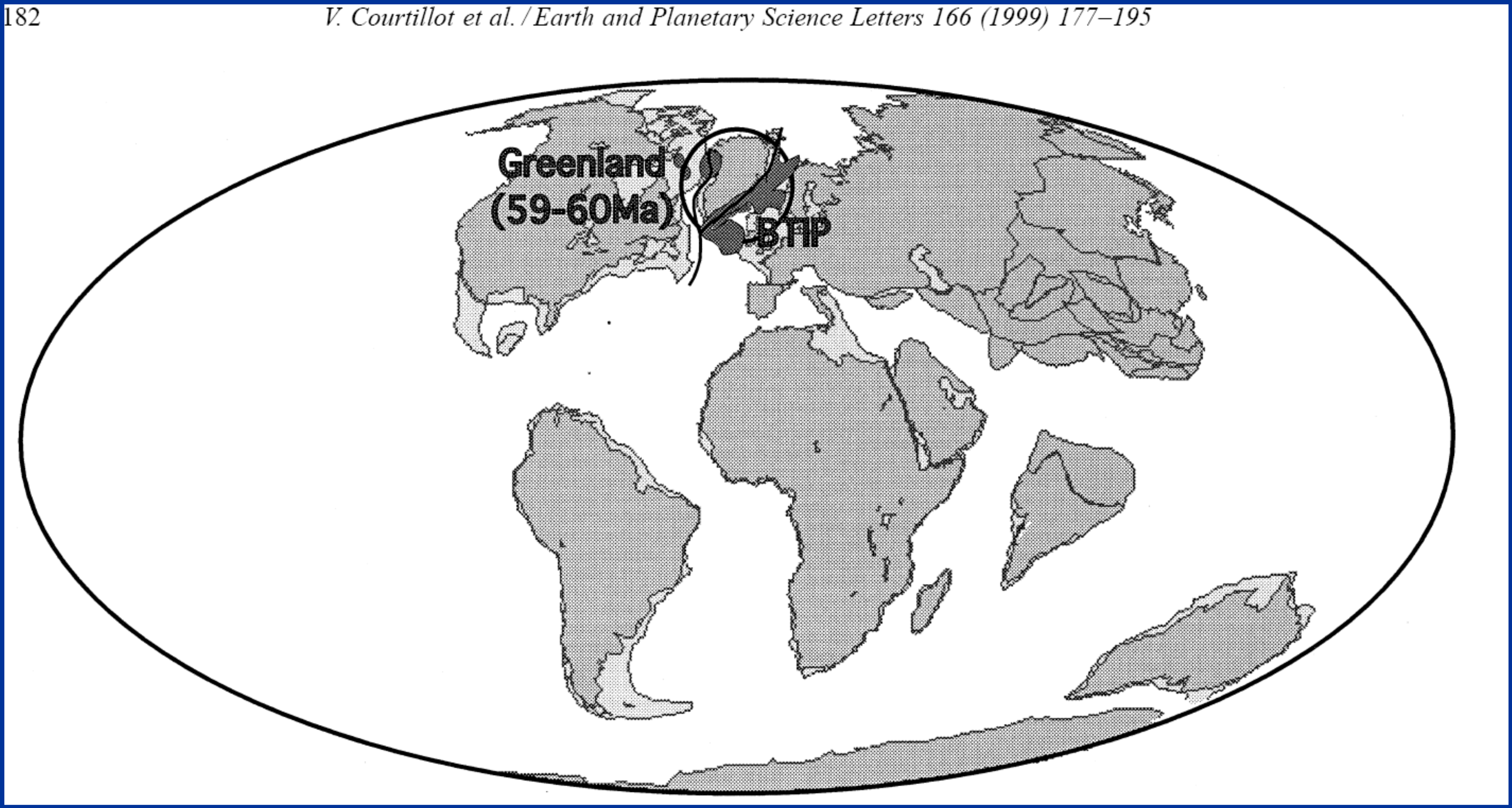


Continental break-up

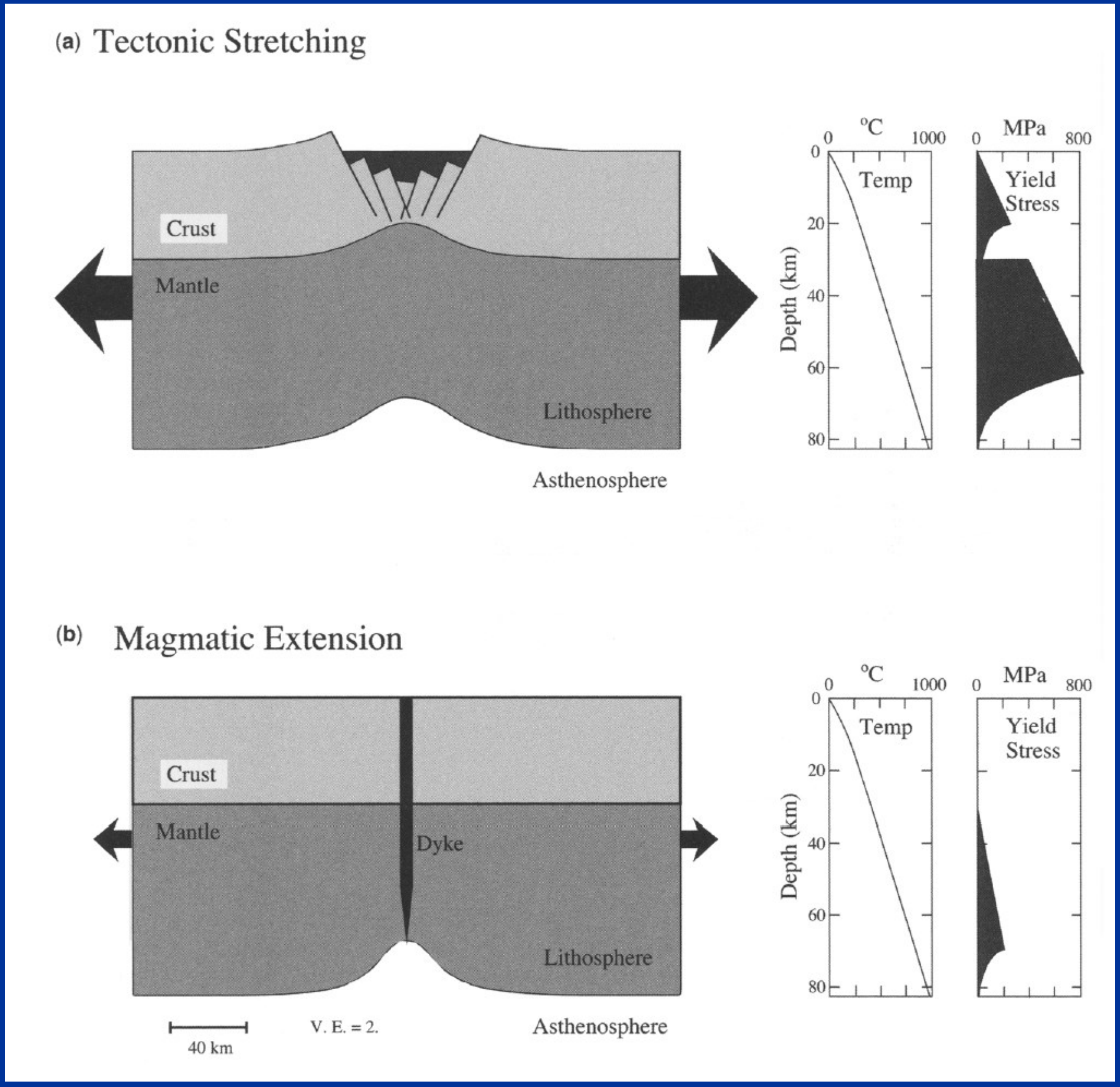
184 V. Courtillot et al. / Earth and Planetary Science Letters 166 (1999) 177–195



Continental break-up

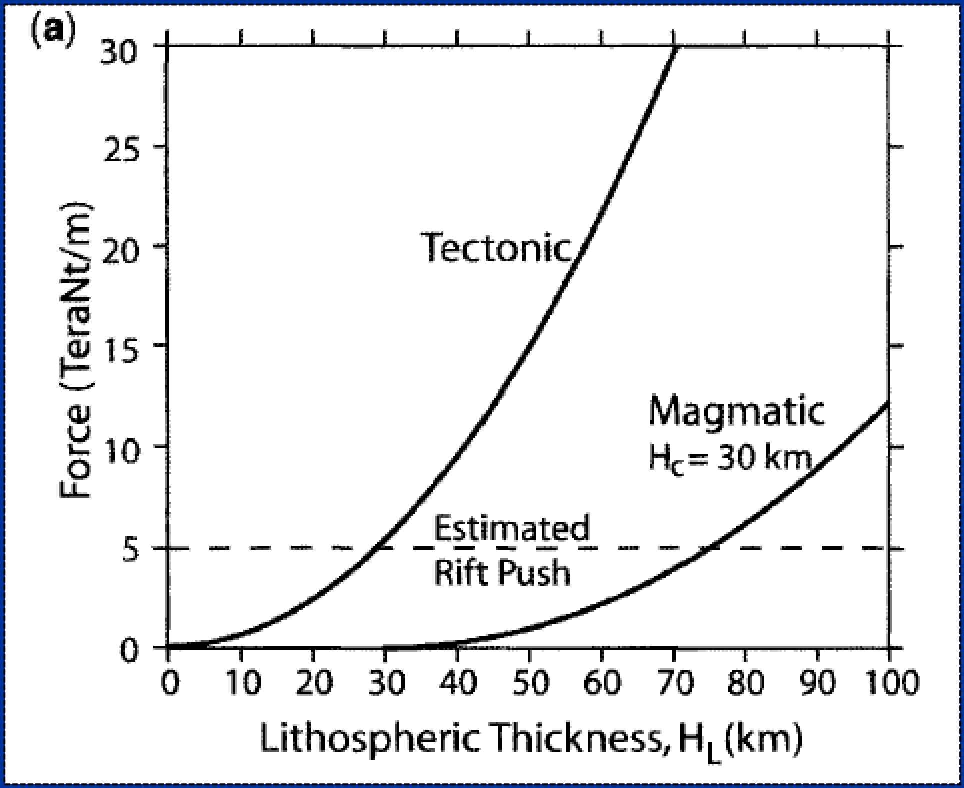


Effect of magma-filled dikes



Buck (2006)

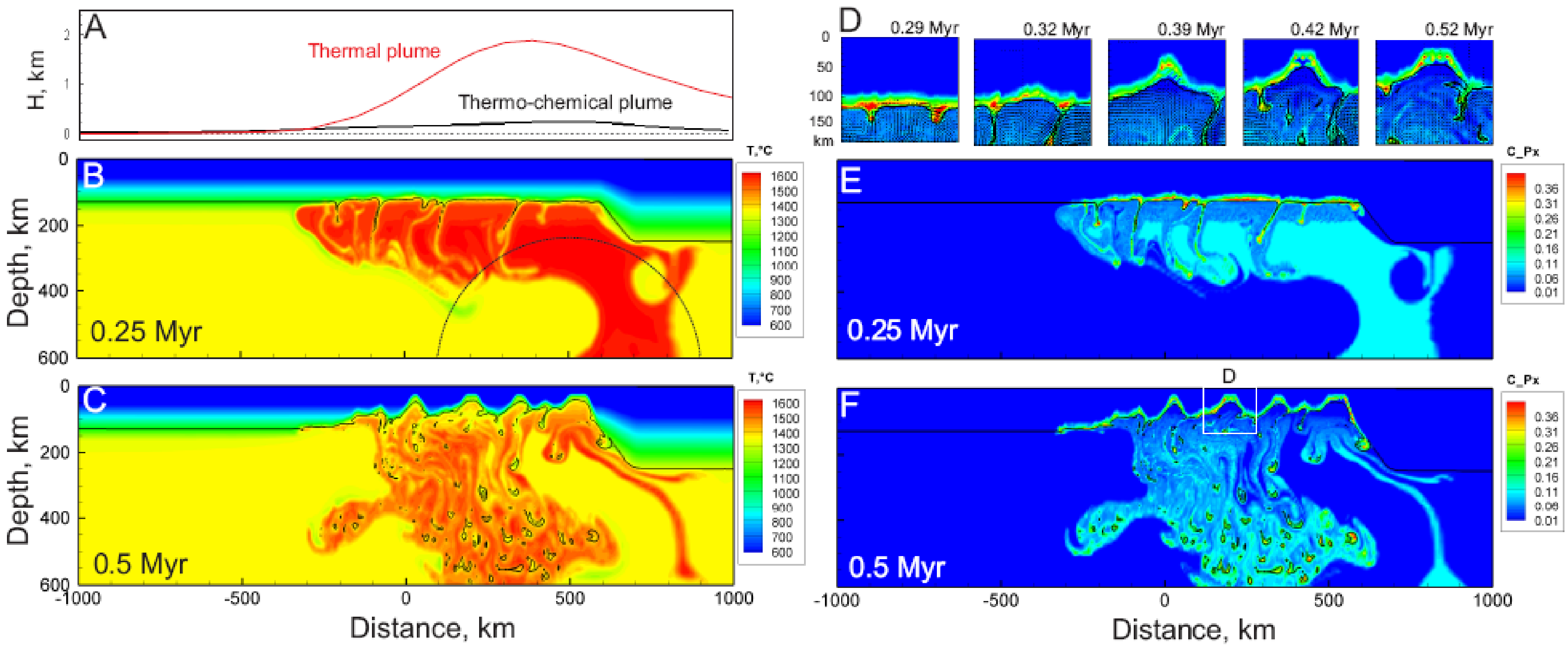
Effect of magma-filled dikes



It works if lithosphere is first thinned to about 75 km

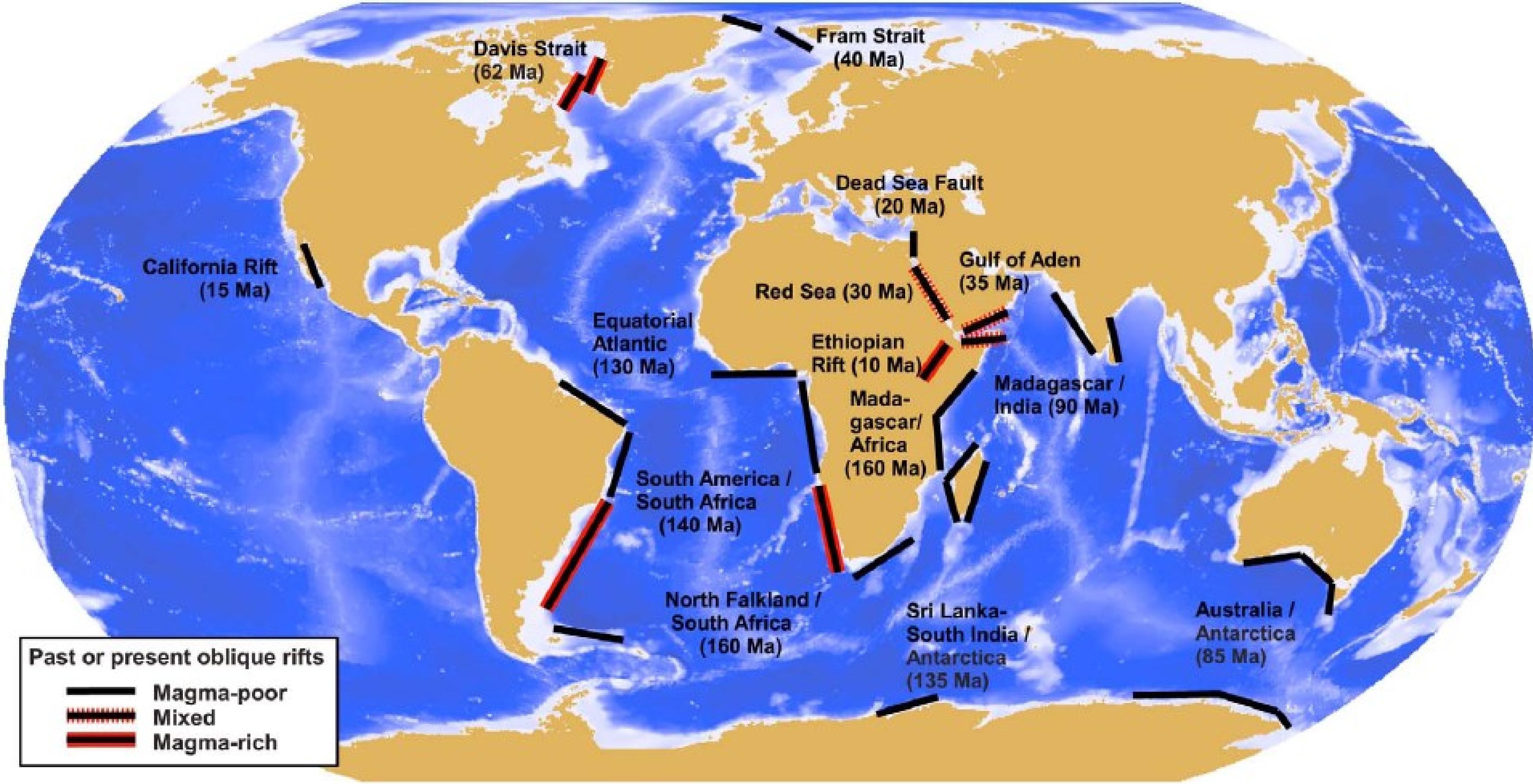
Buck (2006)

Lithospheric thinning above mantle plume



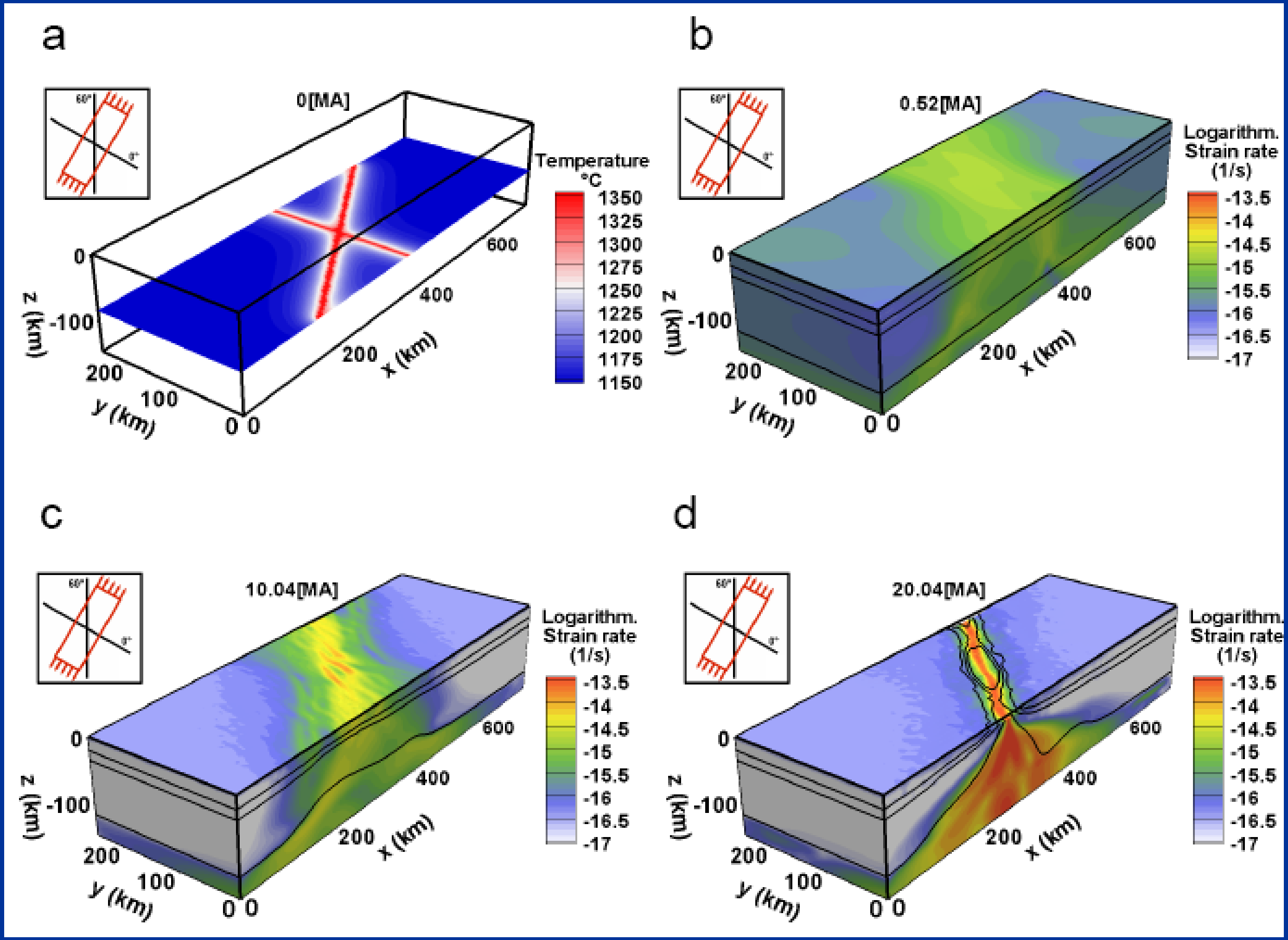
Sobolev et al. Nature 2011

Effect of oblique rifting



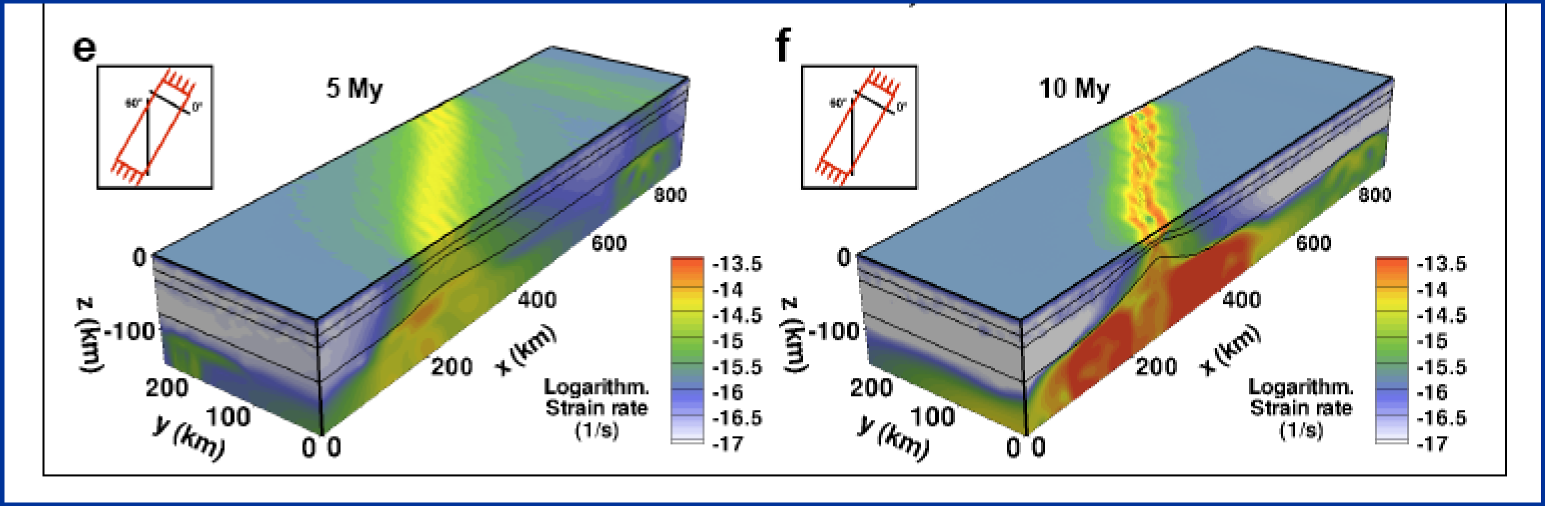
Brune, Popov, Sobolev JGR 2012

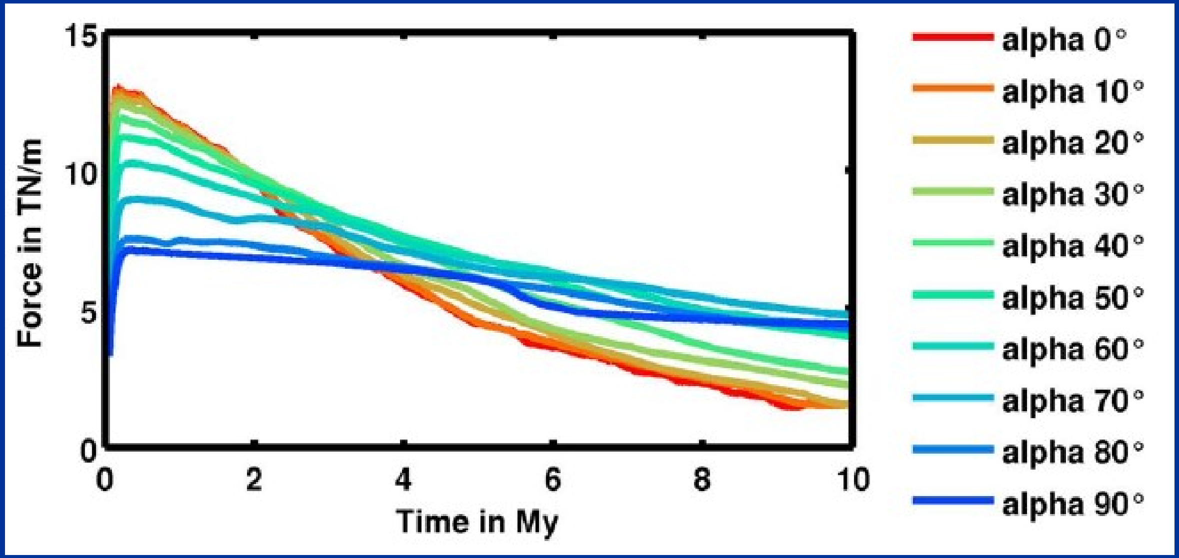
Effect of oblique rifting



Brune, Popov, Sobolev JGR 2012

Effect of oblique rifting



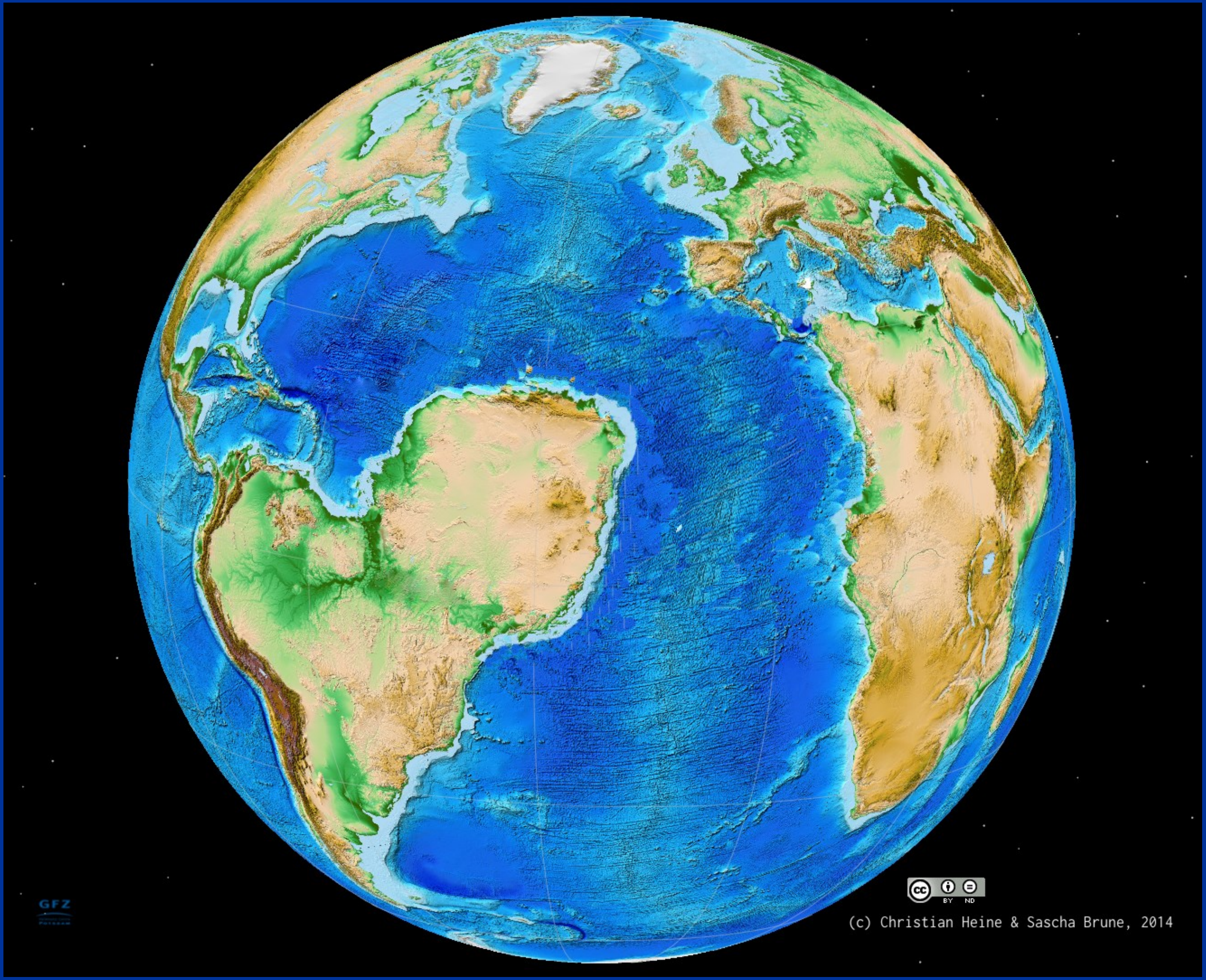


$$F_{strike-slip} = \tau_{yield} L_z$$

$$F_{extension} = \frac{\tau_{yield} L_z}{\sqrt{\frac{1}{3}(\nu^2 - \nu + 1)}}.$$

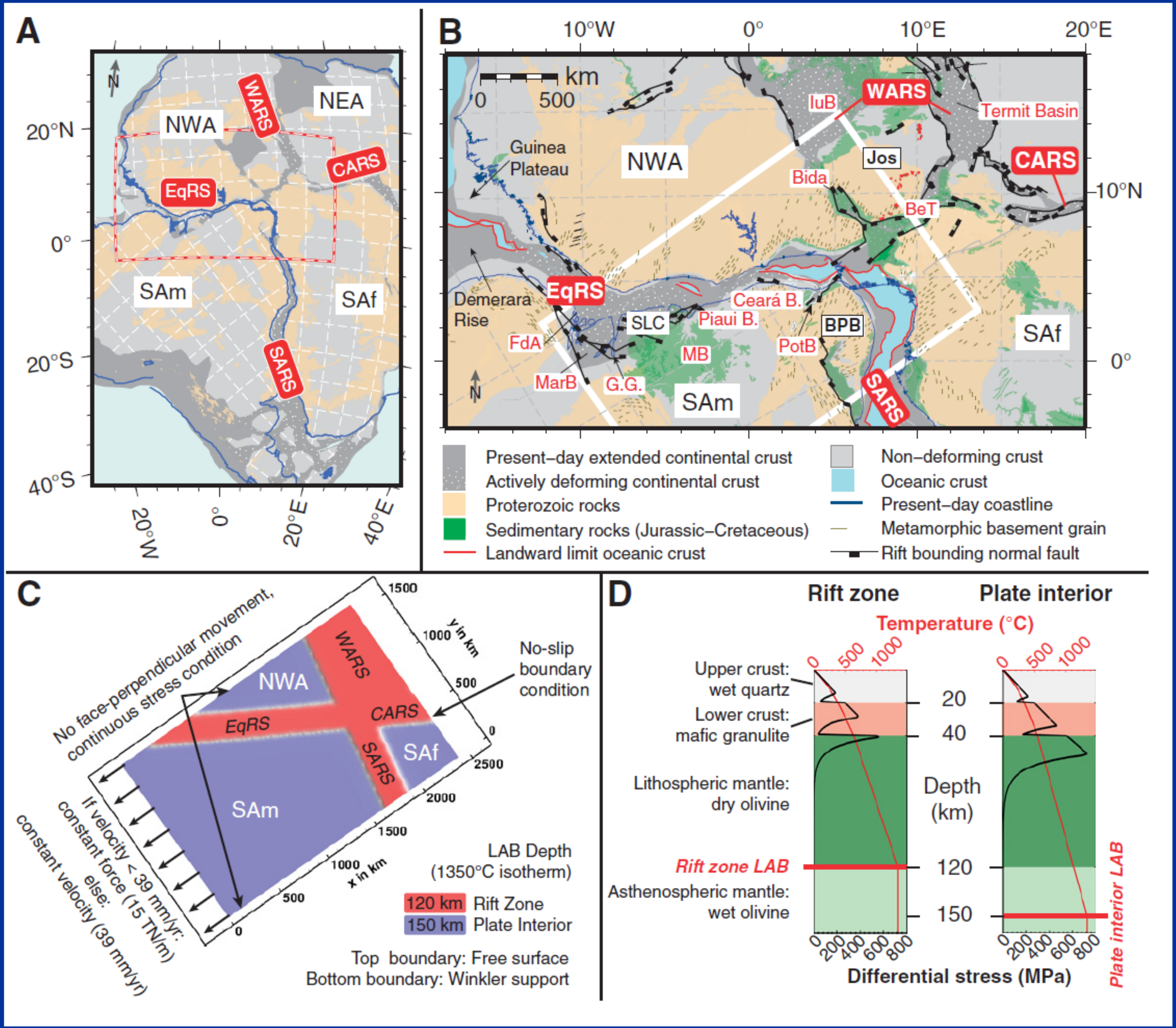
$$F_{extension} = 2\tau_{yield} L_z.$$

Effect of oblique rifting (example)

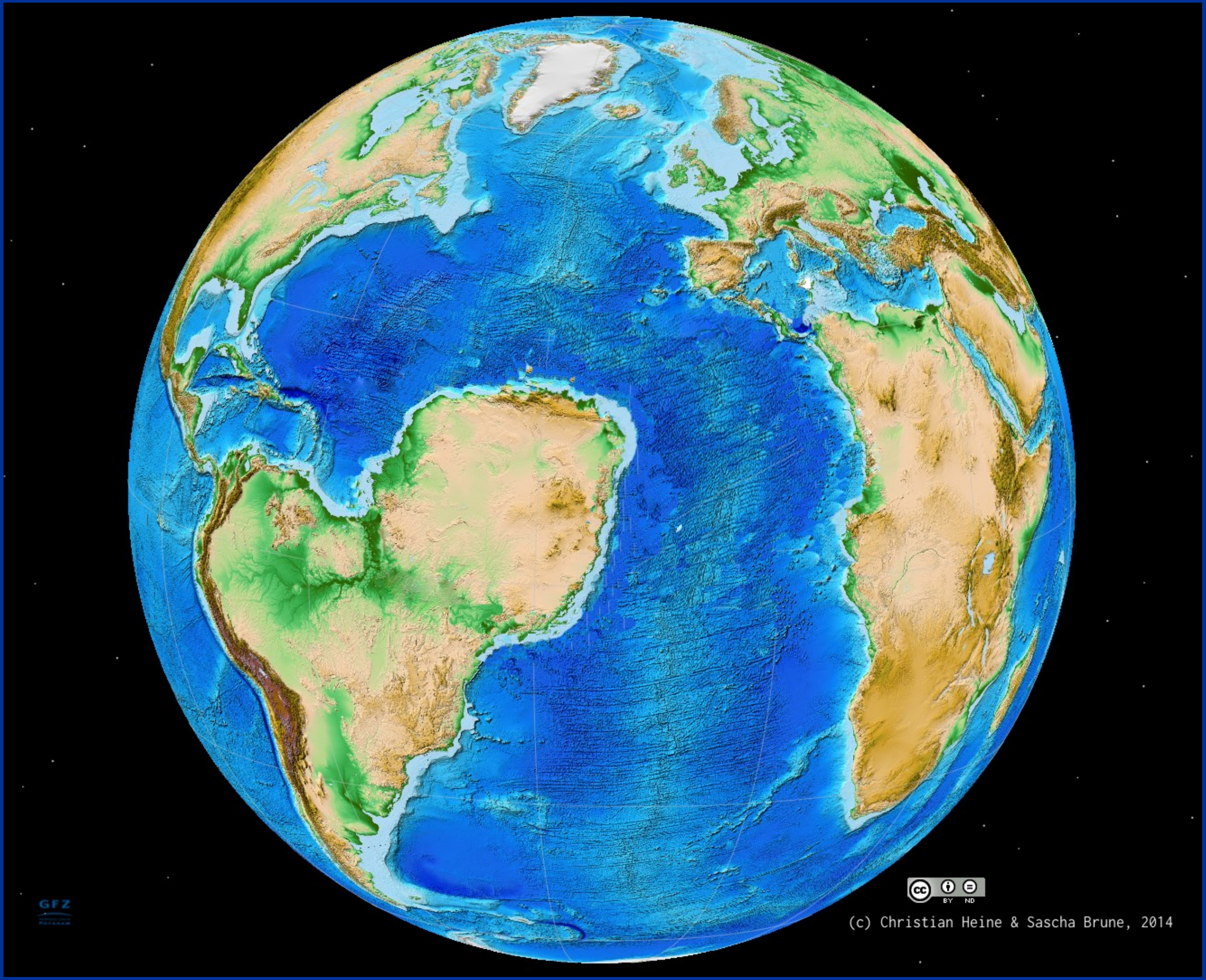


Effect of oblique rifting (example)

Heine and Brune, Geology, 2014

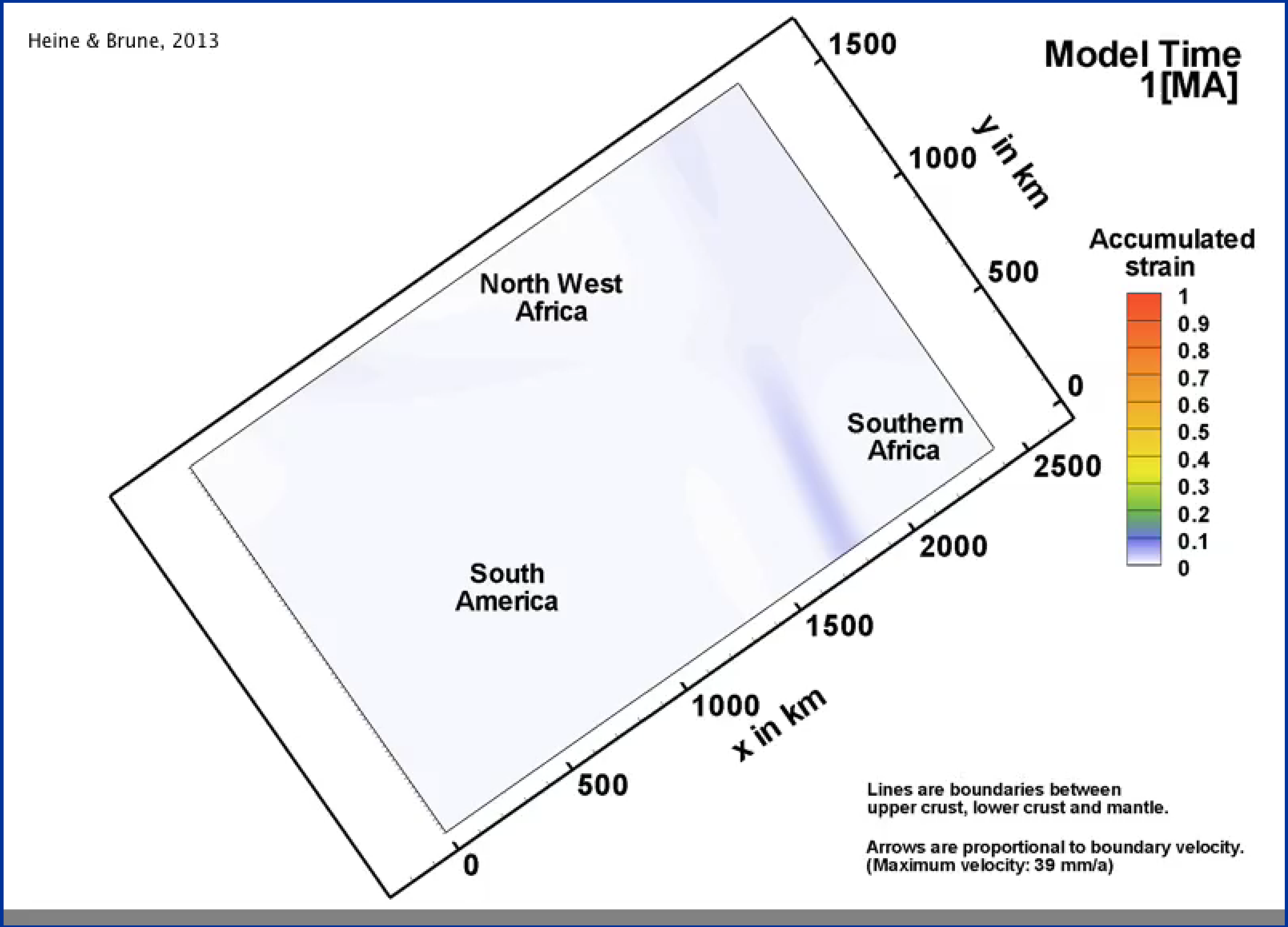


Effect of oblique rifting (example)



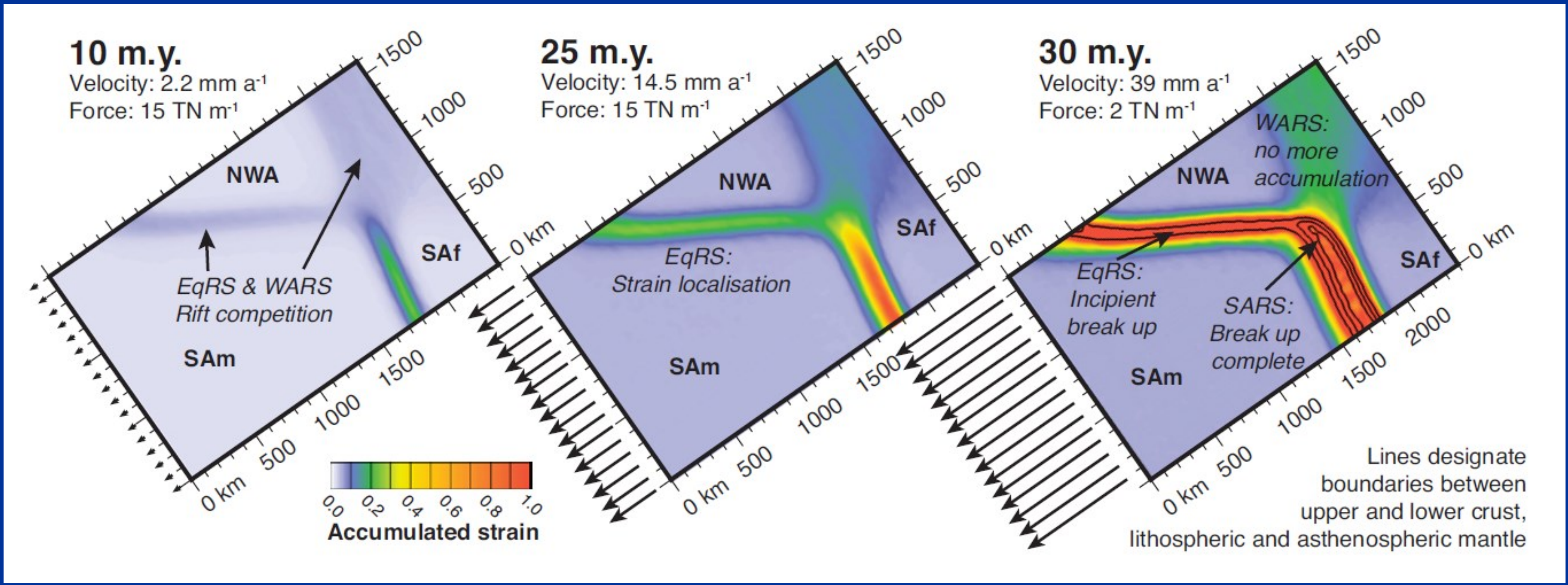
Effect of oblique rifting (example)

Heine and Brune, Geology, 2014



Effect of oblique rifting (example)

Heine and Brune, Geology, 2014



Conclusion

To break a continent are required:

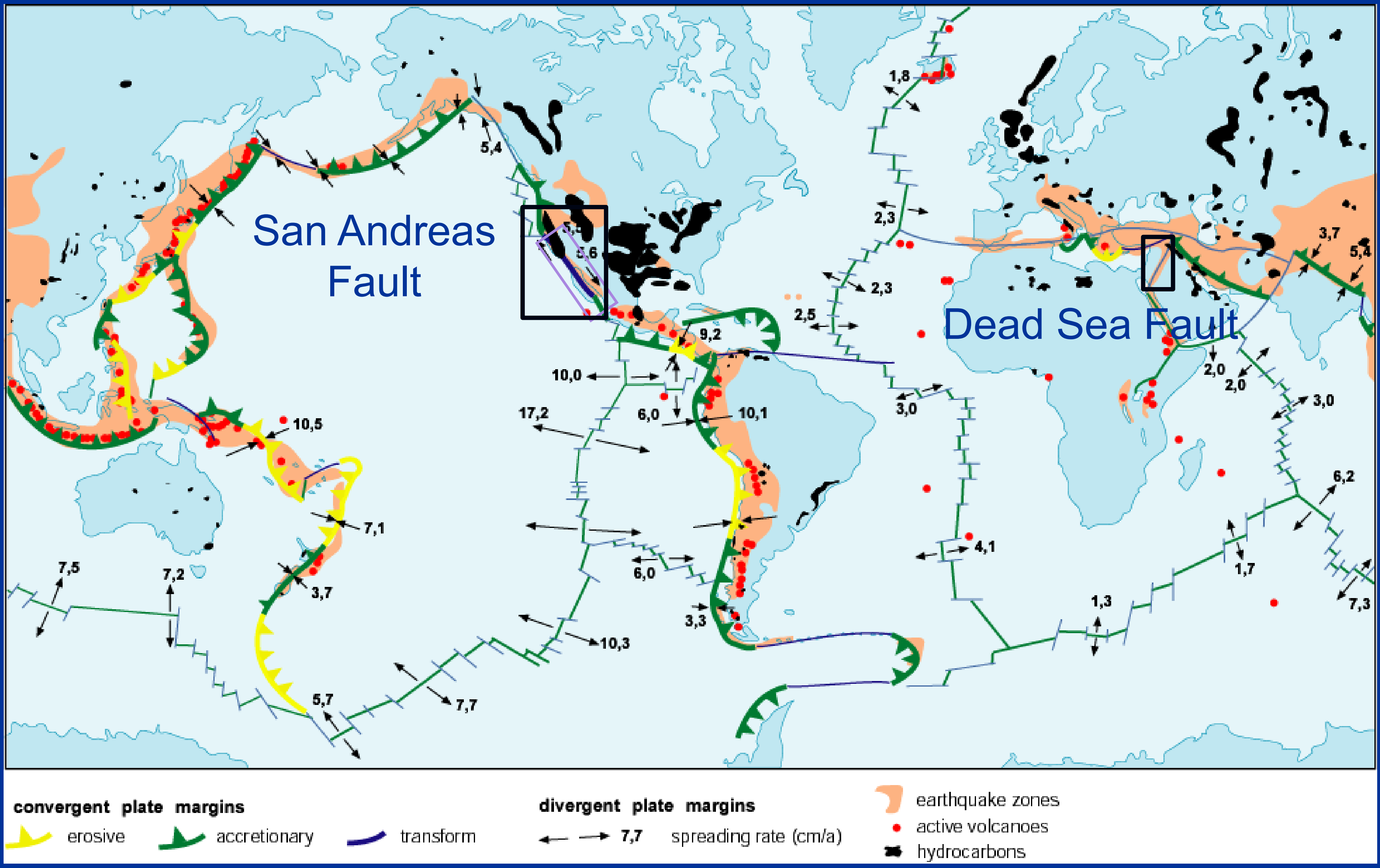
(1) extensional deviatoric stresses (internal, from ridge push or subduction zones roll-back) and (2) lithospheric weakening

Large Igneous Provinces are optimal for lithospheric weakening, as they may both thin lithosphere and generate magma-filled dikes.

Intensive strike-slip deformation is also helpful

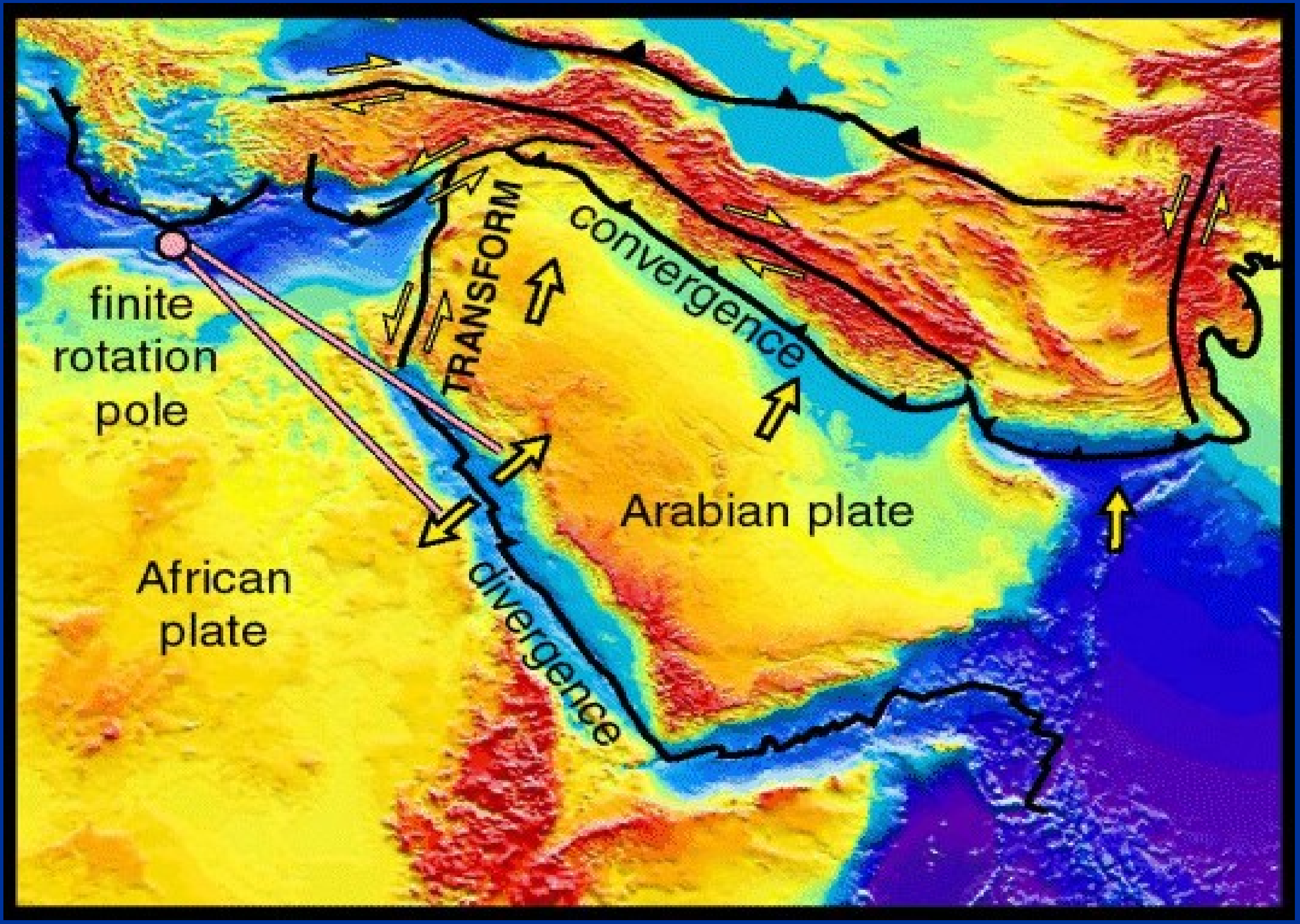
Continental transform faults
(case Dead Sea Transform)

Continental Transform Faults

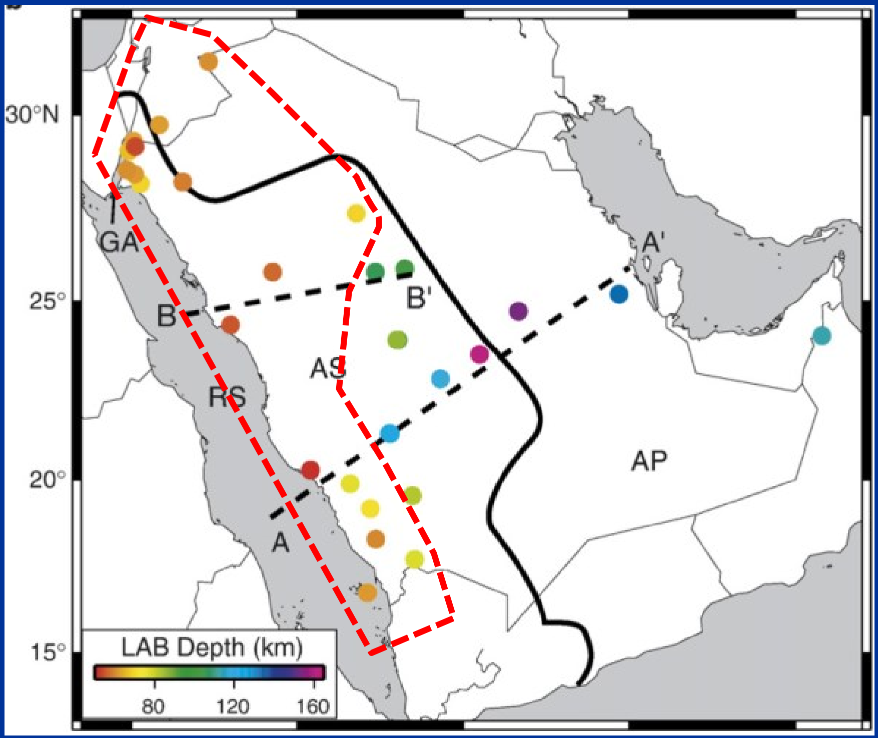


Regional setting

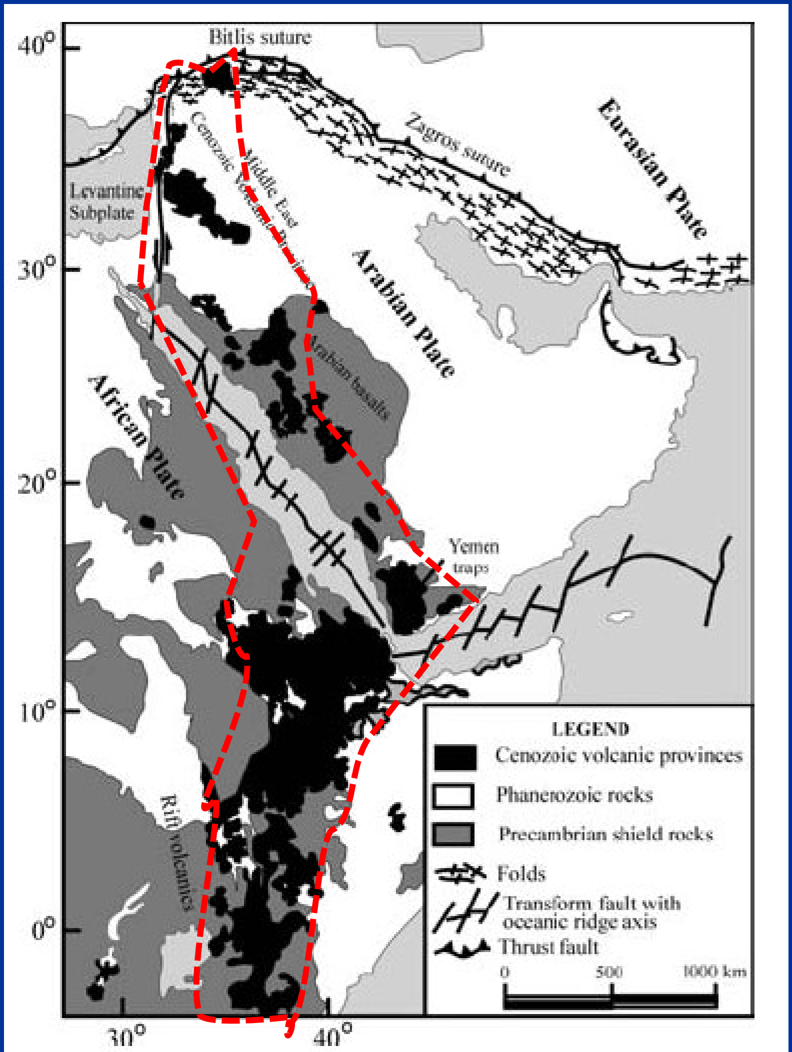
With the surface heat flow of 50-60 mW/m2, the DST is the coldest continental transform boundary



Lithospheric thickness and magmatism

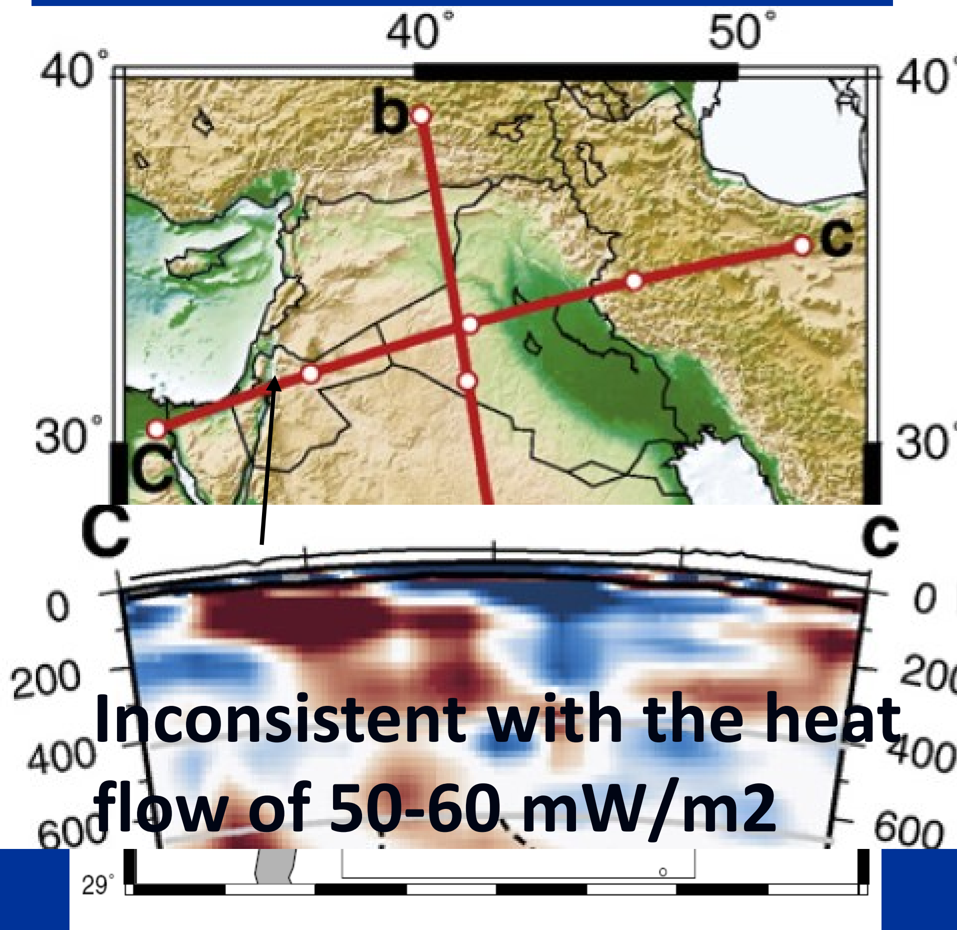


Magmatism at 30-0 Ma



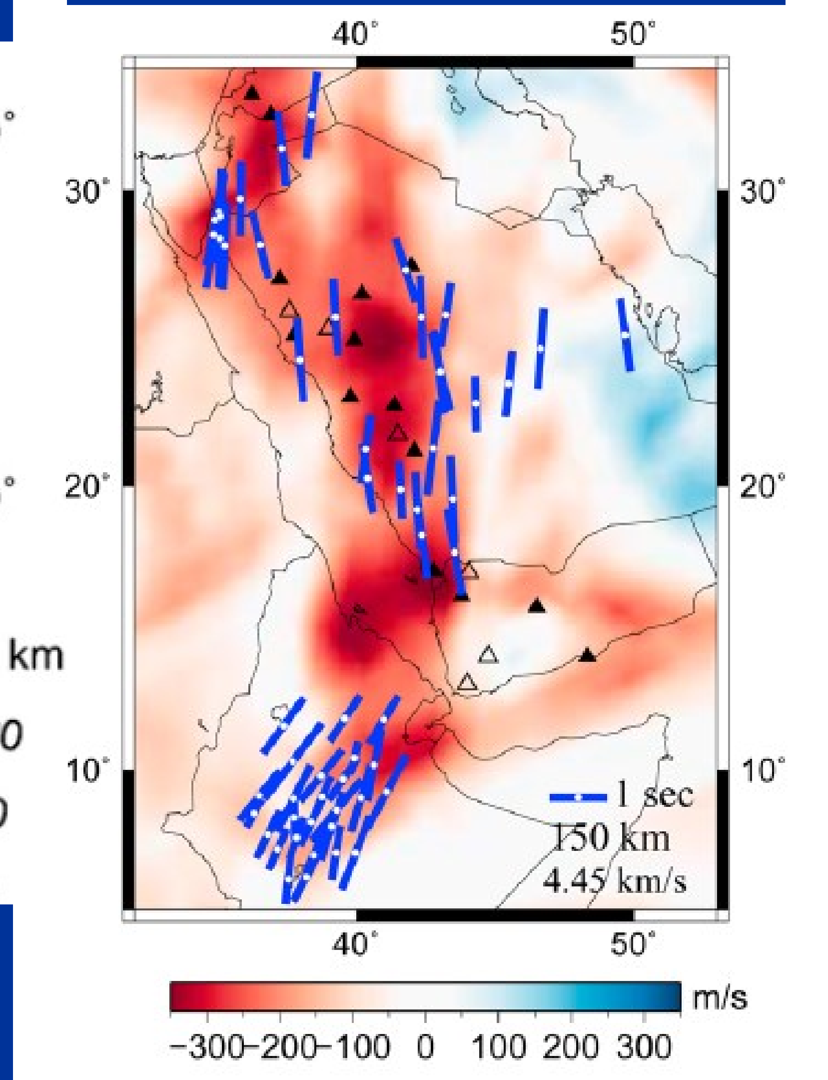
Lithosphere-asthenosphere boundary (LAB) from seismic data

Chang and Van der Lee, EPSL, 2011



Inconsistent with the heat flow of 50-60 mW/m2

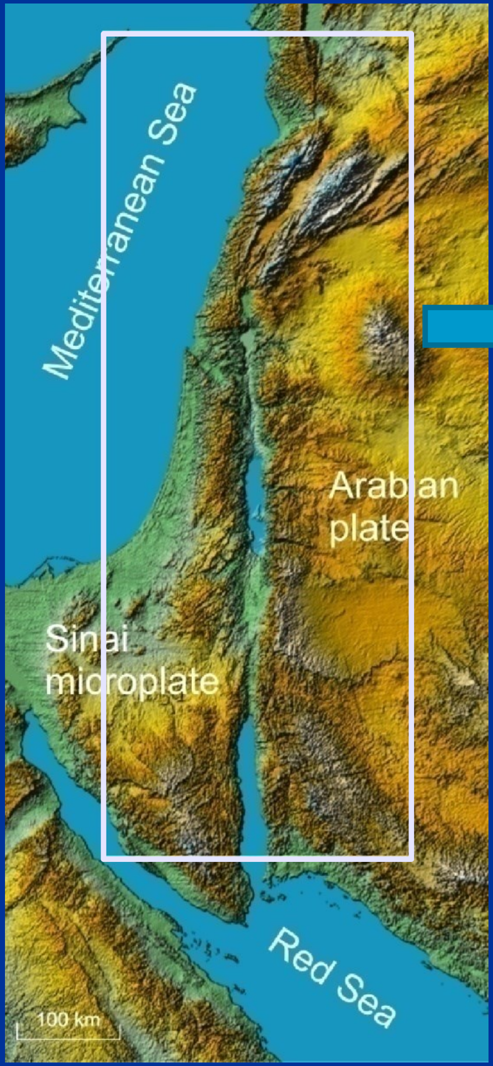
Chang et al, GRL, 2011

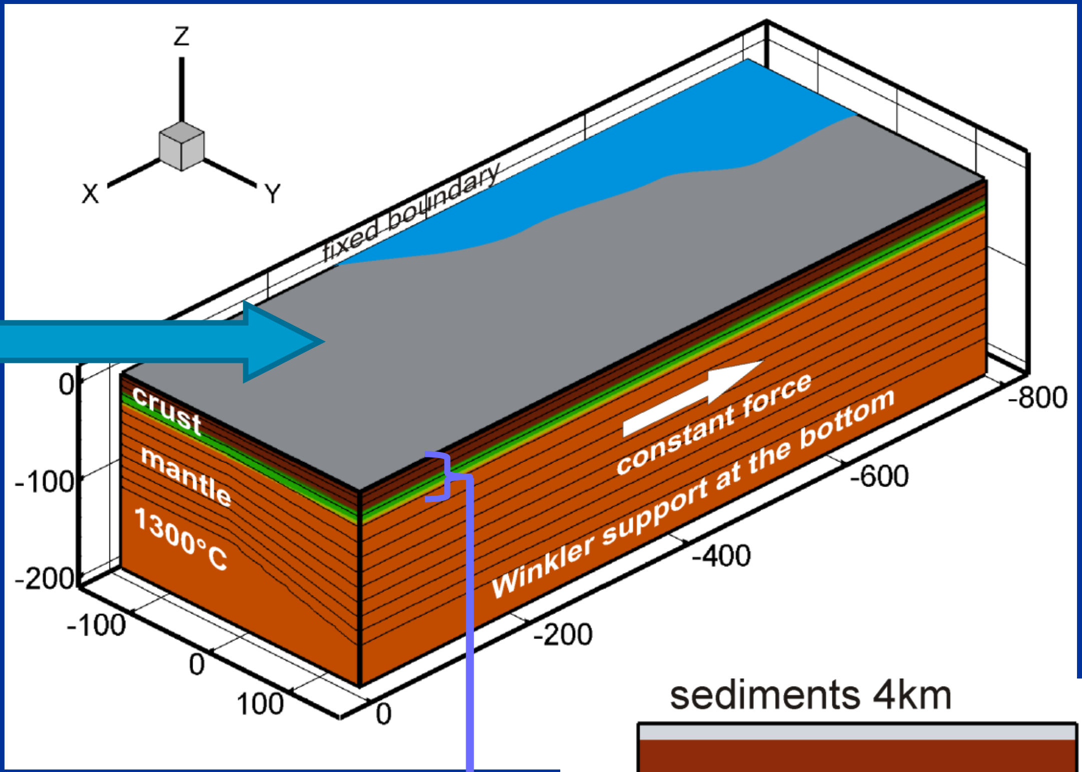


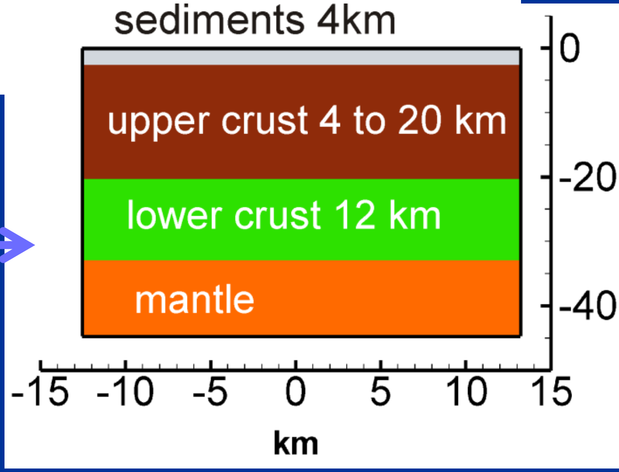
Conclusion

Lithosphere around DST was thinned in the past and related high heat flow had not enough time to reach the surface

Model setup



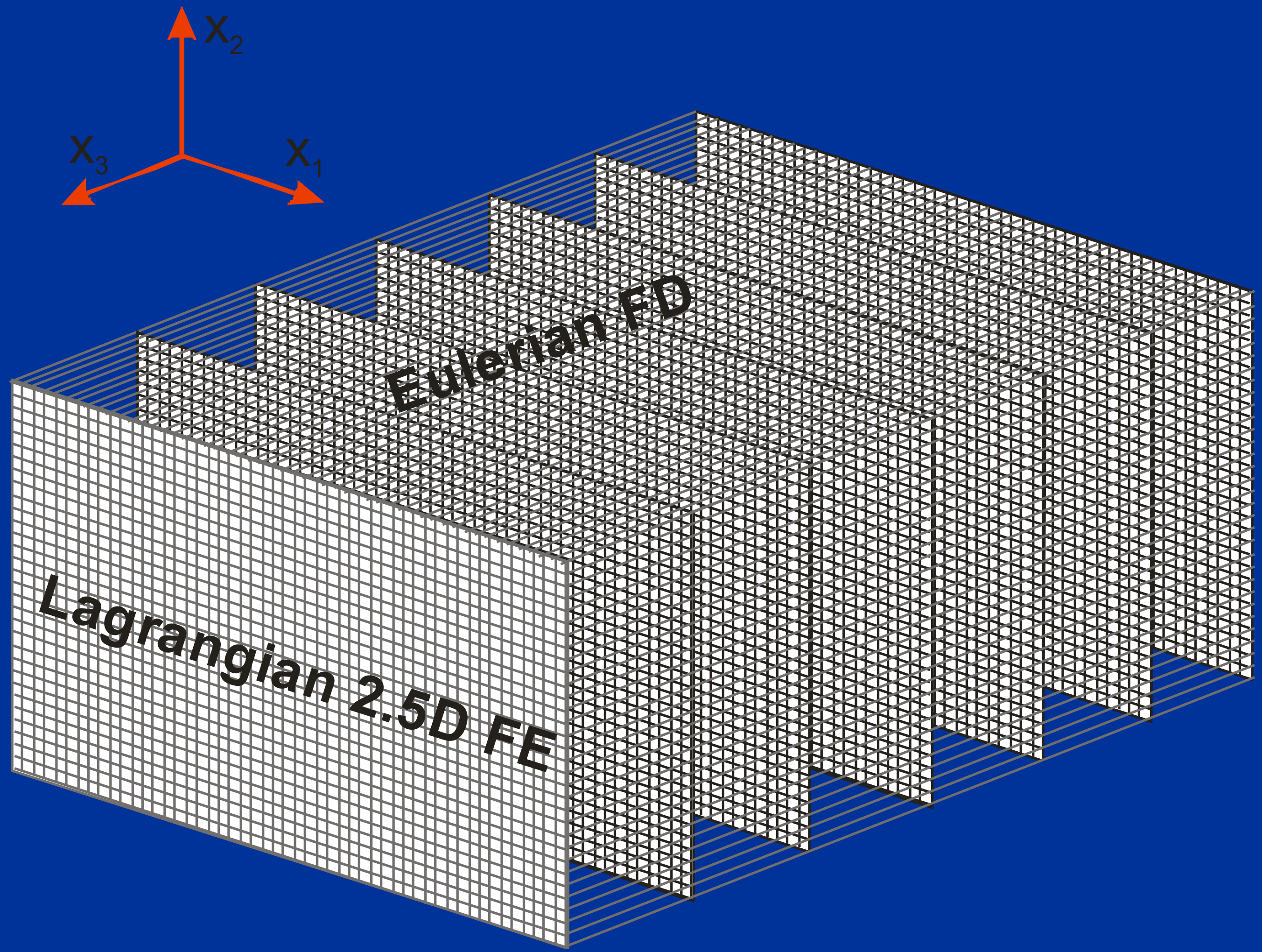




Flat Earth approximation

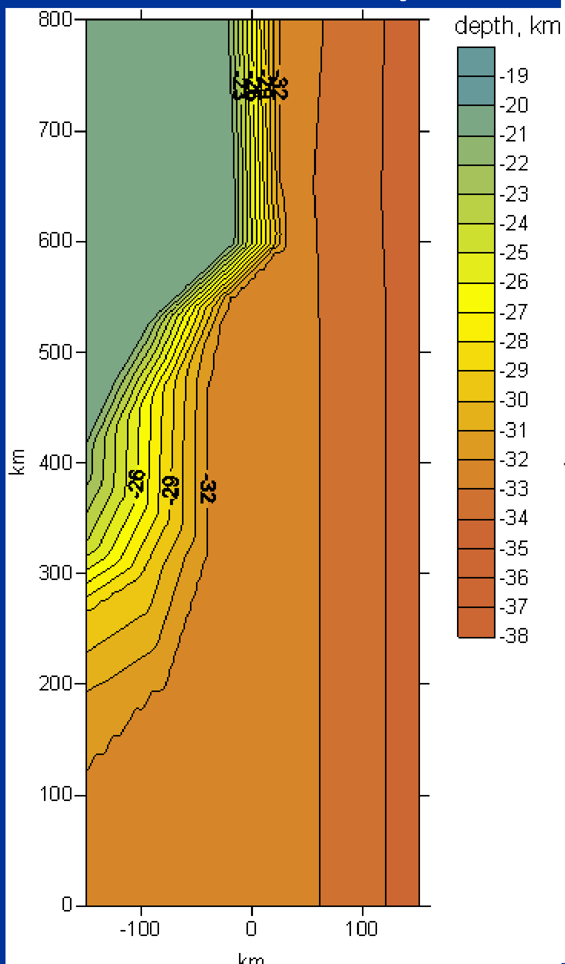
Modeling technique LAPEX 3D combining FE and FD

(Petrunin and Sobolev, Geology, 2006, PEPI, 2008)

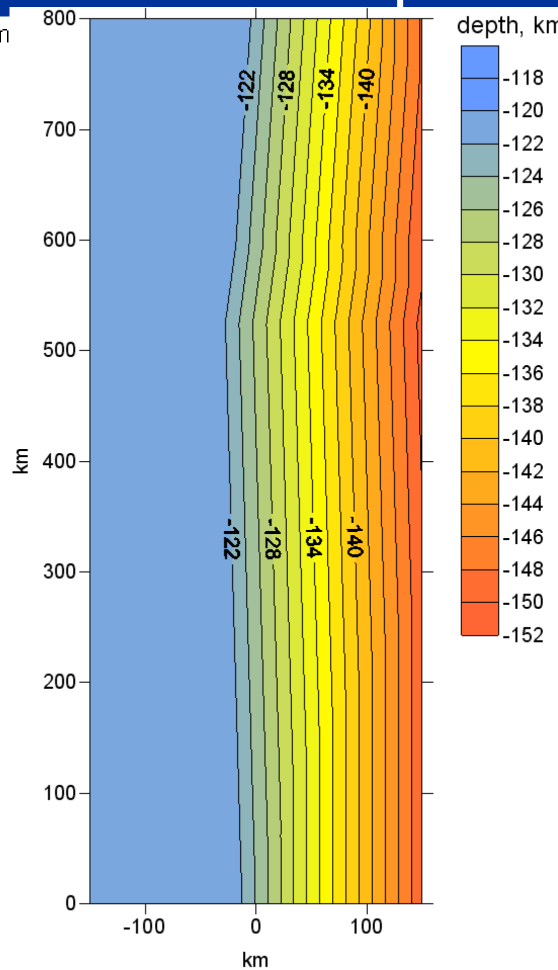


Initial lithospheric structure:

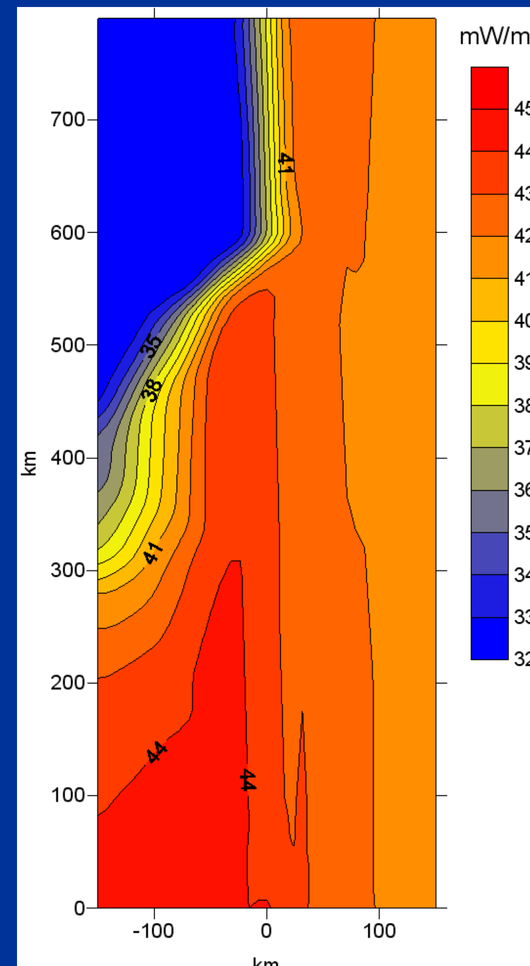
Moho map



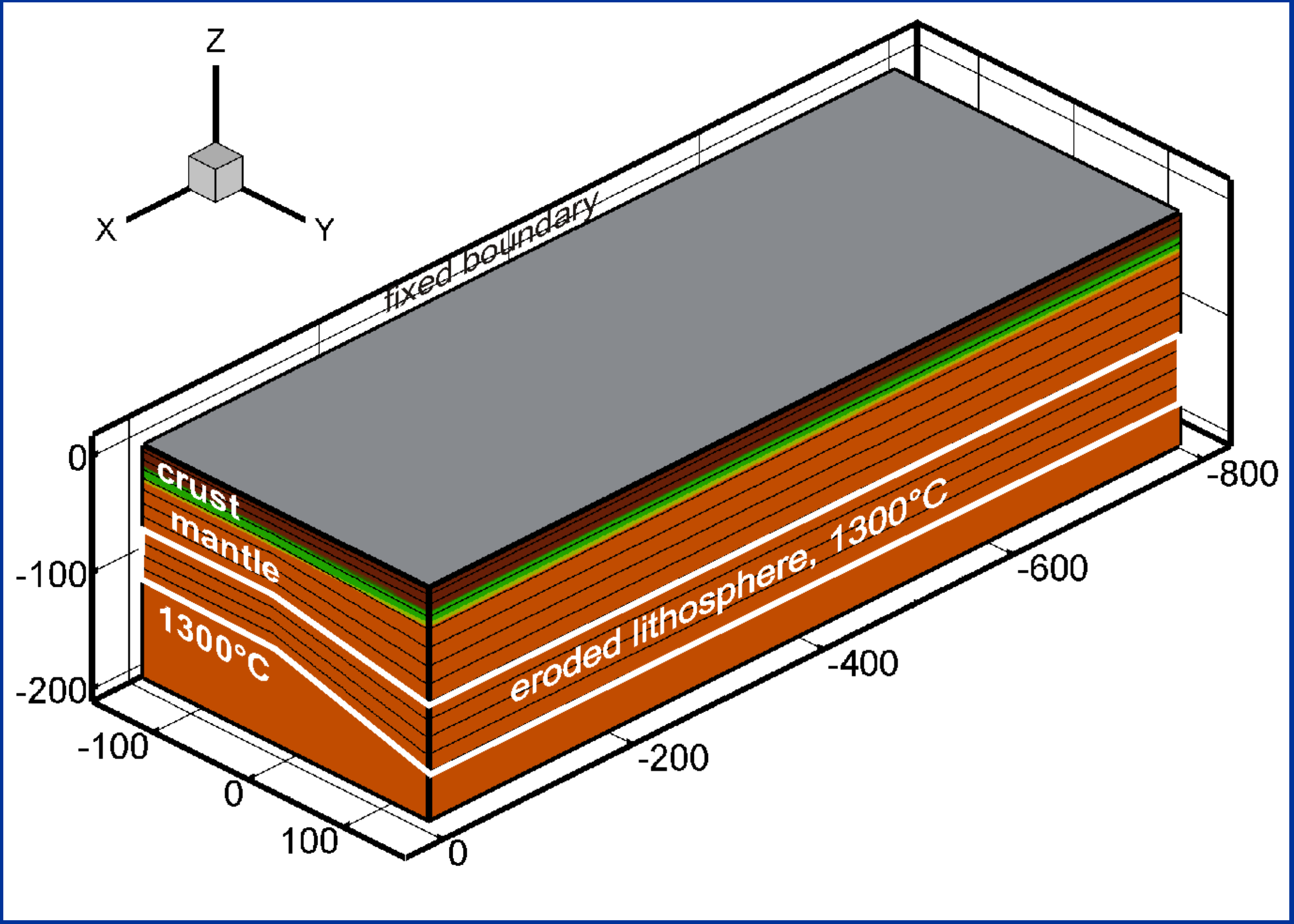
LAB map



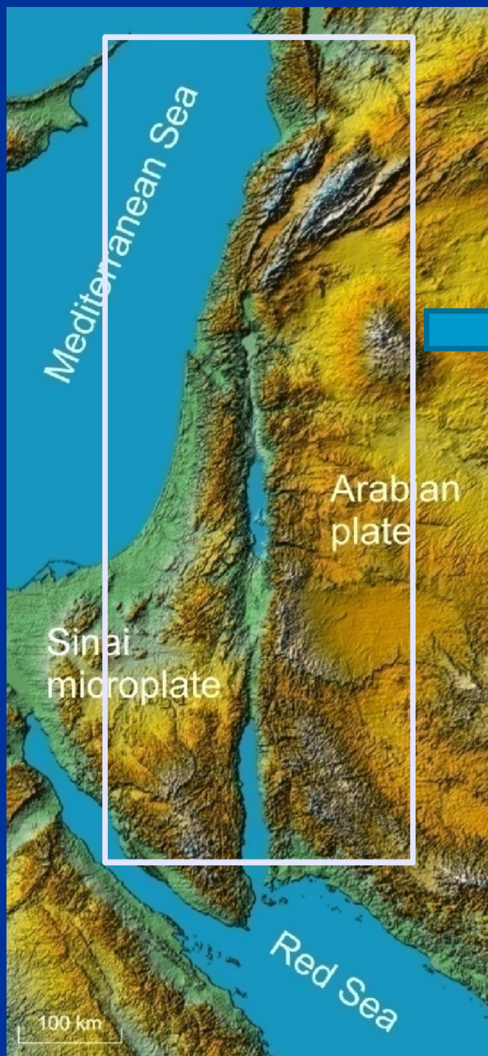
Heat flow

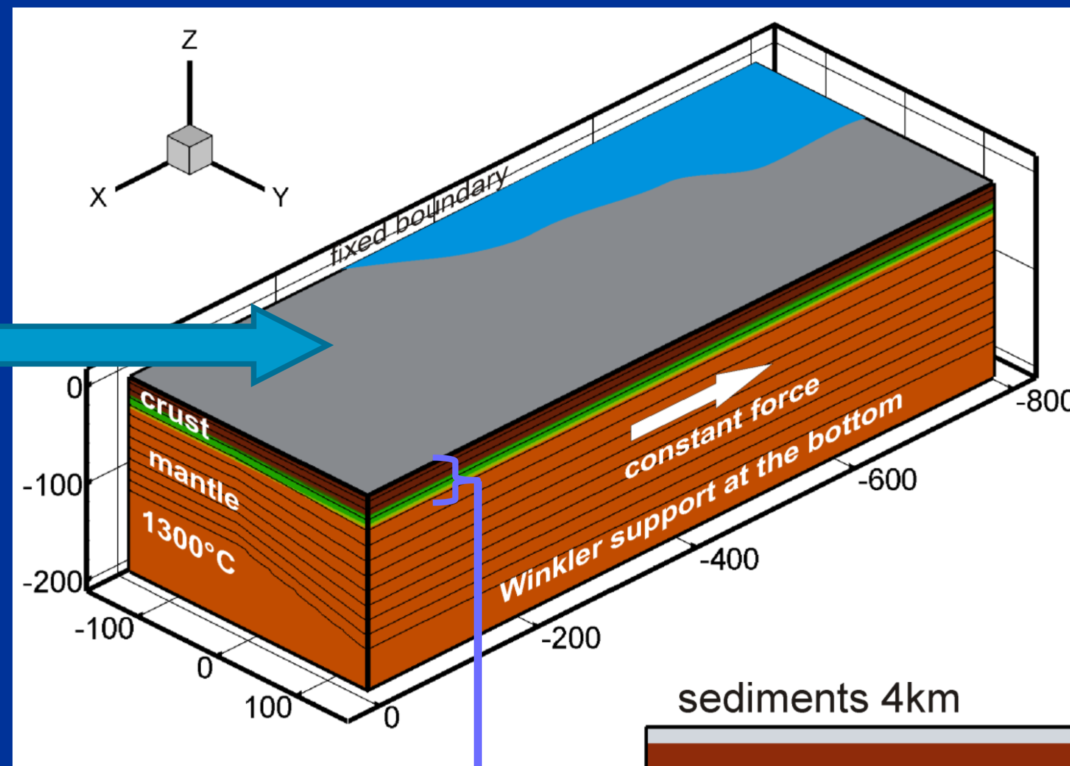


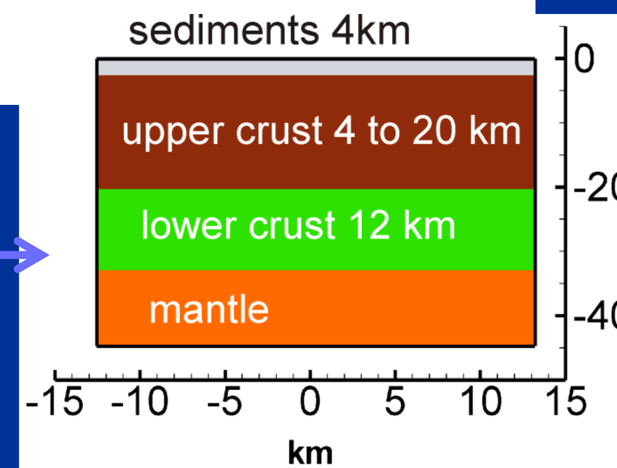
Modeling results: role of the thermal erosion of the lithosphere



Model setup



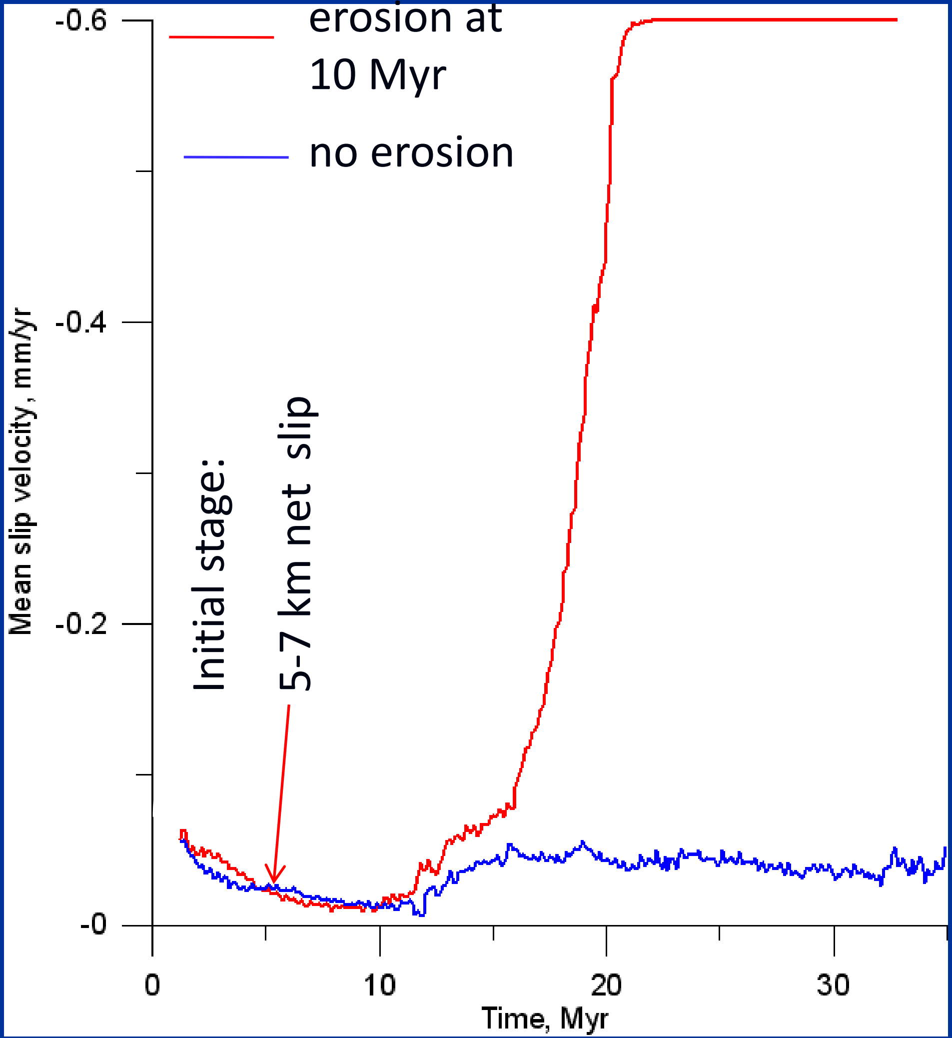


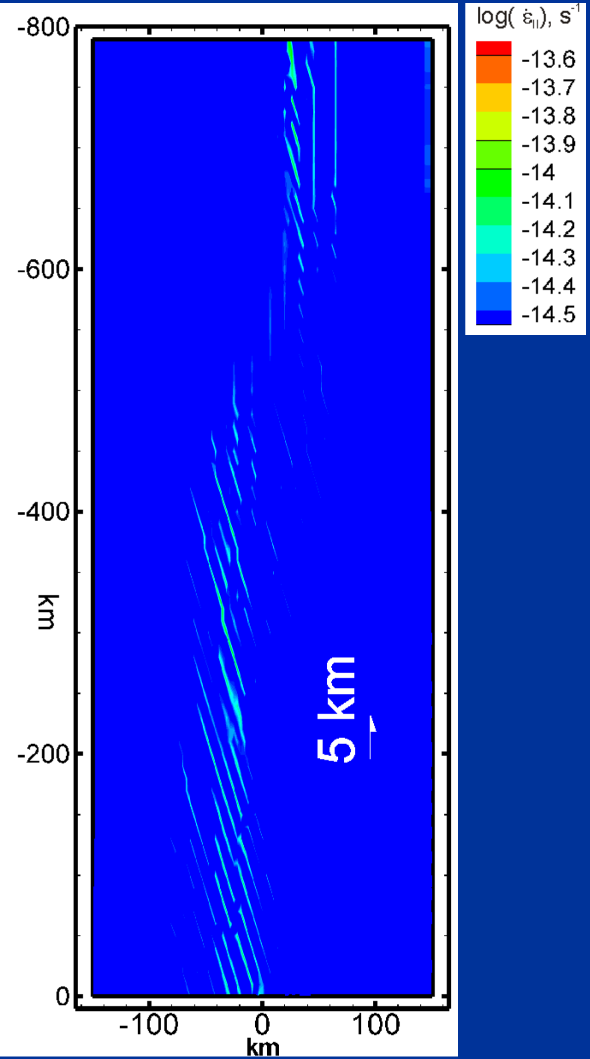


Flat Earth approximation

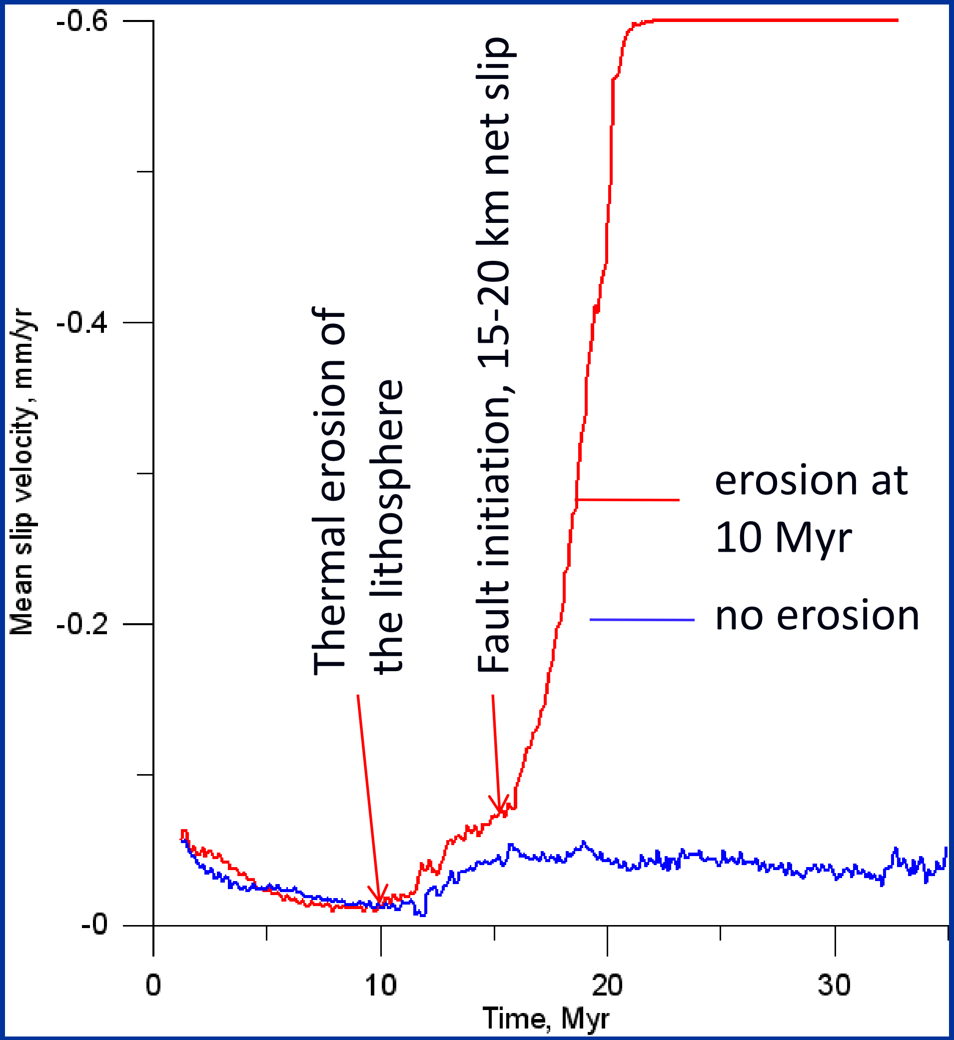
Modeling results: role of the thermal erosion of the lithosphere

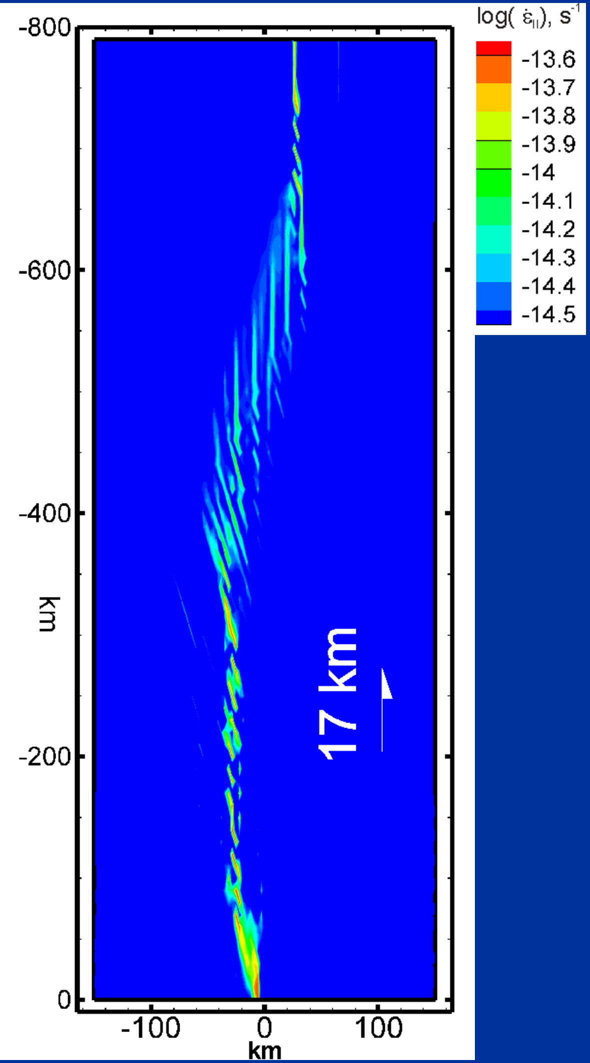
Applied force is 1.6e13N/m



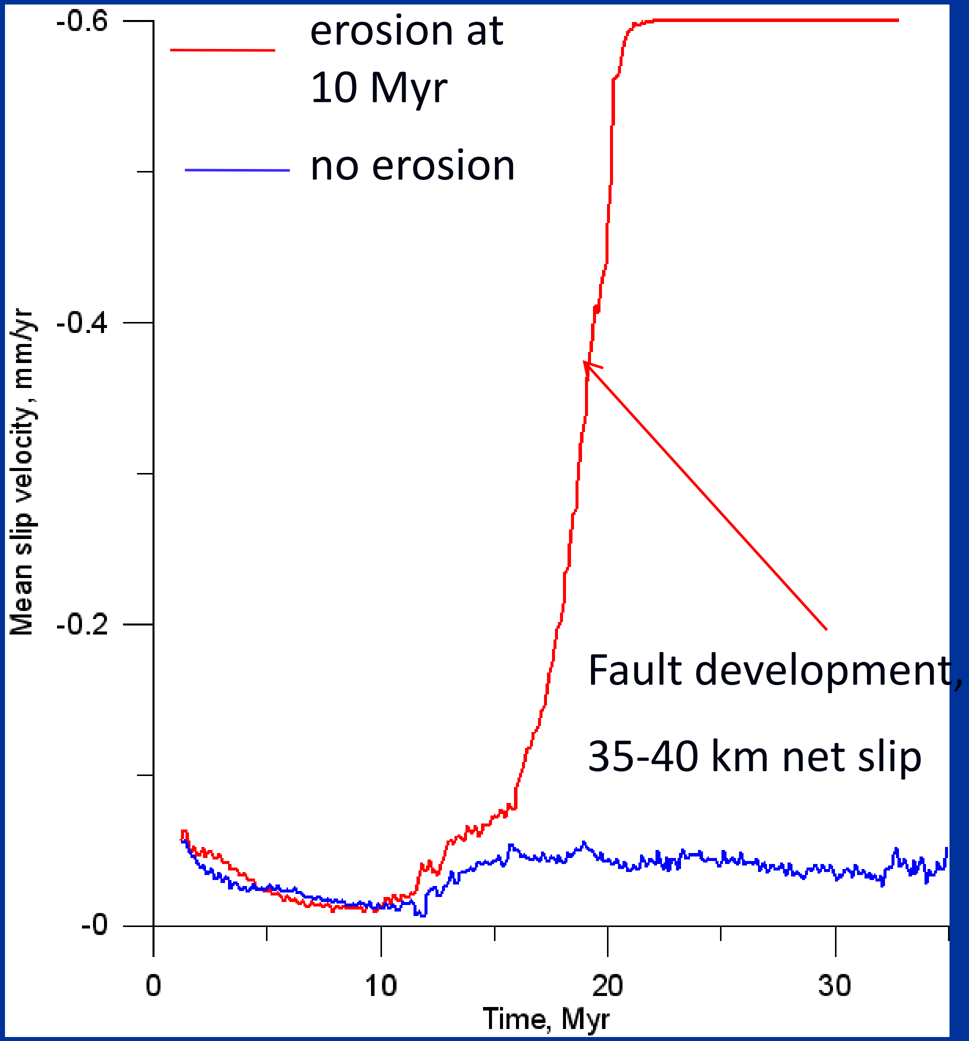


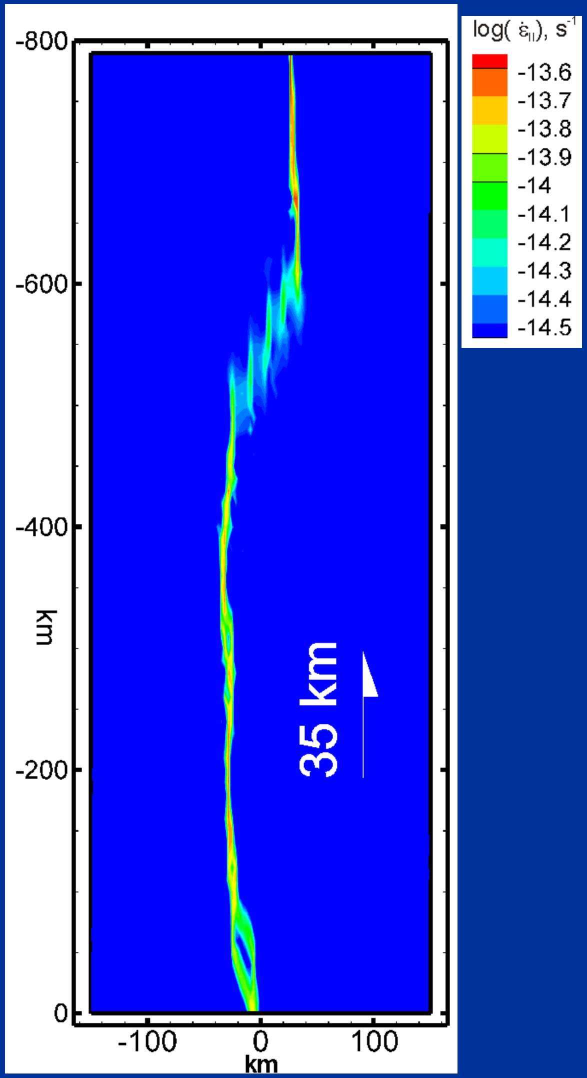
Modeling results: role of the thermal erosion of the lithosphere



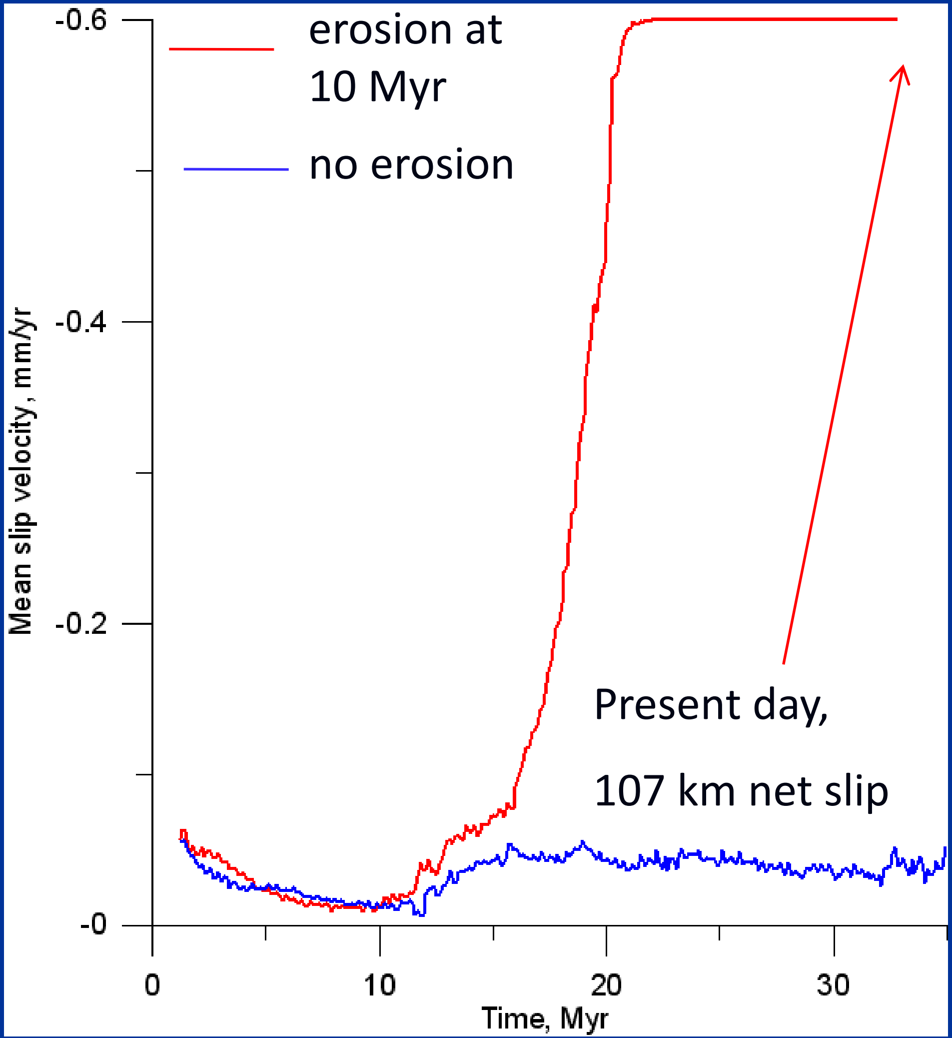


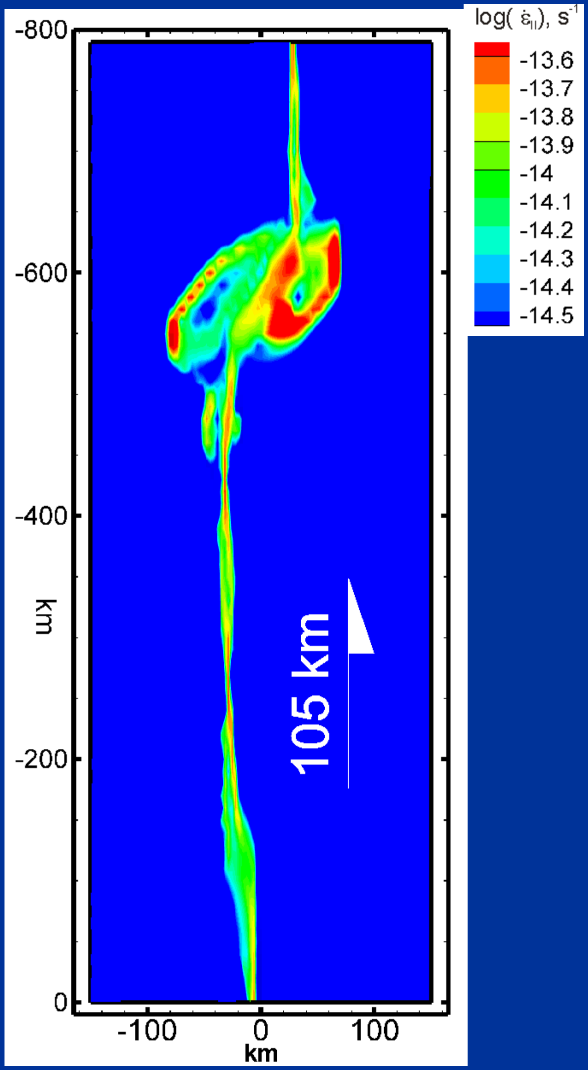
Modeling results: role of the thermal erosion of the lithosphere



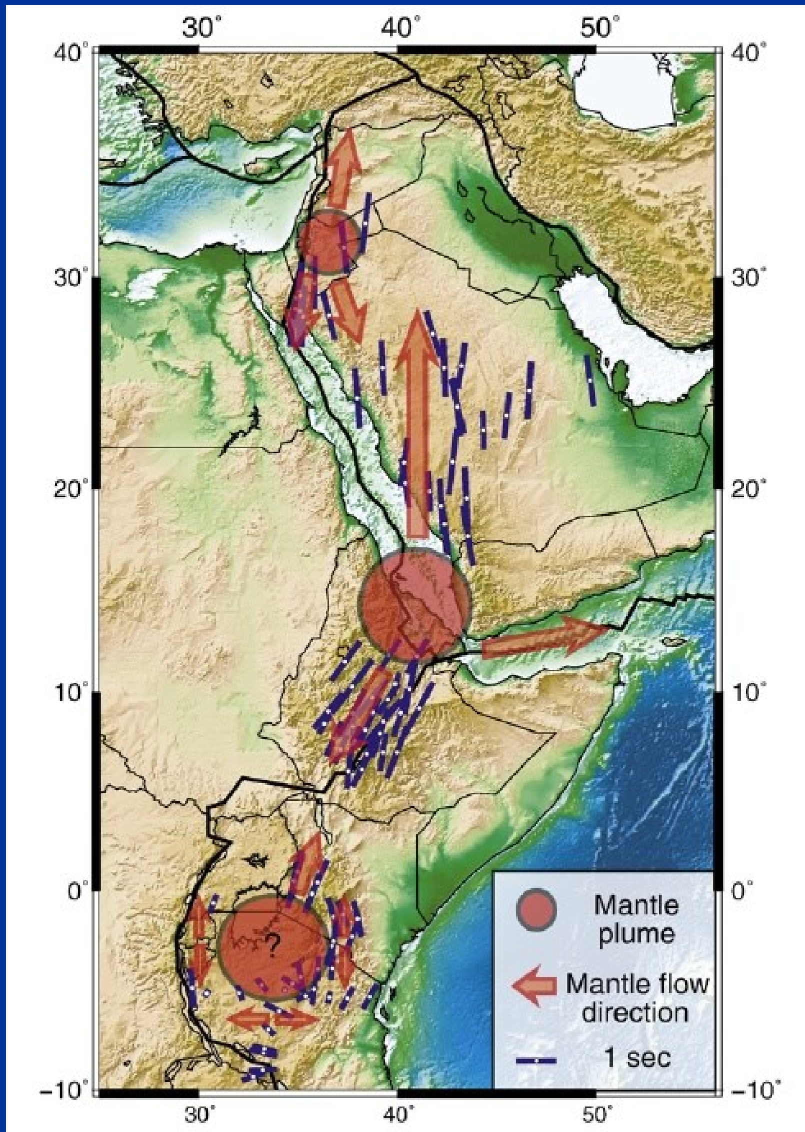


Modeling results: role of the thermal erosion of the lithosphere





Possible scenario



Plumes at 25-35 Ma

Lithospheric erosion 20-30 Ma

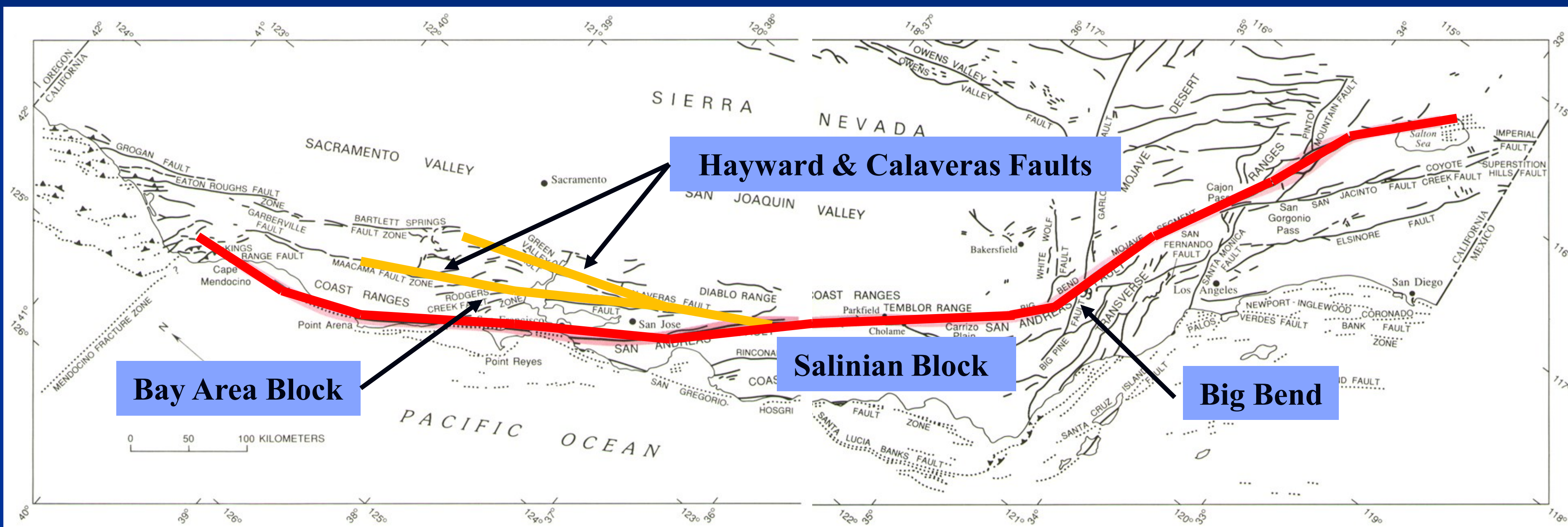
Localization of the DST 15-17 Ma

Lithospheric erosion has triggered the DST

Chang and Van der Lee, EPSL, 2011

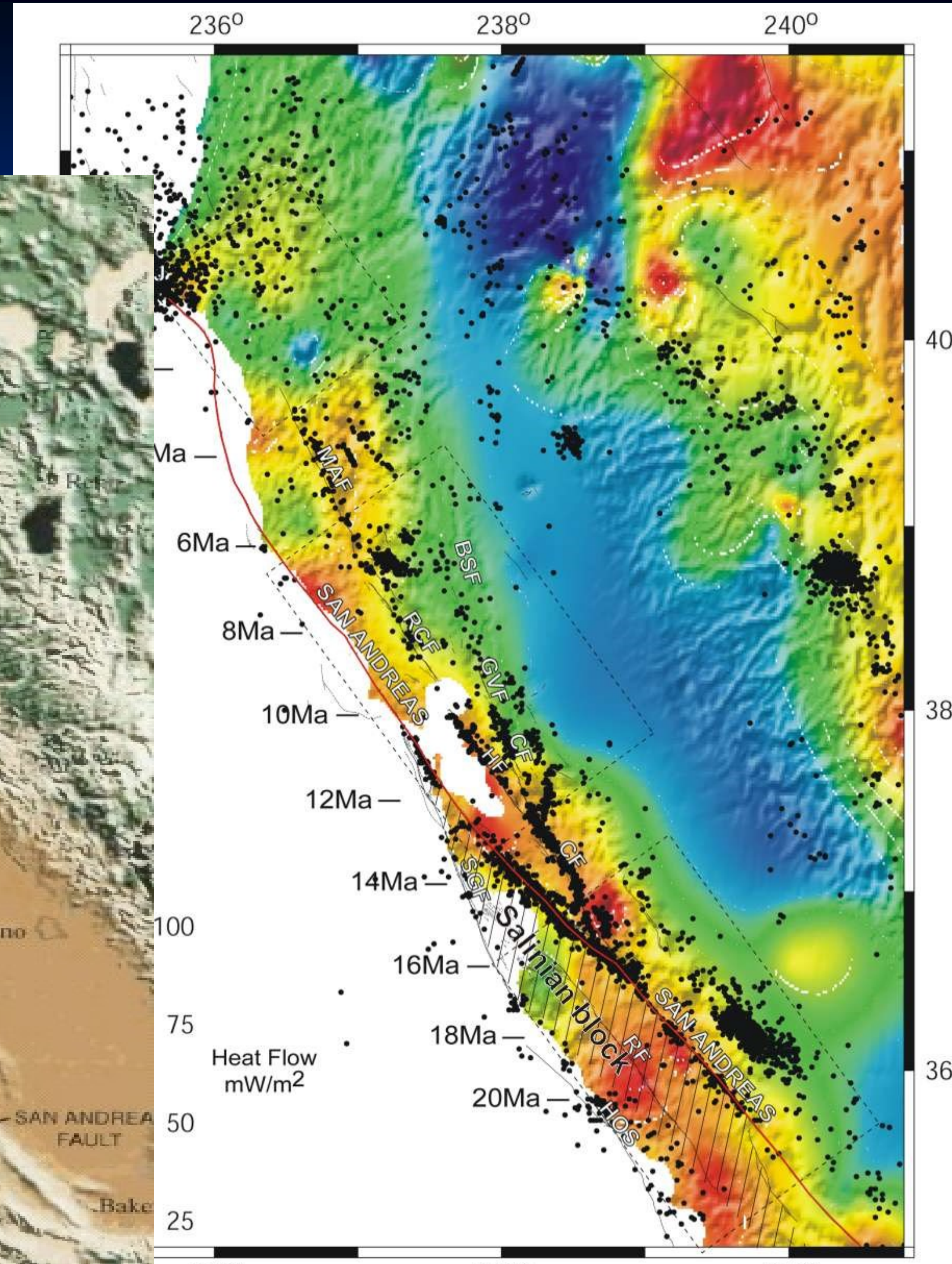
San Andreas Fault System

San Andreas Fault System

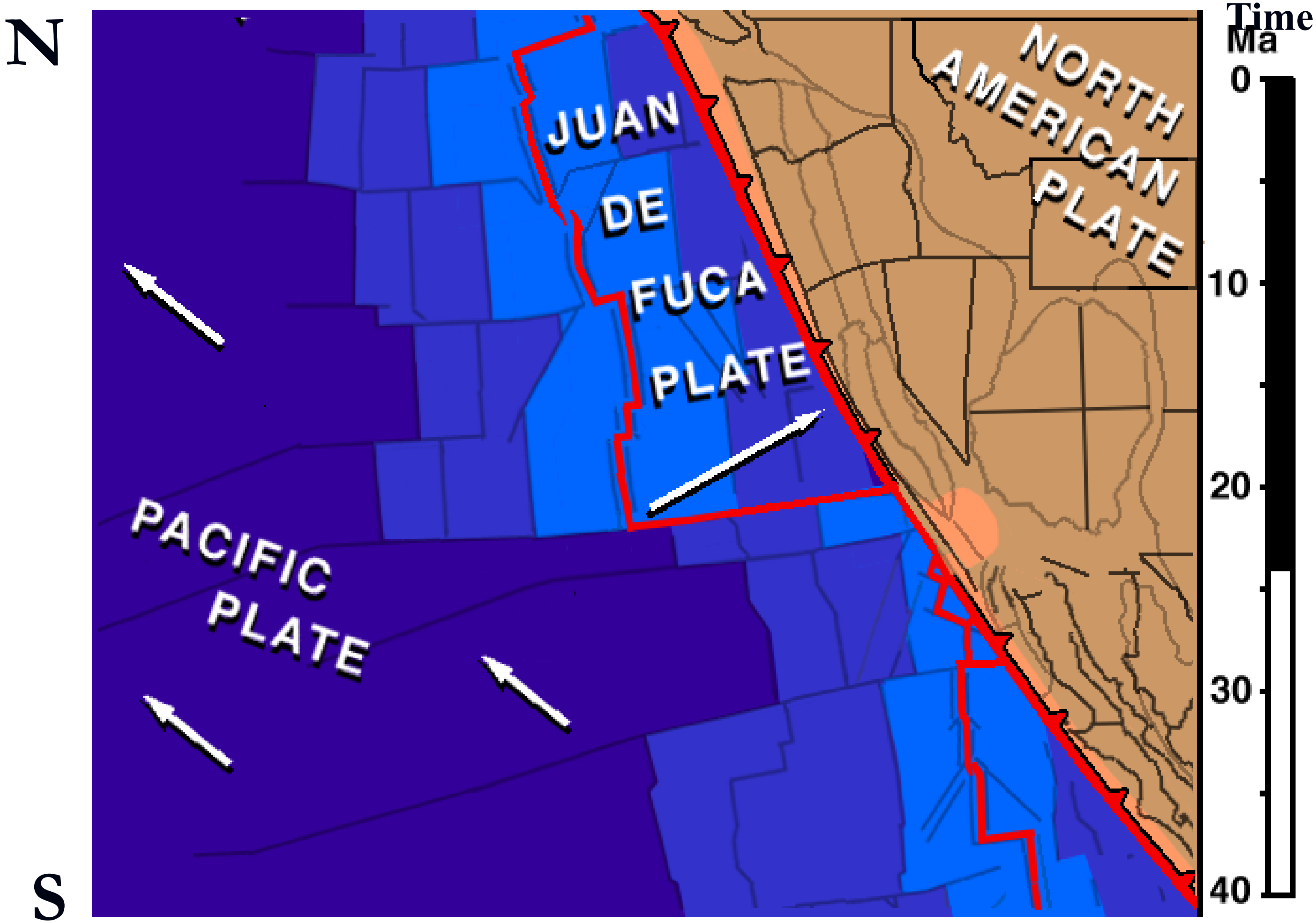


USGS Professional Paper 1515

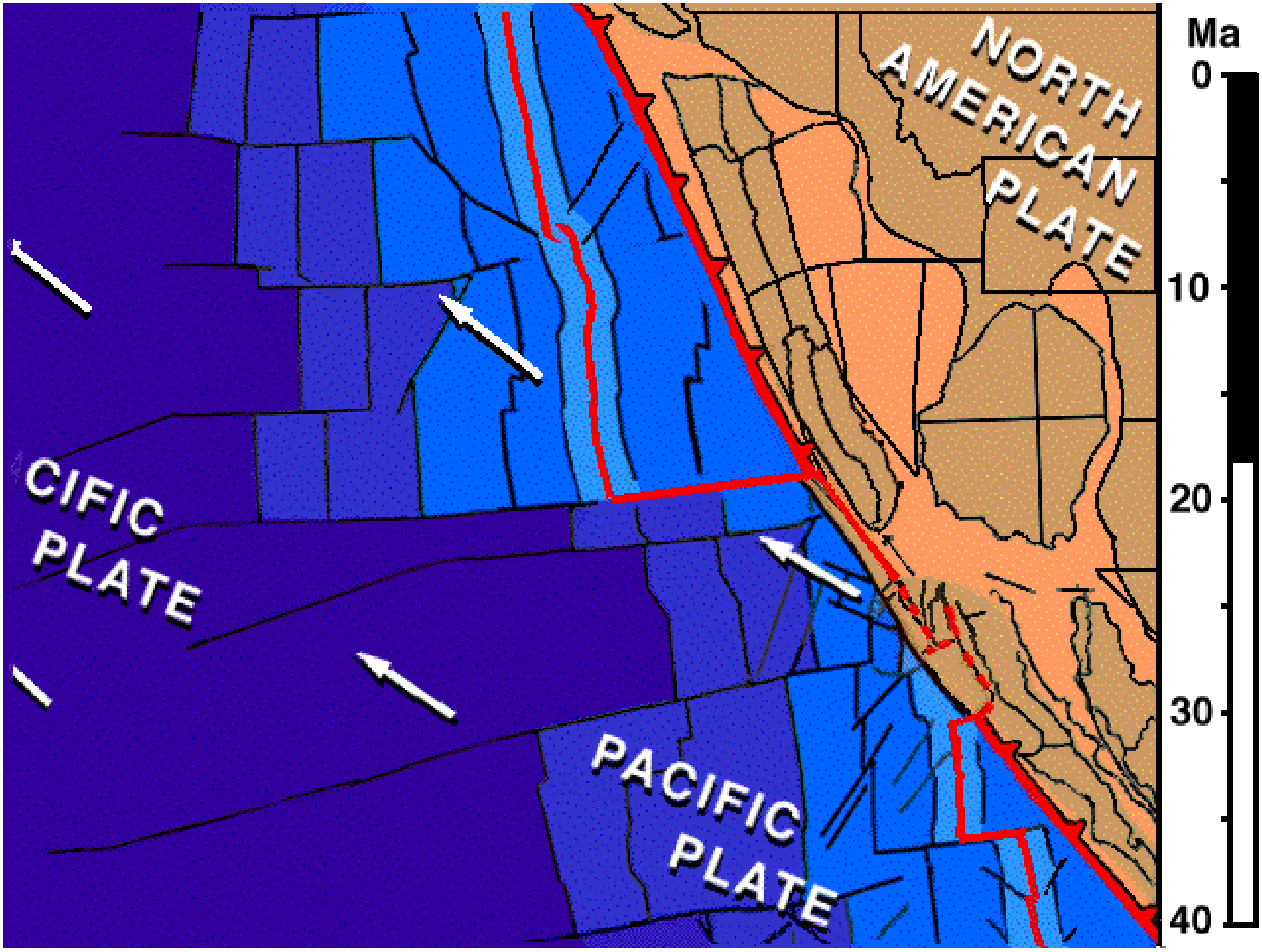

SAN ANDREAS FAULT
SACRAMENTO VALLEY
Sacramento
San Francisco
SAN ANDREAS FAULT
SAN JOAQUIN VALLEY
Fresno
PACIFIC

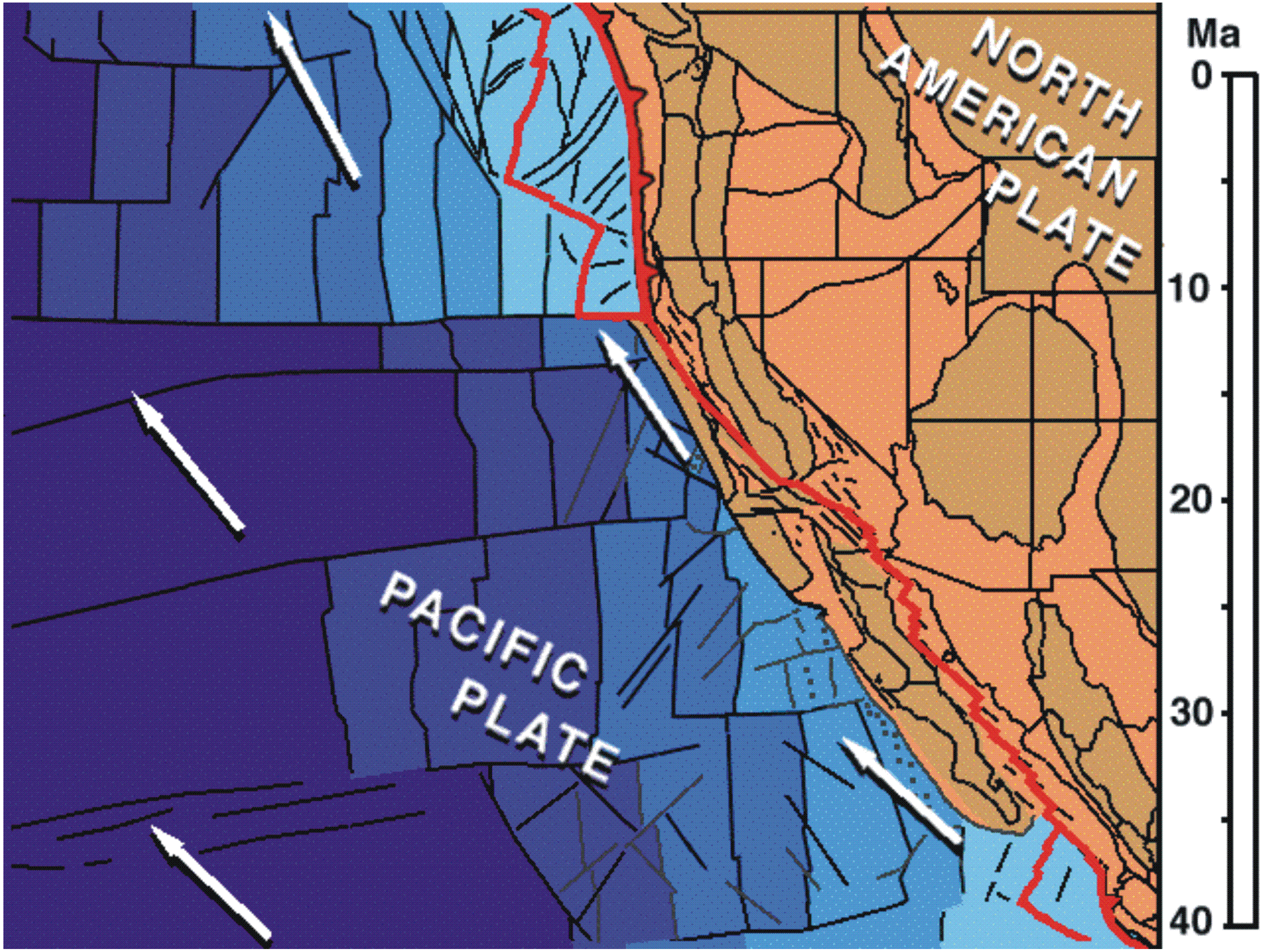

236°
238°
240°
40°
38°
36°
6Ma
8Ma
10Ma
12Ma
14Ma
16Ma
18Ma
20Ma
MAF
BSF
SAN ANDREAS
RCF
GVF
CF
HF
CF
SGF
Salinian block
RF
SAN ANDREAS
HOS
Heat Flow
mW/m2
100
75
50
25

24 Ma: Shortly after Initiation of Strike-Slip



(animation by T. Atwater)


NORTH AMERICAN PLATE
CIFIC PLATE
PACIFIC PLATE
Ma
0
10
20
30
40


NORTH AMERICAN PLATE
PACIFIC PLATE
Ma
0
10
20
30
40

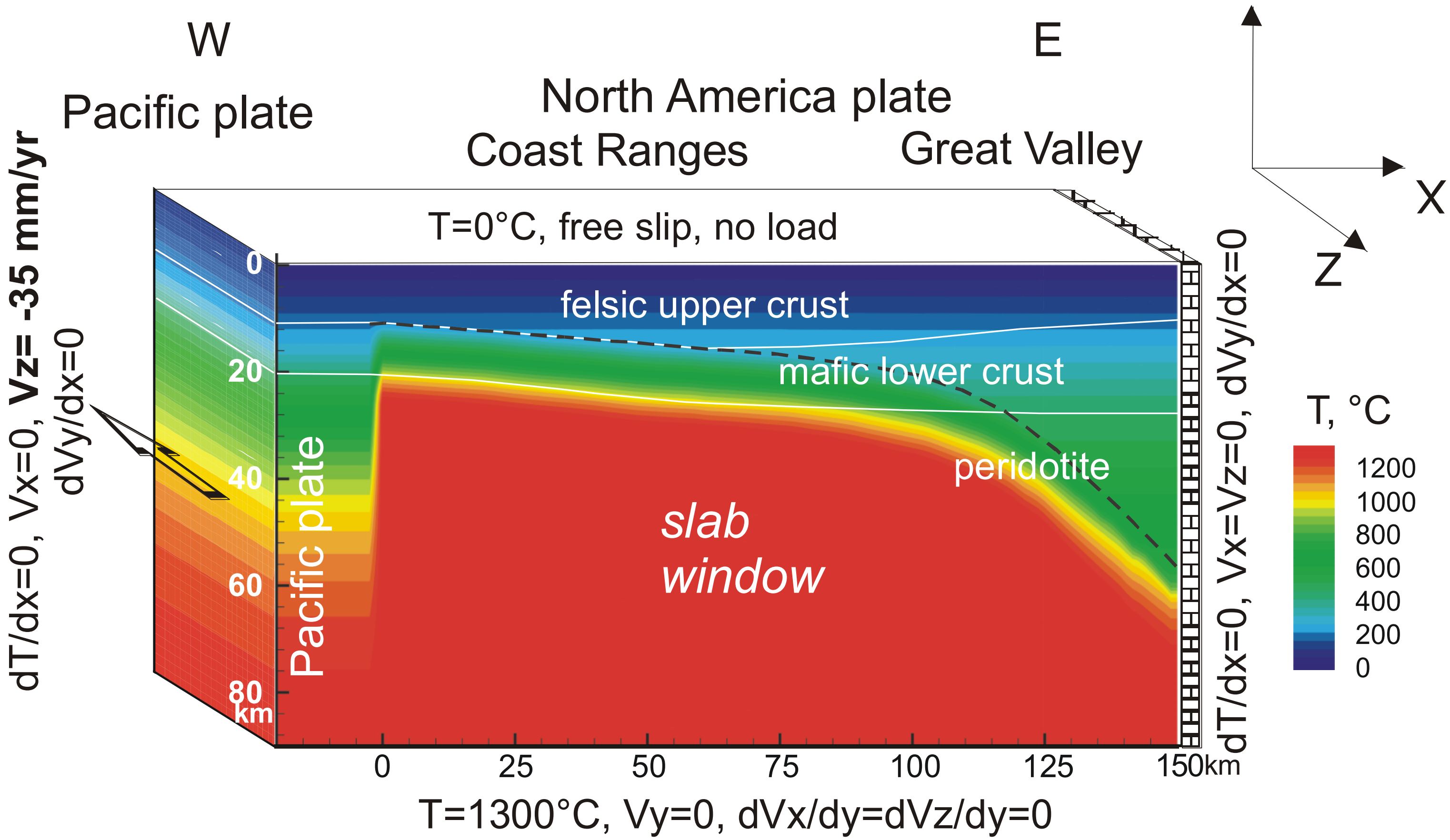
Questions addressed

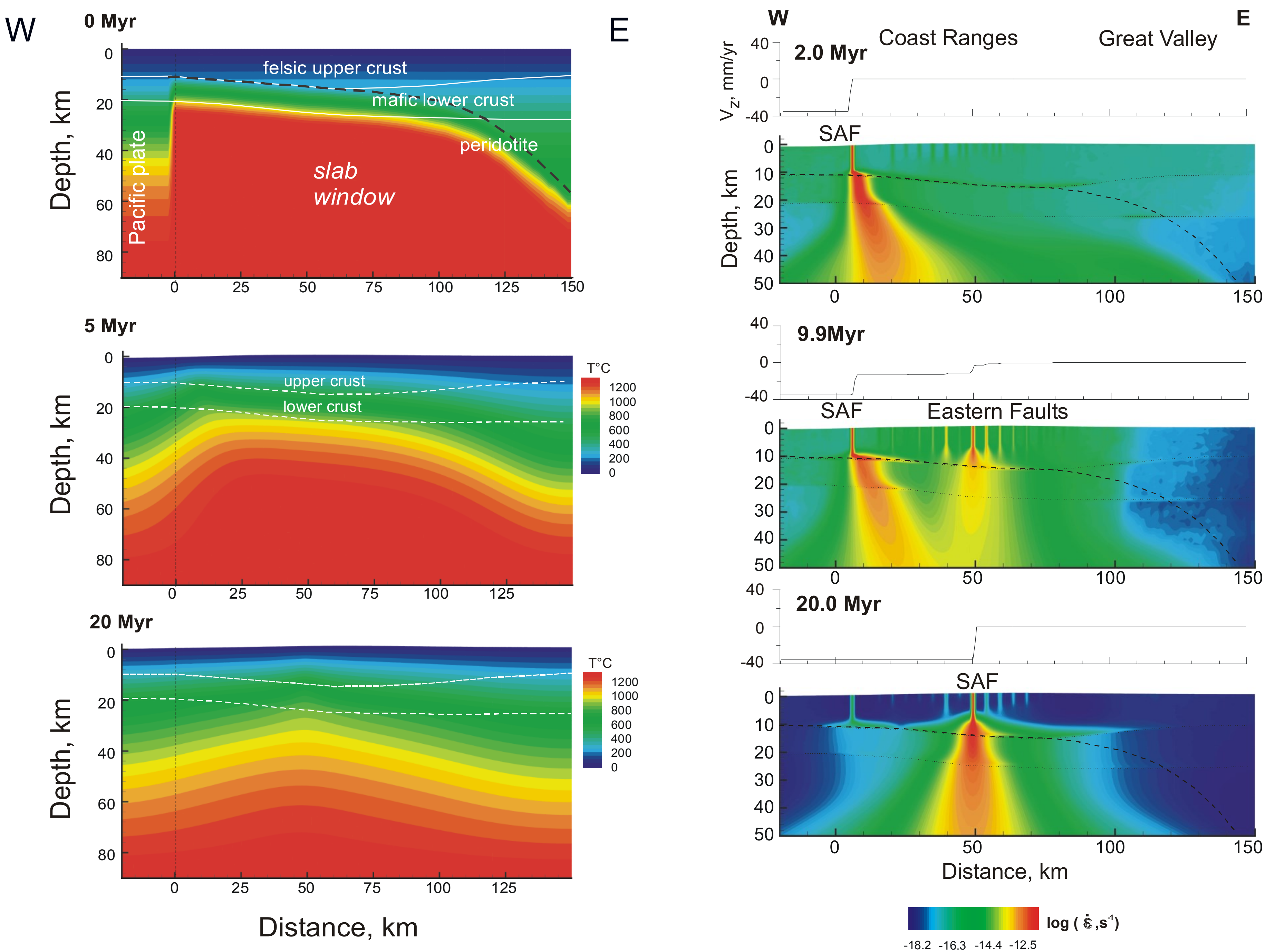
Why the locus of deformation in SAFS migrates landwards with time?

How differently would evolve SAFS with “strong” and “weak” major faults?

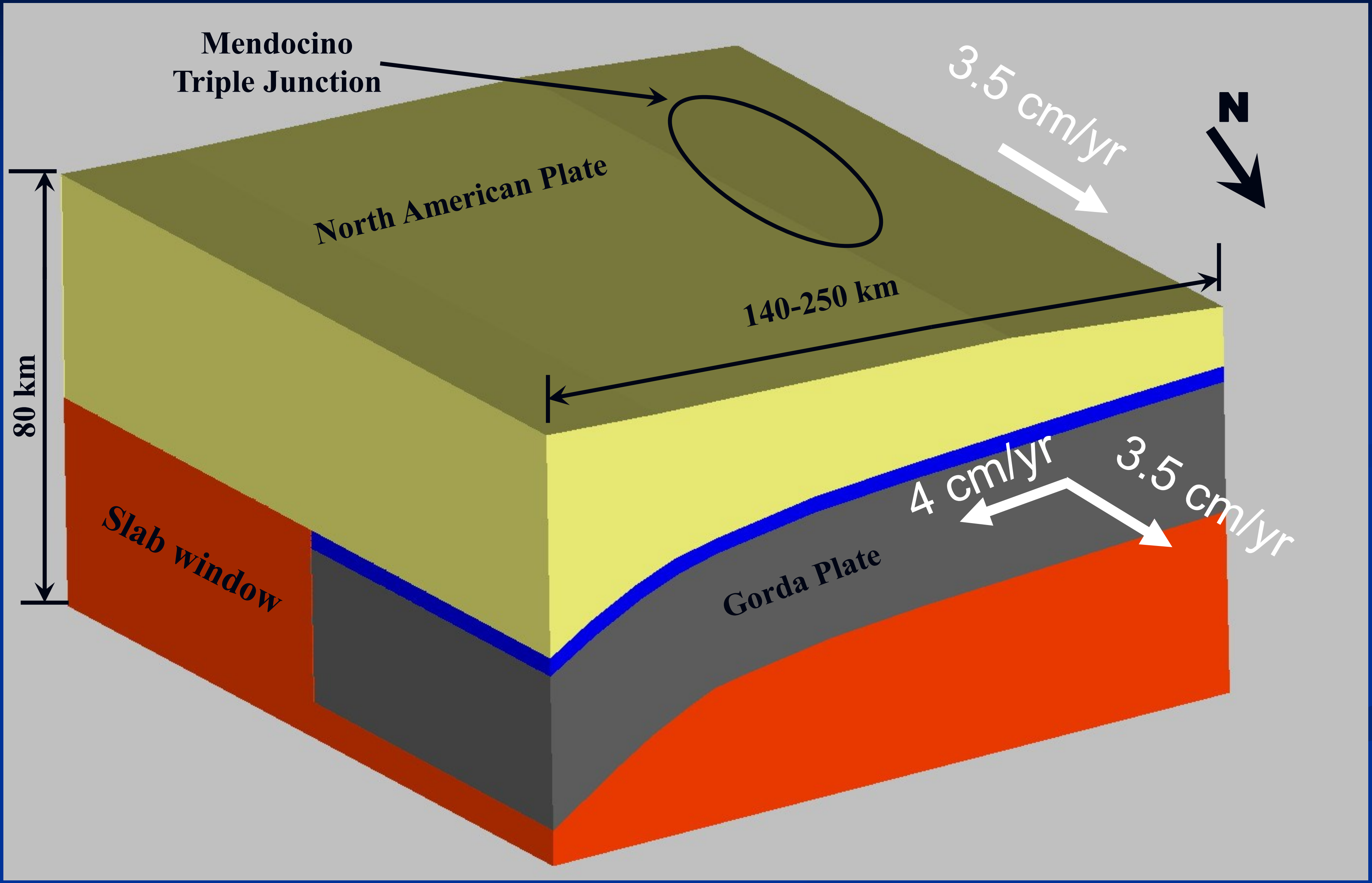
Why the locus of deformation in SAFS migrates landwards with time?

Extended 2D Model Setup (South view)




W
E
0 Myr
felsic upper crust
mafic lower crust
peridotite
slab
window
Pacific plate
Depth, km
5 Myr
upper crust
lower crust
T°C
1200
1000
800
600
400
200
0
20 Myr
Distance, km
2.0 Myr
Coast Ranges
Great Valley
V_z, mm/yr
SAF
9.9Myr
Eastern Faults
20.0 Myr
log ($\dot{\varepsilon}$,s^{-1})
-18.2 -16.3 -14.4 -12.5

Model Setup (view from the North)



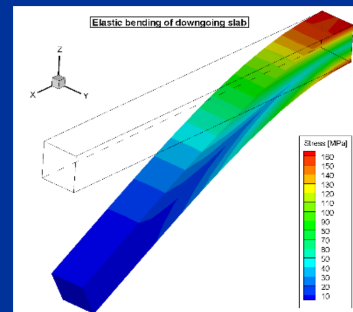
Popov, Sobolev, Zoback, G3 2012

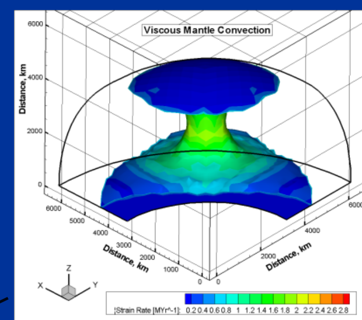
Physical background

Balance equations

Momentum: $$\frac{\partial \sigma_{ij}}{\partial x_j} + \Delta\rho g\, z_i = 0$$

Energy: $$\frac{DU}{Dt} = -\frac{\partial q_i}{\partial x_i} + r$$





Deformation mechanisms

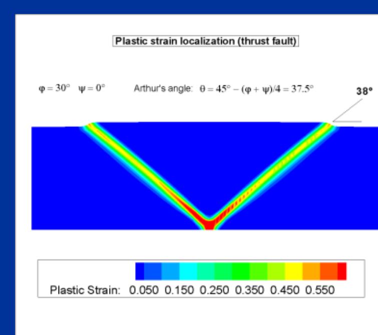
$\dot{\varepsilon}_{ij}$ $\dot{}_{ij}$ $\dot{}_{ij}$ $\dot{}_{ij}$

Elastic strain: $\dot{\varepsilon}_{ij}$ $\frac{1}{2G}$ $_{ij}$

Viscous strain: $\dot{\varepsilon}_{ij}$ $\frac{1}{2\eta_{eff}}\tau_{ij}$

Plastic strain: $\dot{\varepsilon}_{ij}$ $\frac{\partial Q}{\partial \tau_{ij}}$

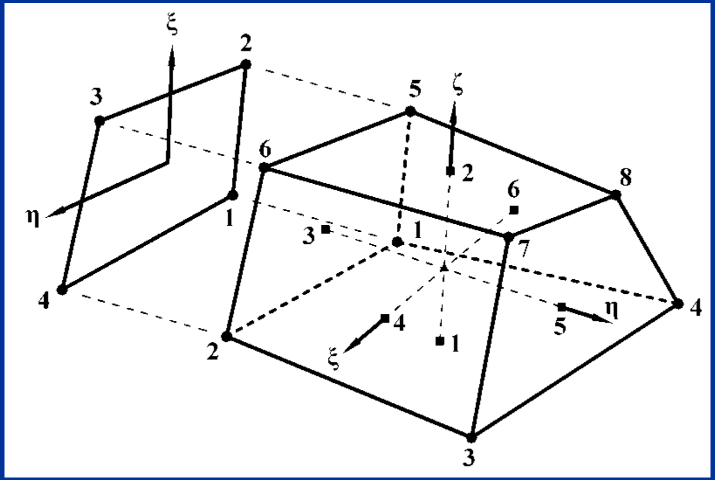
Mohr-Coulomb



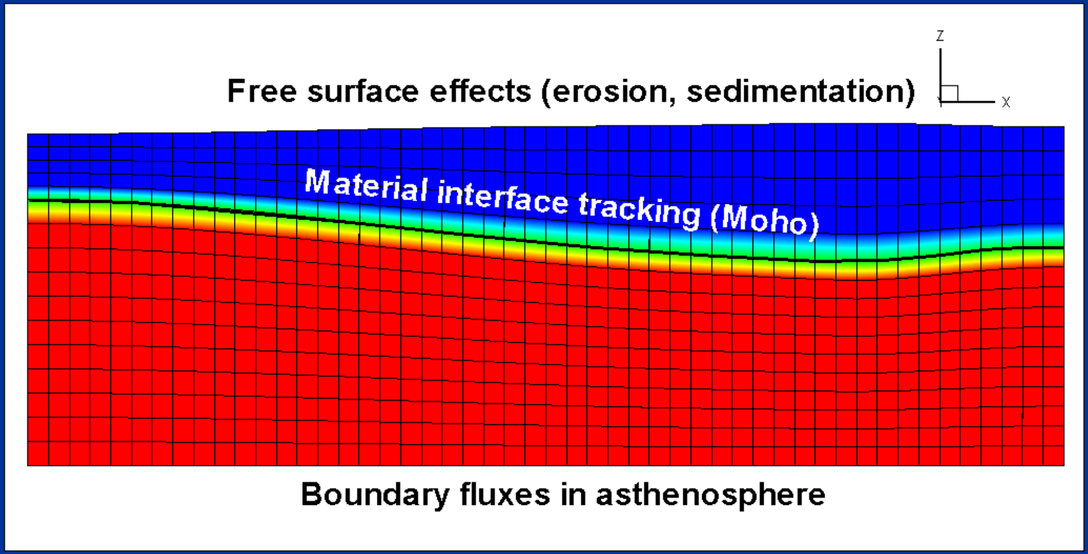
Popov and Sobolev (2008)

Numerical background

Discretization by Finite Element Method



Arbitrary Lagrangian-Eulerian kinematical formulation



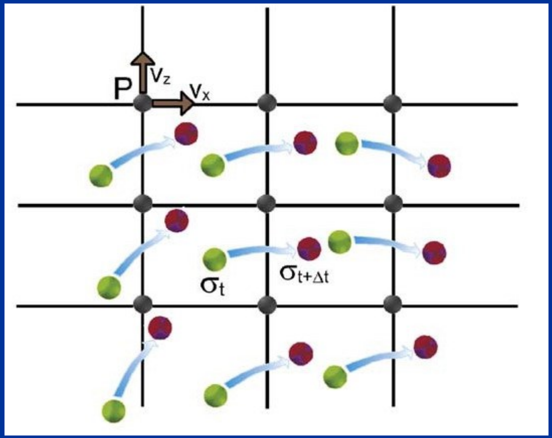
Fast implicit time stepping + Newton-Raphson solver

$$\mathbf{u}_{k+1} = \mathbf{u}_k - \mathbf{K}_k^{-1}\mathbf{r}_k$$

$\mathbf{r}$ – **Residual Vector**

$\mathbf{K} = \dfrac{\partial \mathbf{r}}{\partial \Delta \mathbf{u}}$ – **Tangent Matrix**

Remapping of entire fields by Particle-In-Cell technique



Popov and Sobolev (2008)

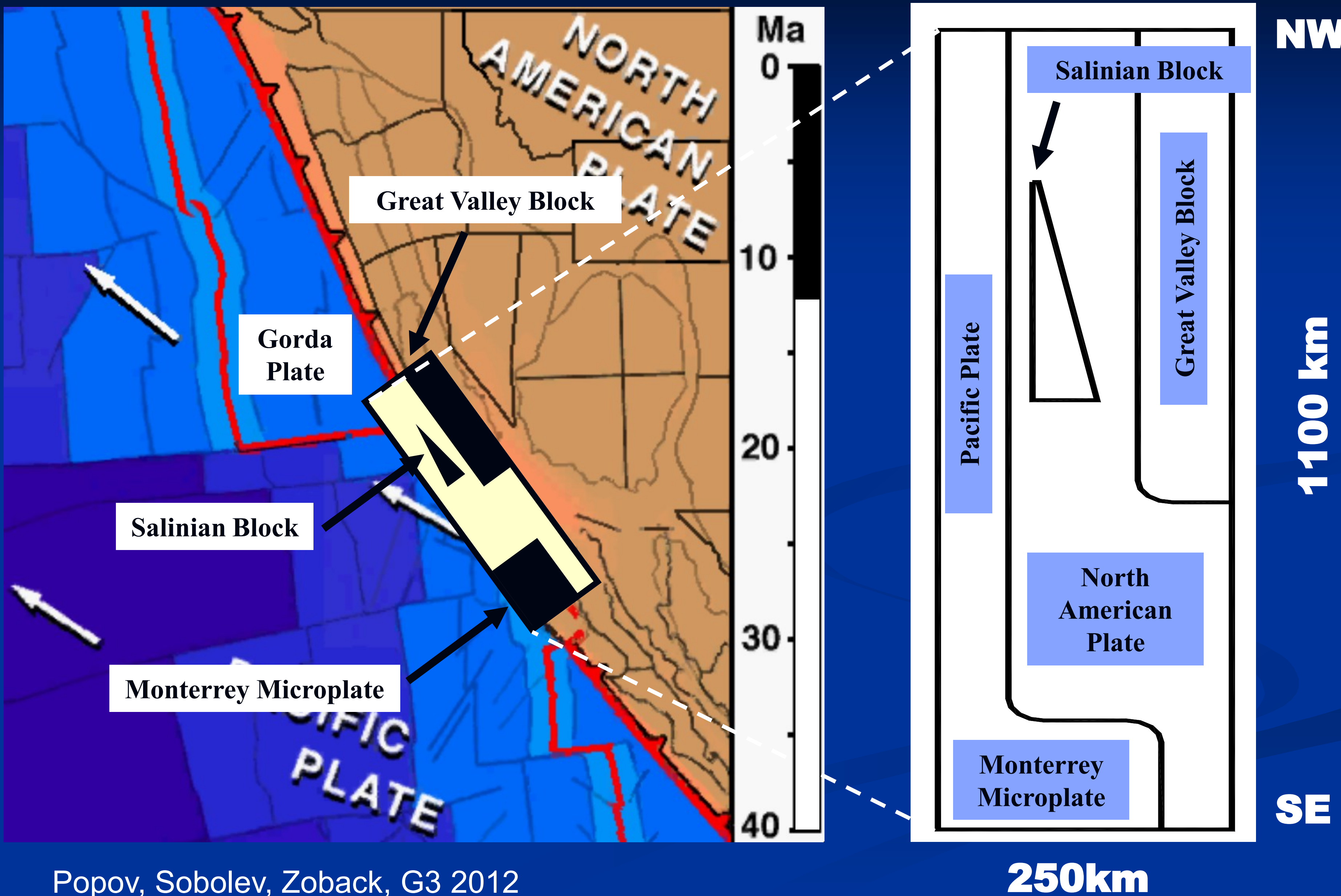
“Strong” and “weak” faults models

“Strong faults” model: the friction coefficient decreases only slightly (from 0.6 to 0.3) with increasing plastic strain

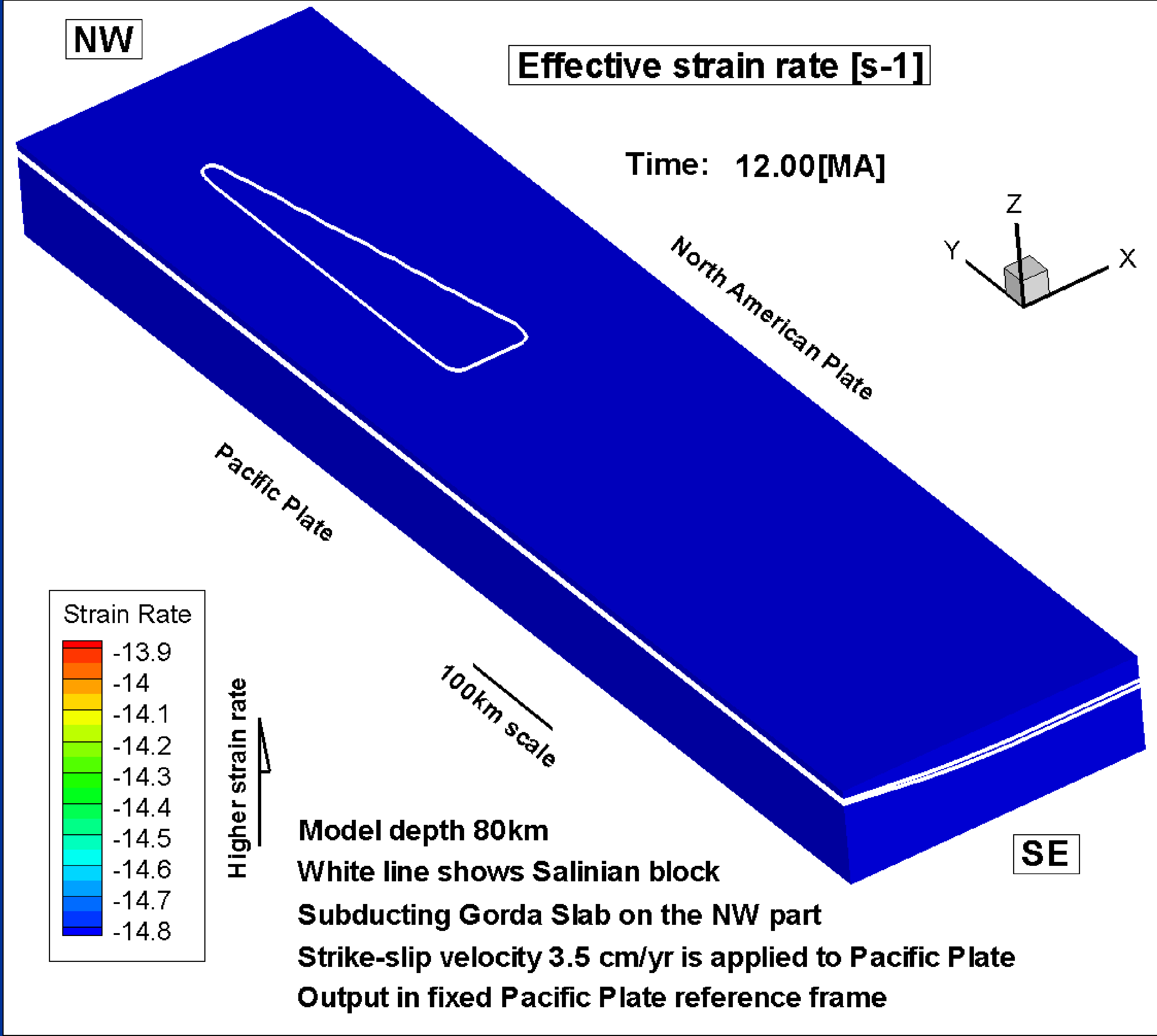
“Weak faults” model: the friction coefficient decreases drastically (from 0.6 to 0.07) with increasing plastic strain

Popov, Sobolev, Zoback, G3 2012

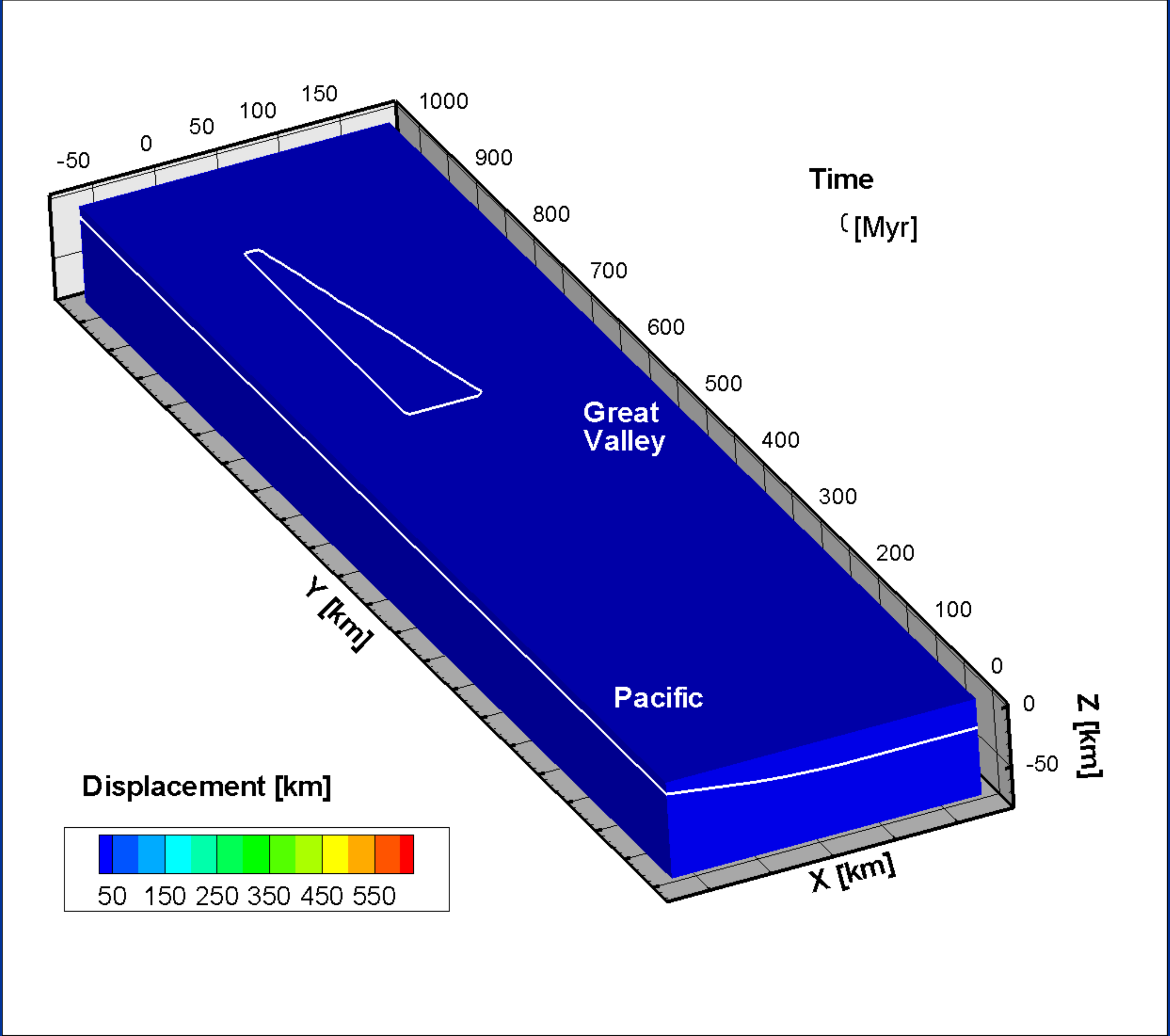
3D Model Setup (12-15 MA)



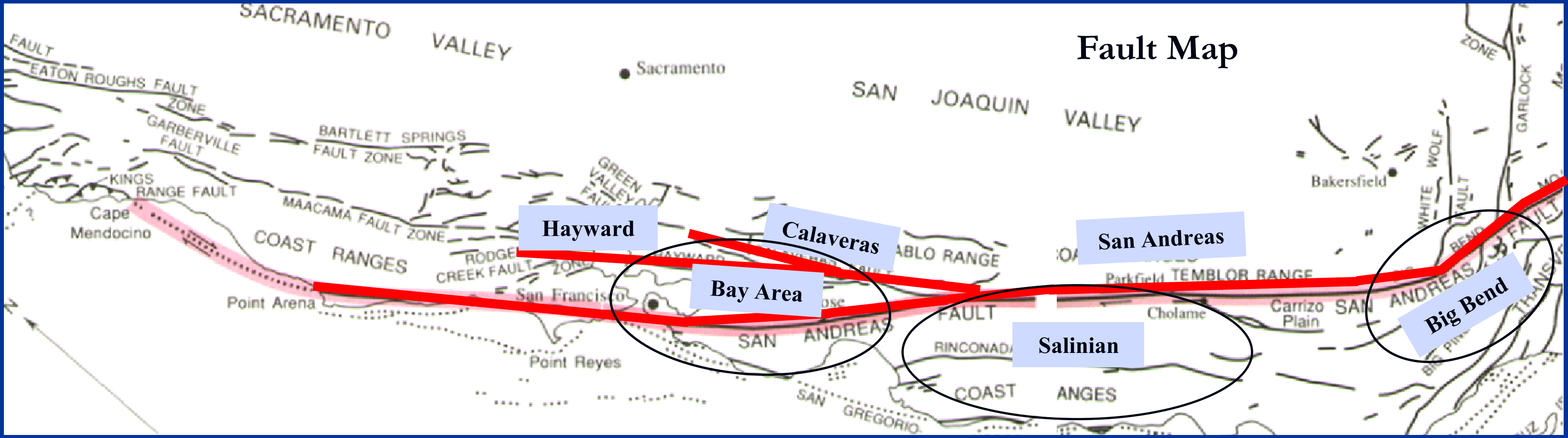
Popov, Sobolev, Zoback, G3 2012

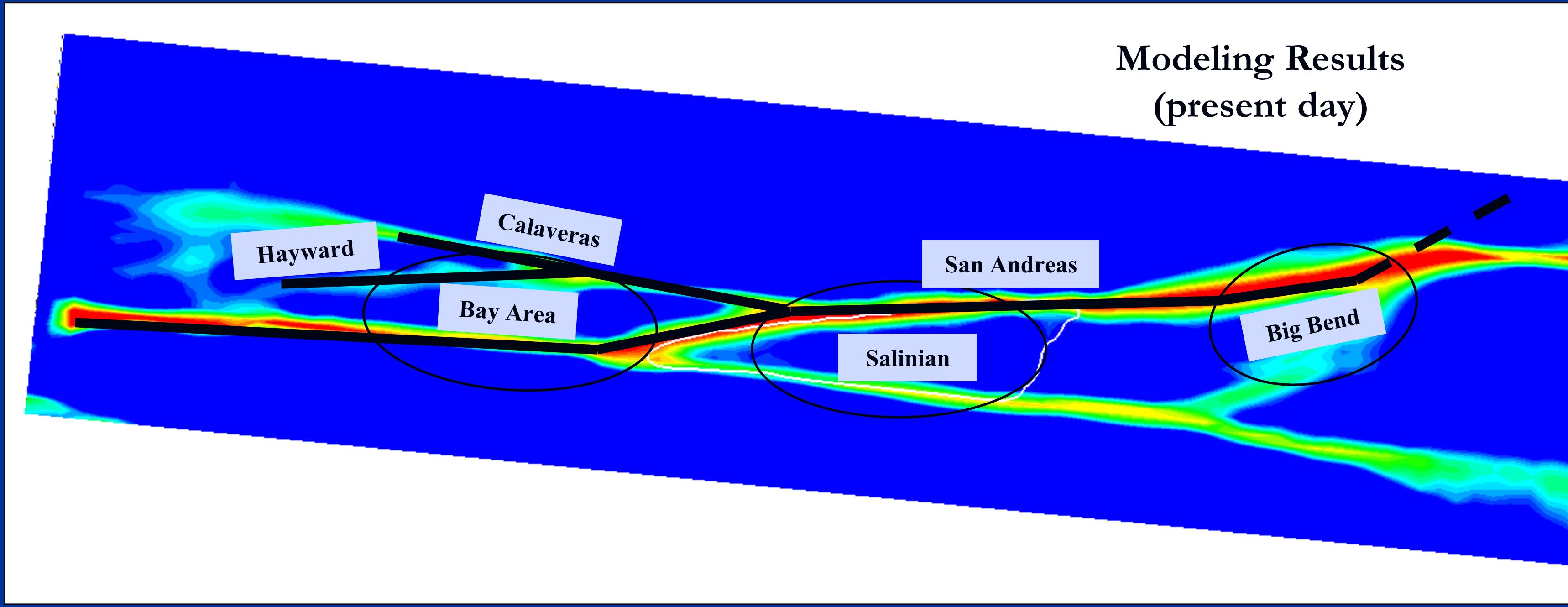


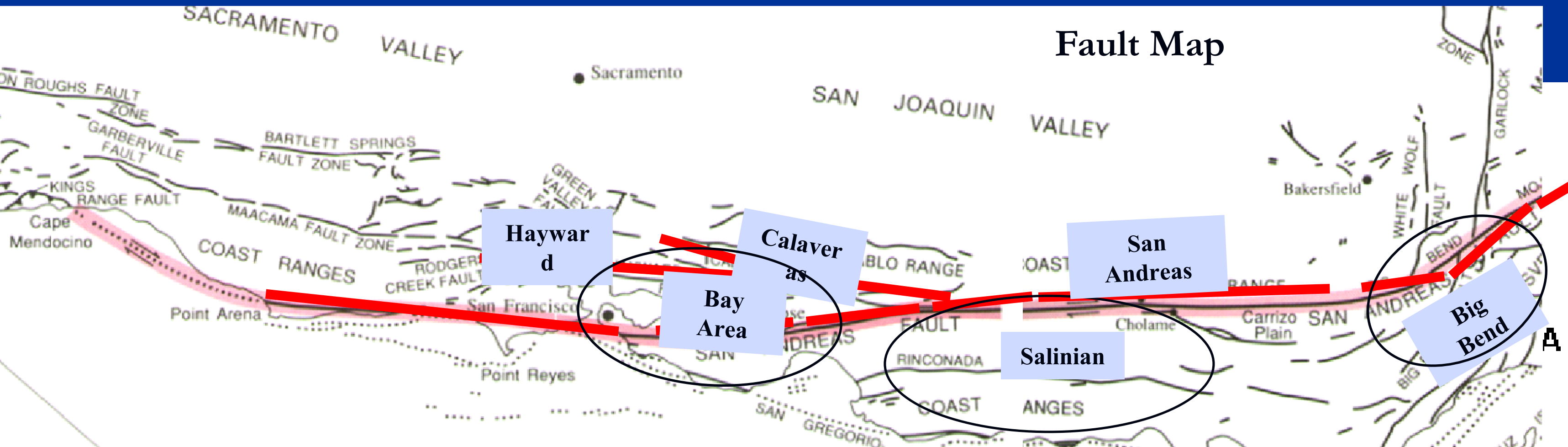
NW
Effective strain rate [s-1]
Time: 12.00[MA]
Z
Y
X
North American Plate
Pacific Plate
100km scale
Strain Rate
-13.9
-14
-14.1
-14.2
-14.3
-14.4
-14.5
-14.6
-14.7
-14.8
Higher strain rate
SE
Model depth 80km
White line shows Salinian block
Subducting Gorda Slab on the NW part
Strike-slip velocity 3.5 cm/yr is applied to Pacific Plate
Output in fixed Pacific Plate reference frame

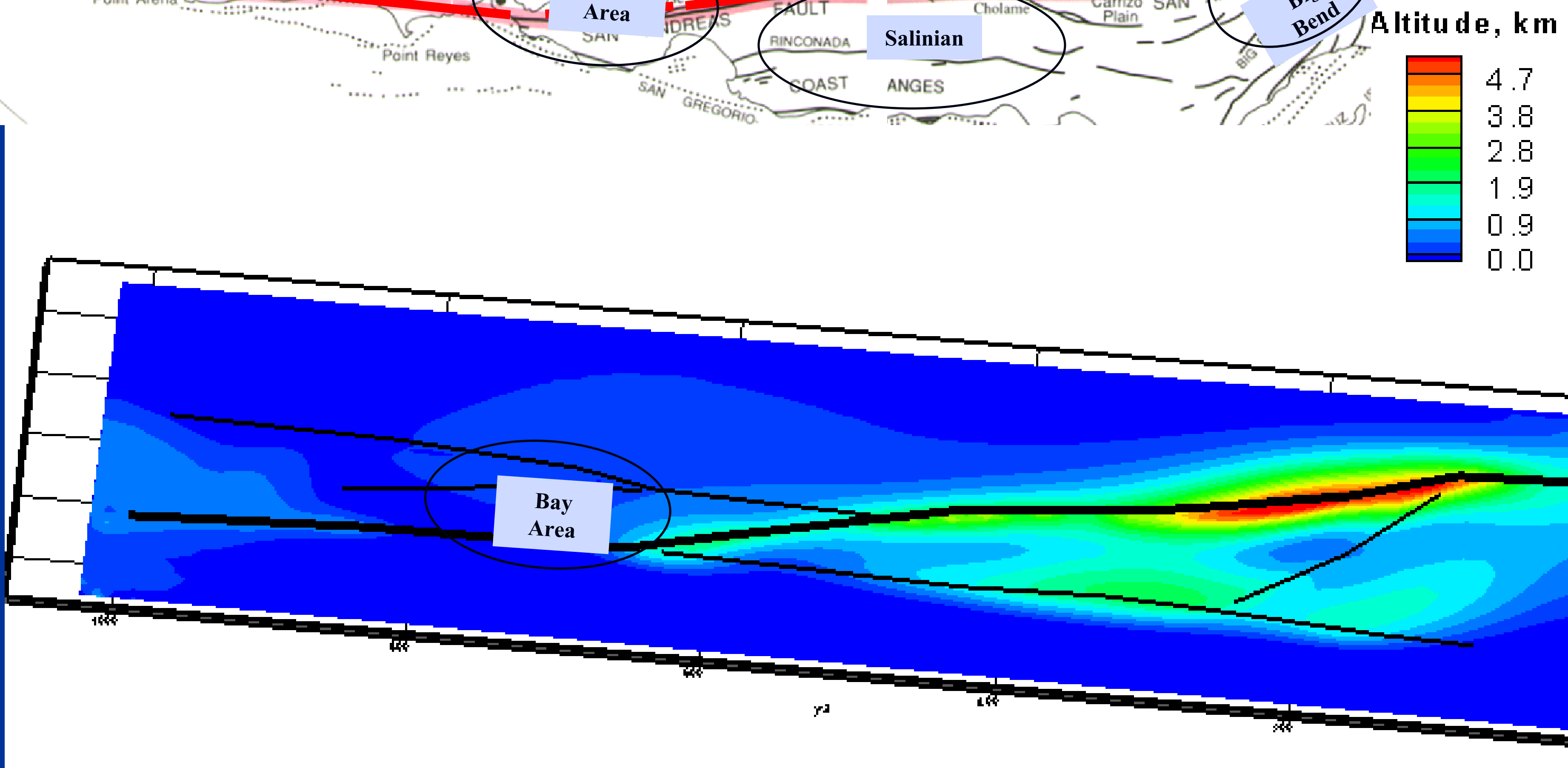

Time
[Myr]
-50
0
50
100
150
1000
900
800
700
600
500
400
300
200
100
0
Great
Valley
Pacific
Y [km]
X [km]
Z [km]
0
-50
Displacement [km]
50 150 250 350 450 550

Qualitative comparison of basic fault features

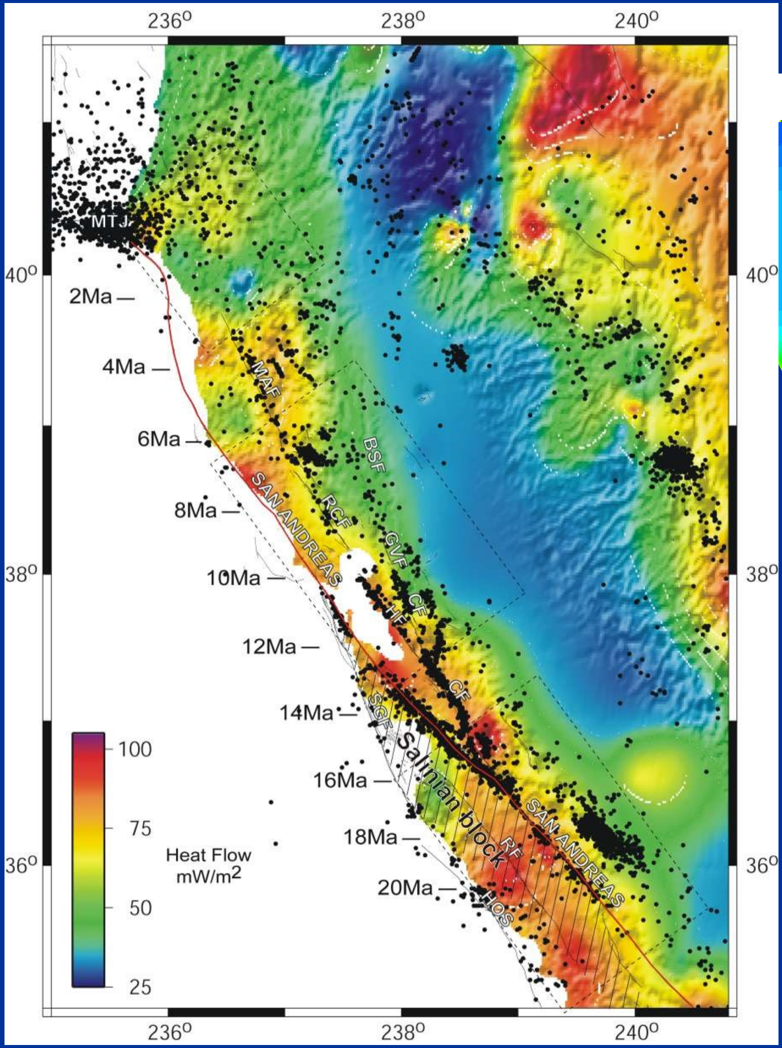


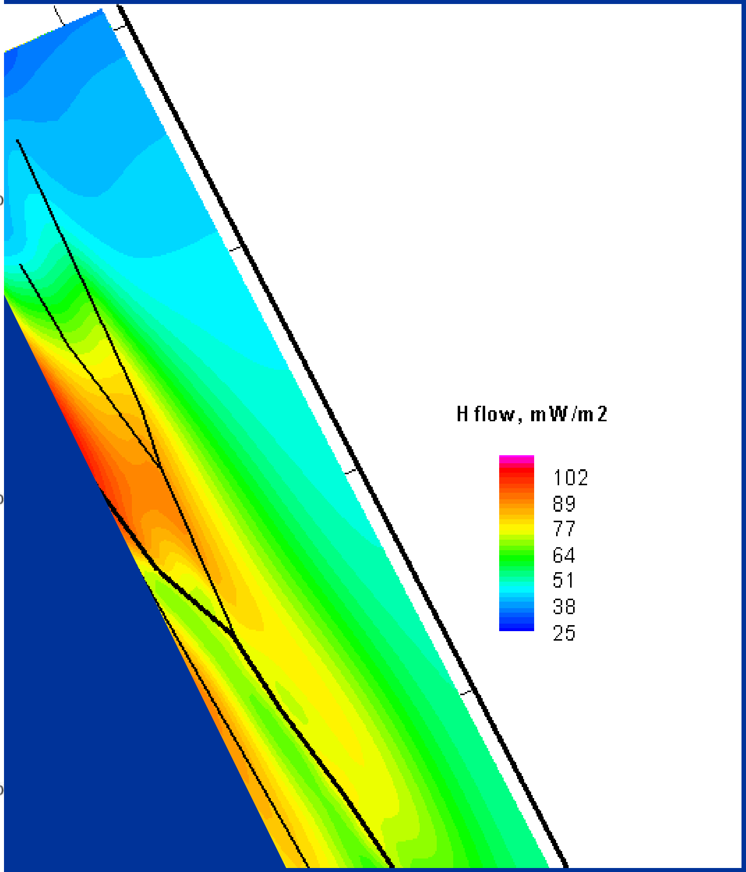



Fault Map
SACRAMENTO
VALLEY
Sacramento
SAN JOAQUIN VALLEY
Bakersfield
GARBERVILLE FAULT
BARTLETT SPRINGS FAULT ZONE
KINGS RANGE FAULT
MAACAMA FAULT ZONE
Cape Mendocino
COAST RANGES
RODGERS CREEK FAULT
San Francisco
Point Arena
Point Reyes
Haywar d
Calaver as
Bay Area
San Andreas
Salinian
Big Bend
RINCONADA
Cholame
Carrizo Plain
GARLOCK
WHITE WOLF


Altitude, km
4.7
3.8
2.8
1.9
0.9
0.0
Bay Area

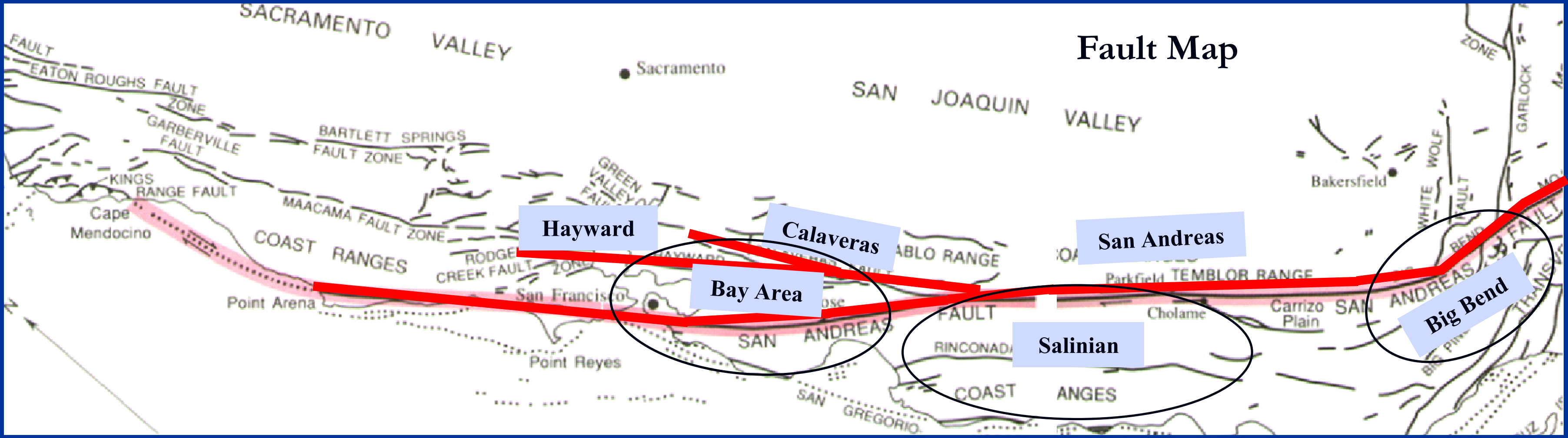
Modeled surface heat flow

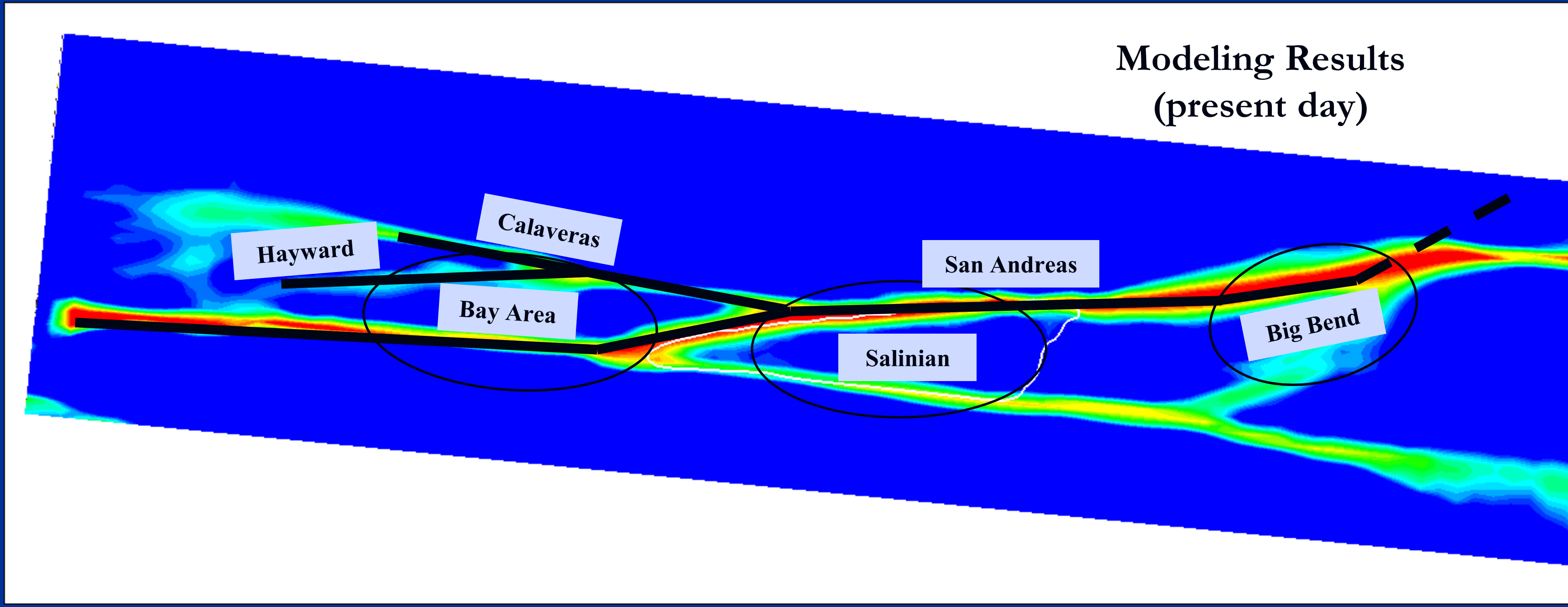




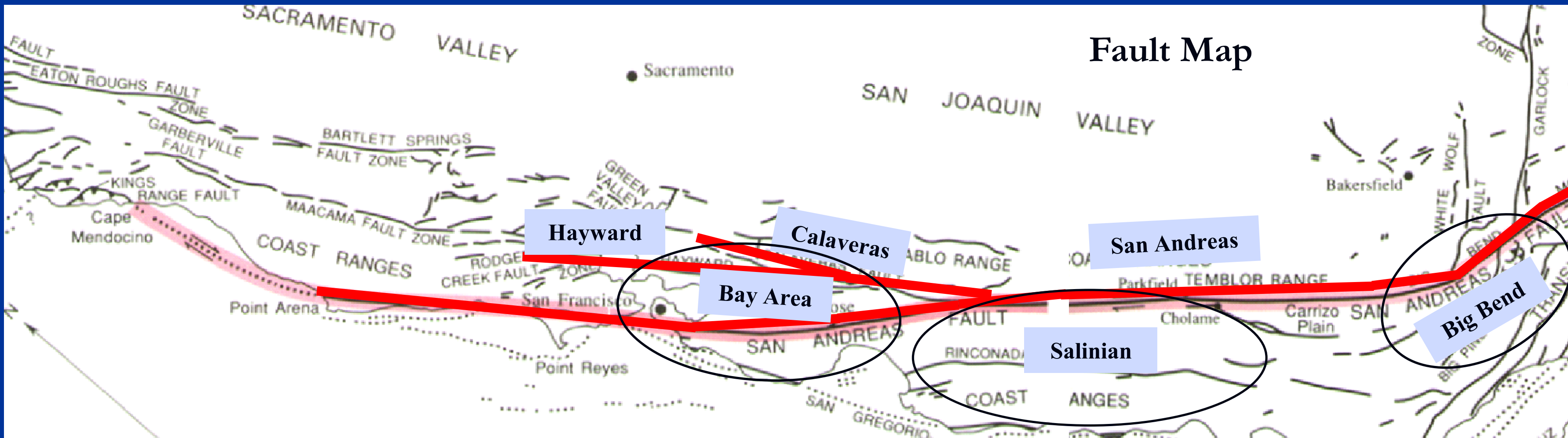
“Weak faults” versus “strong faults” model

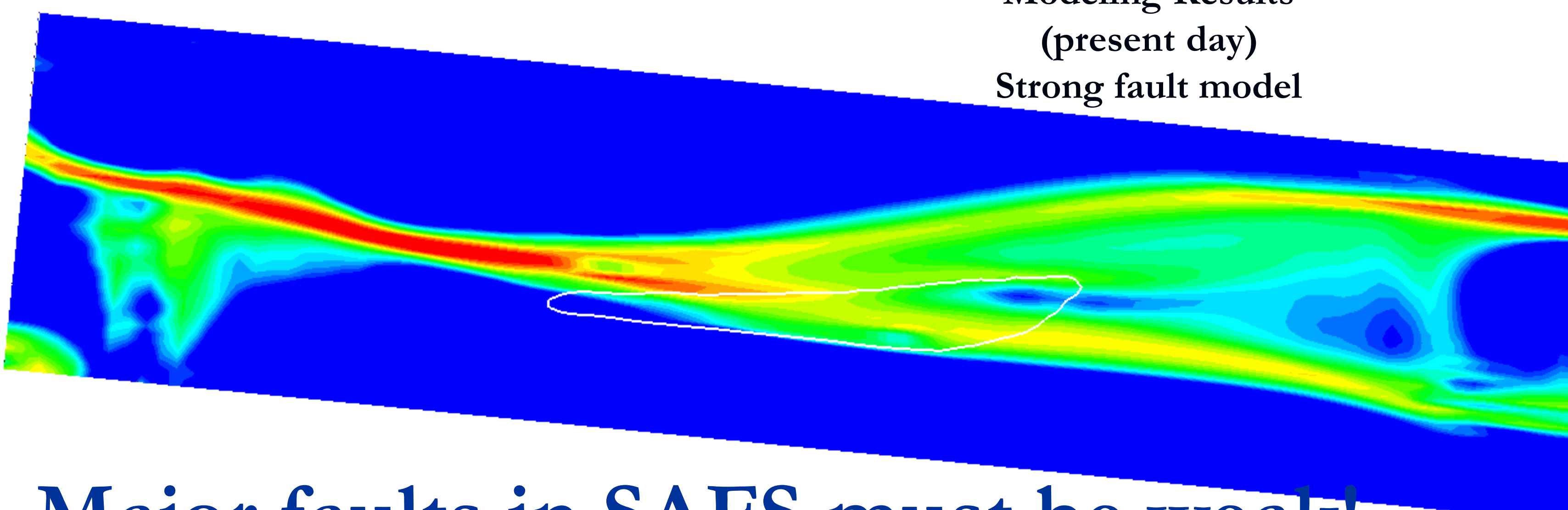
Weak-faults model





Strong-faults model





Major faults in SAFS must be weak!

Conclusions for SAFS

Present day structure and landward motion of SAFS is controlled by kinematic boundary conditions and lithospheric heterogeneity, including captured Monterray microplate

Major faults at SAFS must be “week”