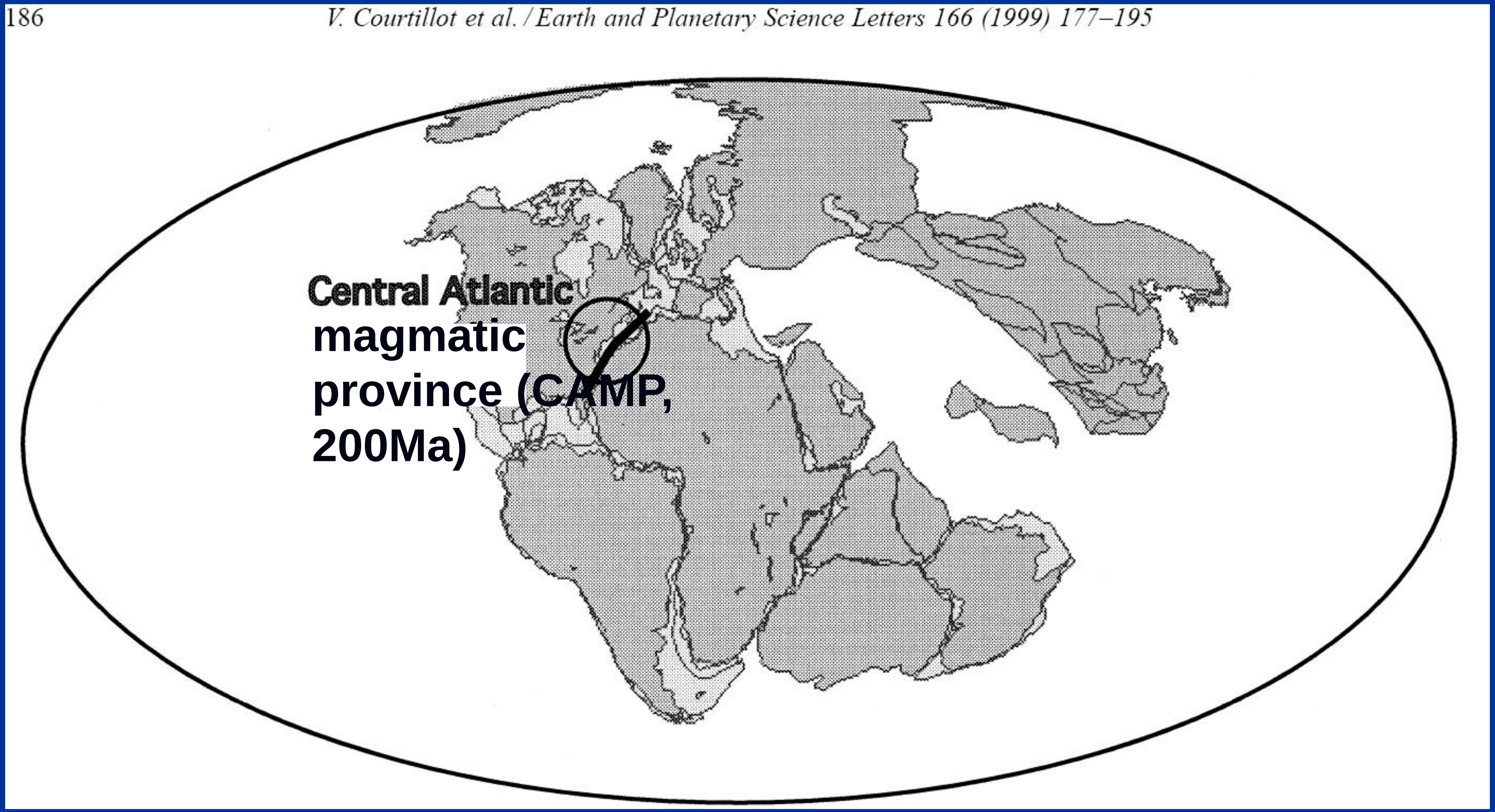
# Lecture 5. Rifting, Continental break-up, Transform faults

- 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

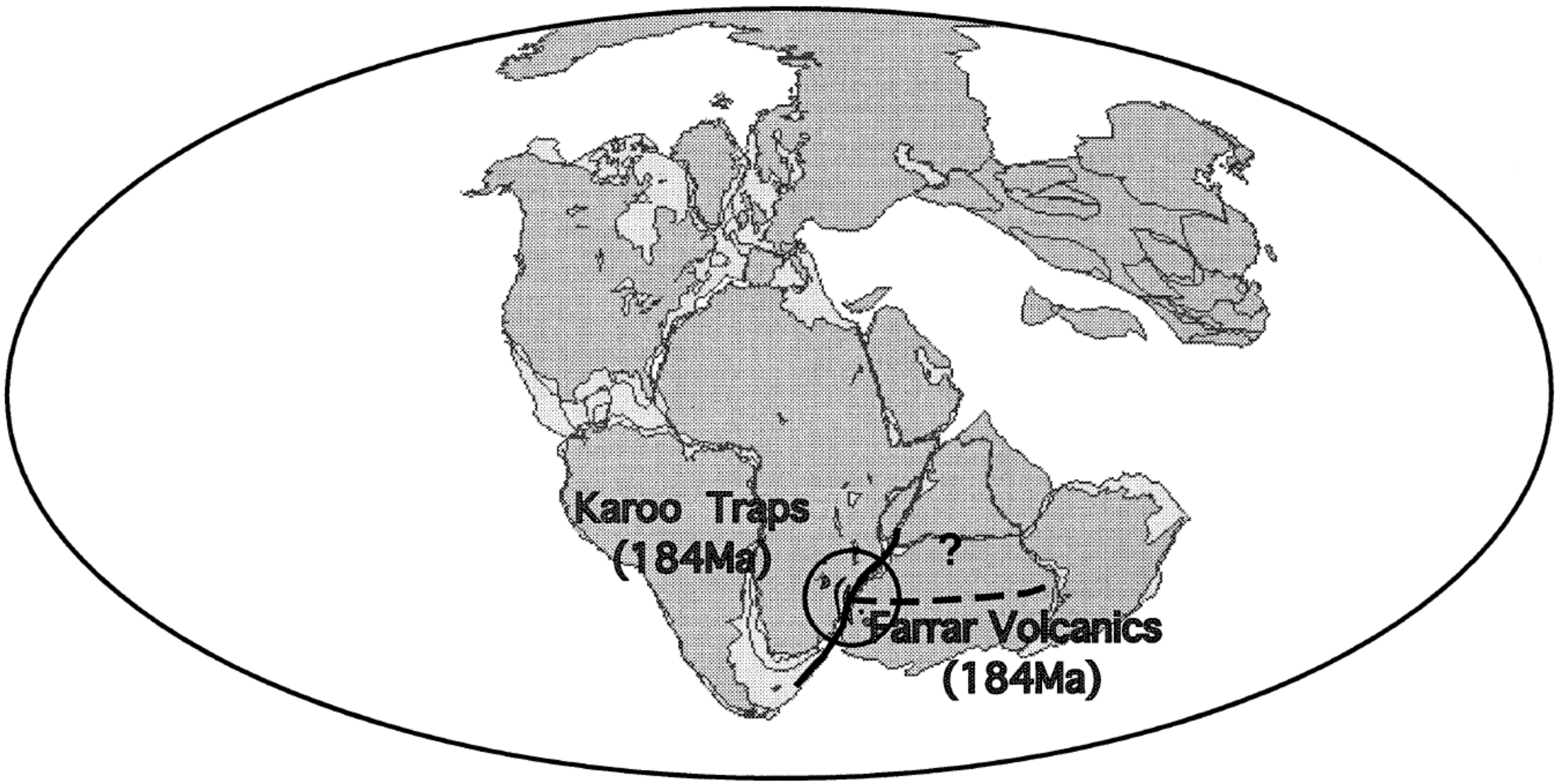
# Continental break-up

# Continental break-up

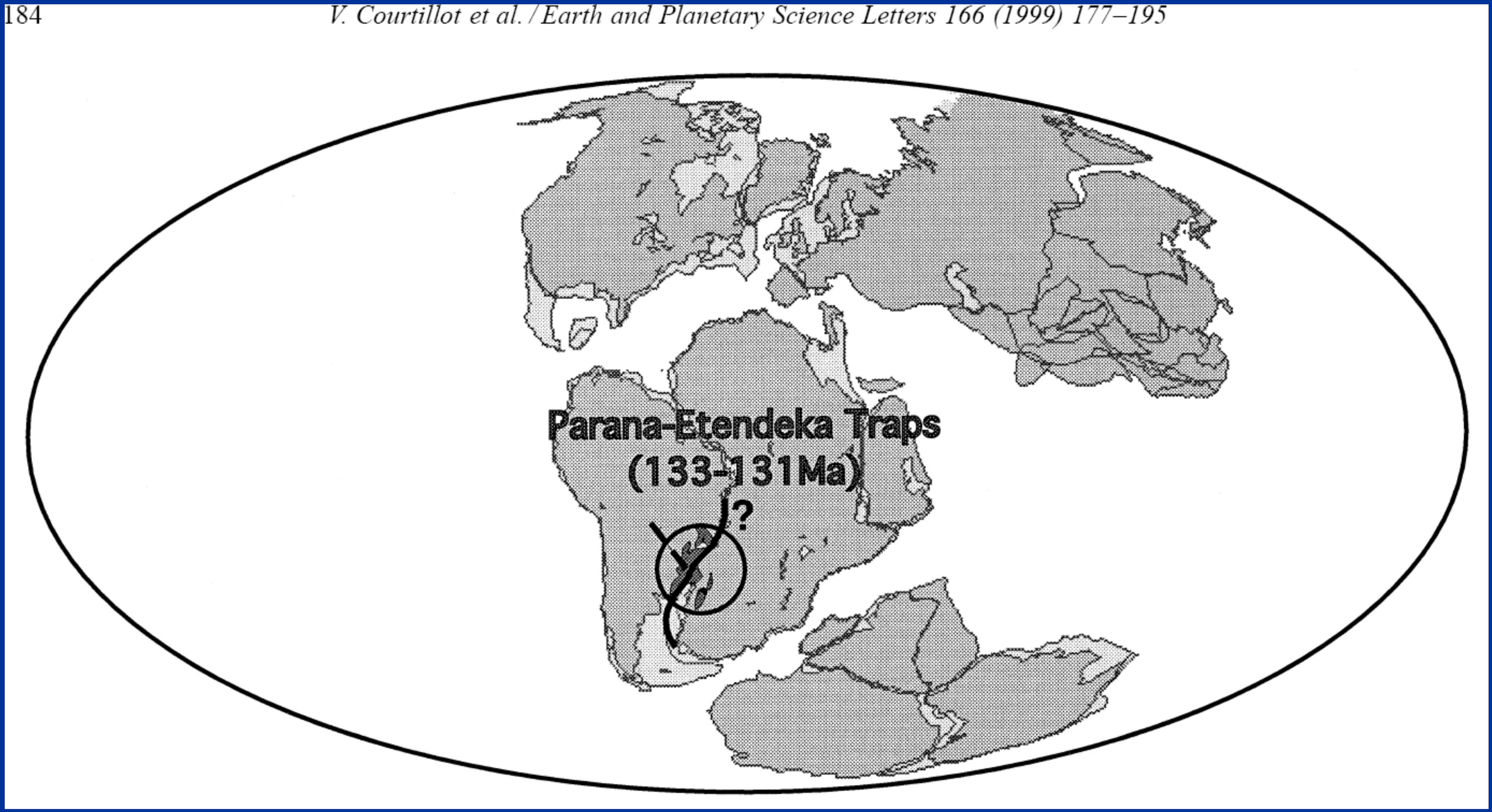


# Continental break-up

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

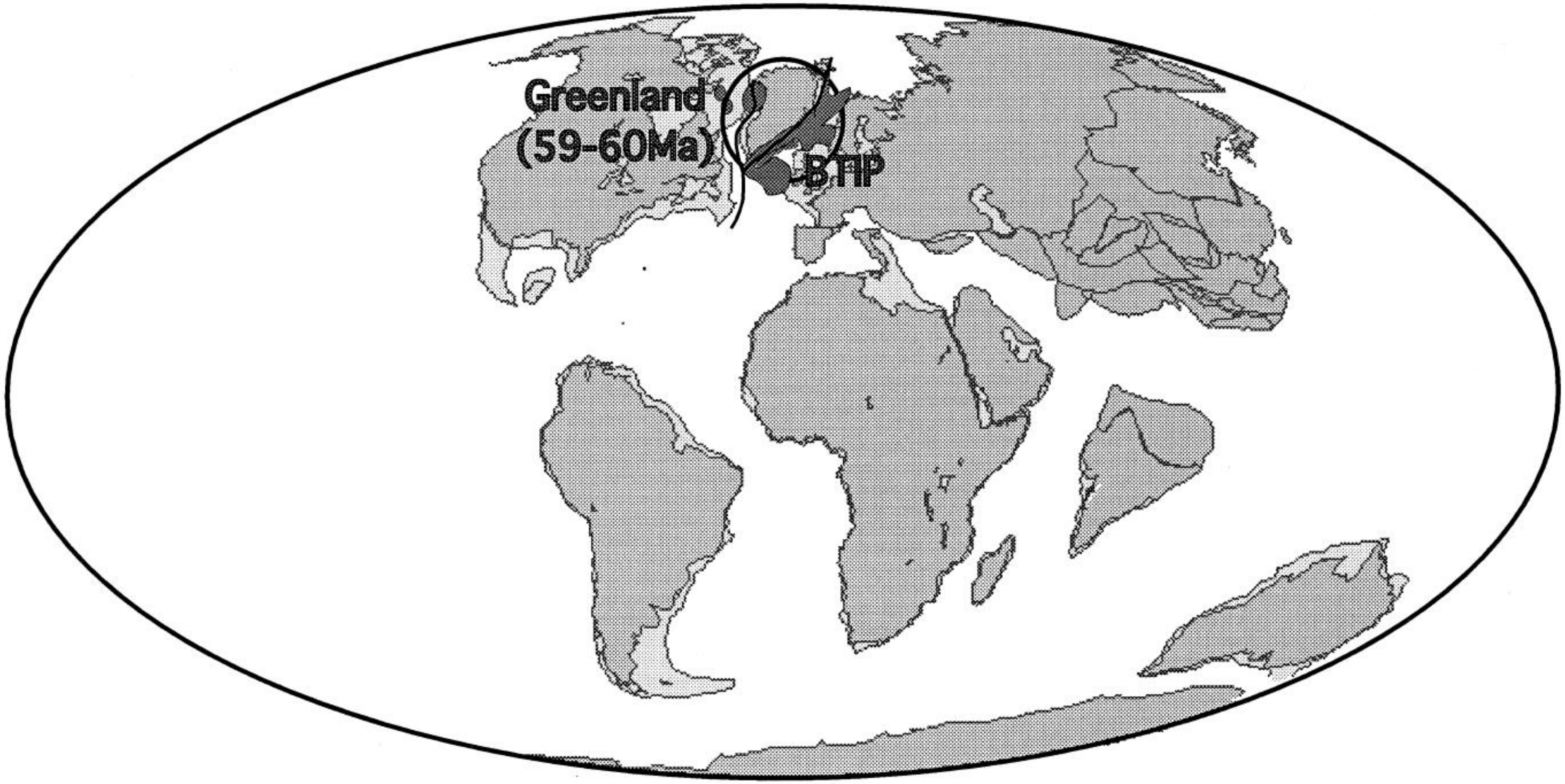


# Continental break-up

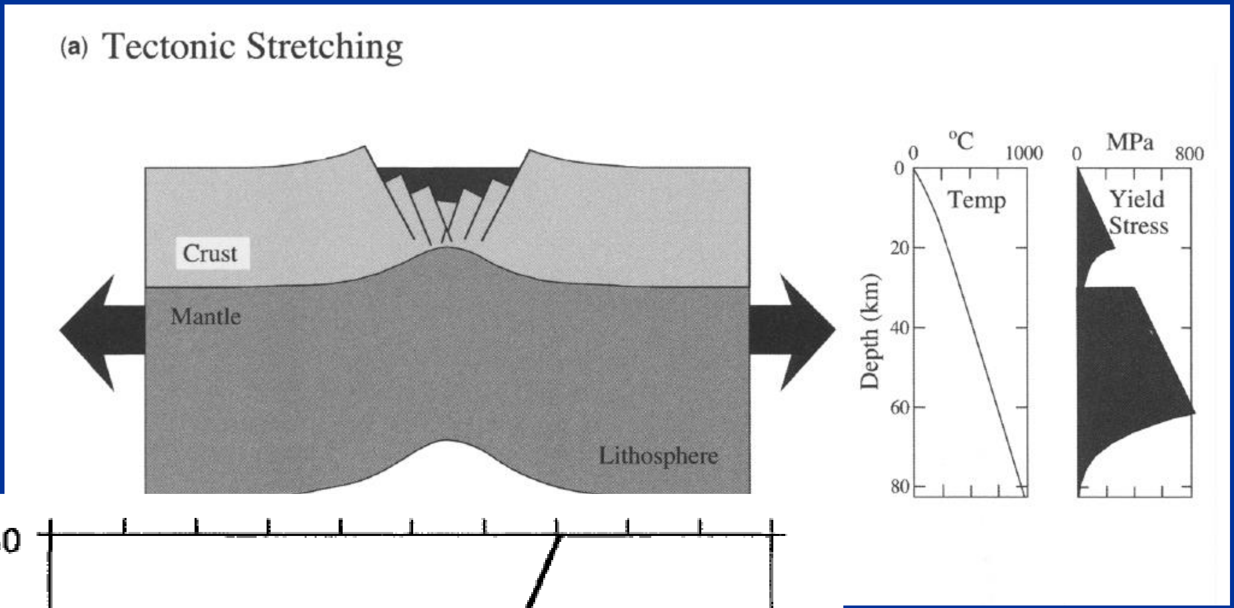


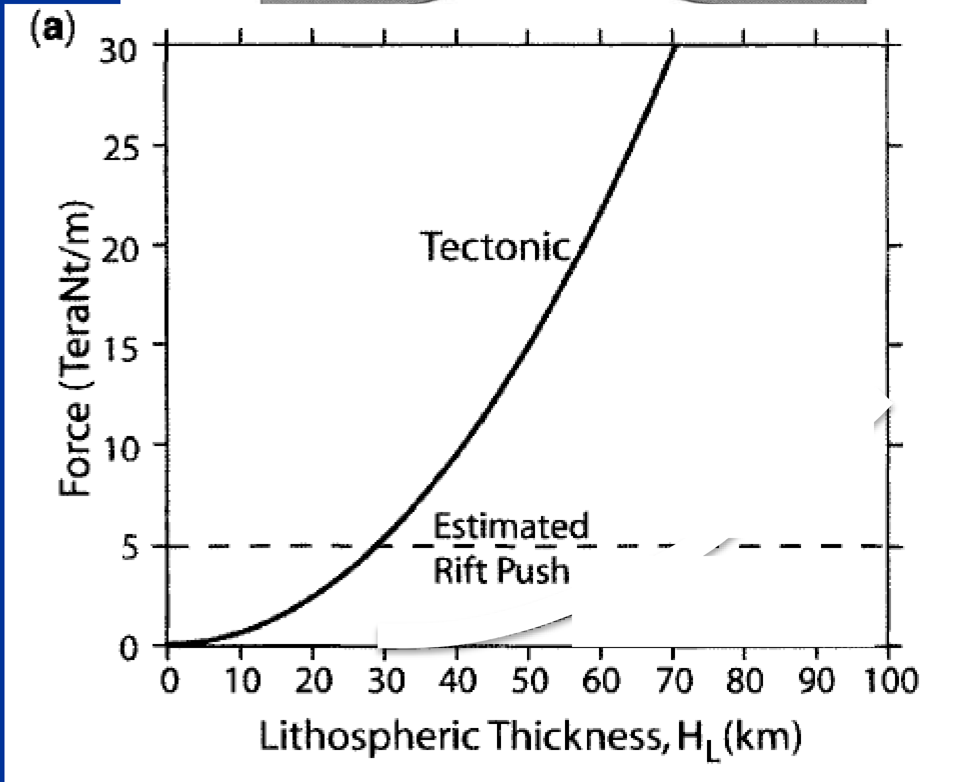
# Continental break-up

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



# How to break continent?

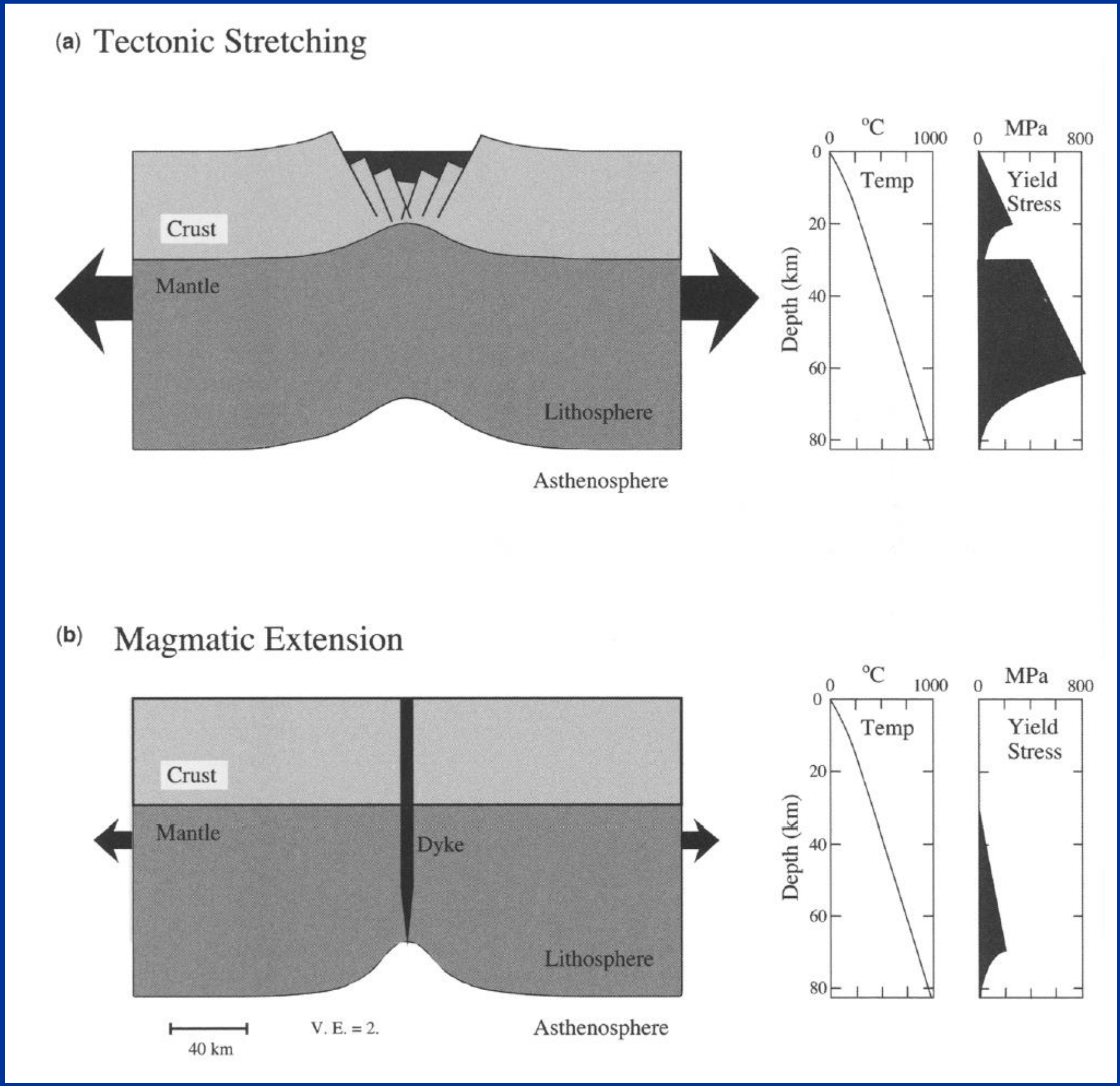



Cold lithosphere is too strong

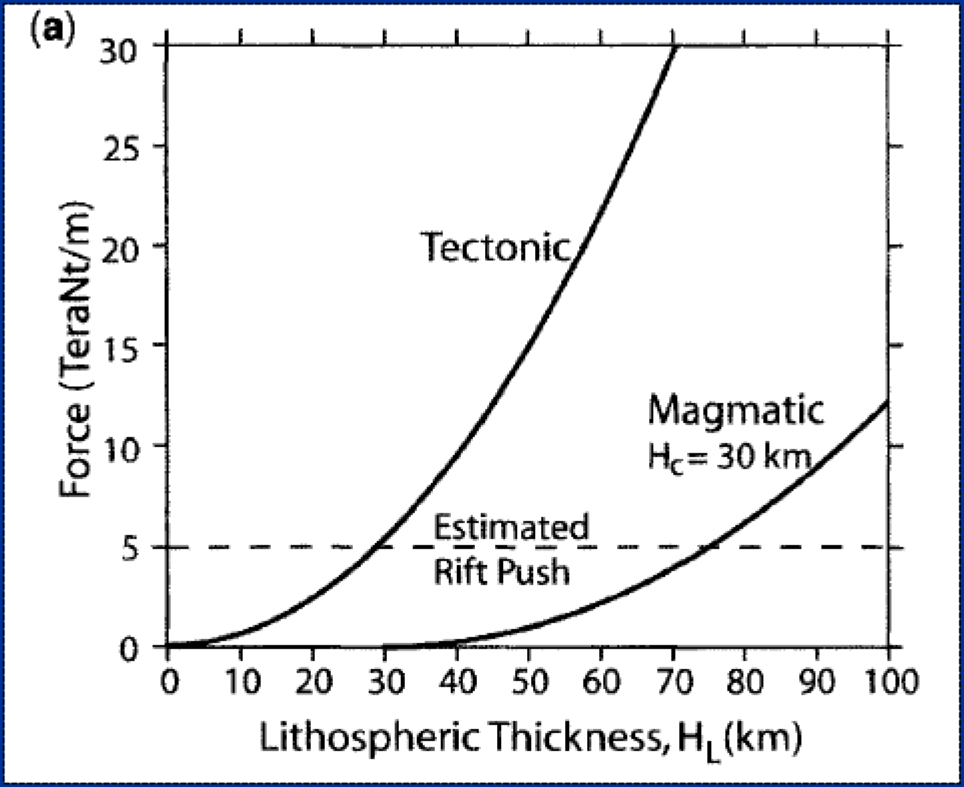
Buck (2006)

# Effect of magma-filled dikes




Buck (2006)

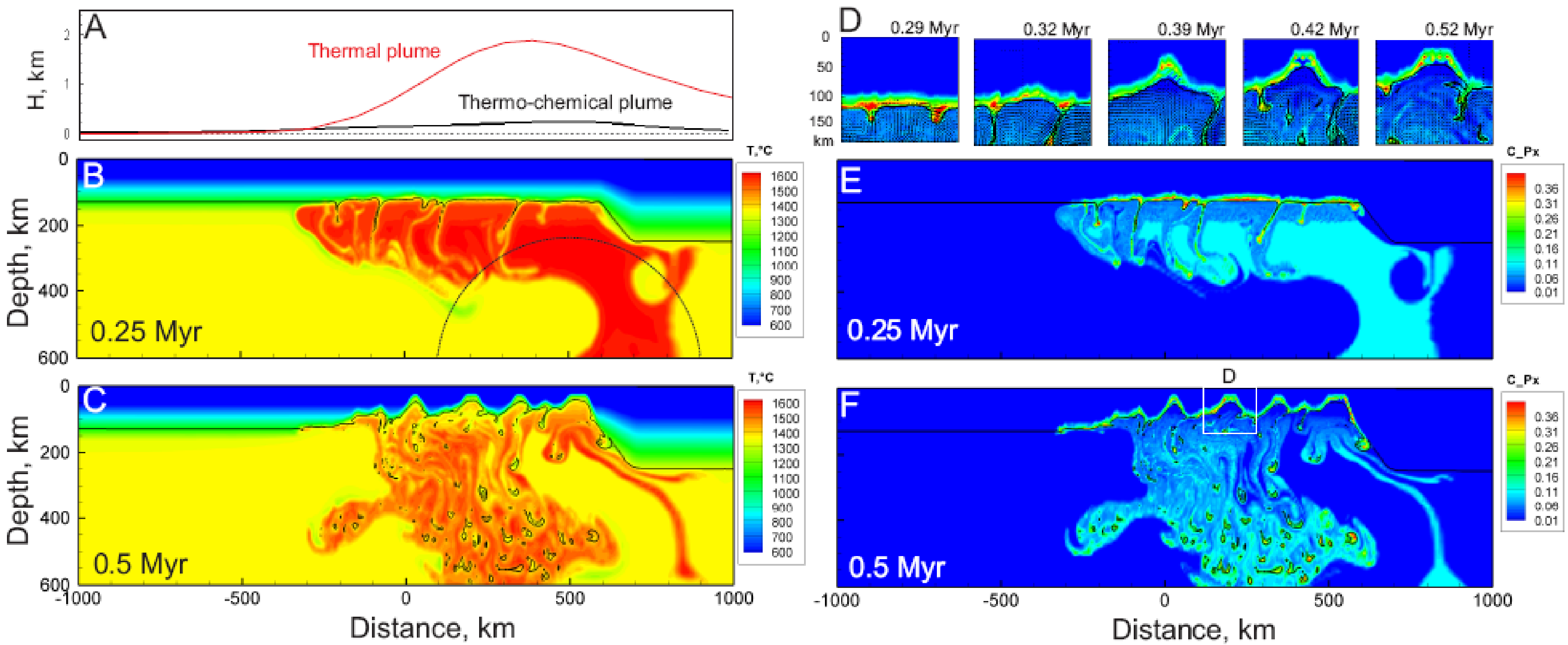
# Effect of magma-filled dikes




*It works if lithosphere is first thinned to about 75 km*

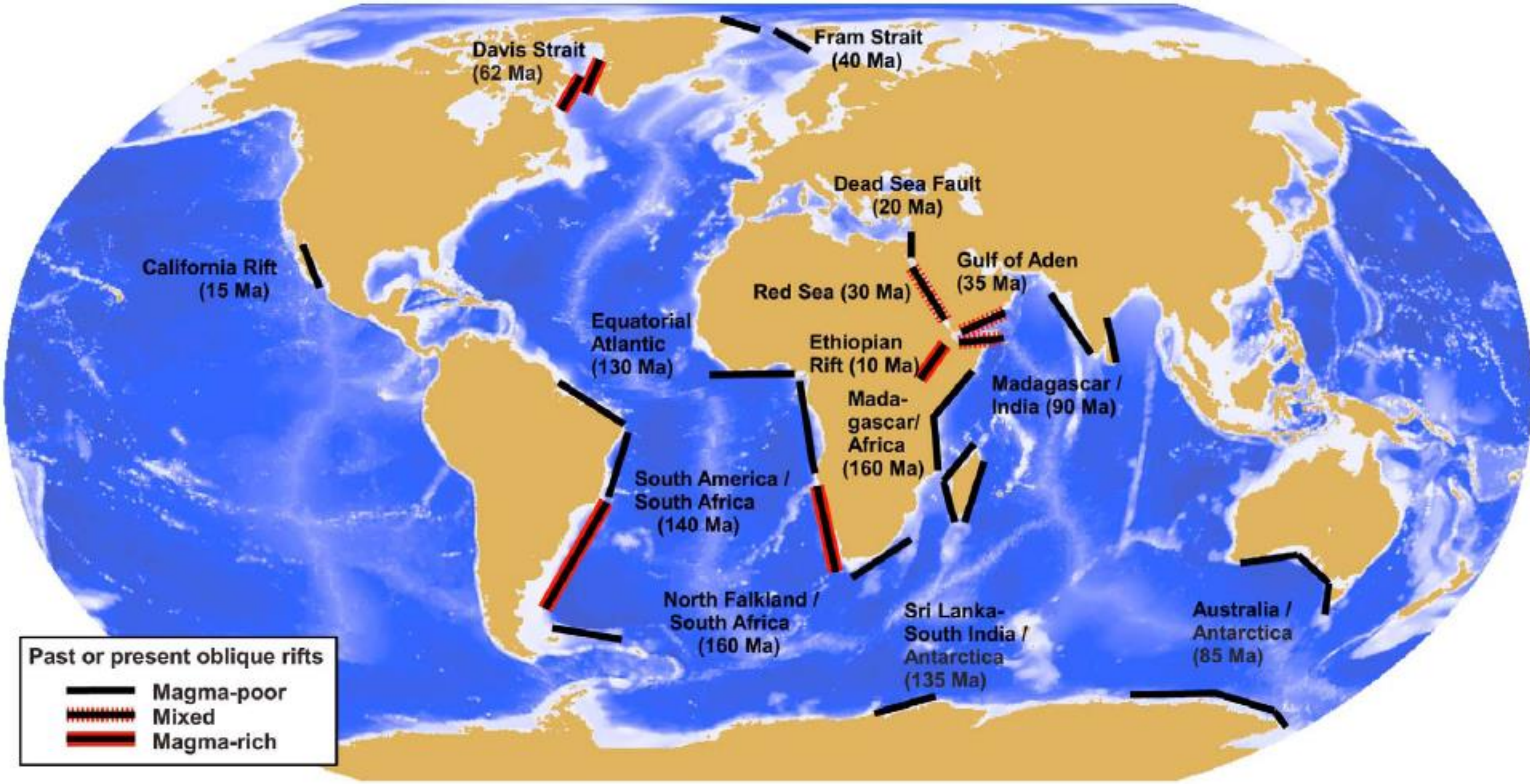
Buck (2006)

# Lithospheric thinning above mantle plume



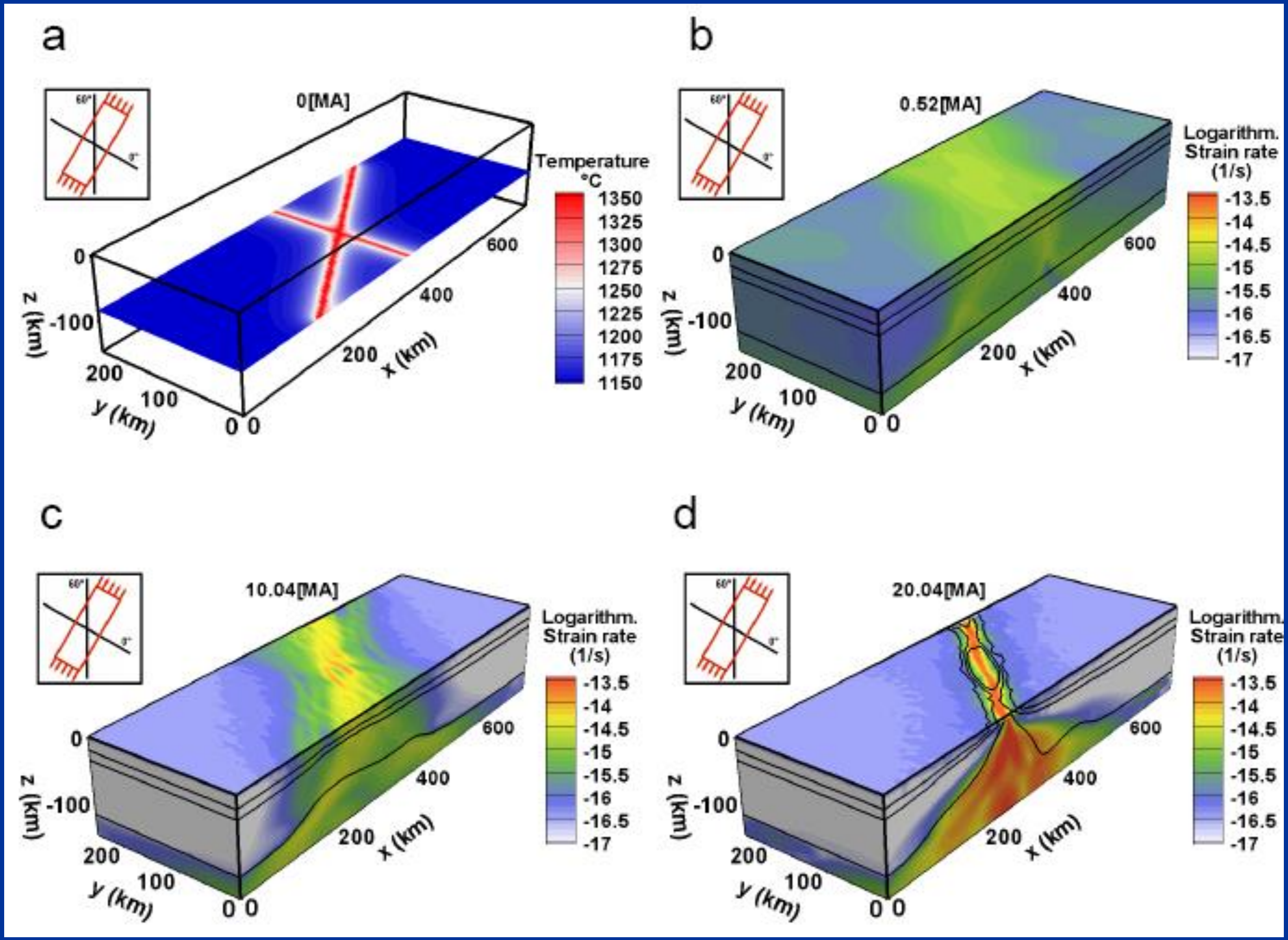

Sobolev et al. Nature 2011

# Effect of oblique rifting



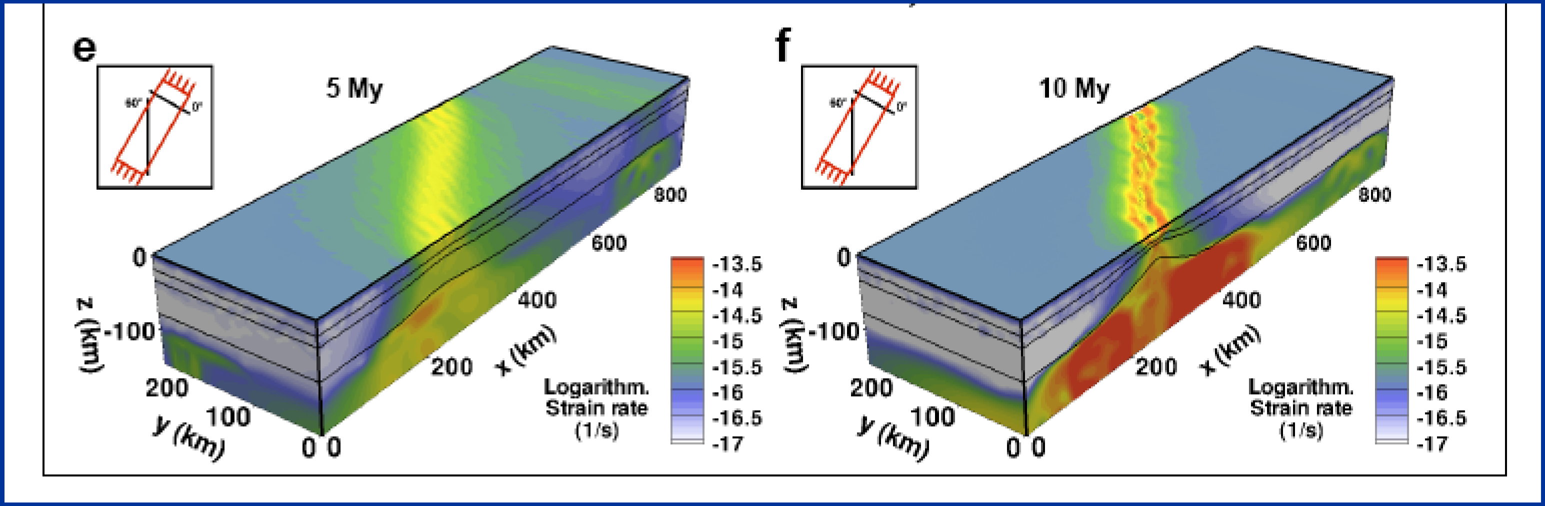

Brune, Popov, Sobolev JGR 2012

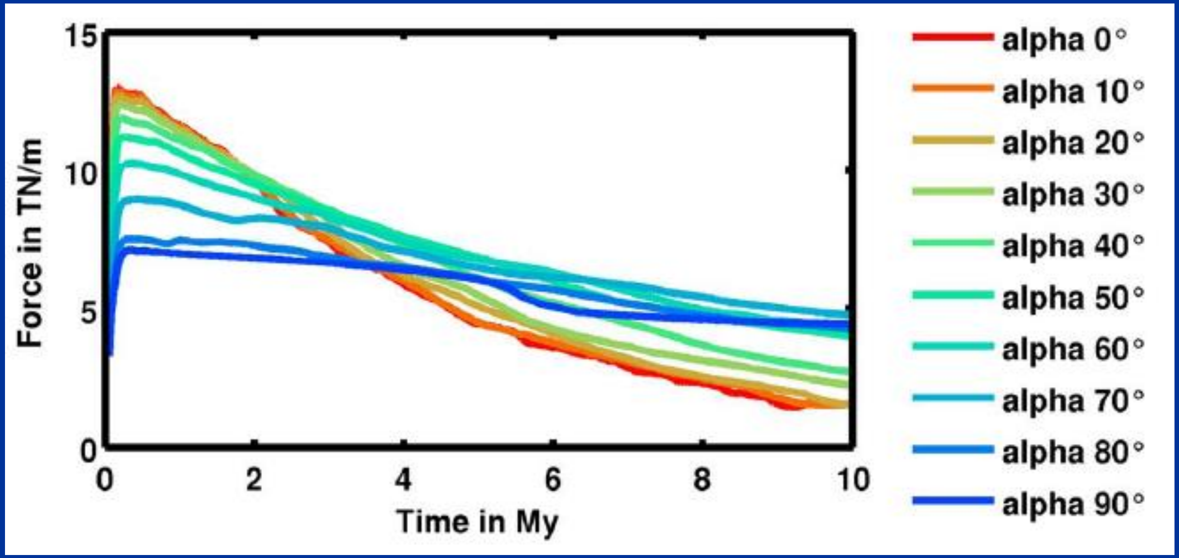
# Effect of oblique rifting




Brune, Popov, Sobolev JGR 2012

# Effect of oblique rifting



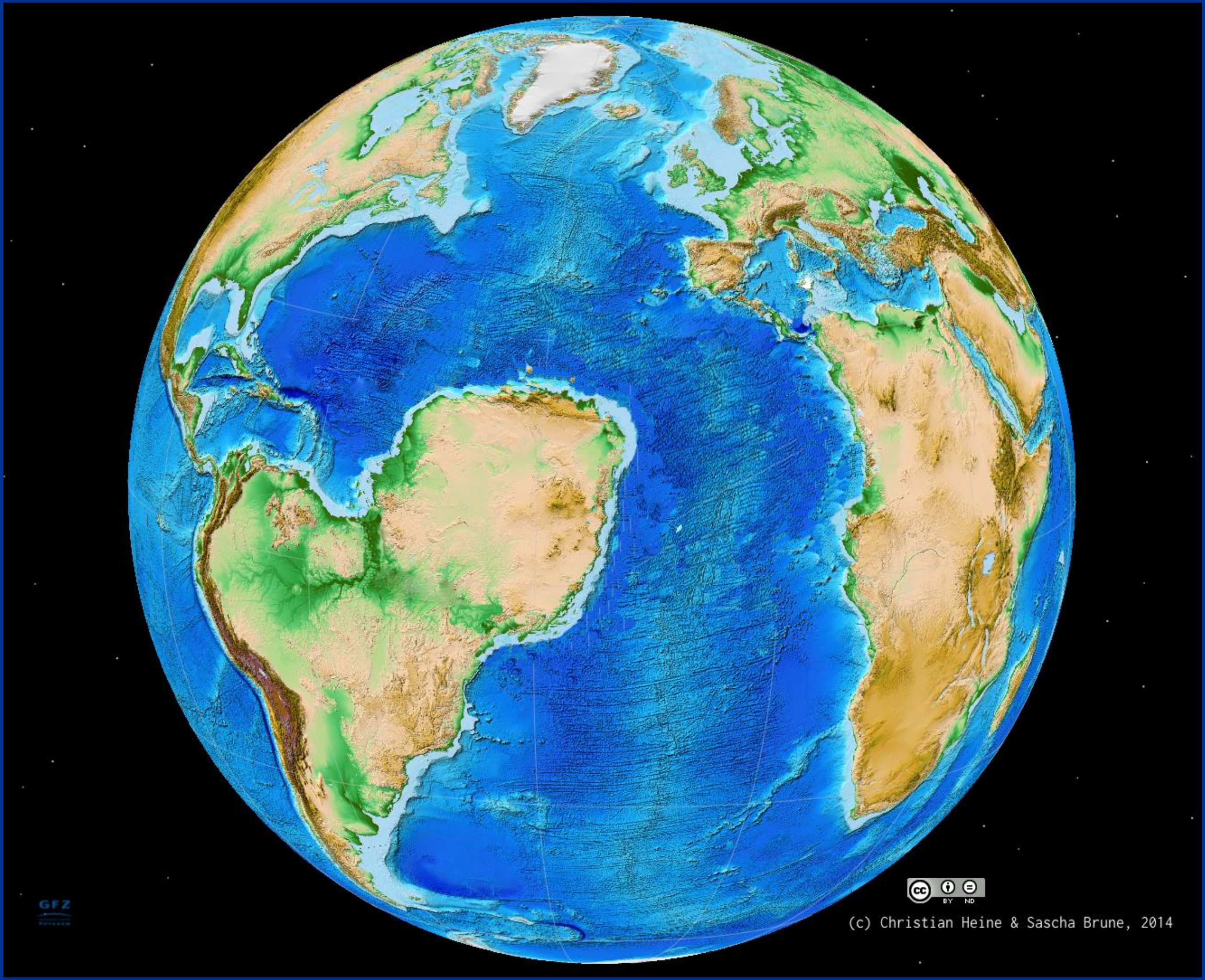




$$F_{strike-slip} = \tau_{yield} L_z$$

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

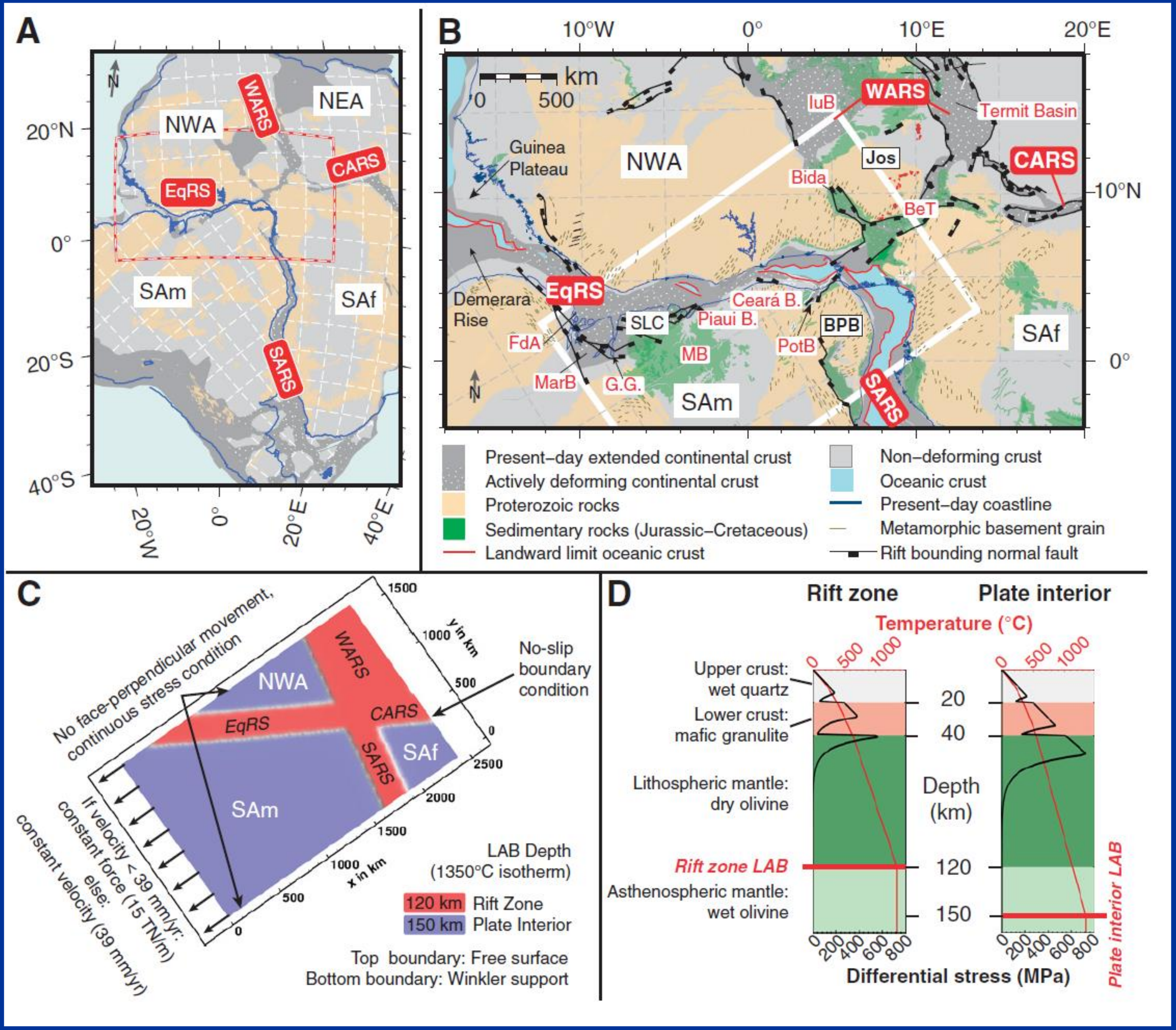
$$F_{extension} = 2\tau_{yield} L_z.$$

# Effect of oblique rifting (example)



# Effect of oblique rifting (example)

Heine and Brune, Geology, 2014



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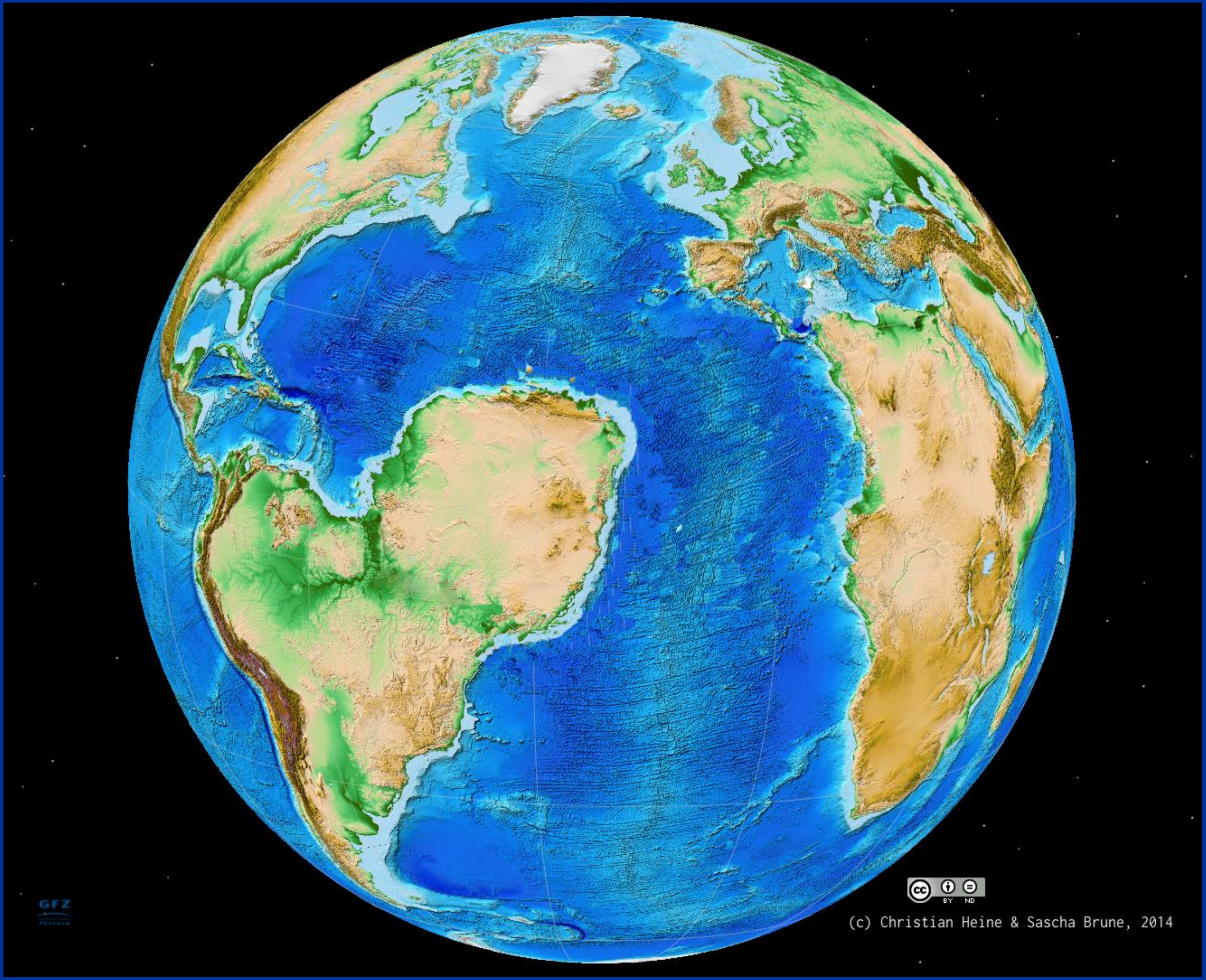

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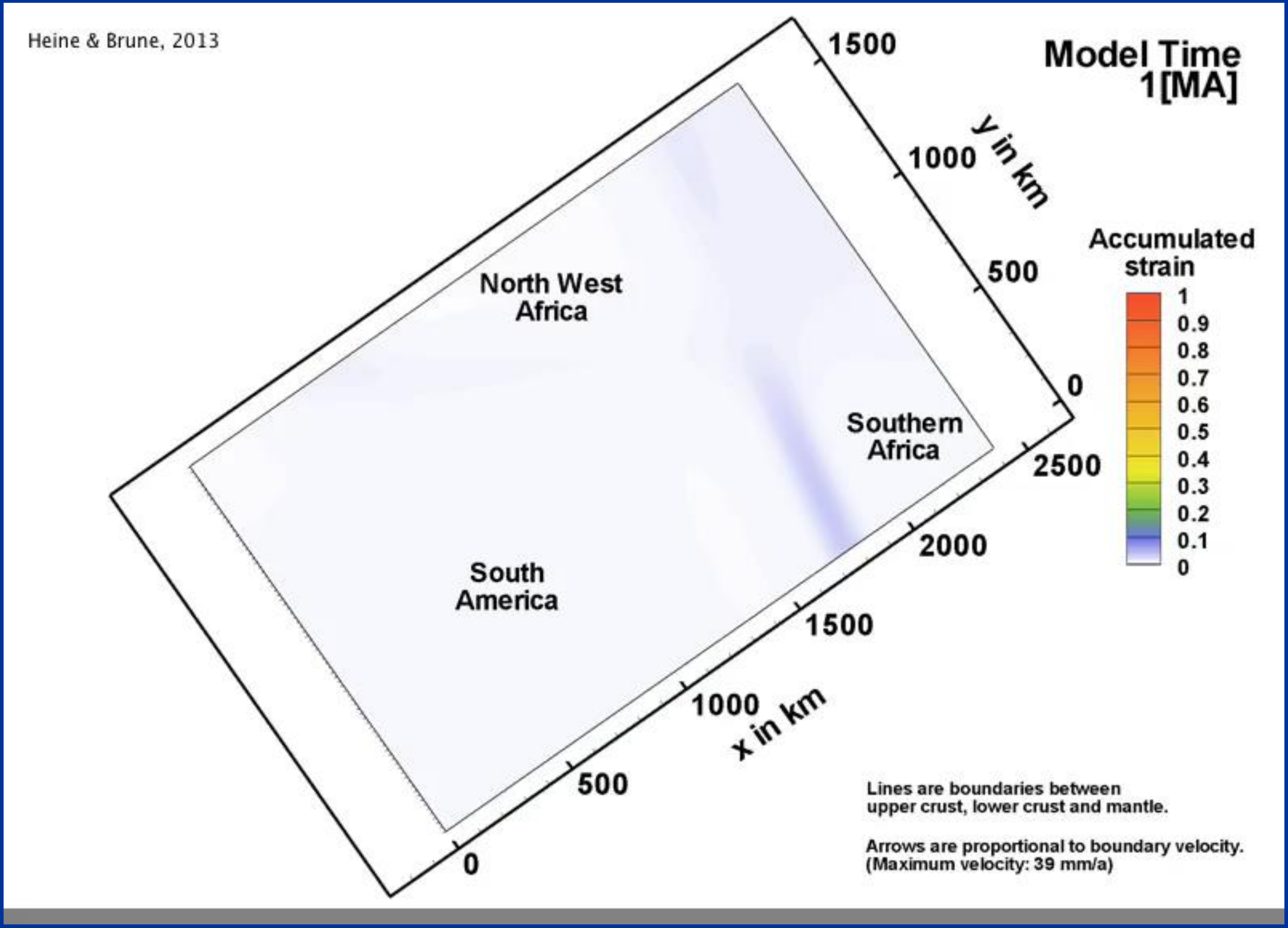
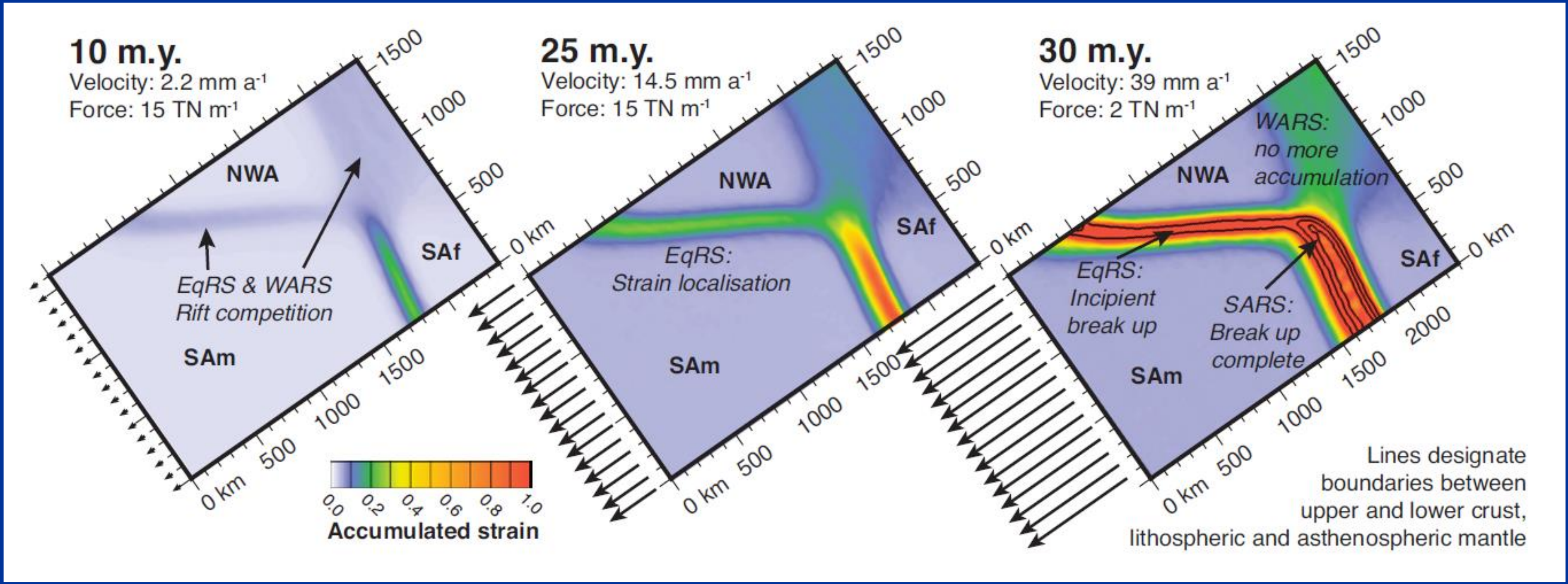


# Effect of oblique rifting (example)

Heine and Brune, Geology, 2014



# Conclusion

To break a continent are required:

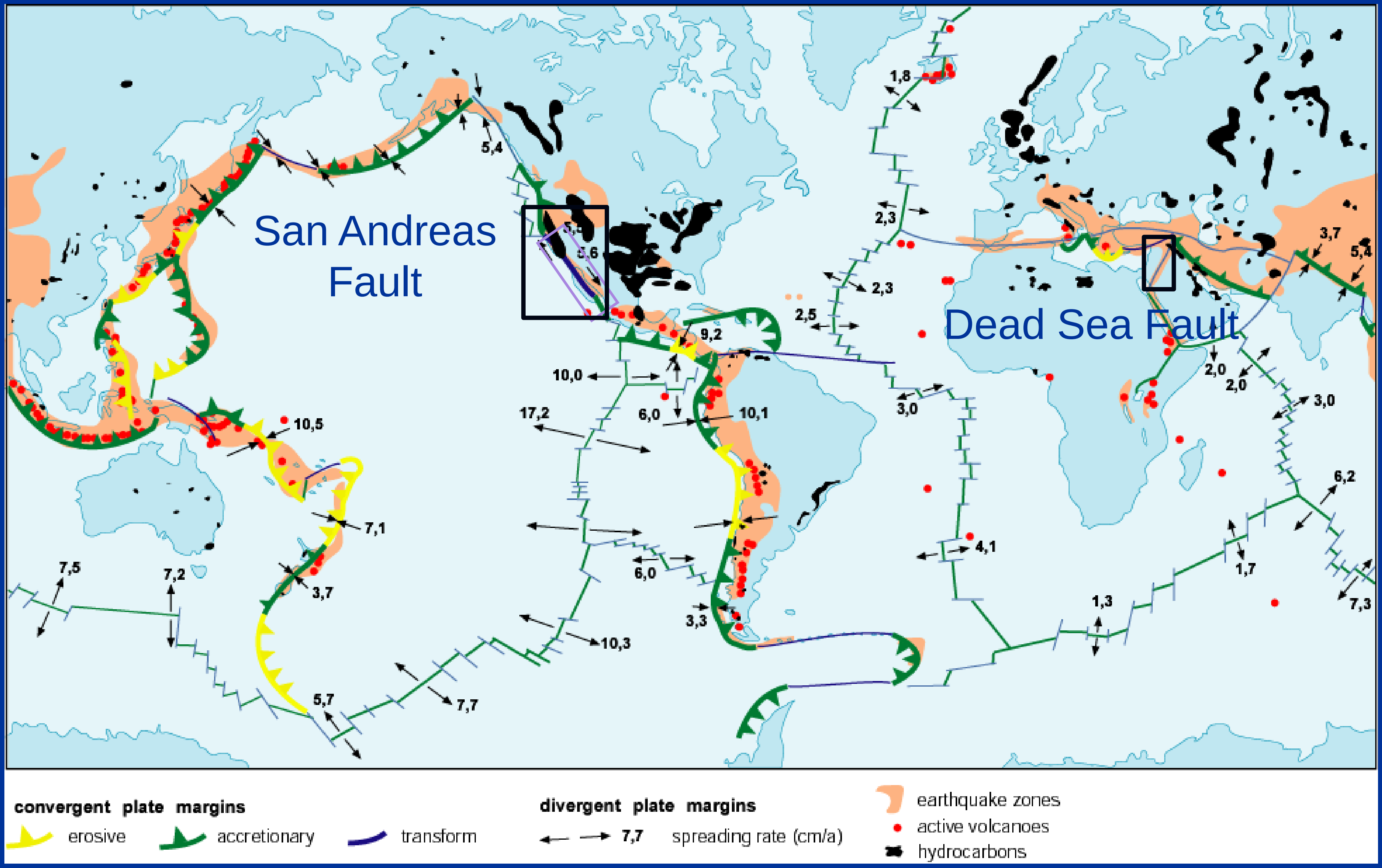
(1) extensional deviatoric stresses (internal, from ridge push or subduction zones roll-back) and (2) lithospheric weakening

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

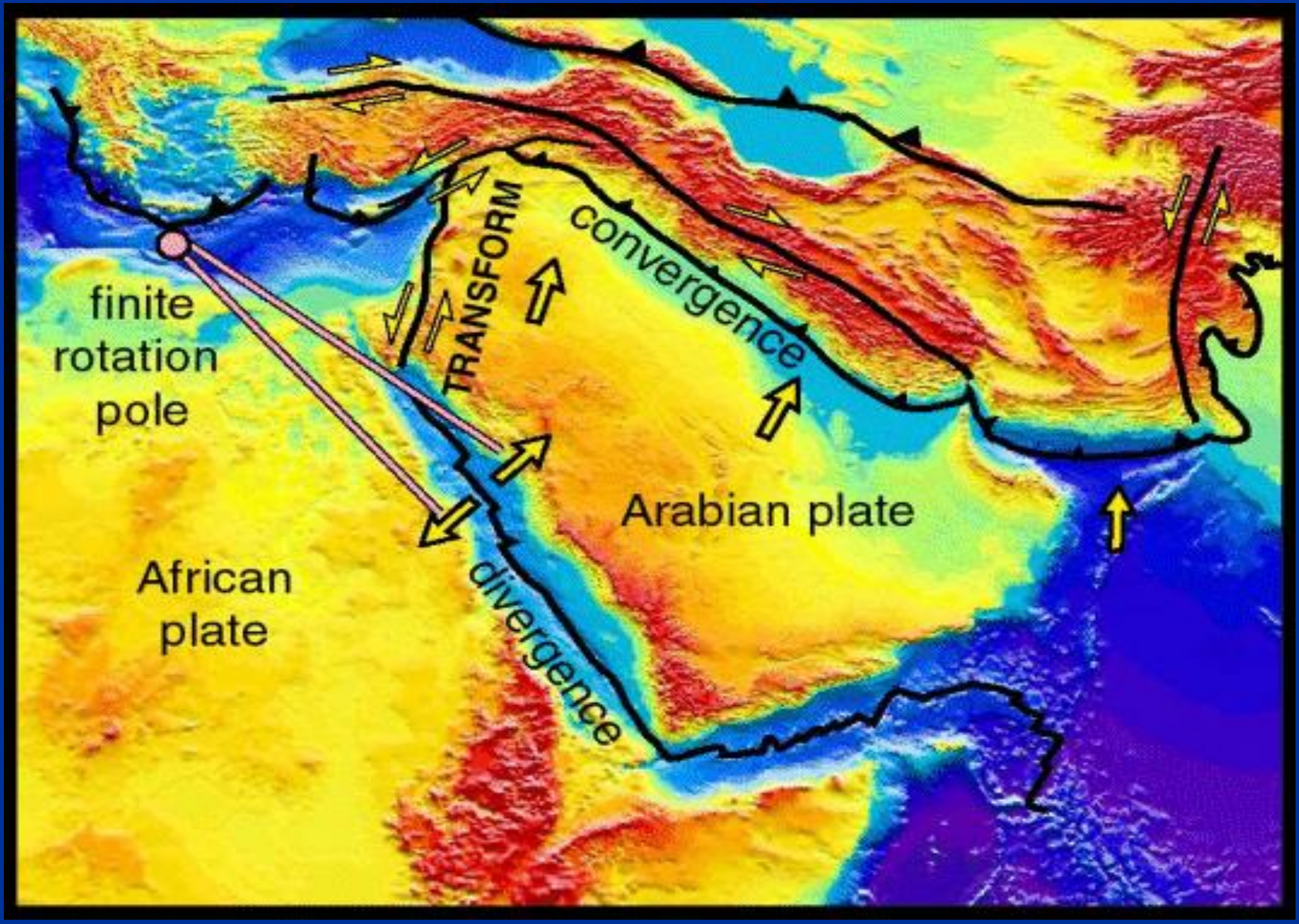
# Continental transform faults
# (case Dead Sea Transform)

# Continental Transform Faults



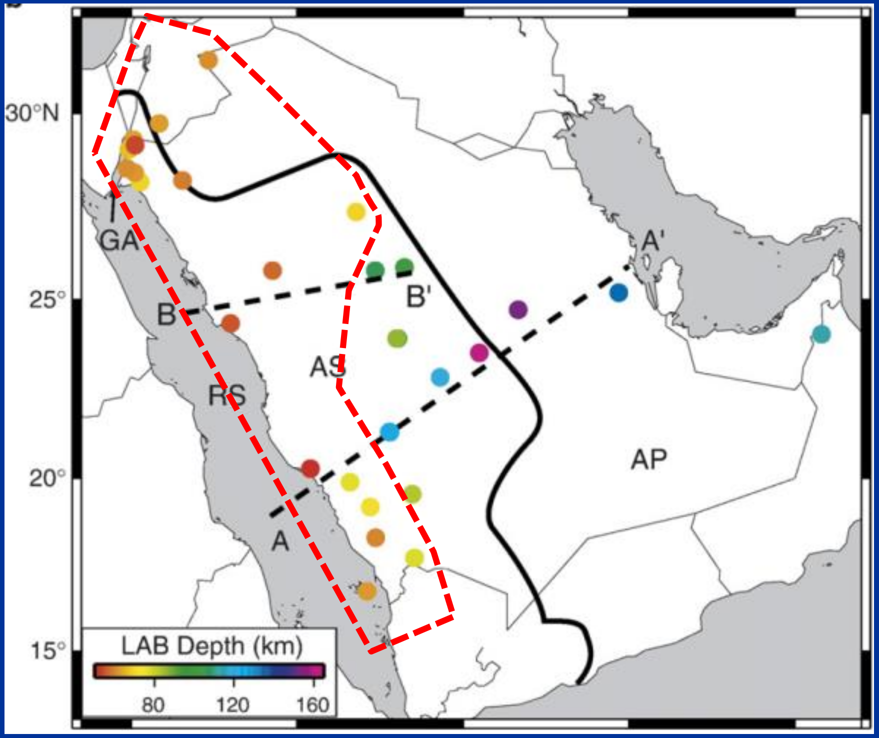
## Regional setting

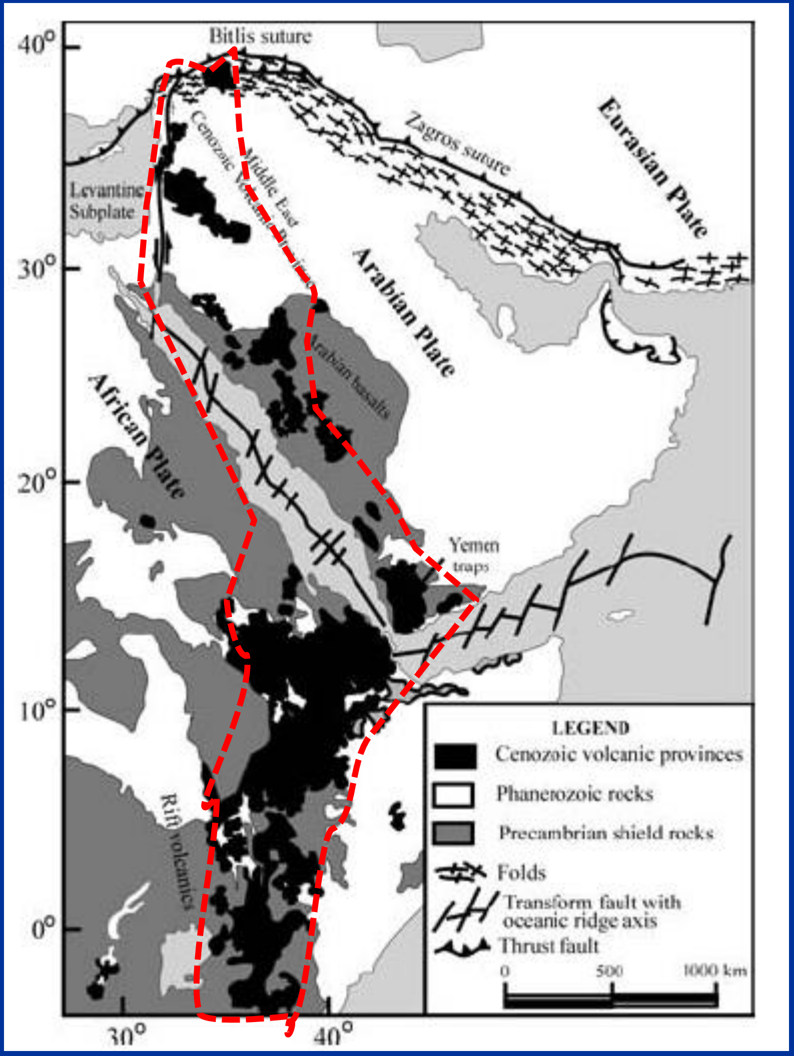
With the surface heat flow of 50-60 mW/m2, the DST is the coldest continental transform boundary



# Lithospheric thickness and magmatism

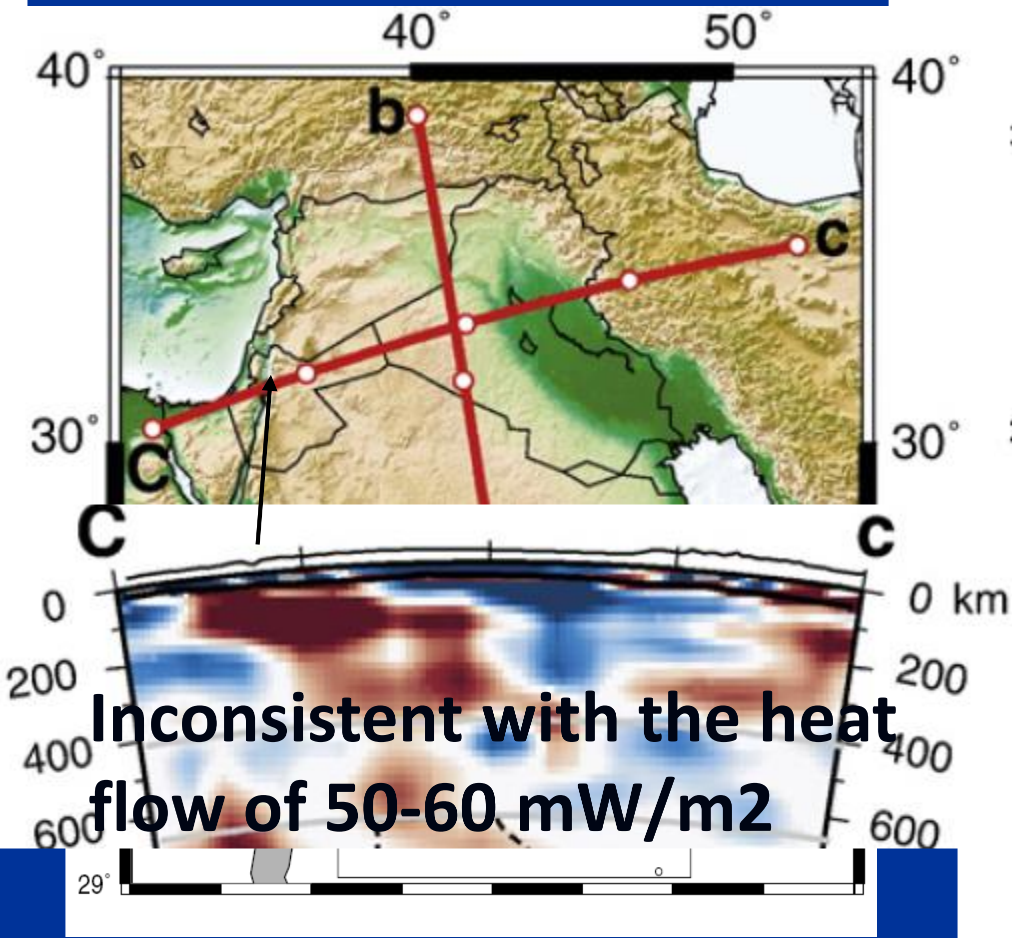
## Magmatism at 30-0 Ma



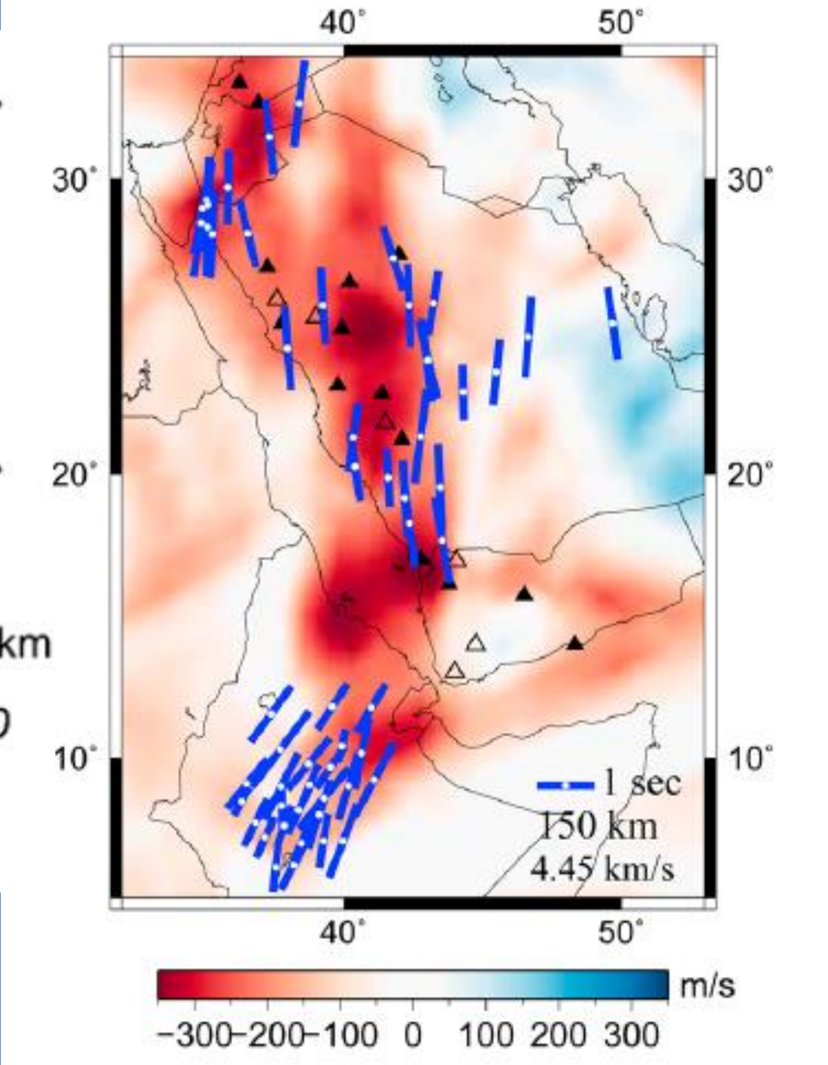
# Lithosphere-asthenosphere boundary (LAB) from seismic data

Chang and Van der Lee, EPSL, 2011




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

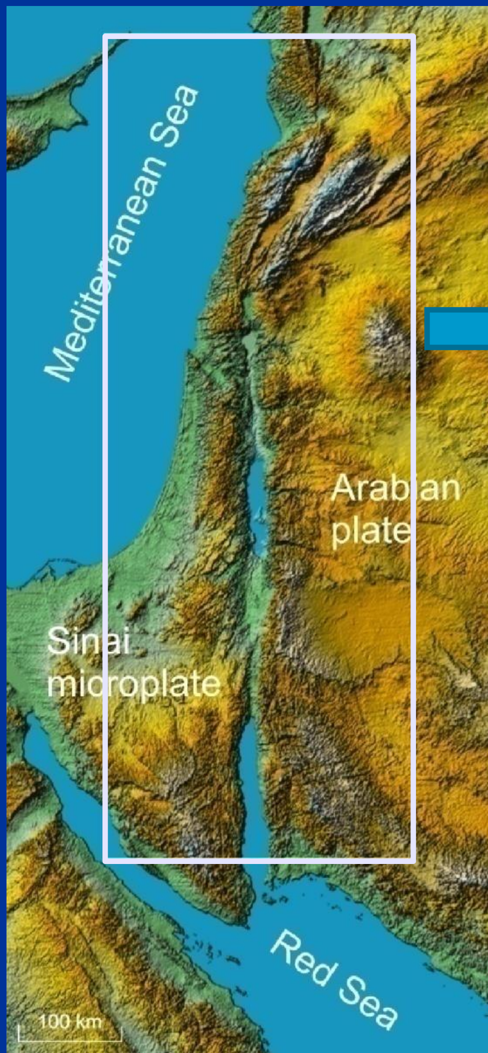
Chang et al, GRL, 2011

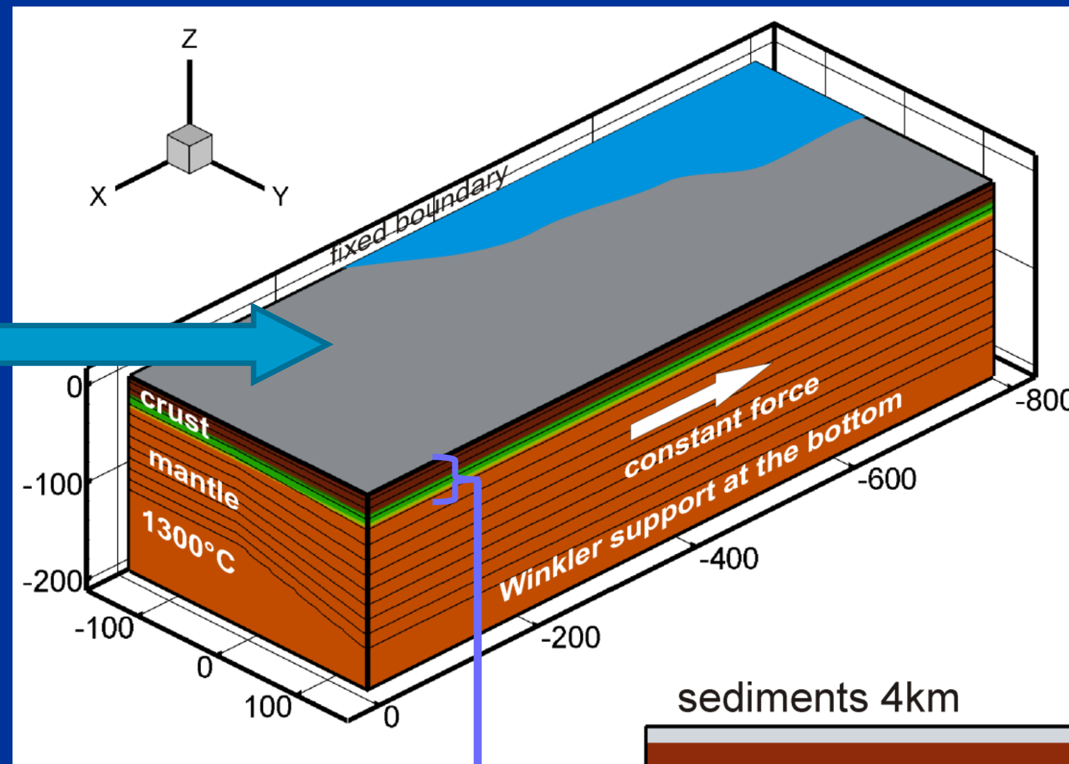


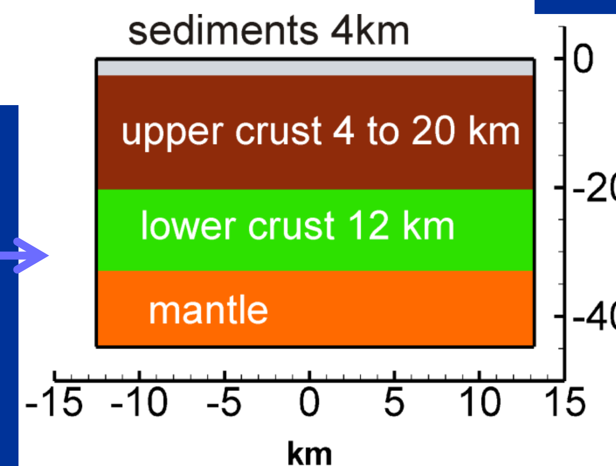
# Conclusion

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

# Model setup



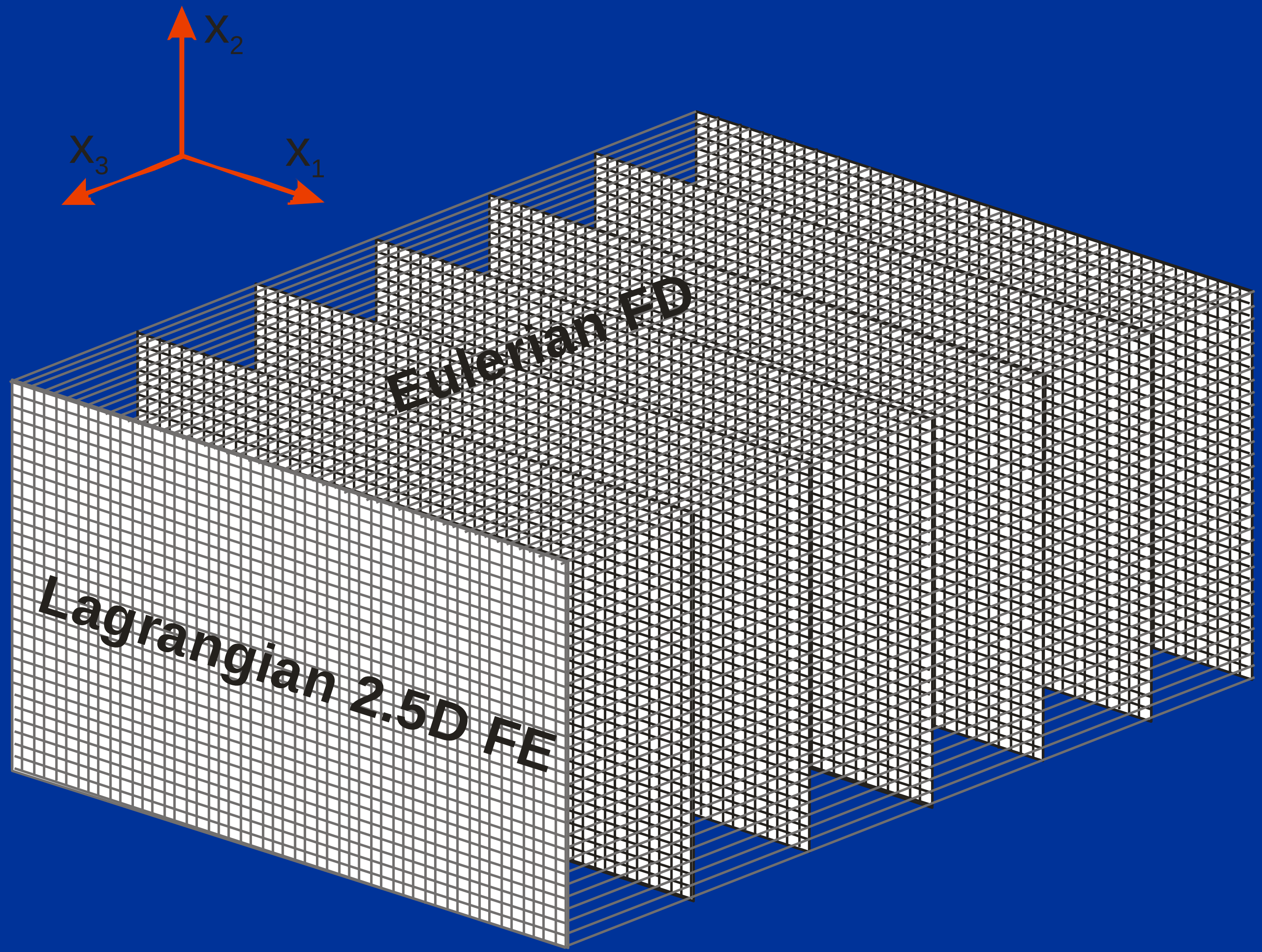




Flat Earth approximation

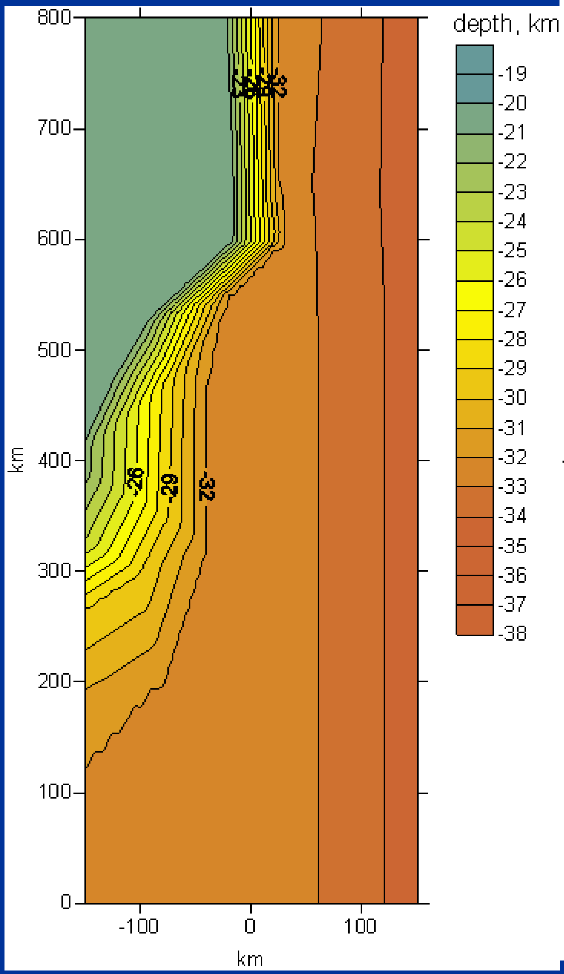
# Modeling technique LAPEX 3D combining FE and FD

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

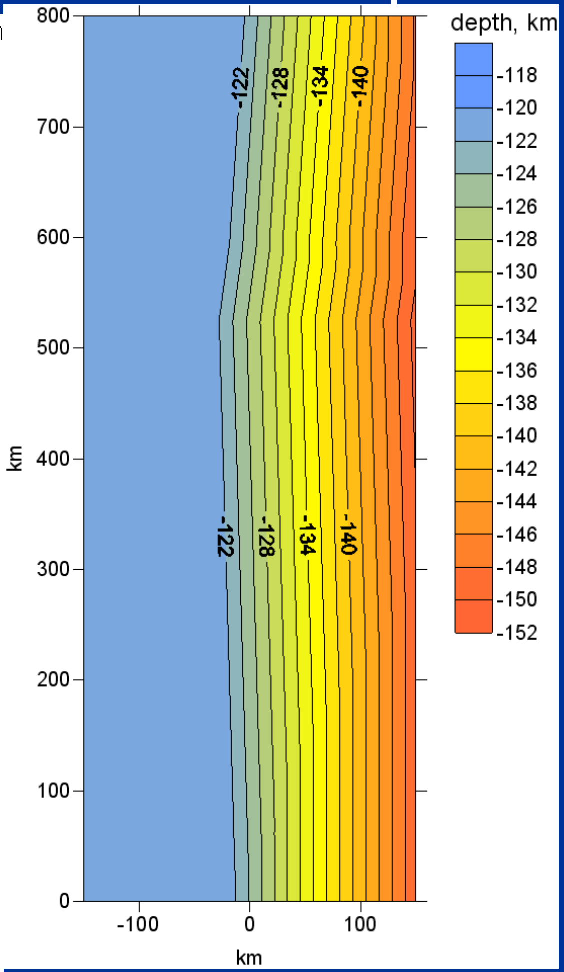


# Initial lithospheric structure:

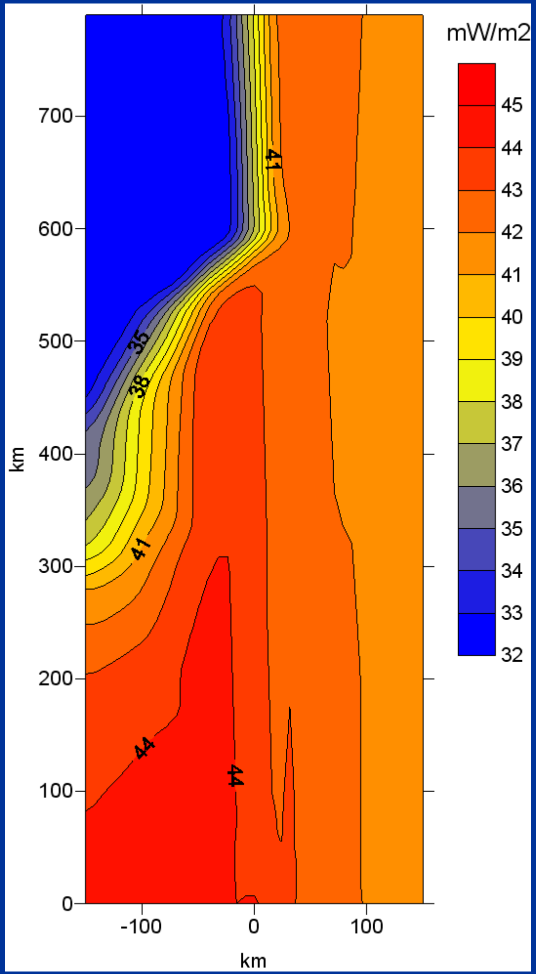
## Moho map



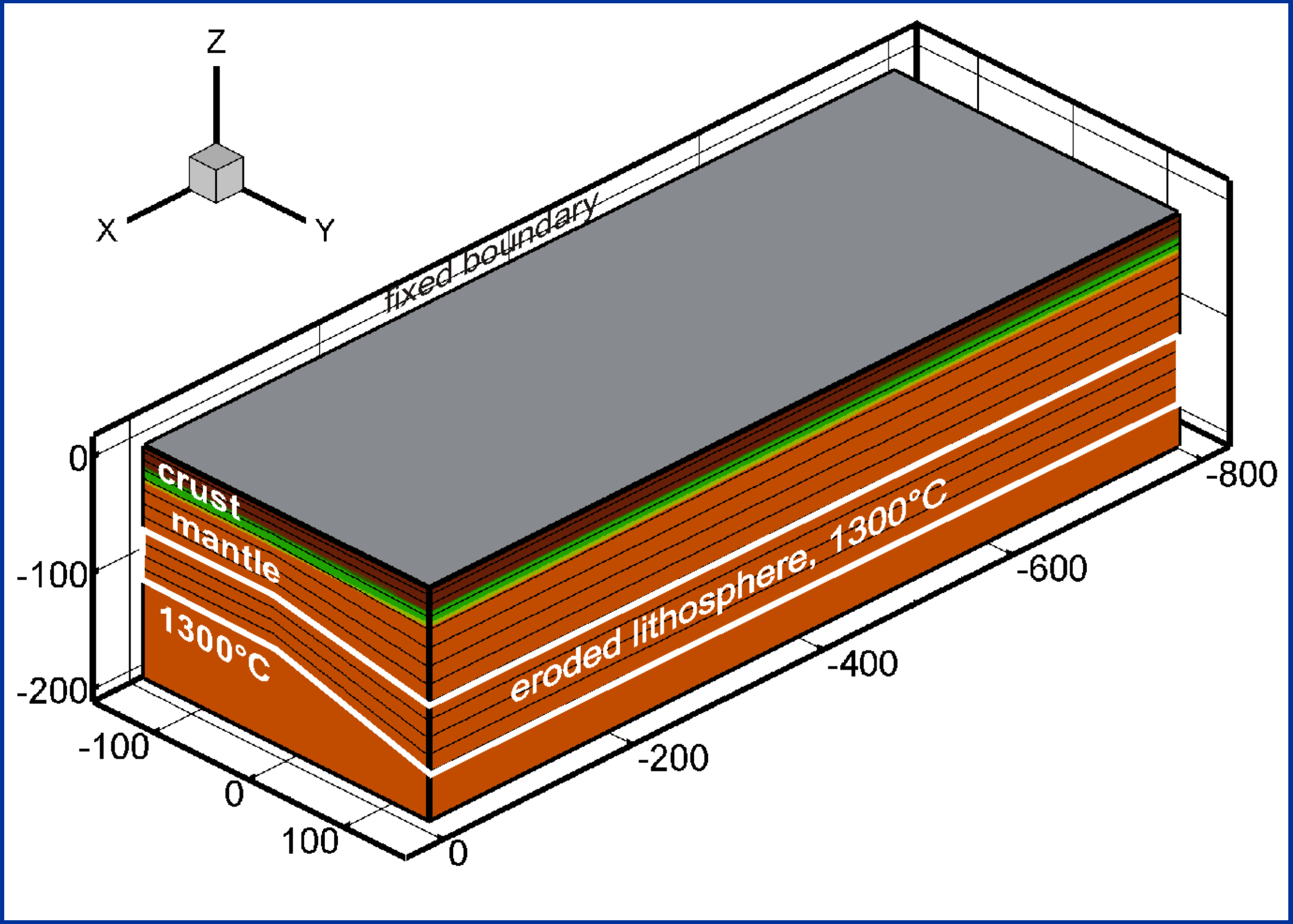

## LAB map




## Heat flow



# Modeling results: role of the thermal erosion of the lithosphere



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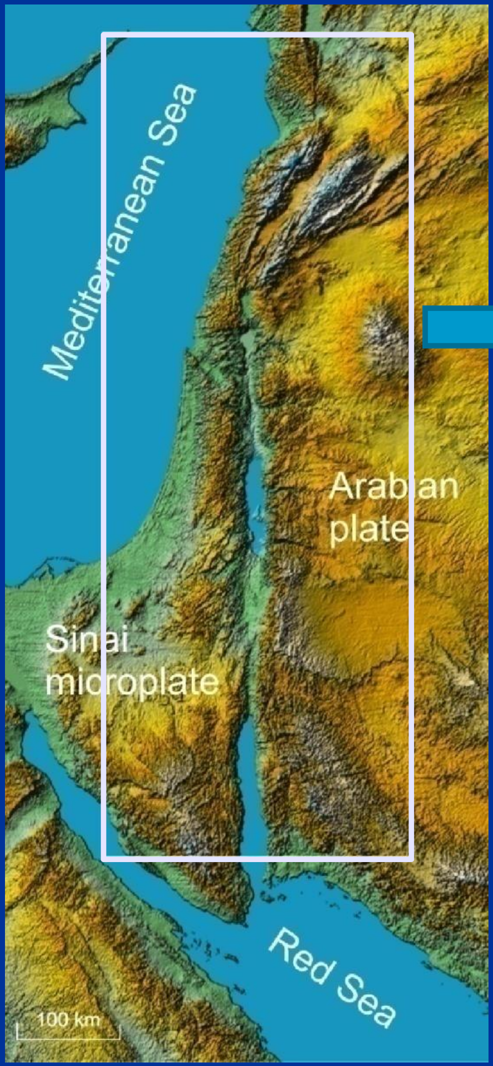
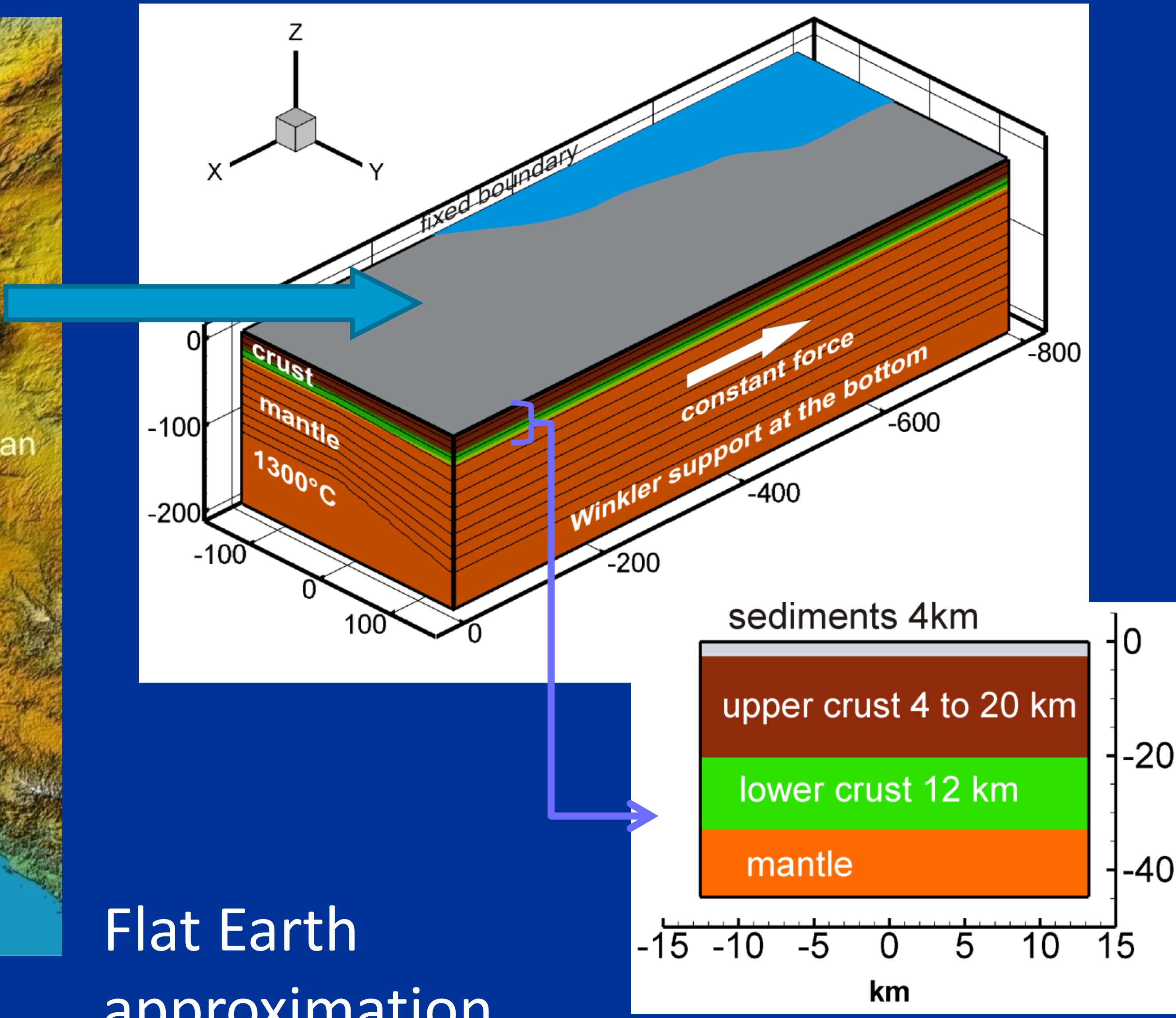
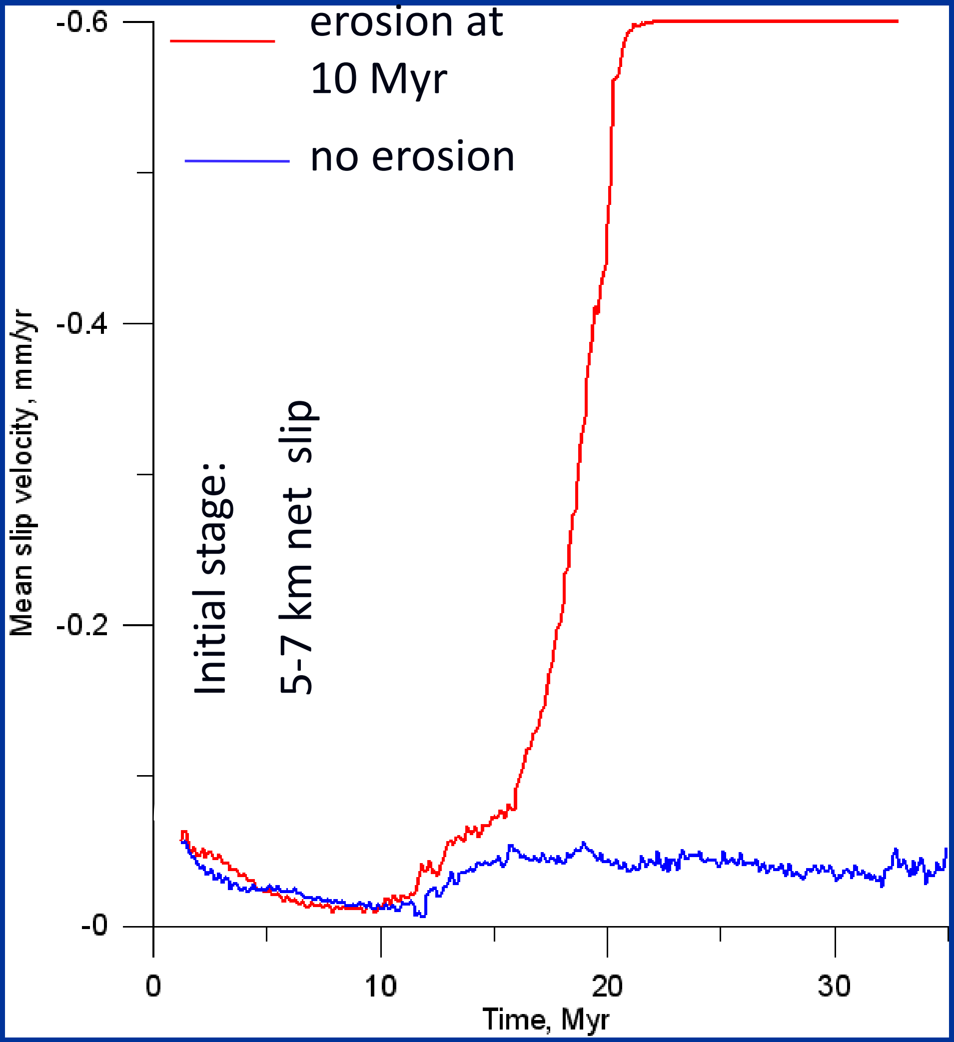


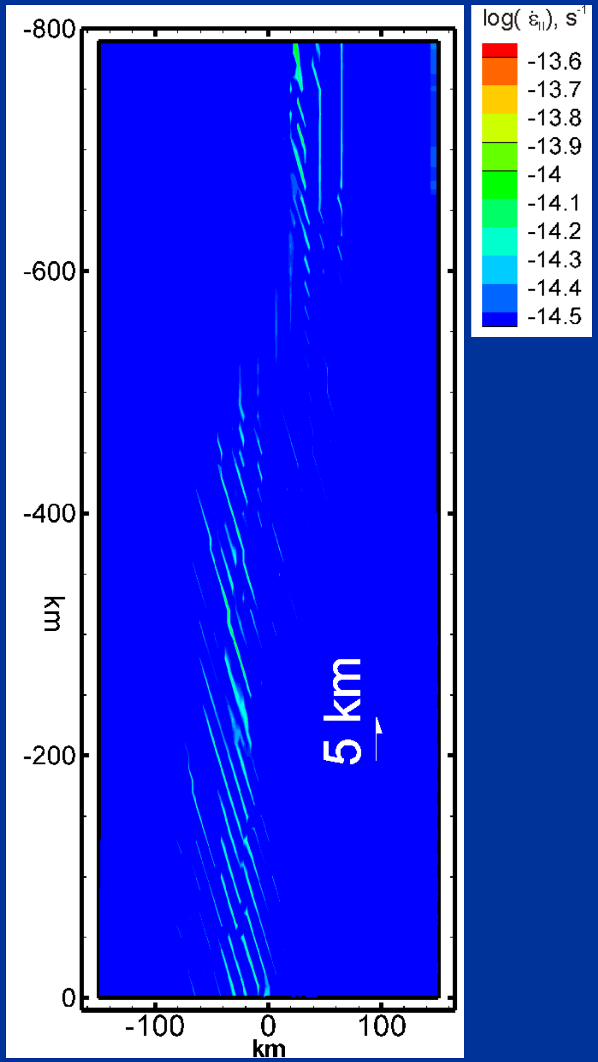




Flat Earth approximation

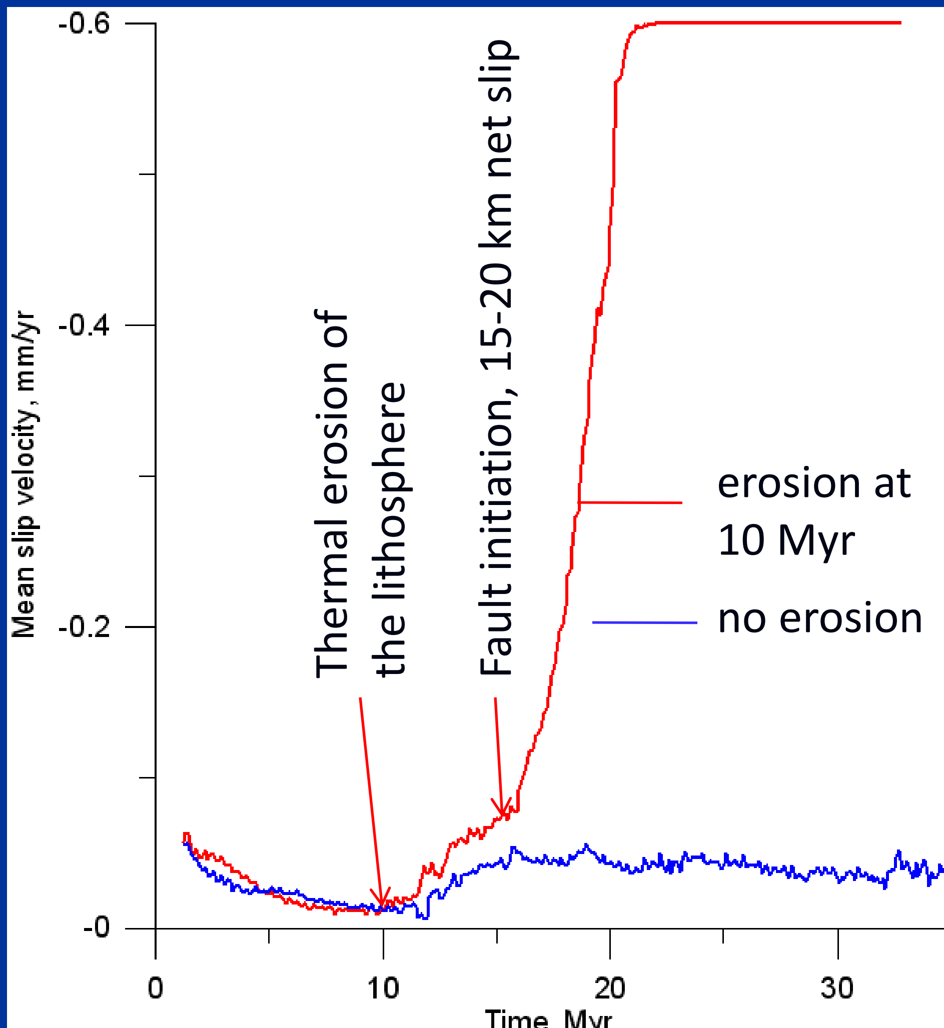
# Modeling results: role of the thermal erosion of the lithosphere

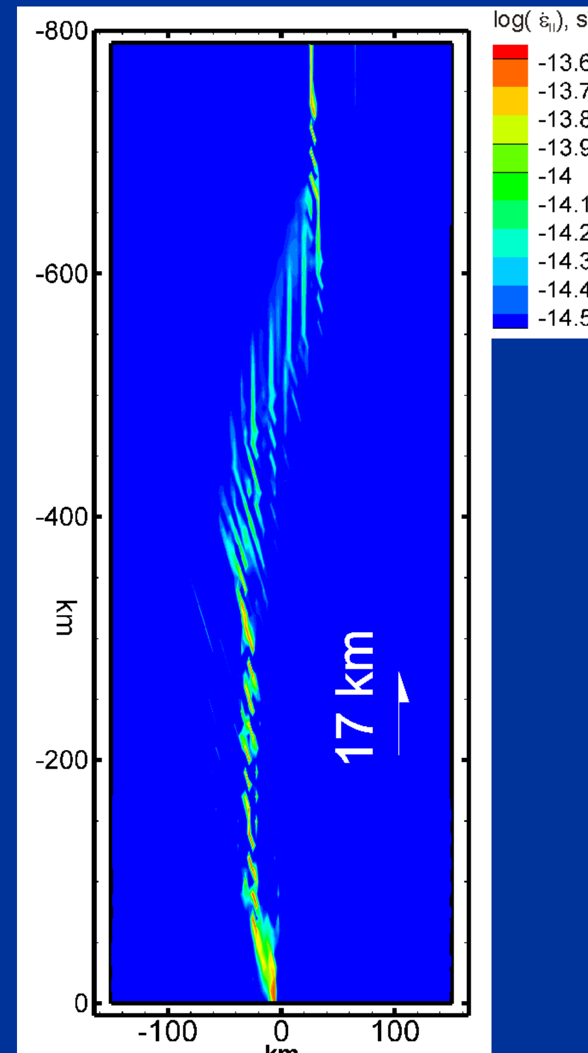
Applied force is 1.6e13N/m



# Modeling results: role of the thermal erosion of the lithosphere



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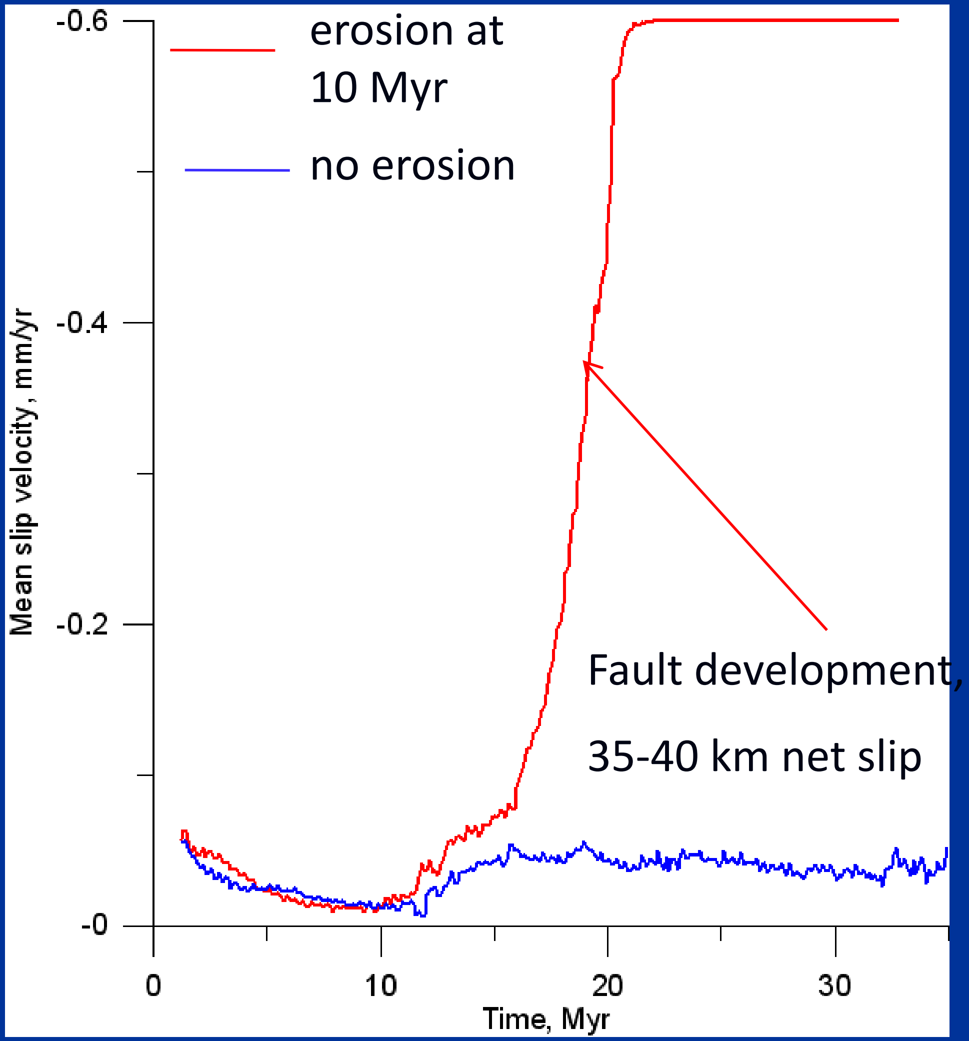
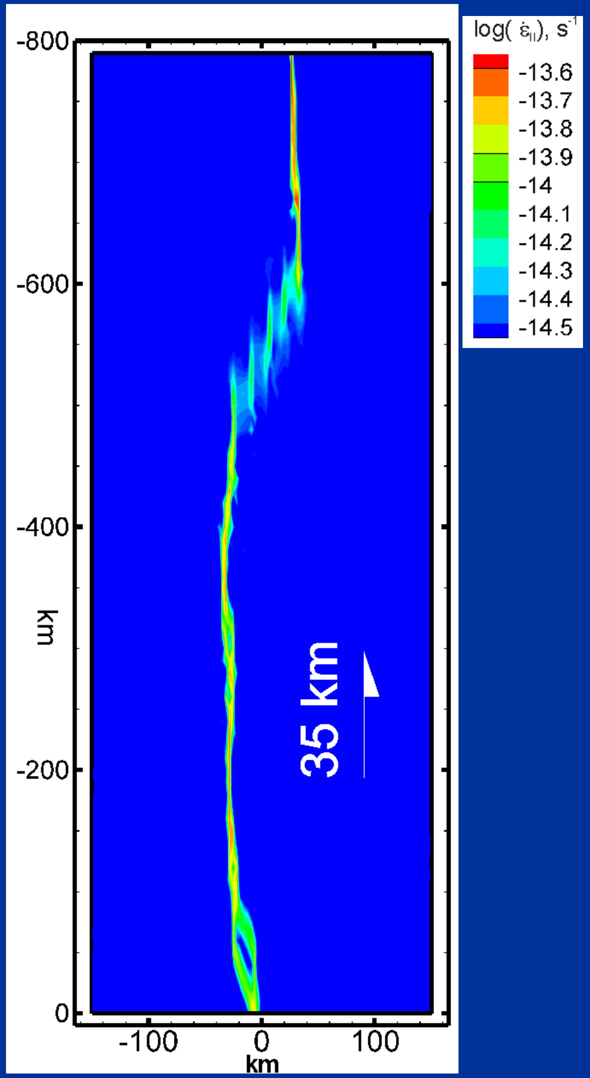
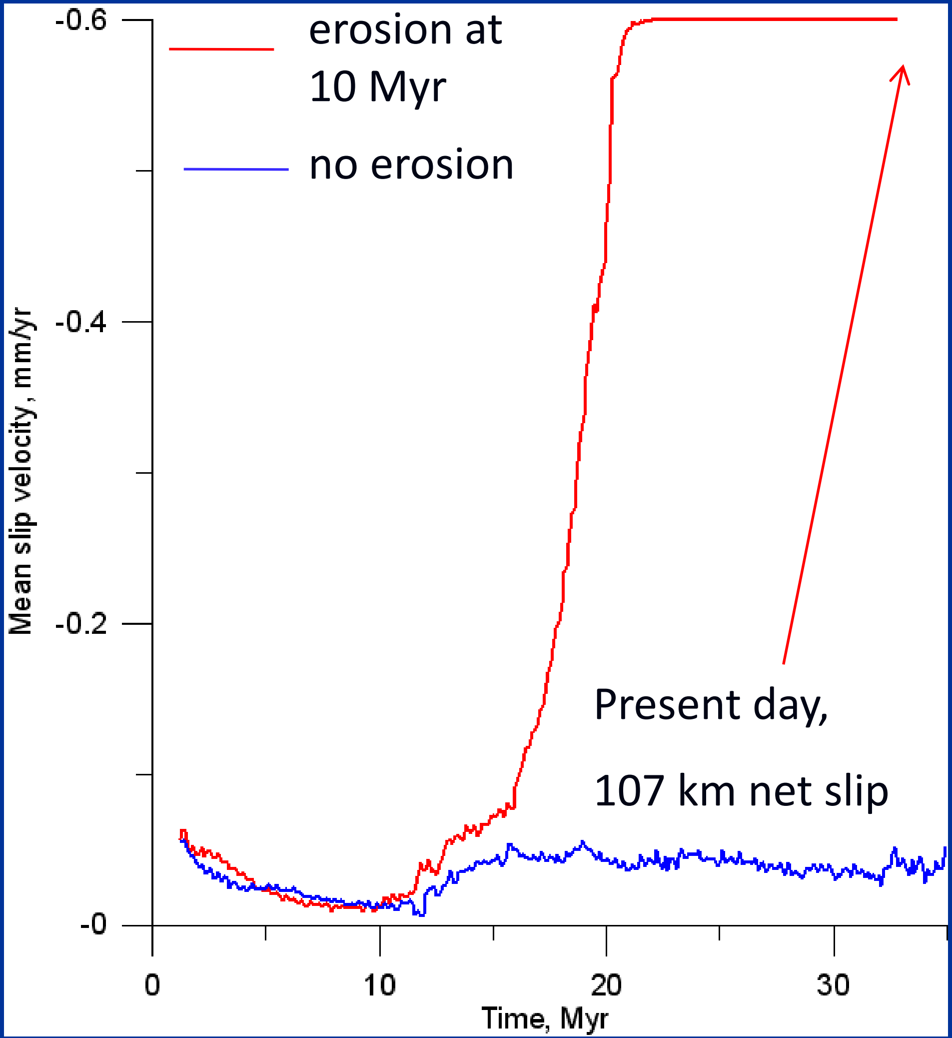
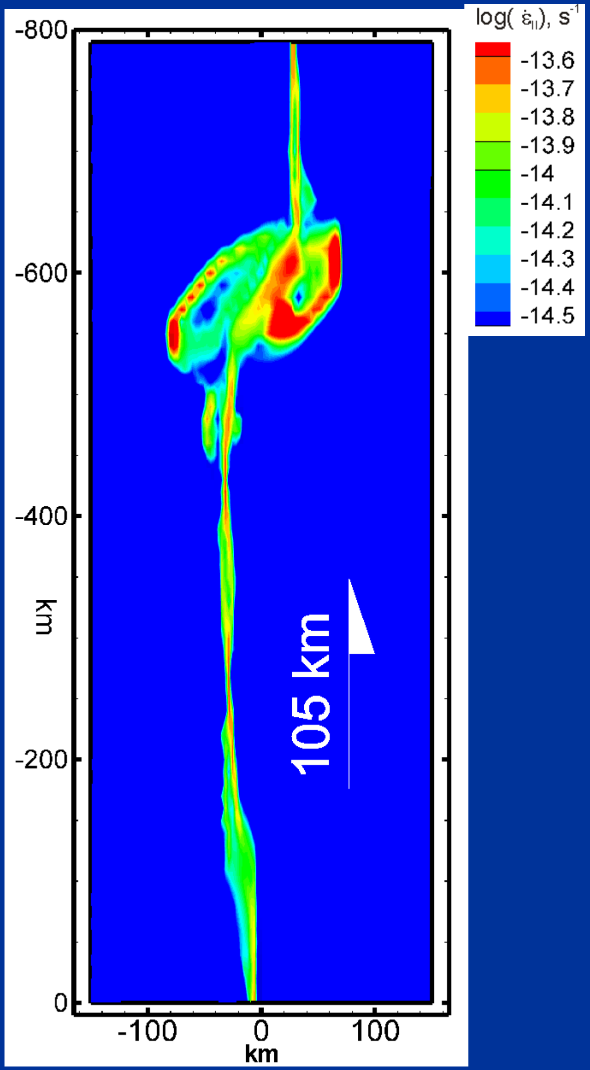


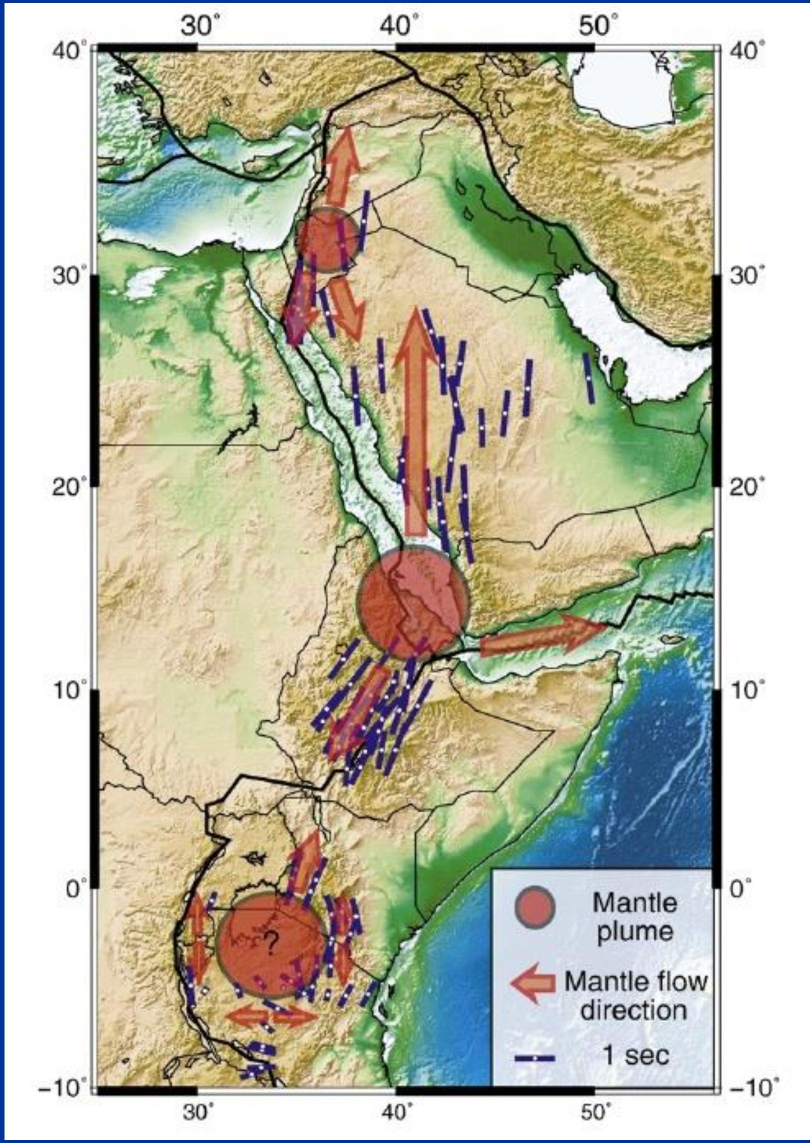



# Modeling results: role of the thermal erosion of the lithosphere



# Possible scenario




Plumes at 25-35 Ma

Lithospheric erosion 20-30 Ma

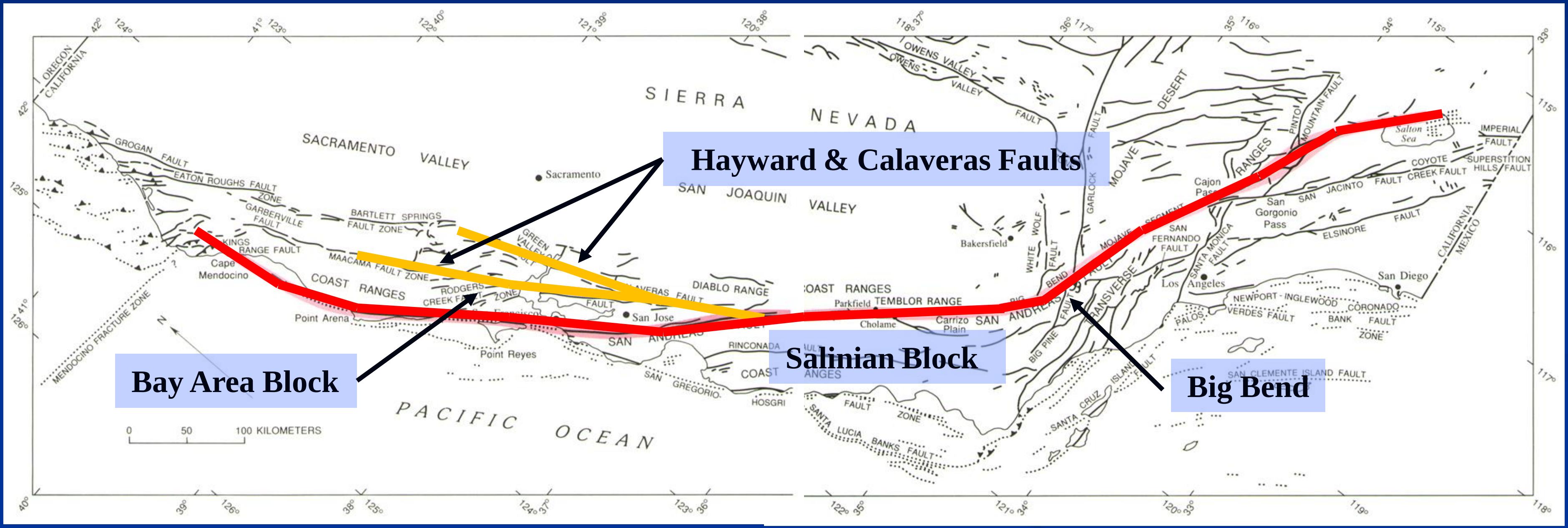
Localization of the DST 15-17 Ma

**Lithospheric erosion has triggered the DST**

Chang and Van der Lee, EPSL, 2011

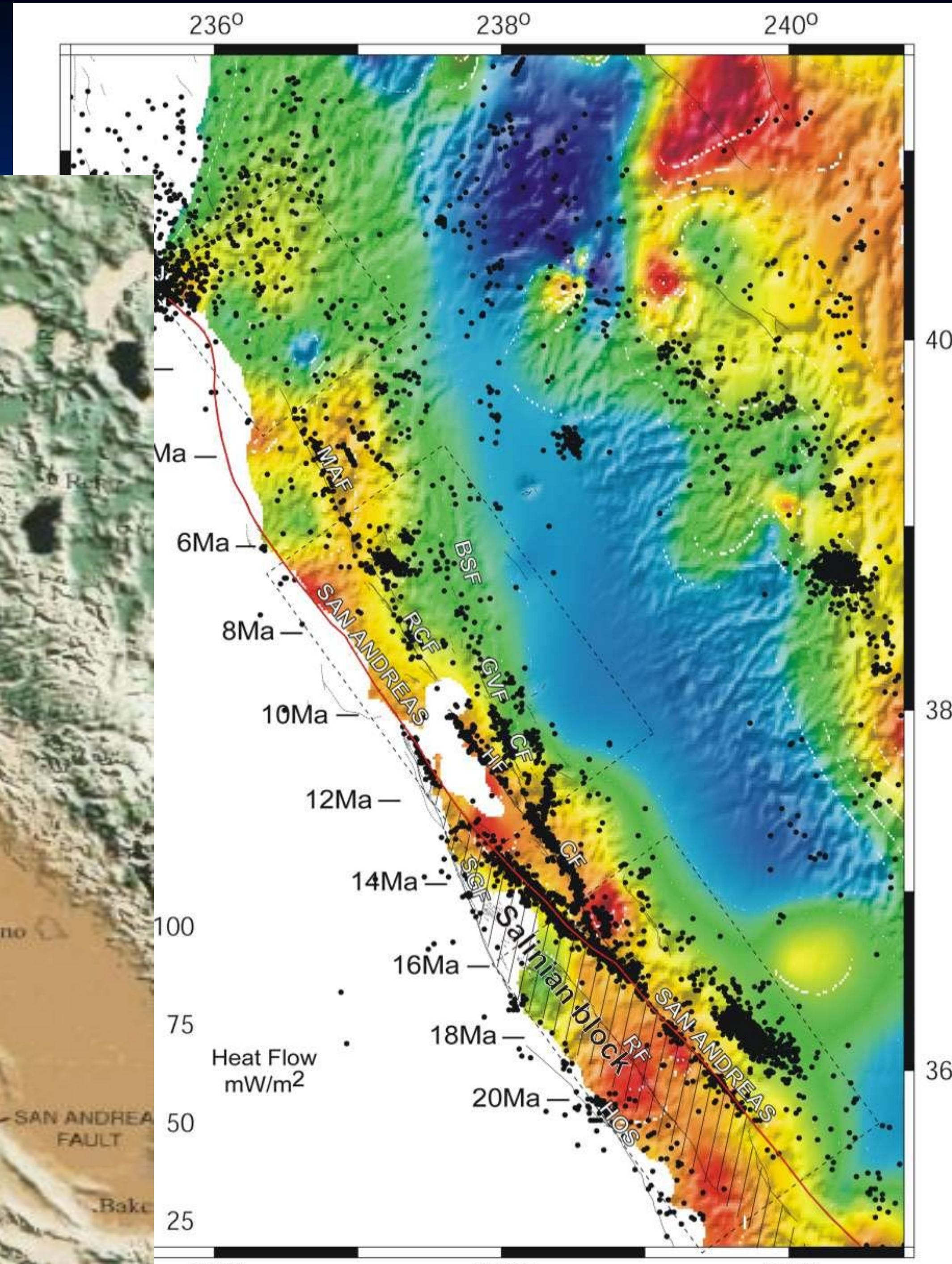
# San Andreas Fault System

# San Andreas Fault System

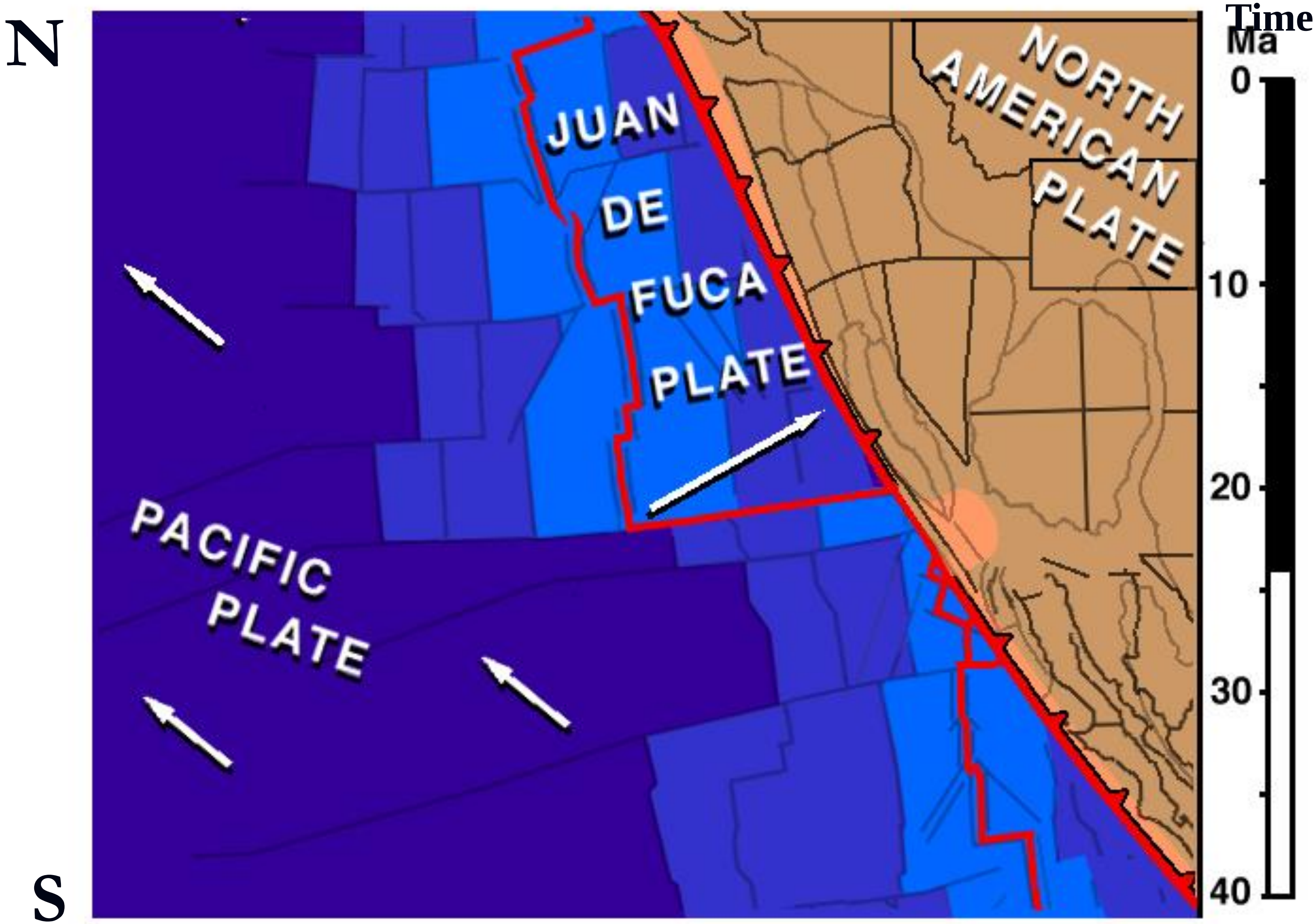



USGS Professional Paper 1515

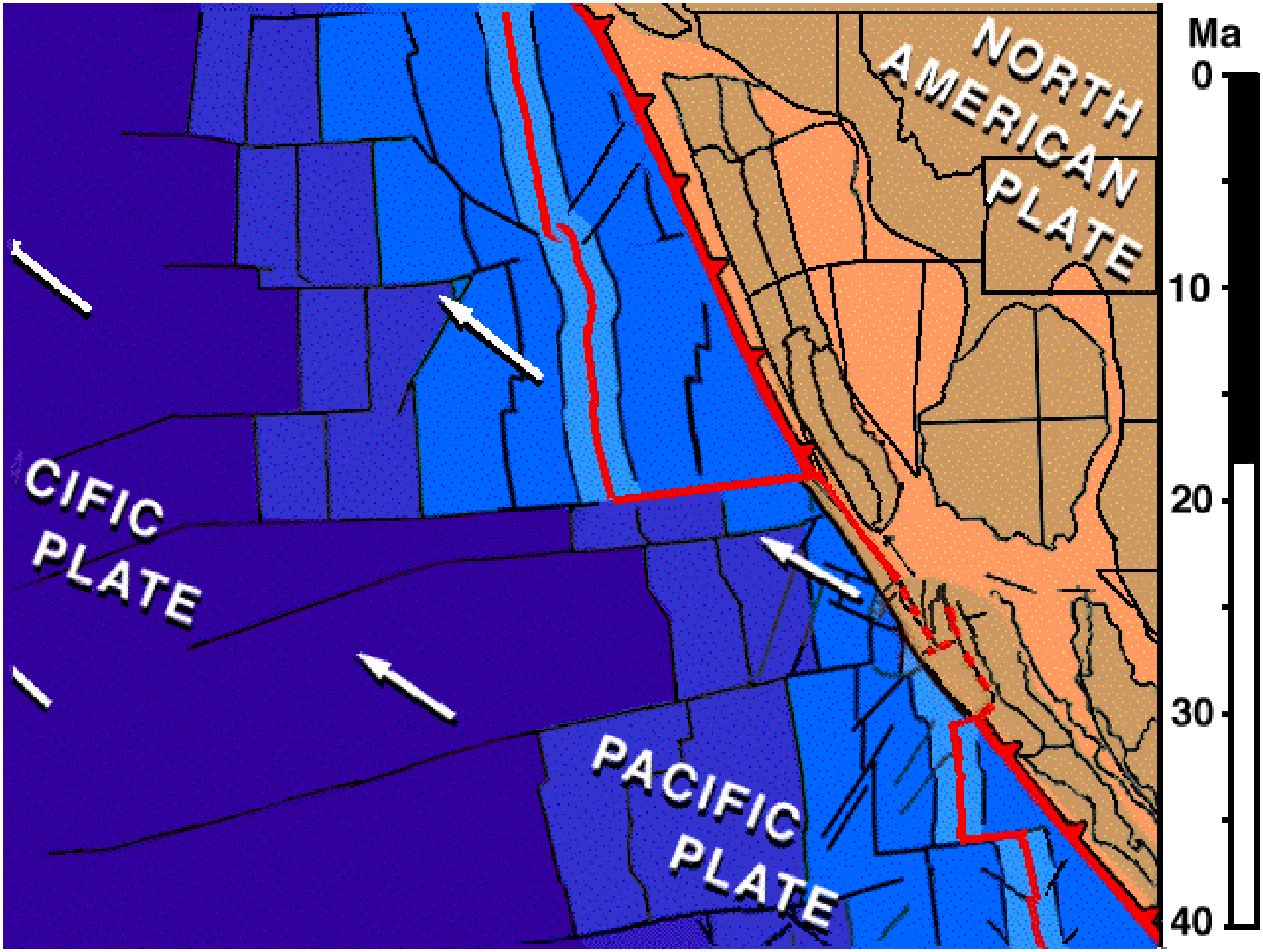

SAN ANDREAS FAULT
SACRAMENTO VALLEY
Sacramento
San Francisco
SAN ANDREAS FAULT
SAN JOAQUIN VALLEY
Fresno
PACIFIC
OCE
COAST RA
SAN ANDREA FAULT

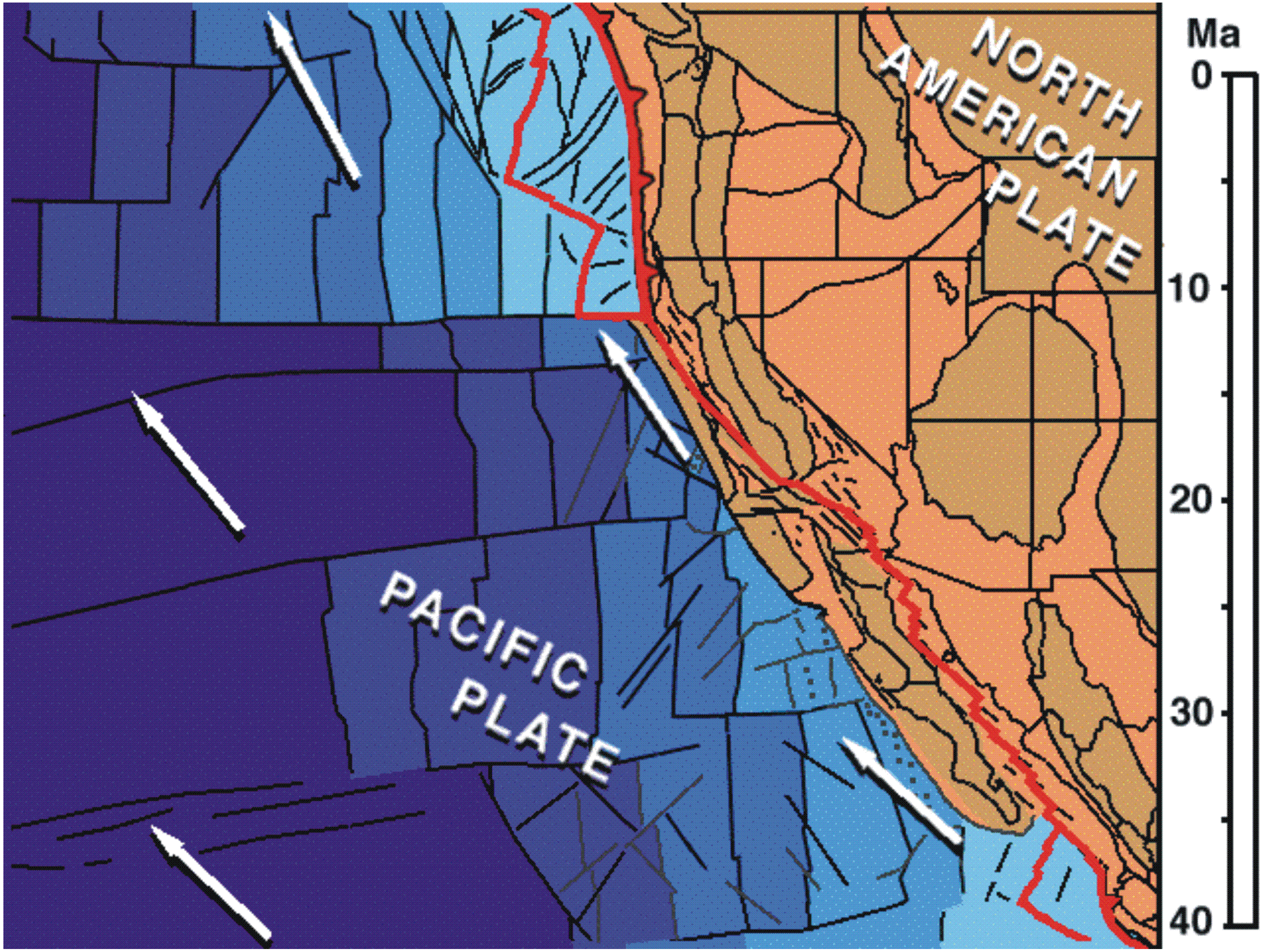

236°
238°
240°
40°
38°
36°
Ma
6Ma
8Ma
10Ma
12Ma
14Ma
16Ma
18Ma
20Ma
MAF
BSF
RCF
GVF
CF
HF
CF
SAN ANDREAS
SGF
Salinian block
RF
SAN ANDREAS
HOS
Heat Flow
mW/m2
100
75
50
25

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

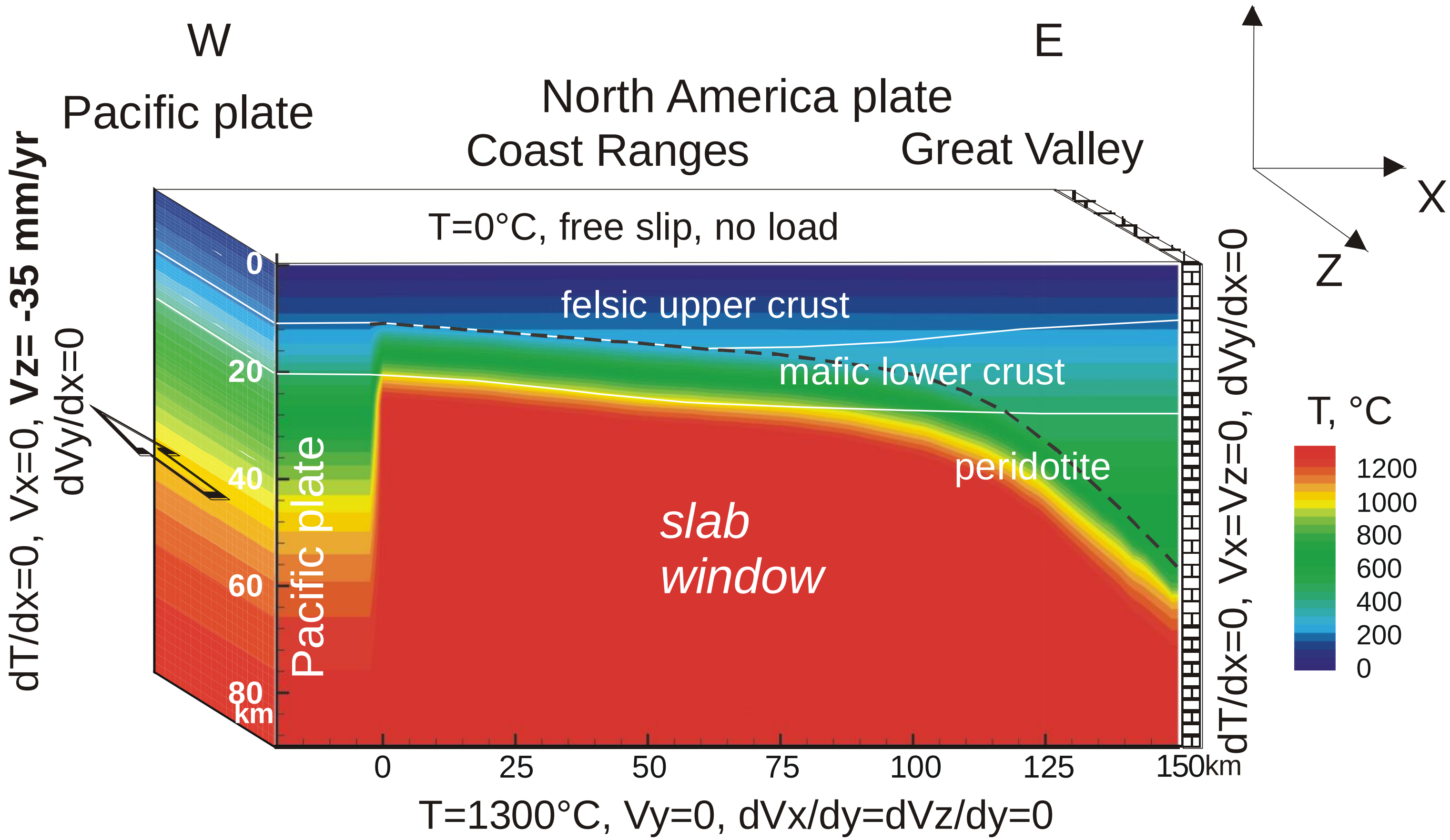
# Questions addressed

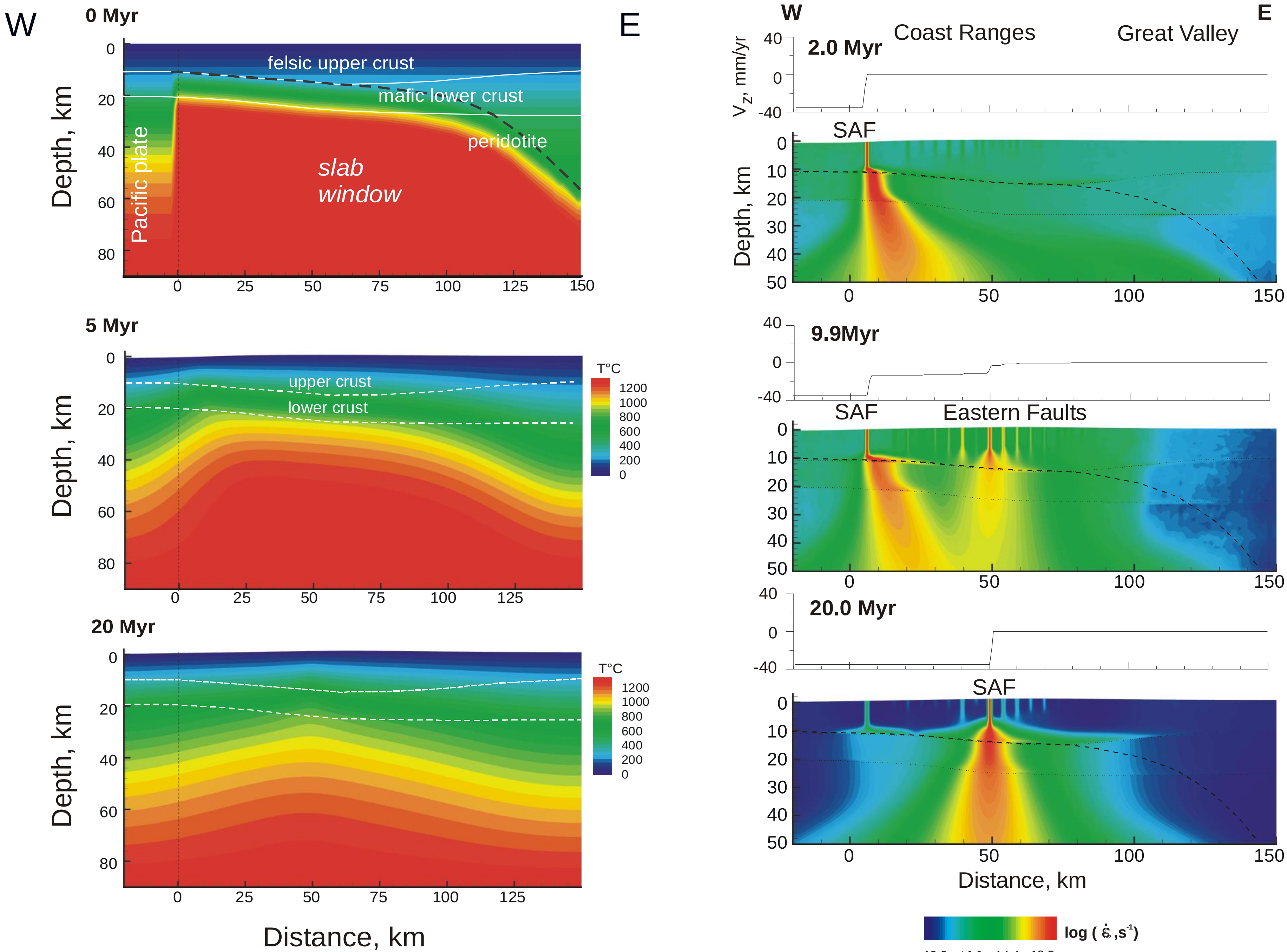
Why the locus of deformation in SAFS migrates landwards with time?

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

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

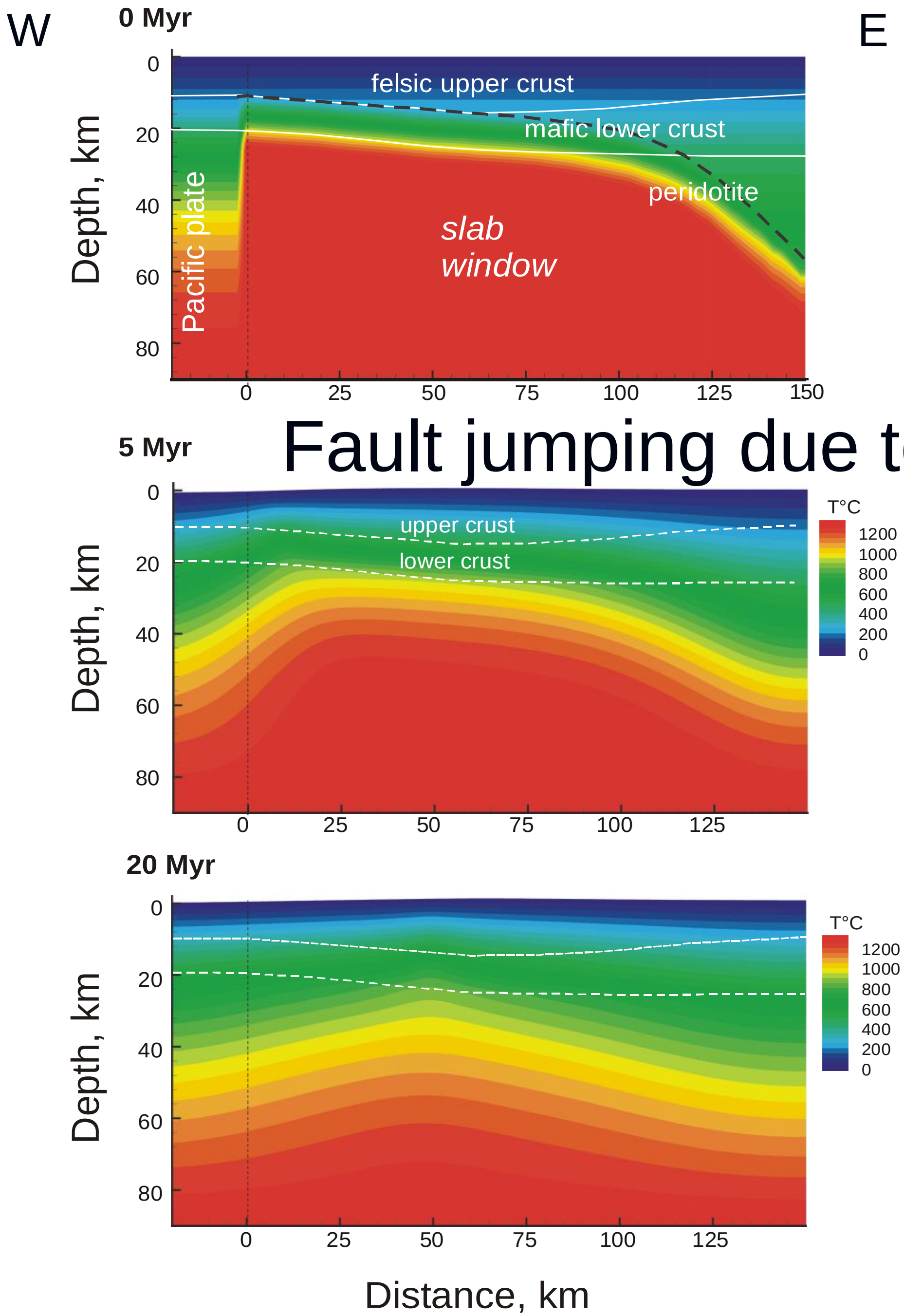
# Extended 2D Model Setup (South view)

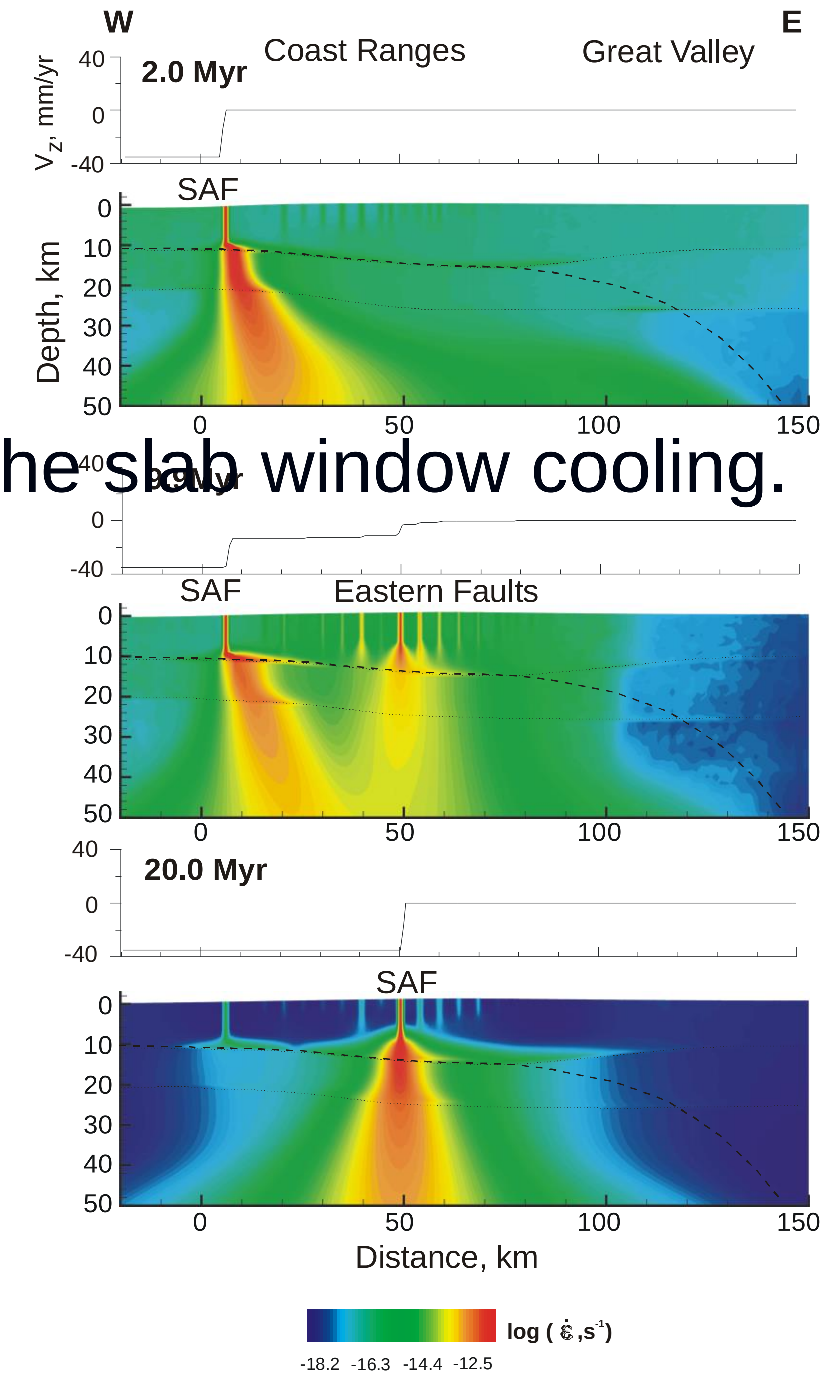




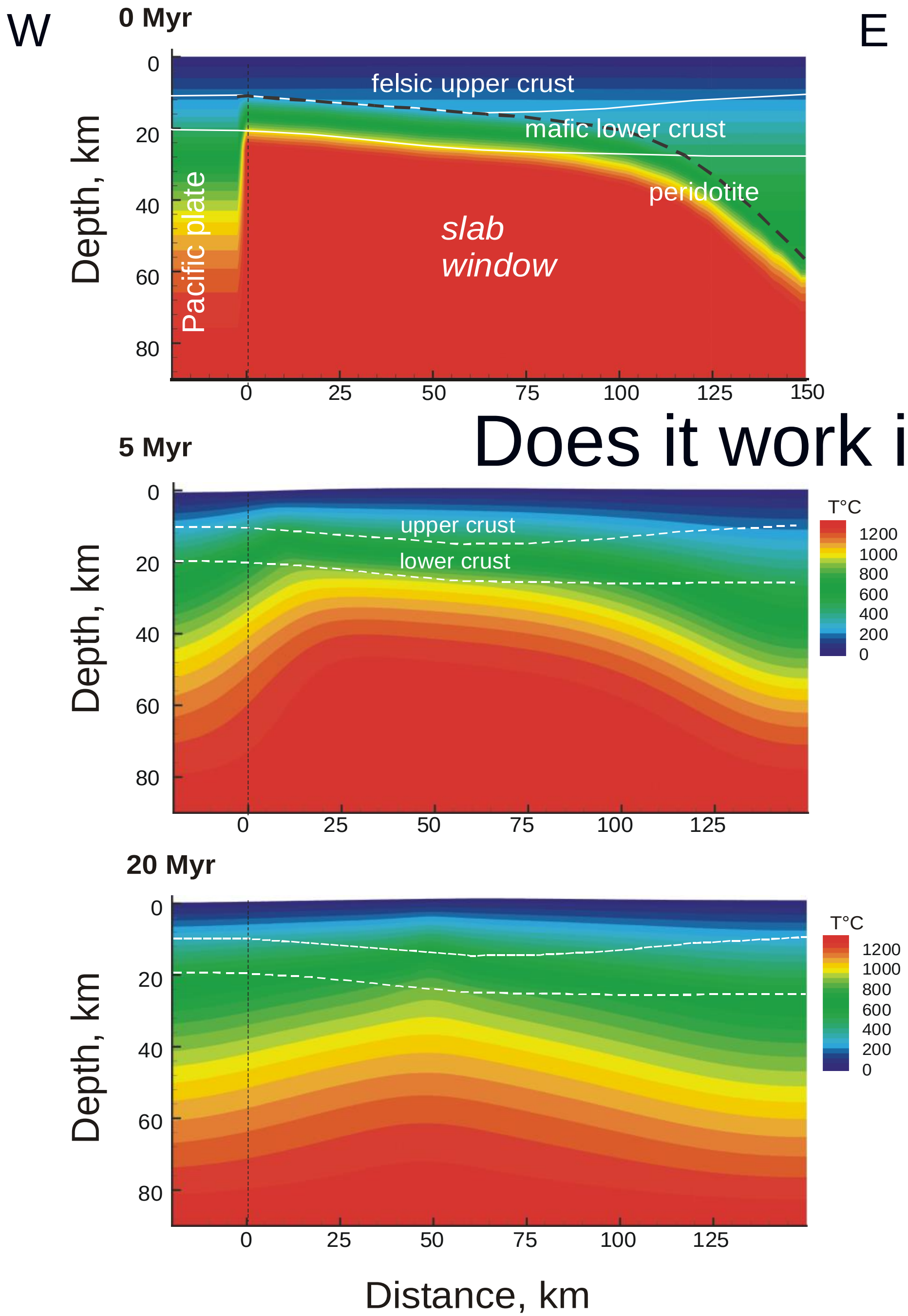
W
E
0 Myr
felsic upper crust
mafic lower crust
peridotite
slab window
Pacific plate
5 Myr
upper crust
lower crust
20 Myr
T°C
1200
1000
800
600
400
200
0
Depth, km
Distance, km
2.0 Myr
Coast Ranges
Great Valley
$V_z$, mm/yr
SAF
9.9Myr
Eastern Faults
20.0 Myr
log ( $\dot{\varepsilon}$, $s^{-1}$)
-18.2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

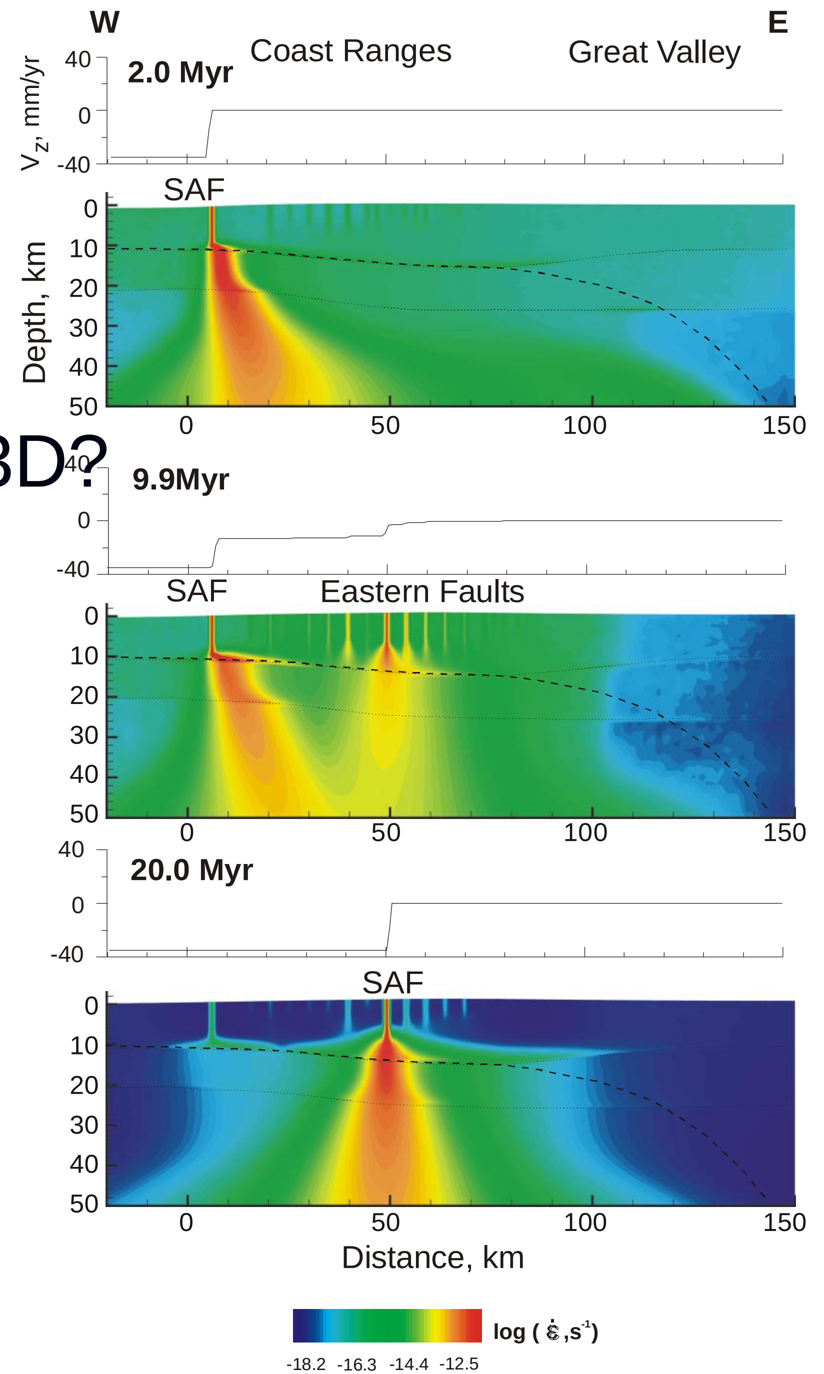
# Fault jumping due to the slab window cooling.



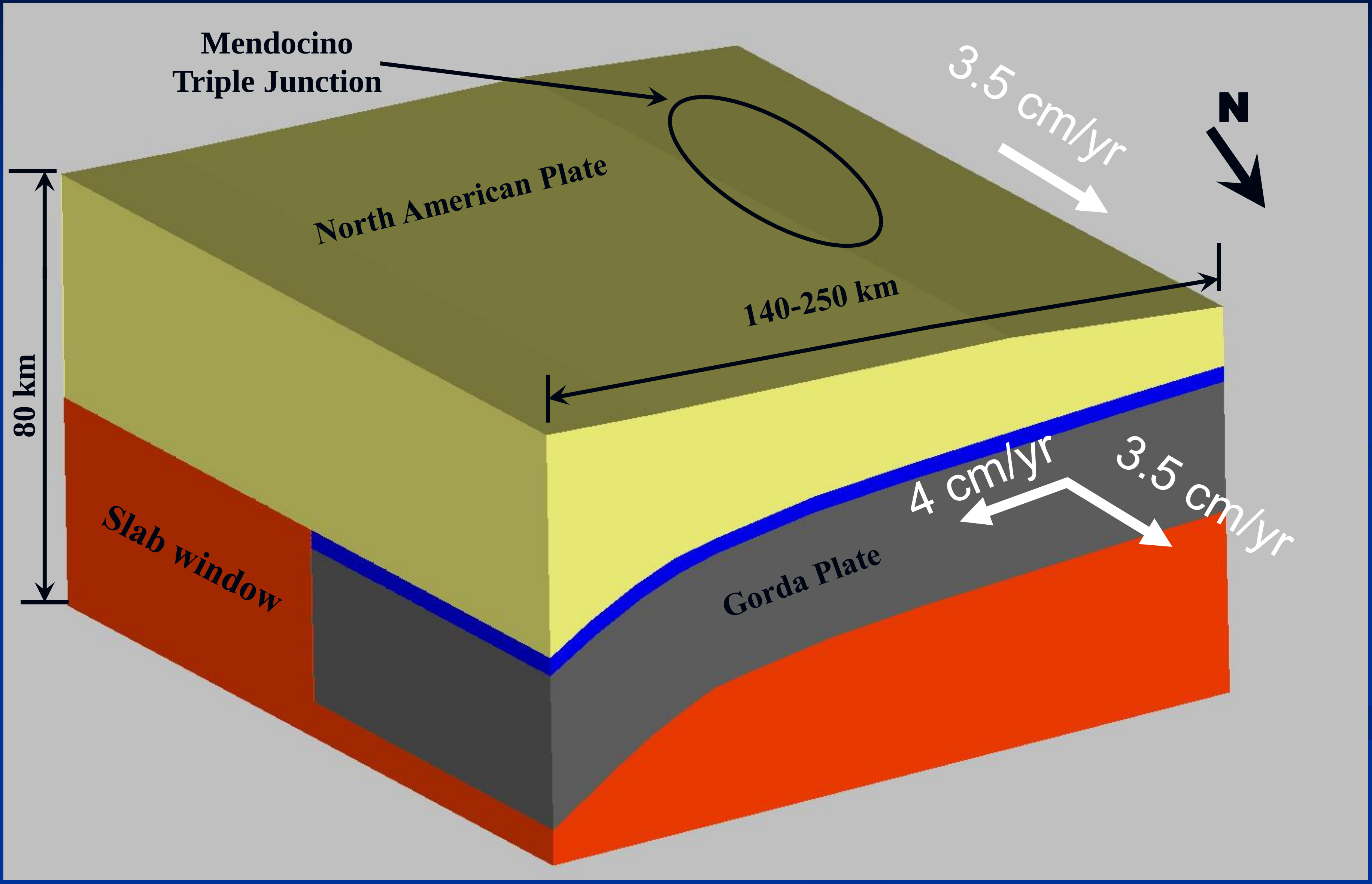



# Does it work in 3D?



# 3D Model Setup ( view from the North )



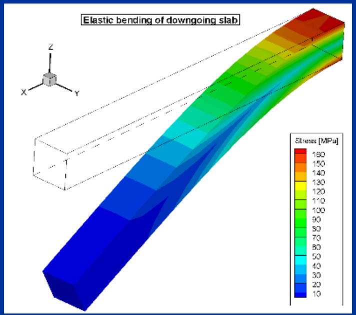

Popov, Sobolev, Zoback, G3 2012

# Physical background

## Balance equations

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

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



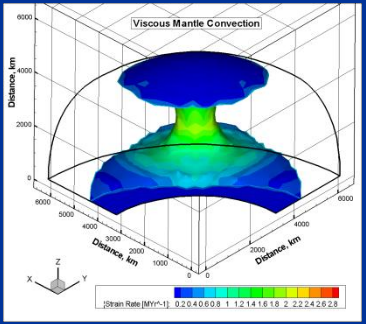

## Deformation mechanisms

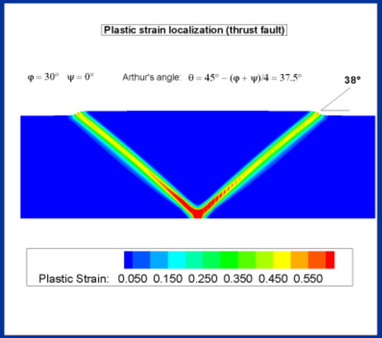
$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{el} + \dot{\varepsilon}_{ij}^{vs} + \dot{\varepsilon}_{ij}^{pl}$$

Elastic strain: $$\dot{\varepsilon}_{ij}^{el} = \frac{1}{2G}\hat{\tau}_{ij}$$

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

Plastic strain:
Mohr-Coulomb
$$\dot{\varepsilon}_{ij}^{pl} = \dot{\gamma}\frac{\partial Q}{\partial \tau_{ij}}$$

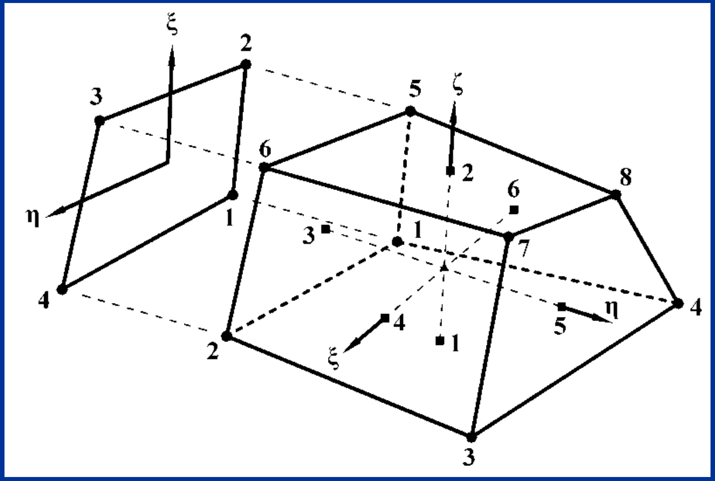


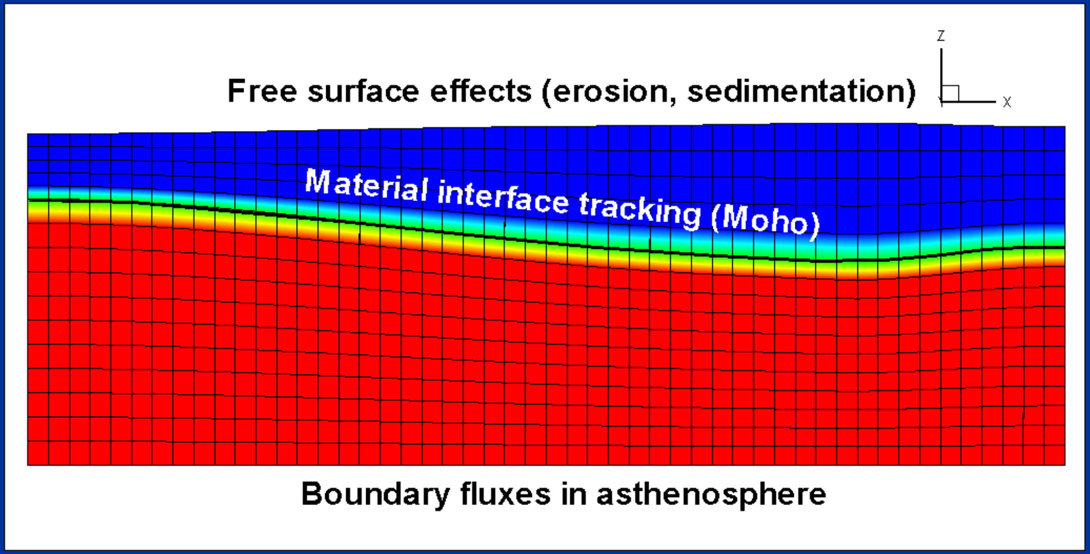

Popov and Sobolev (2008)

# Numerical background

## Discretization by Finite Element Method



## Arbitrary Lagrangian-Eulerian kinematical formulation



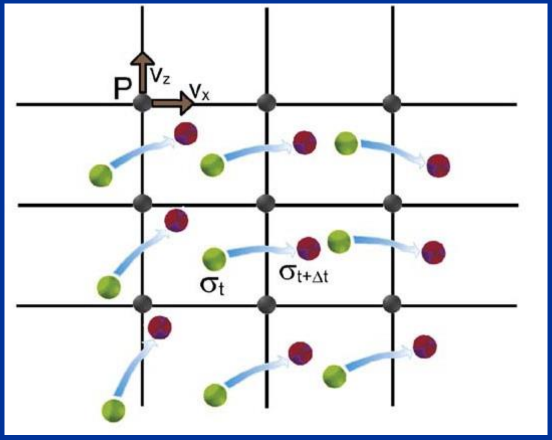

## Fast implicit time stepping + Newton-Raphson solver

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

$\mathbf{r}$ – **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)

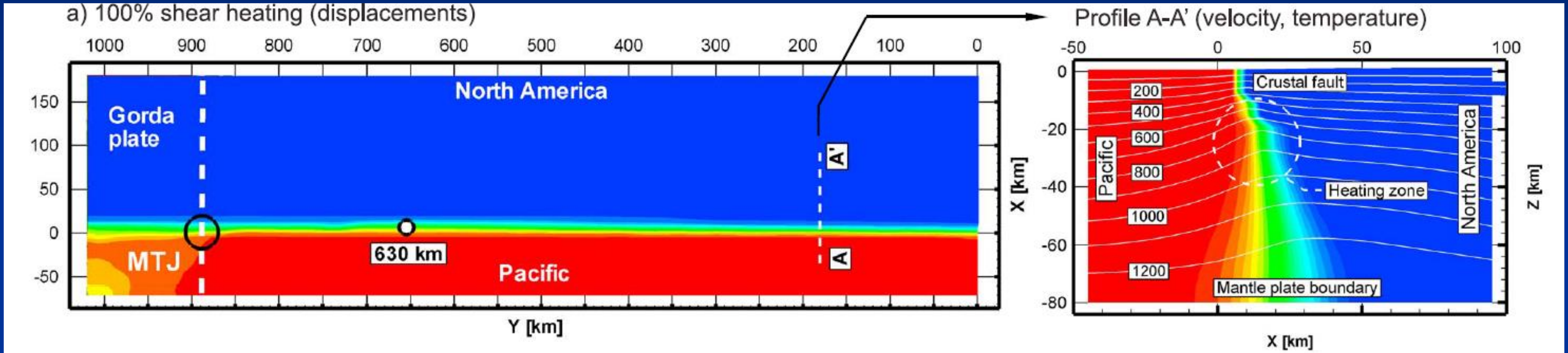
# “Strong” and “weak” faults models

**“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

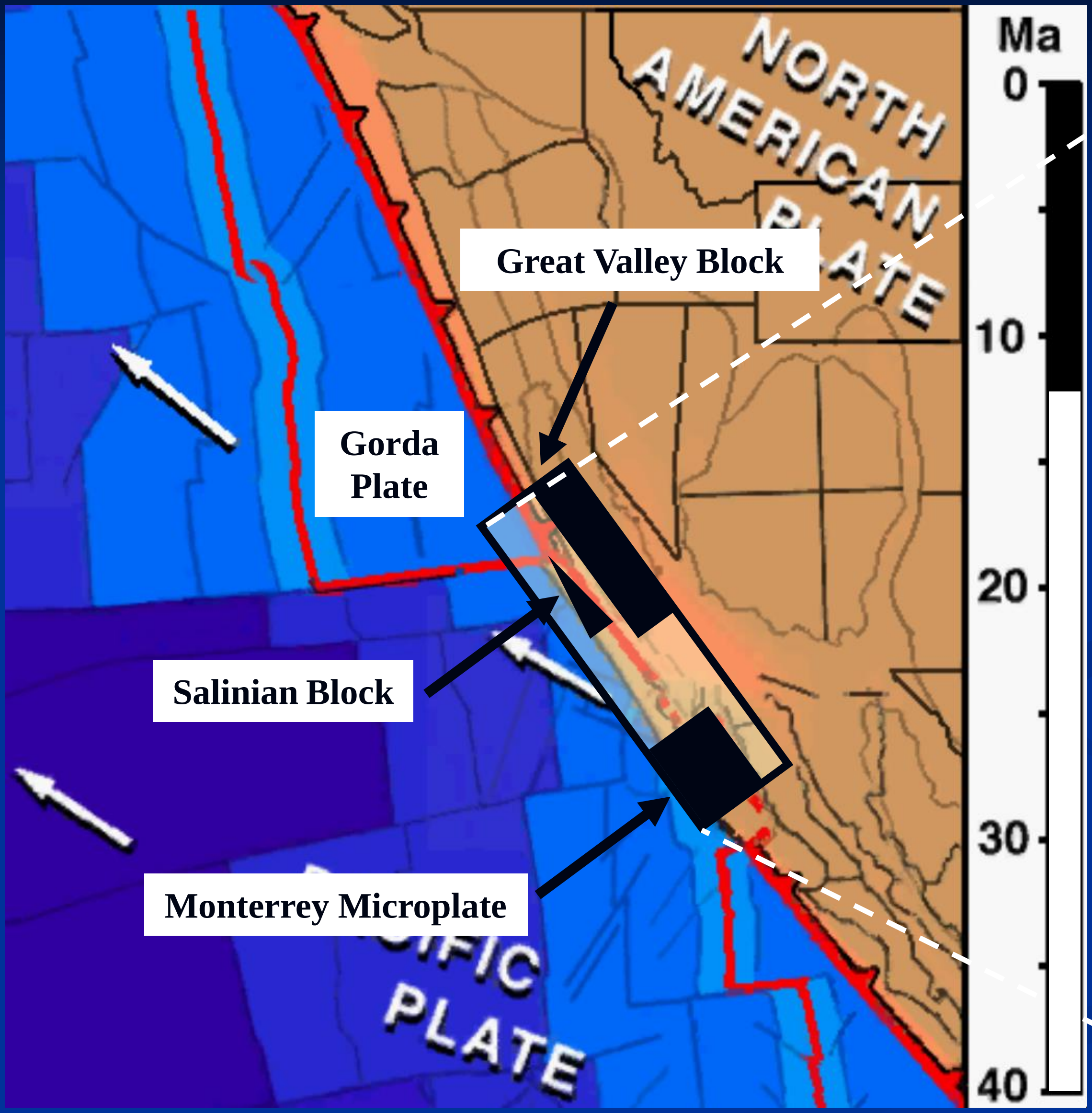
# 3D Model (slab window cooling)

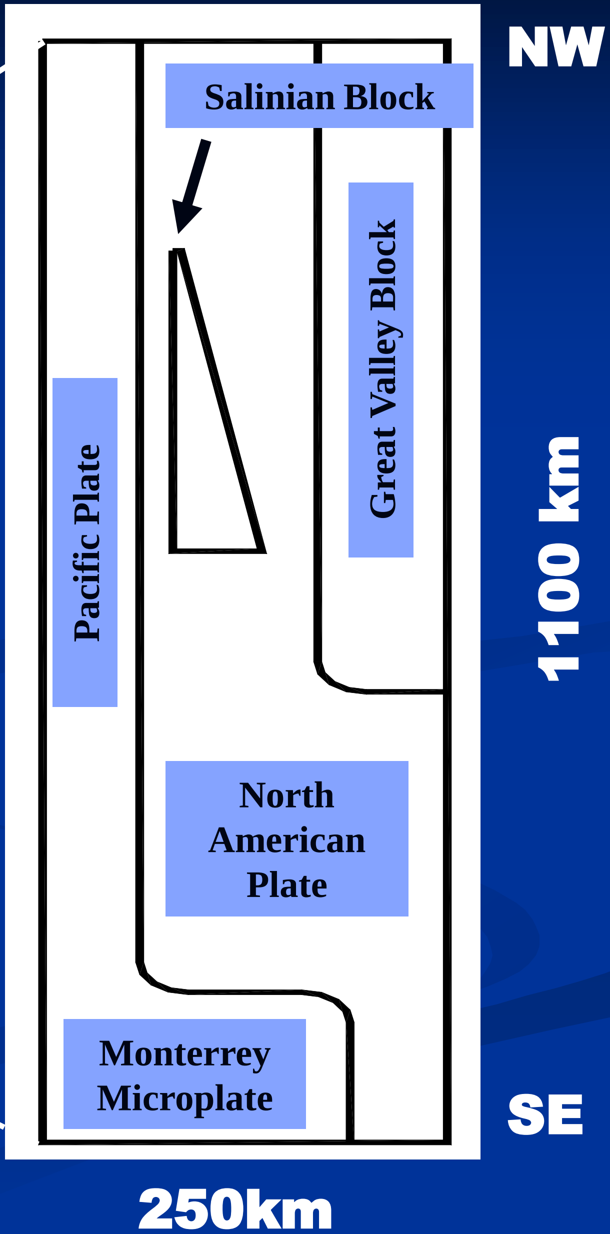



In 3D fault doesn‘t jump due to the slab window cooling. The reason is along-strike mechanical interaction (transpression) inhibiting fault jumping.

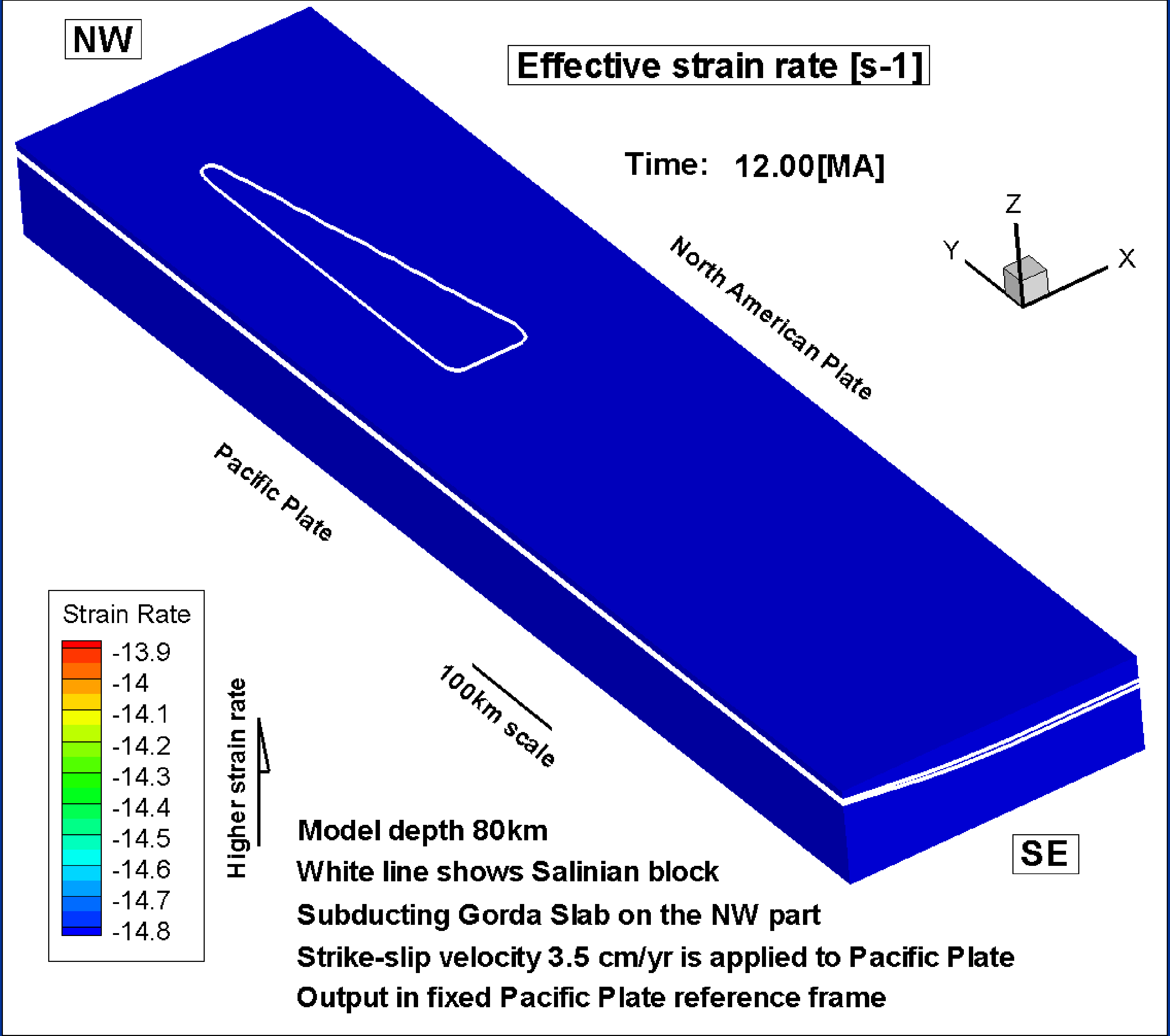
Therefore new explanation is required

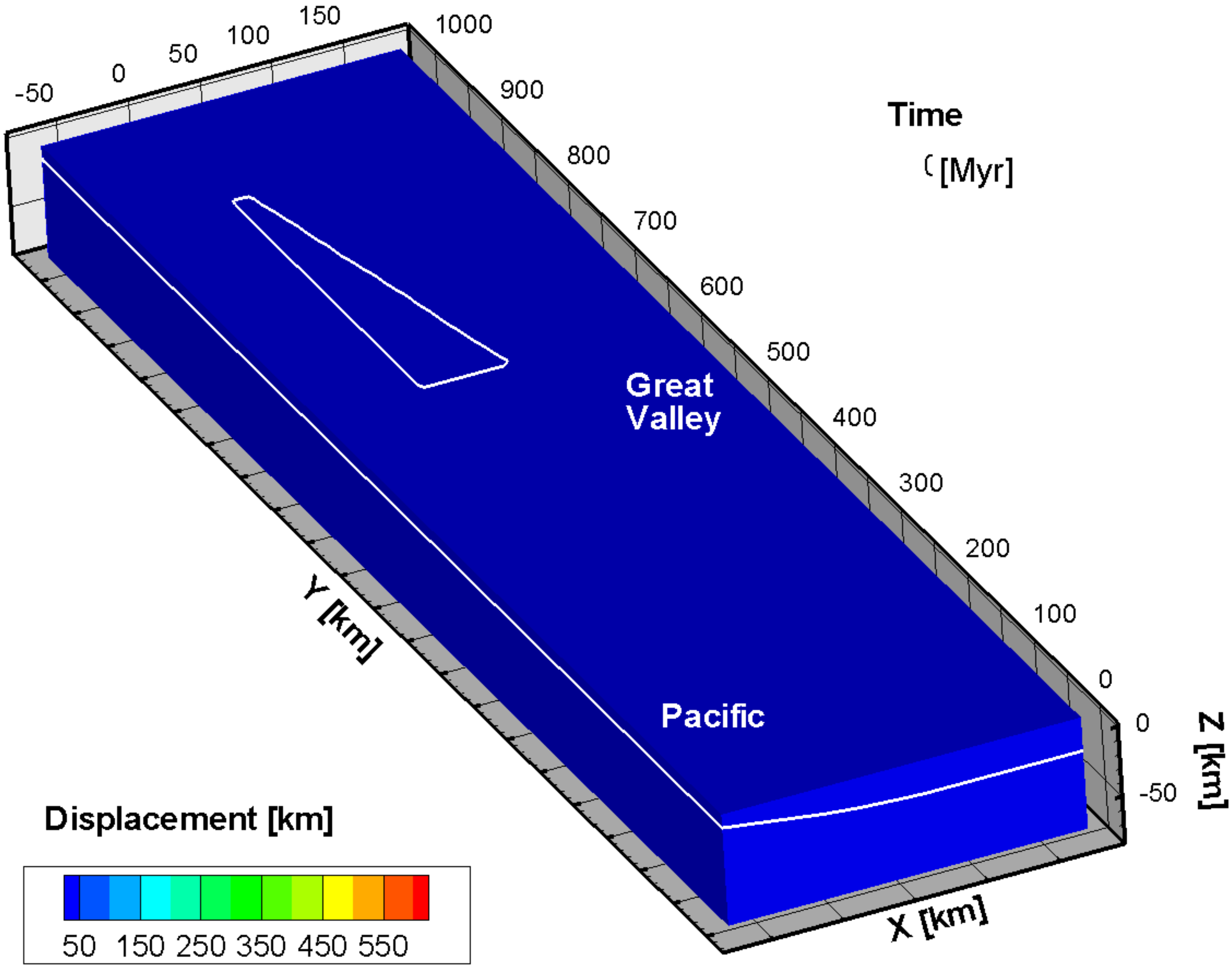
# 3D Model Setup with heterogeneity (at 12-15 MA)



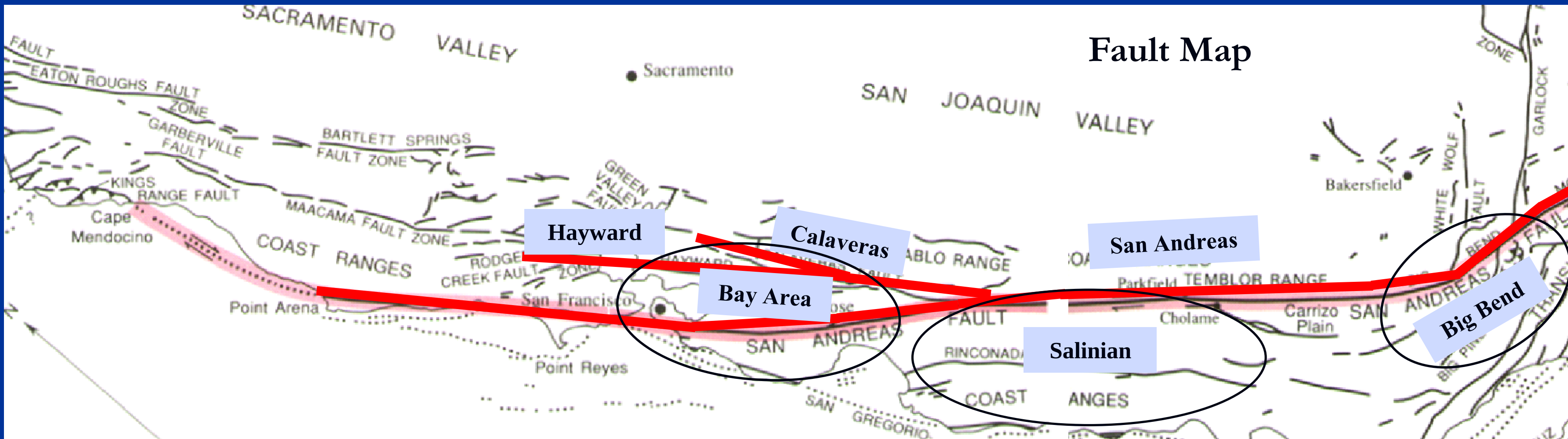

Popov, Sobolev, Zoback, G3 2012

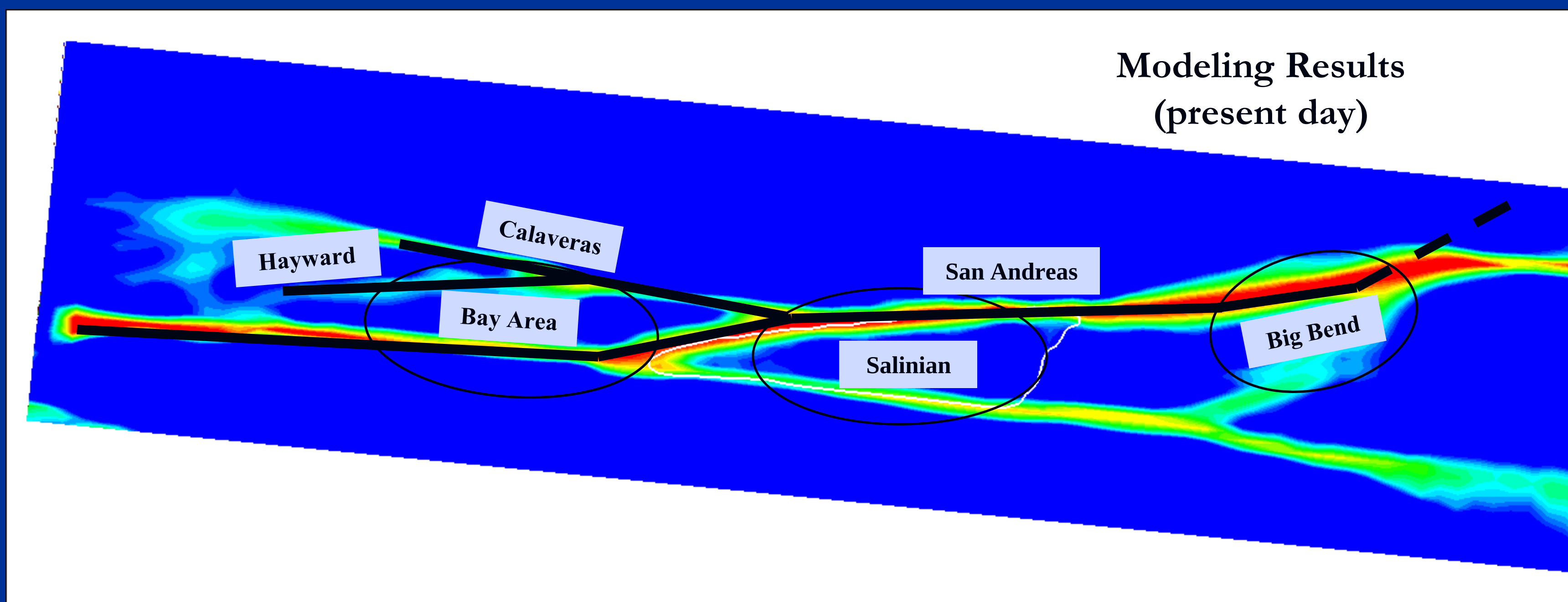

NW
Effective strain rate [s-1]
Time: 12.00[MA]
Z
Y
X
North American Plate
Pacific Plate
Strain Rate
-13.9
-14
-14.1
-14.2
-14.3
-14.4
-14.5
-14.6
-14.7
-14.8
Higher strain rate
100km scale
SE
Model depth 80km
White line shows Salinian block
Subducting Gorda Slab on the NW part
Strike-slip velocity 3.5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

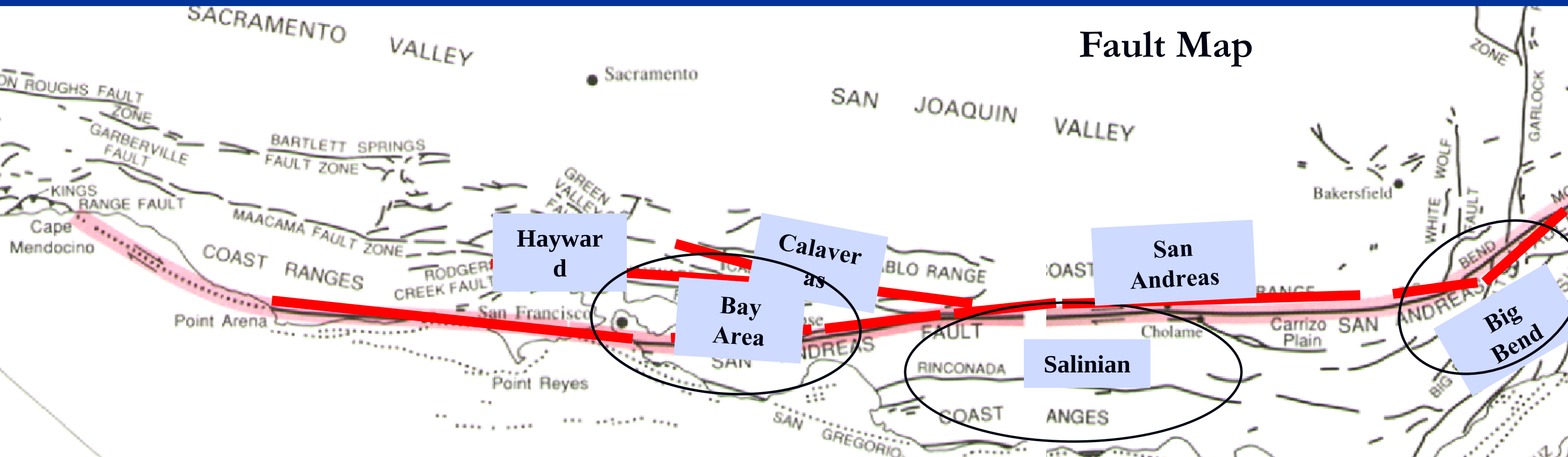


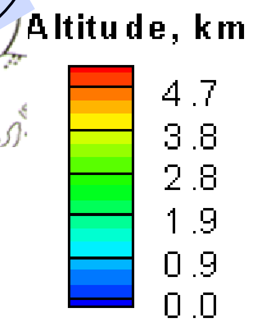
-50
0
50
100
150
1000
900
800
700
600
500
400
300
200
100
0
Time
[Myr]
Great
Valley
Pacific
Y [km]
X [km]
0
-50
Z [km]
Displacement [km]
50 150 250 350 450 550

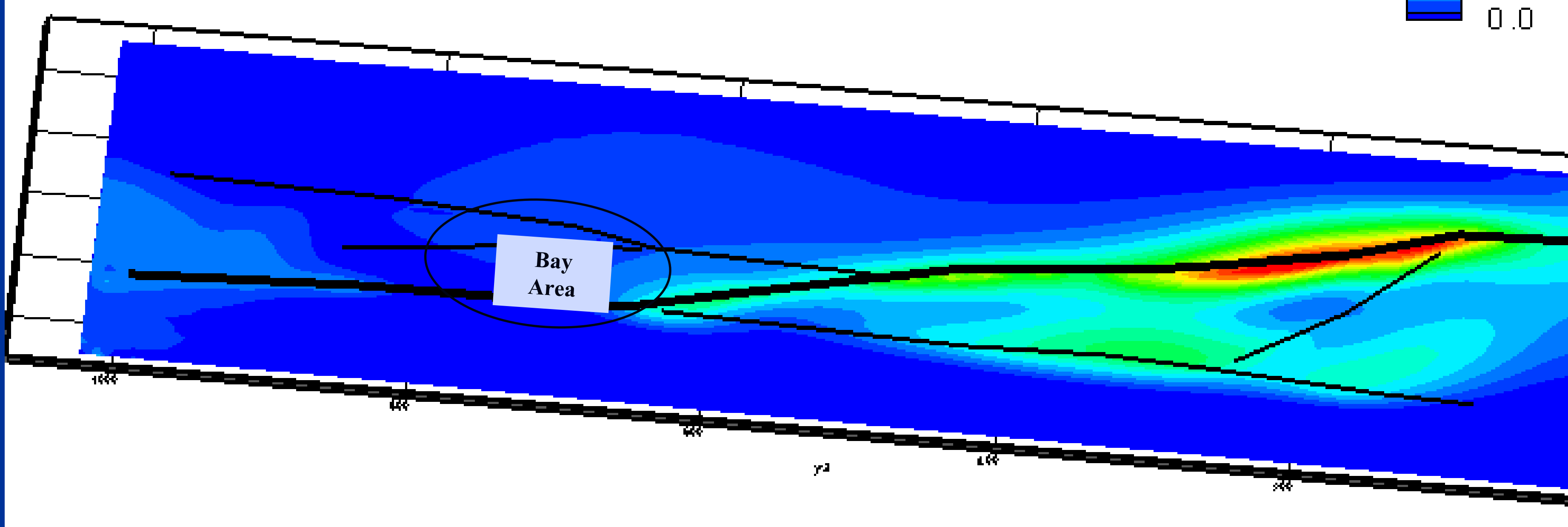
# Qualitative comparison of basic fault features



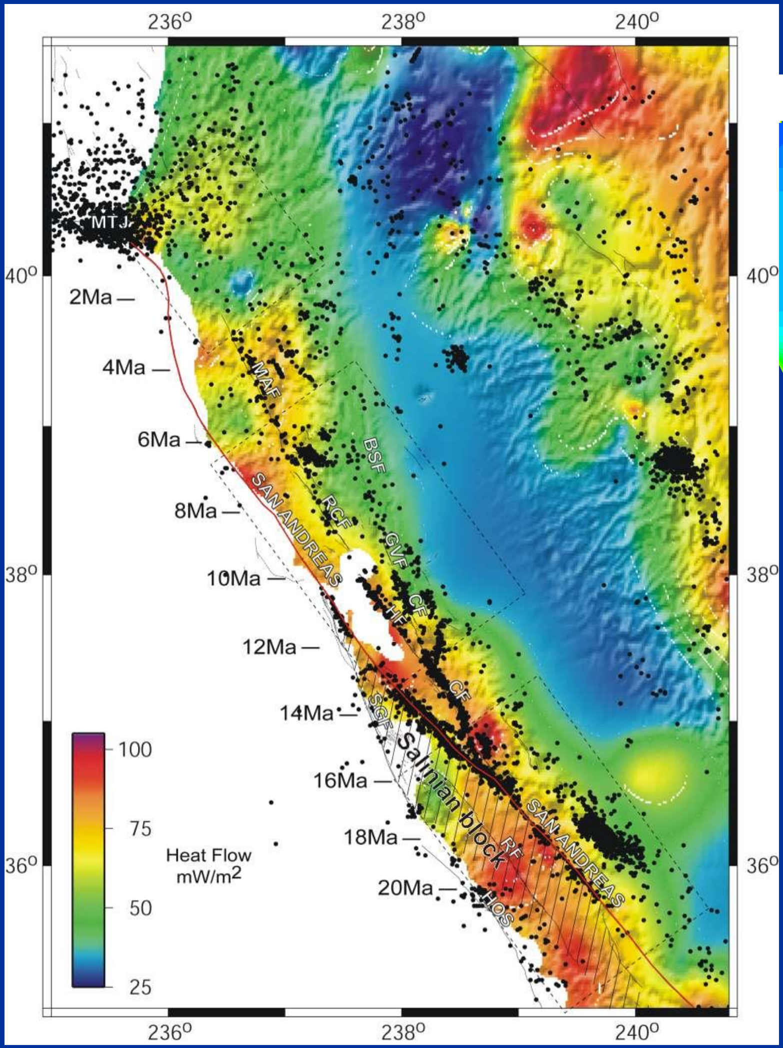



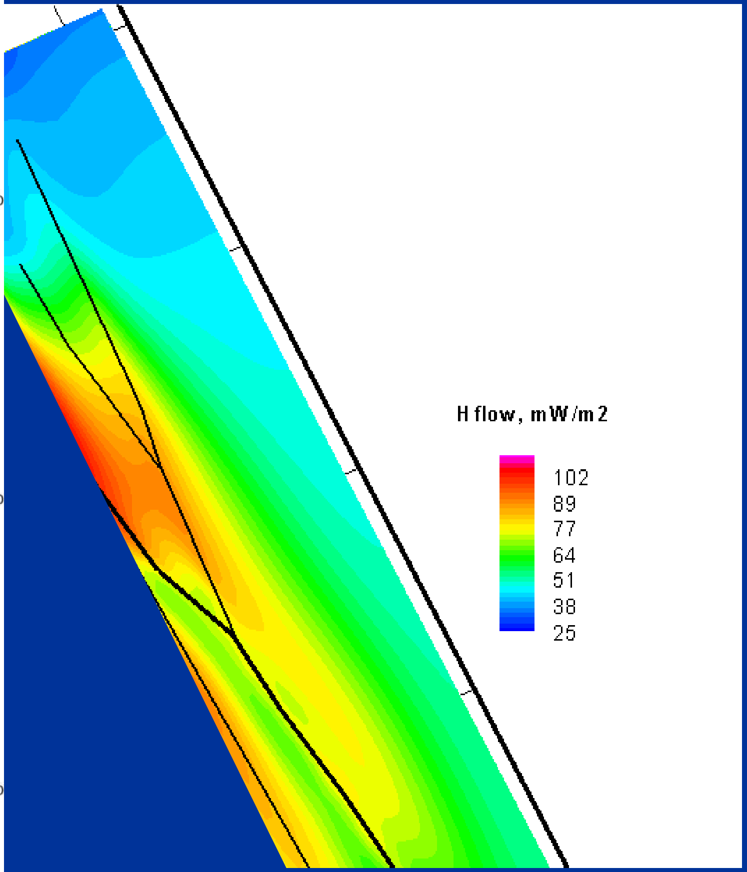

Fault Map
SACRAMENTO VALLEY
Sacramento
SAN JOAQUIN VALLEY
Bakersfield
BARTLETT SPRINGS FAULT ZONE
GARBERVILLE FAULT
KINGS RANGE FAULT
MAACAMA FAULT ZONE
Cape Mendocino
COAST RANGES
Point Arena
San Francisco
Point Reyes
Haywar d
Calaver as
Bay Area
San Andreas
Salinian
Big Bend
RINCONADA
Cholame
Carrizo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


Altitude, km
4.7
3.8
2.8
1.9
0.9
0.0


Bay Area

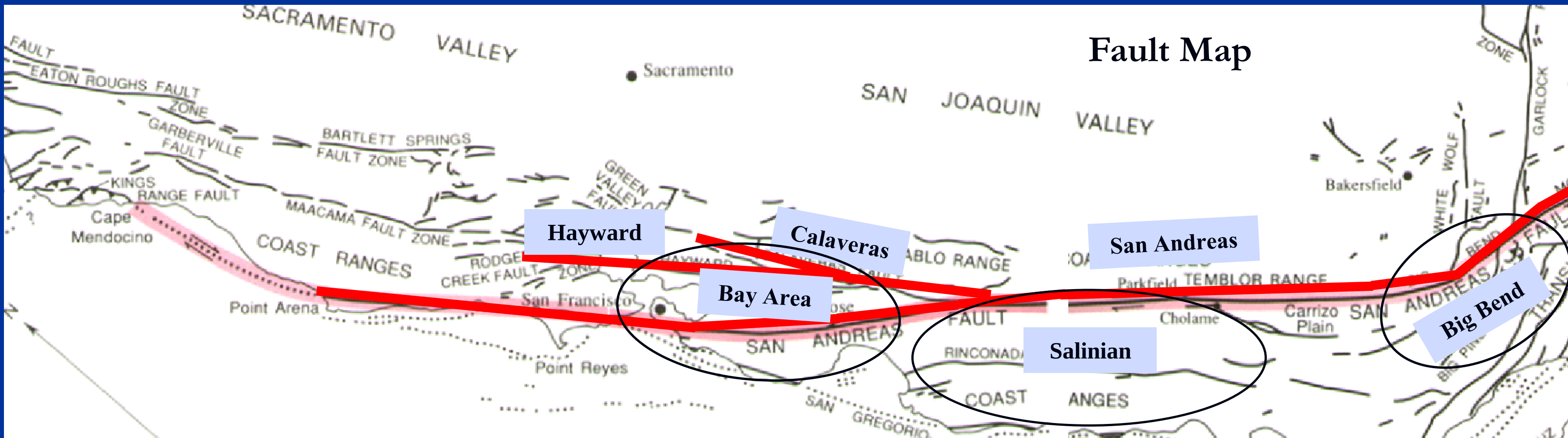
# Modeled surface heat flow

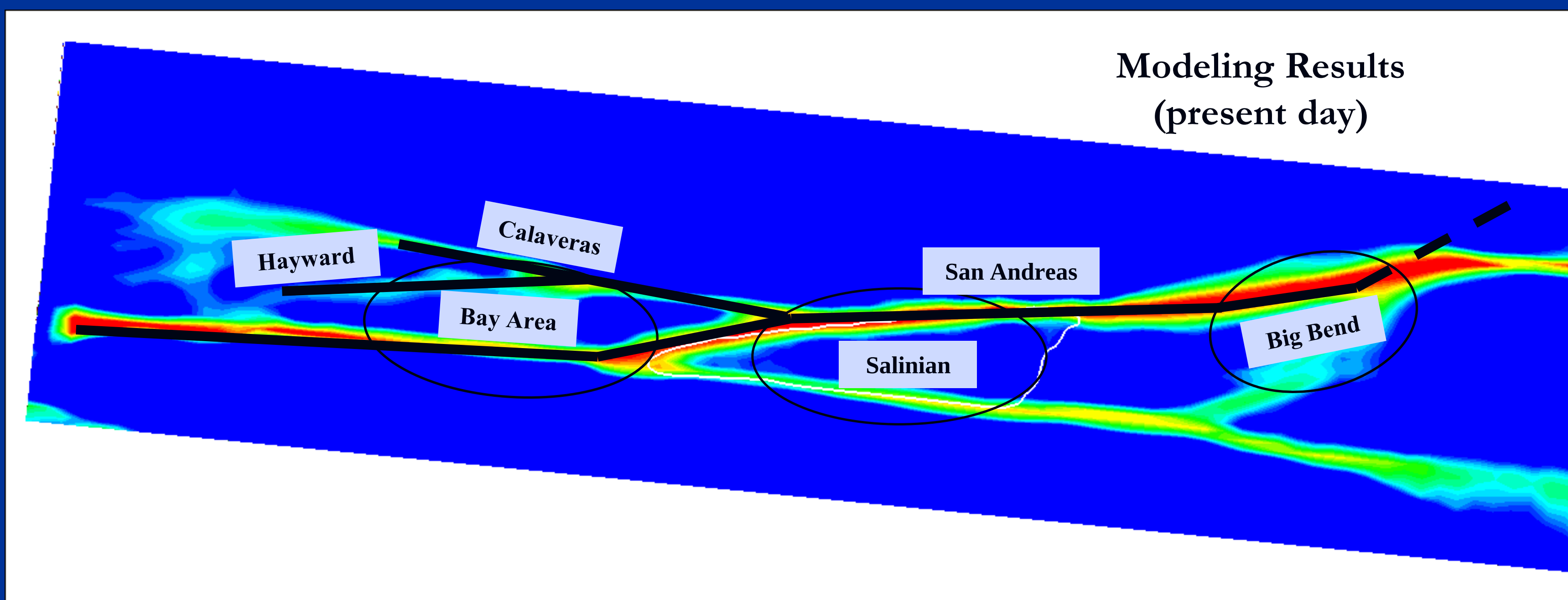


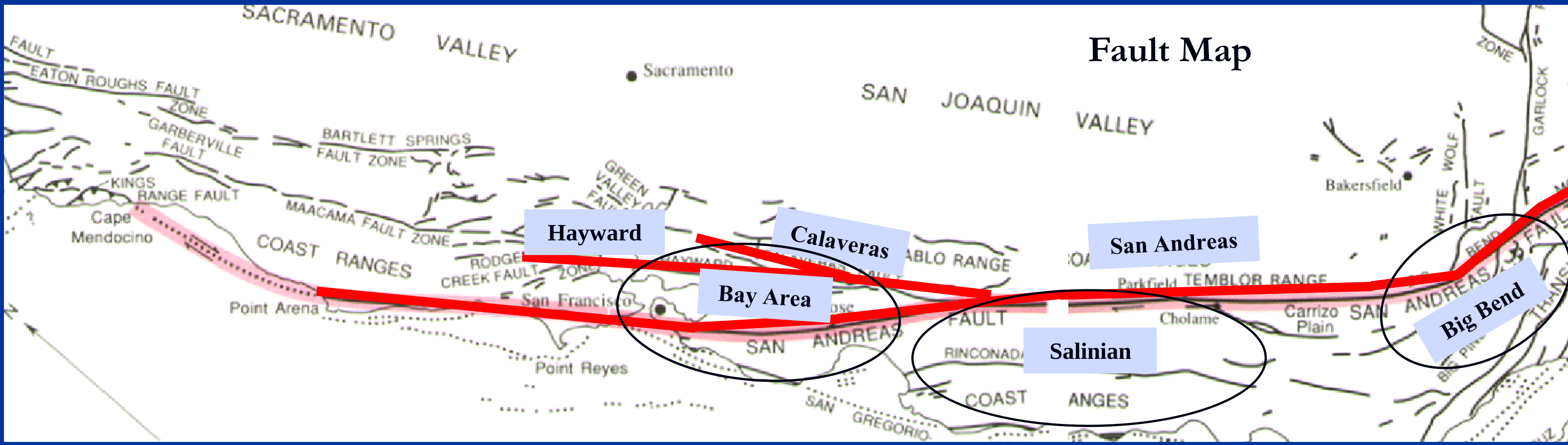
# “Weak faults” versus “strong faults” model

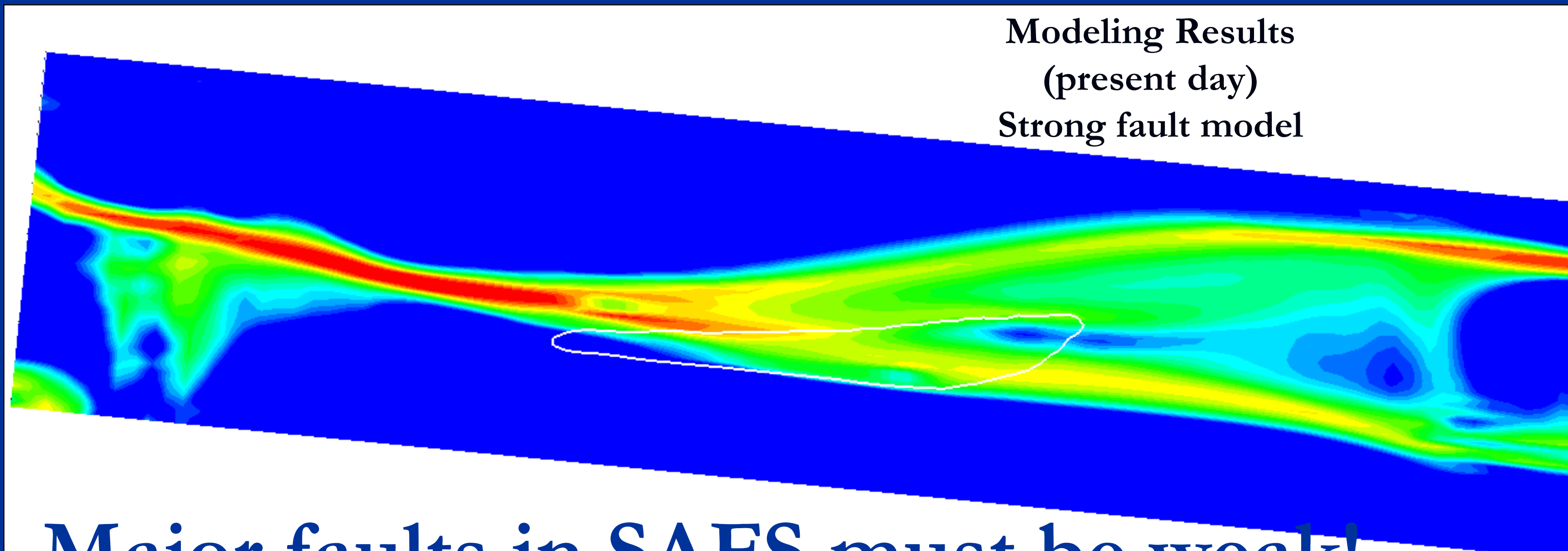
# Weak-faults model



# 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”