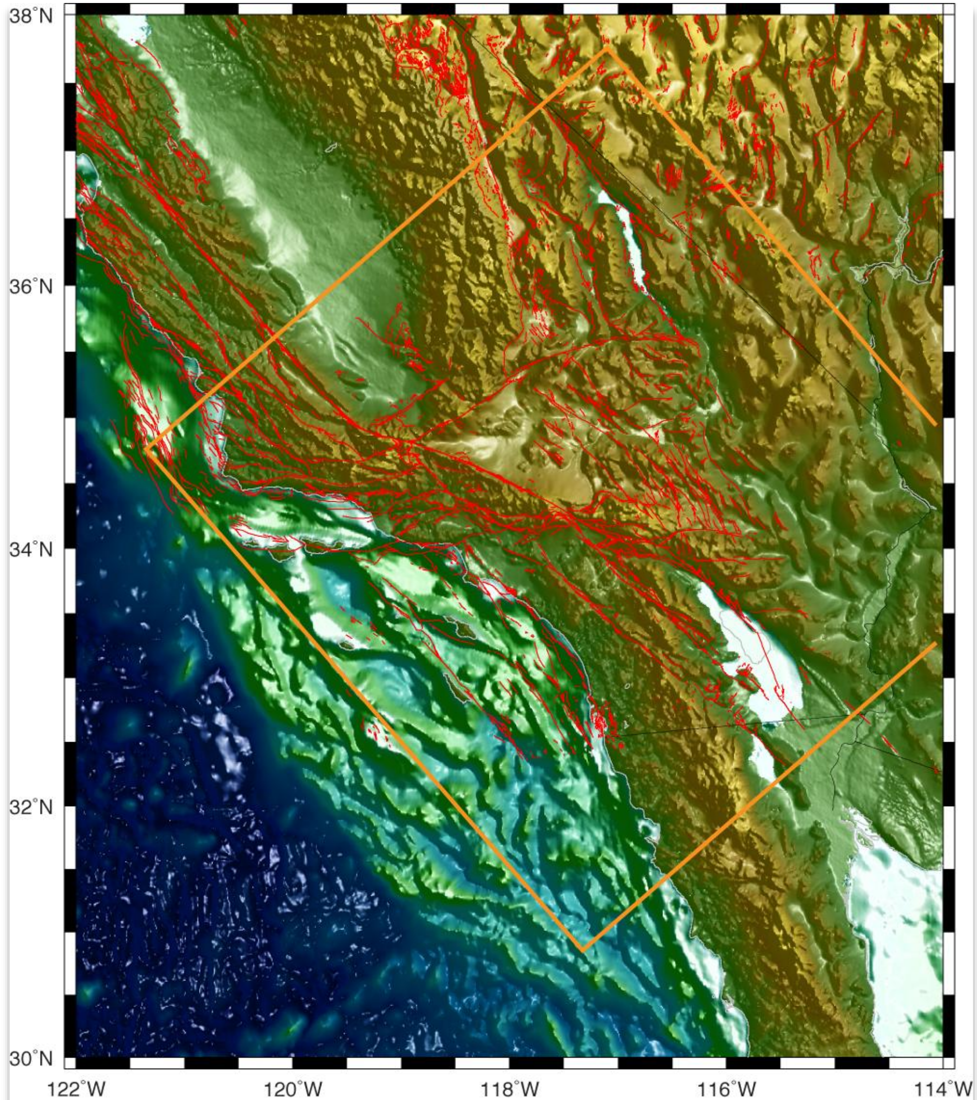
# 3D numerical mechanical modeling of the southern San Andreas Fault system




B.P. Hooks[1,2] and B.R. Smith-Konter[1]

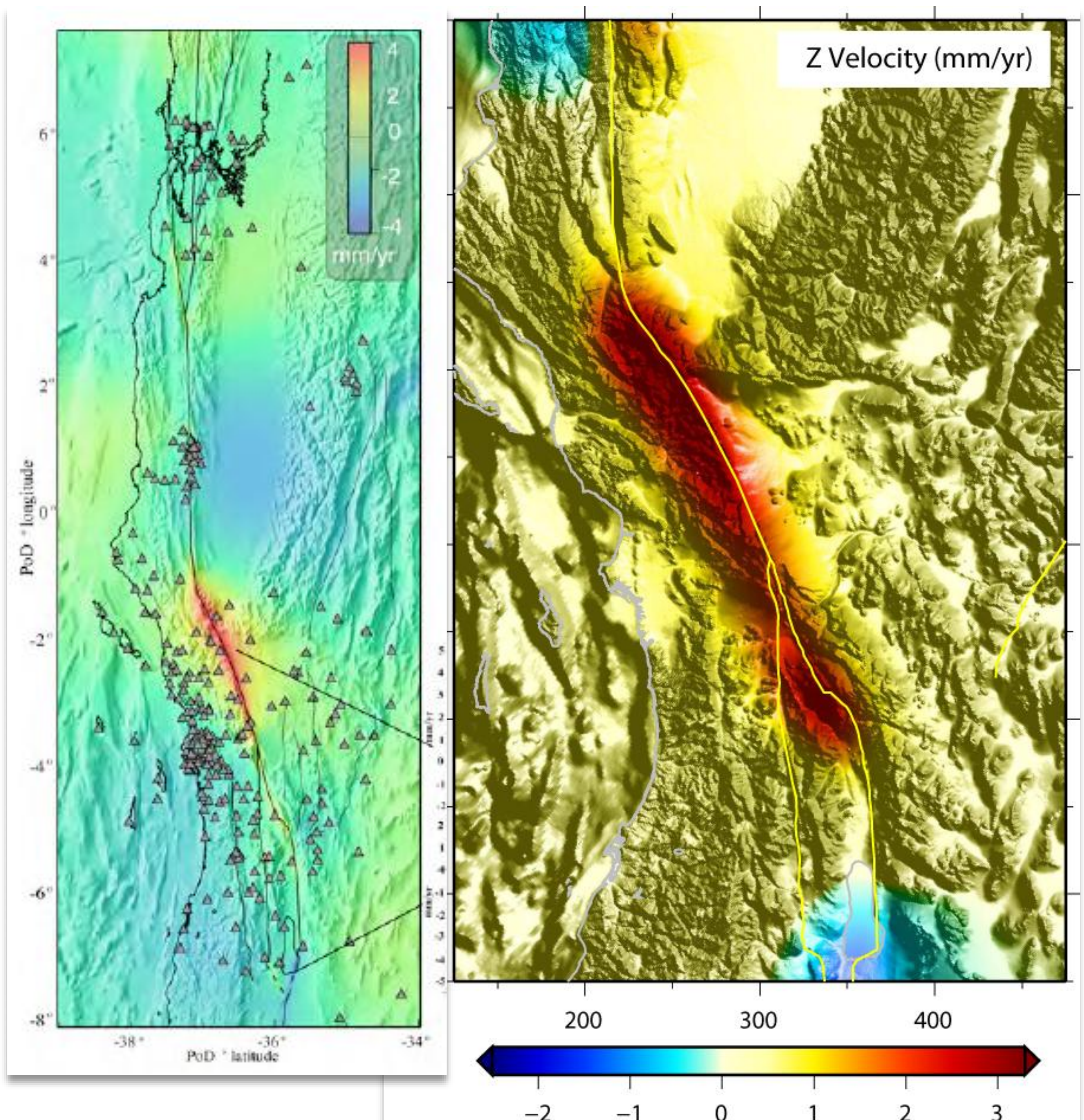
1) University of Texas at El Paso, El Paso, TX 79968 ; bphooks@utep.edu
2) University of Tennessee at Martin, Martin, TN 38238

## Project Objective

Our goal is to reproduce the long-term (10's thousands to millions of years ) strain and uplift patterns associated with the San Andreas Fault System (SAFS).

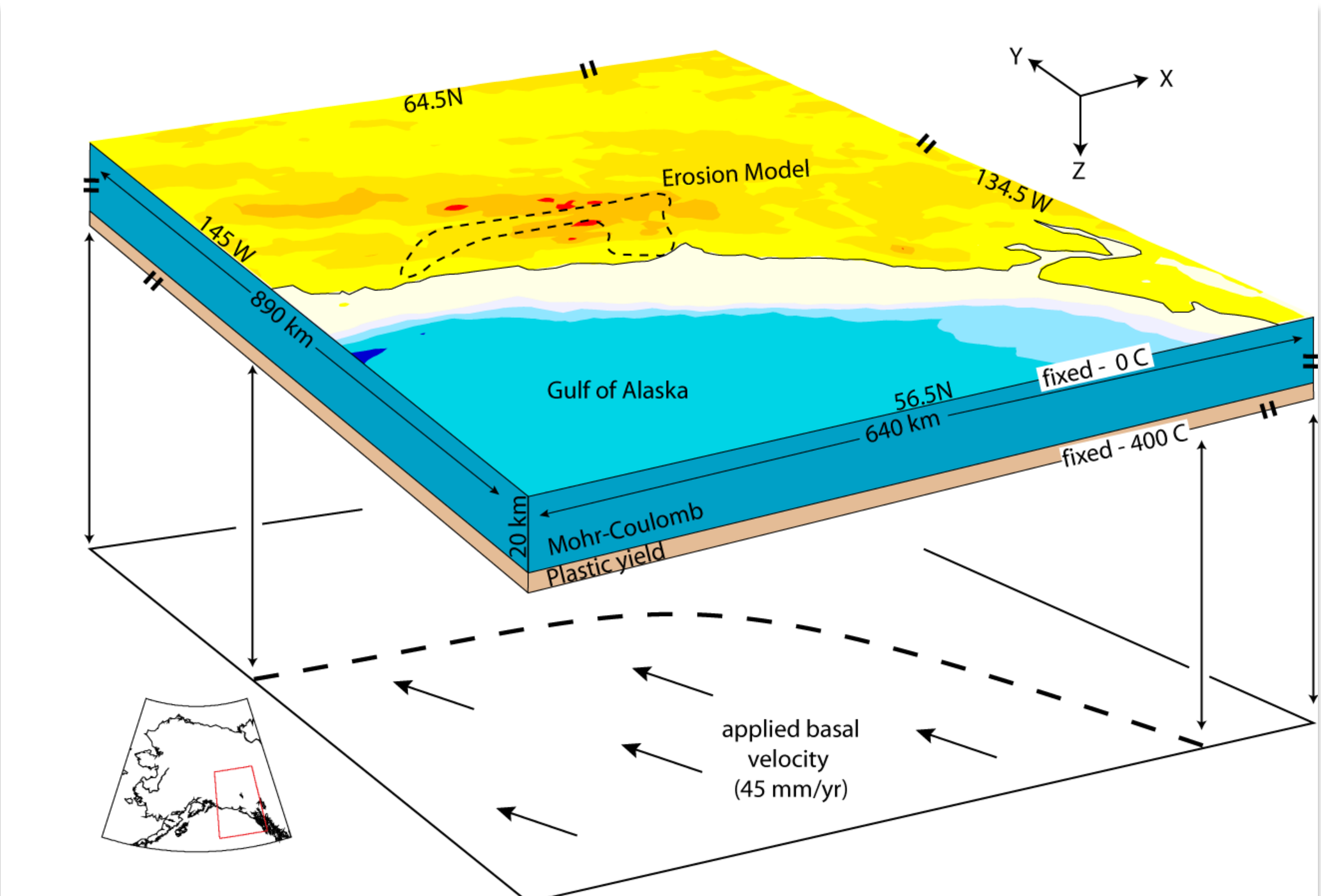
Compare the modeled patterns with observations of geology (uplift markers) and previous modeling efforts (analytical and block models).

Here we present models for the southern portion of the SAFS.




Smith and Sandwell, 2004

# Methodology




Enkelmann et al., 2010

# Numerical Methods

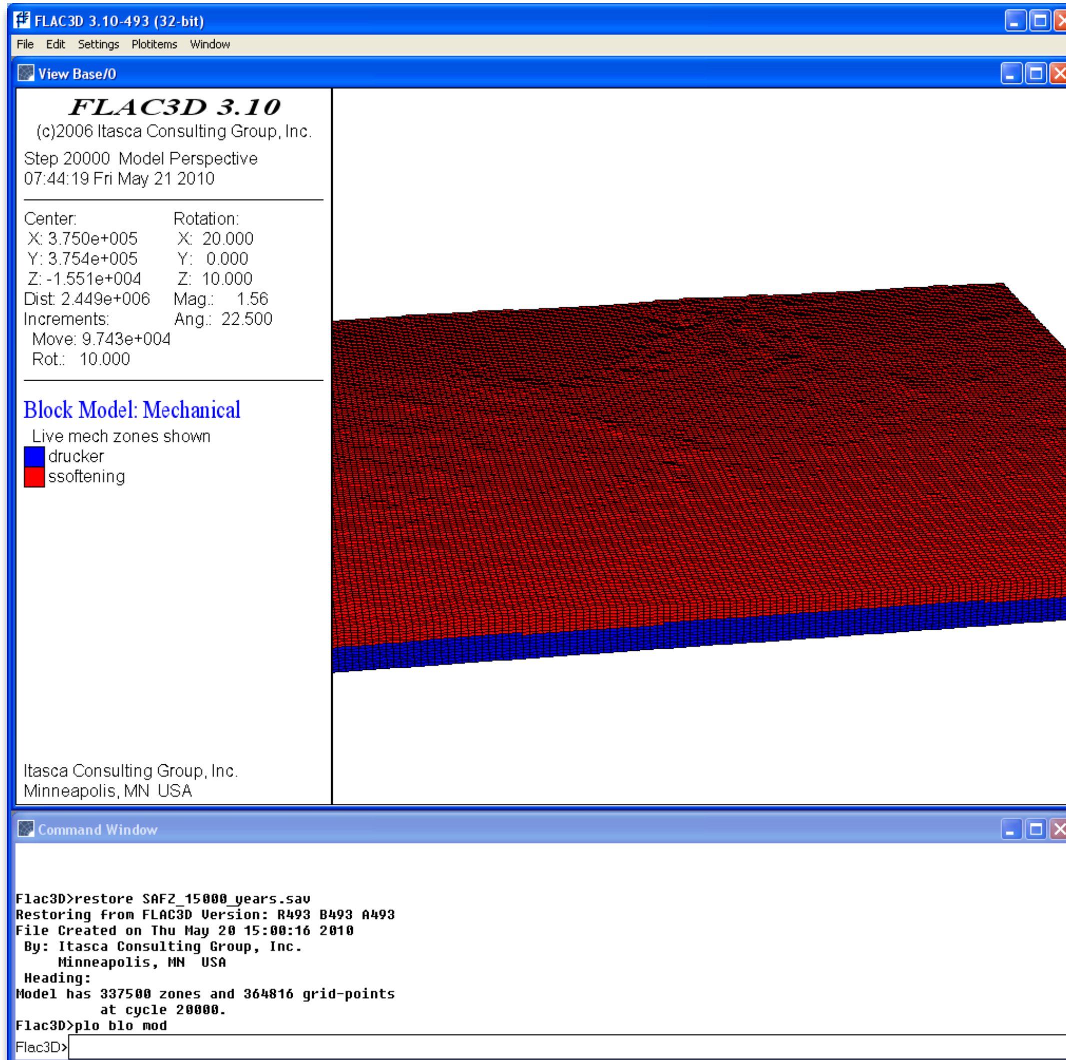
**F**ast **L**agrangian **A**nalysis of **C**ontinua in 3D
FLAC$^{3D}$
Itasca Consulting Group

Commercial finite difference code
Continuum mechanics approach
Civil Engineering applications

Dynamic, explicit, time-marching
solves for motion, stress equations

Rheological options:
plastic, elastic, viscous
Thermal model:
conduction, convection
Fluid:
Interfaces:

User defined functions ('FISH')
boundary conditions, rheology



**FLAC$^{3D}$**

Benefits:

“Easy” to use:

Geometries, rheologies, meshing

Mixed discretization

Adaptable:

User-defined functions

Scalable

Limitations:

Lagrangian grid

Limits run length without re-gridding

Non-linear rheologies

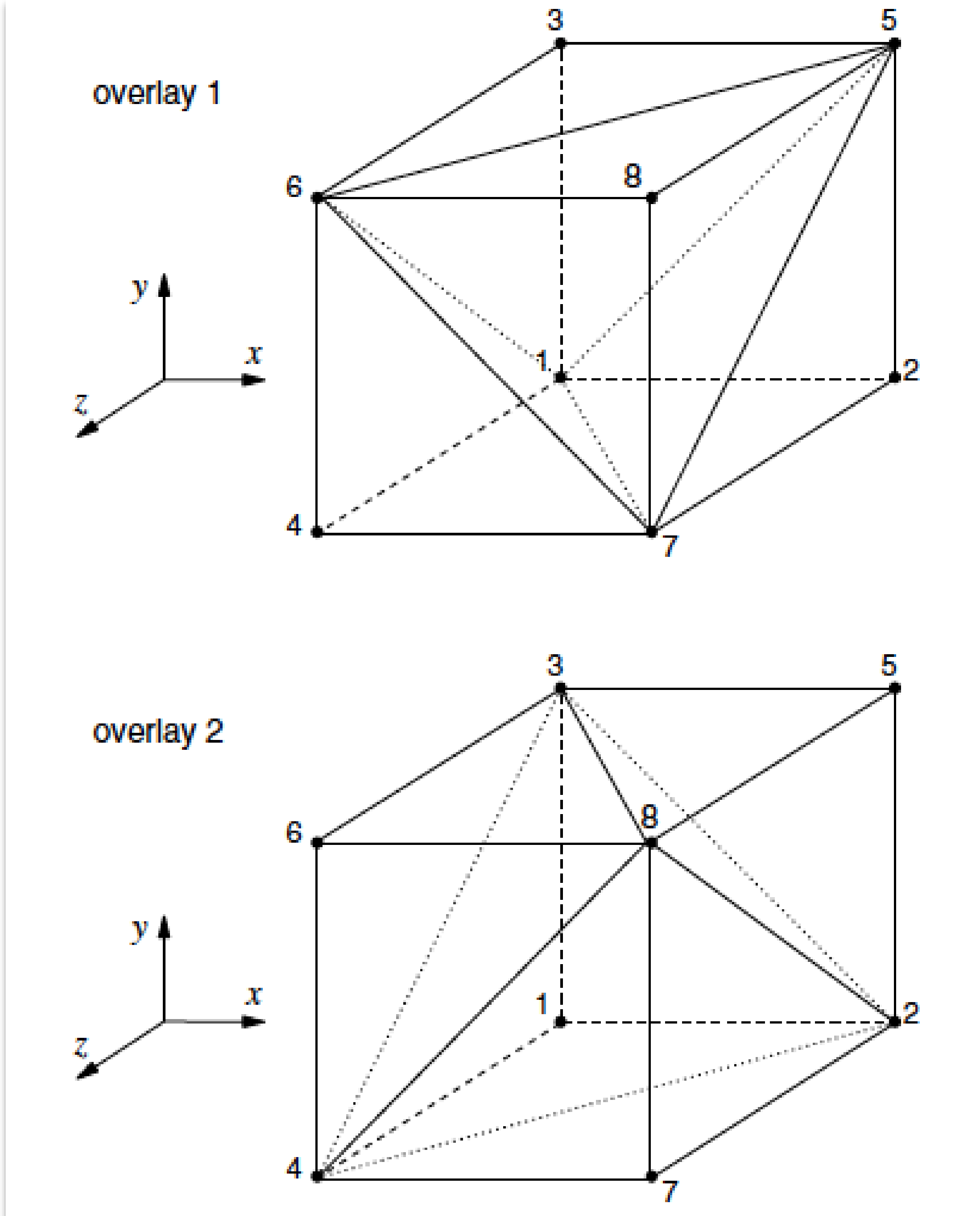
Calculation difficulties

Model size limit

Not parallel capable

Learning curve

Expensive



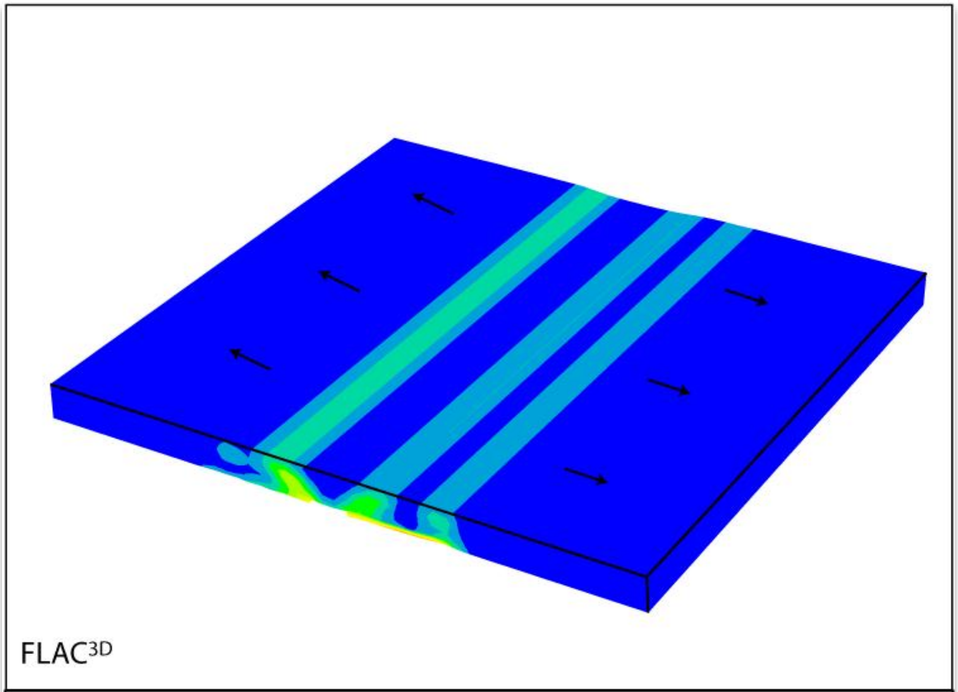
# CIG Software vrs. FLAC$^{3D}$?

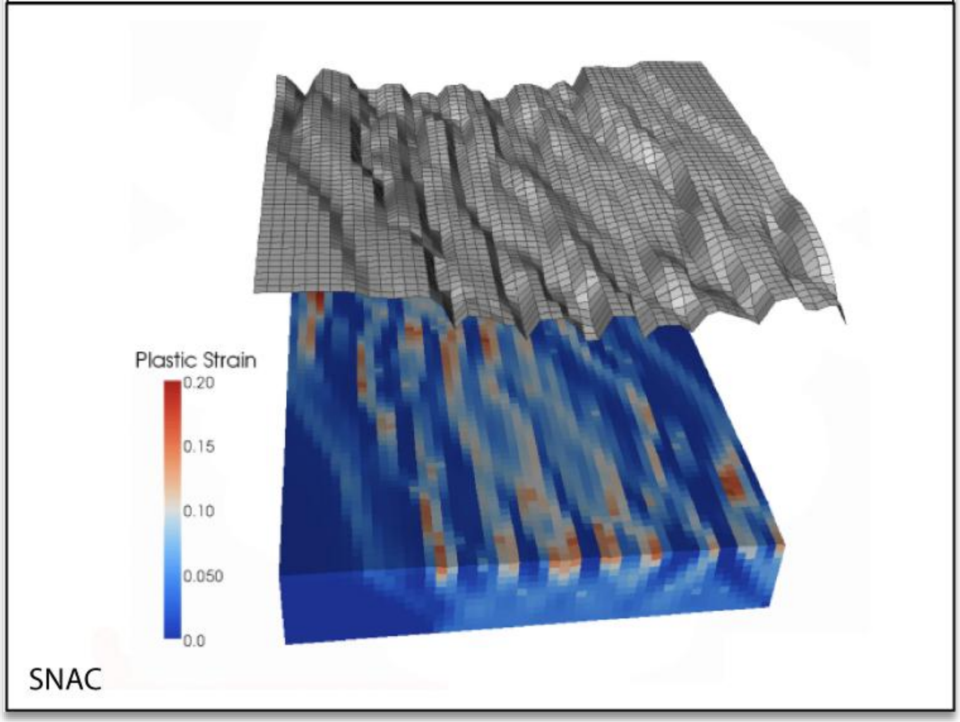
Long-term crustal dynamics

- Gale - FEM ALE
- SNAC – very similar to FLAC$^{3D}$

Short term

- Pylith



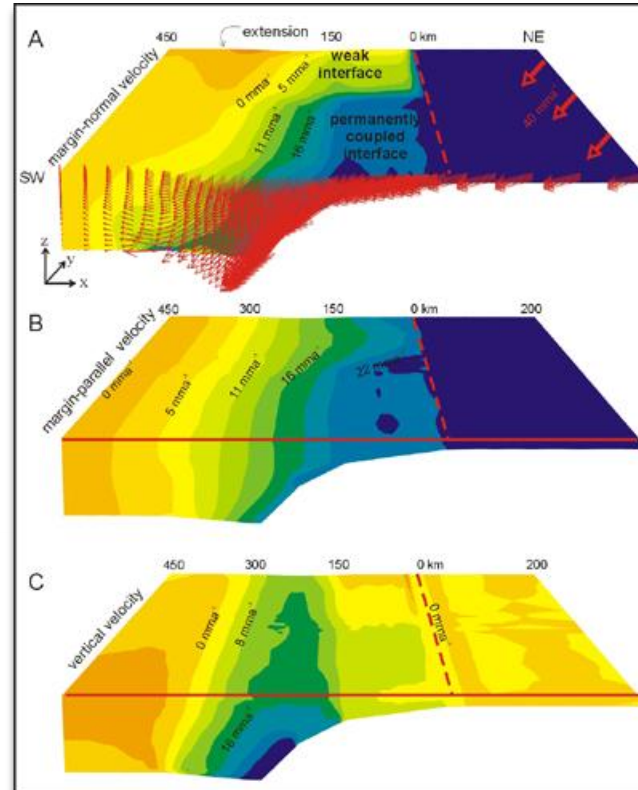
# Previous, current, and future work:

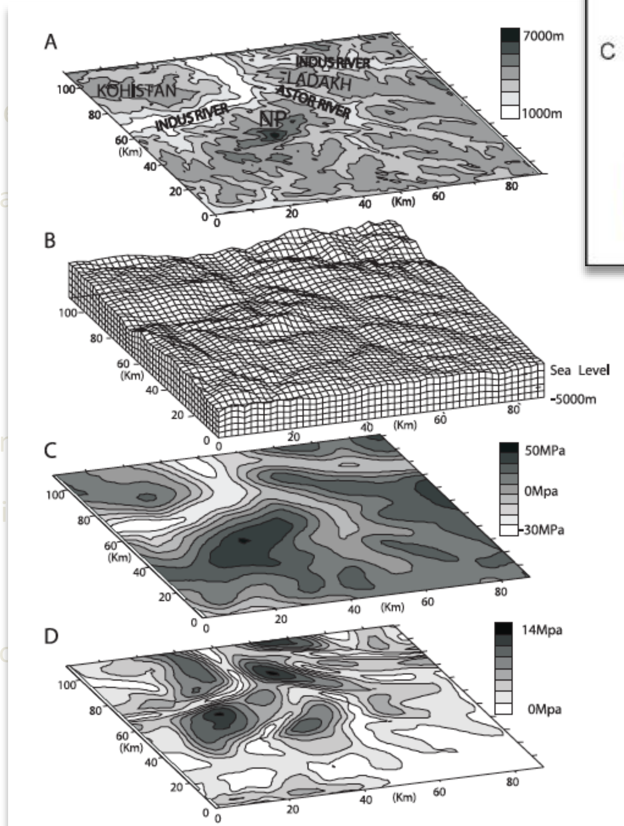
1) Himalaya (Koons et al., 2002) and New Zealand (Upton et al., 2003)
    1) Reproduction of strain localization, fast uplift, and exhumation

1) Southern Alaska (Koons et al., 2010; Hooks, 2009; Enkelmann e al., 2010)
    1) Large-scale (1000km) and loca scale (10-100km) tectonics; orogen evolution; uplift and exhumation histories

1) World topographic stresses
    1) Future project; link generatio of stresses related to topography to strain partitioni

1) Rio Grande Rift
    1) Explore driving mechanisms f the RGR



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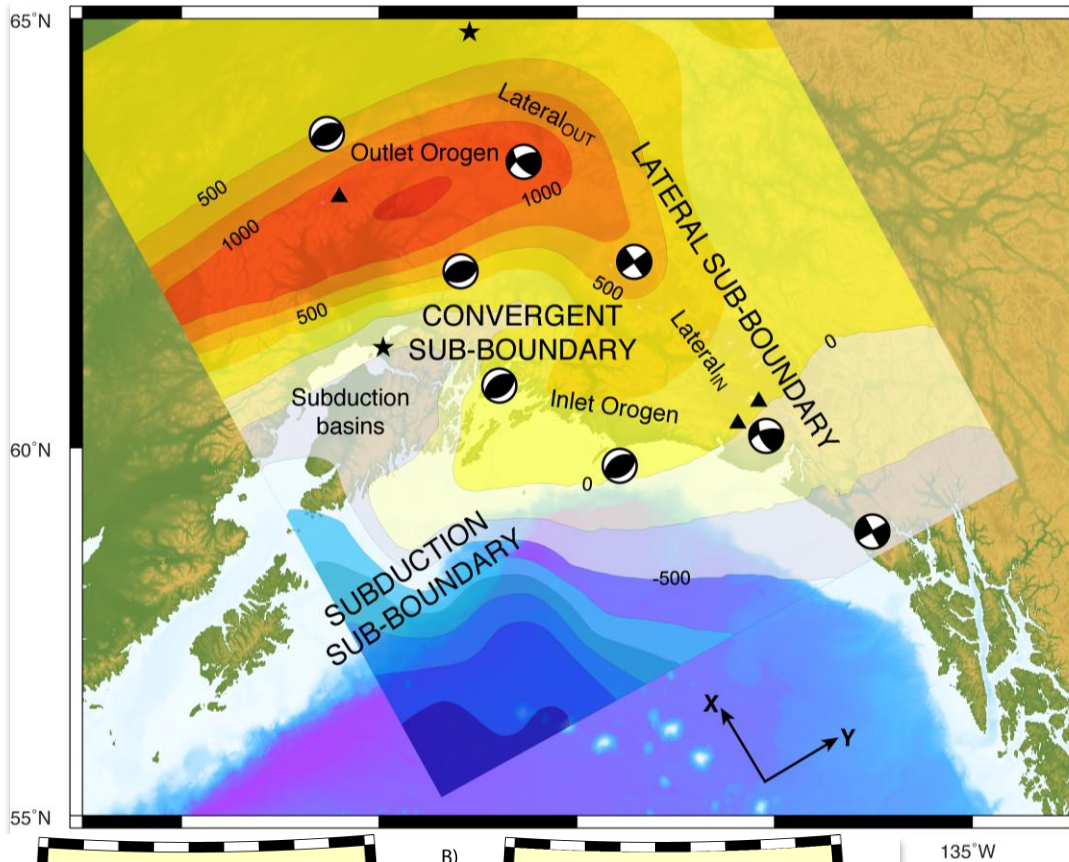


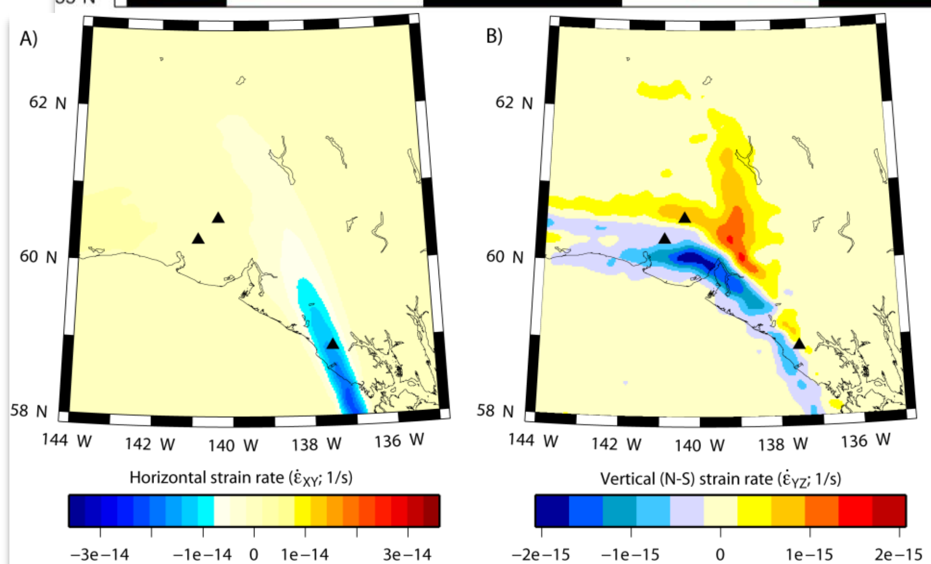

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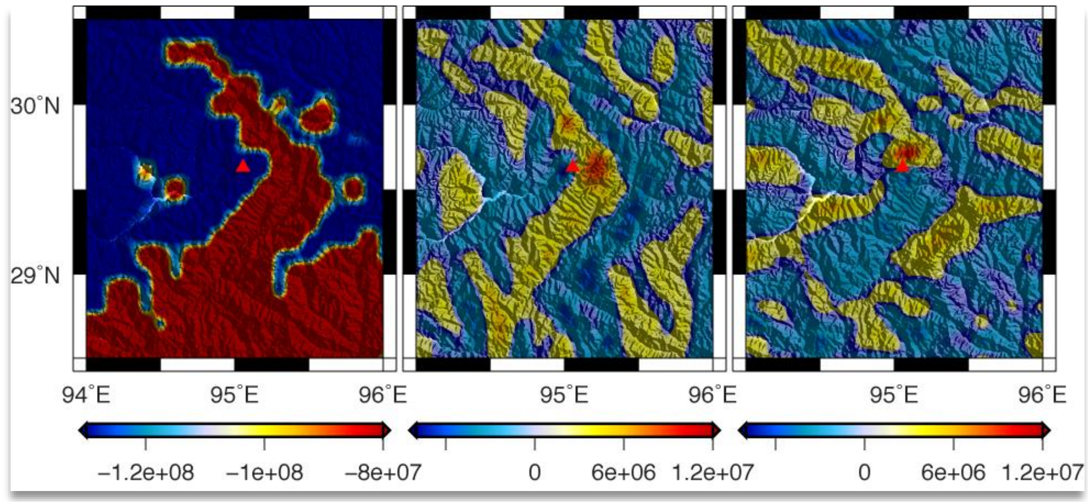


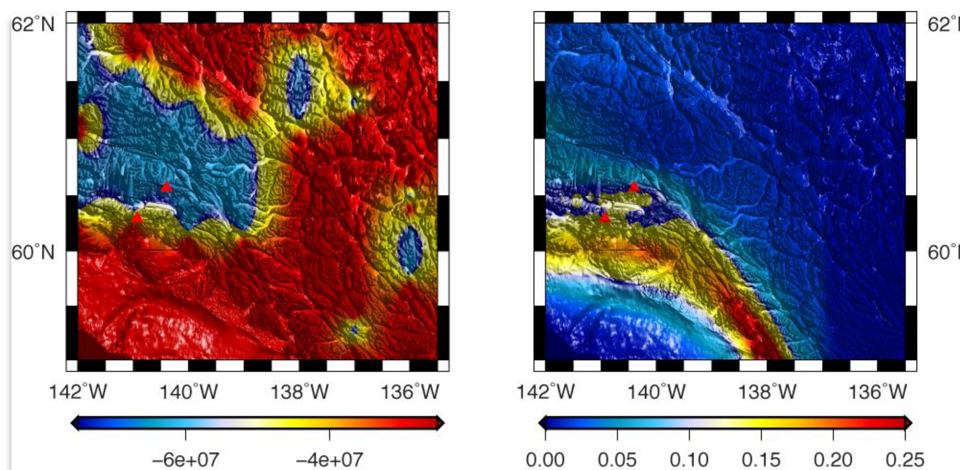

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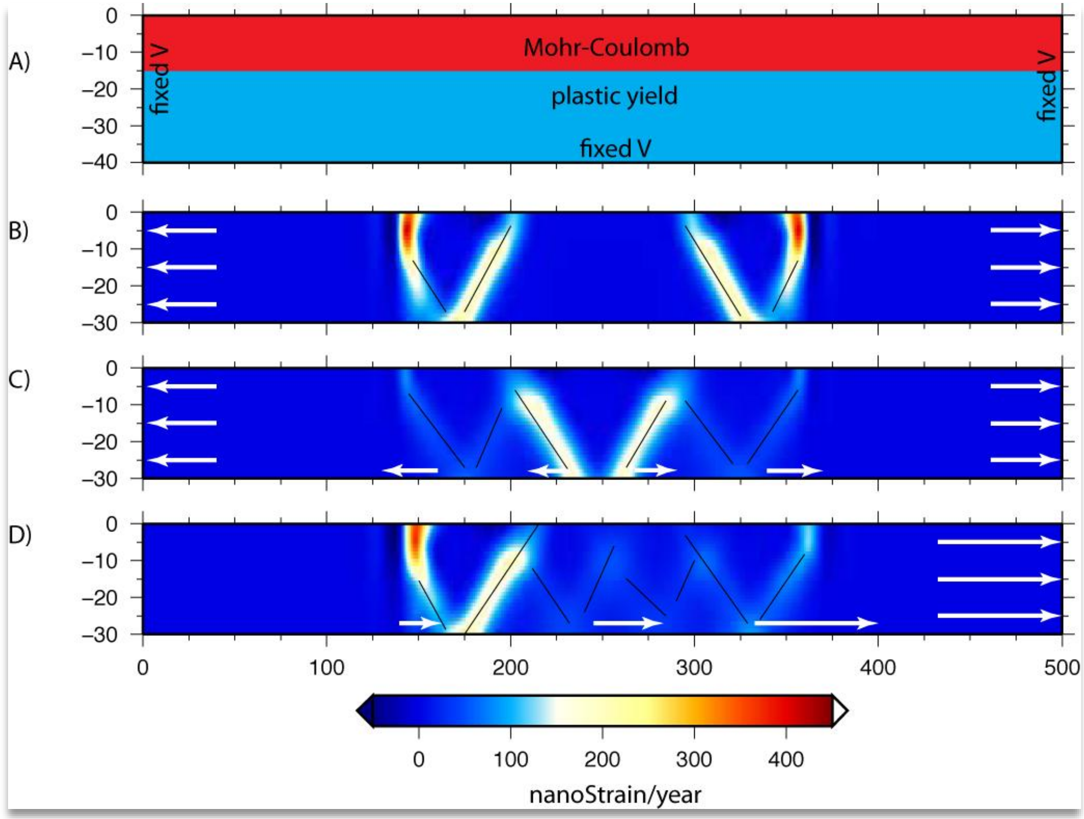
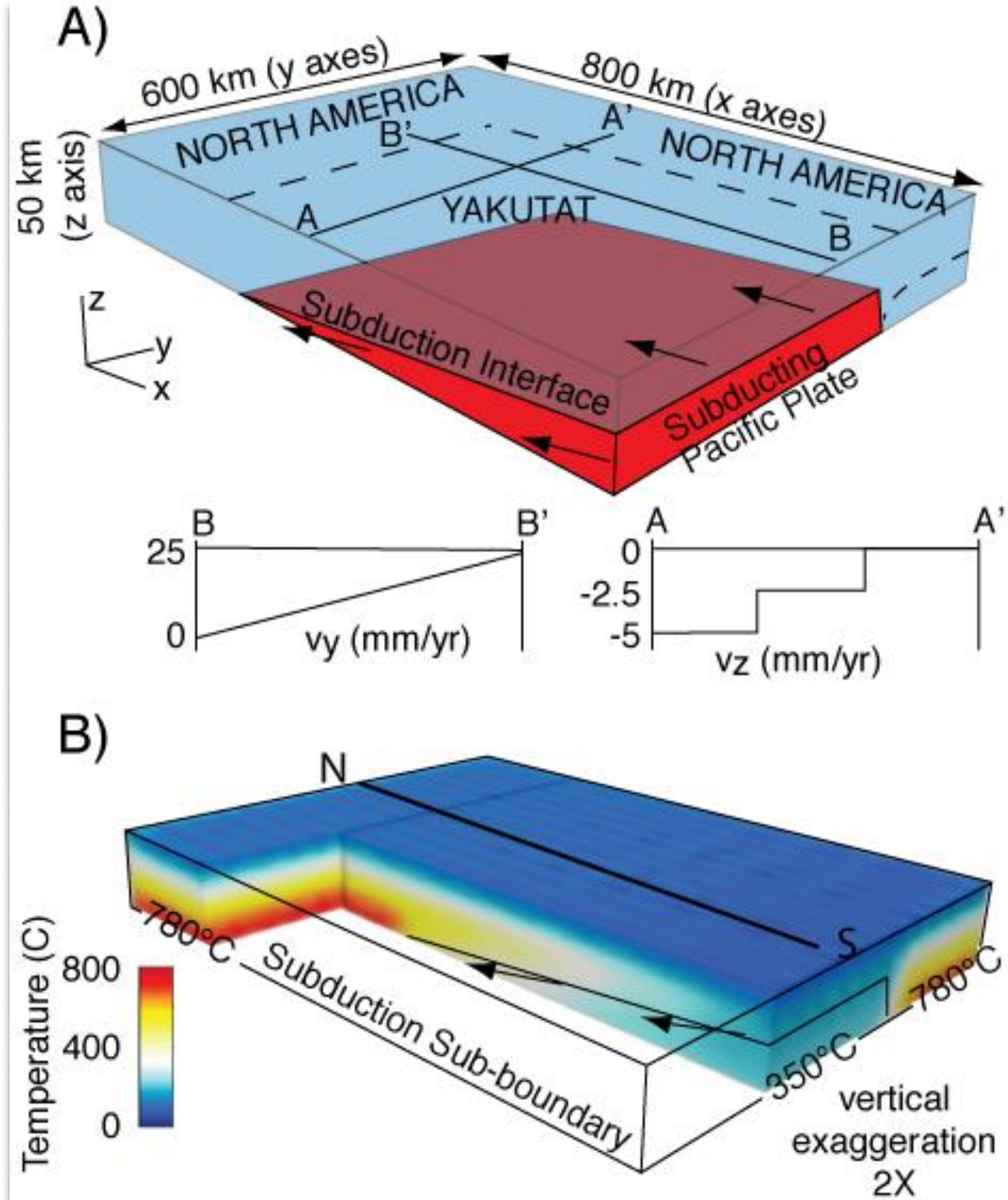


# Boundary Conditions




Koons et al., 2010

## **Boundary Conditions:**
## **Geometry**

Models are completed on two scales:

1) Plate boundary scale
2) Southern California scale

Maximize model resolution:

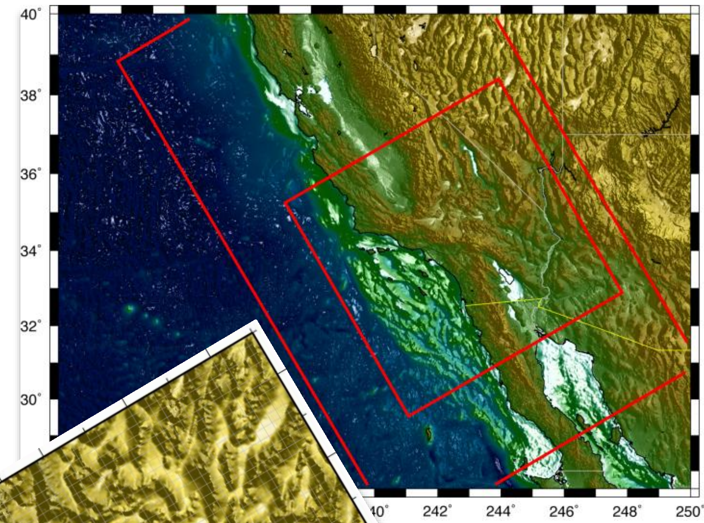
1) 10-km horizontal, 2-km vertical for plate boundary scale
2) 5-km horizontal, 2-km vertical for SC model

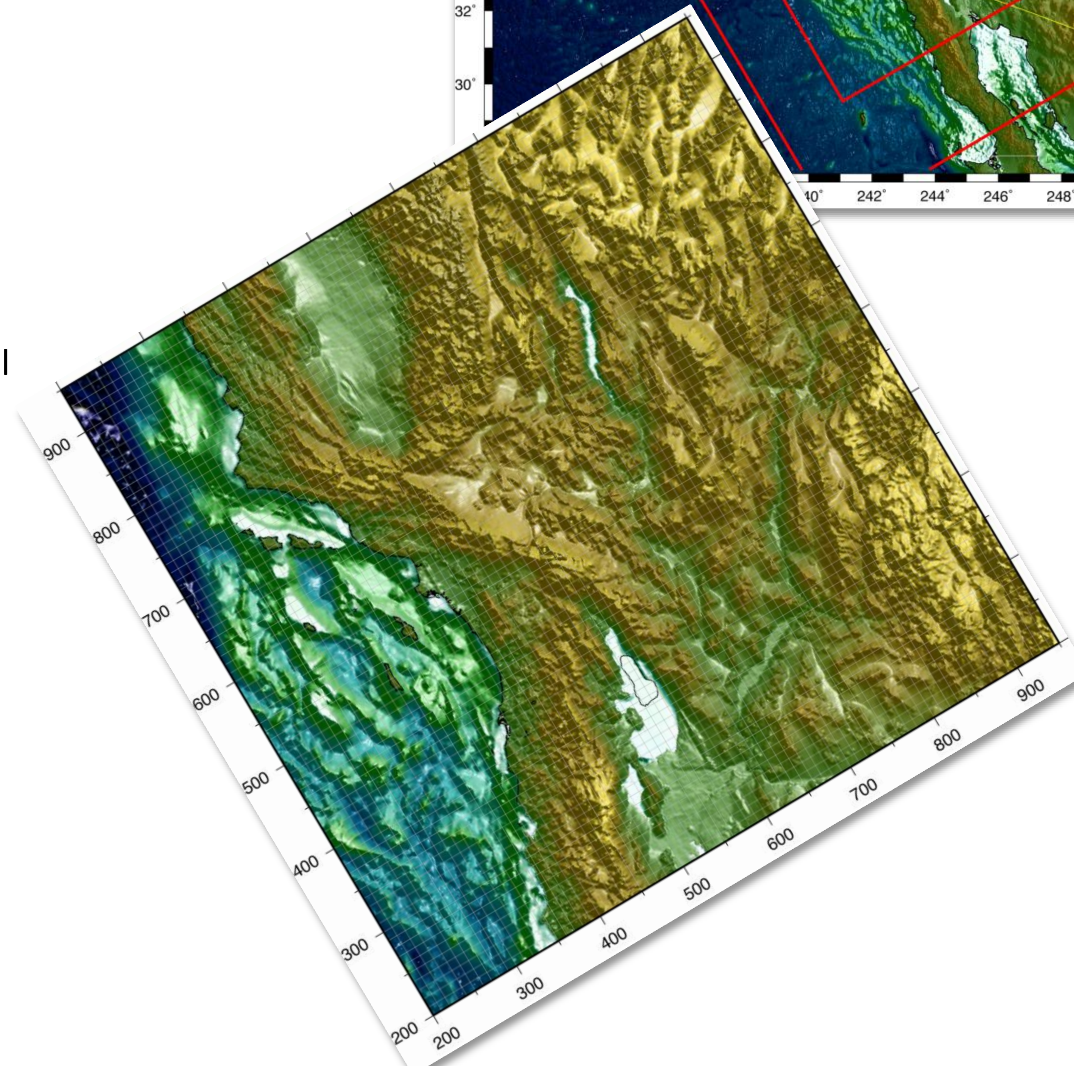
Include topographic surface

Based upon SRTM dataset

Crustal thickness is constant

This will change in future iterations



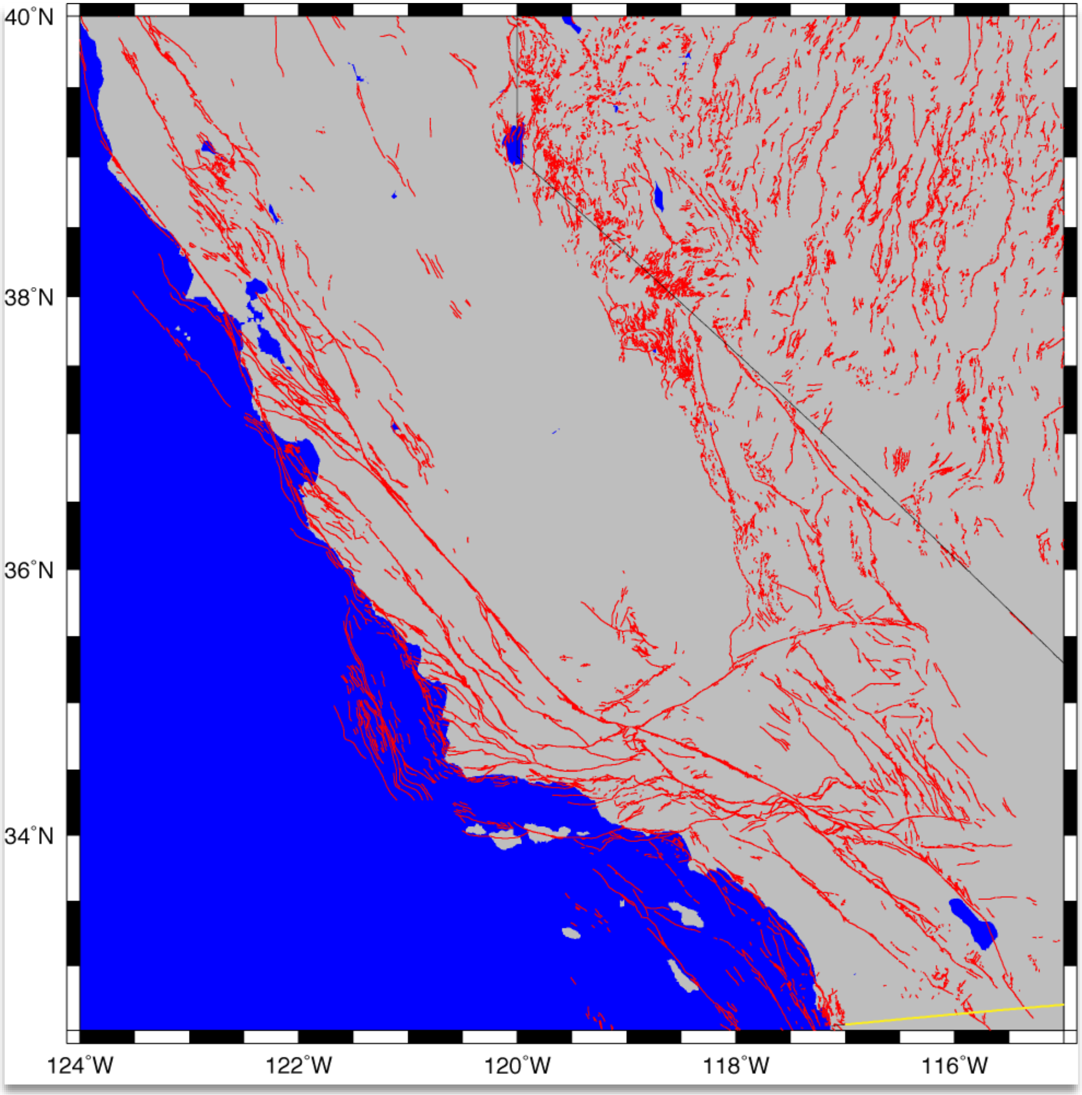
# Boundary Conditions: Geometry 2

Three ‘styles’ of model geometries are considered:

All utilize fault traces to some degree

1) ‘Block model’
   - The model geometry consists of a series of independent blocks
   - Each block can be given an individual velocity condition
2) Fault model
   - Include a rough embedded fault model
   - Fault properties can be varied spatially
3) Homogeneous model
   - Model is driven by basal drag, no internal heterogeneities
   - Strain is partitioned using a rheological weakening criteria

Preferred model: Homogeneous




USGS Quaternary Fault database

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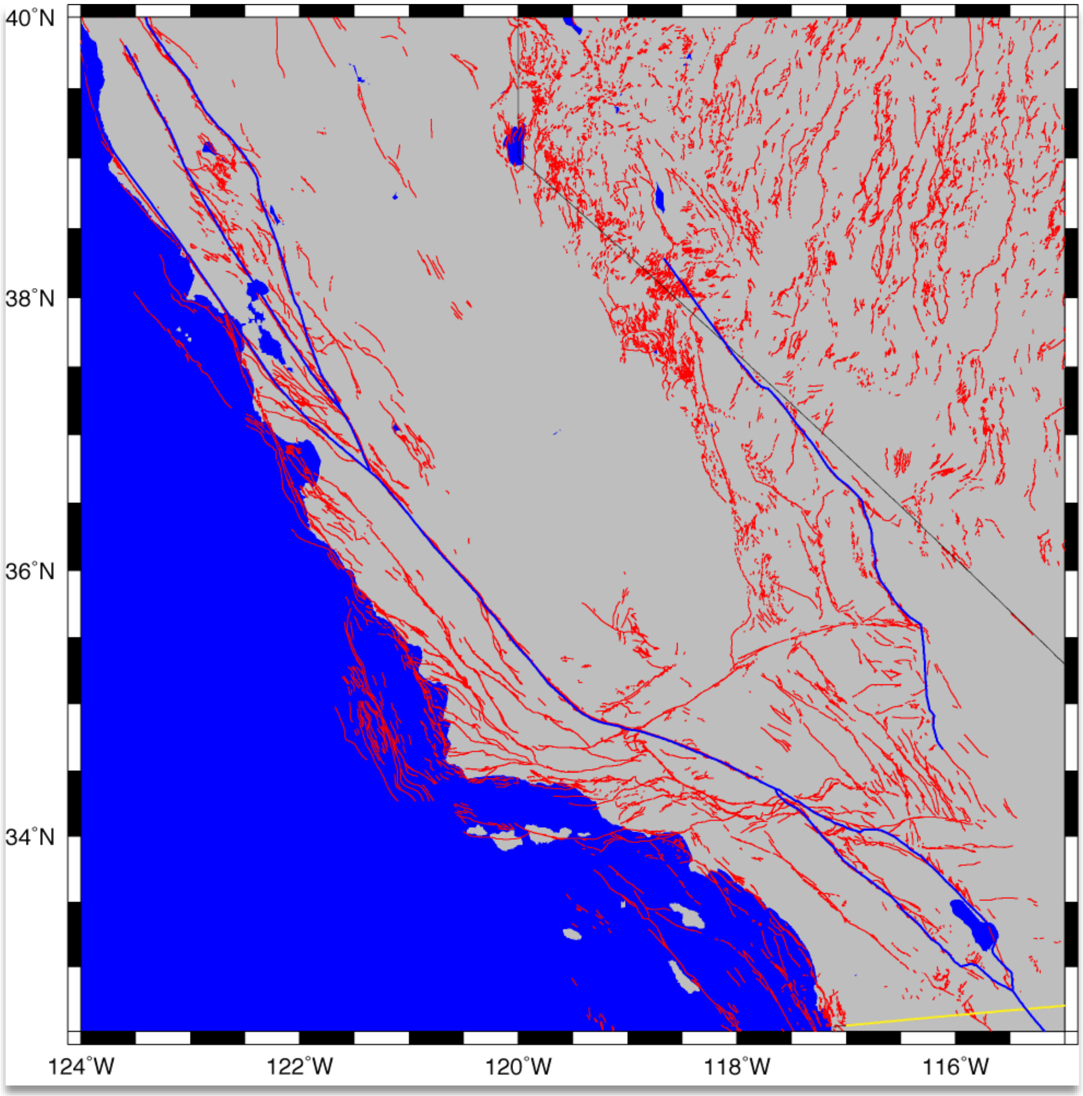

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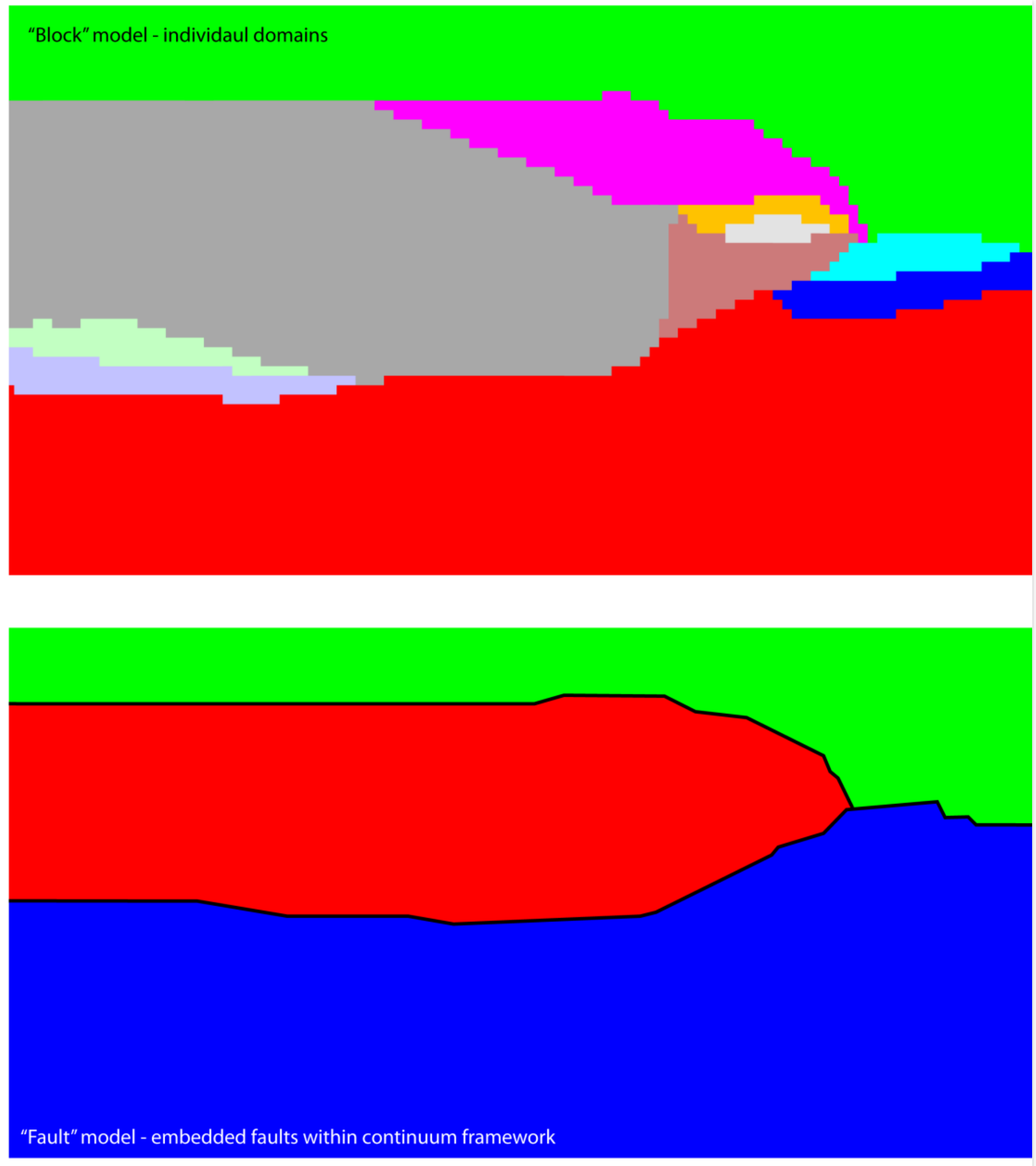


# Boundary Conditions: Mechanics

Basis of strain partitioning

Two ‘options’

1) Fixed rheology
   Doesn’t change as model evolves
2) Dynamic rheology
   Linked with strain, temperature

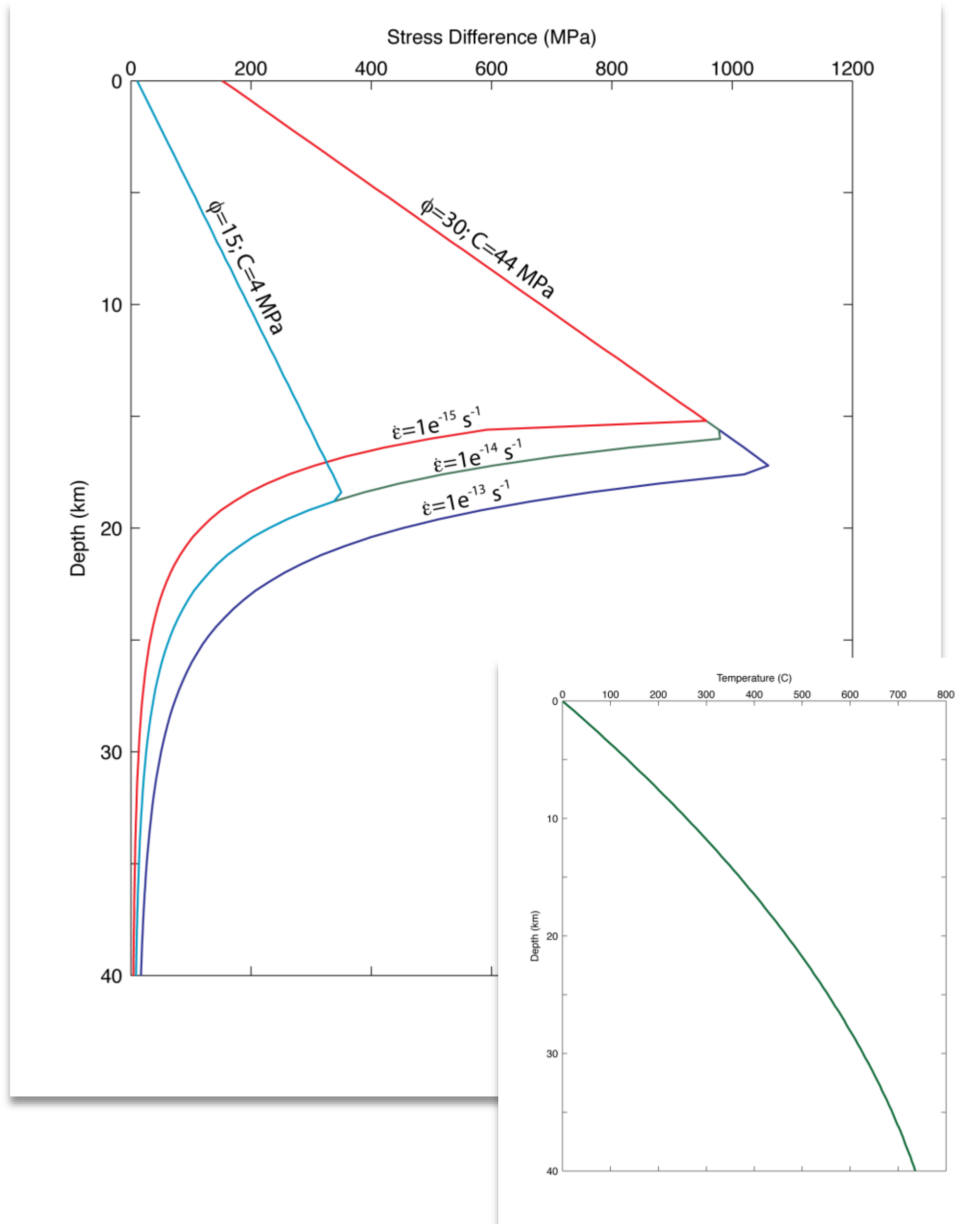
We use a simple dynamic rheology:
  Upper crust – Mohr-Coulomb (< 350 °C)
    Includes strain weakening

$$f^S = \sigma_1 - \left[\frac{1+\sin\phi}{1-\sin\phi}\right]\sigma_3 + 2C\sqrt{\frac{1+\sin\phi}{1-\sin\phi}}$$

Where $\phi_1 = 30$; $C_1 = 44$ MPa; at $\varepsilon < 5\%$
  $\phi_2 = 15$; $C_2 = 4$ MPa; at $\varepsilon > 5\%$

Lower crust - plastic yield criteria (~ 350 °C)

$$f^S = \tau - k_\phi$$



# Boundary Conditions:
# Thermo-mechanics

Model assumes a simple geothermal gradient

Thermal calculations are not explicitly solved, though they are implicit in the rheological definition (plastic yield):

Lower crust flow law (i.e. Mackwell et al., 1998):

$$k_{\phi} = \frac{1}{2}\left[\frac{\dot{\varepsilon}}{A} e^{E/RT}\right]^{n}$$

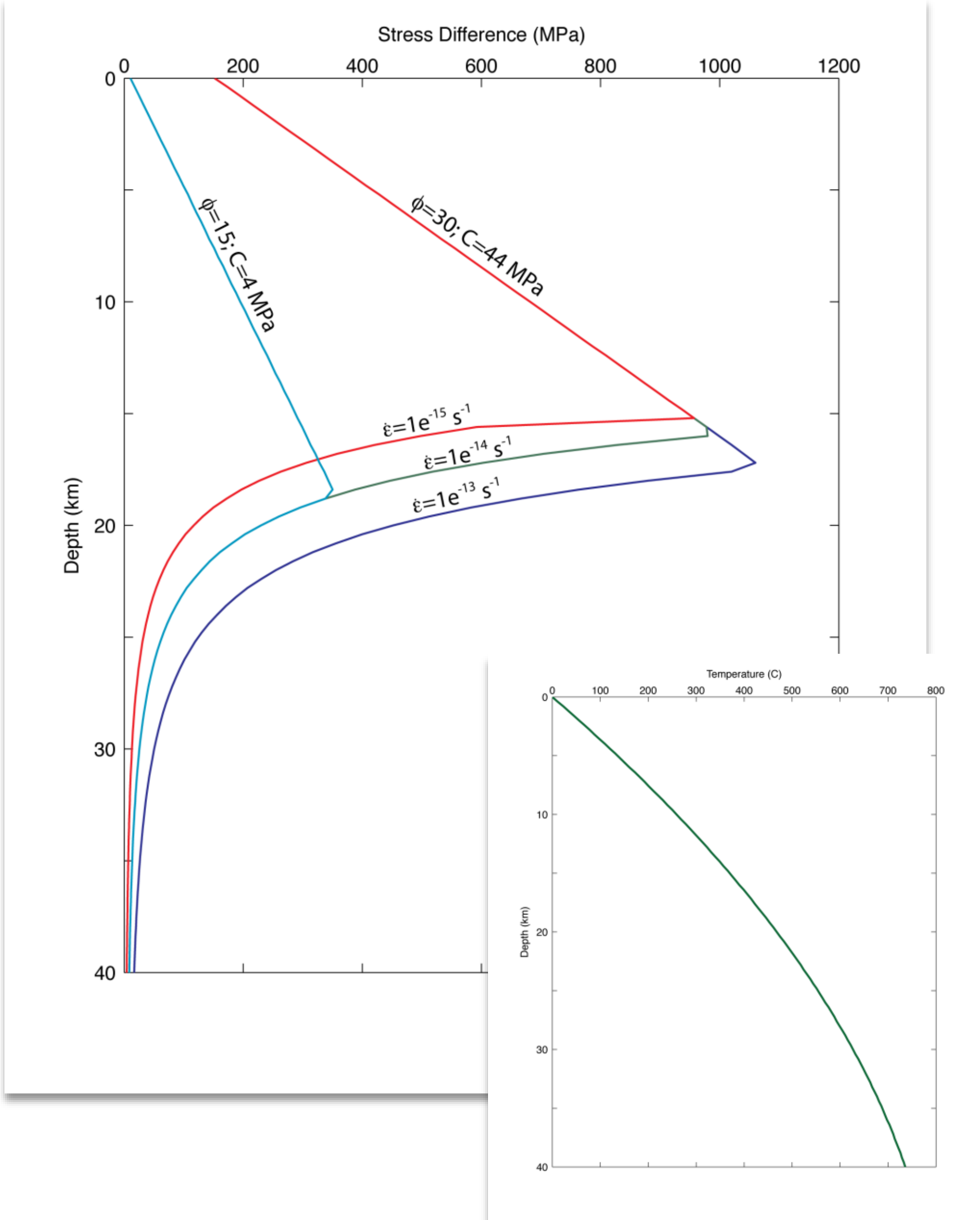
$A = 2e^{-4}\ Pa^{-1}s^{-1}$

$E = 260\ Jmol^{-1}$

$n = 0.2941$

T and $\dot{\varepsilon}$ come from the model results

Future models will include a thermal component!



# Boundary Conditions: Driving forces

Need to drive the deformation within the model

Options:

1) Use available dataset
   1) SCEC, PBO, etc
   2) Could include anthropogenic and/or seismic velocities
2) Use a subset/average velocity
   1) Avoids errant estimates
   2) Essentially a spatial average (can be constant or gradational)

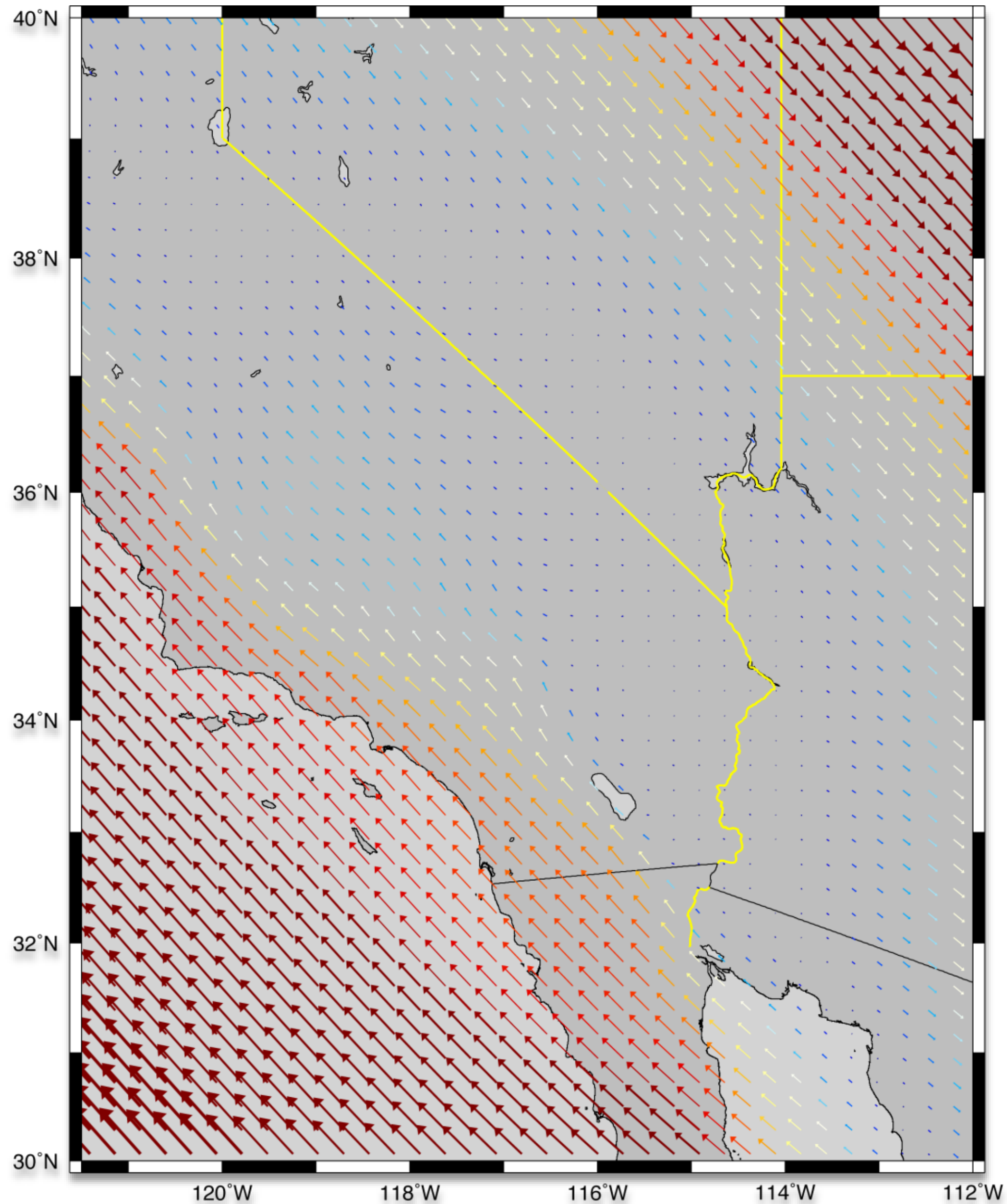
Preferred model:

Applies average/representative SCEC geodetic velocity as a basal drag

To avoid model boundary conditions we fix model edges at derived velocities

Surface free to deform

*No isostatic compensation*
base of model fixed at Vz = 0




SCEC v3 dataset

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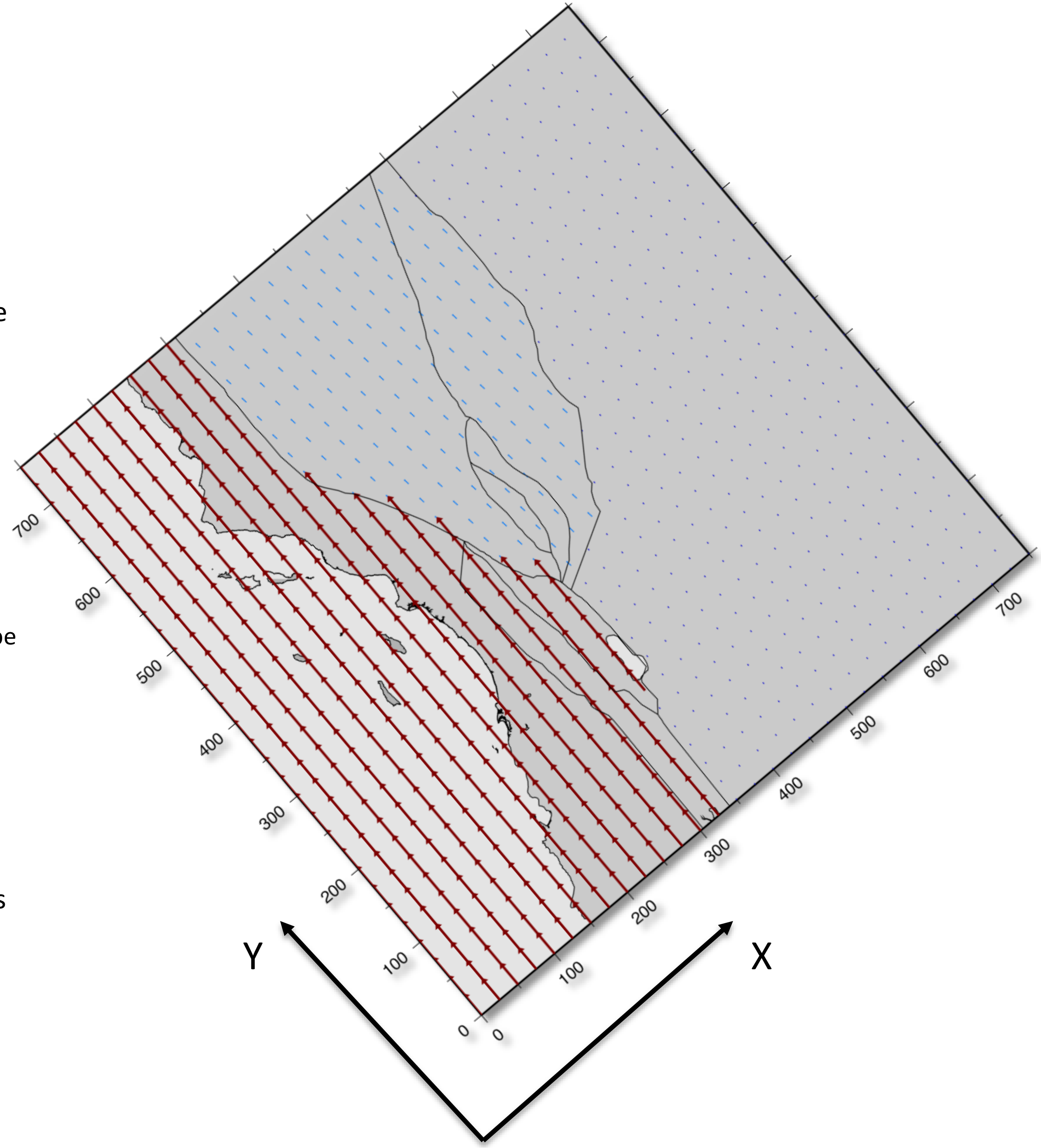
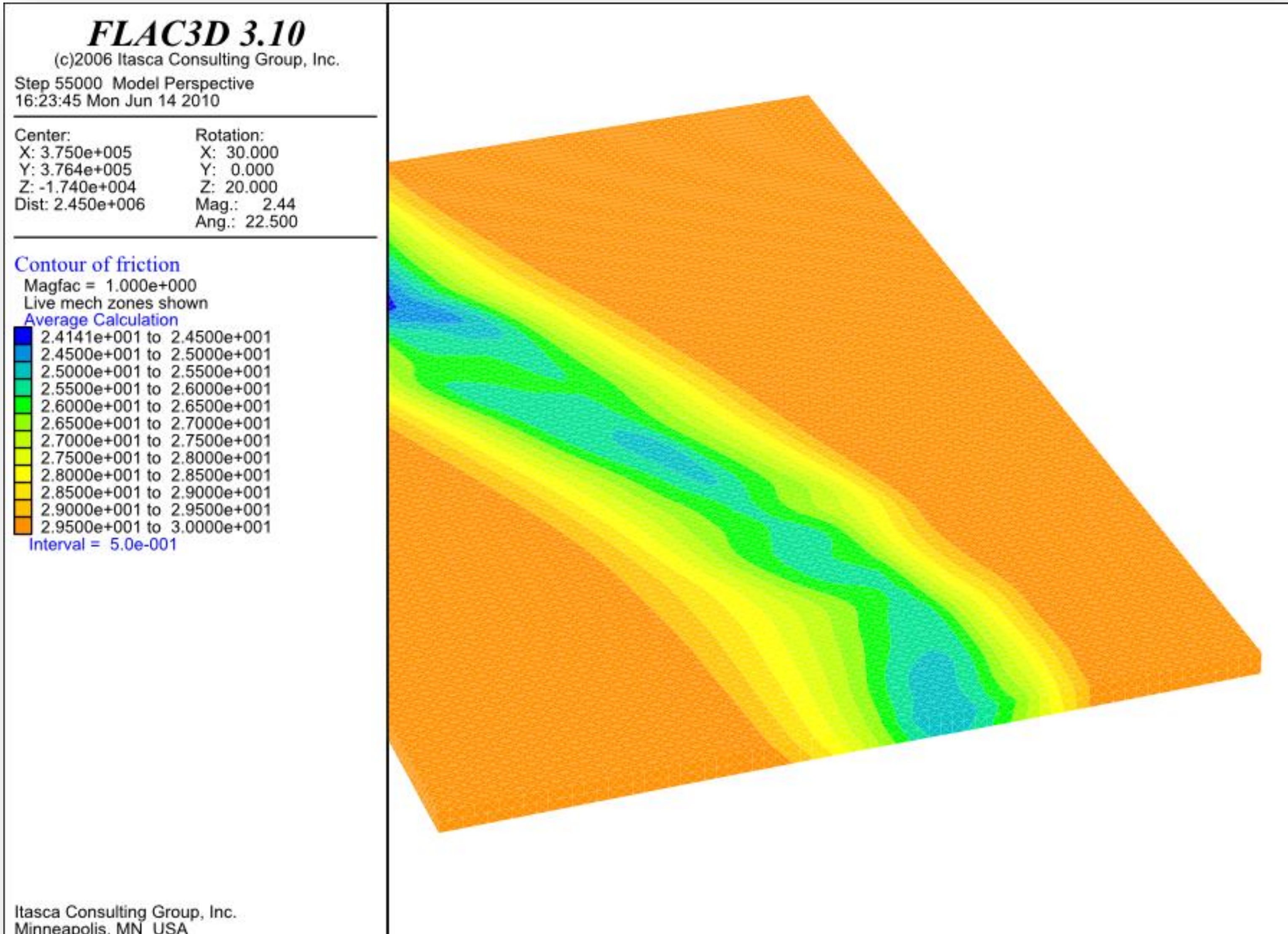


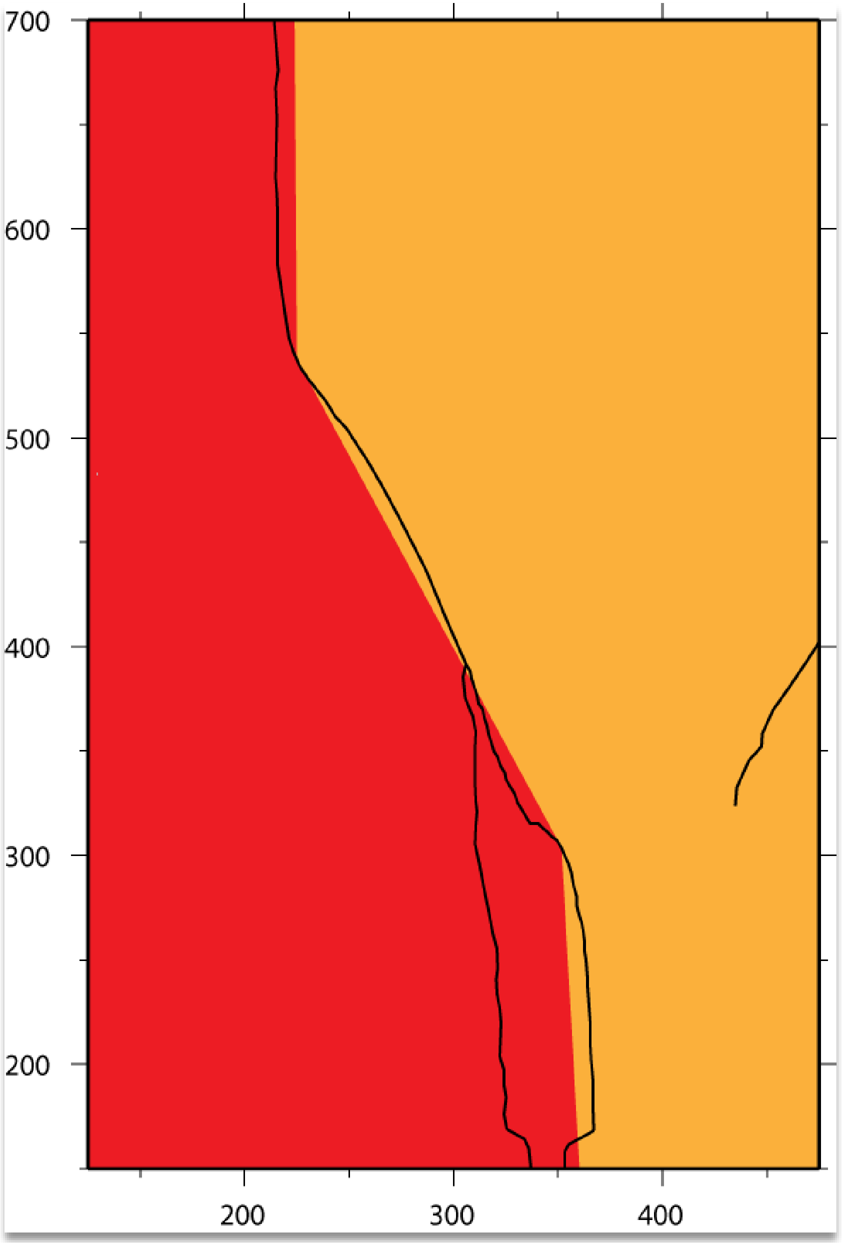
# Results


FLAC3D 3.10
(c)2006 Itasca Consulting Group, Inc.
Step 55000 Model Perspective
16:23:45 Mon Jun 14 2010
Center:
X: 3.750e+005
Y: 3.764e+005
Z: -1.740e+004
Dist: 2.450e+006
Rotation:
X: 30.000
Y: 0.000
Z: 20.000
Mag.: 2.44
Ang.: 22.500
Contour of friction
Magfac = 1.000e+000
Live mech zones shown
Average Calculation
2.4141e+001 to 2.4500e+001
2.4500e+001 to 2.5000e+001
2.5000e+001 to 2.5500e+001
2.5500e+001 to 2.6000e+001
2.6000e+001 to 2.6500e+001
2.6500e+001 to 2.7000e+001
2.7000e+001 to 2.7500e+001
2.7500e+001 to 2.8000e+001
2.8000e+001 to 2.8500e+001
2.8500e+001 to 2.9000e+001
2.9000e+001 to 2.9500e+001
2.9500e+001 to 3.0000e+001
Interval = 5.0e-001
Itasca Consulting Group, Inc.
Minneapolis, MN USA

## Generic Model

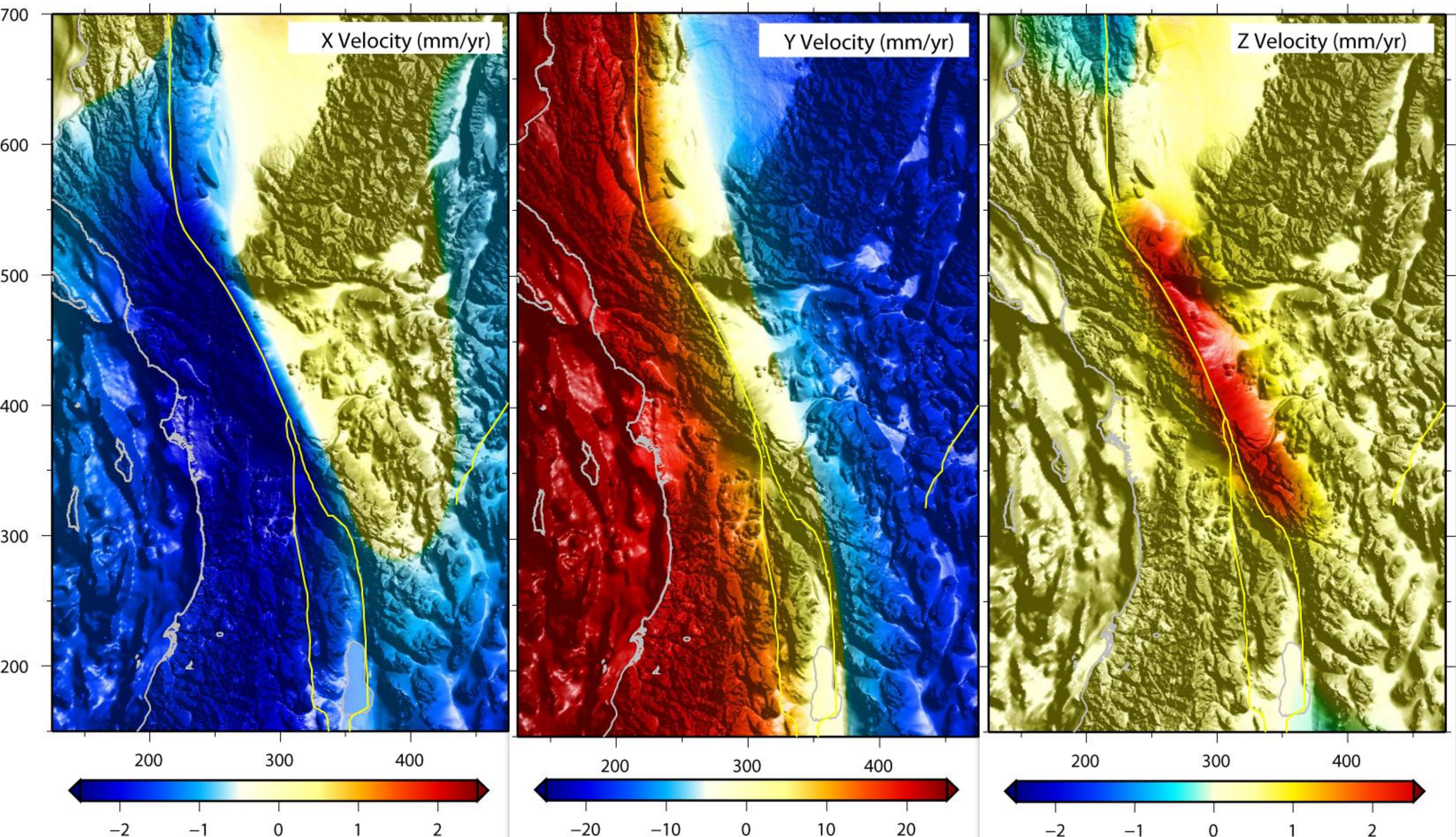
Simple straight lines depicting SAFS

Reproduces basic/characteristic patterns



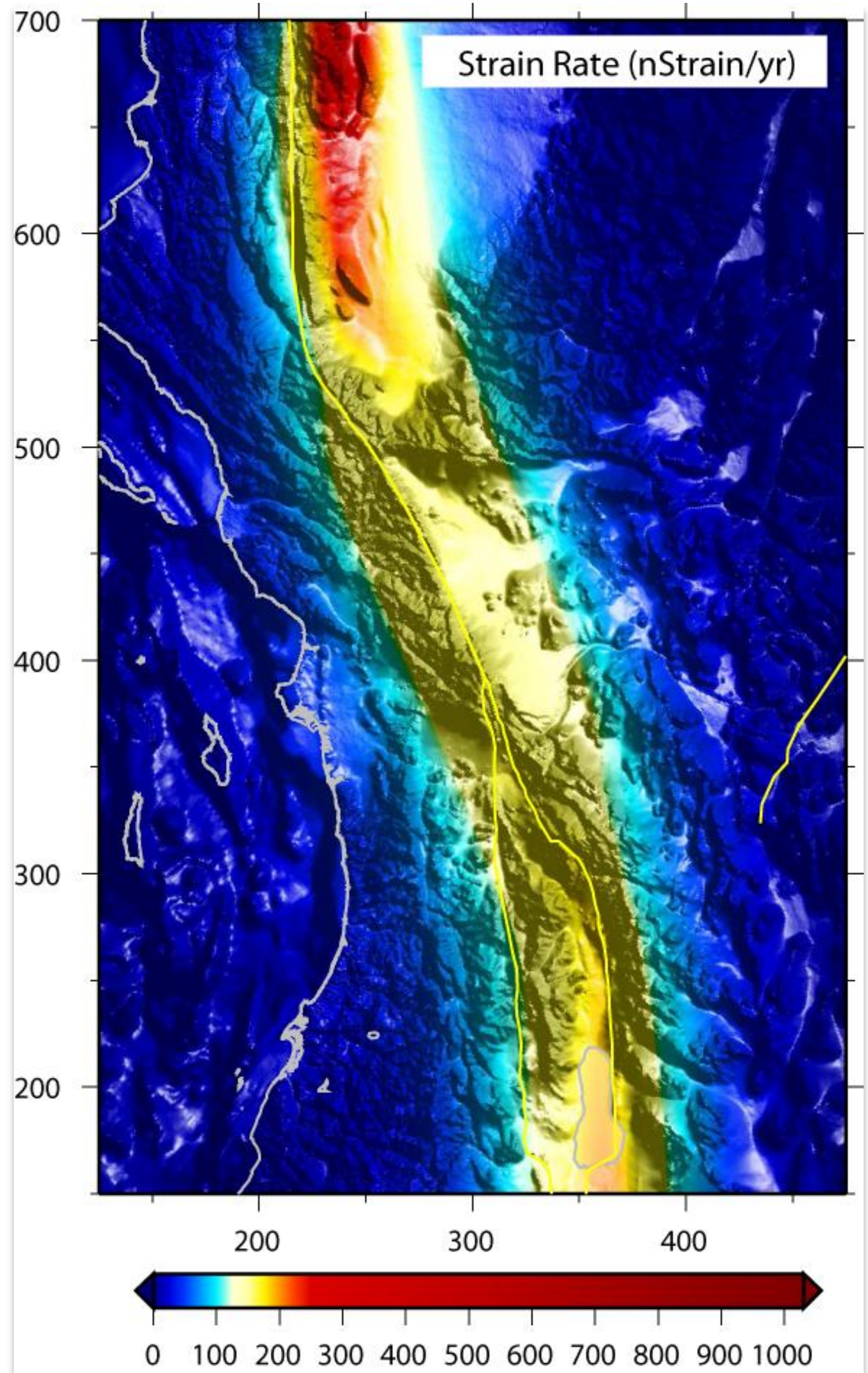
# Velocity Results

## Generic model



**Strain Results**
**2nd invariant**

3D total shear strain (nStrain/year)
(maximum - ~ 2000 nStrain/yr)

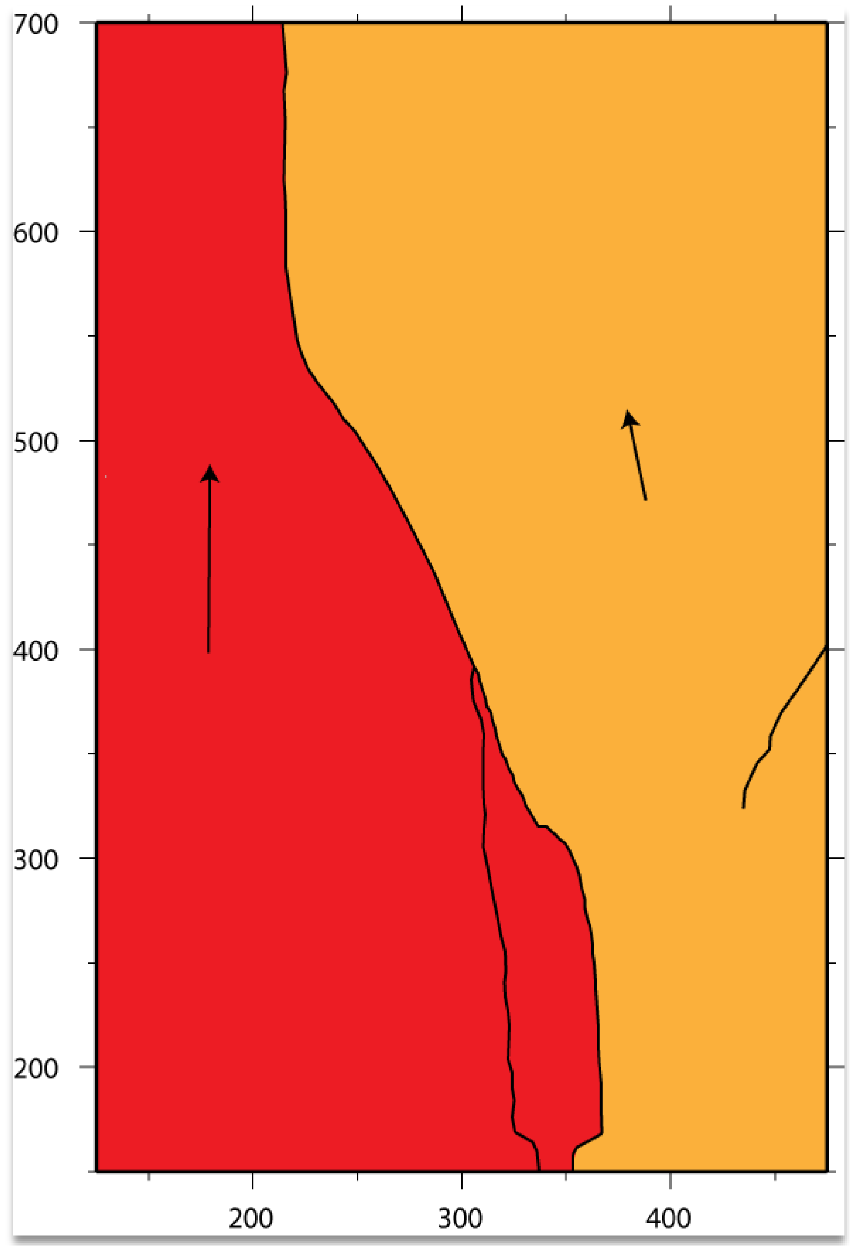


## Favored Model

Velocity boundary conditions take into account the SAFS

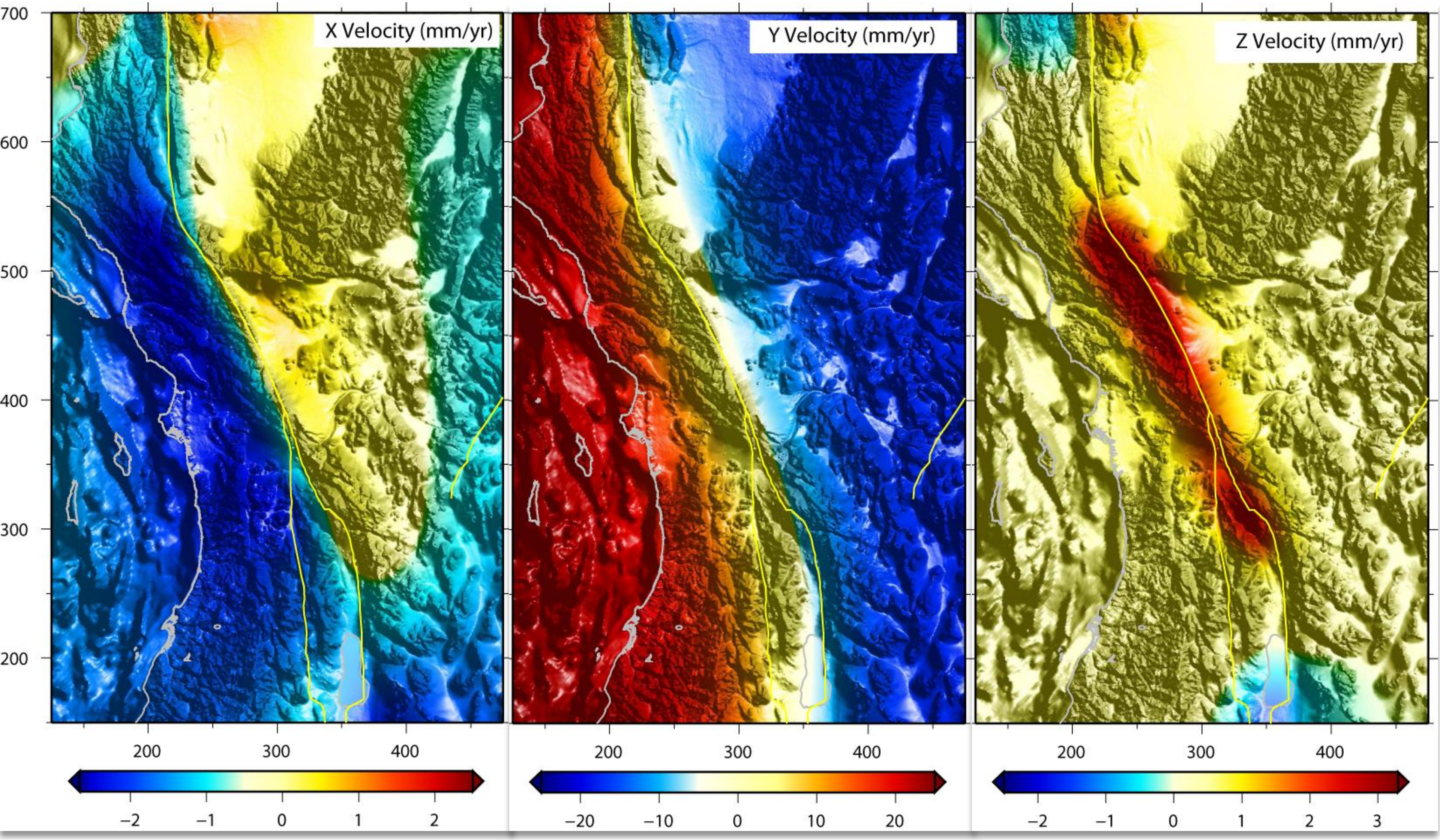
Discontinuity across the fault

Reproduces basic/characteristic patterns with a more realistic geometry



# Velocity Results

## Preferred model



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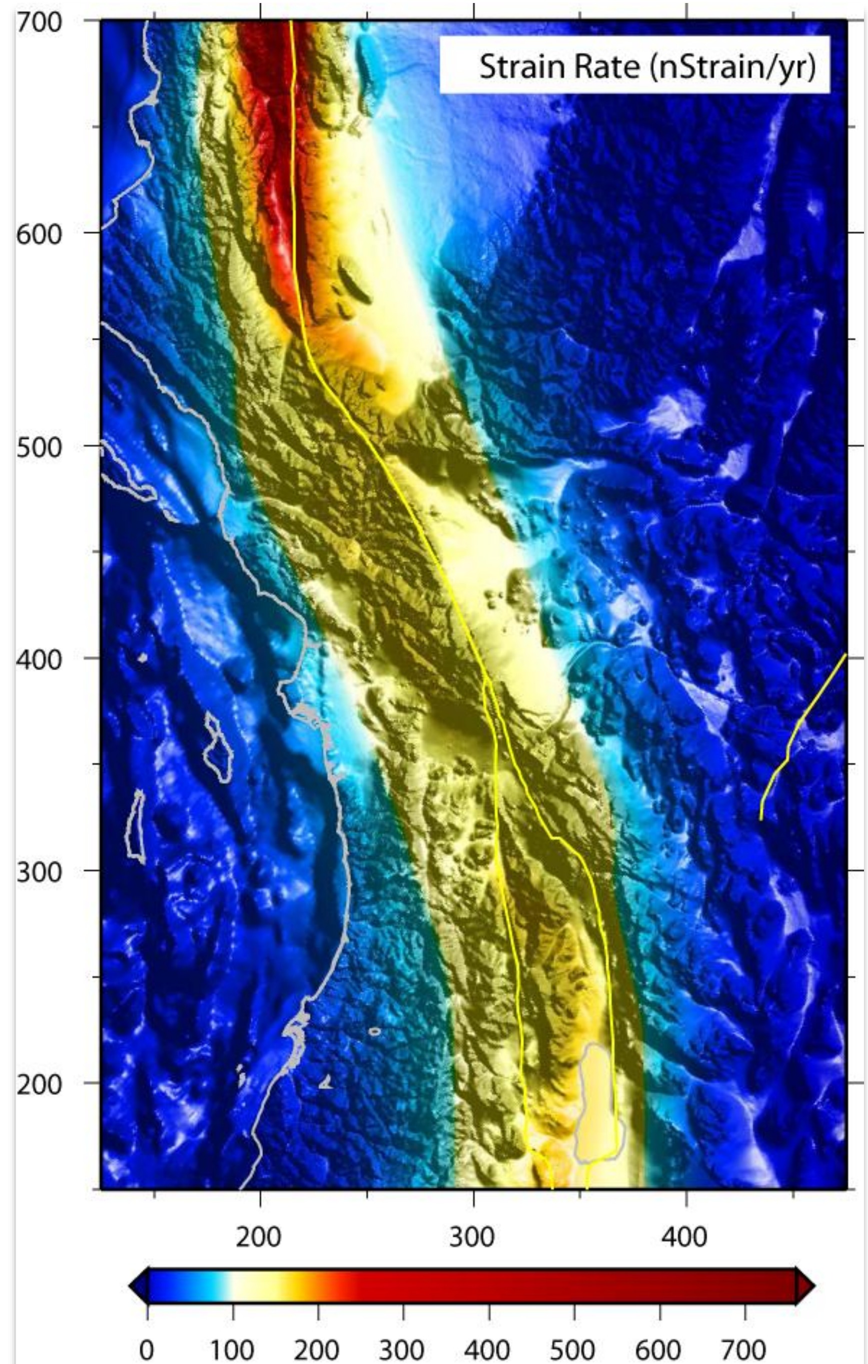


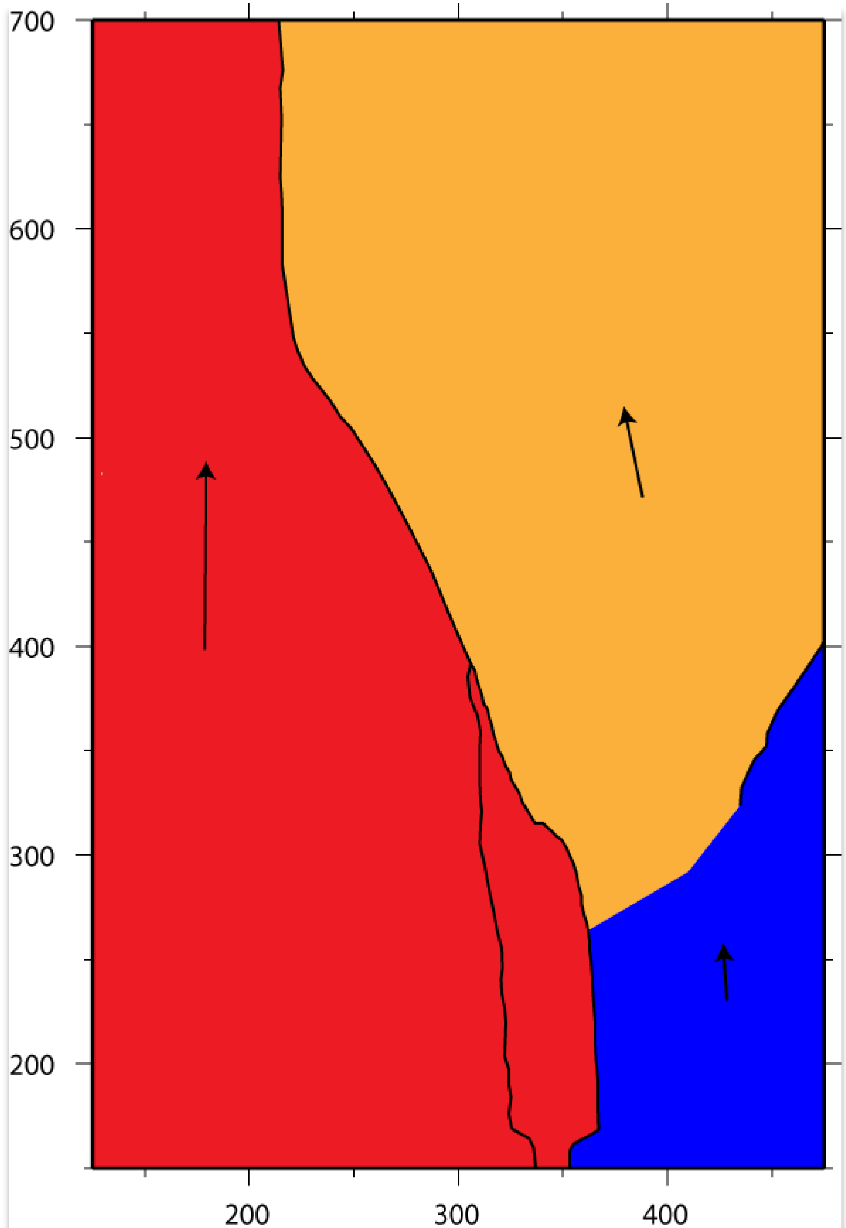
# “3-Block” Model

Discontinuities in velocity conditions across SAFS and Death Valley Fault system

3 “Blocks”

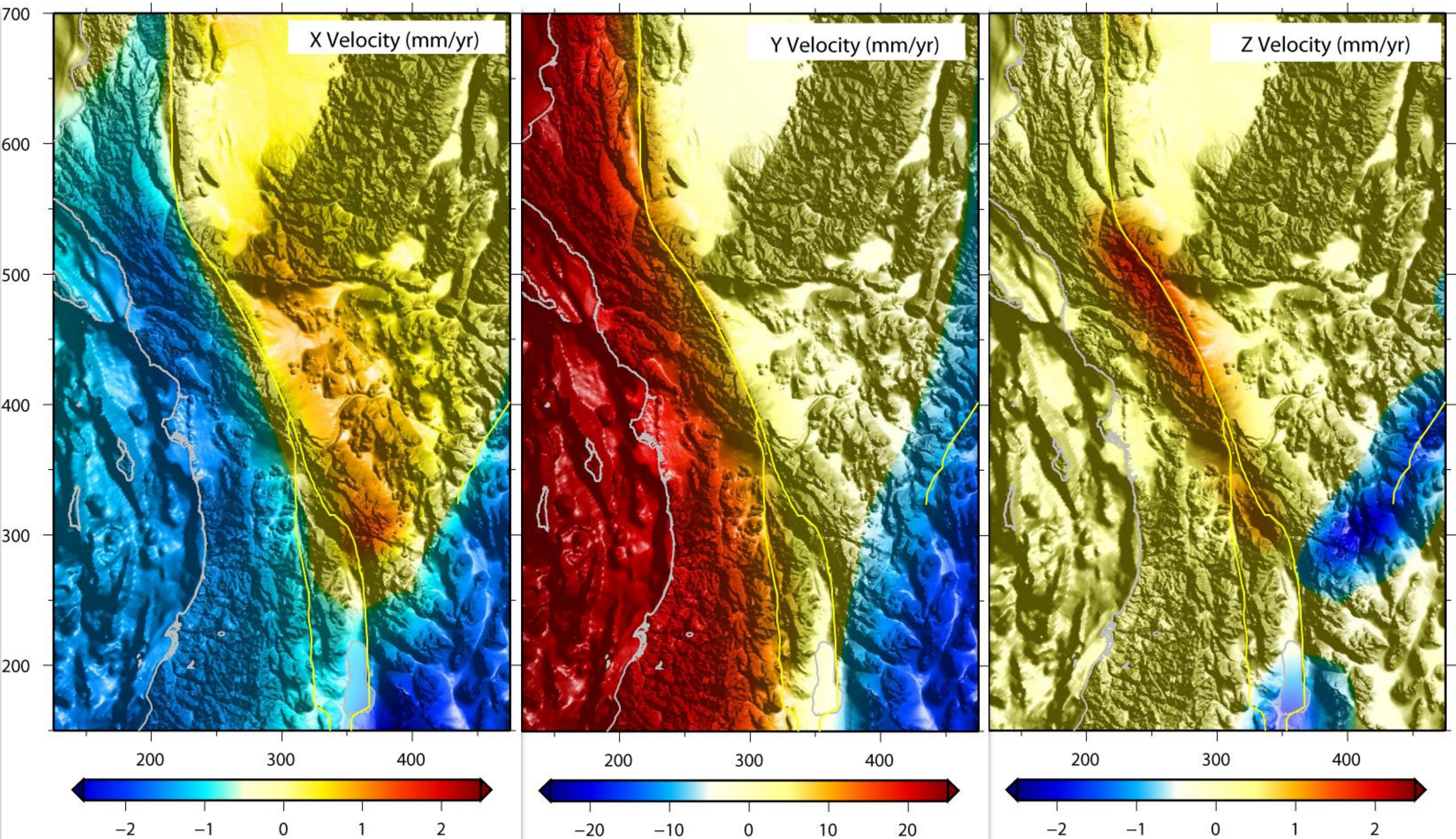
Reproduces basic/characteristic patterns

Produces some possibly anomalous results



**Velocity Results**

**"3 Block" model**



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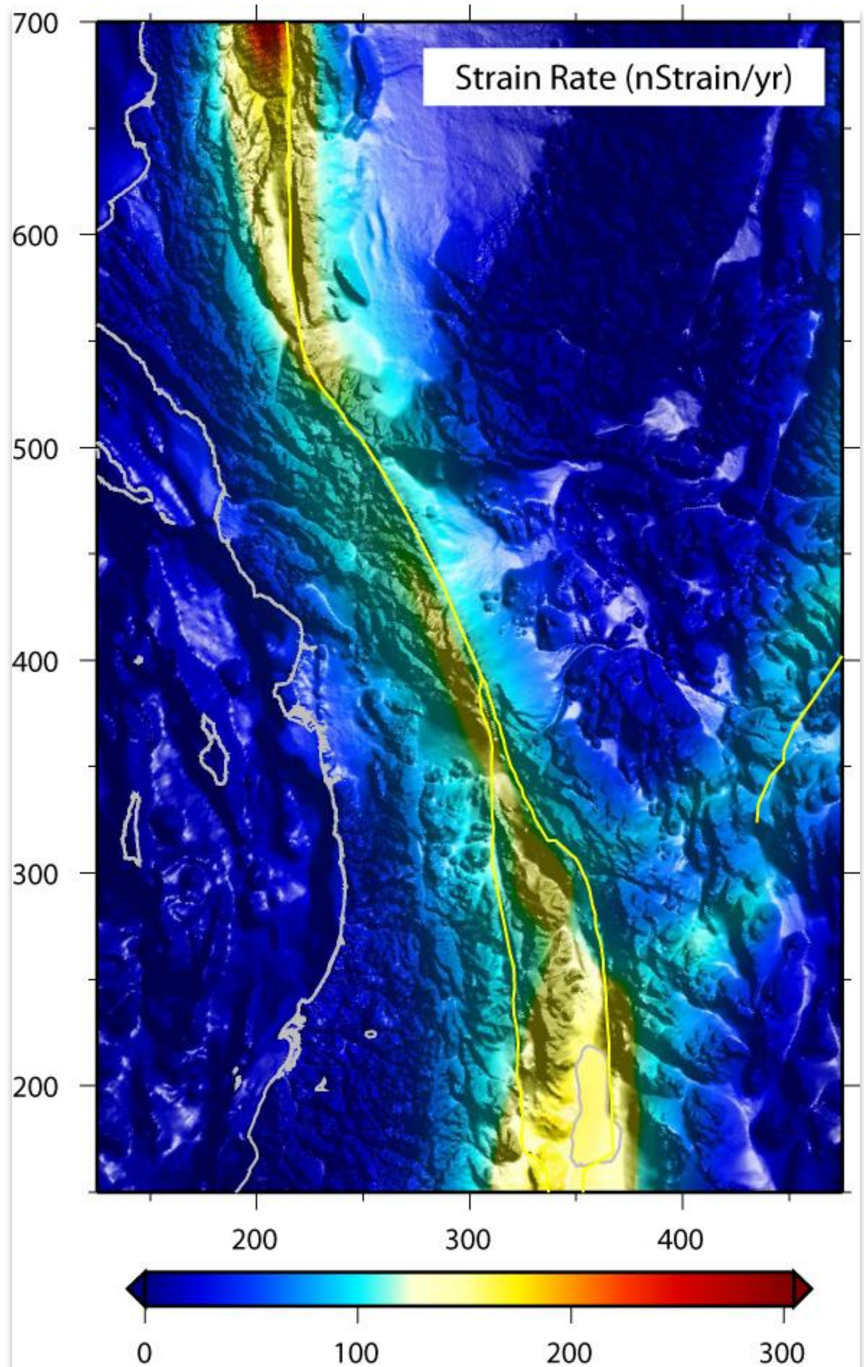
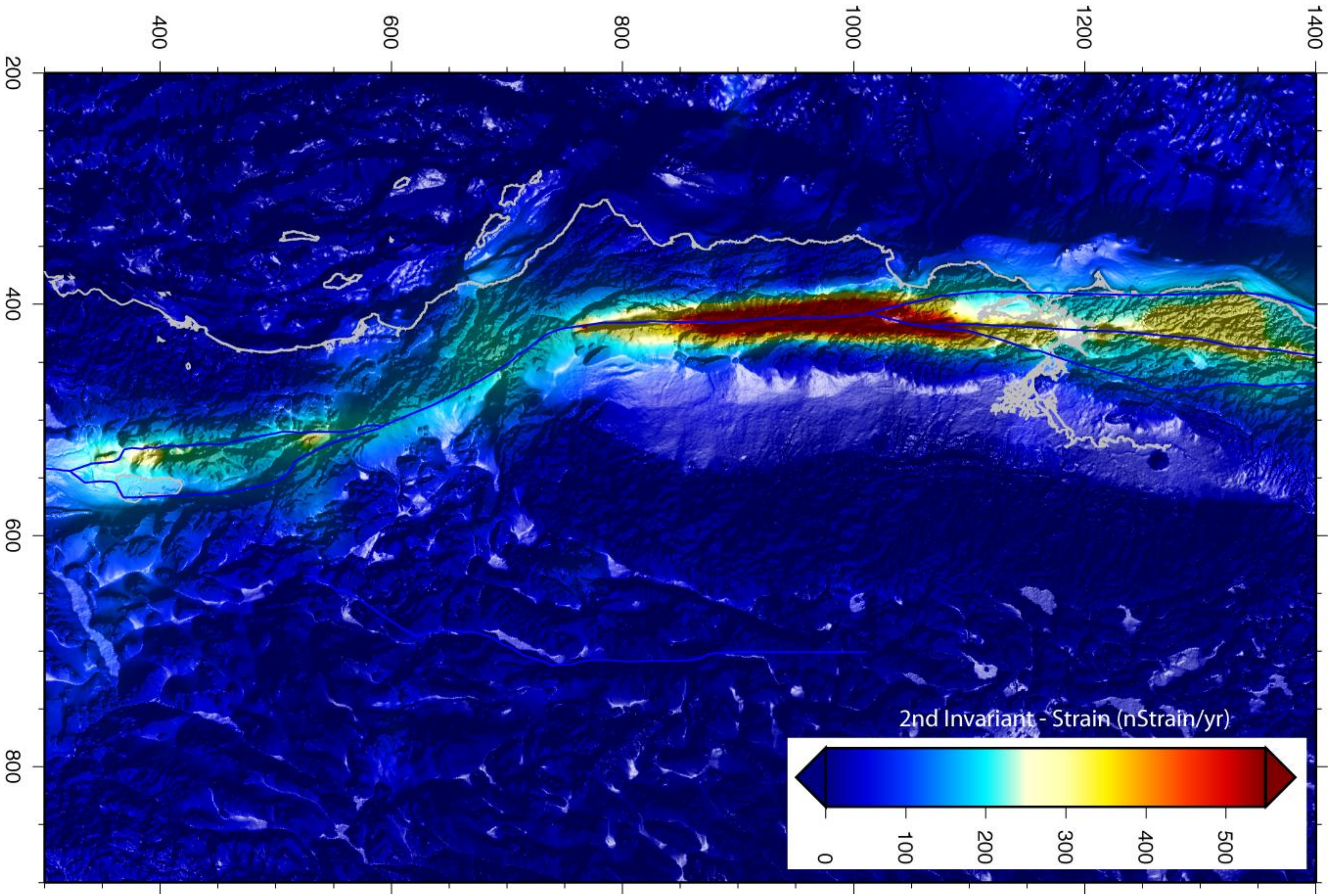
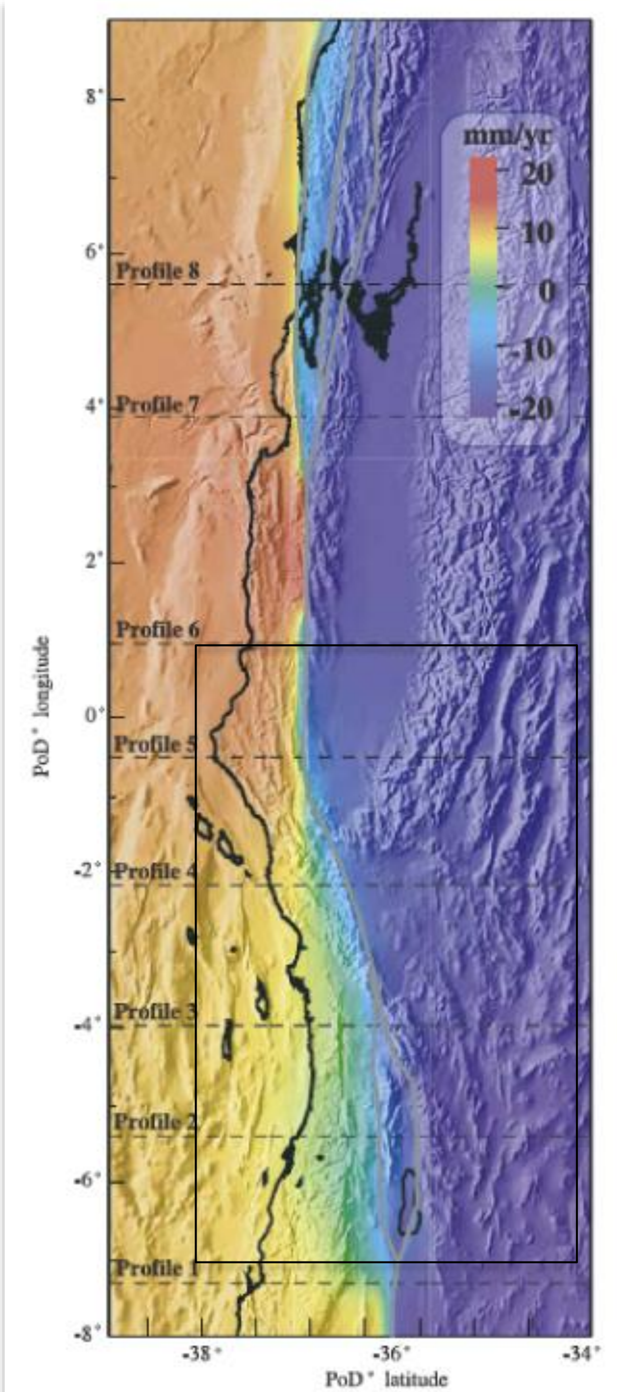


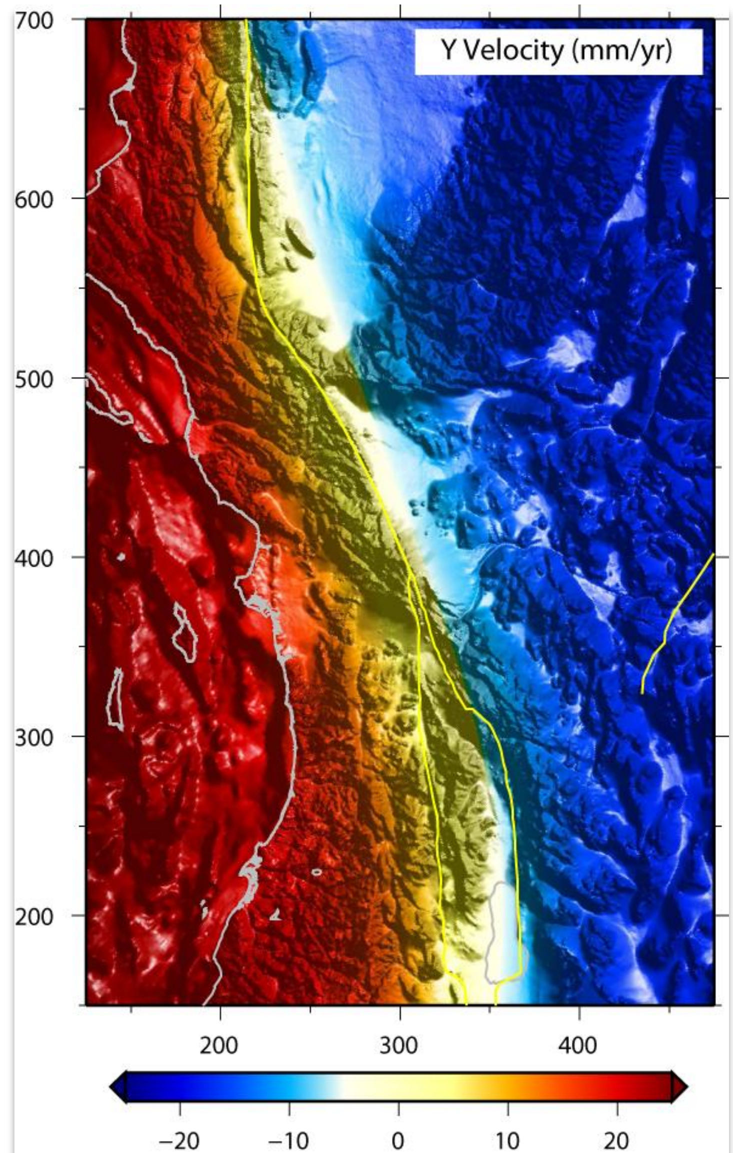
# Discussion



400
600
800
1000
1200
1400
200
400
600
800
2nd Invariant - Strain (nStrain/yr)
0
100
200
300
400
500

# Model Results: Velocities



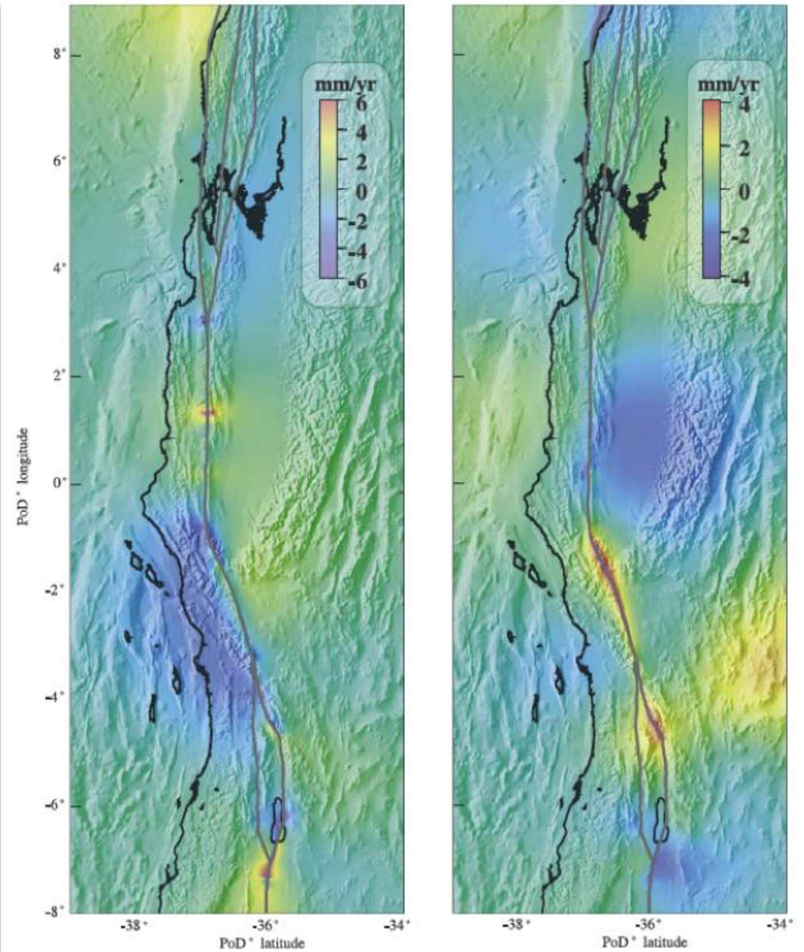



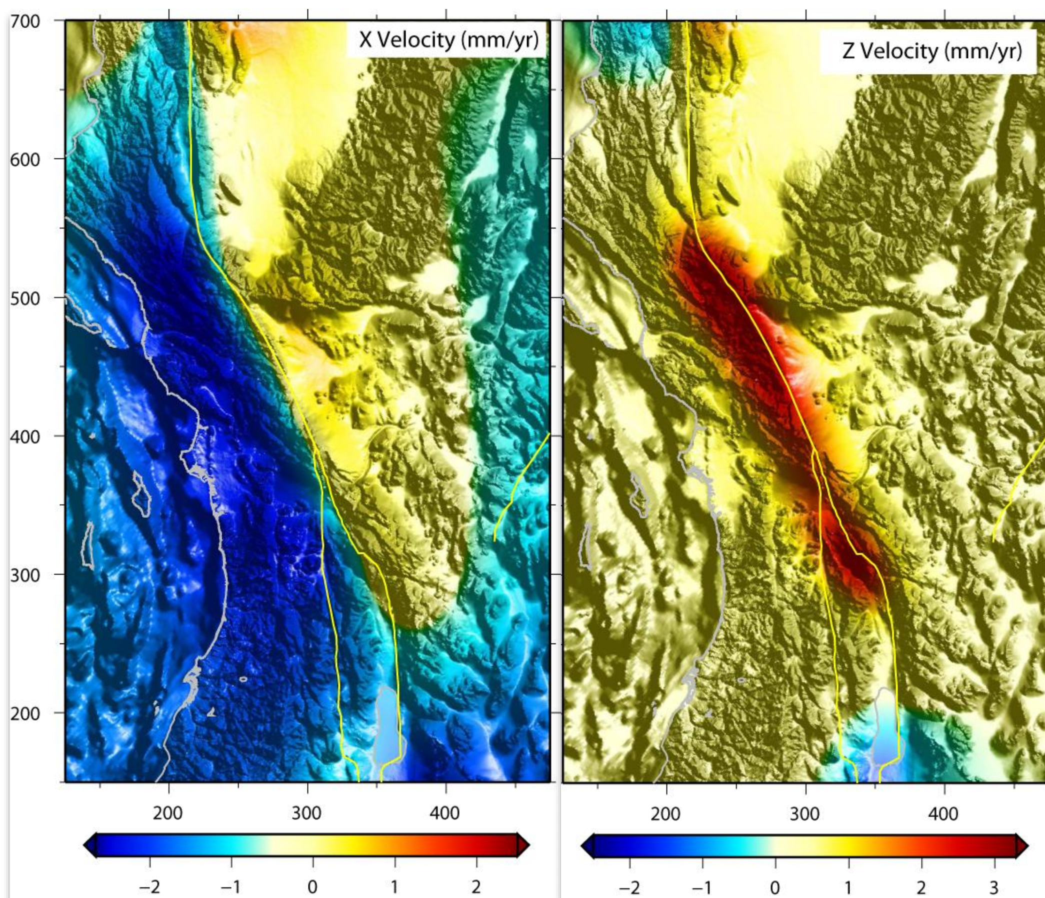

Smith and Sandwell, 2006

# Comparison of results: Velocities

## Vx and Vz

(Smith and Sandwell, 2006)



# Conclusions

The general deformation patterns are reproduced by the current models.

Boundary conditions can greatly alter the resultant strain pattern

Future considerations:

We will include a thermal model
  1) shear heating

Include variable crustal thickness

Embedded fault model
  1) fault rheological properties?

Additional sensitivity analysis