Magma-Tectonic Interactions in Central America

Pete La Femina

Penn State

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UNAVCO

Outline

Tectonic Setting
Deformation of Central America
- Fore-arc migration
Seismicity
Bookshelf faulting in Nicaragua
Volcanism
Magma-Tectonic Interactions

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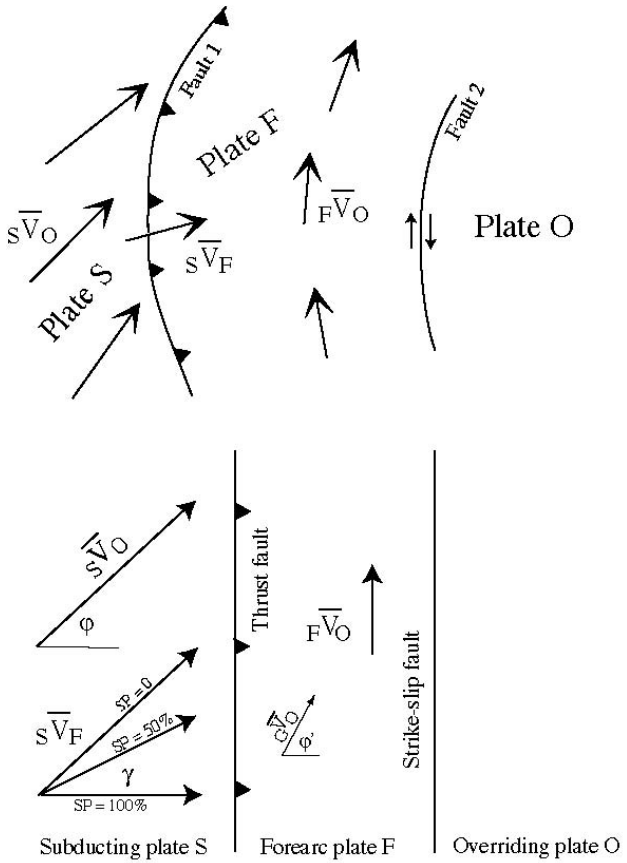
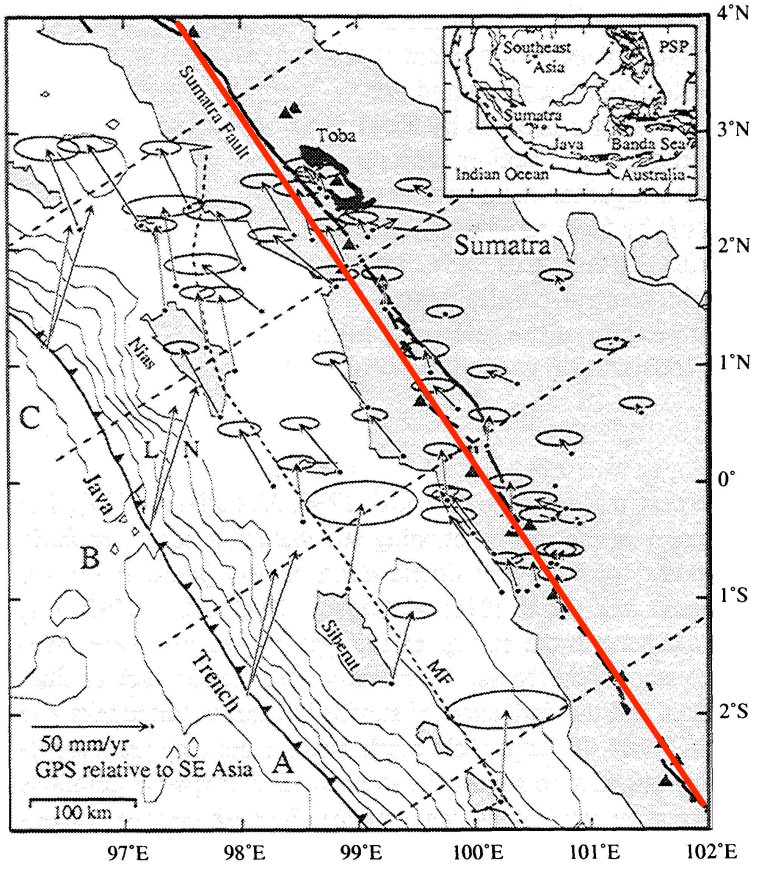
Central America - Tectonics

Oblique Convergence & Strain Partitioning



McCaffrey (2002)

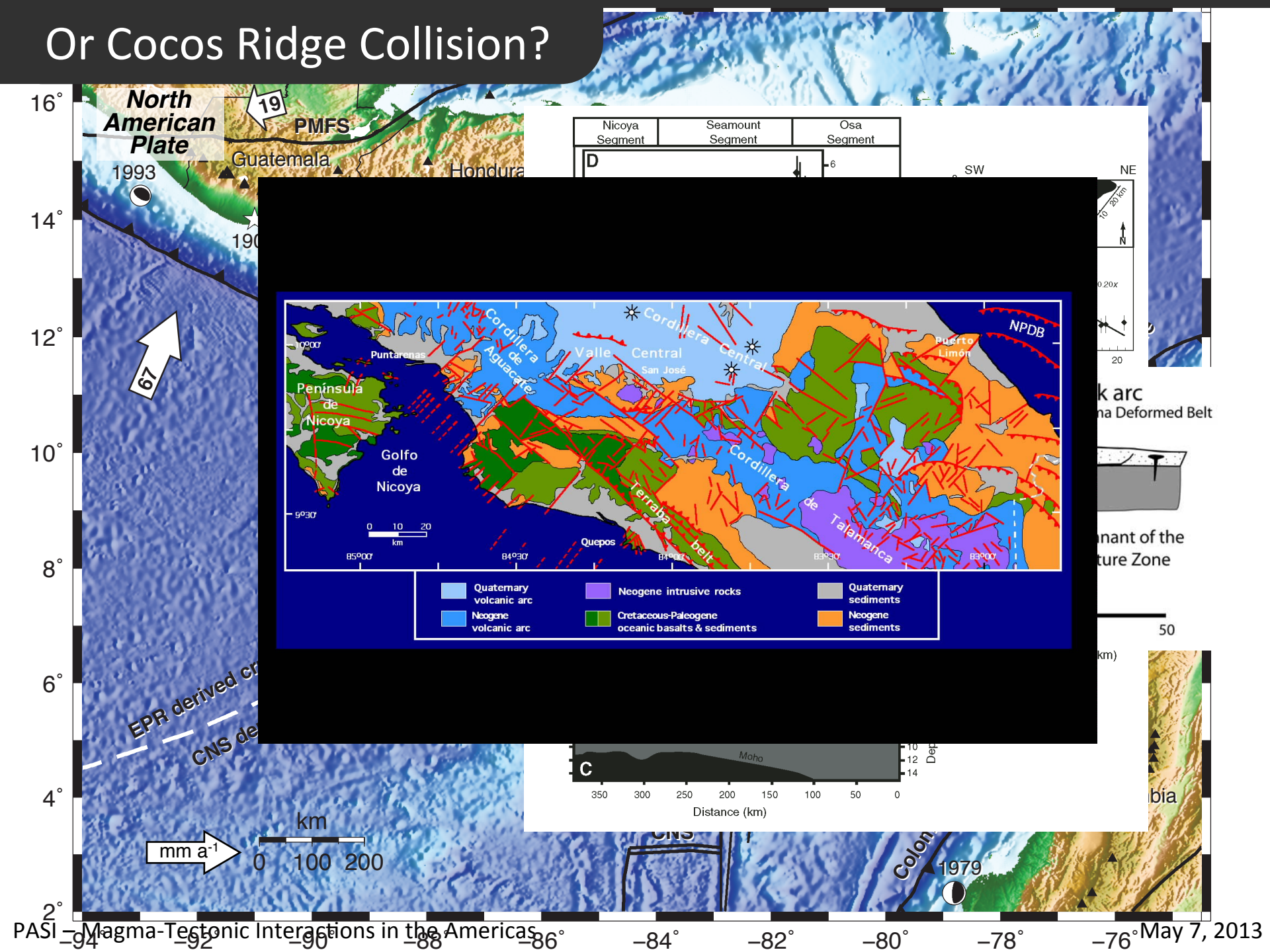


McCaffrey et al (2000)

Oblique Convergence & Strain Partitioning in Central America?

Oblique Convergence & Strain Partitioning

Or Cocos Ridge Collision?



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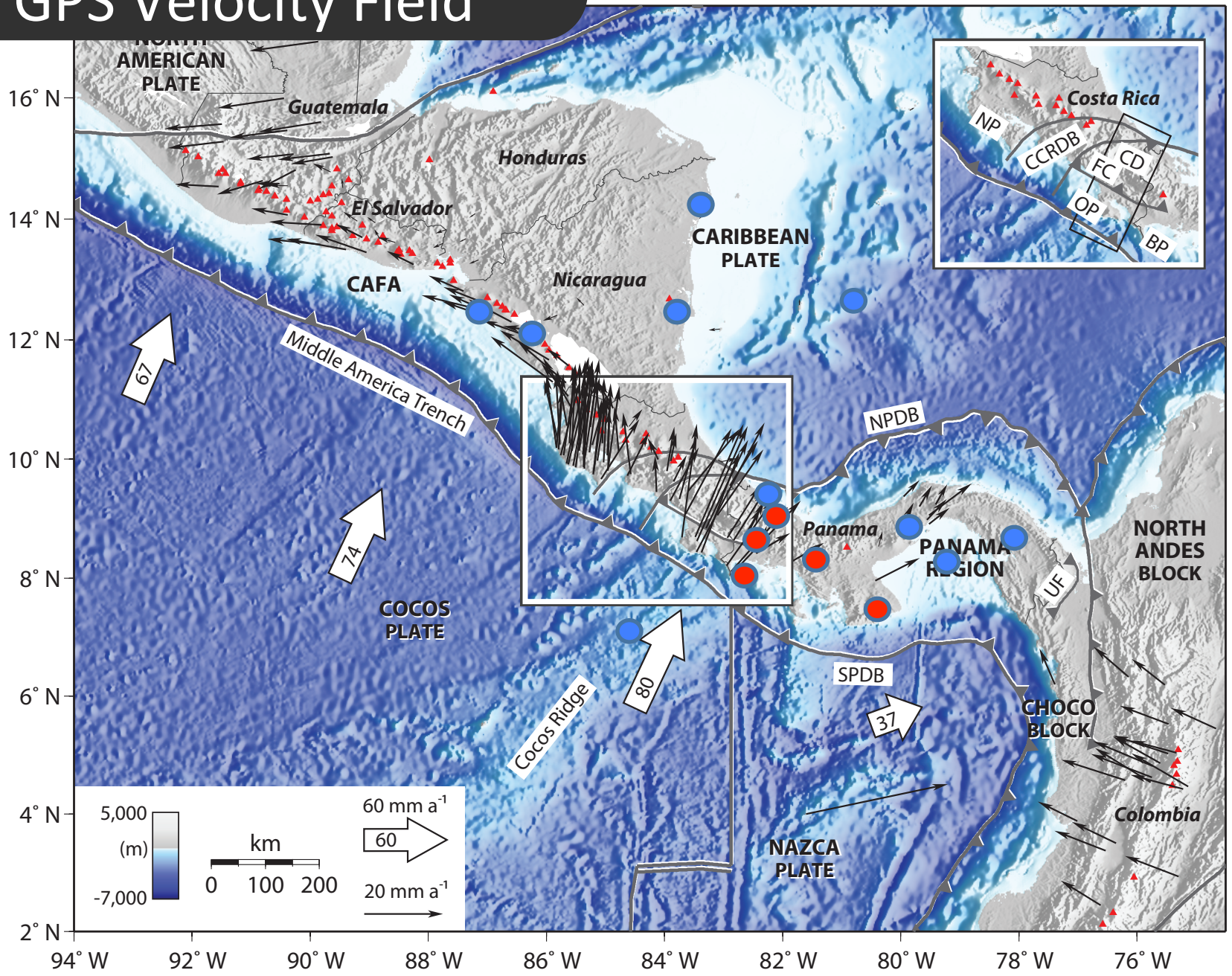
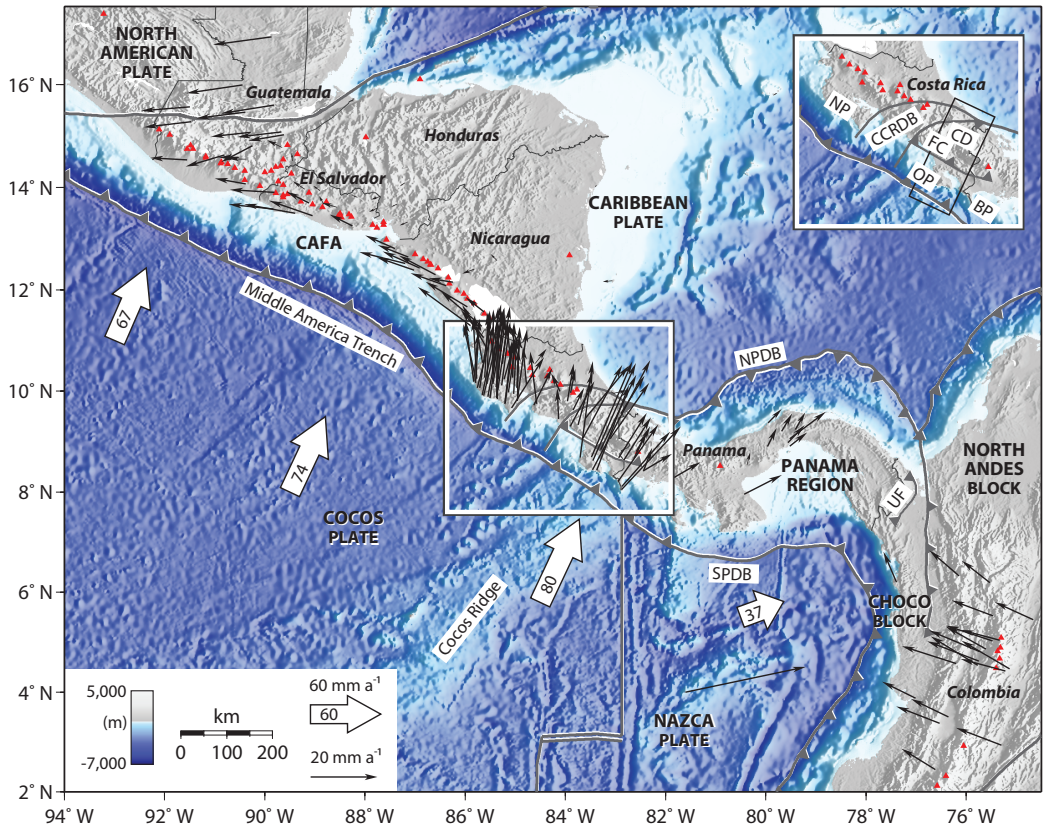
GPS Velocity Field

Kobayashi et al. (2012 – submitted)



GPS Velocity Field

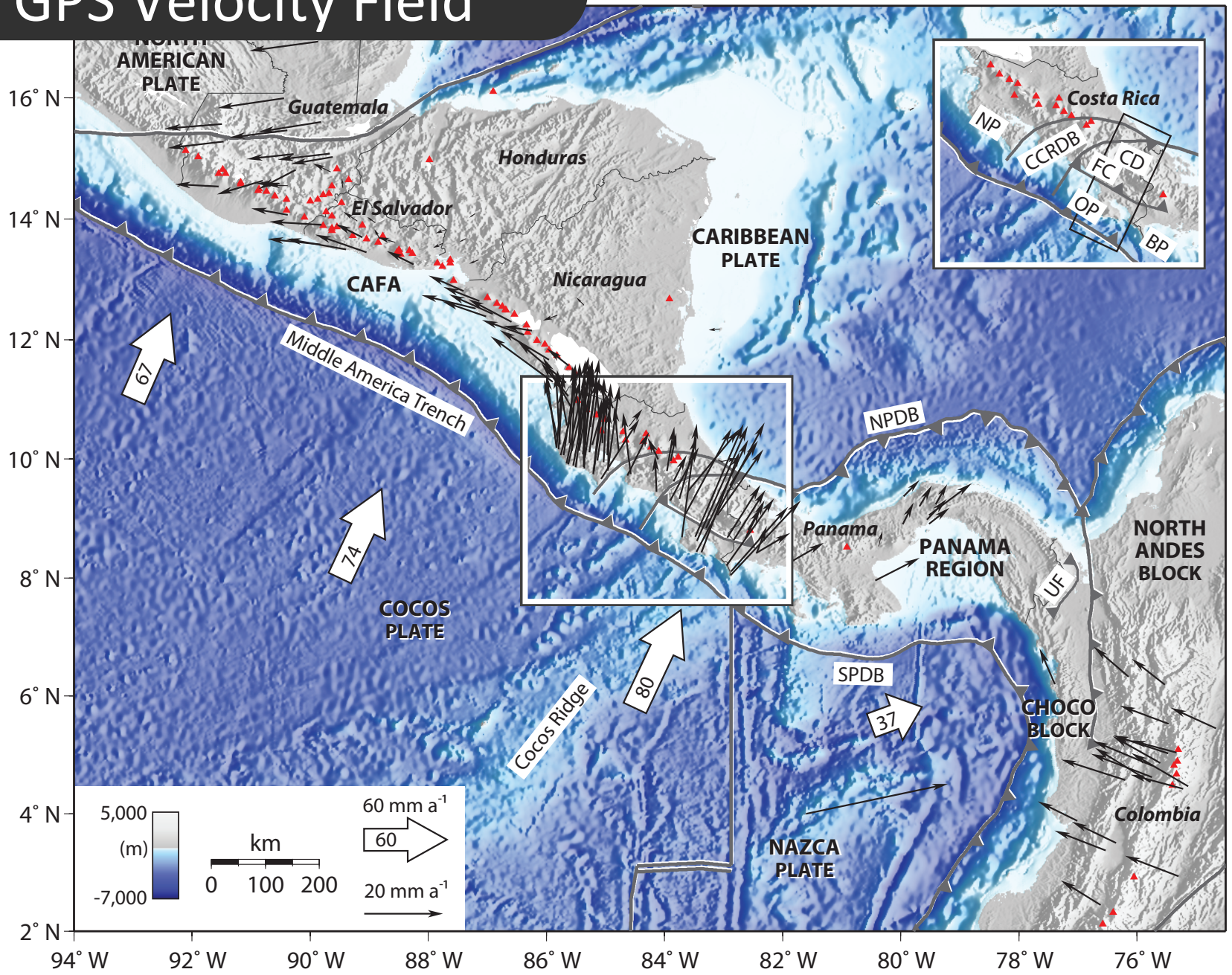


Kobayashi et al. (2012 – submitted)

1. High convergence rate inboard of Cocos Ridge
2. Northwest motion of the CAFA
3. Fanning out pattern about the Cocos Ridge axis
4. Northeast motion of the PR
5. West-northwest motion of Choco & North Andes blocks

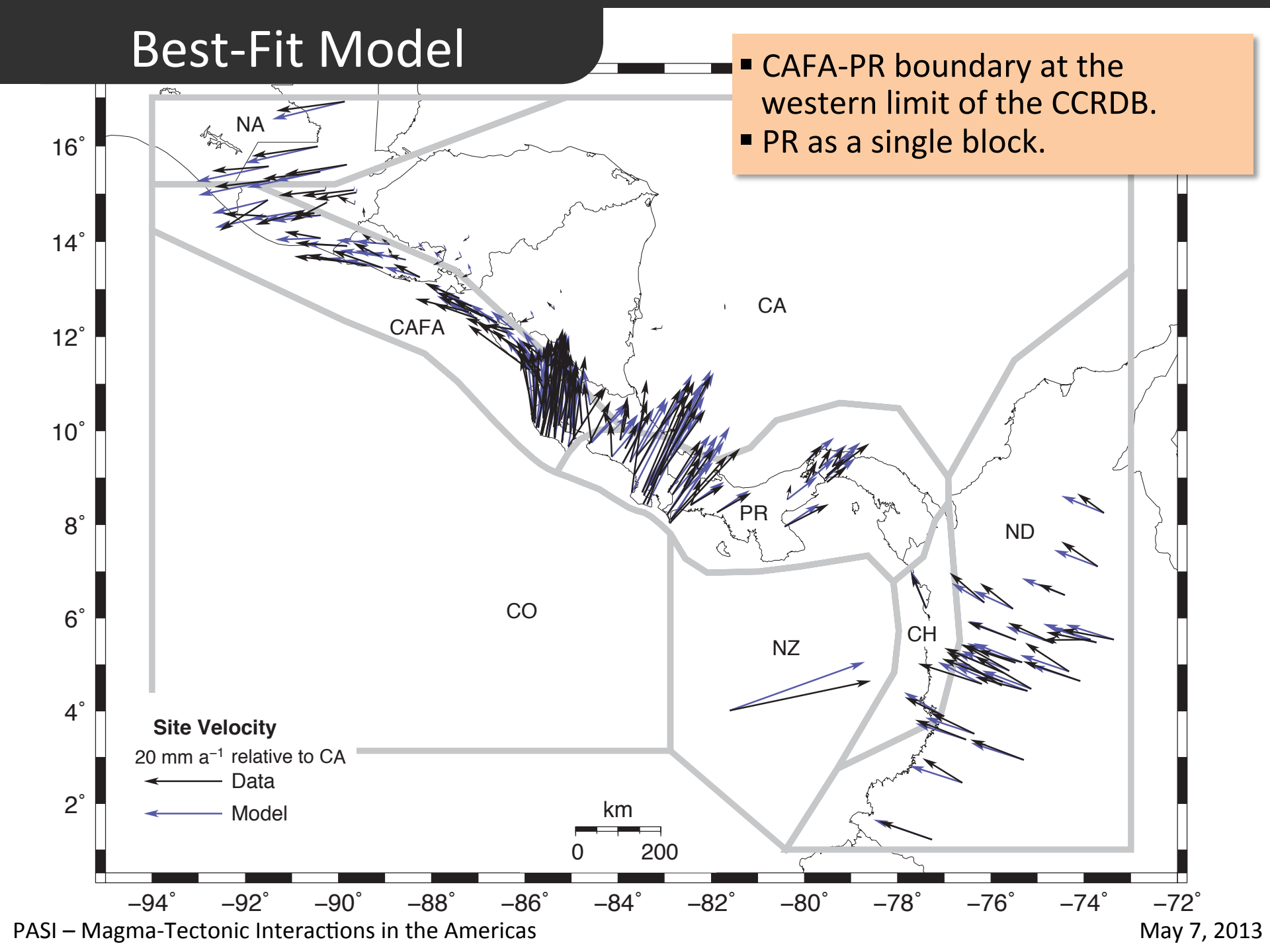
GPS Velocity Field

Kobayashi et al. (2012 – submitted)



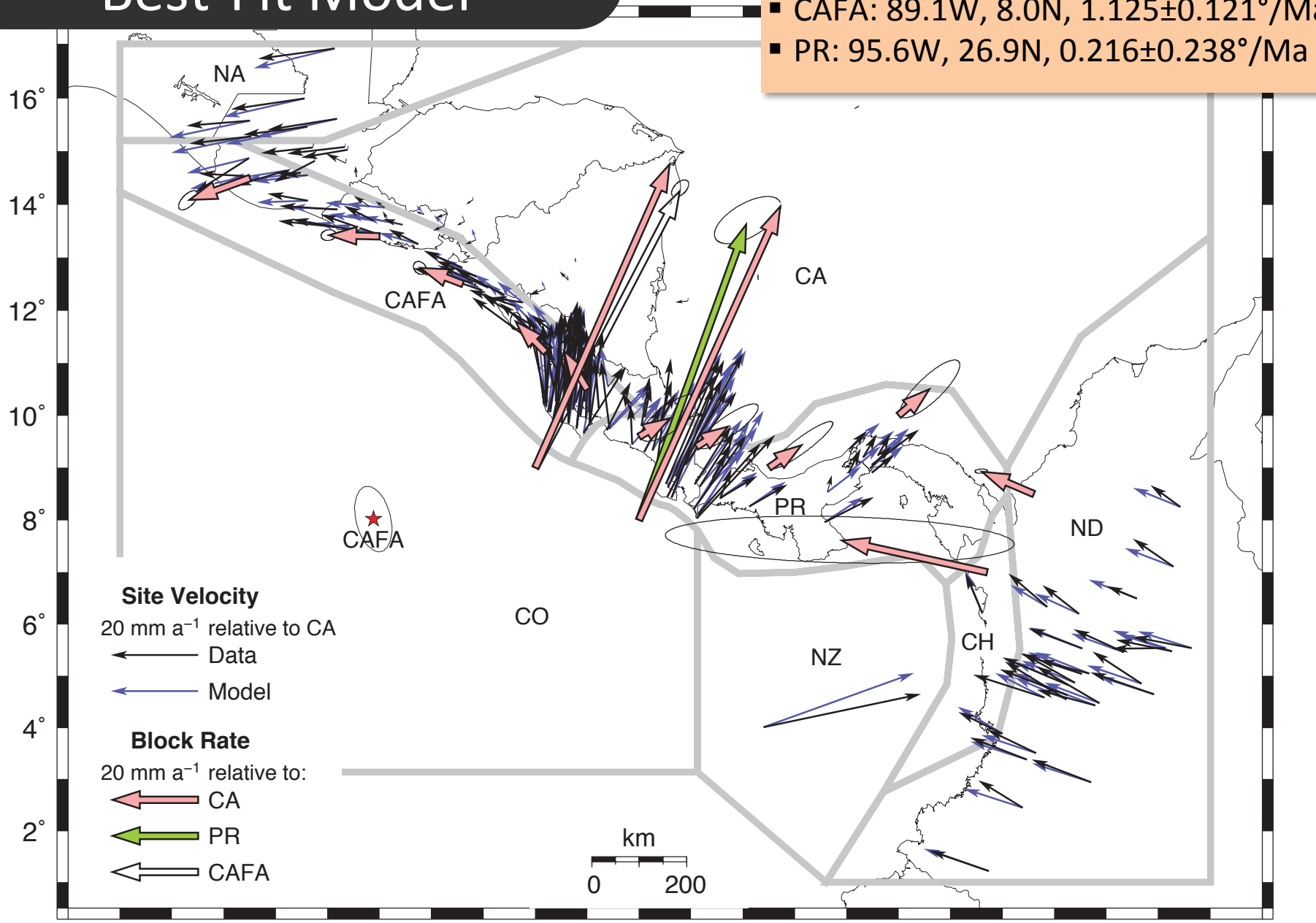
Best-Fit Model

- CAFA-PR boundary at the western limit of the CCRDB.
- PR as a single block.



Best-Fit Model

- CAFA: 89.1W, 8.0N, 1.125±0.121°/Ma
- PR: 95.6W, 26.9N, 0.216±0.238°/Ma



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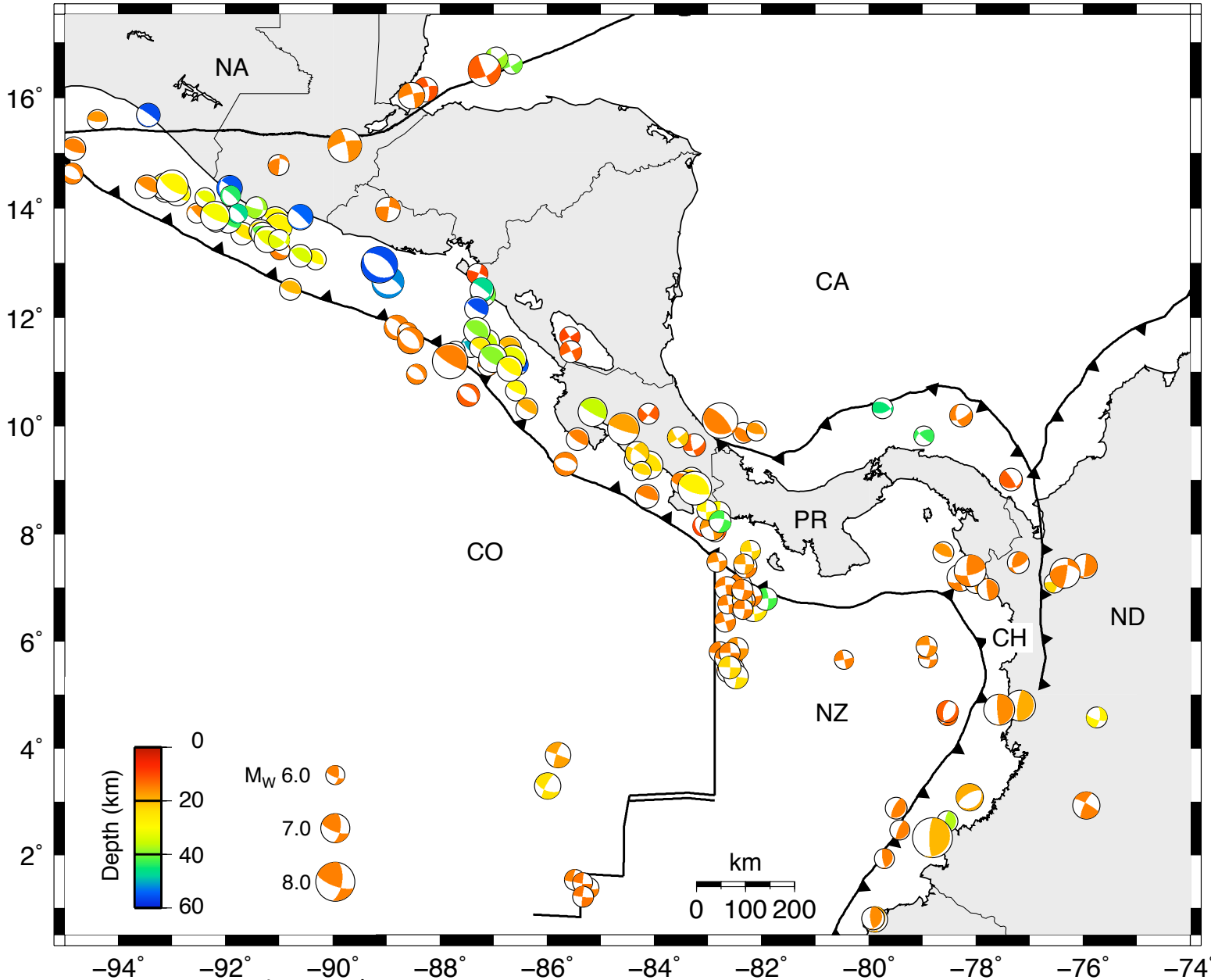
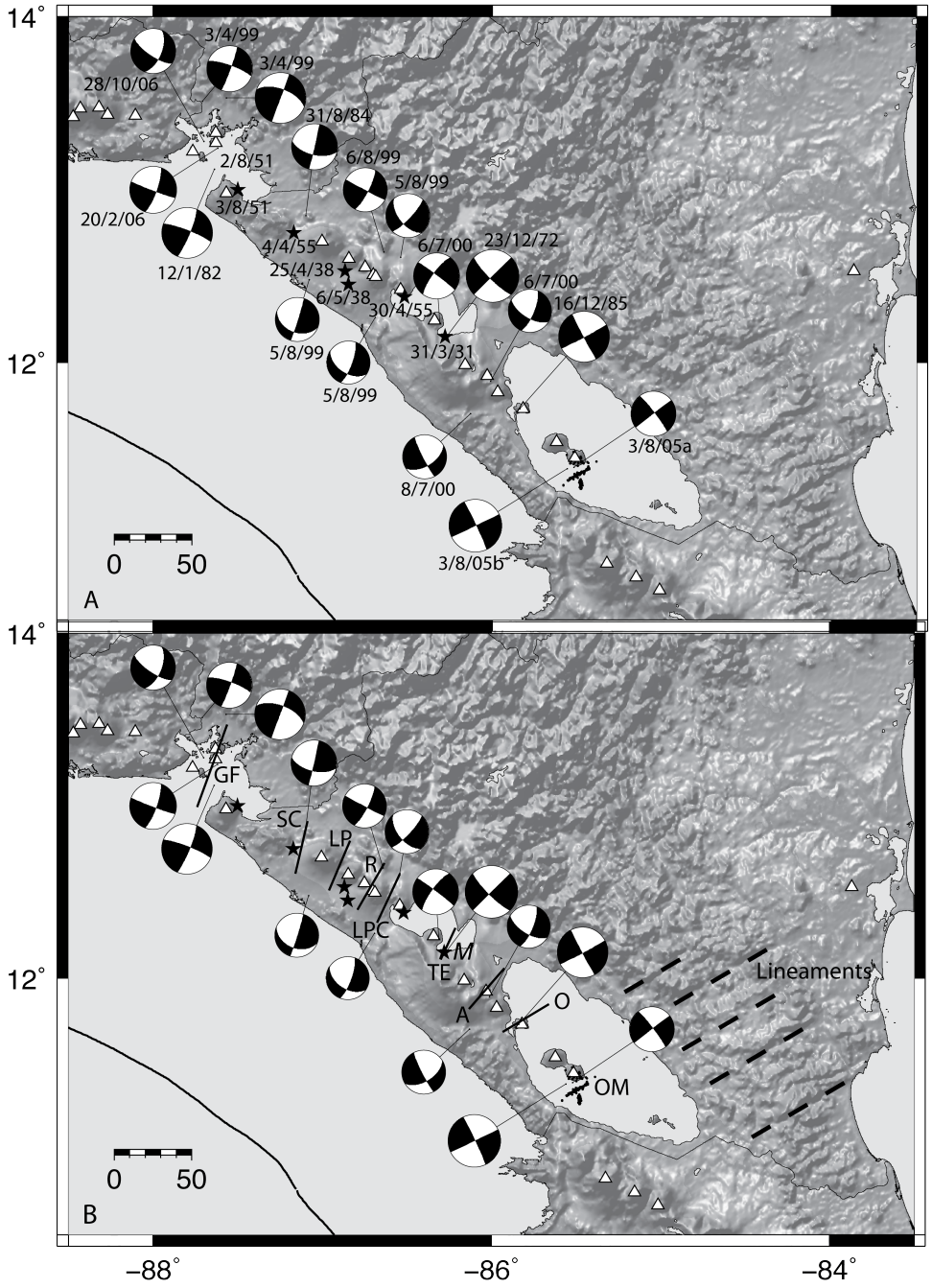
Seismicity

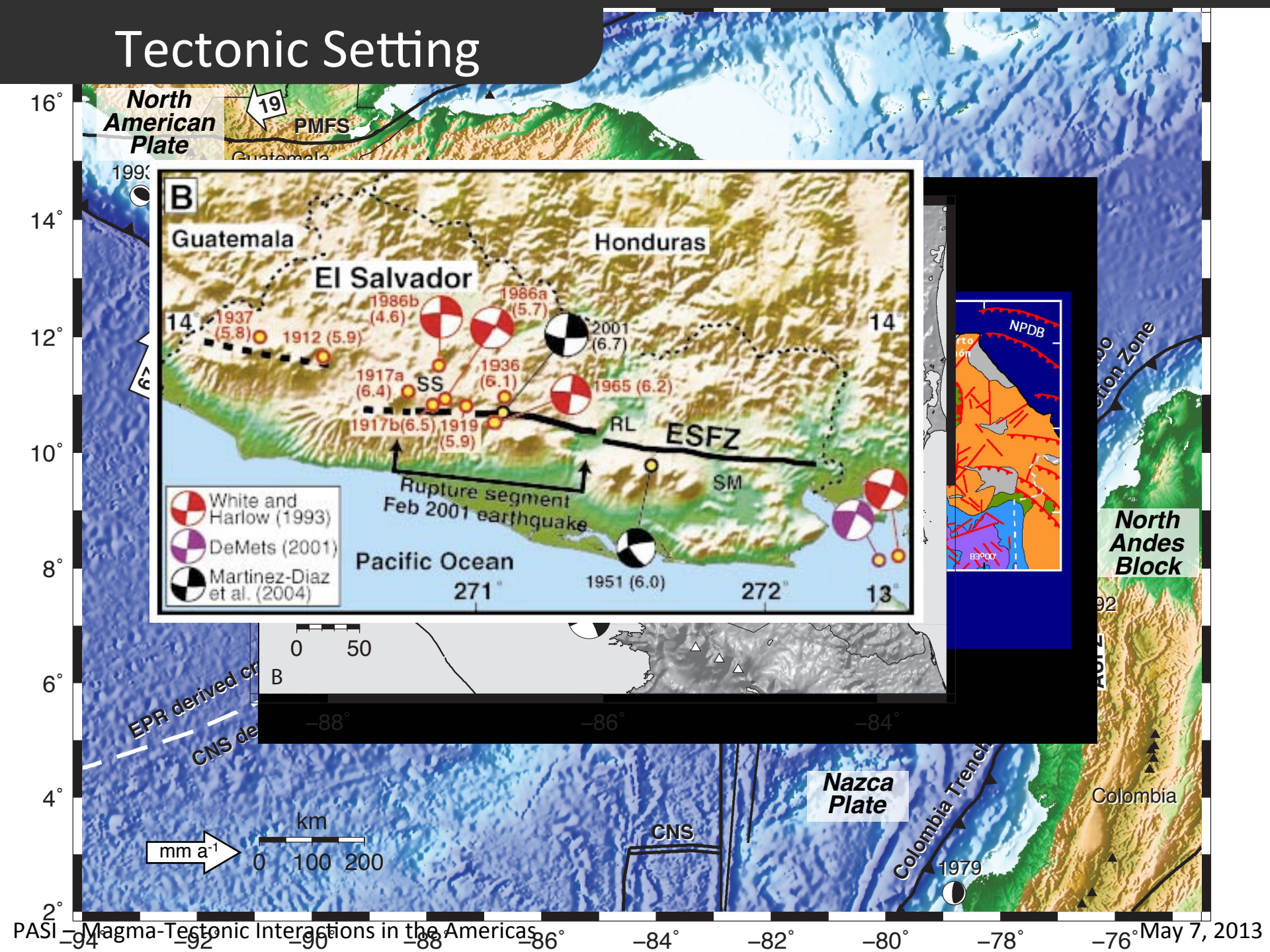

NA
CA
CO
PR
ND
CH
NZ
16˚
14˚
12˚
10˚
8˚
6˚
4˚
2˚
−94˚
−92˚
−90˚
−88˚
−86˚
−84˚
−82˚
−80˚
−78˚
−76˚
−74˚
Depth (km)
0
20
40
60
M_W 6.0
7.0
8.0
km
0 100 200

Forearc Seismicity

- Upper plate seismicity indicates northwest directed fore arc sliver transport
  - Central Costa Rica to Guatemala
- Diffuse deformation in CCRDB
- Shallow (<20 km) & located within 20 km of arc
- Focal mechanisms are consistent w/ NE or NW trending fault planes
- M_s <6.5
- Elongated damage zones & focal mechanisms NW to NE
- Cluster & Migrate along strike
- Historically have caused greater damage and loss of life (e.g., 23/12/72 M6.2 Managua)



Tectonic Setting



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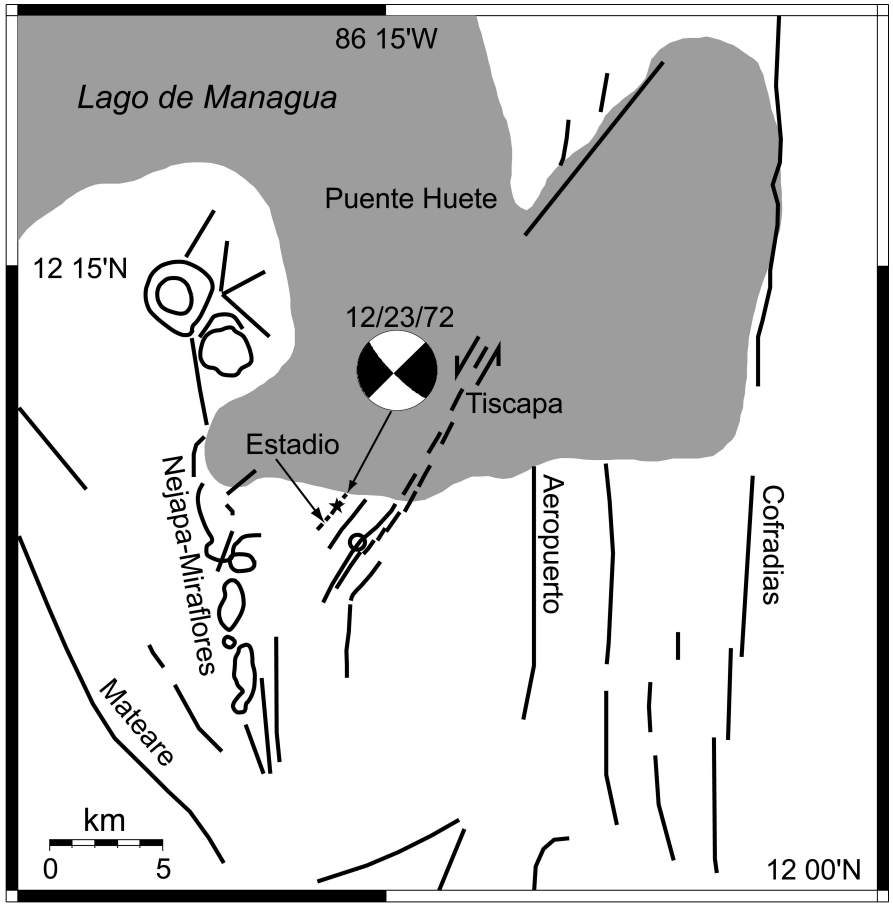
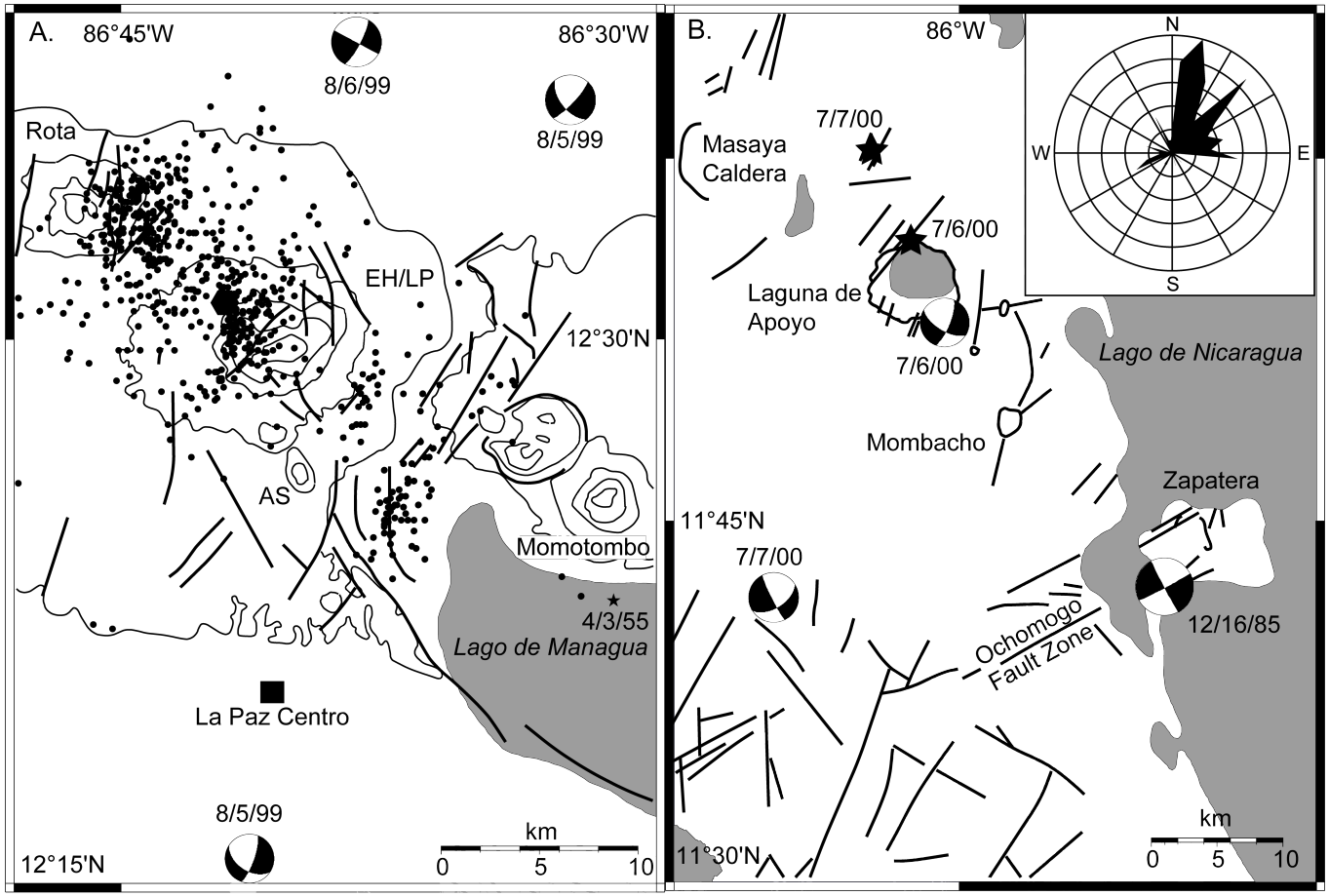
Managua Graben



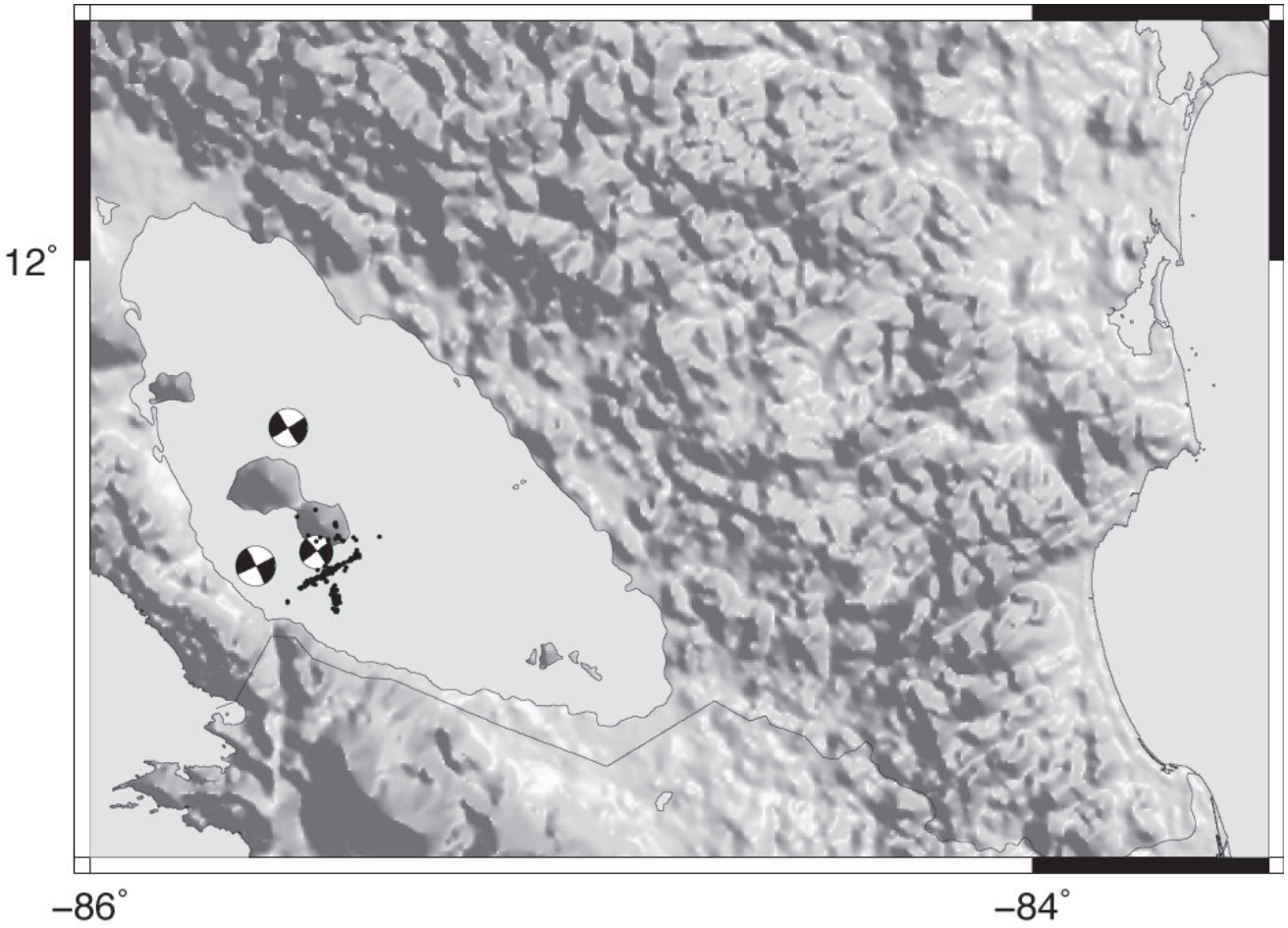
- March 31, 1931
- December 23, 1972
  - >11,000 people killed
  - ~$1 billion in damage

Maribios Range and Apoyo

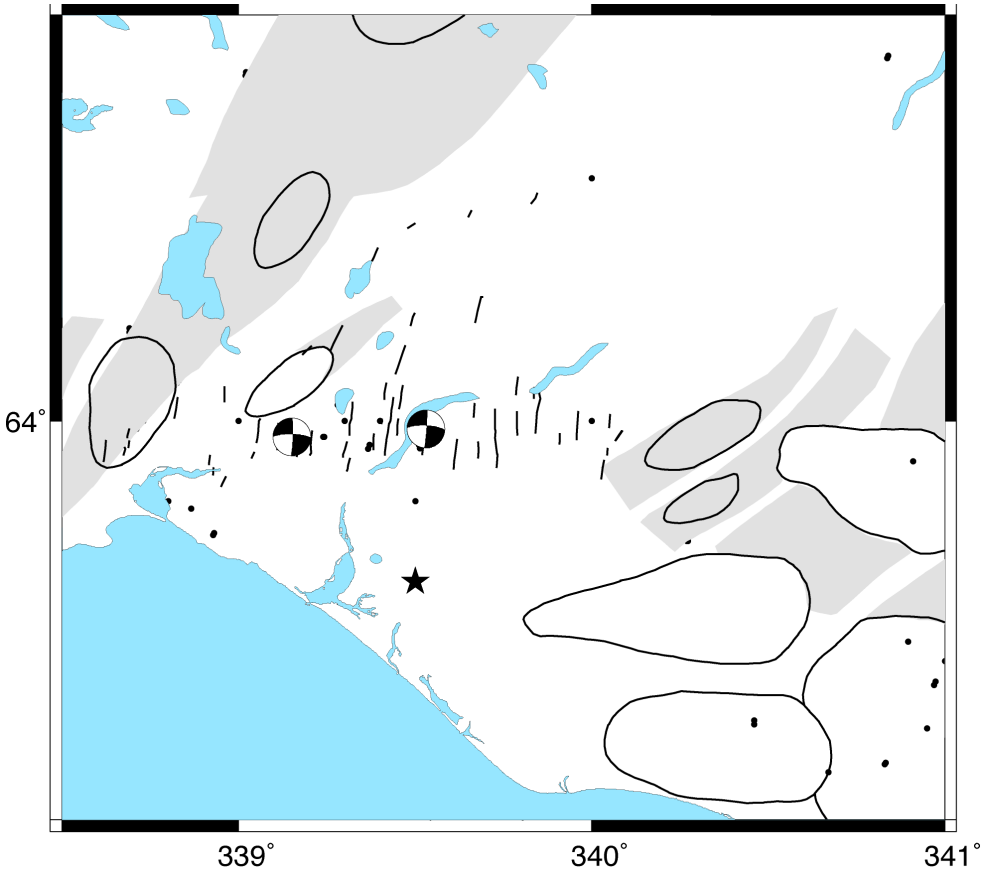


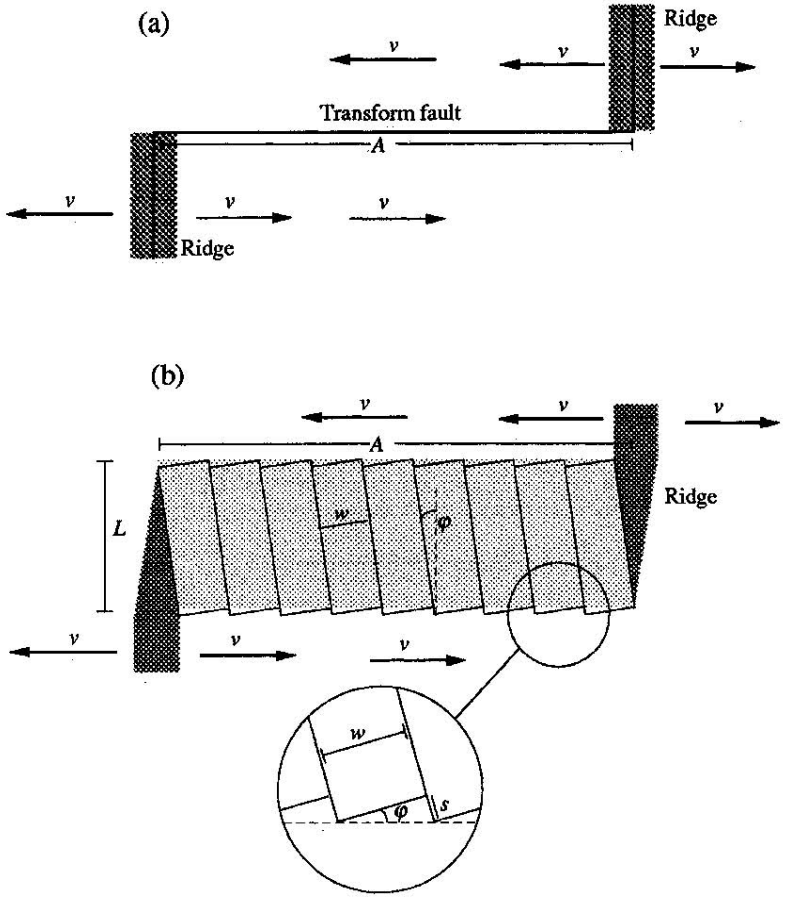
Ometepe Fault Zone

1) 2005 M_w 6.3 earthquake
2) Aftershocks indicate NE trending fault and N trending fault
3) NE-trend is parallel with topographic lineaments in backarc



Iceland Analog





Sigmundsson et al. (1995)

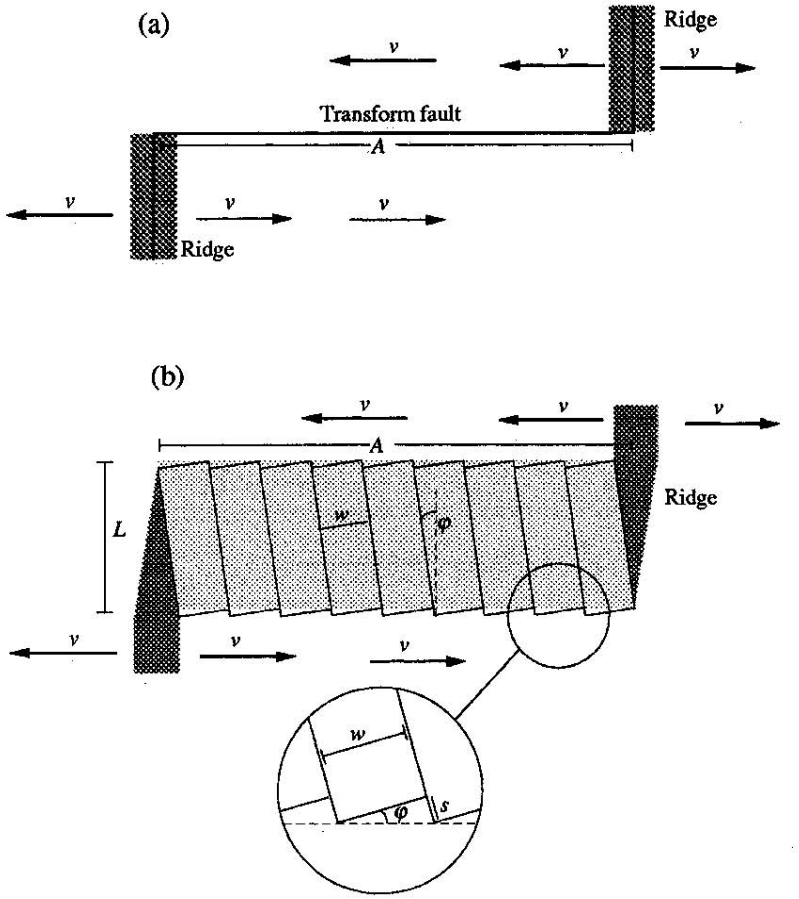
Iceland Analog

Rotation rate of faults (urad yr^{-1}):

$$\dot{\varphi} = \frac{2v}{L}$$

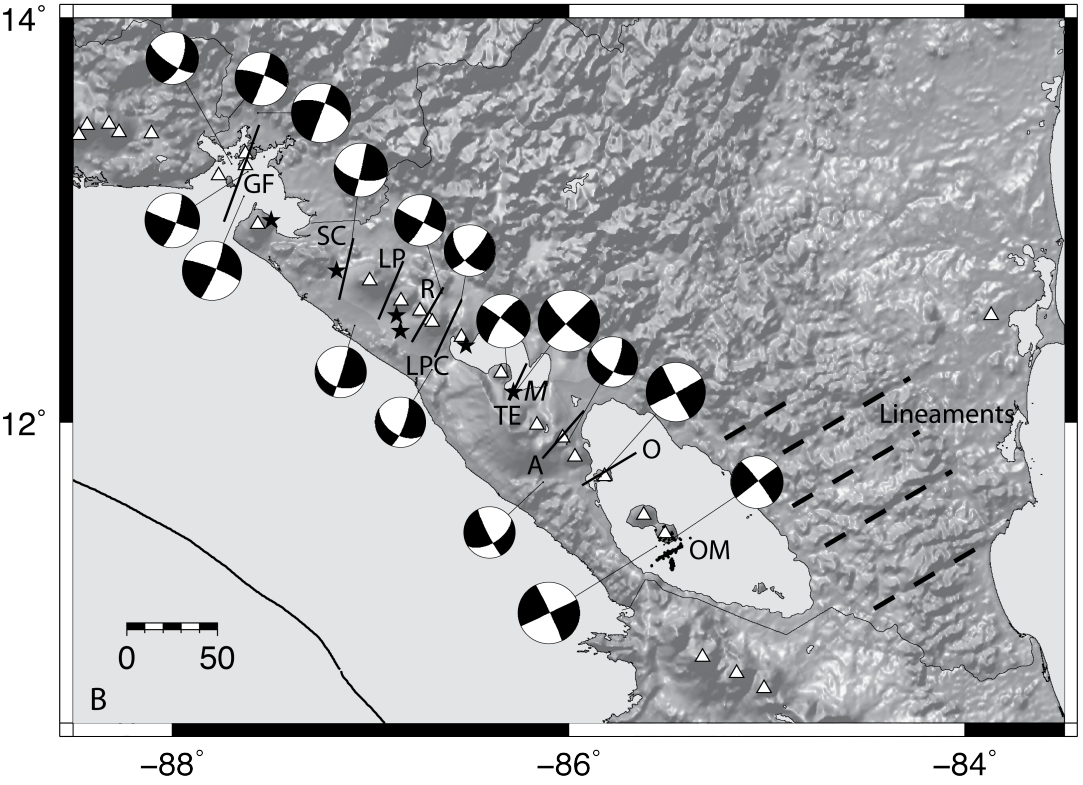
Slip rate of faults (mm yr^{-1}):

$$\dot{s} = w\dot{\varphi}$$



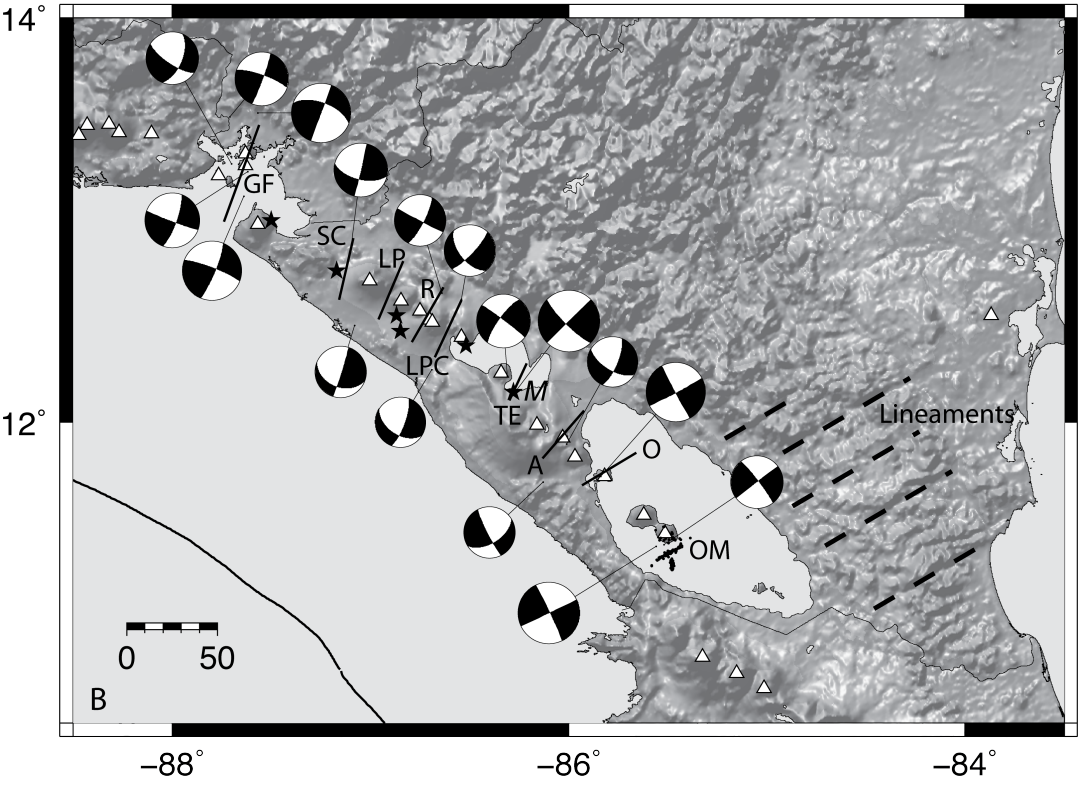
Sigmundsson et al. (1995)

Nicaragua Fore-Arc Motion



- Fault zone parameters
  - 2v = 8 mm yr^{-1}
  - L = 20-40 km
  - W = 39 km (avg)
- φ = 2x10^{-7} urad yr^{-1}
- S = ~8.5-17.5 mm yr^{-1}

Nicaragua Fore-Arc Motion

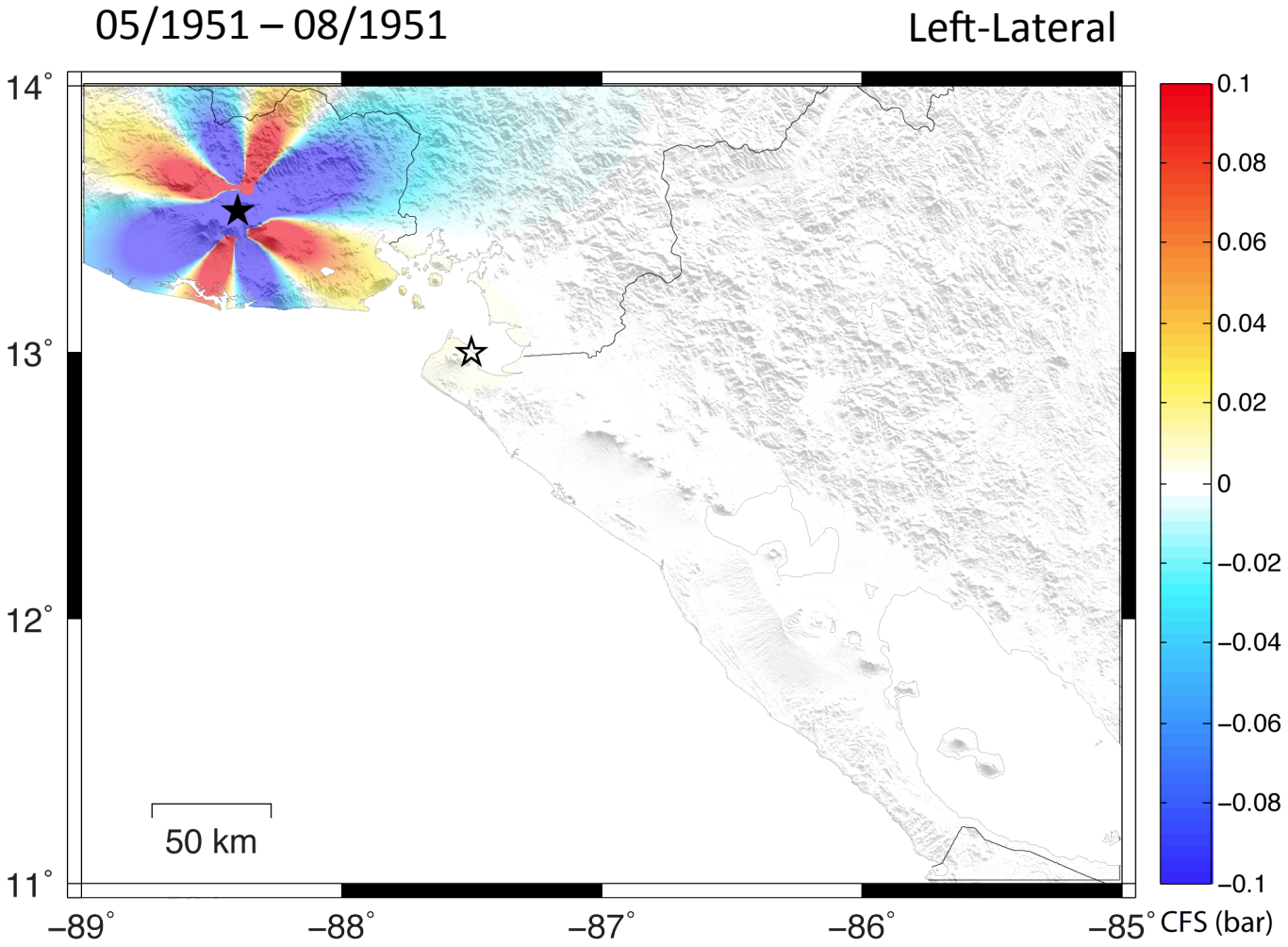


- Geometric Moment rate:

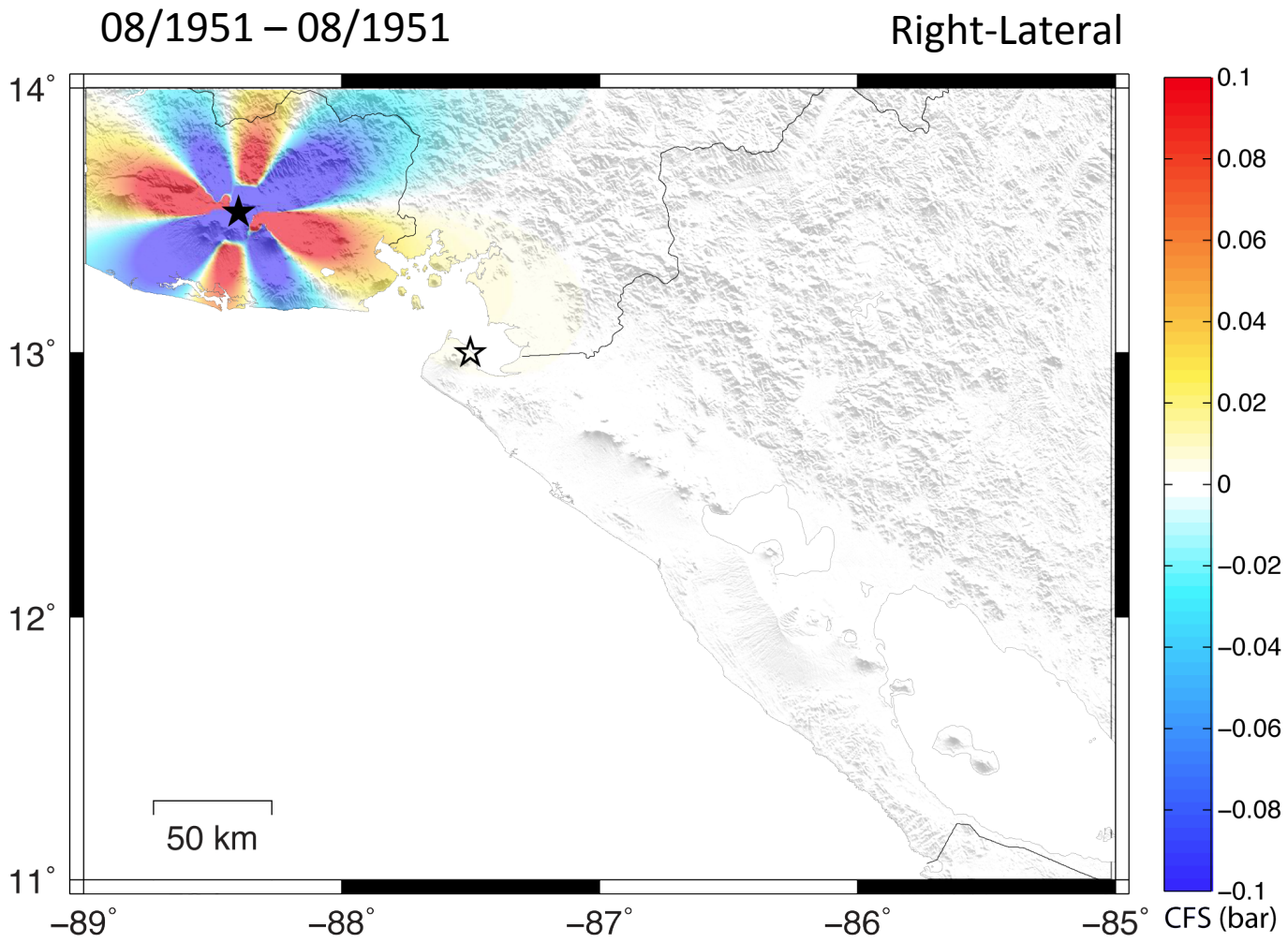
$$\dot{M}_o = 2vAD$$

- Efficiency
  - Single margin-parallel strike slip fault
    - 2.77×10^7 m^3 yr^{-1}
  - Bookshelf faults
    - 2.62×10^7 m^3 yr^{-1}
- Compared to Geometric M_o rate from seismicity
  - 1.01×10^7 m^3 yr^{-1}
- How is the strain accommodated?

Earthquake Synchronicity/Stress Triggering



Earthquake Synchronicity/Stress Triggering



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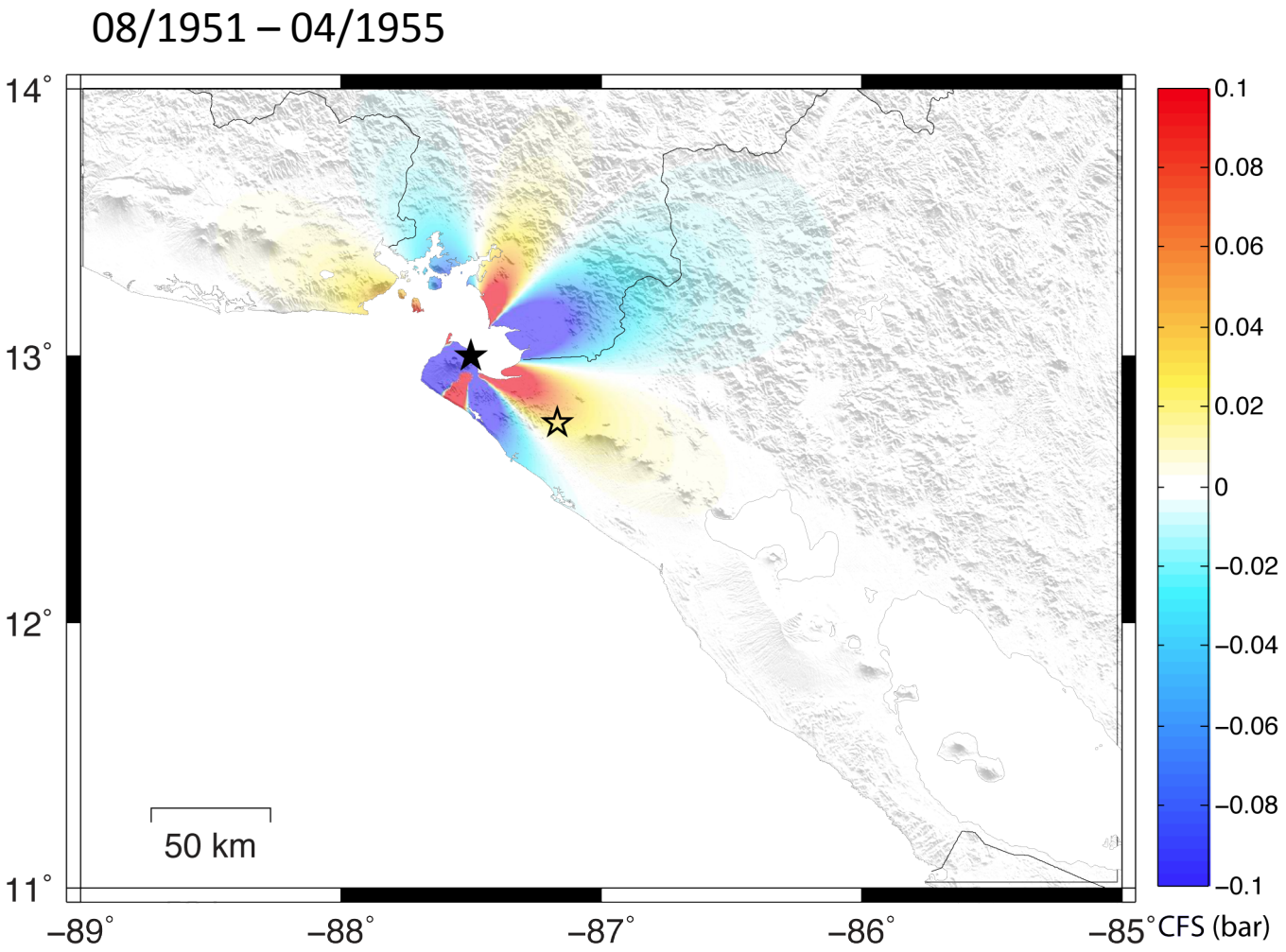

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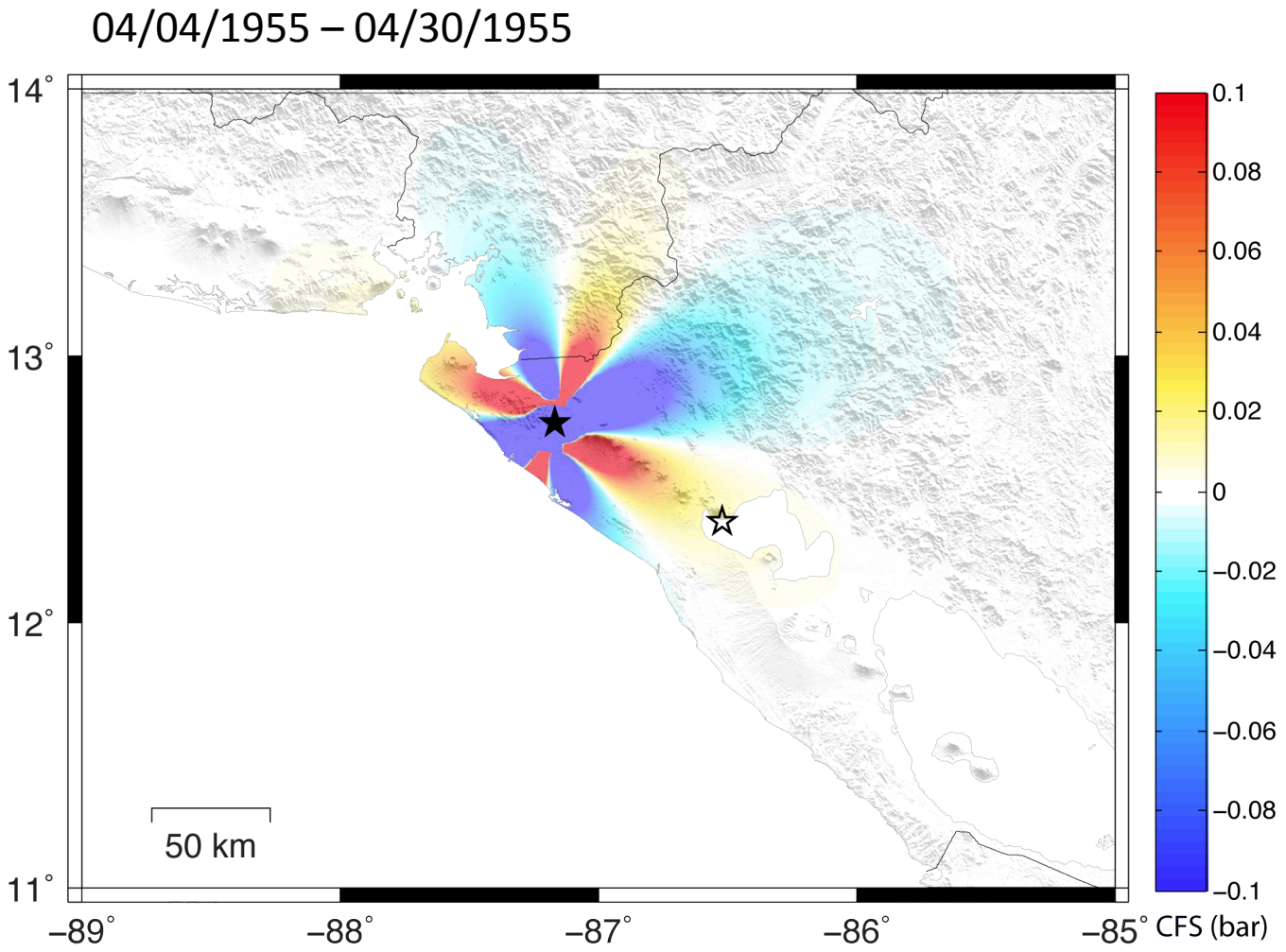

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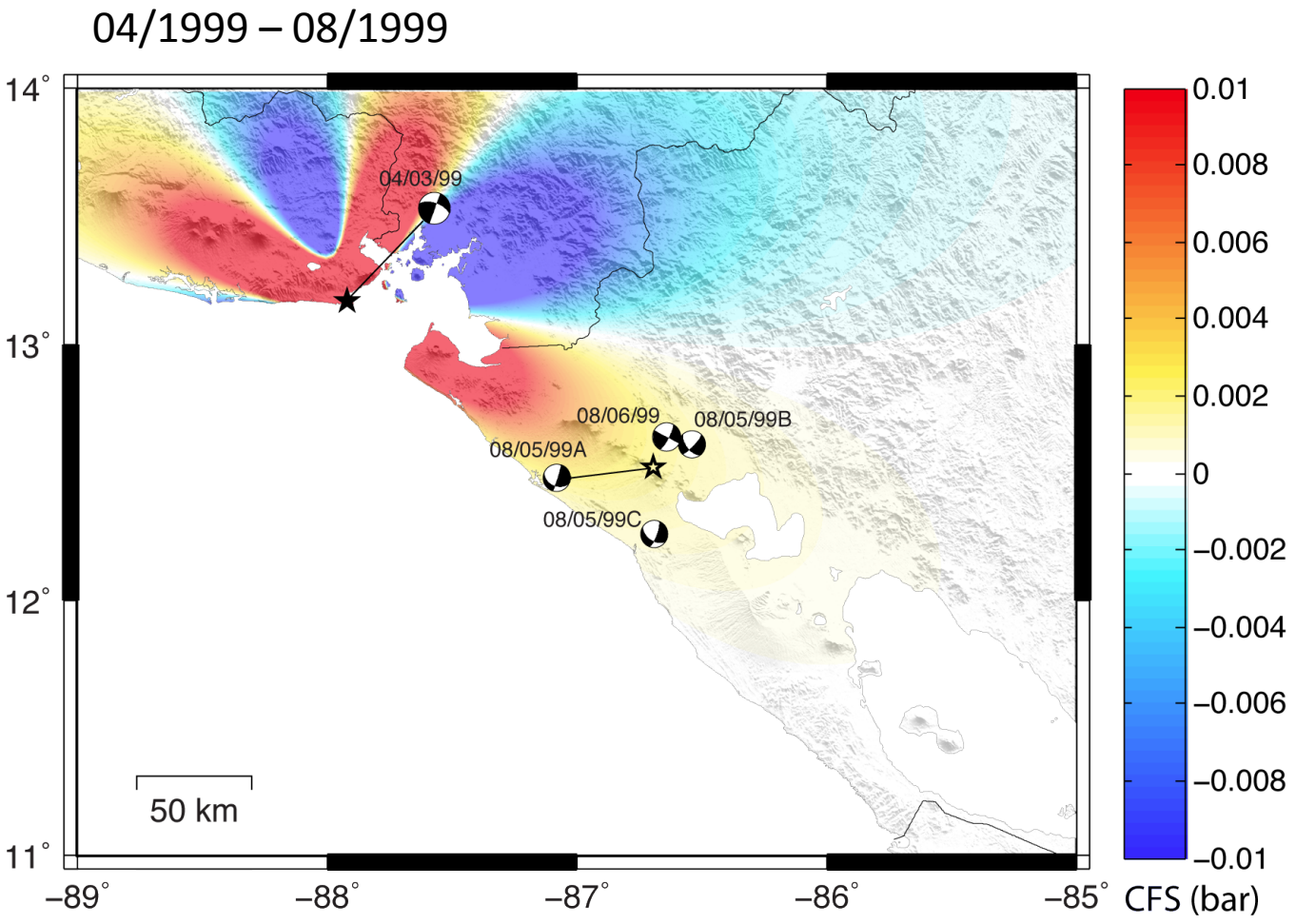

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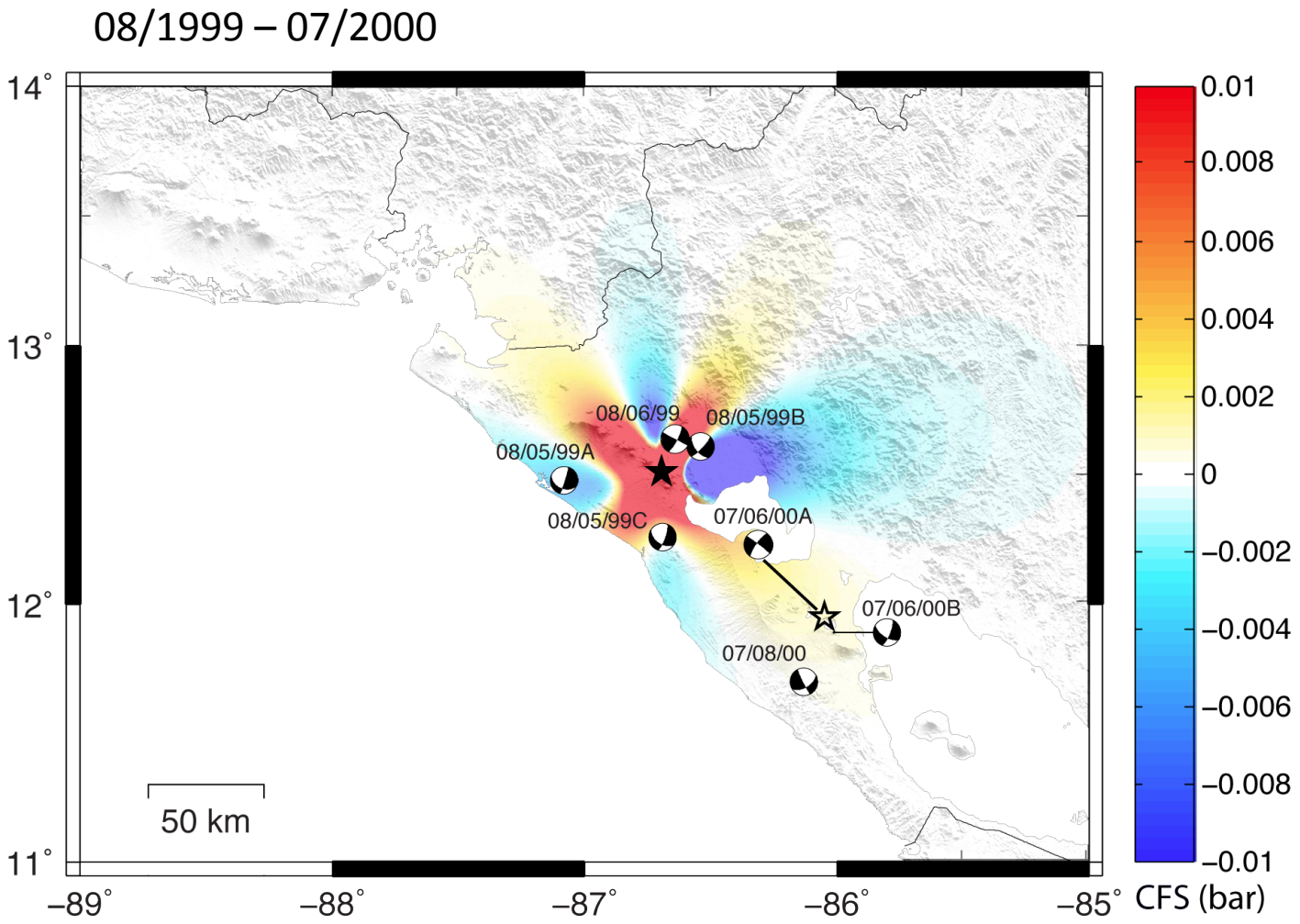

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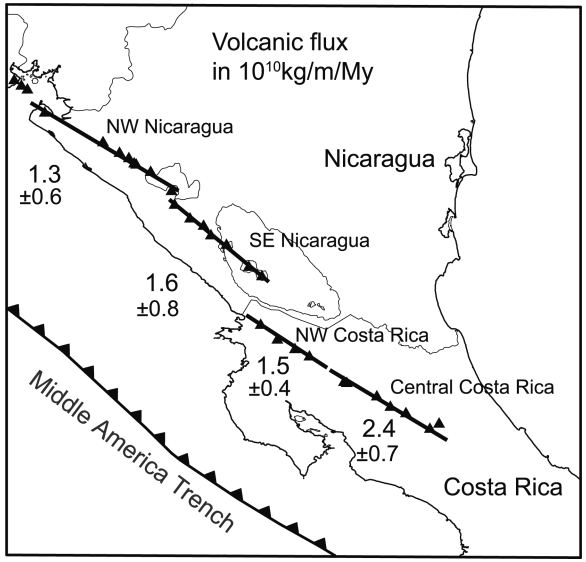
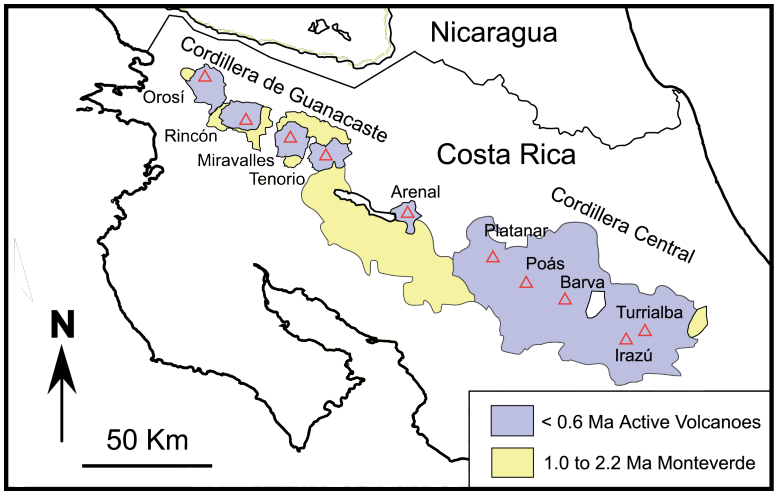
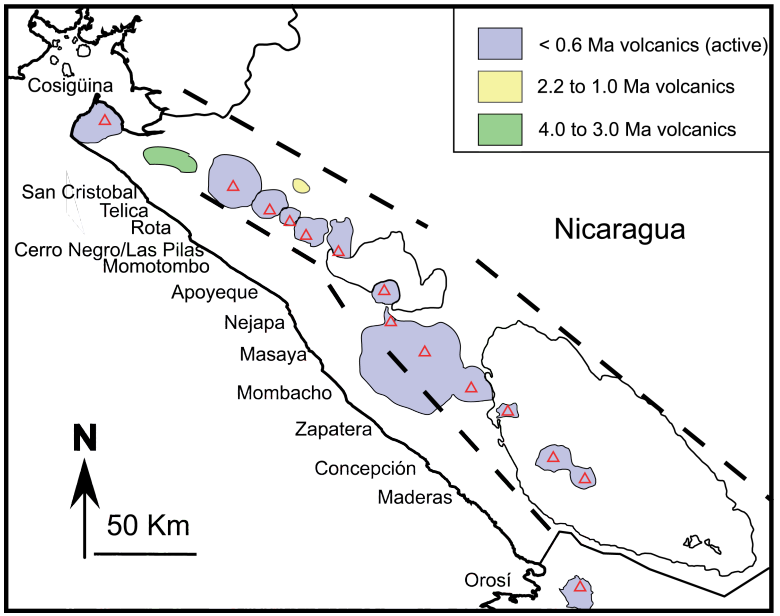
Volcanism

- Current volcanic arc
  - Costa Rica - <0.6 Ma
  - Nicaragua – 0.3-0.6 Ma
- CAVA – segmented
- Constant extrusive flux along strike
  - 5 to 9 $km^3/km/Myr$
- Global average arc flux 90 $km^3/km/Myr$ (Clift & Vannucchi, 2004)







Carr et al. (2007)

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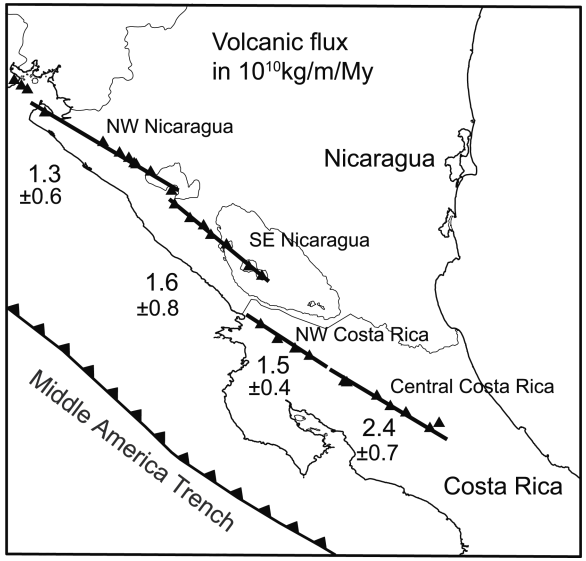
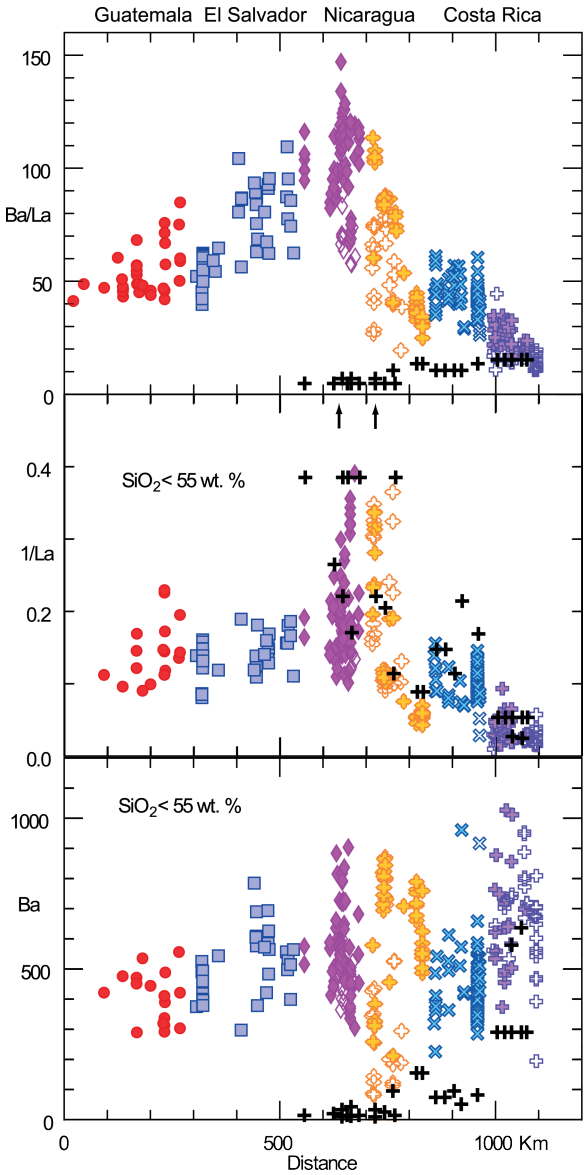
Magma-Tectonic Interactions

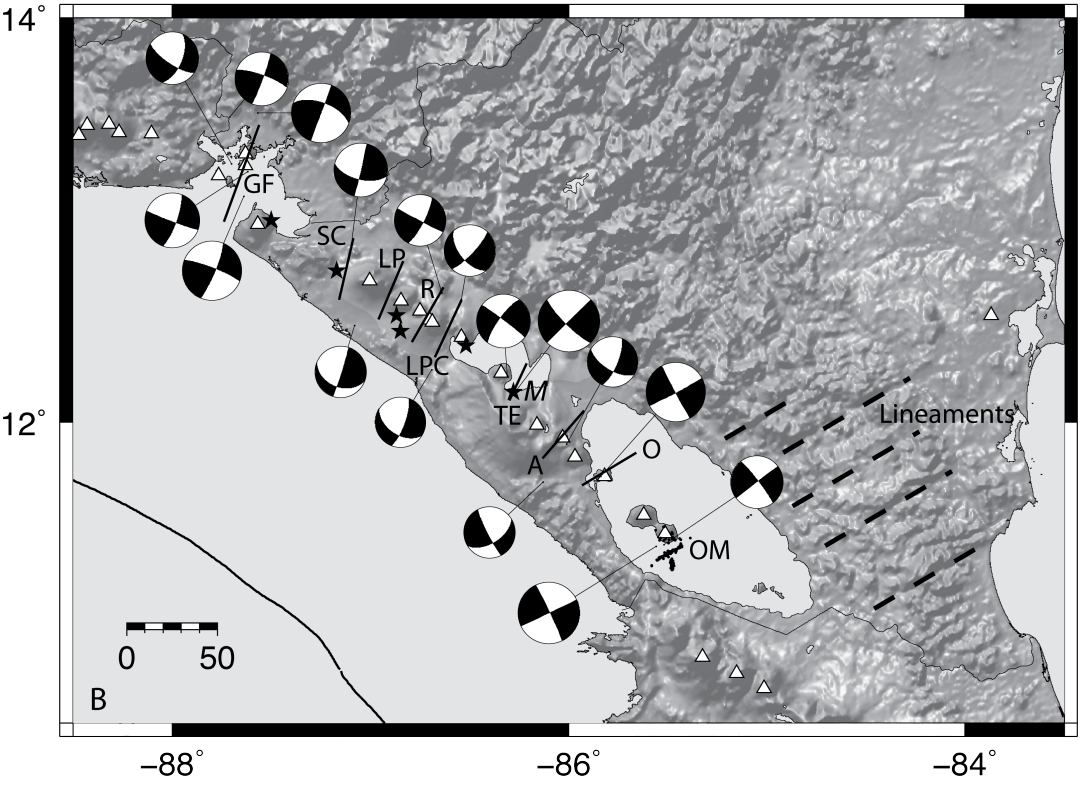
- North-trending volcanic alignments
  - Granada, Nejapa-Mira Flores, Cerro Negro, Telica
- Less evolved, non-depleted HFSE
- Extrusive mass flux 0.03 kg/m/Myr (Carr et al., 2007)





Carr et al. (2007)

Nicaragua Fore-Arc Motion



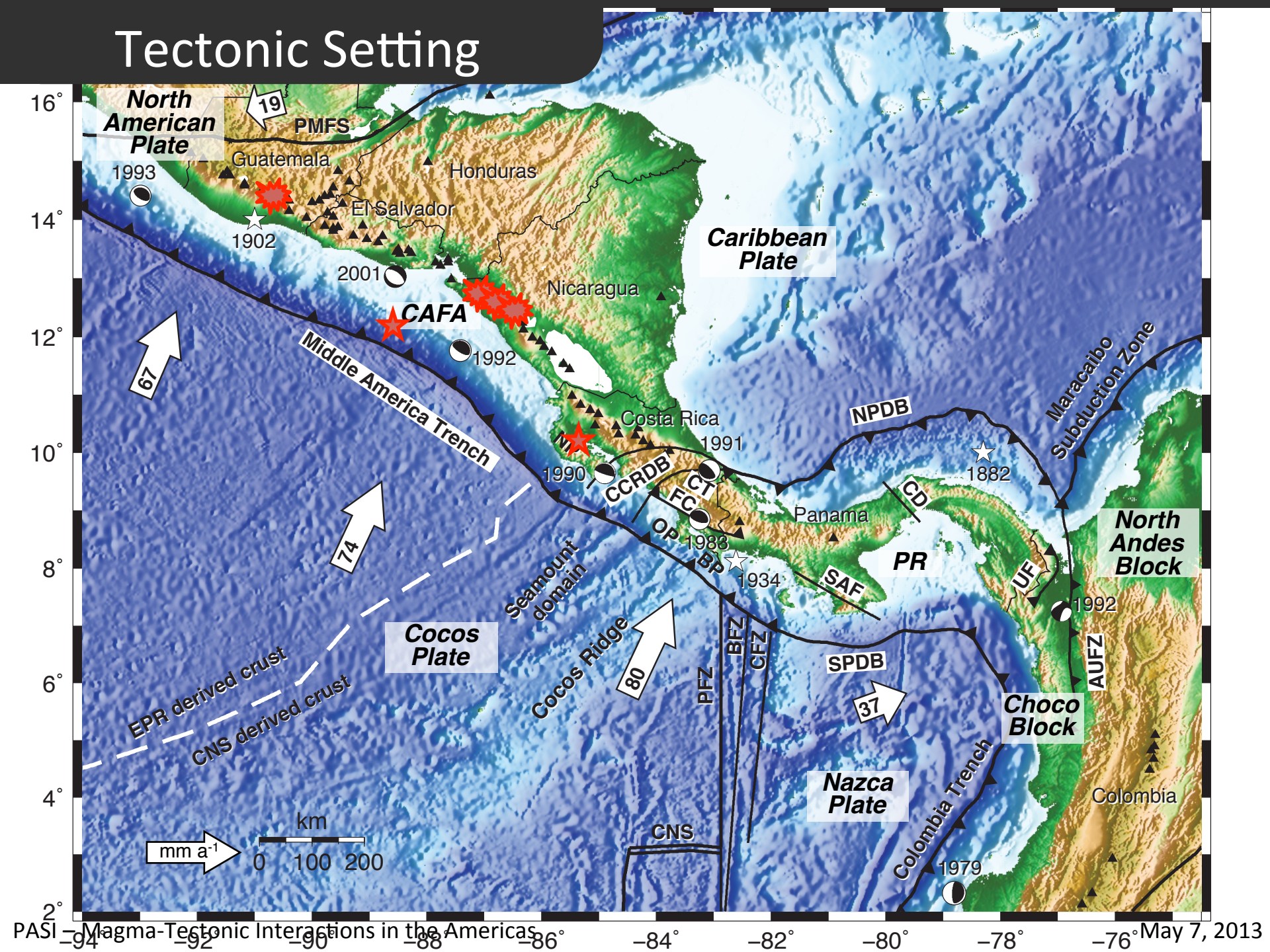
- Geometric Moment rate
  - Single margin-parallel strike slip fault
    - 2.77×10^7 m^3 yr^{-1}
  - Bookshelf faults
    - 2.62×10^7 m^3 yr^{-1}
- Compared to Geometric M_o rate from seismicity
  - 1.01×10^7 m^3 yr^{-1}
- How is the strain accommodated?

If the difference in M_o is accommodated entirely by magmatic intrusions along north-trending volcanic alignment and through endogenous volcanic growth – 50 km^3/km/Myr.

Conclusions

1. Improved Euler vector for the CAFA relative to CA is (89.1W, 8.0N, 1.125°/Ma).
   - It is expressed as relative block rates of 10.4-15.0 mm a^{-1} from northern Costa Rica to Guatemala.
2. Motion of fore-arc accommodated by bookshelf faulting in northern Costa Rica and Nicaragua.
3. Bookshelf faulting system is as efficient as margin parallel strike-slip fault system – M_o = 2.62×10^7 m^3 yr^{-1}
4. Earthquakes – M_o = 1.01×10^7 m^3 yr^{-1}
5. Fore-arc motion is accommodated by earthquakes on north-east trending, sinistral faults and by magmatism on north-trending volcanic alignments and endogenous volcano growth

Tectonic Setting




CAFA
PR
Thank You
Cocos Ridge
80
km
0 100 200

Conclusions

1 The PR is a single tectonic block (PB) in the best-fit model.
- The CAFA-PB boundary is at the western limit of the CCRDB.

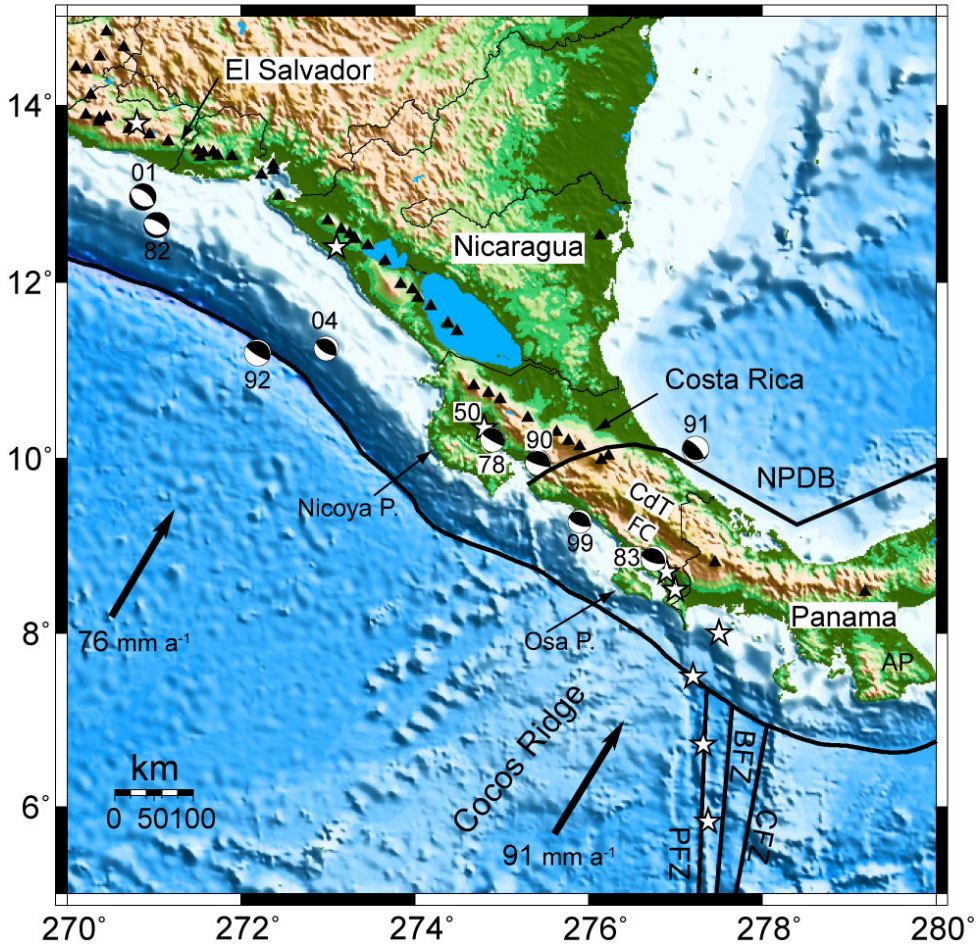
2 Improved Euler vector for the CAFA relative to CA is (89.1W, 8.0N, 1.125°/Ma).
- It is expressed as relative block rates of 10.4-15.0 mm a^{-1} from northern Costa Rica to Guatemala.

3 New Euler vector for PB motion is (95.6W, 26.9N, 0.216°/Ma).
- Relative block rates are 8.4-9.4 mm a^{-1} northeastward relative to the CA.
- This motion in interpreted as tectonic escape from the Cocos Ridge redirected by the ND and/or CH blocks.

4 Region of coupling along the Nicoya segment correlates with historic EQs.
- A larger strain than that for the 1950 event had accumulated and was partially released during the September 5, 2012 M_w7.6 earthquake.

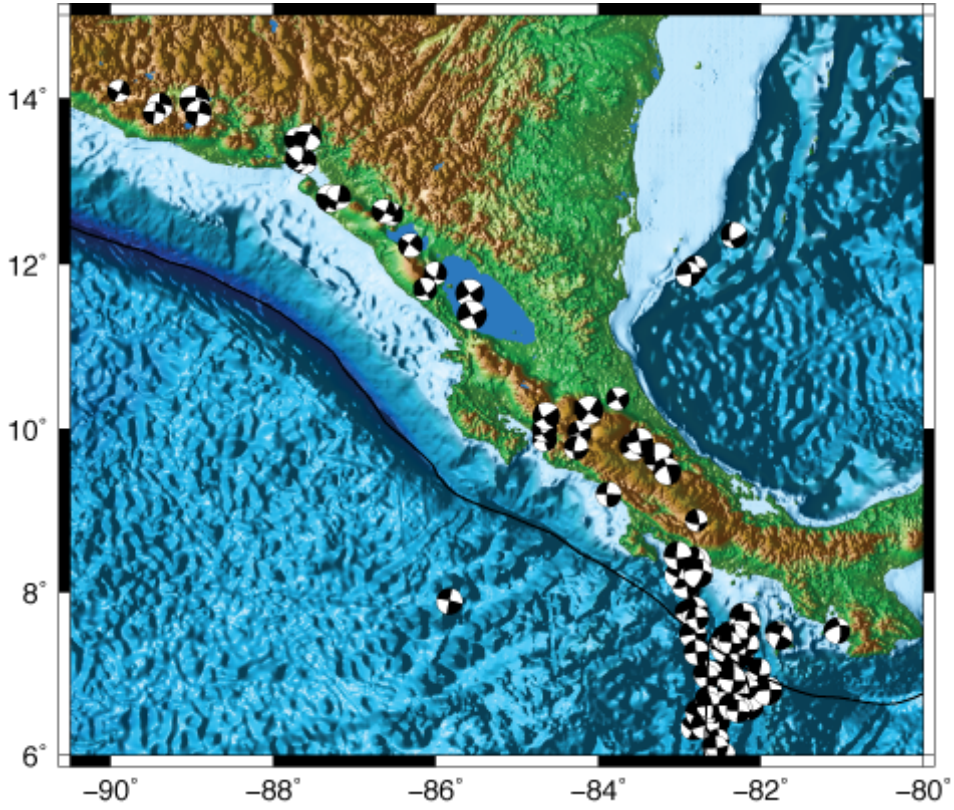
5 Region of coupling along the Osa segment correlates with historic EQs and upper plate deformation.
- If ~14 mm a^{-1} of slip deficit is accommodated as elastic strain, ≥22 mm a^{-1} is accommodated as plastic deformation.
- 0.6 m of potential slip, comparable to slip of the 1983 event, will accumulate by 2025.

Seismicity



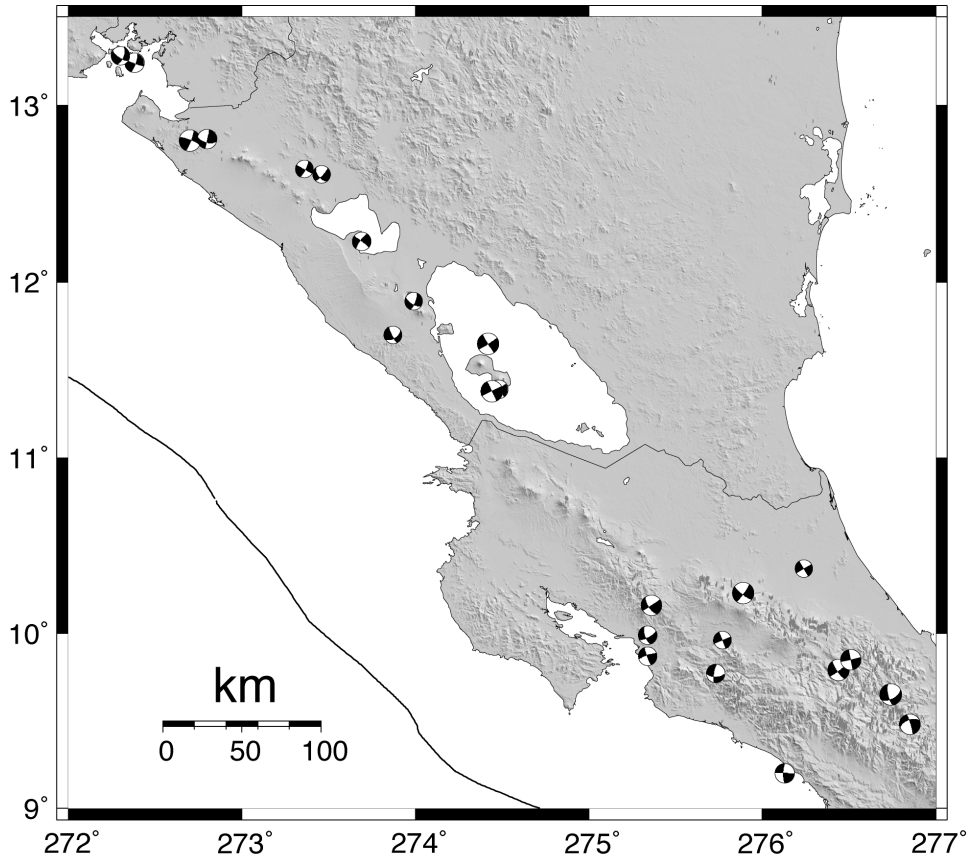
- 1950 M_w 7.7, 1990 M_w 7.3 & 2012 M_w 7.6 Nicoya Peninsula
- 1983 M_w 7.4 Osa Peninsula
- 1992 M_w 7.6 & 2012 M_w 7.3 Nicaraguan/El Salvadoran tsunamigenic
- 1991 M_w 7.7 El Limon/La Estrella
- 1906 M_w8.8 Esmeraldes

Seismicity



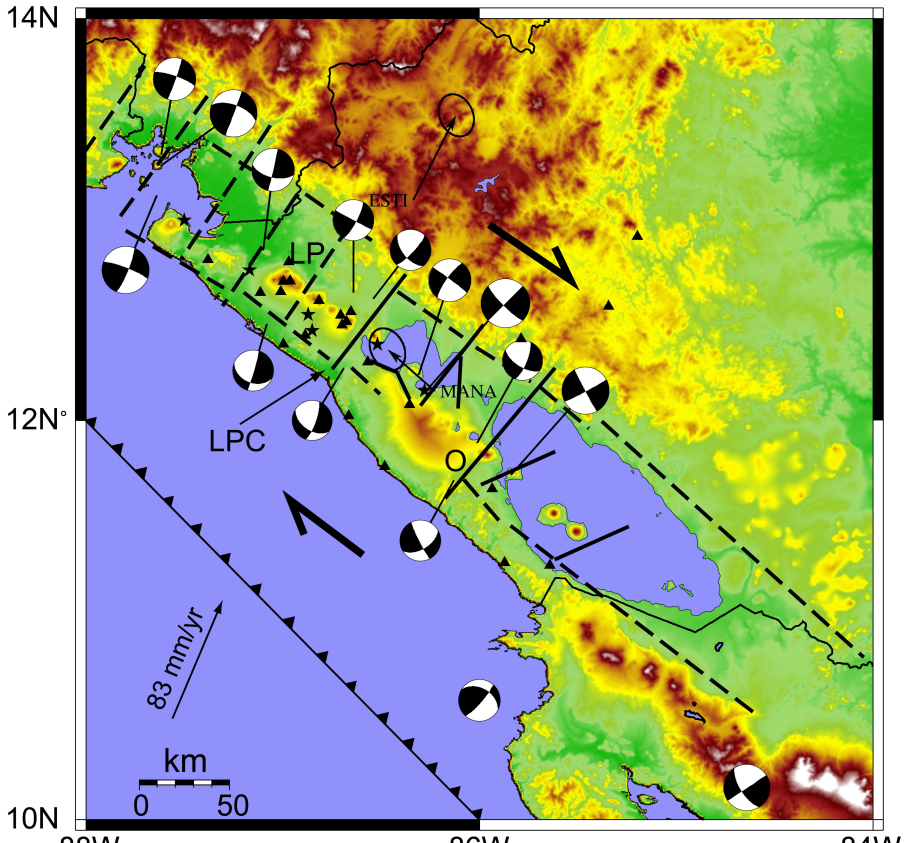
- Upper plate seismicity indicates northwest directed fore arc sliver transport
  - Central Costa Rica to Guatemala
- Diffuse deformation in CCRDB
- Shallow (<20 km) & located within 20 km of arc
- <M 6.5
- Elongated damage zones & focal mechanisms NW to NE
- Cluster & Migrate along strike
- Historically have caused greater damage and loss of life (e.g., 23/12/72 M6.2 Managua)

Fore-arc Motion



- Oblique Convergence or Cocos Ridge collision?
- Upper plate earthquake focal mechanisms (e.g., Molnar & Sykes, 1969)
- Upper plate deformation
  - NW, NE & N - trending faults and volcanic alignments

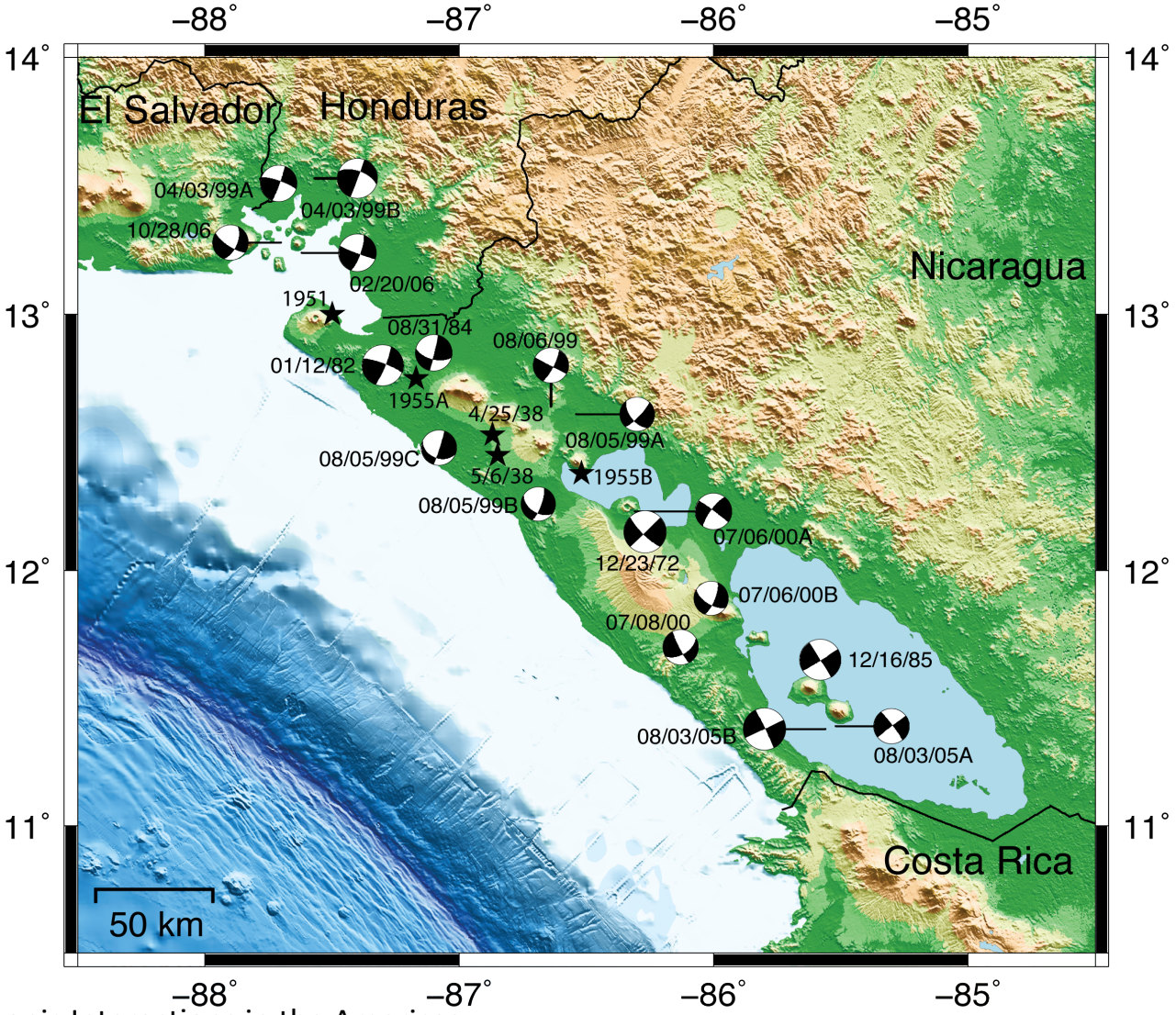
Central Costa Rica to Nicaraguan Fore-arc Motion

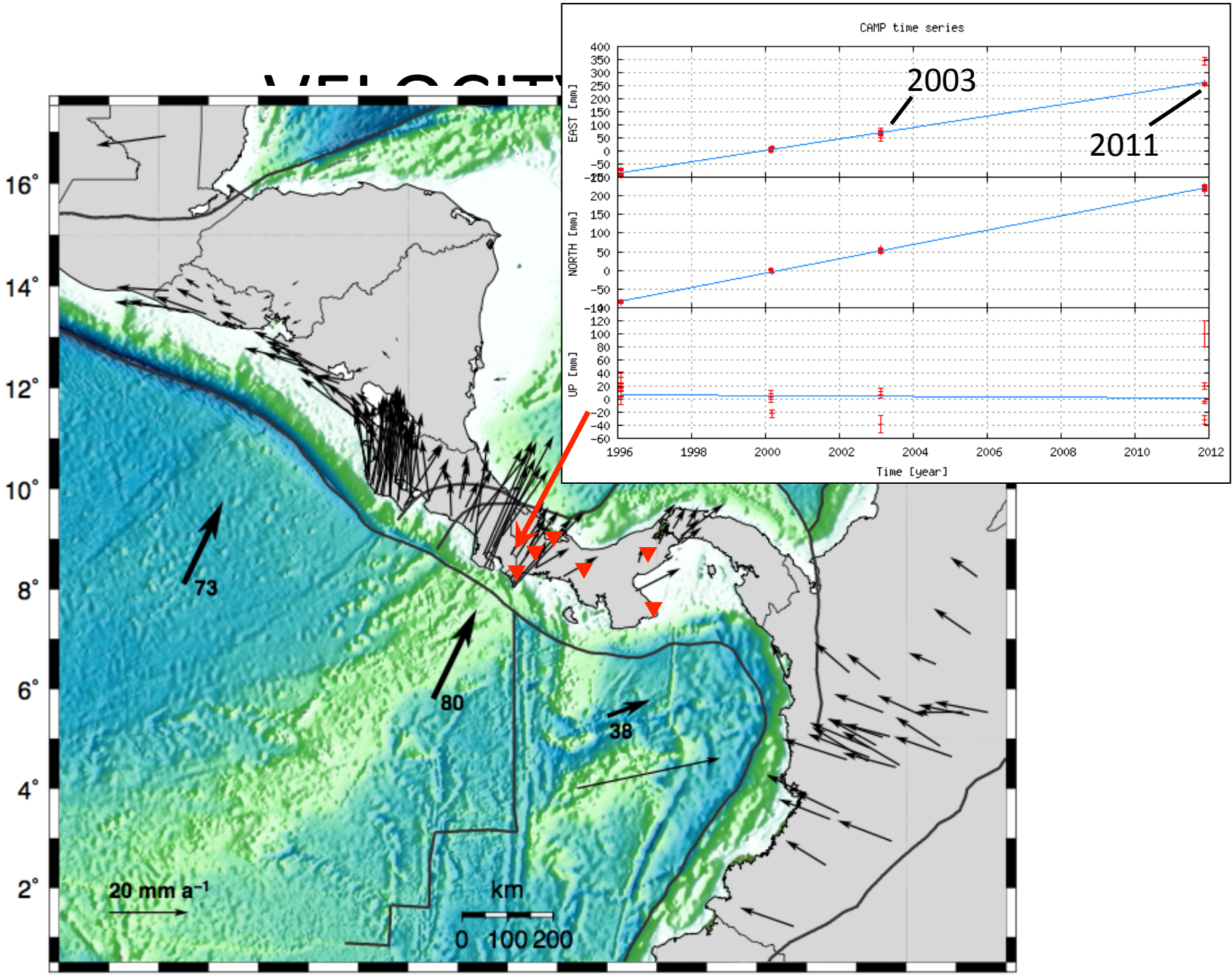


LaFemina et al. (2002) *Geology*

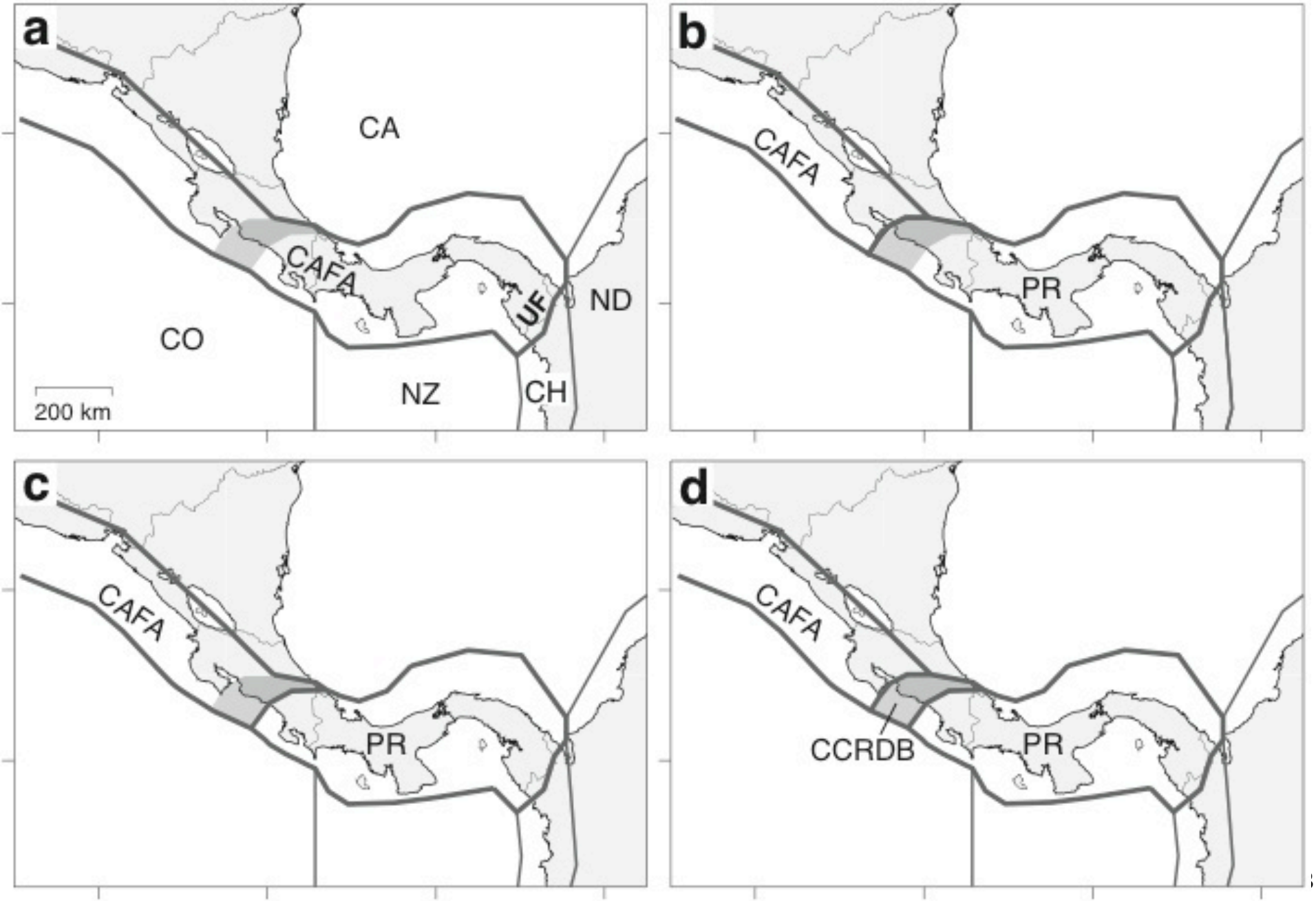
- Focal mechanisms are consistent w/ NE or NW trending fault planes
- Aftershocks and surface ruptures trend NE
- Vertical axis block rotation - "bookshelf" faulting

Nicaraguan Fore-arc Motion – Earthquake Focal Mechanisms

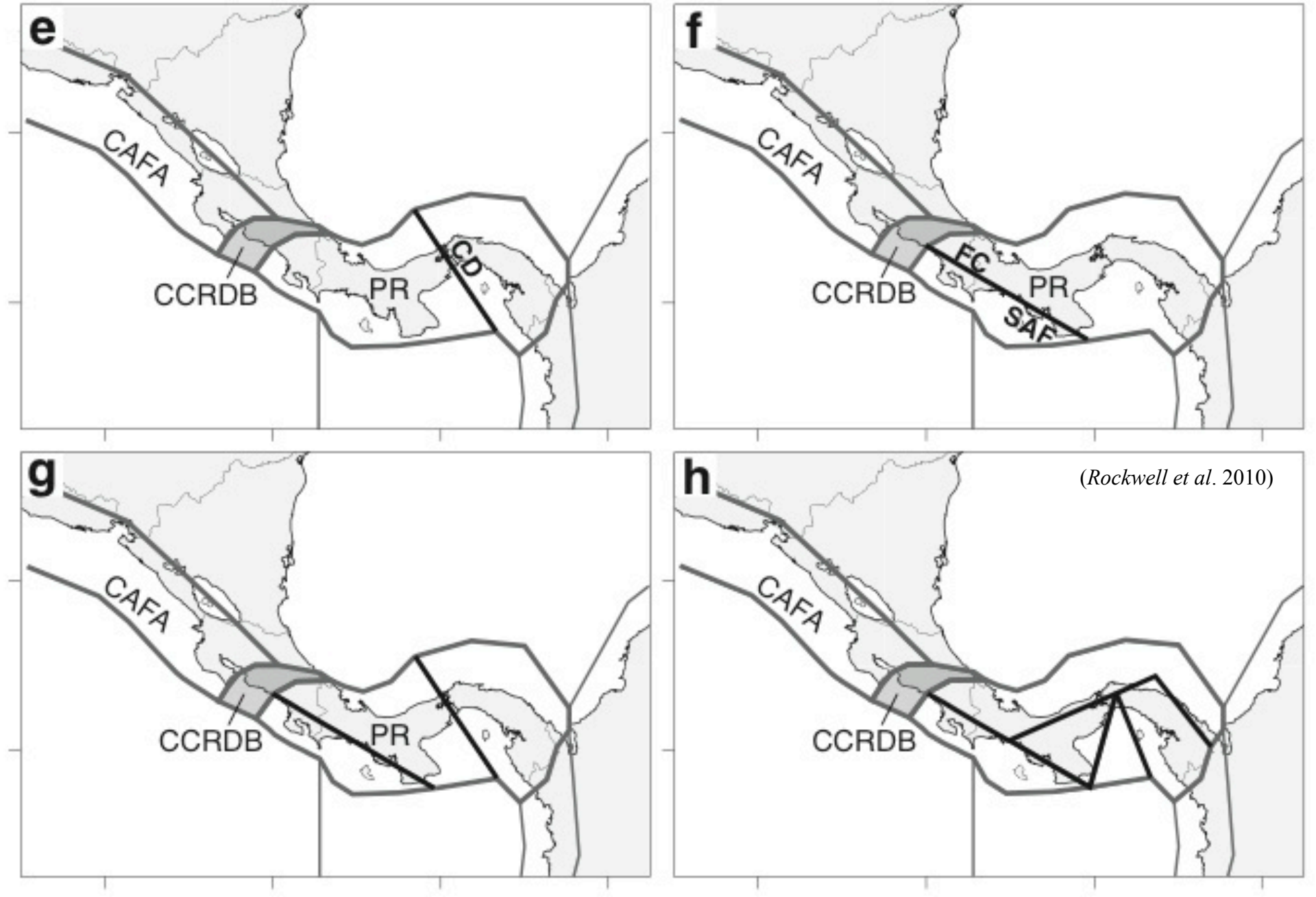



CAMP time series
2003
2011
EAST [mm]
NORTH [mm]
UP [mm]
Time [year]
1996
1998
2000
2002
2004
2006
2008
2010
2012
16°
14°
12°
10°
8°
6°
4°
2°
73
80
38
20 mm a⁻¹
km
0 100 200
−92°
−90°
−88°
−86°
−84°
−82°
−80°
−78°
−76°
−74°

Models

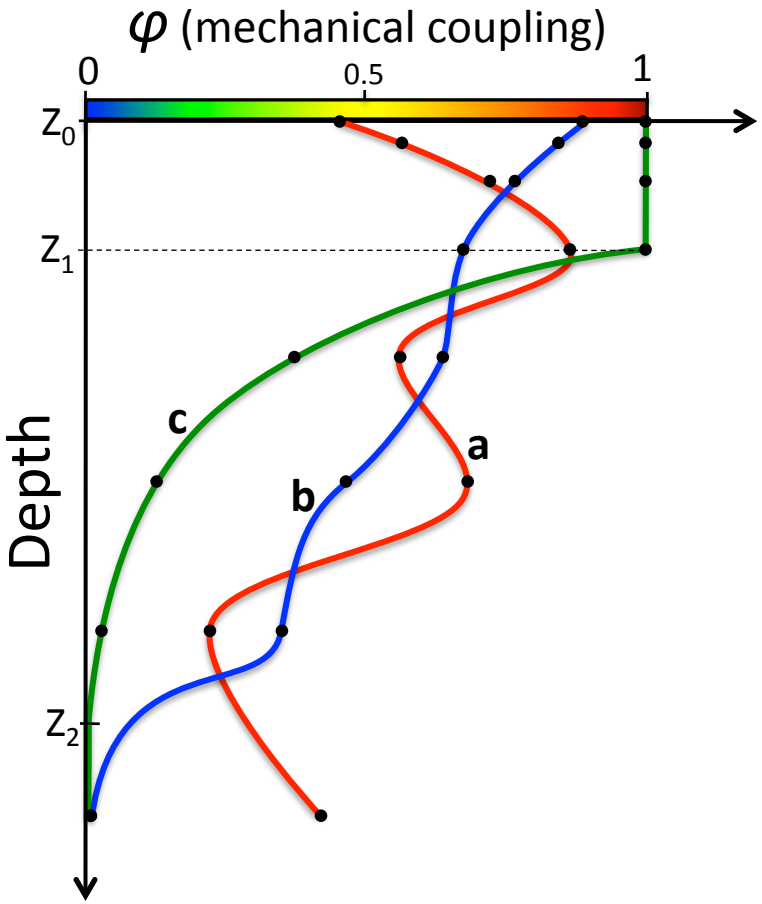


Models



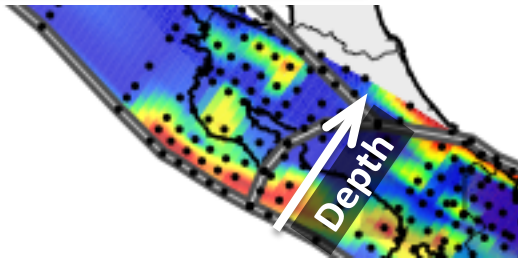
(*Rockwell et al*. 2010)

PARAMETARIZATION



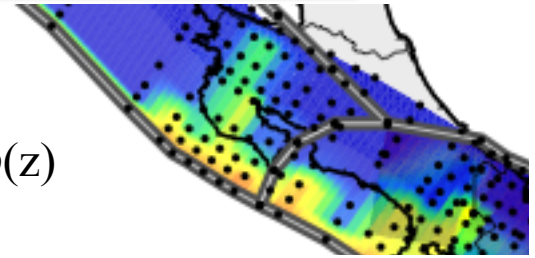
Three Types of Along-Dip Distribution

a. Independent

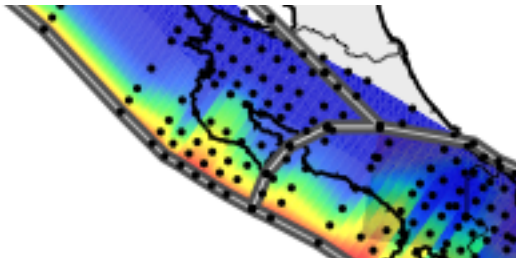


b. Down-dip Constraint

$\varphi(z+1) \leq \varphi(z)$



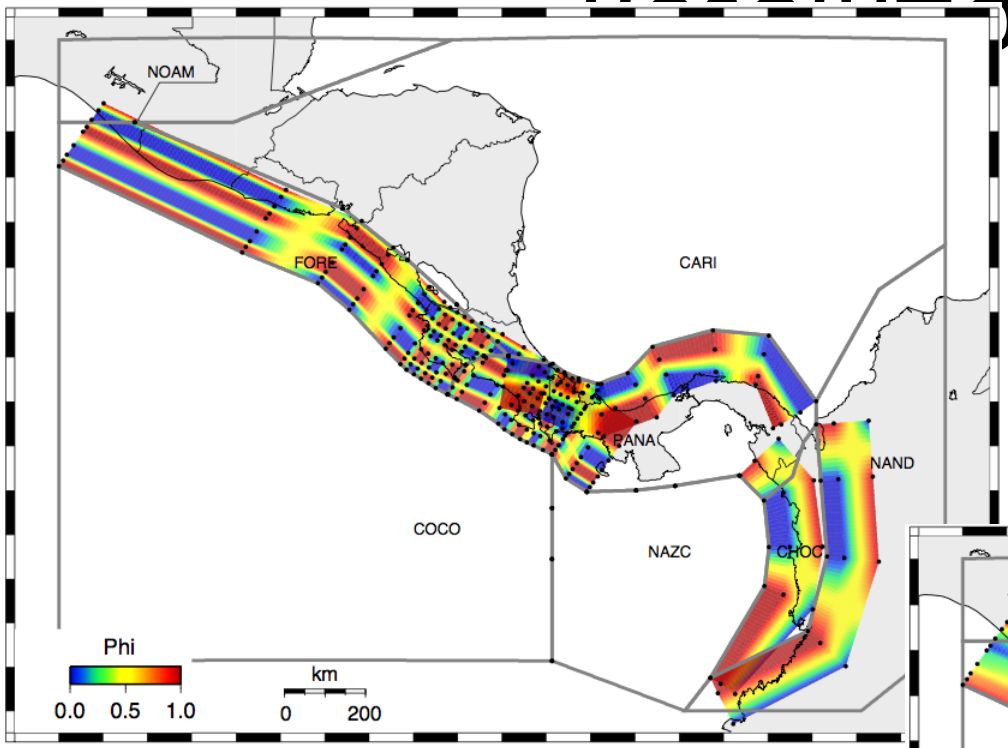
c. Exponential Decay (Wang et al. 2003)



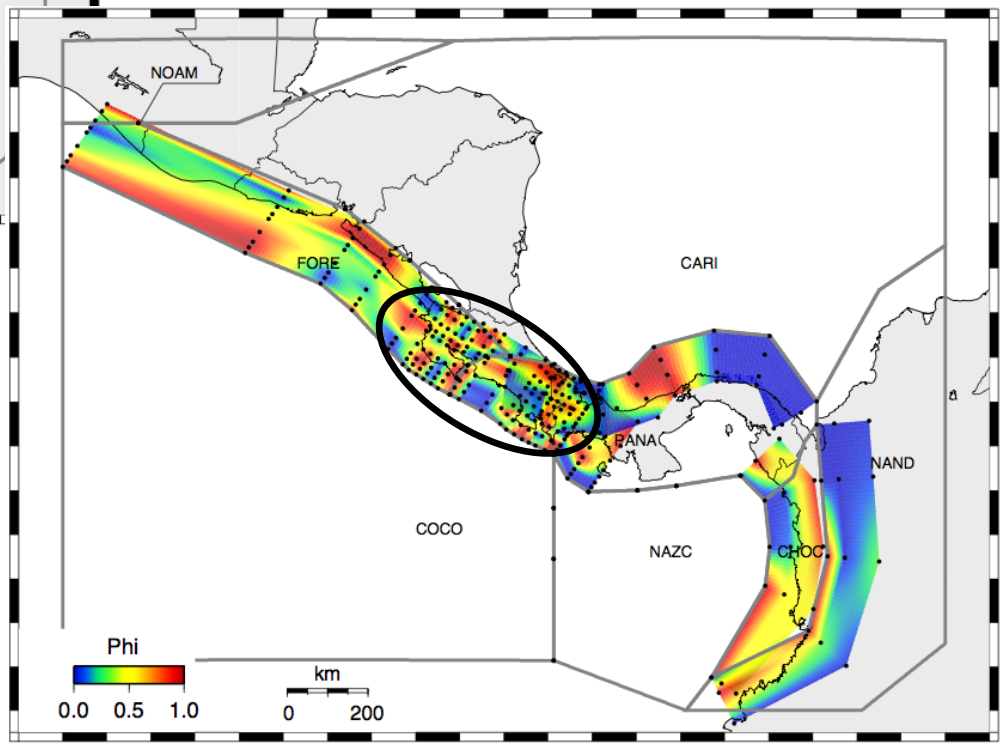
Non-Vertical Faults

Resolution Test

Input

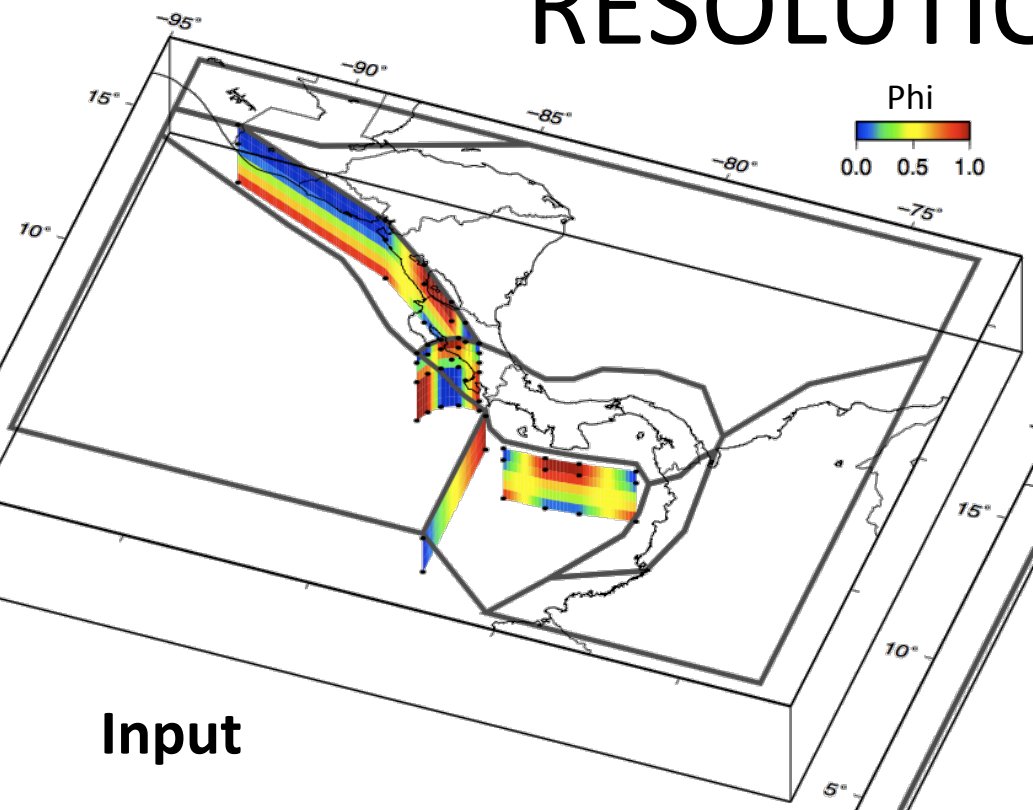


Output

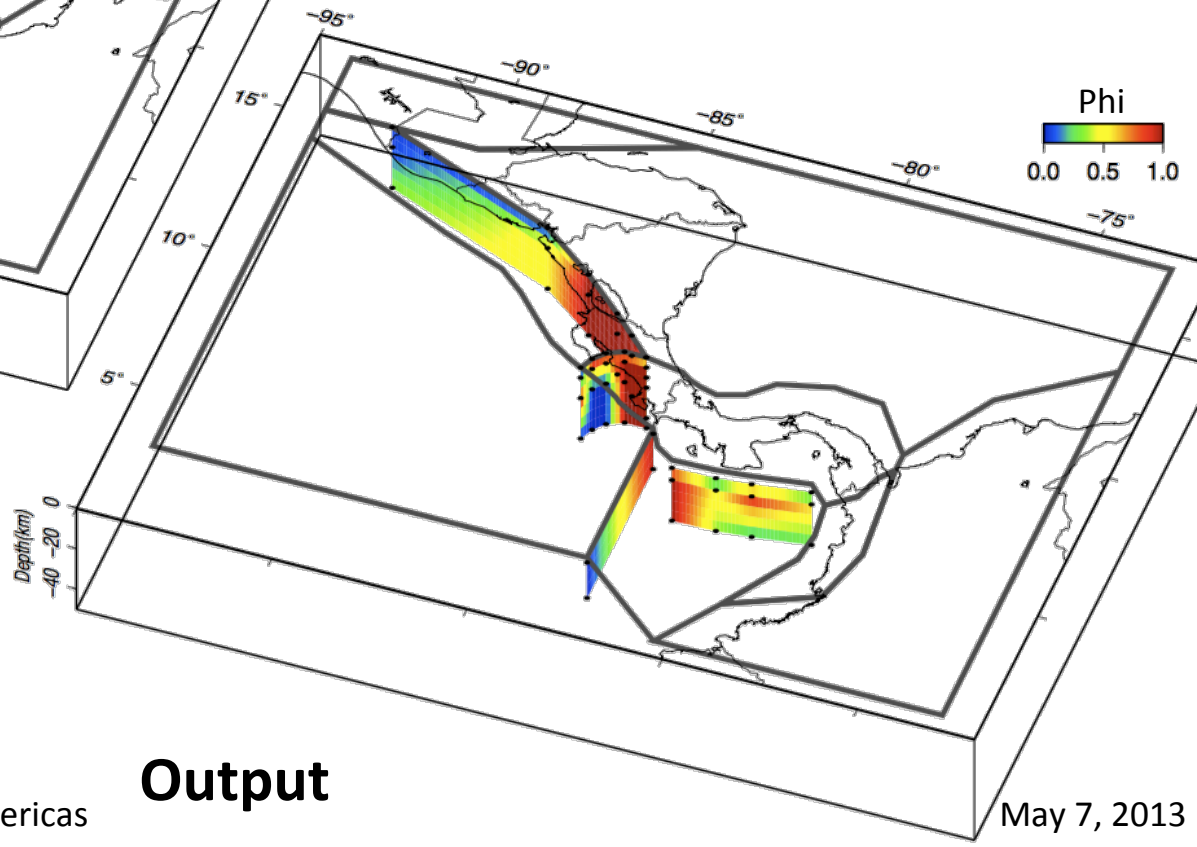


Vertical Fault

RESOLUTION TEST

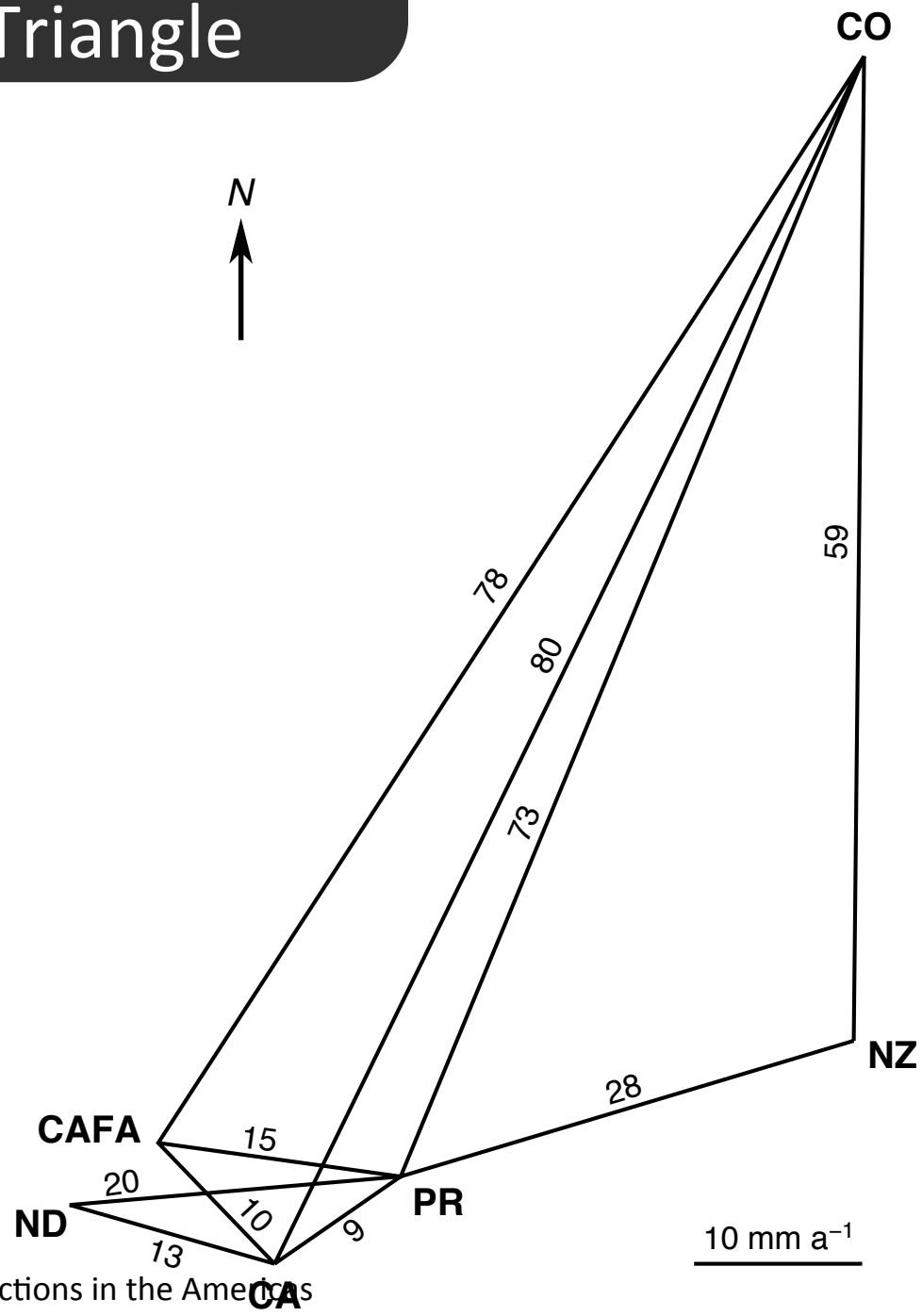


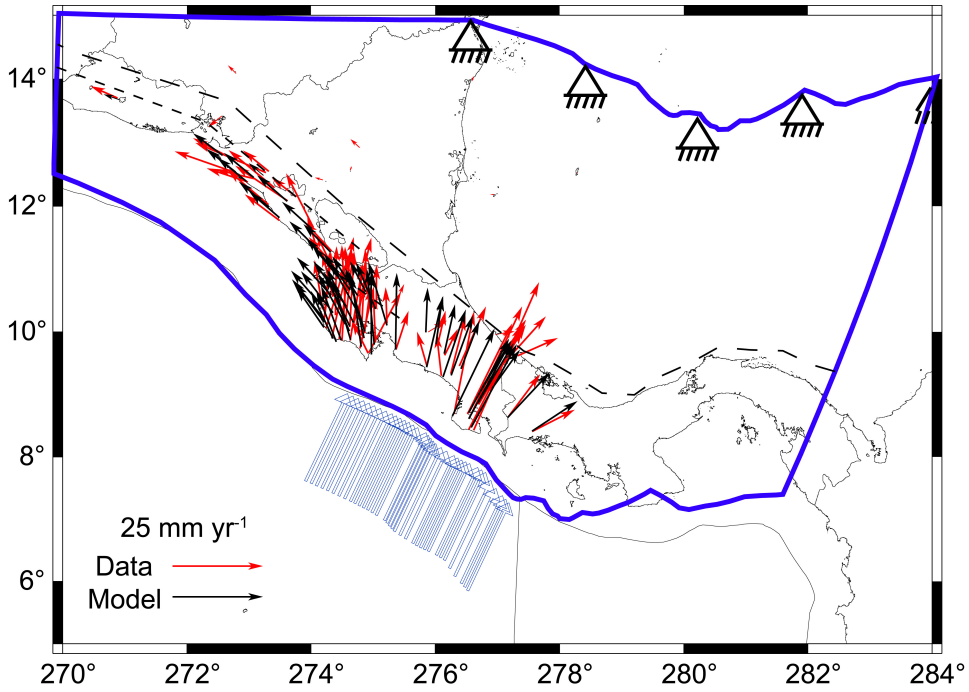
Input



Output

Velocity Triangle





LaFemina et al. (2009)

- FEM of Ridge Collision (GTECTON)
  - Spherical shell elements
  - Variable rheology b/w forearc/arc (viscoelastic) and Caribbean crust (elastic)
  - Low-friction faults along arc aid in accommodating forearc motion
  - North fixed; East and west free
  - Velocity boundary condition - CNS-2 - Cocos Ridge crust
- Captures main features of velocity field and long-term deformation
  - High rates inboard CR
  - Forearc transport

Ridge Collision

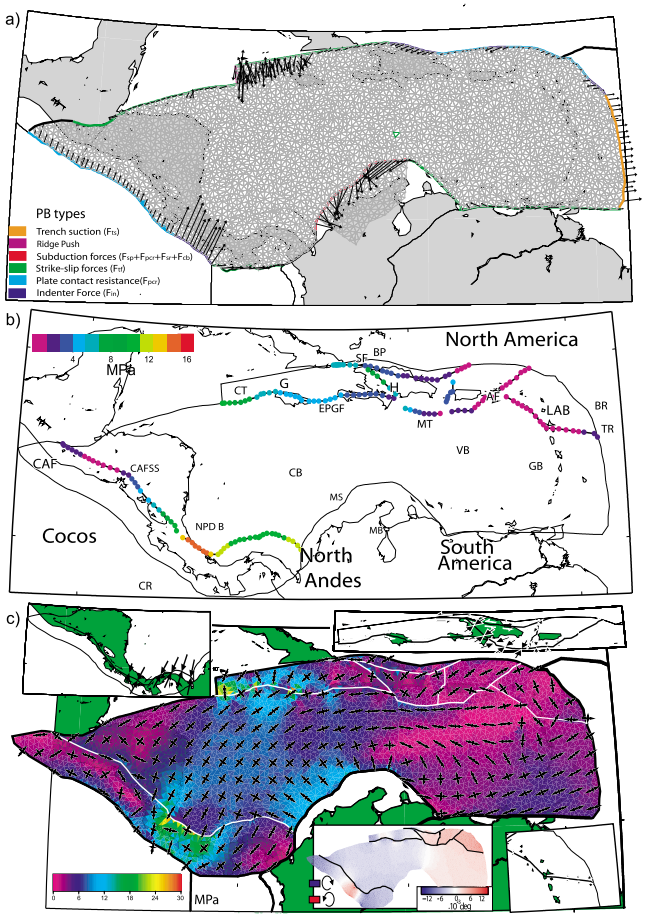
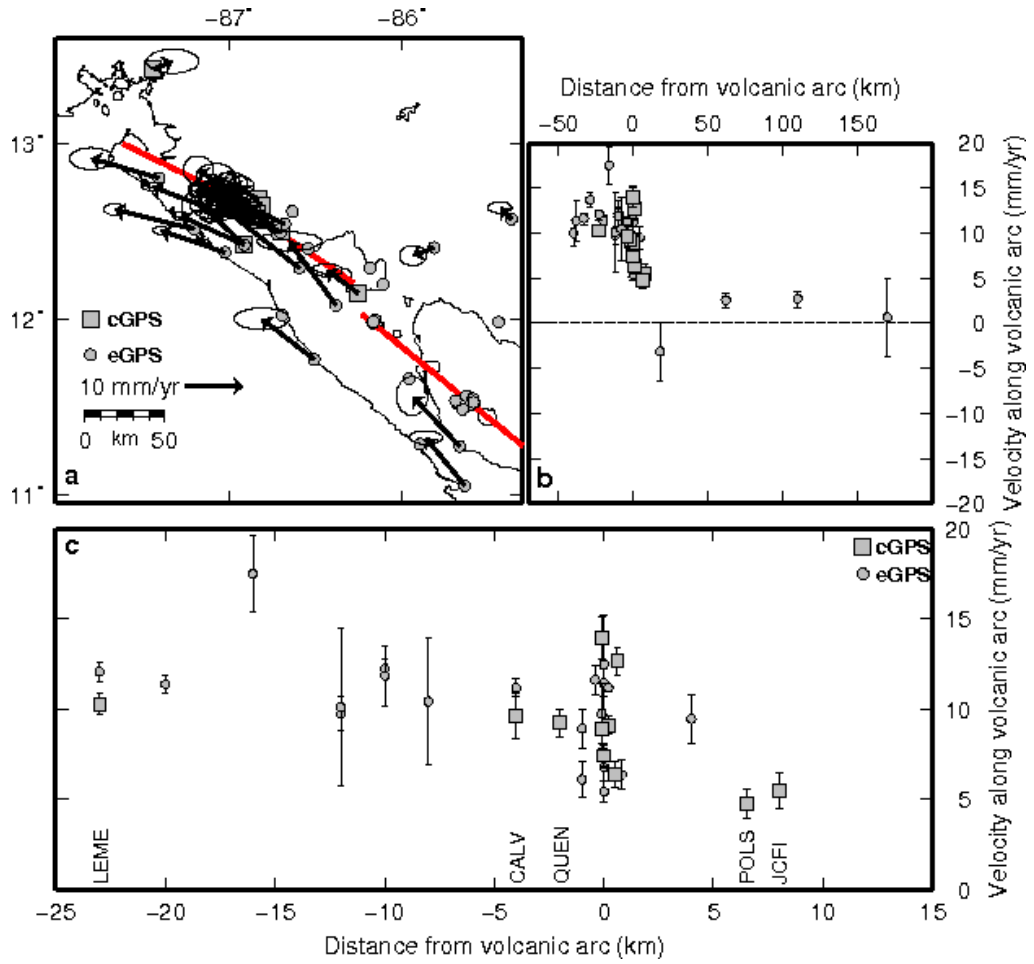


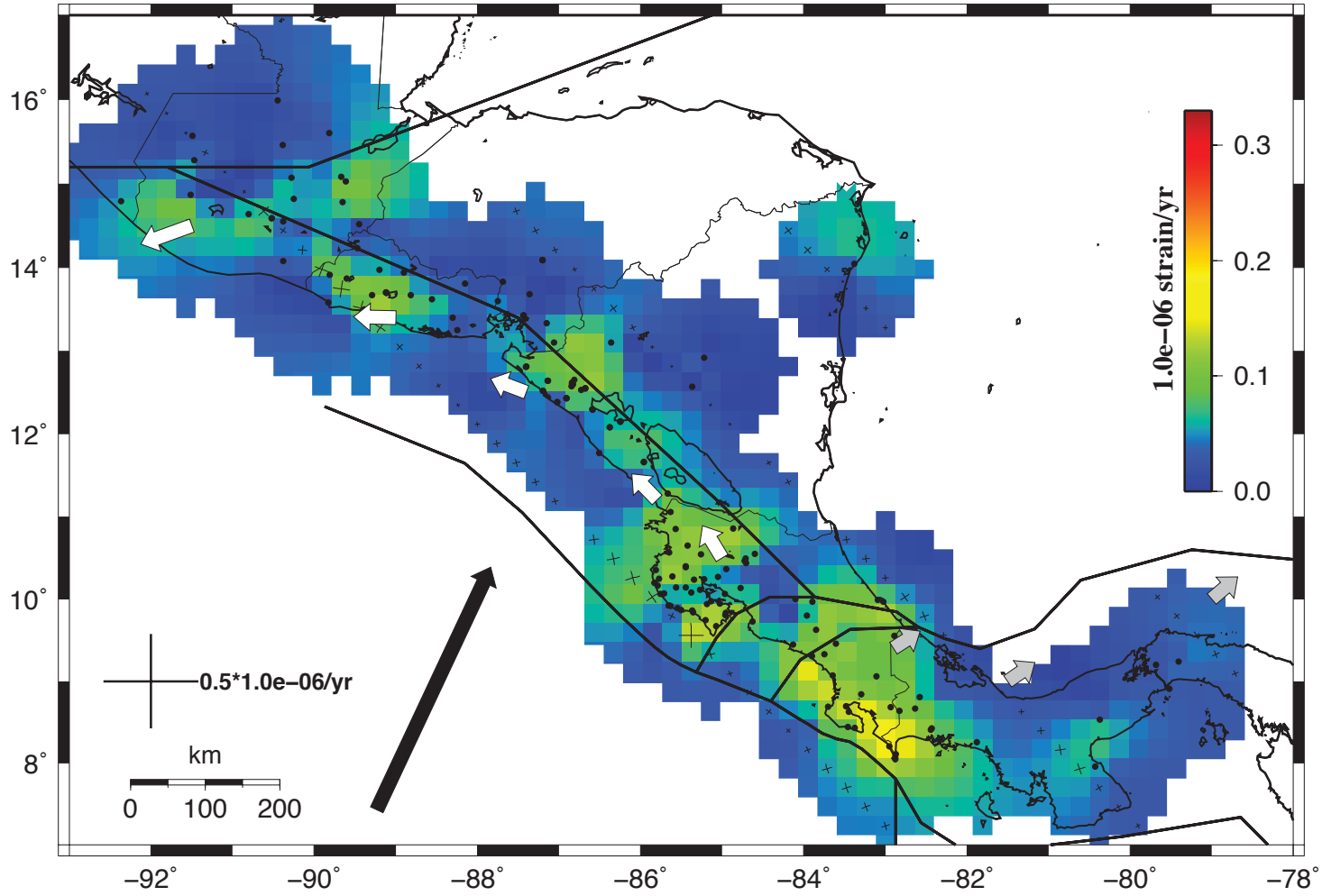
Figure 7

- Van Benthem & Govers (2010)
  - The Caribbean Plate: Pushed, Pulled or Dragged
- Cocos Ridge is the largest force acting on the Caribbean plate

Northern Nicaragua Fore-Arc



Strain Rate

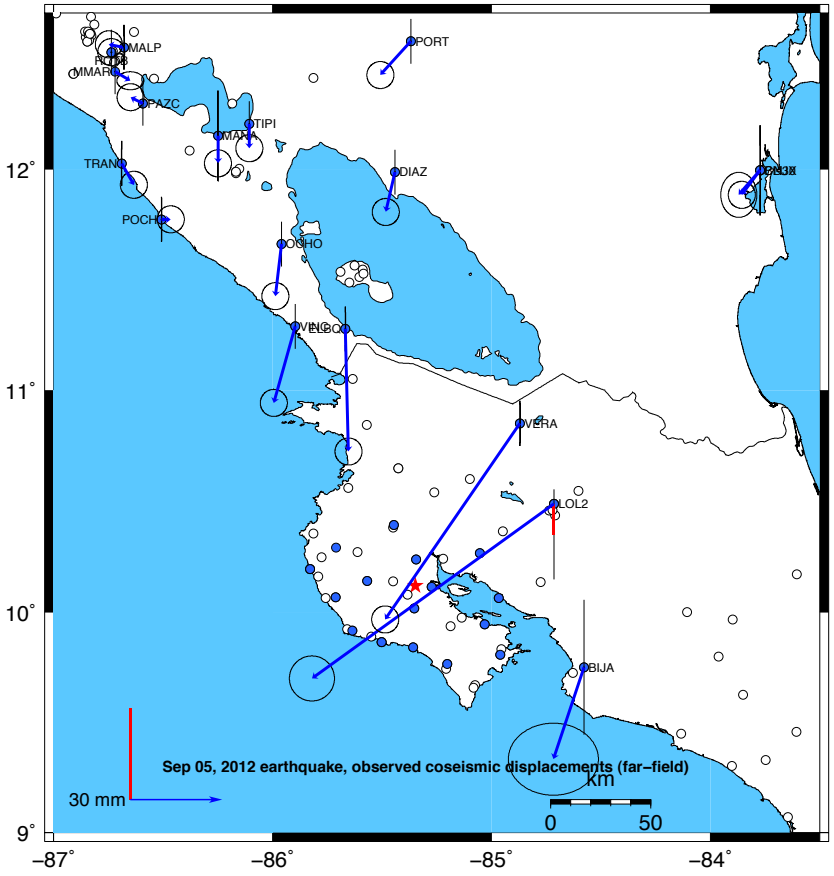


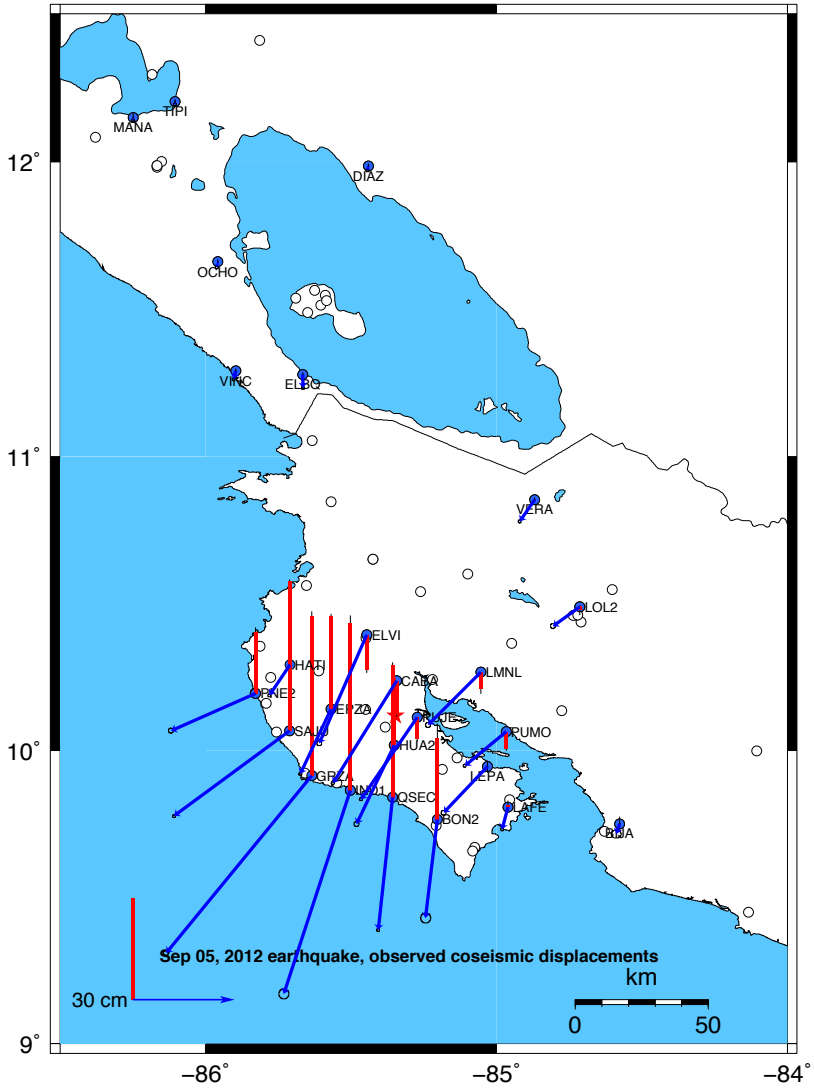
- High shear strain rates associated with fore-arc motion and ridge collision
- Low strain rates in central Panama and back-arc

2012 Earthquakes

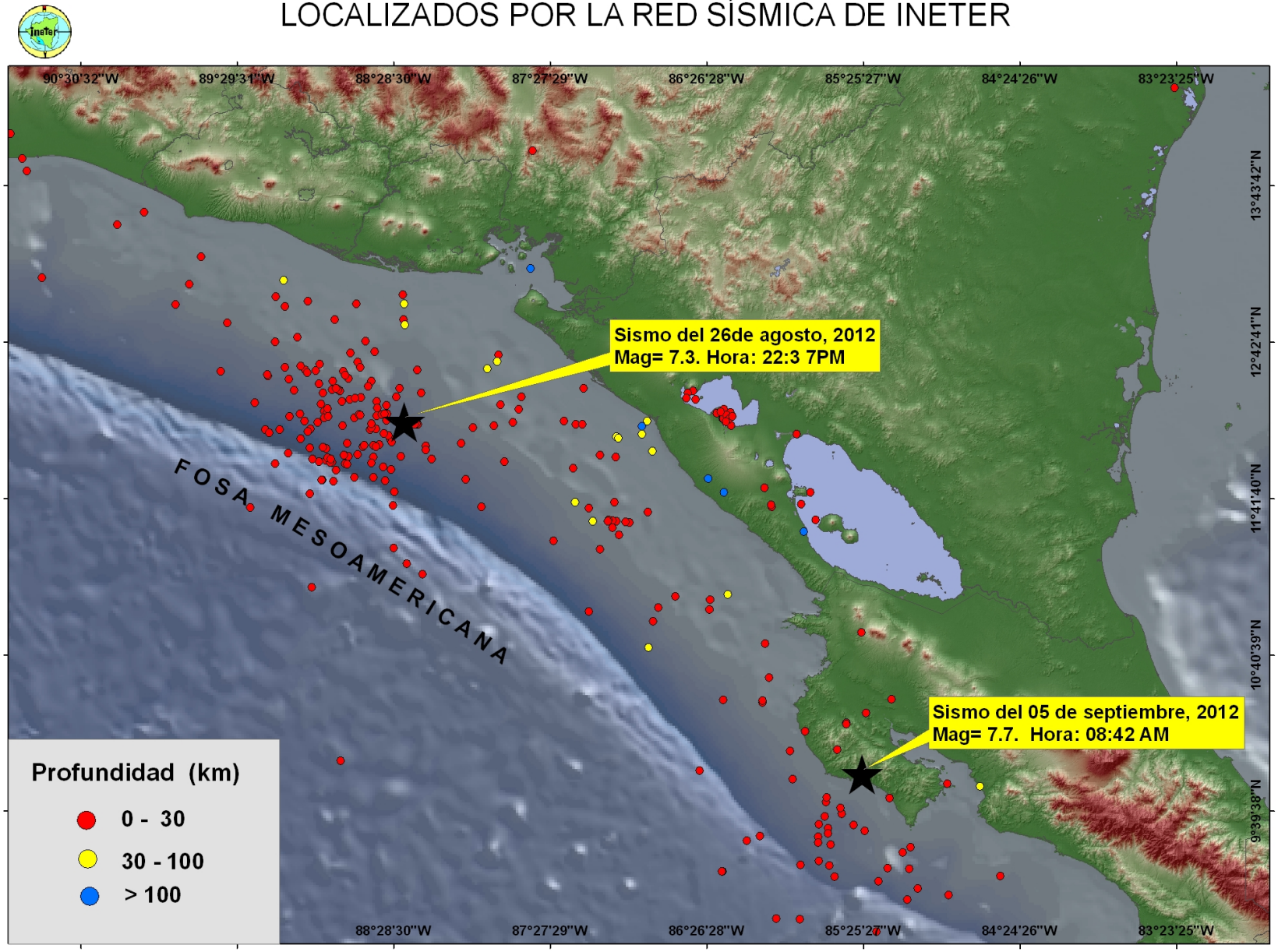
5/09/12 M_w7.6 Nicoya

Coseismic Offsets

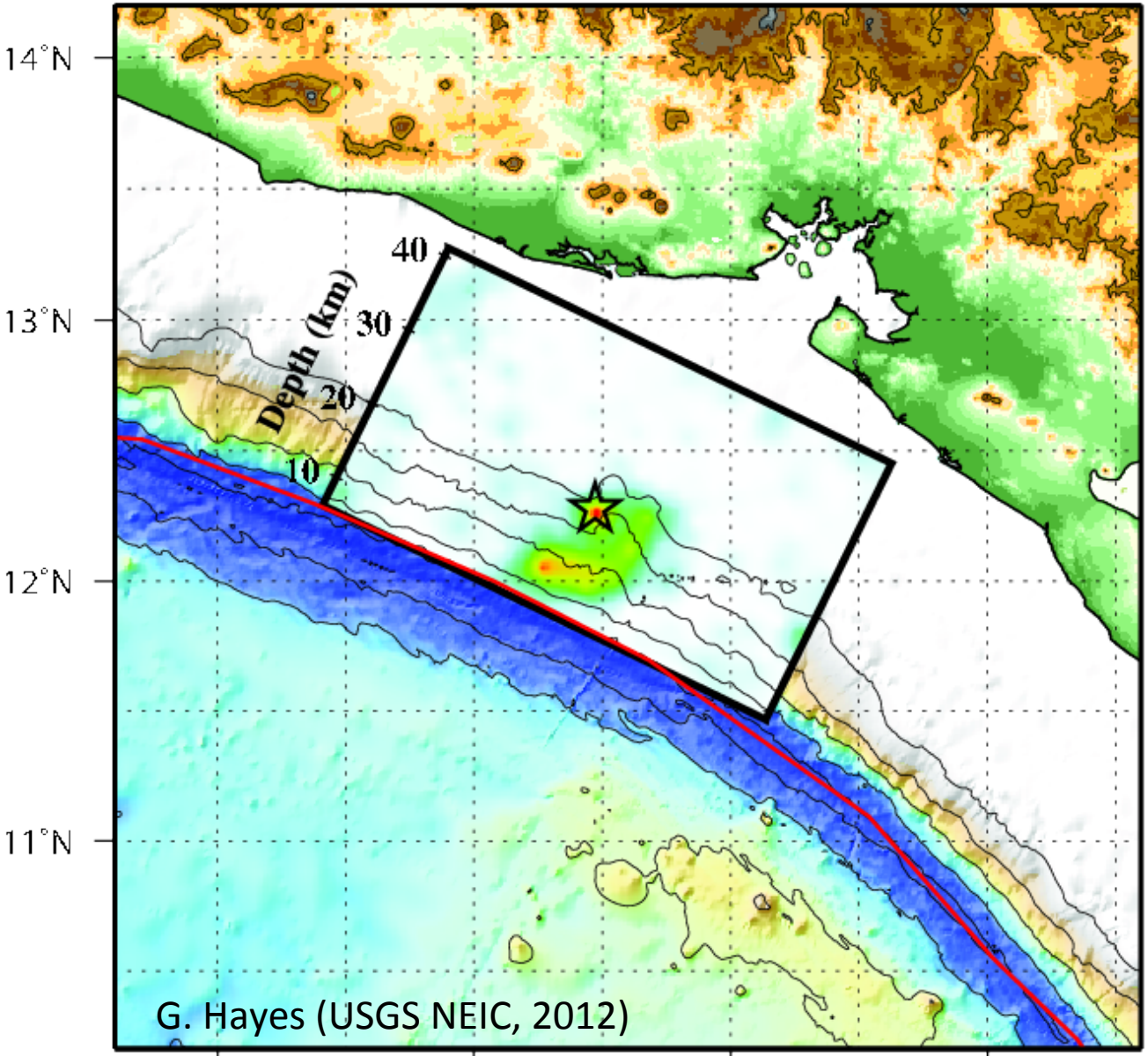




August 27, 2012 M_w7.3



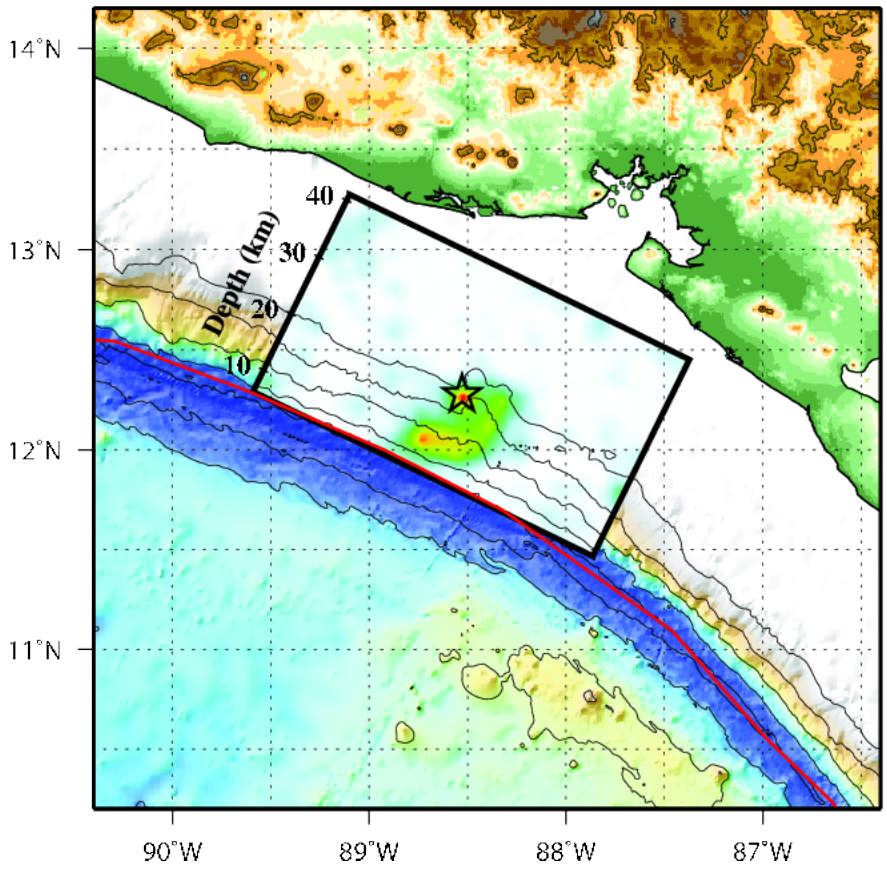
August 27, 2012 M_w7.3



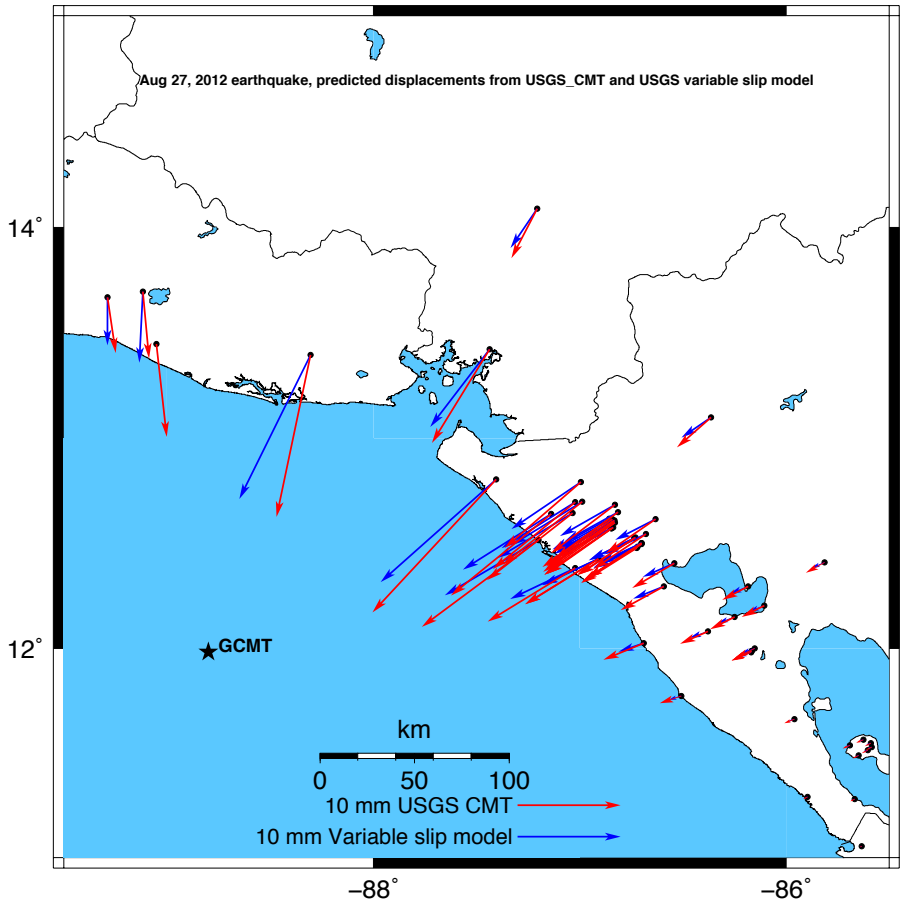
Media frenzy following the El Salvador earthquake


August 27, 2012 M_w7.3
Tsunami in Mechapa, Nicaragua

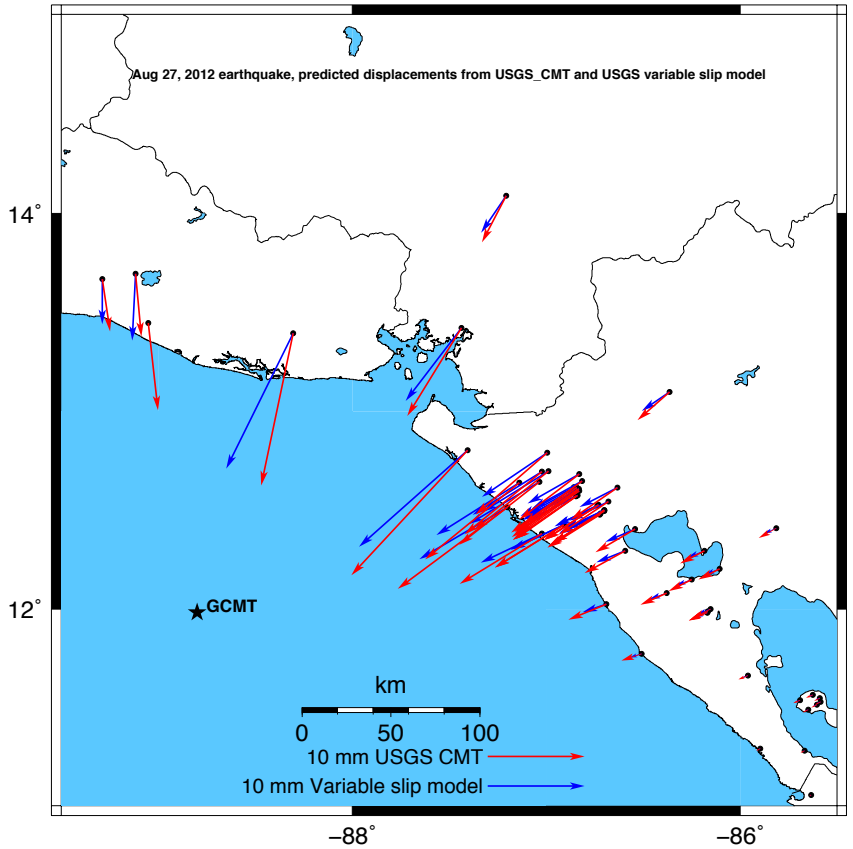
August 27, 2012 M_w7.3

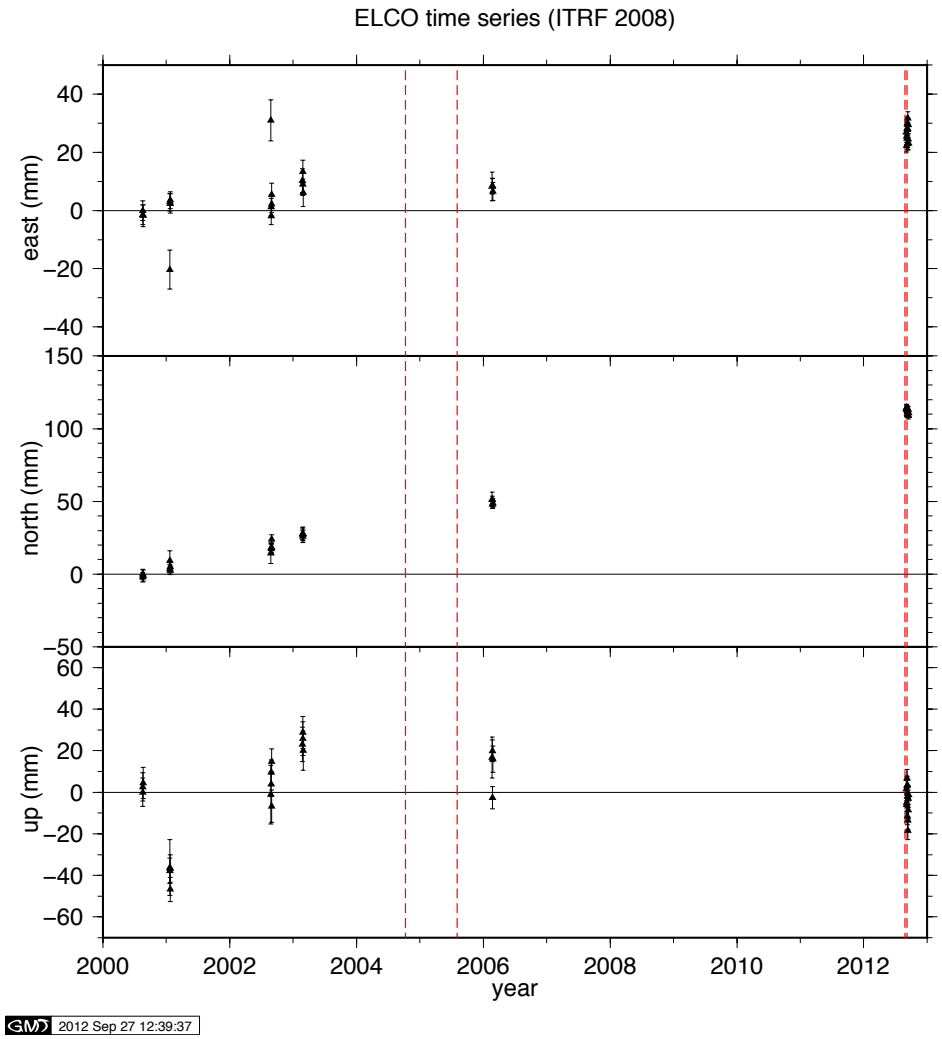


G. Hayes (USGS NEIC, 2012)

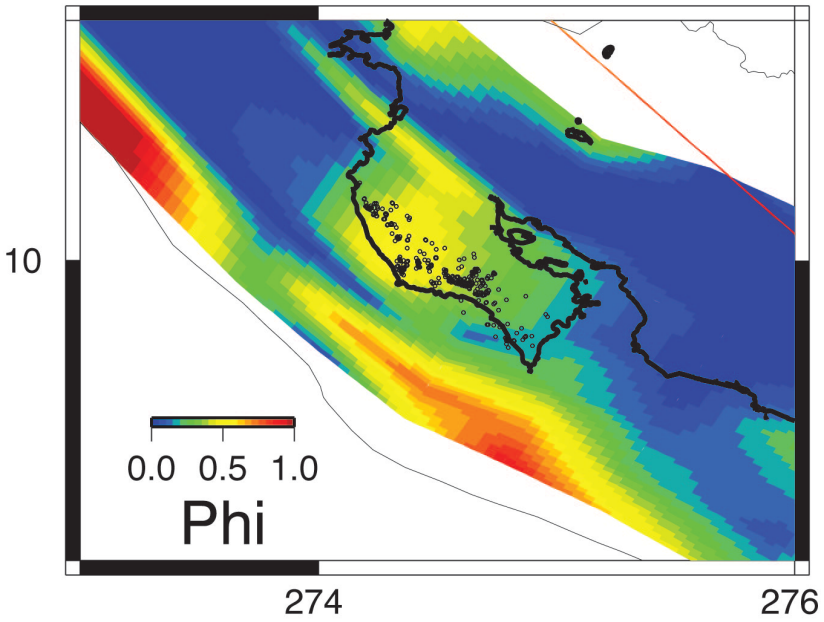


August 27, 2012 M_w7.3

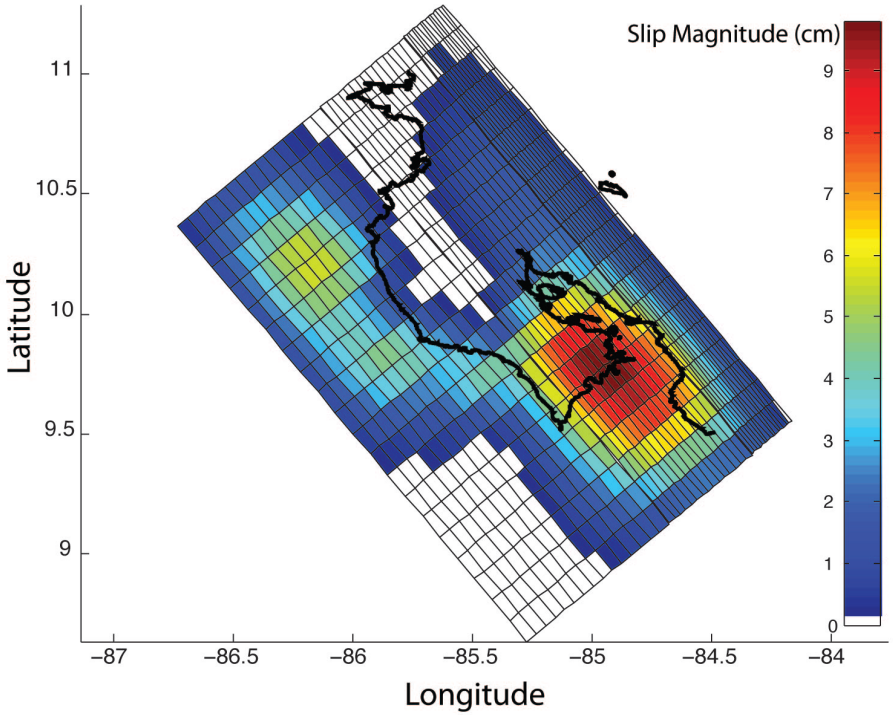




Coupling & SSE Patterns

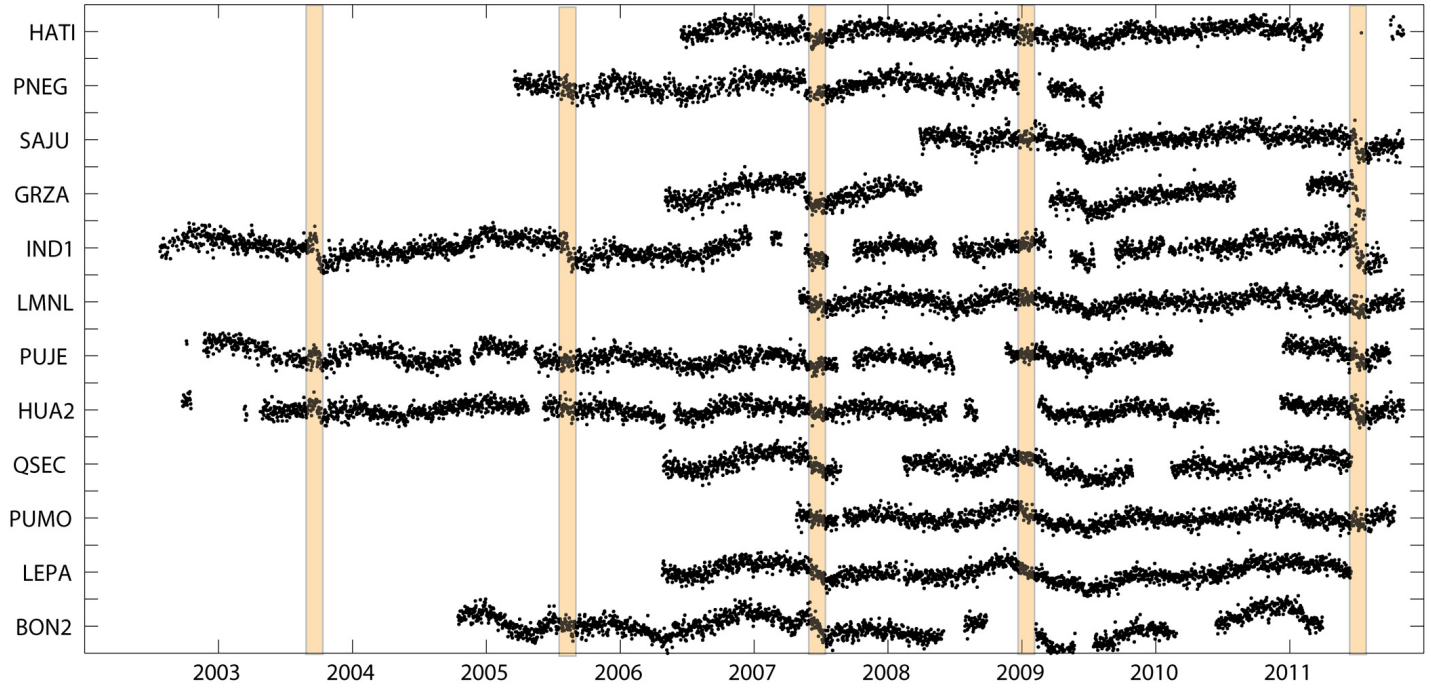


LaFemina et al. (2009)



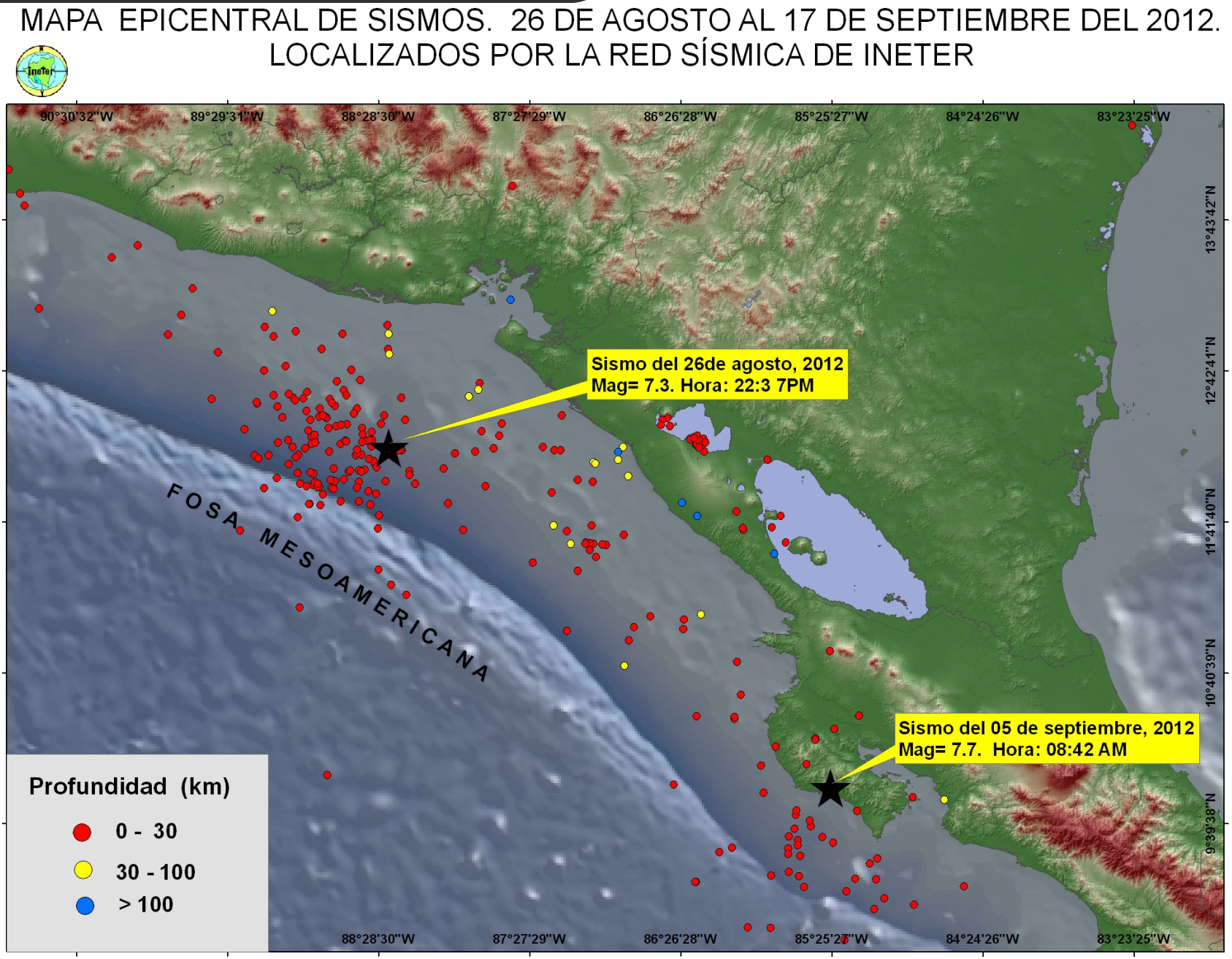
Outerbridge et al. (2010)

Nicoya Slow Slip Events



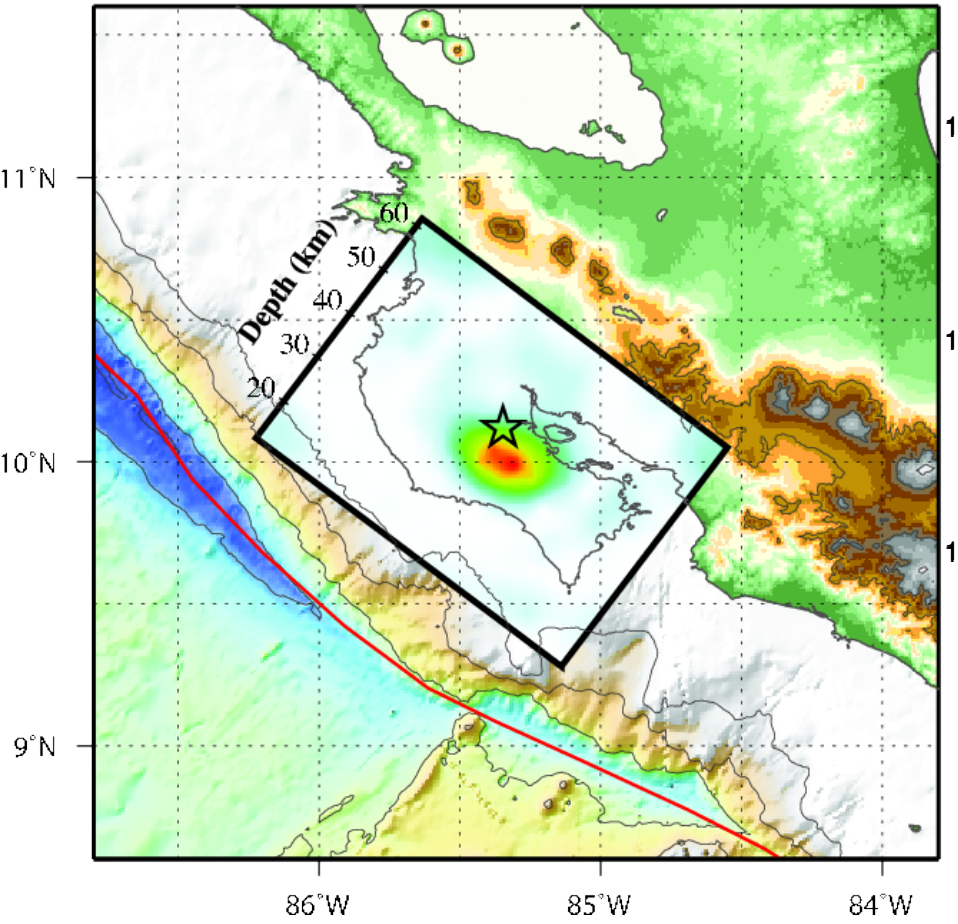
Jiang et al. (2012)

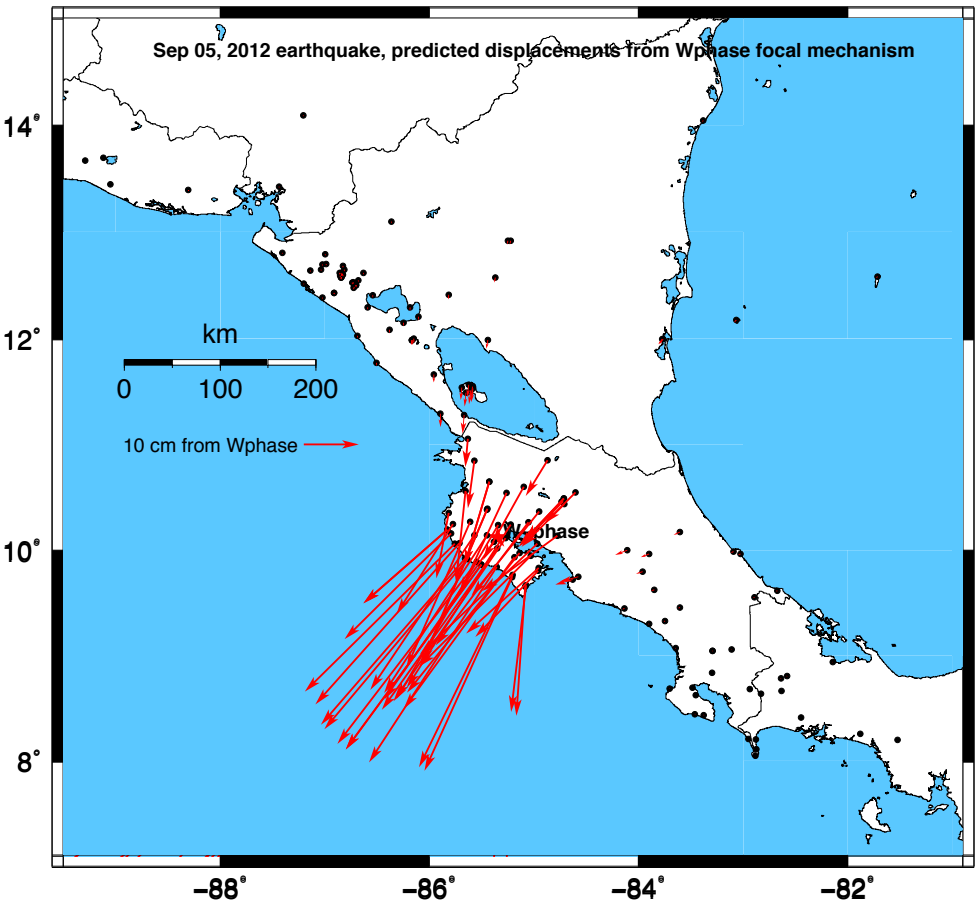
September 5, 2012 M_w7.6



September 5, 2012 M_w7.6

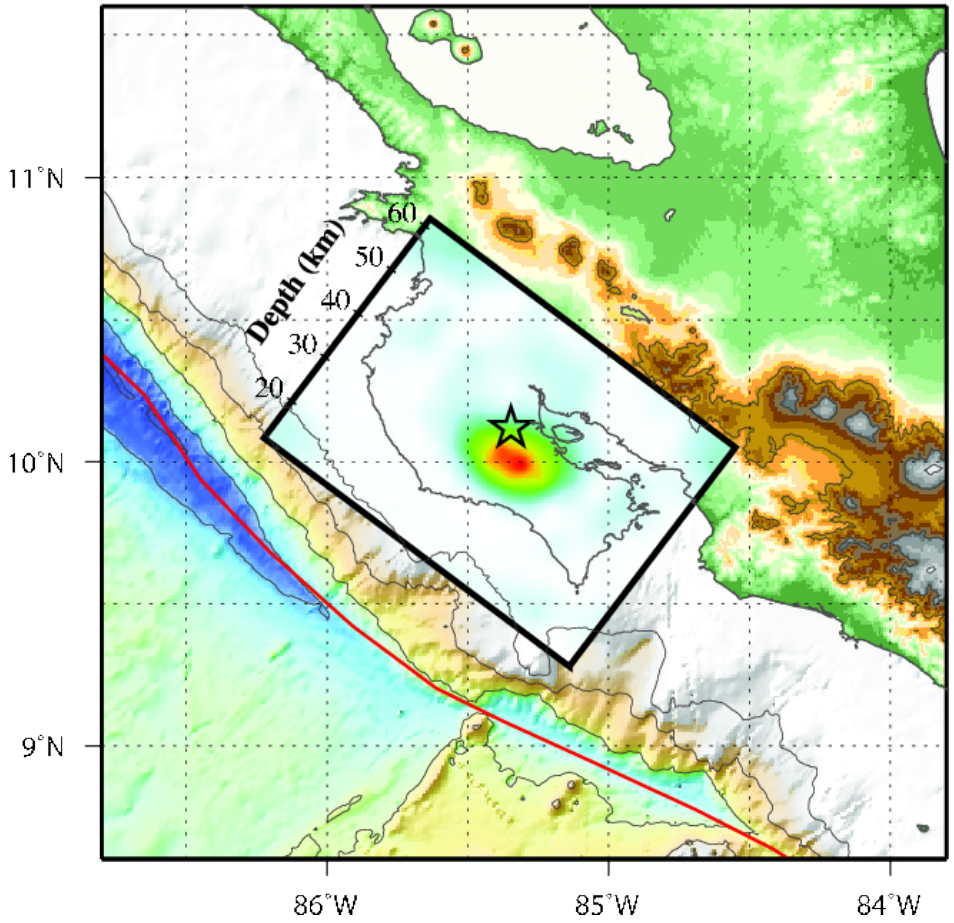
Predicted Coseismic Displacements





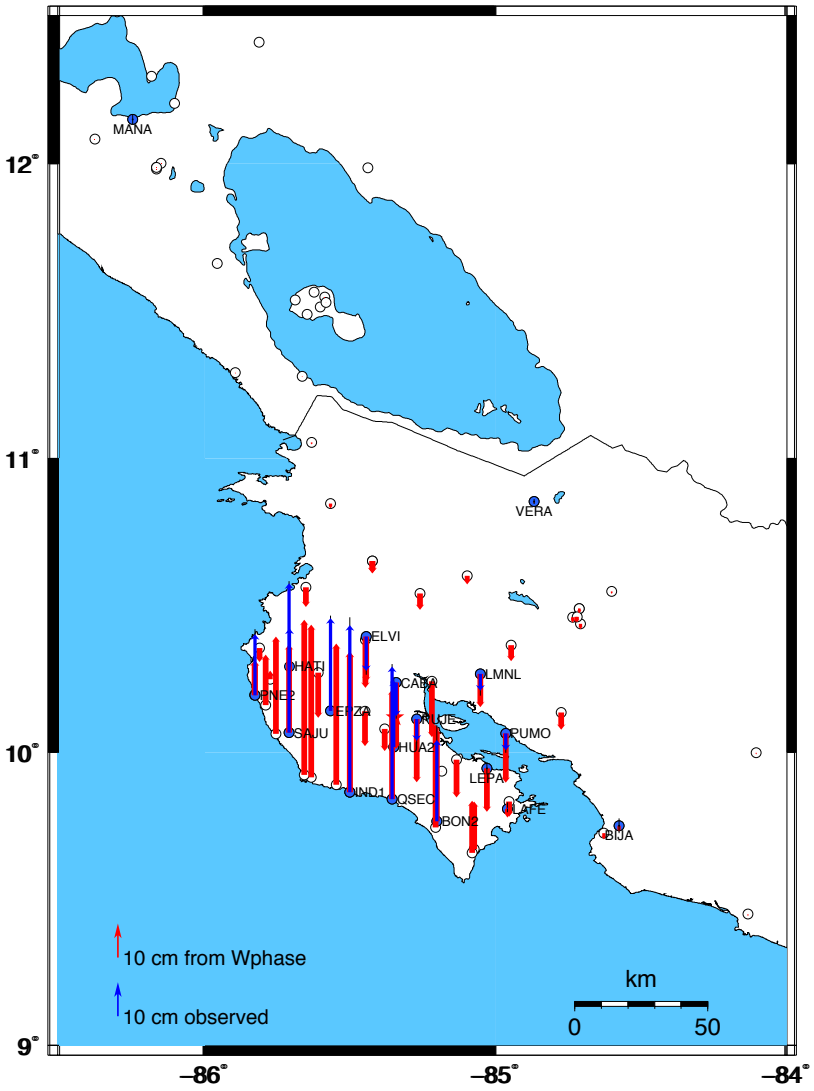
G. Hayes (USGS NEIC, 2012)

September 5, 2012 M_w7.6

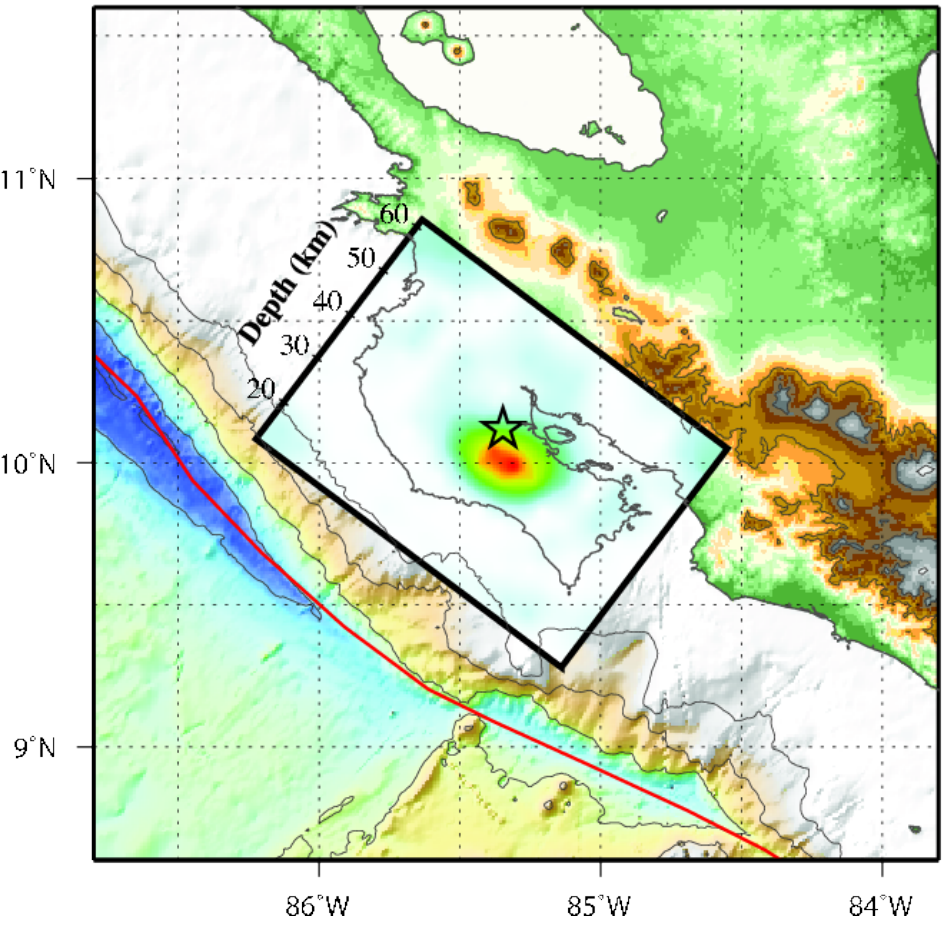


G. Hayes (USGS NEIC, 2012)

Predicted & Observed Coseismic Displacements

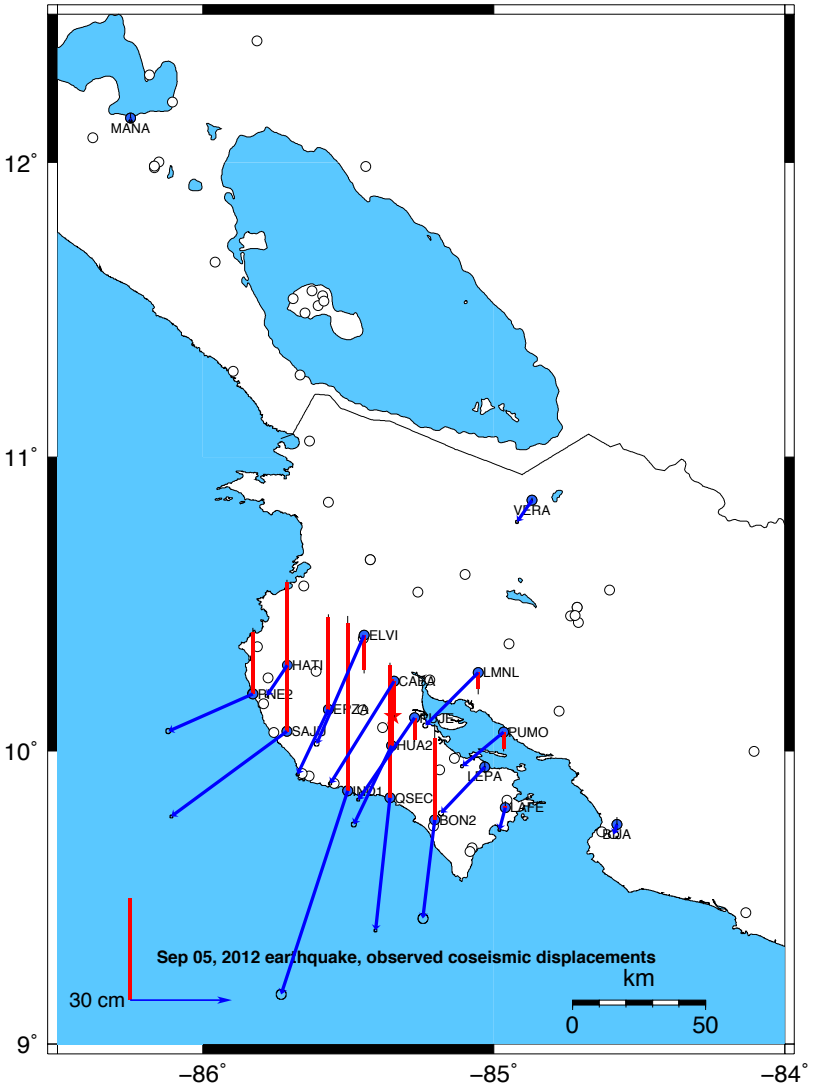


September 5, 2012 M_w7.6

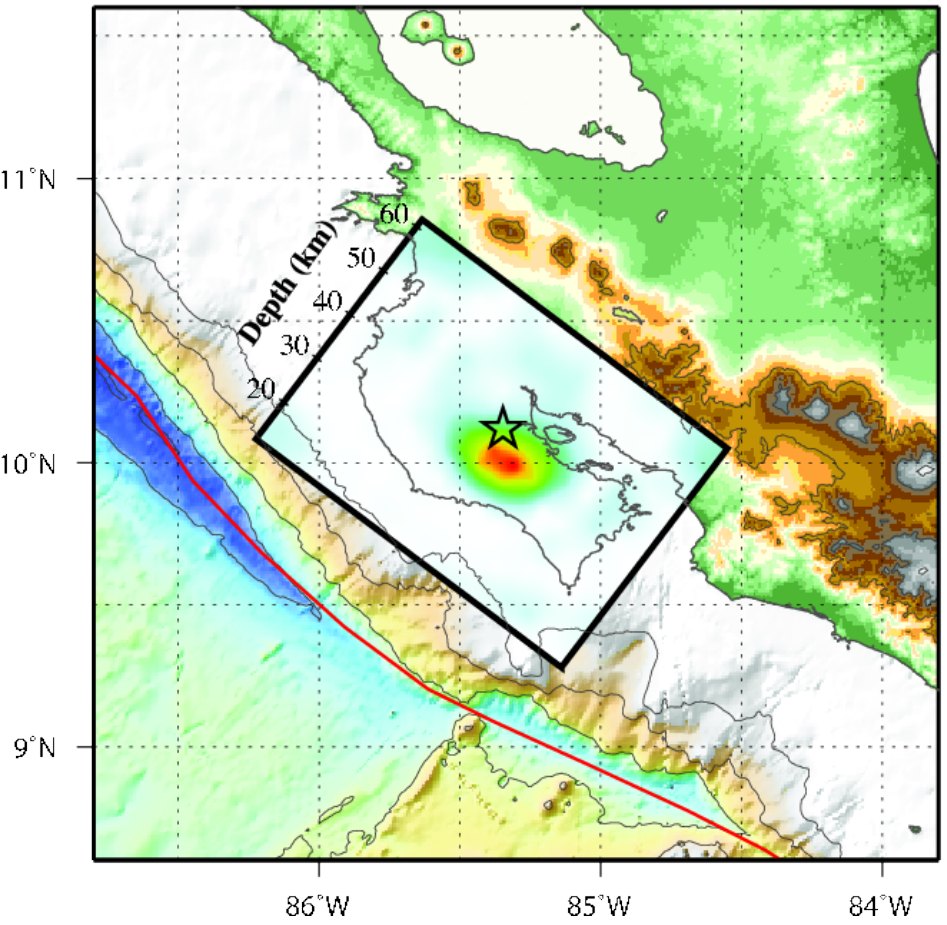


G. Hayes (USGS NEIC, 2012)

Observed Coseismic Displacements

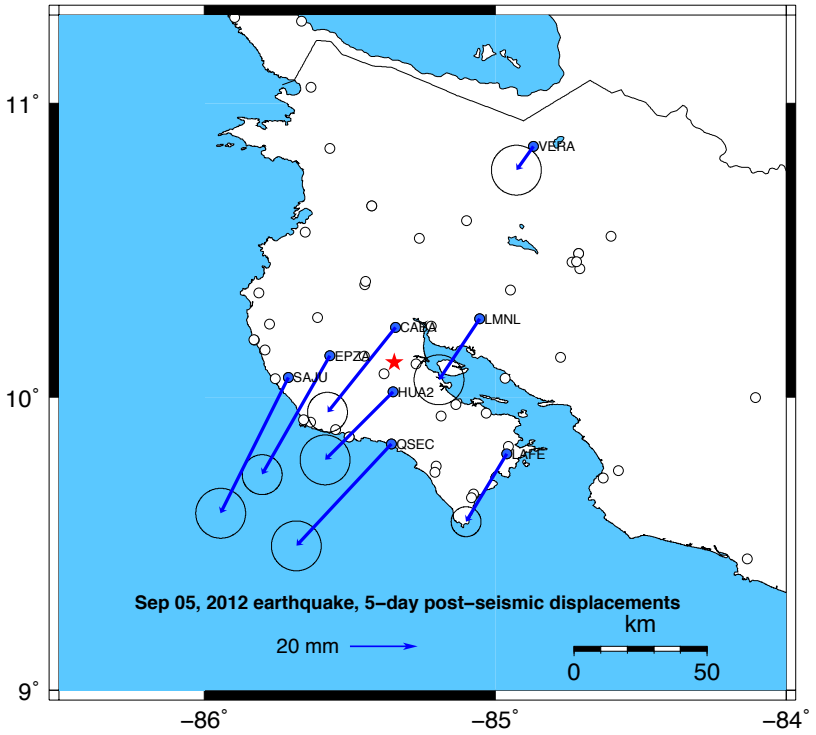


September 5, 2012 M_w7.6

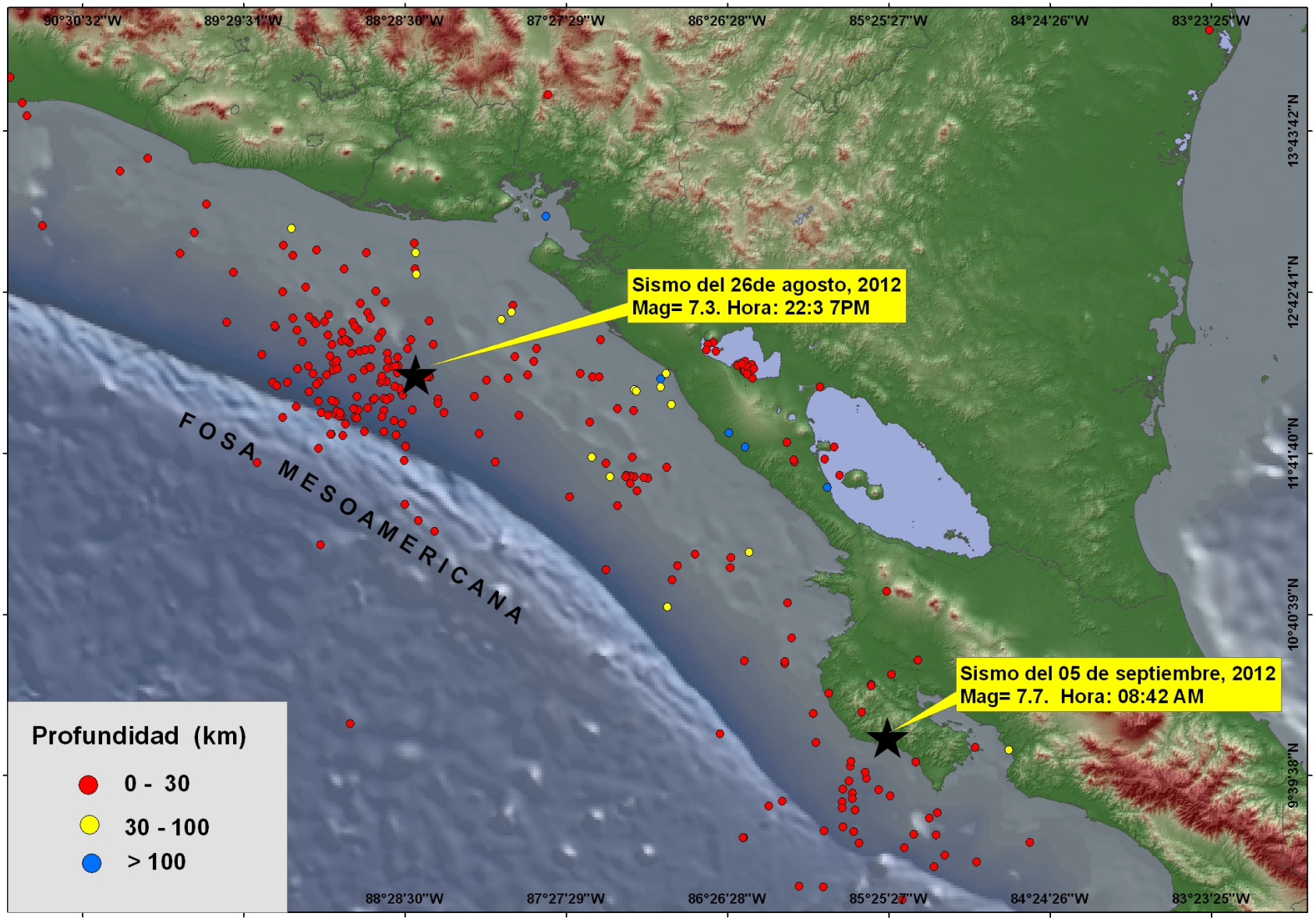


G. Hayes (USGS NEIC, 2012)

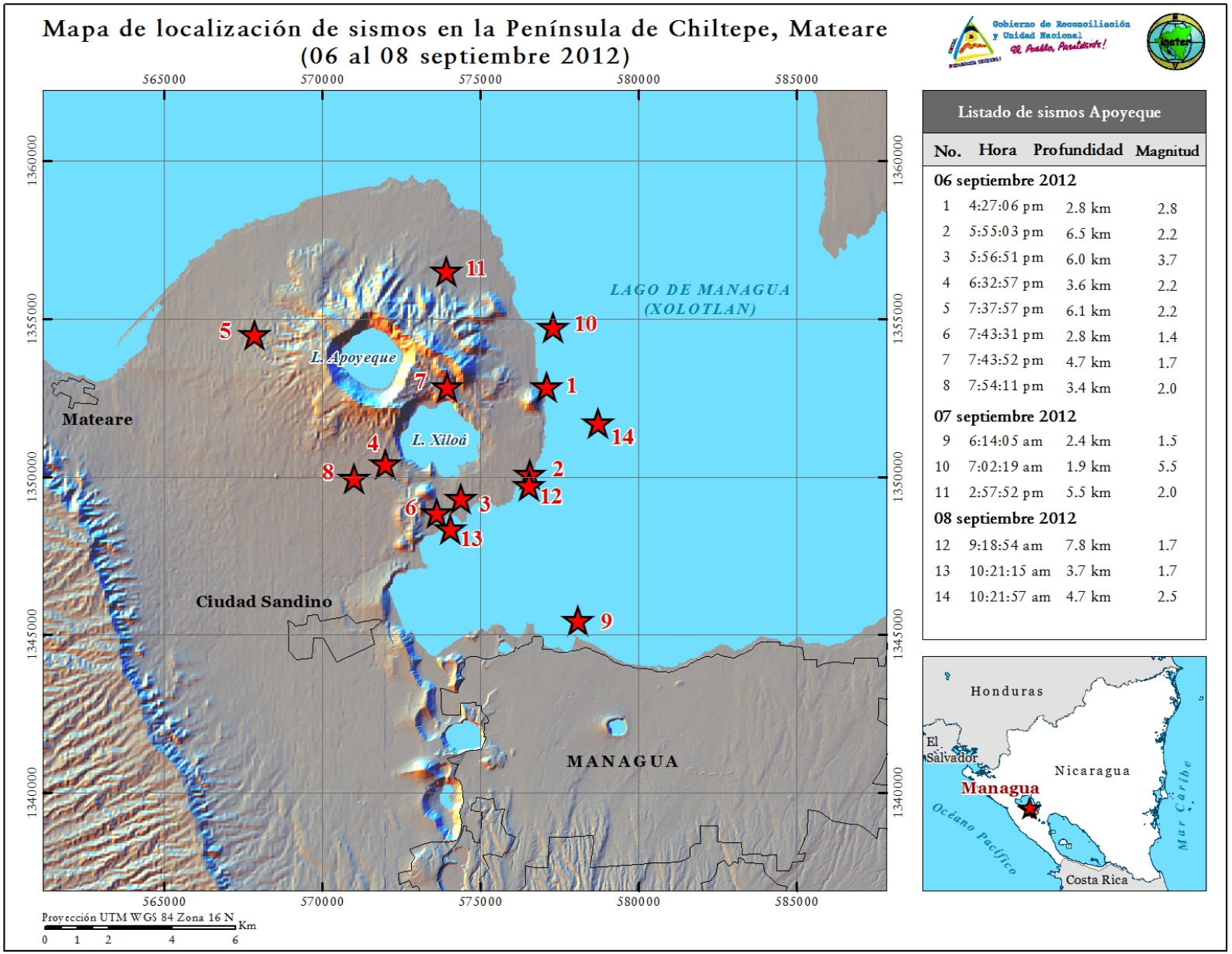
Observed Post-seismic Displacements



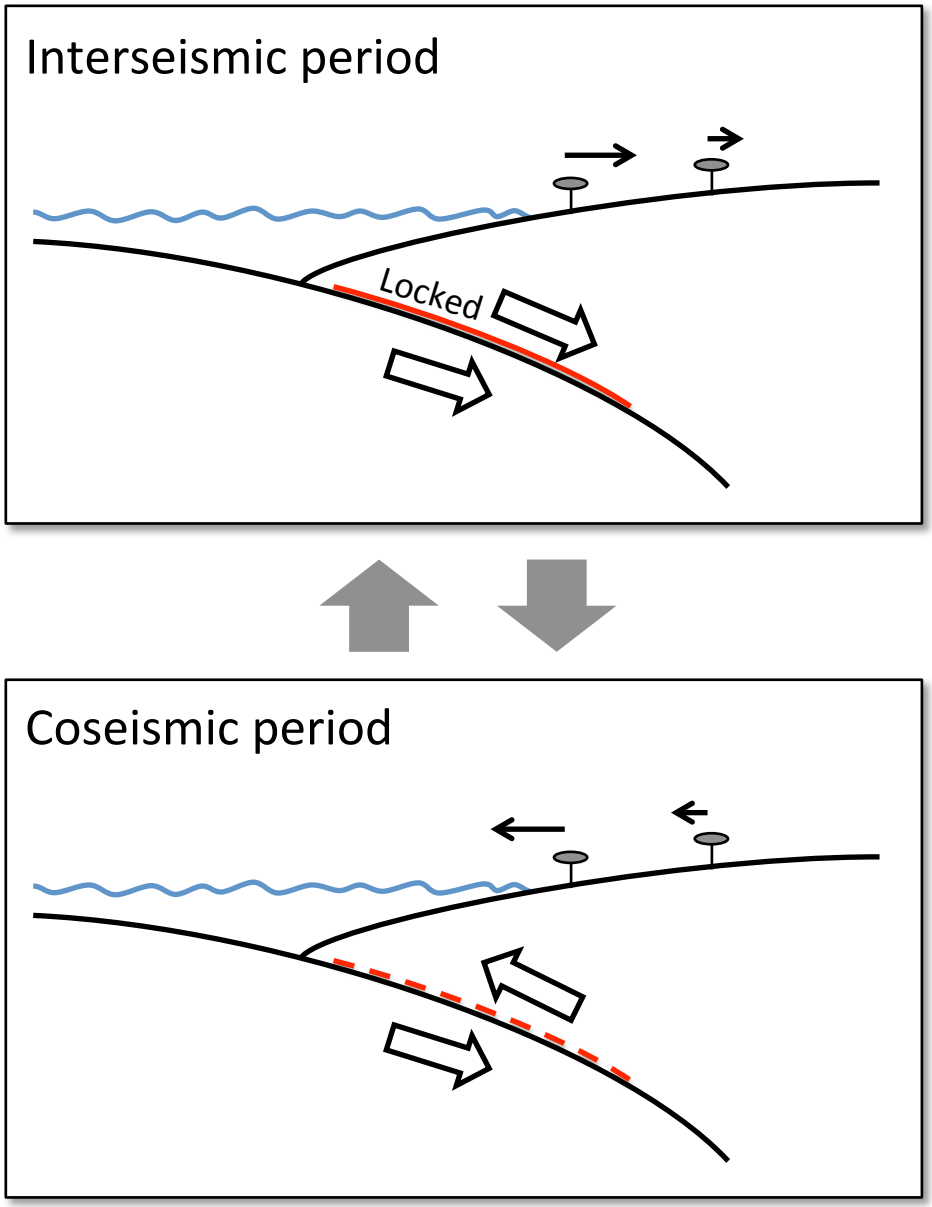
Triggered Volcanism?



September 6, 2012 Apoyeque



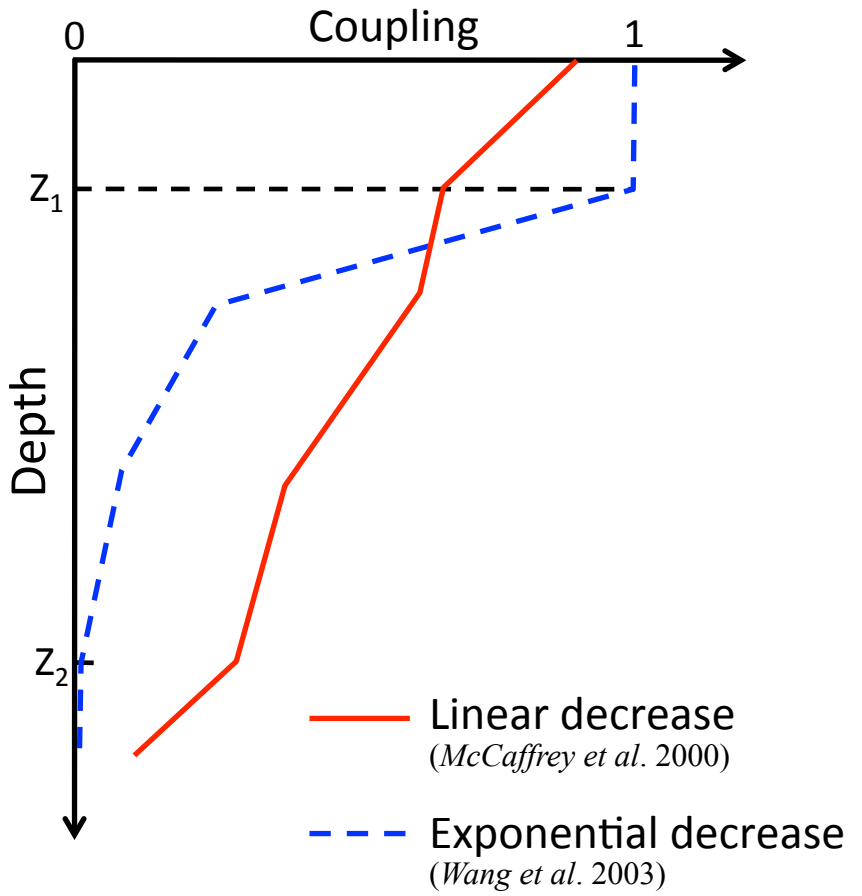
Coupling



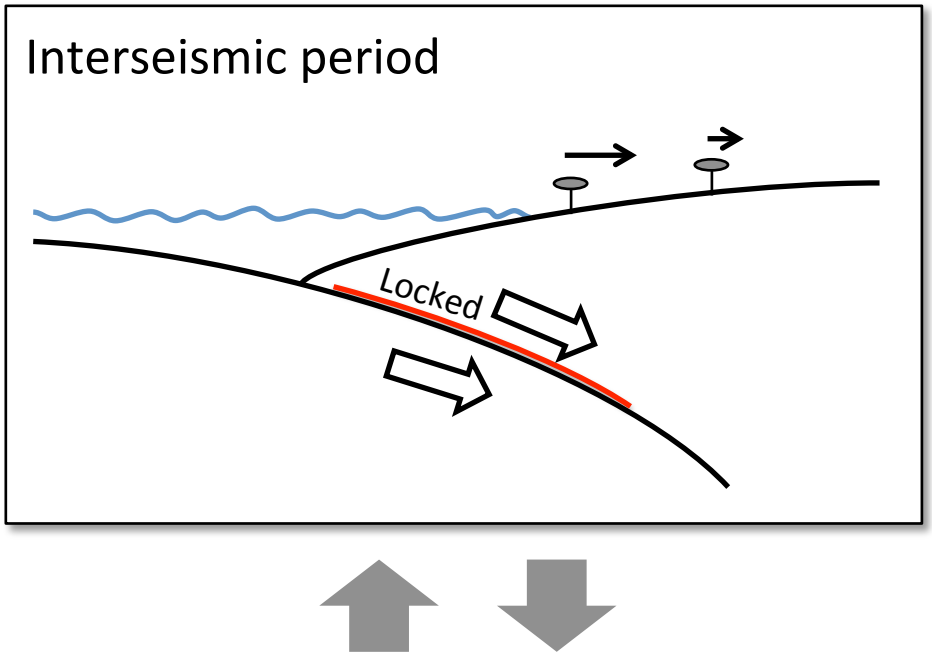
Coupling (φ; Elastic strain accumulation)

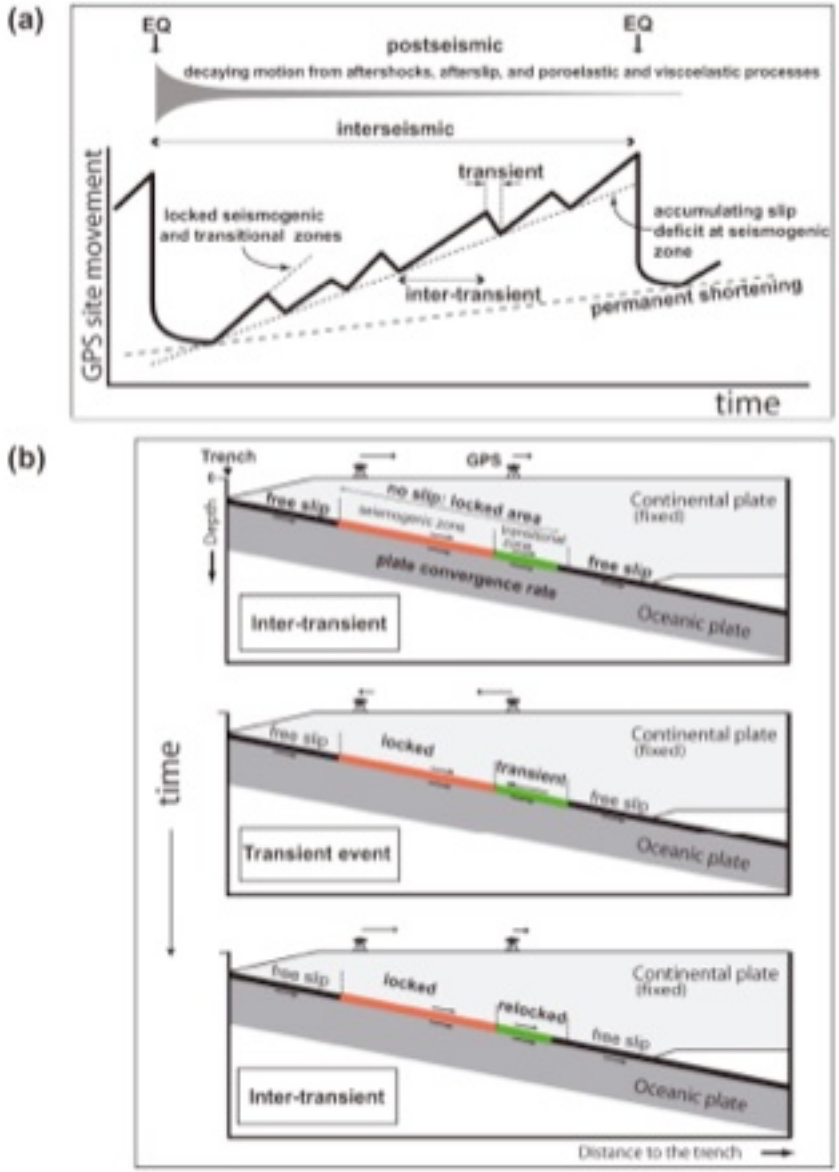
$$= \frac{\text{Locked Slip}}{\text{Total relative motion}}$$

- Coupling Constraints



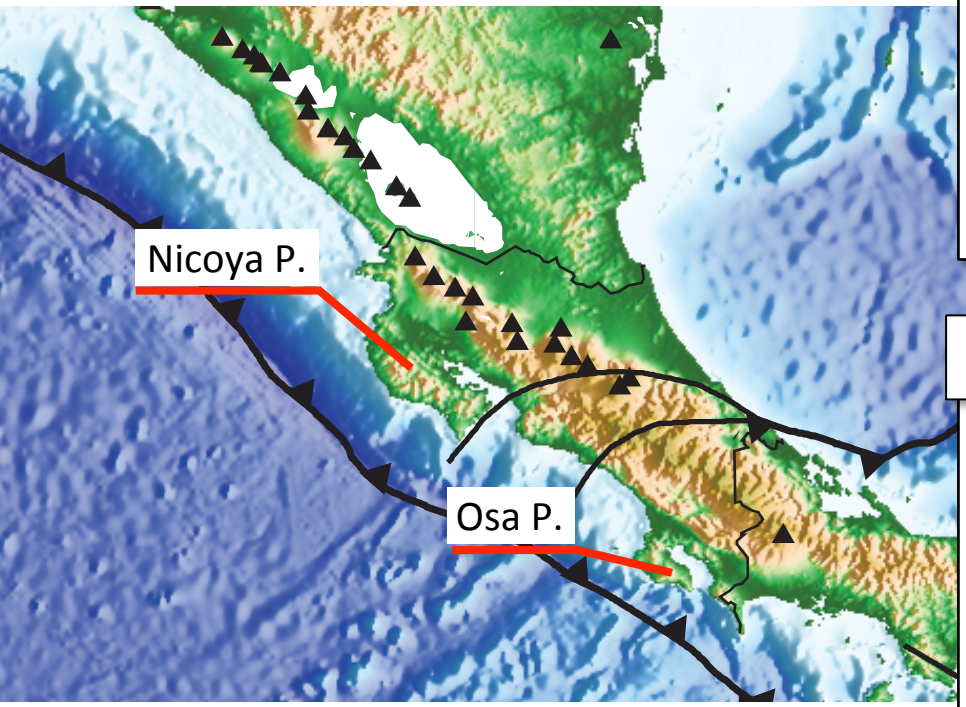
Earthquake Cycle

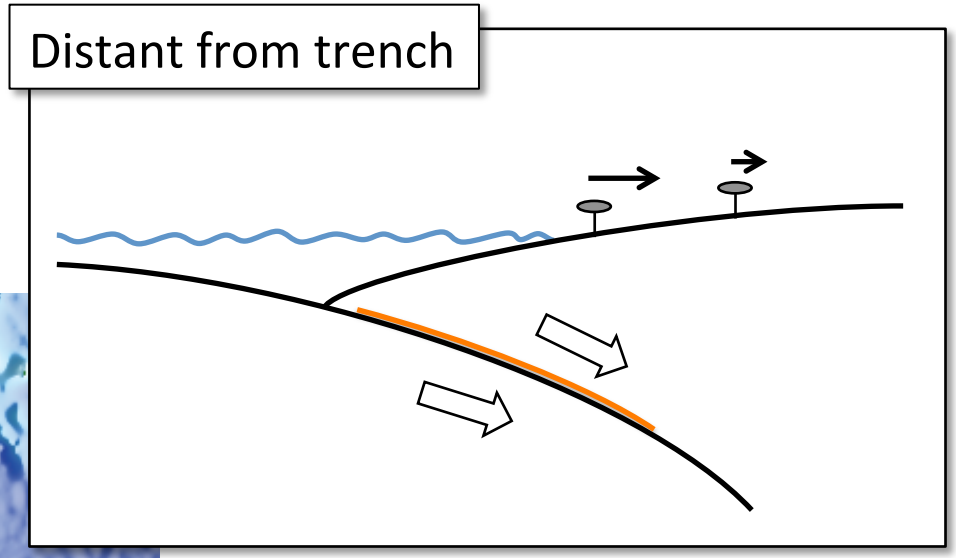


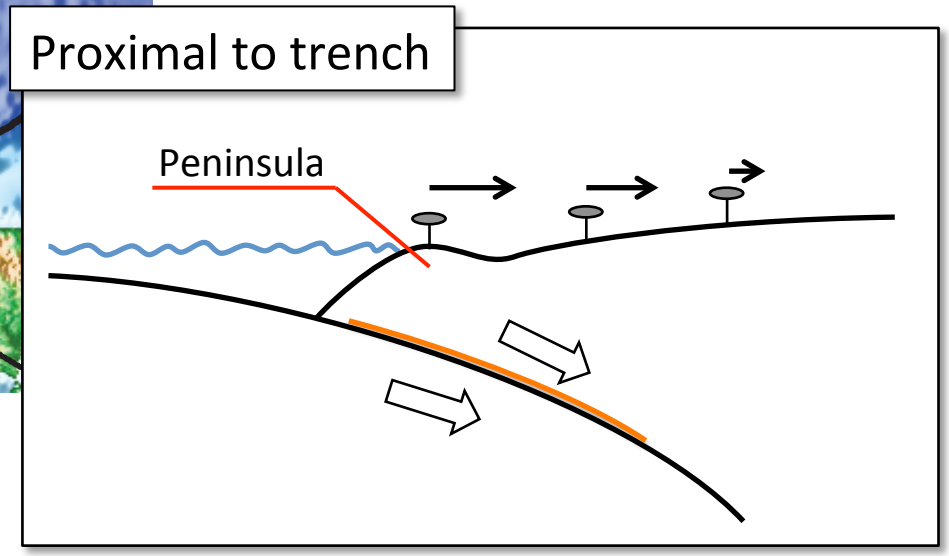


C. DeMets, personal com. 2012

Coupling


Nicoya P.
Osa P.

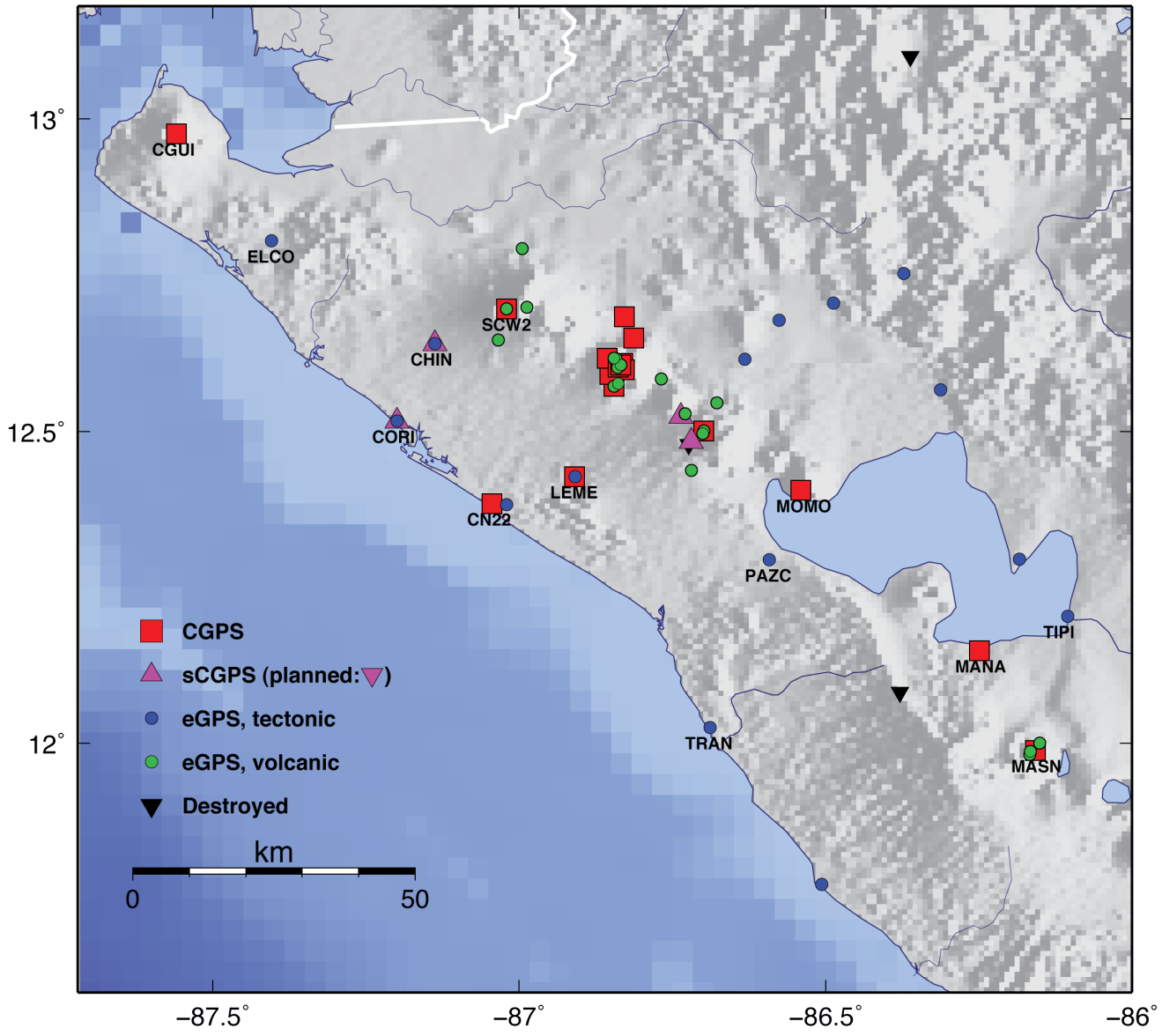

Distant from trench


Proximal to trench
Peninsula

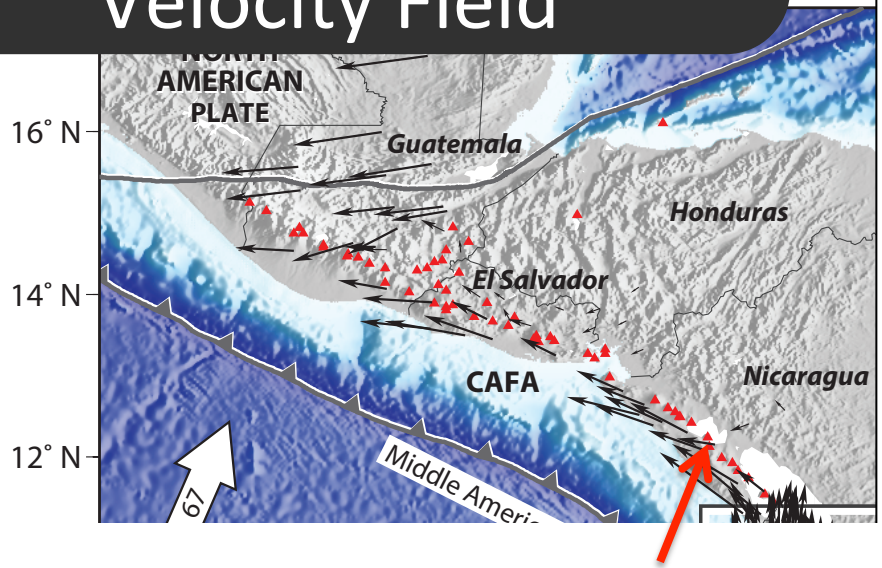
GPS in Central America

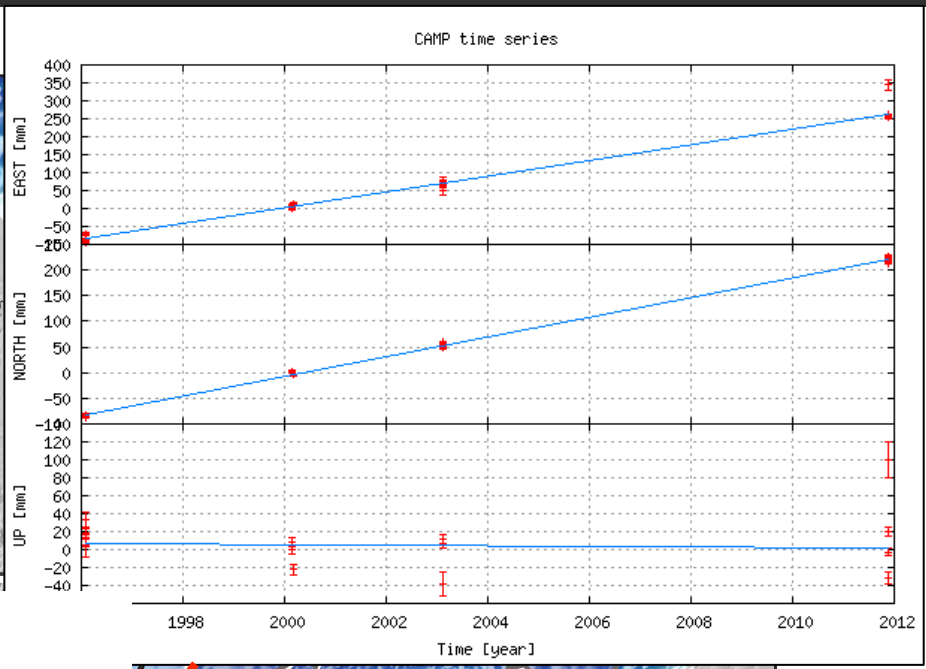
cGPS in Central America

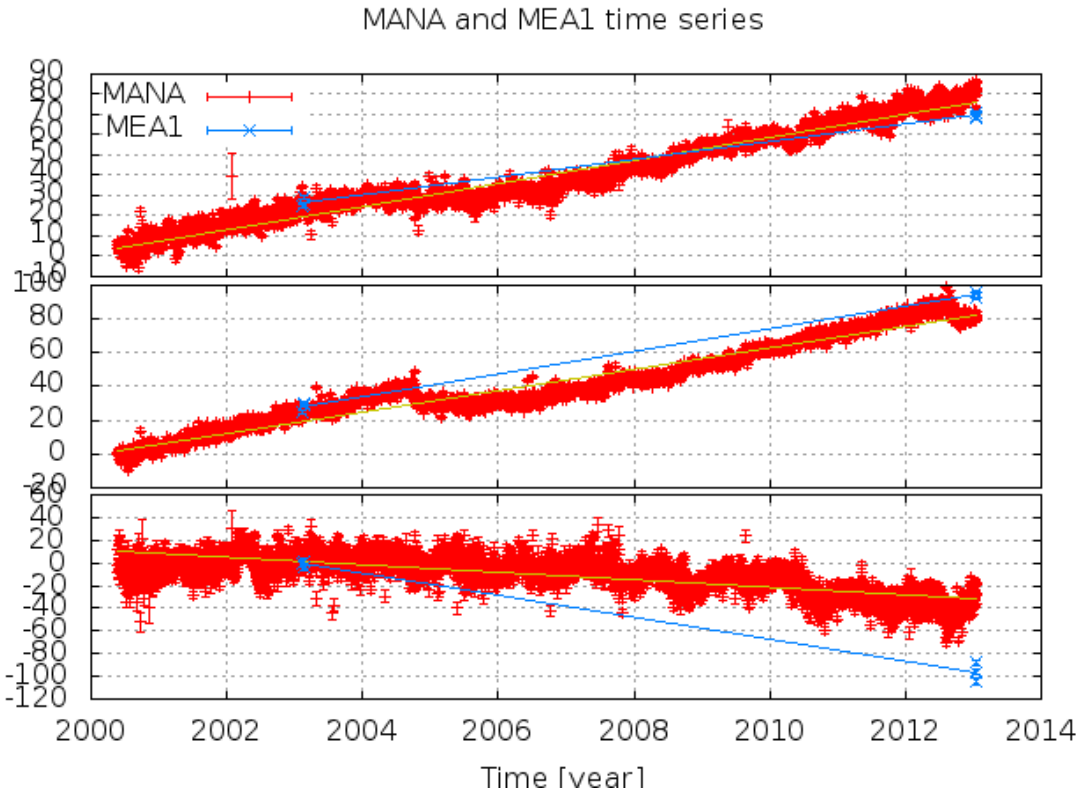
cGPS in Central America

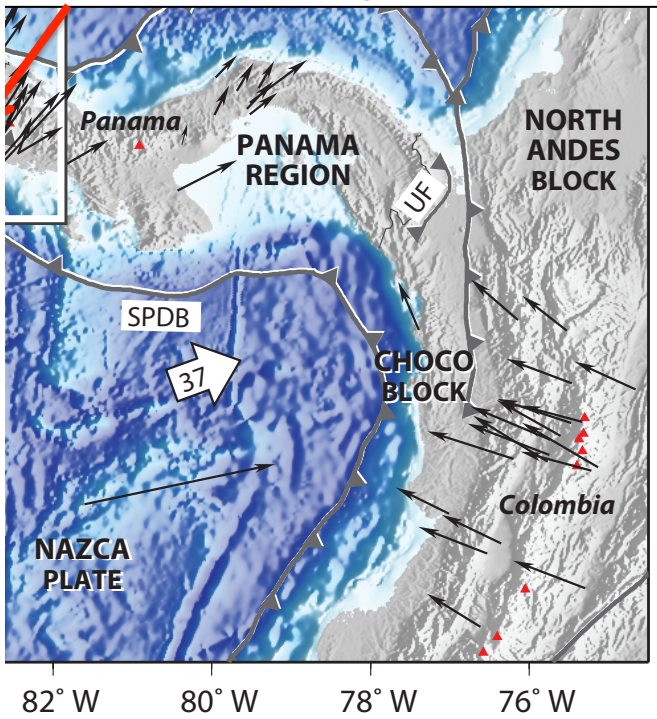


Velocity Field



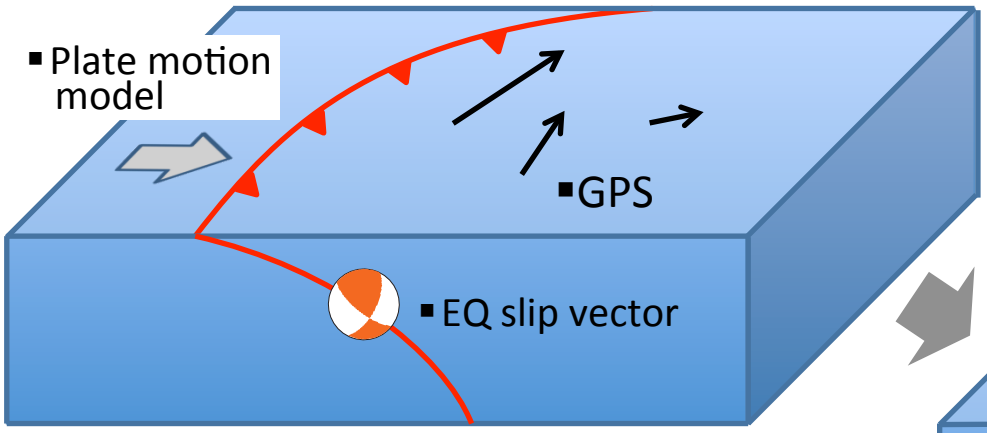




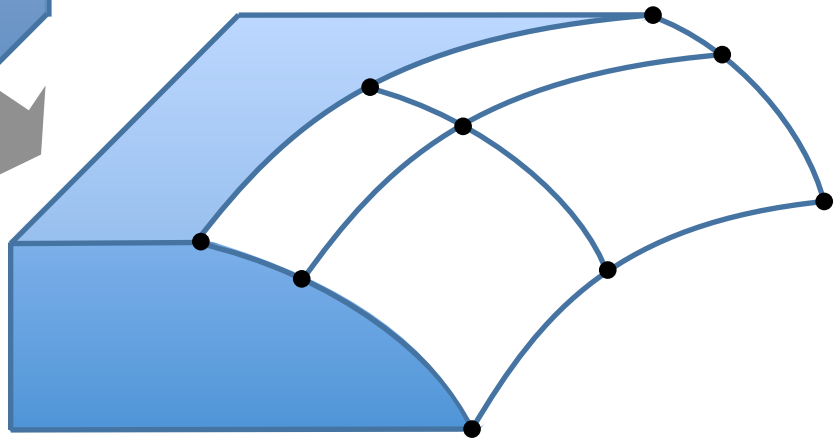


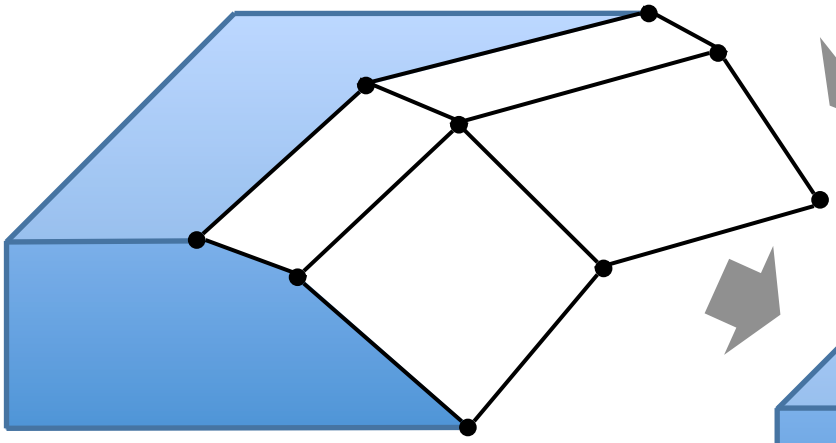
May 7, 2013

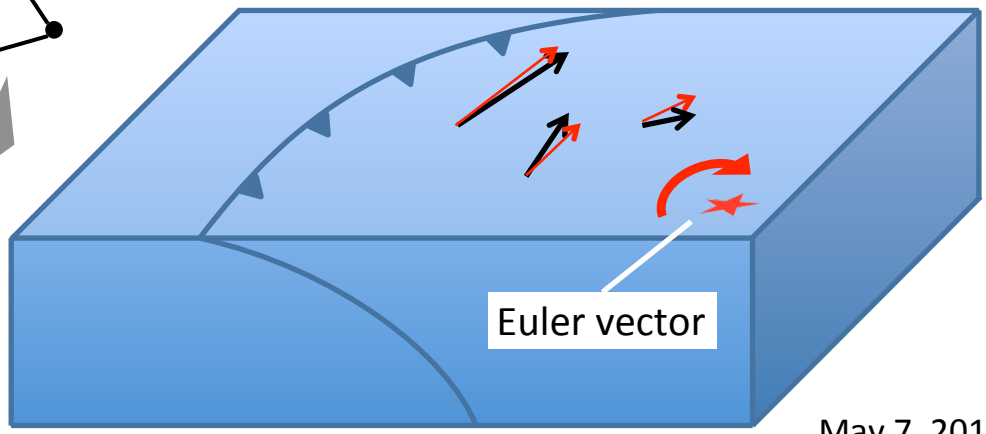
Block Modeling



- Seismic reflection profiles
- Seismic tomography
- Structural studies
- Geologic studies



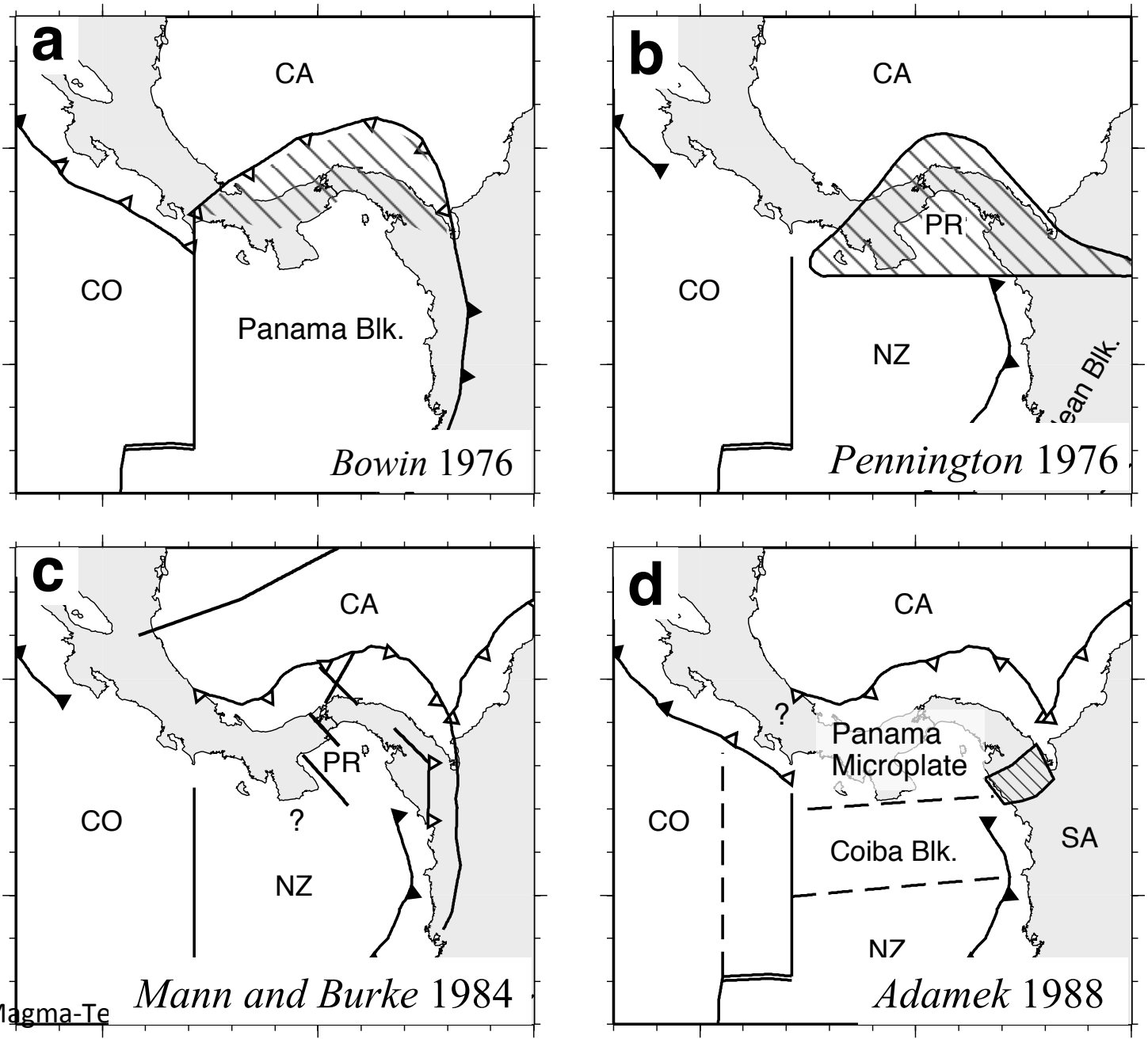





Central American Fore Arc
8-16 mm a-1
Caribbean Plate
Panama Region
?
Cocos Plate
Cocos Ridge
80 mm a-1
Nazca Plate
km
0 100 200

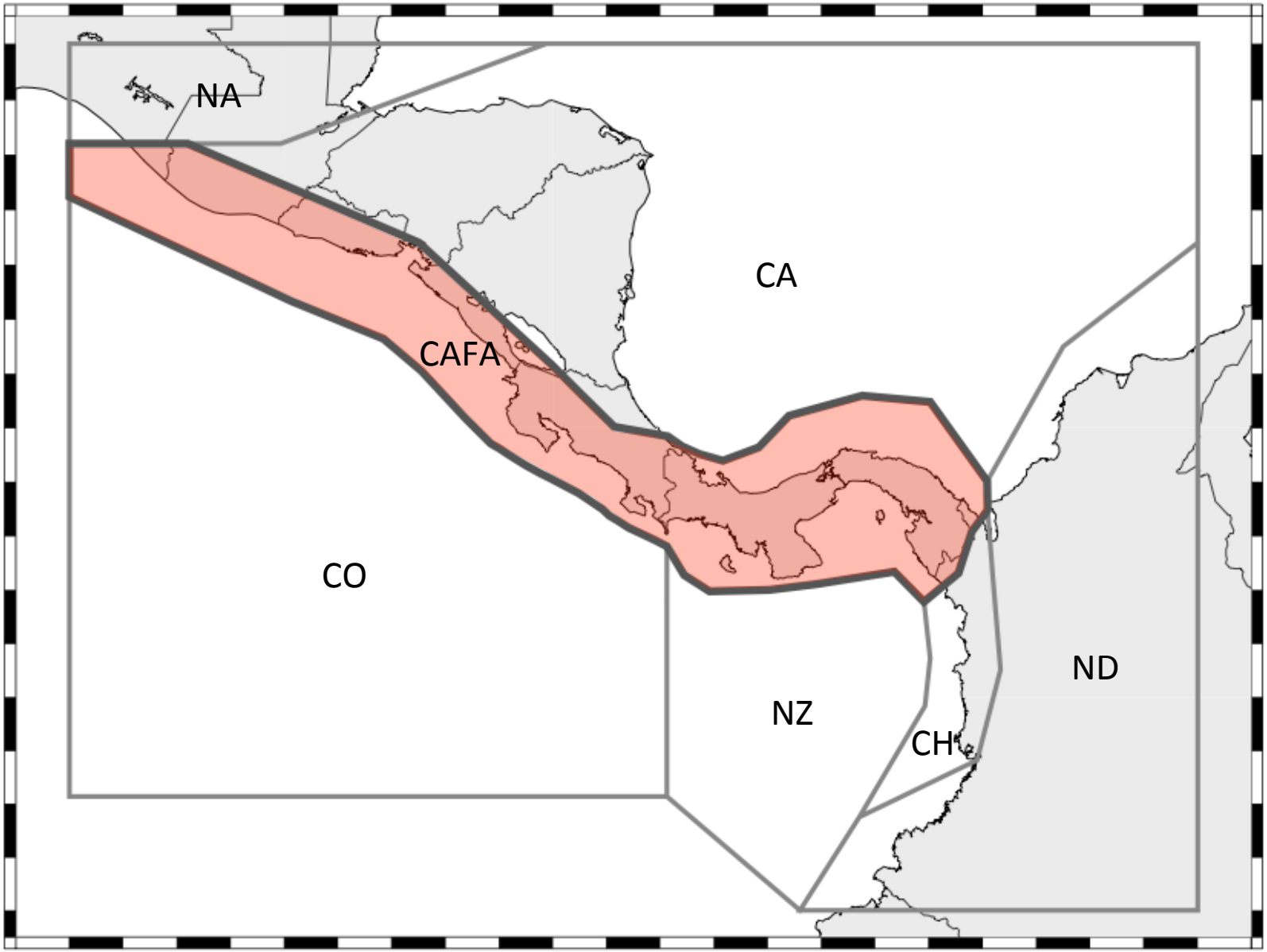

Central American Fore Arc
8-16 mm a-1
Caribbean Plate
Panama Region
?
Cocos Plate
Cocos Ridge
80 mm a-1
Nazca Plate
km
0 100 200

Previous Interpretations



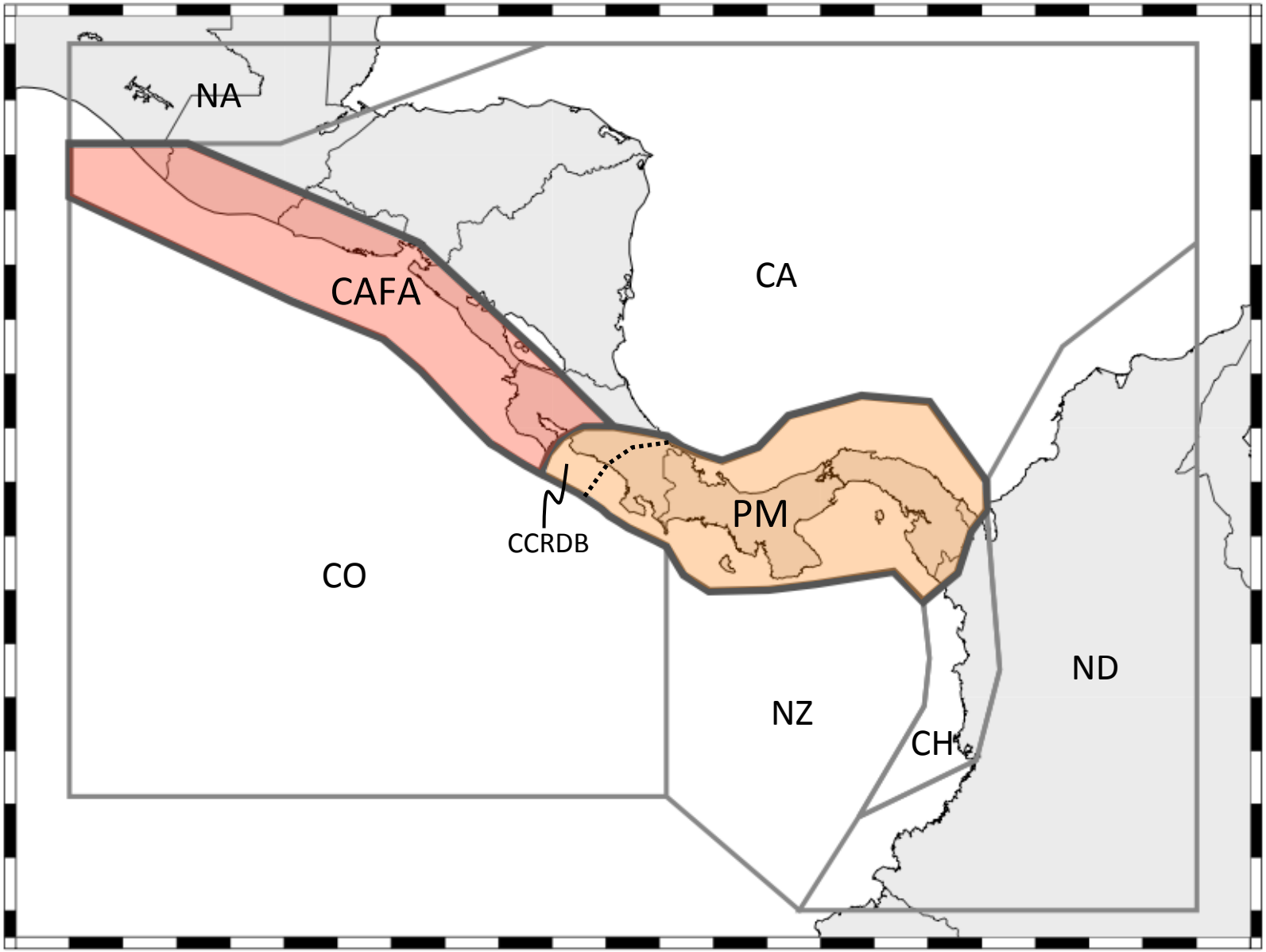
Model 1

One Block model



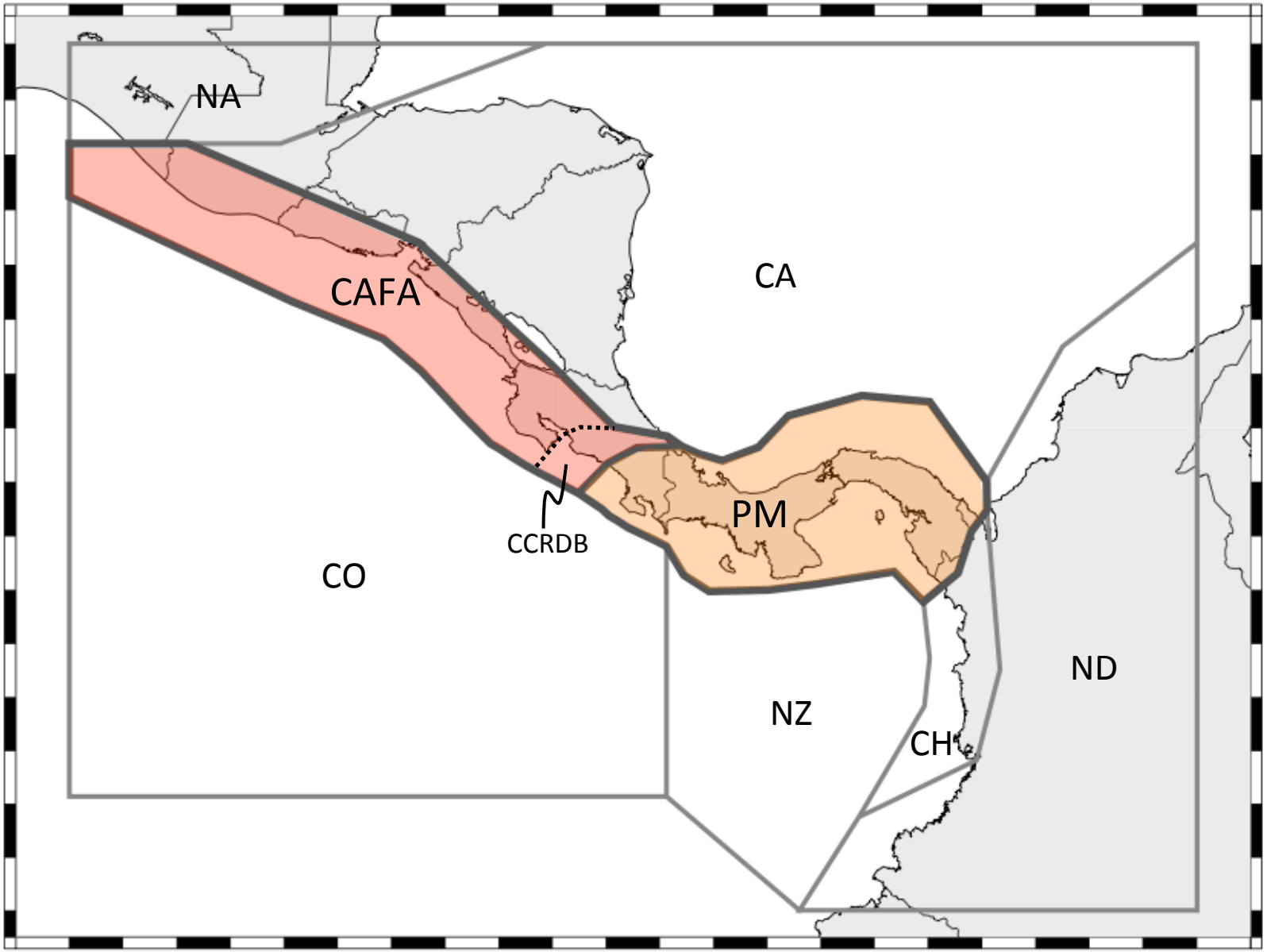
Model 2

Two Block model - I



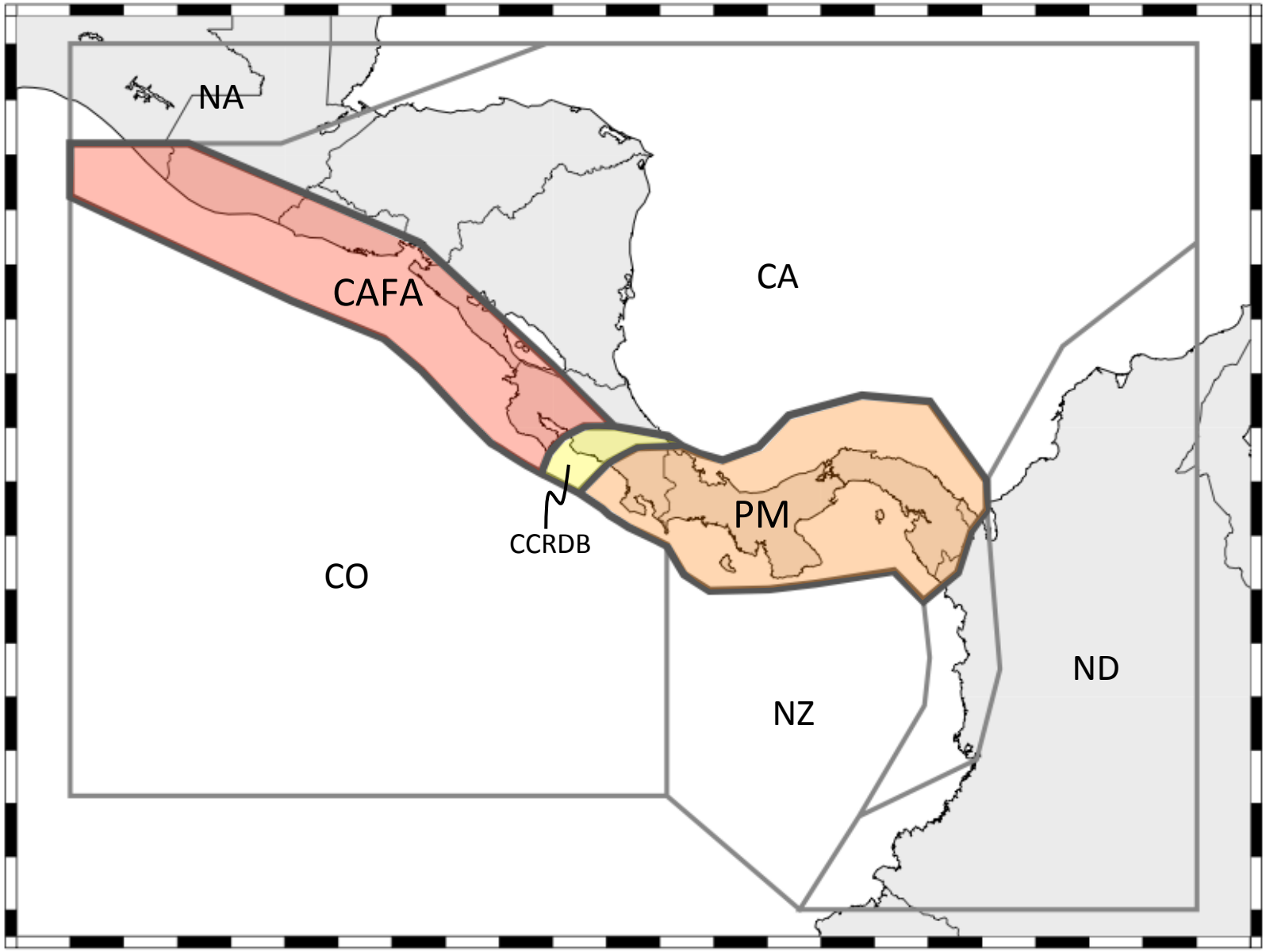
Model 3

Two Block model - II



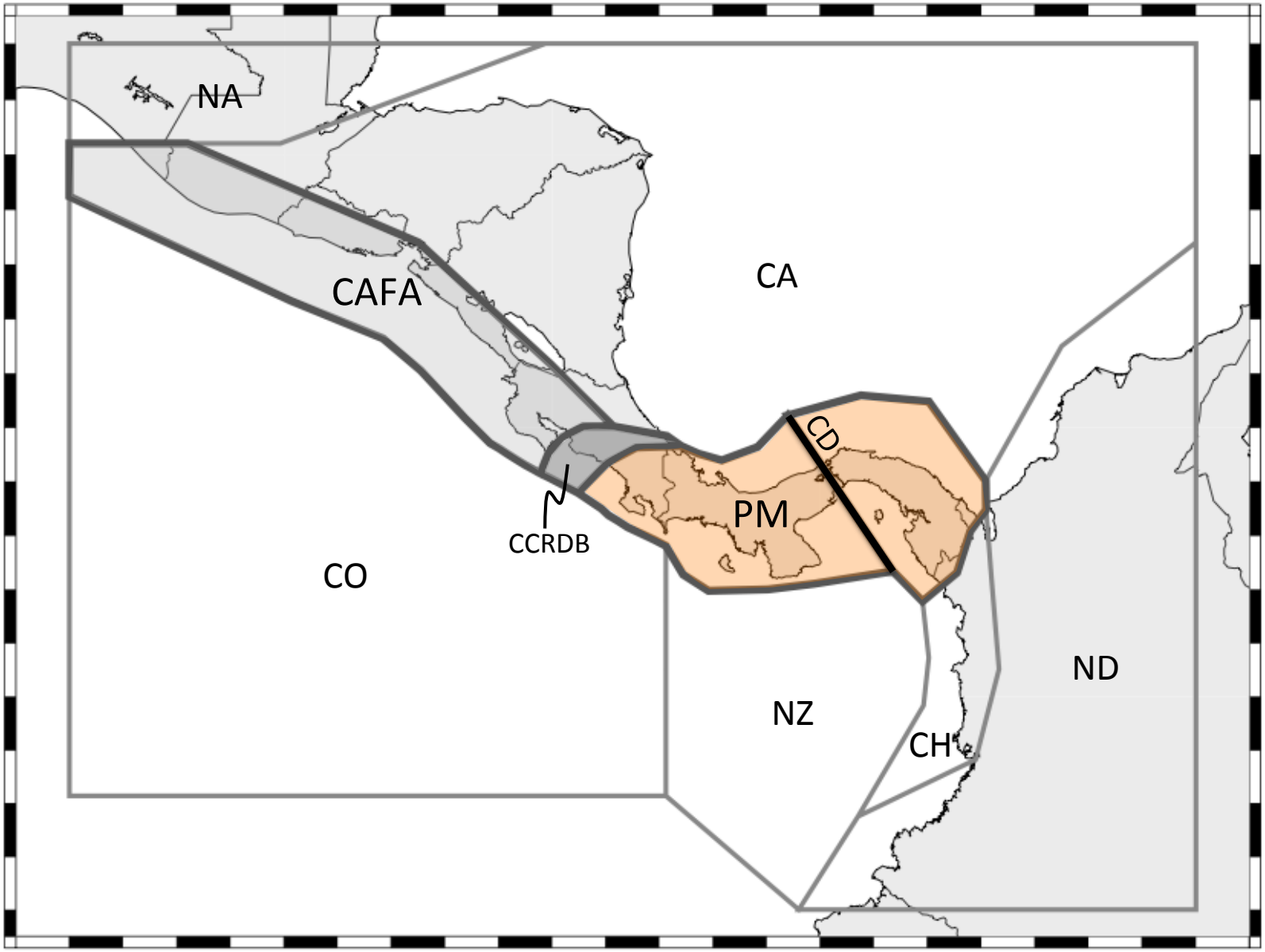
Model 4

Three Block model



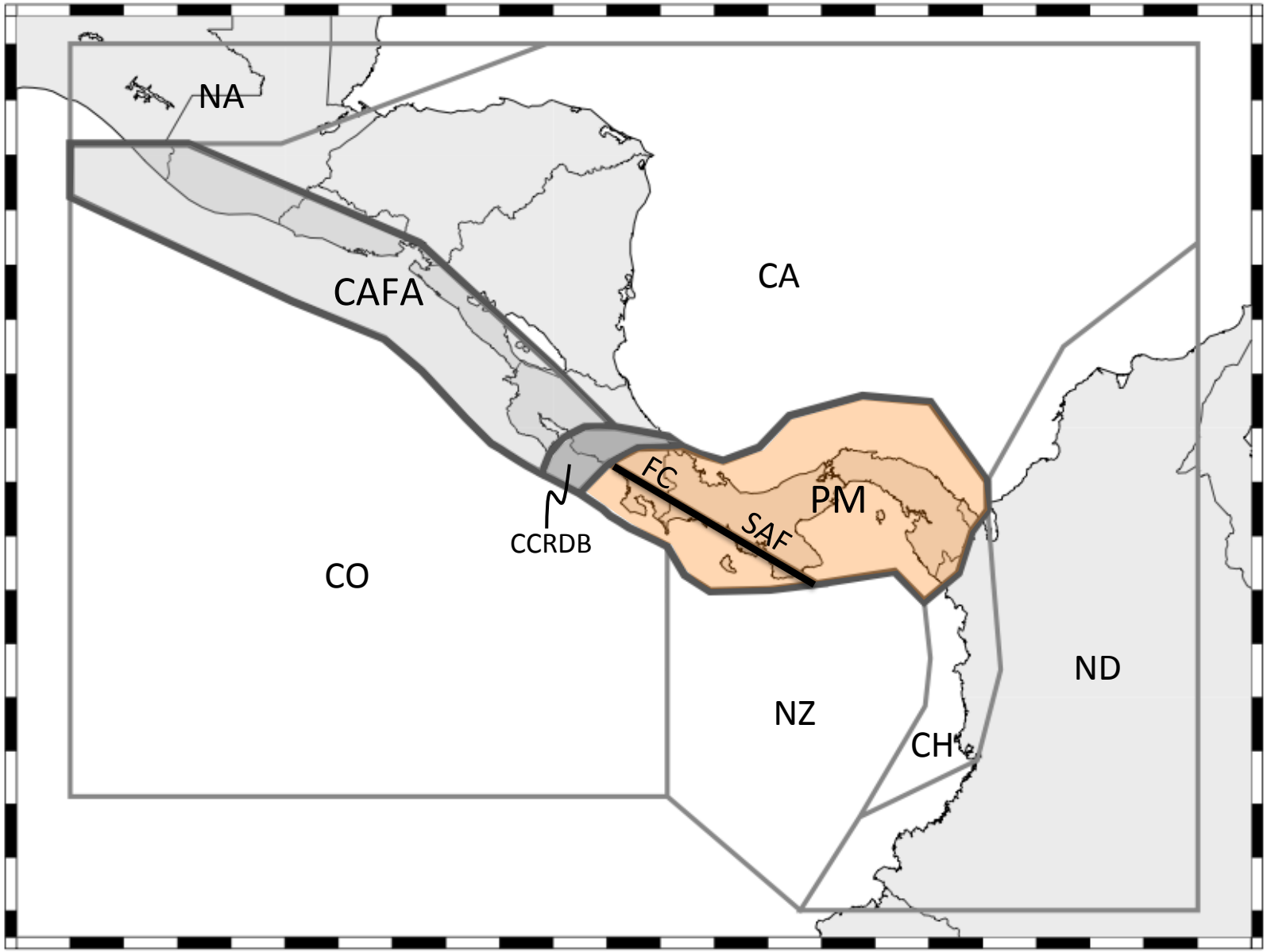
Model 5

Canal Discontinuity



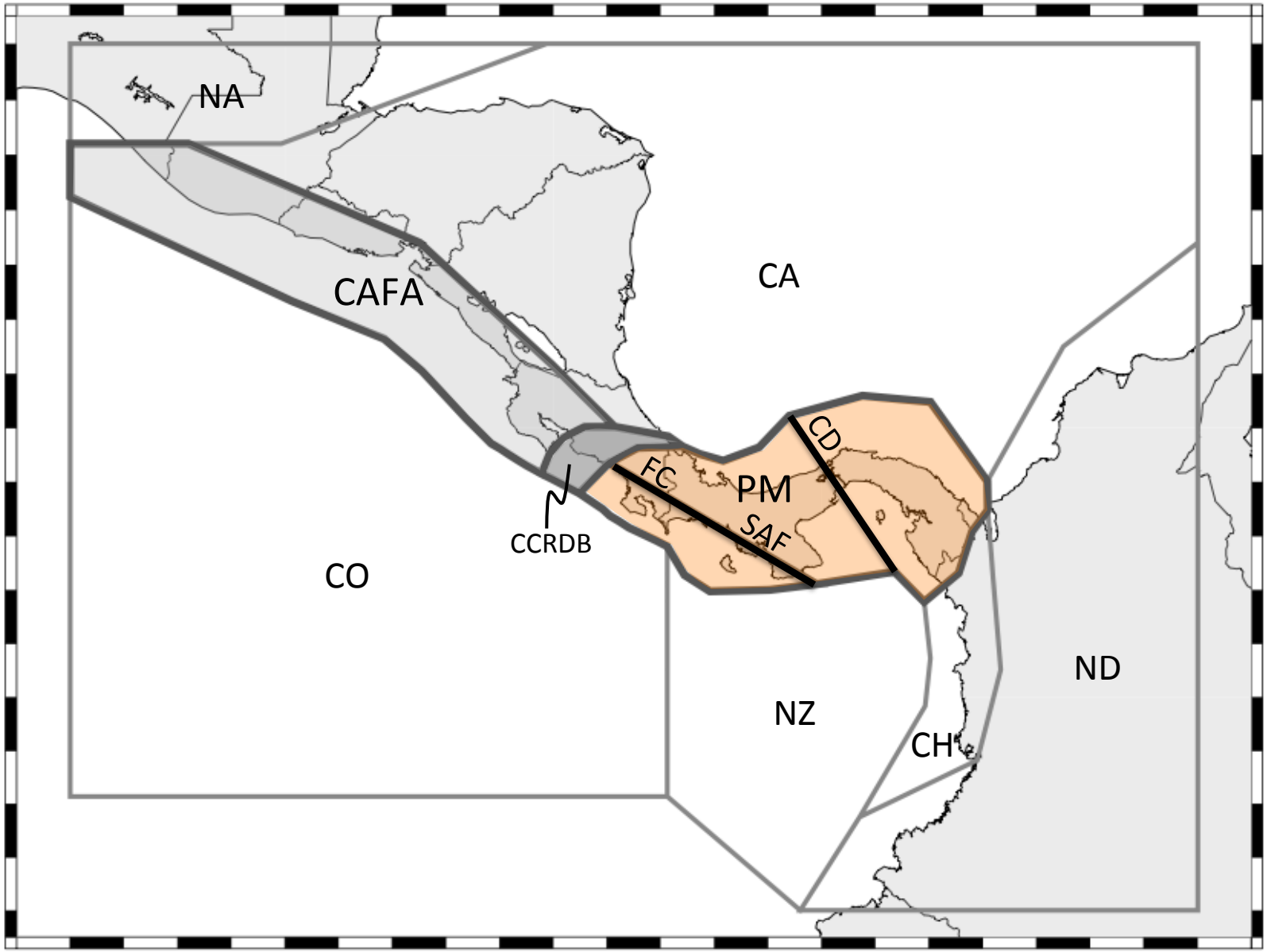
Model 6

Sona-Azuero Fault & Fila Costeña



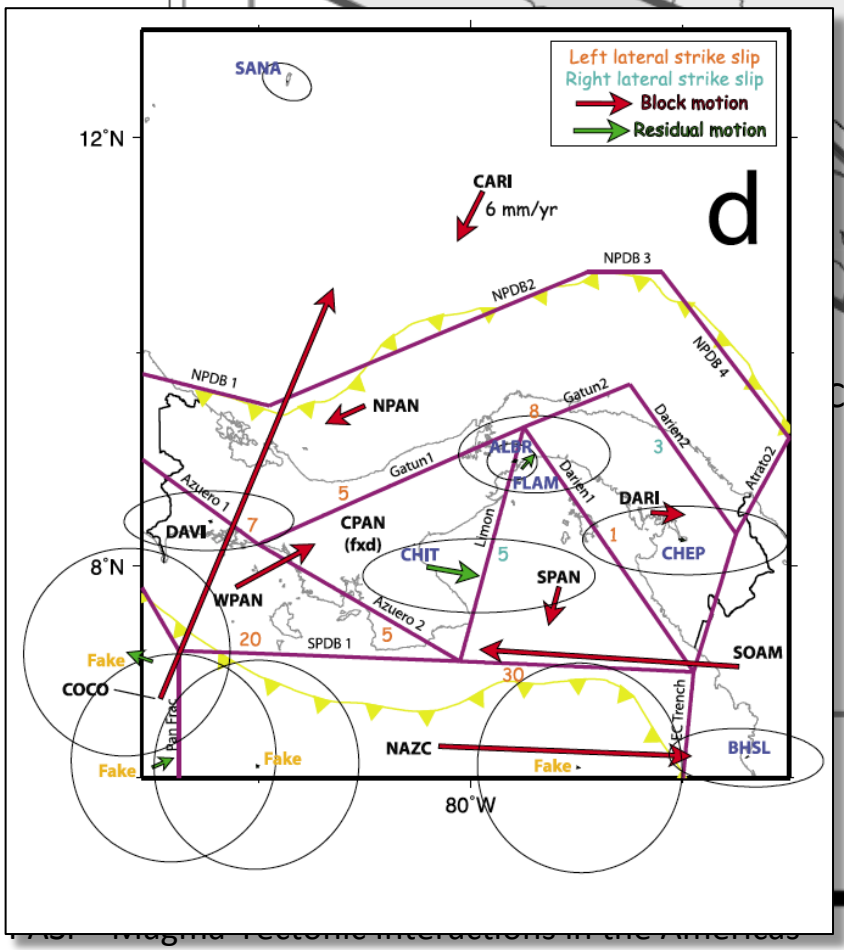
Model 7

SAF & FC and Canal Discontinuity



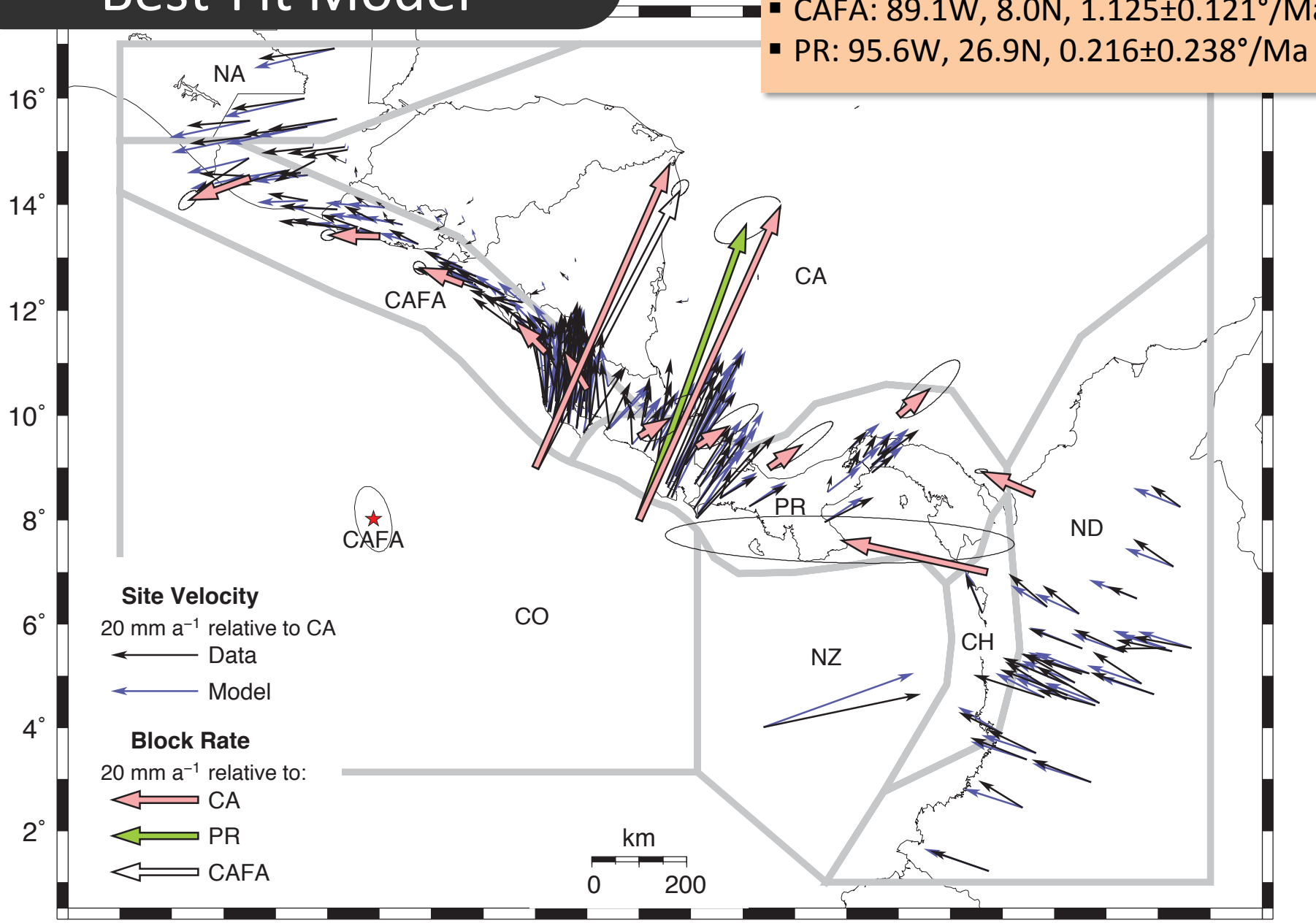
Model 8

Rockwell et al. (2010) Model



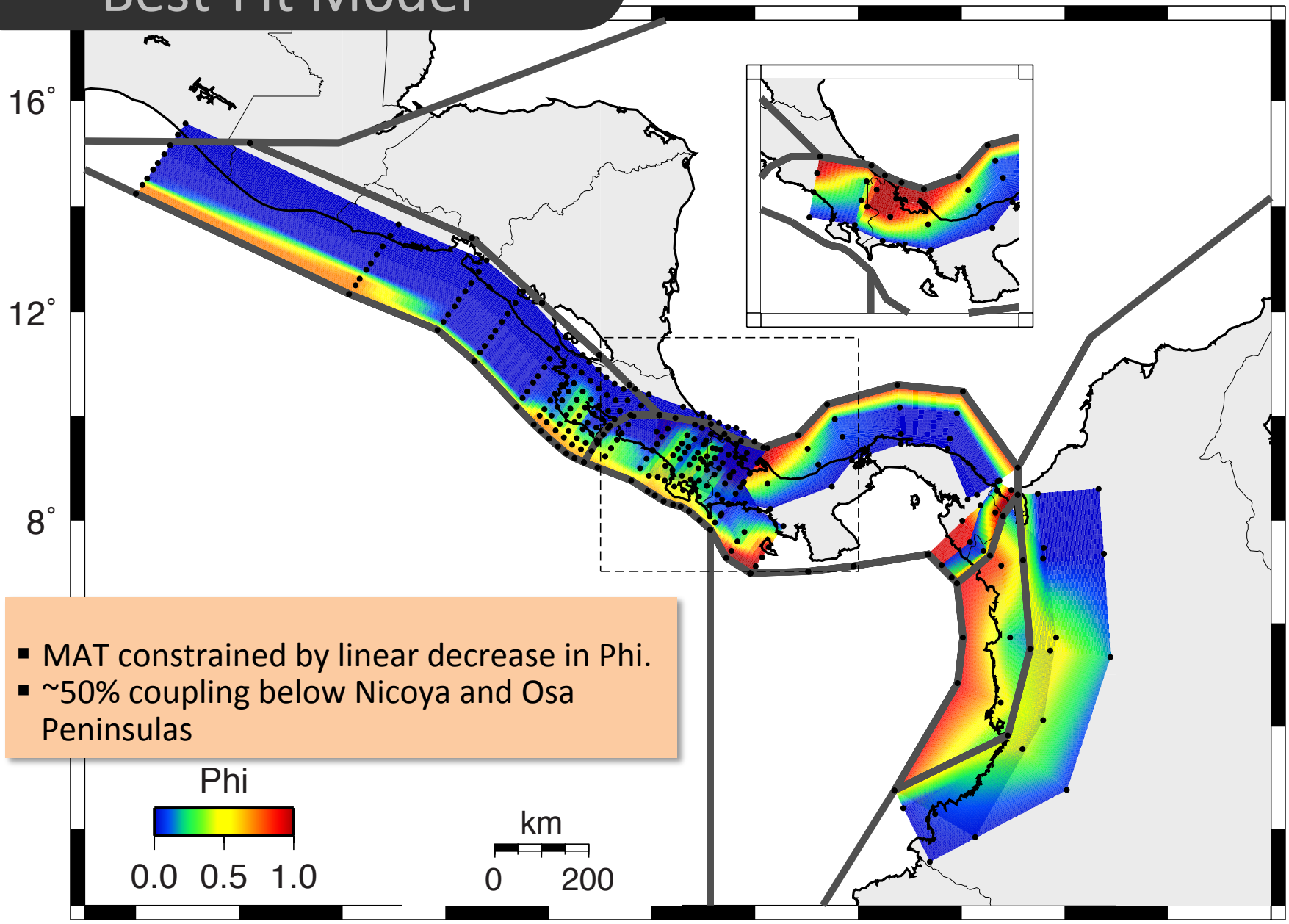
Best-Fit Model

- CAFA: 89.1W, 8.0N, 1.125±0.121°/Ma
- PR: 95.6W, 26.9N, 0.216±0.238°/Ma



Best-Fit Model

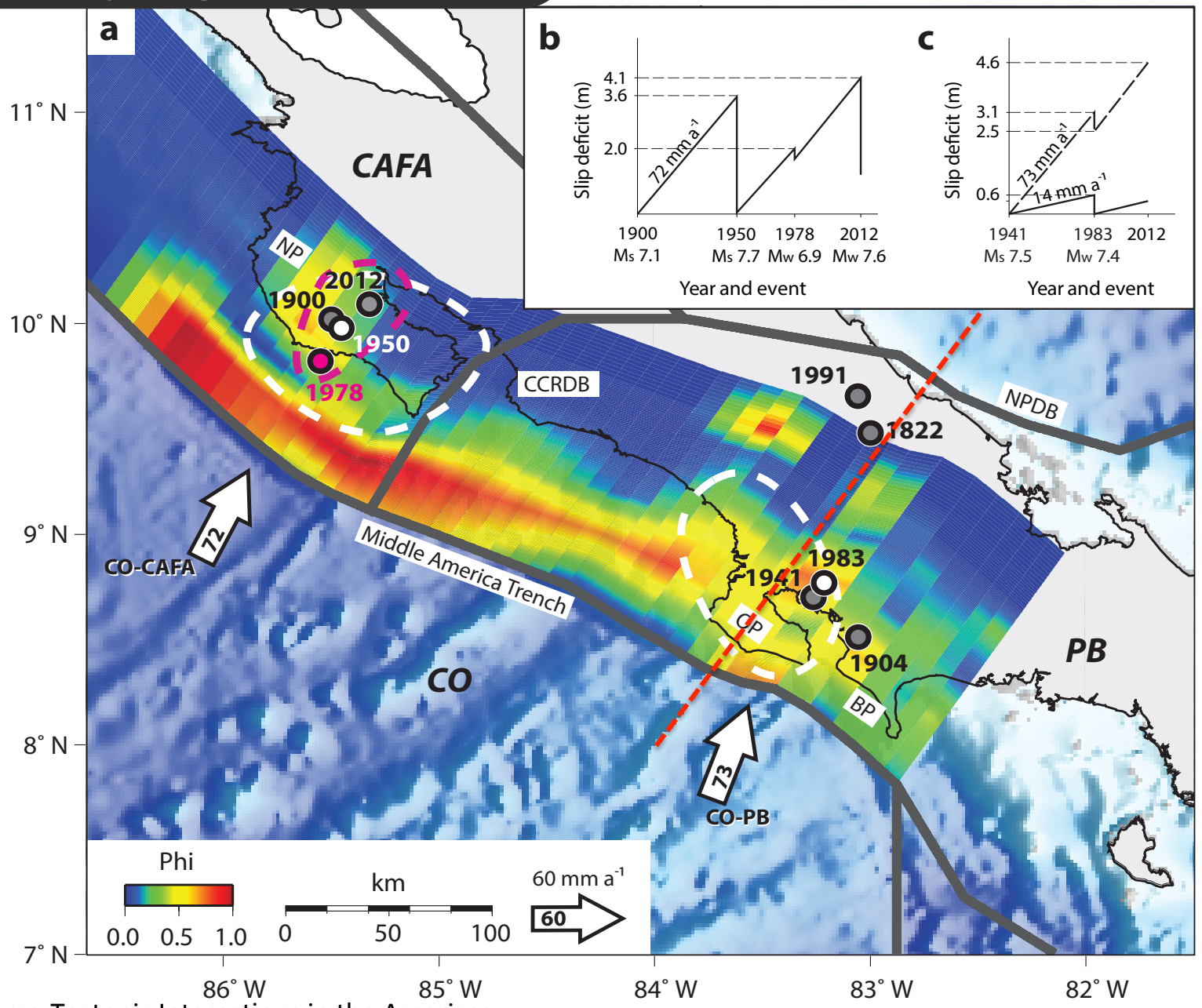
Kobayashi et al. (2012 – submitted)



- MAT constrained by linear decrease in Phi.
- ~50% coupling below Nicoya and Osa Peninsulas

Coupling Pattern

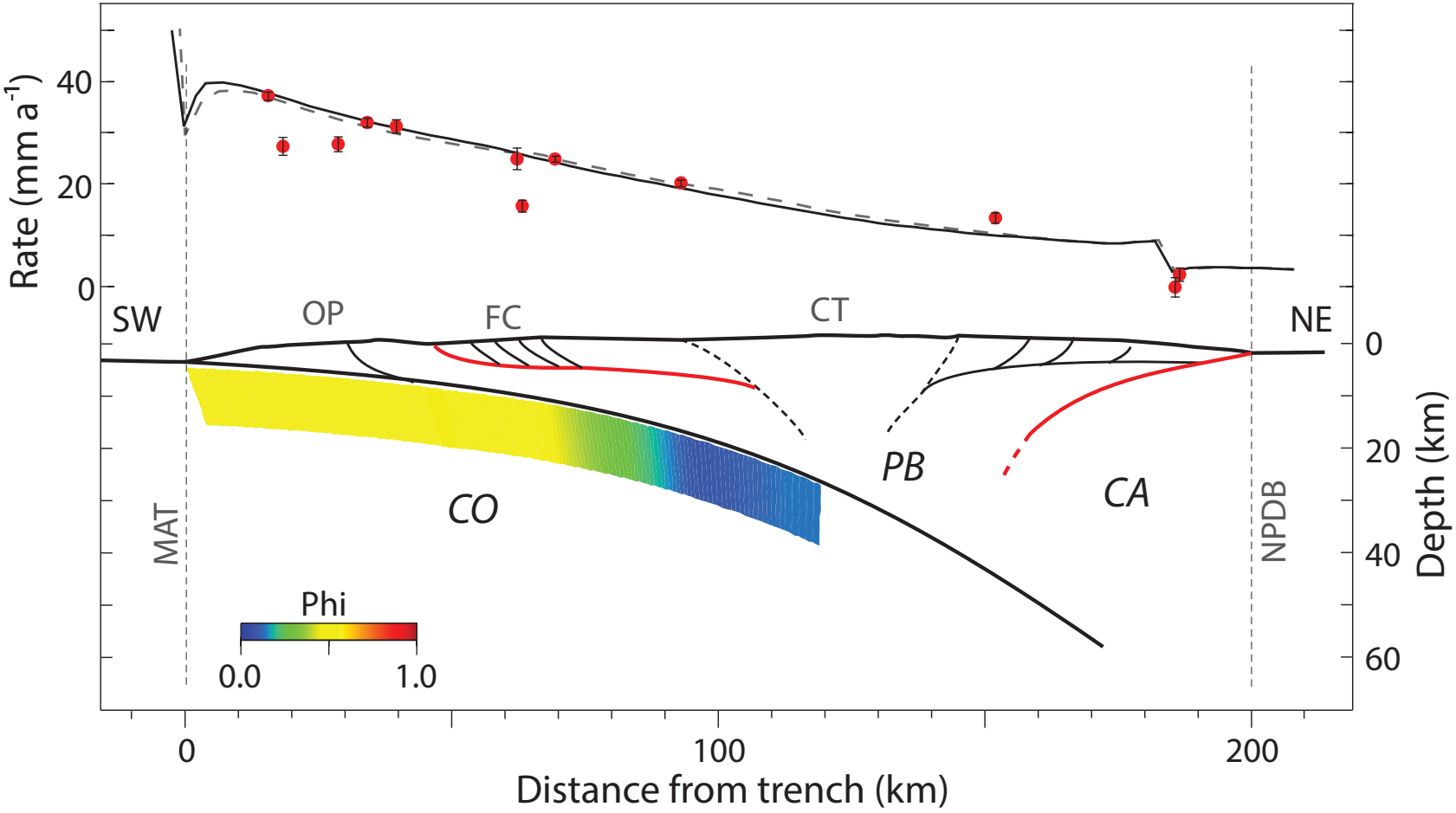
Kobayashi et al. (2012 – submitted)



EQ Cycle: Osa Segment

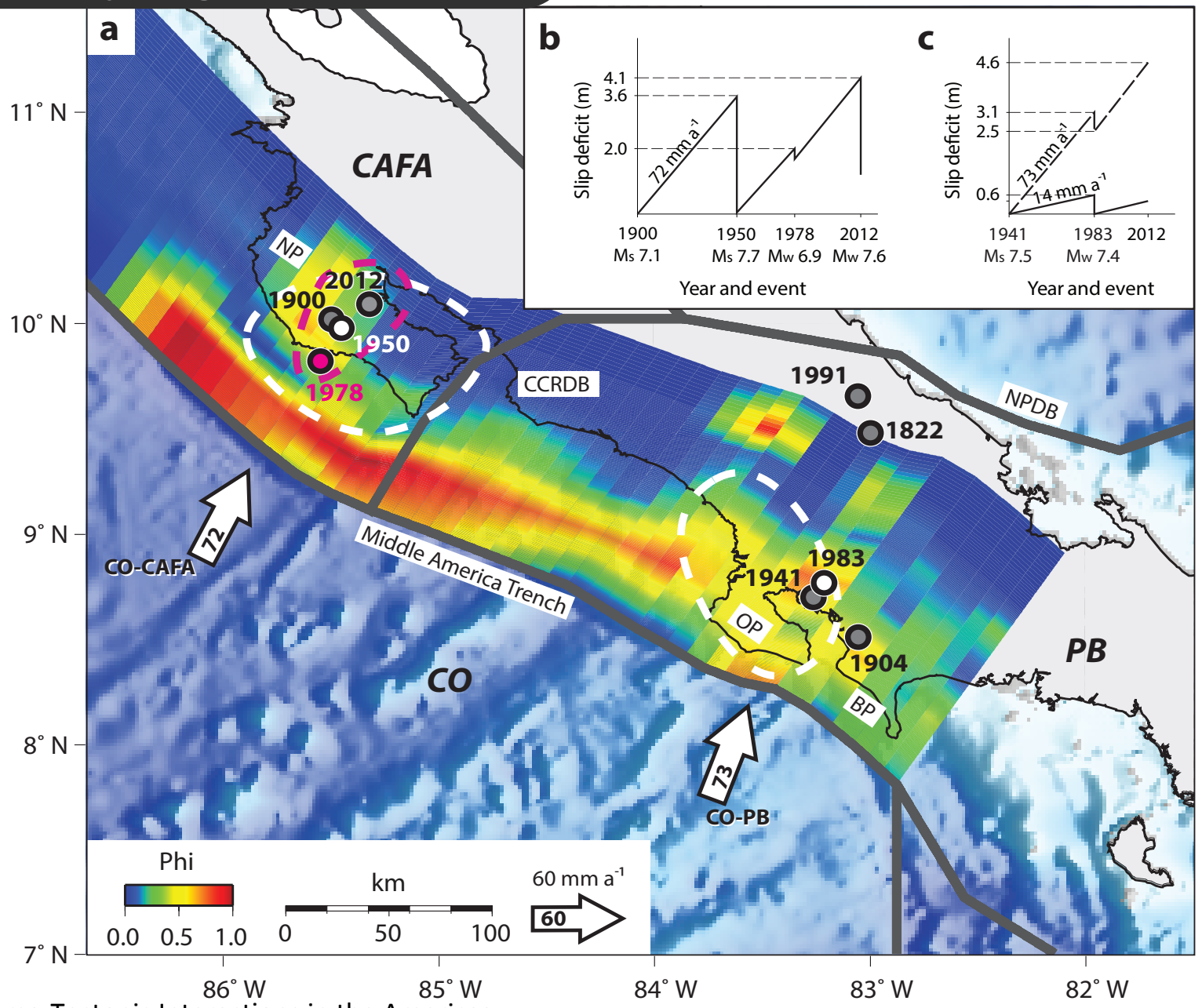
Kobayashi et al. (2012 – submitted)

- Estimated shortening across the Fila Costeña thrust belt: 10-40 mm a^{-1} (*Fisher et al.* 2004; *Sitchler et al.* 2007).

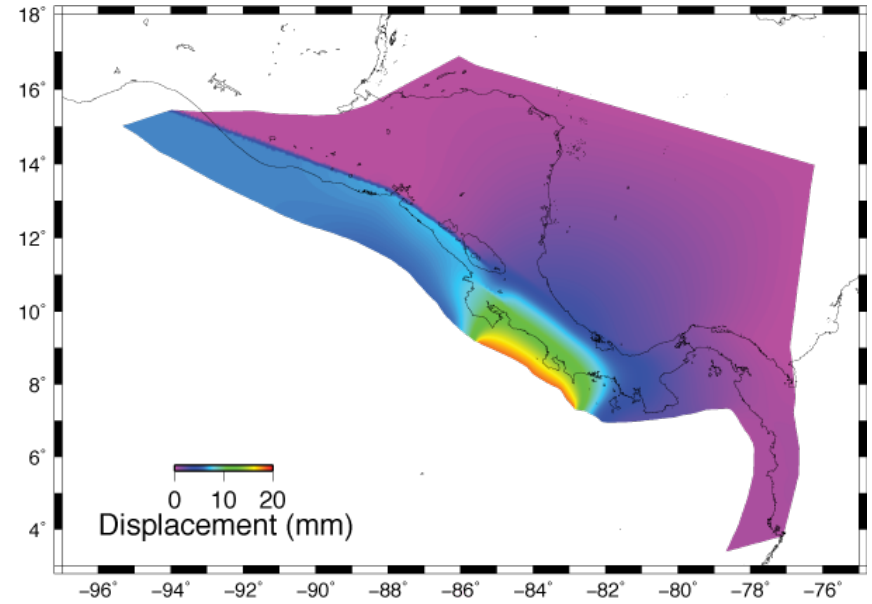


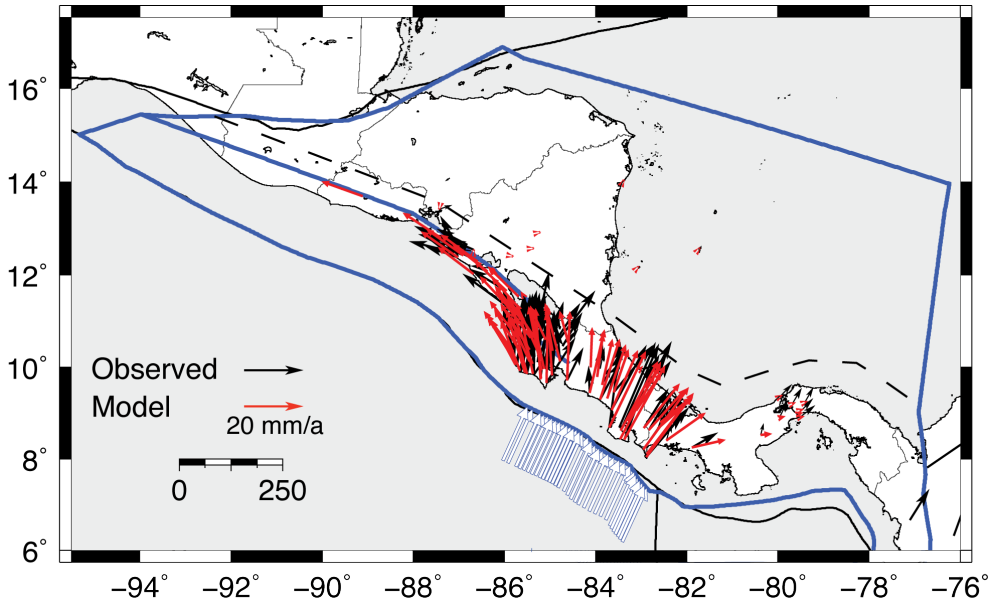
Coupling Pattern

Kobayashi et al. (2012 – submitted)



Cocos Ridge Collision - PB Motion





- FEM of Ridge Collision (GTECTON)
  - Spherical shell elements
  - Variable rheology b/w forearc/arc (viscoelastic) and Caribbean crust (elastic)
  - Low-friction faults along arc aid in accommodating forearc motion
  - North fixed; East and west free
  - Velocity boundary condition - CNS-2 - Cocos Ridge crust
- Captures main features of velocity field and long-term deformation
  - High rates inboard CR
  - Forearc transport

Mechanism for PR Motion

Kobayashi et al. (2012 – submitted)