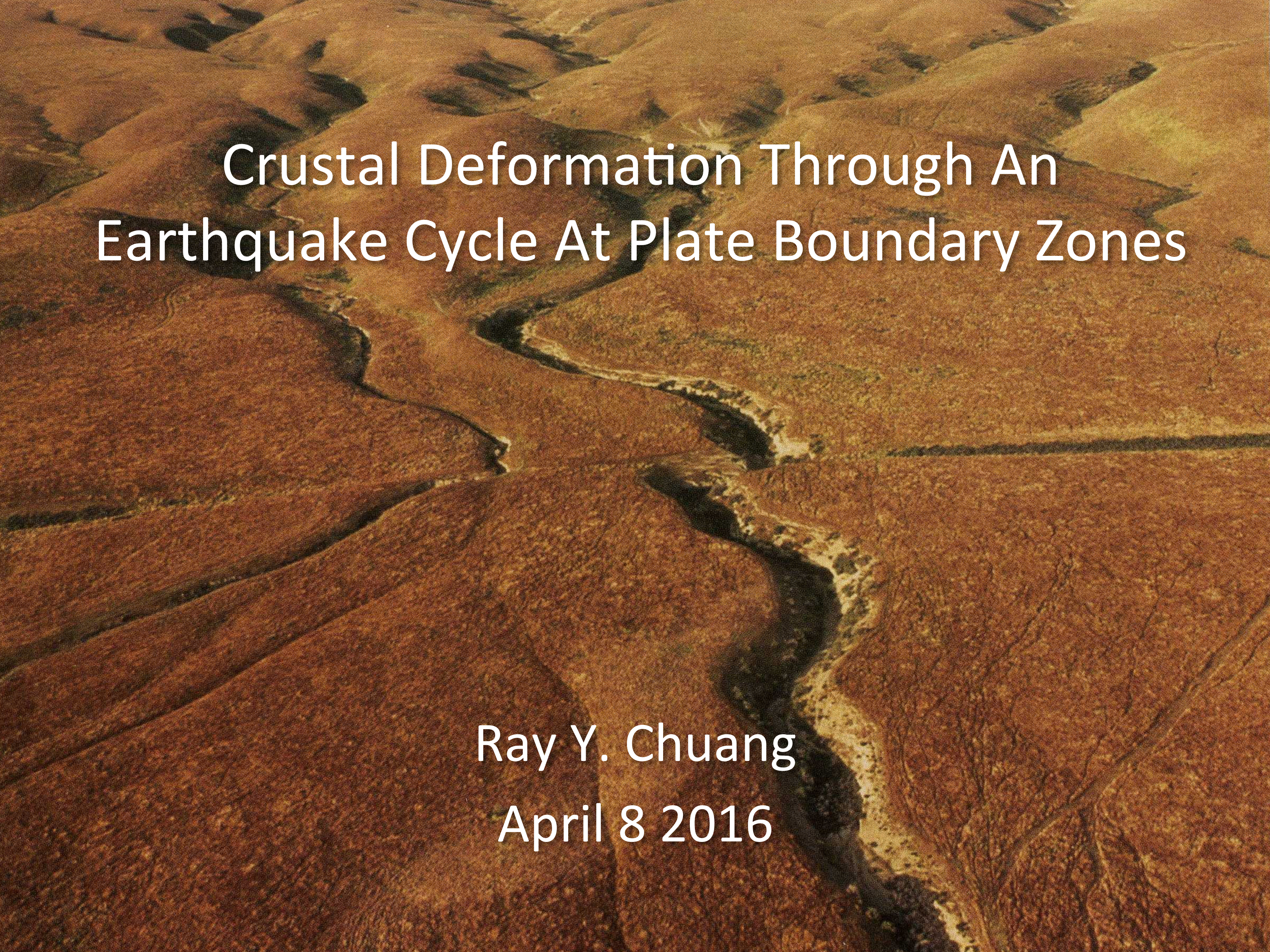

Crustal Deformation Through An Earthquake Cycle At Plate Boundary Zones

Ray Y. Chuang

April 8 2016

About Me

- Professional Background
  - B.S., **Geography**, National Taiwan University
  - M.S., **Geology**, Pacific Northwest Geodetic Array, Central Washington University
  - Ph.D., **Geology** with **mathematics** minor, Indiana University
  - Research Fellow, Earthquake Research Institute, University of Tokyo
- Research Interests
  - Tectonic geodesy, crustal deformation, active tectonics, natural hazards

Outline

- Introduction
- Monitoring surface and topographic changes
- Analysis of deformation through earthquake cycle
- Future directions

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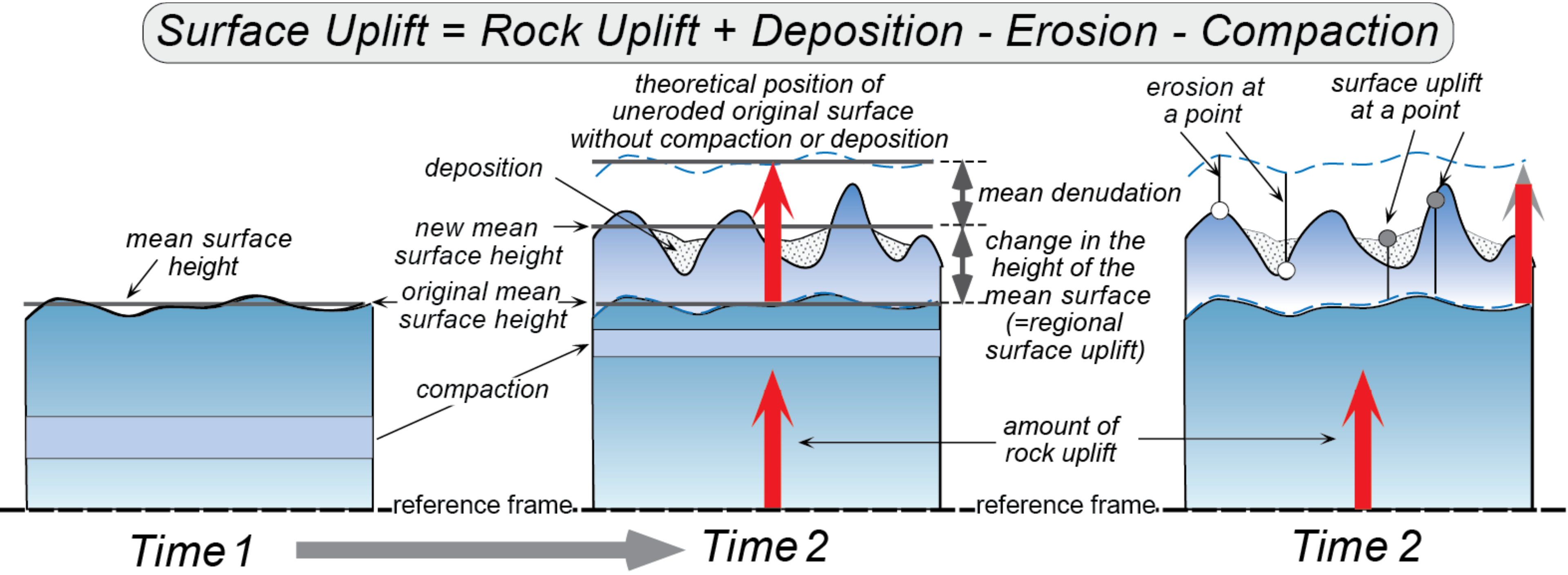
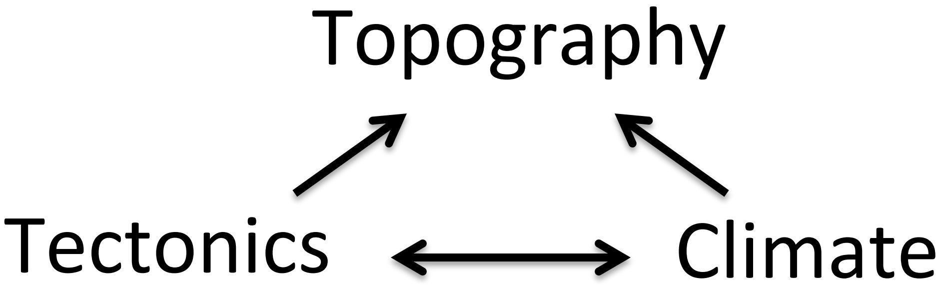


Burbank and Anderson (2012)



Topography

Tectonics

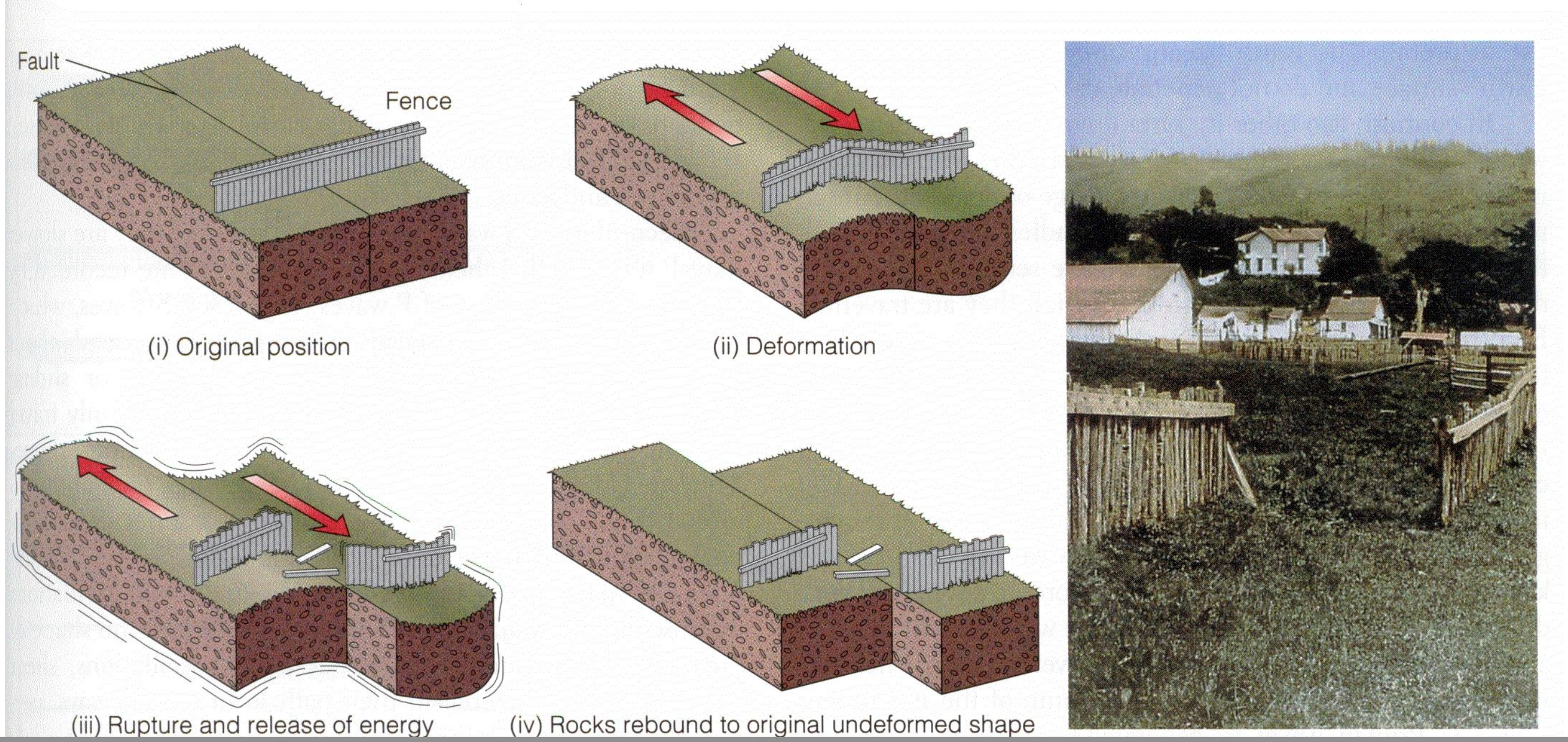
Climate

Deformation (uplift, subsidence)
Isostasy
Dynamic topography

erosion (physical, chemical)
landslides

Elastic Rebound Theory

- After 1906 M7.9 SF EQ, Henry F. Reid proposed:
  - Earthquakes represent rapid release of elastic strain build up over a long period of time
  - Confirmed by geodetic (triangulation) and geologic measurements

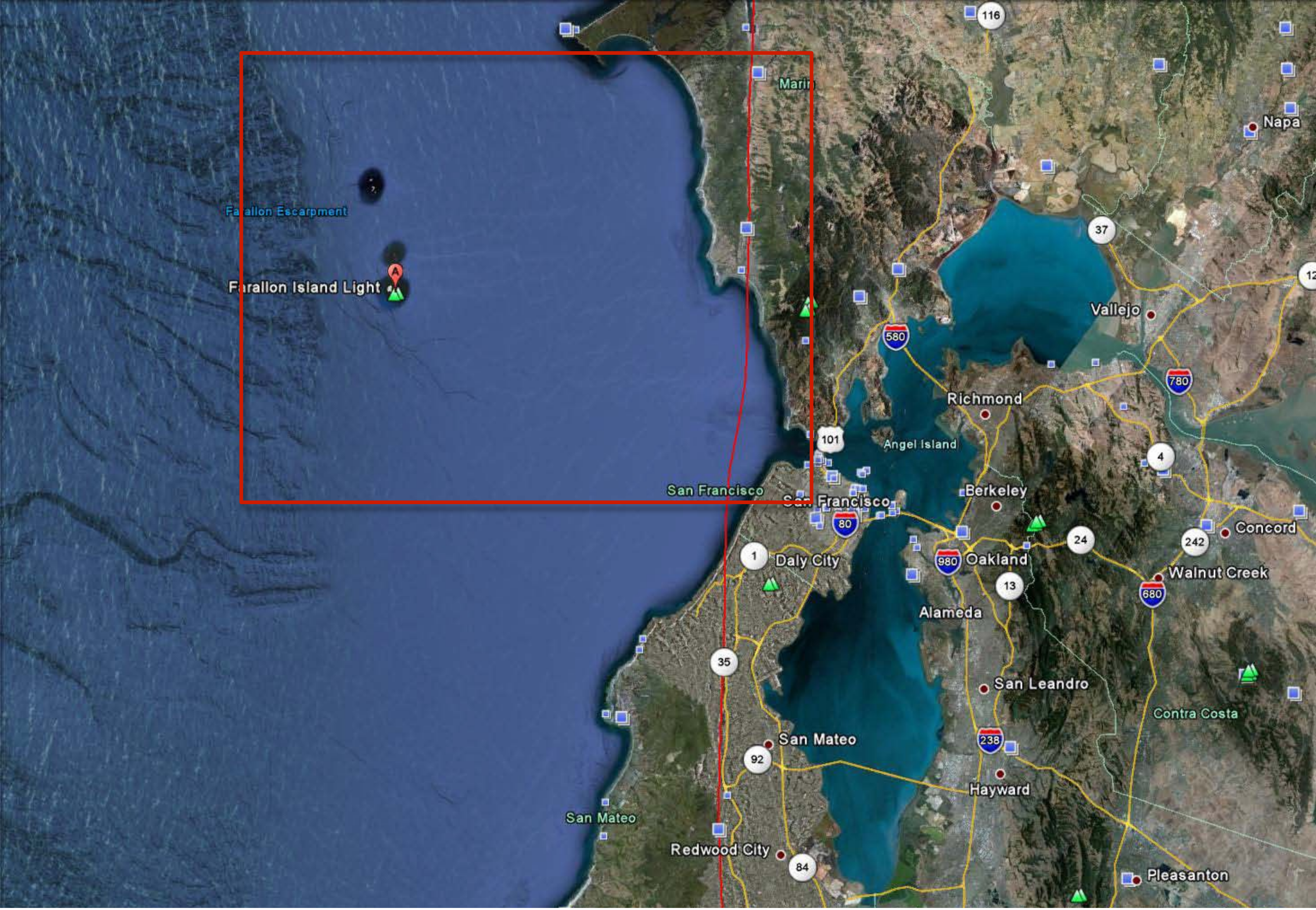


(i) Original position

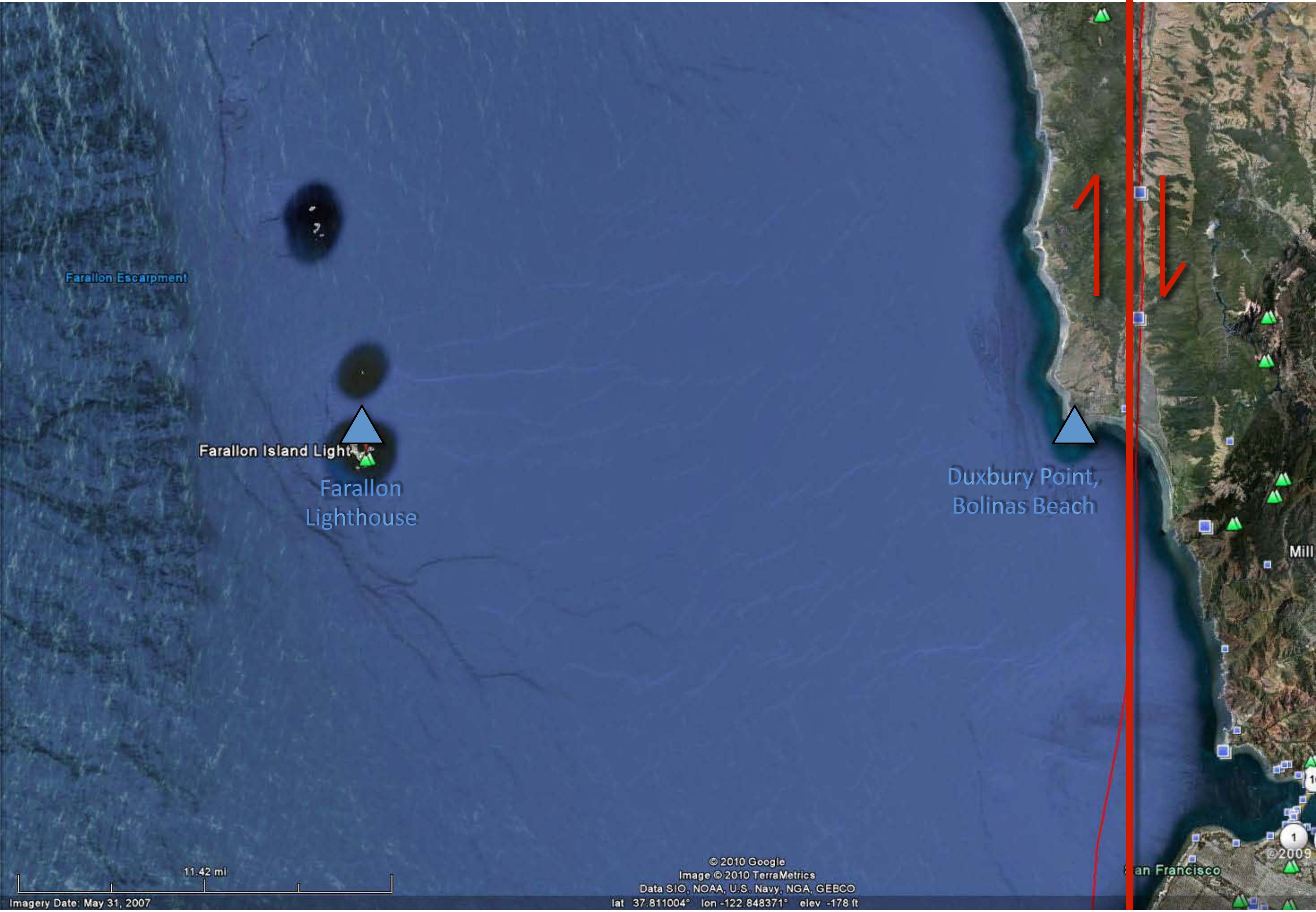
(ii) Deformation

(iii) Rupture and release of energy

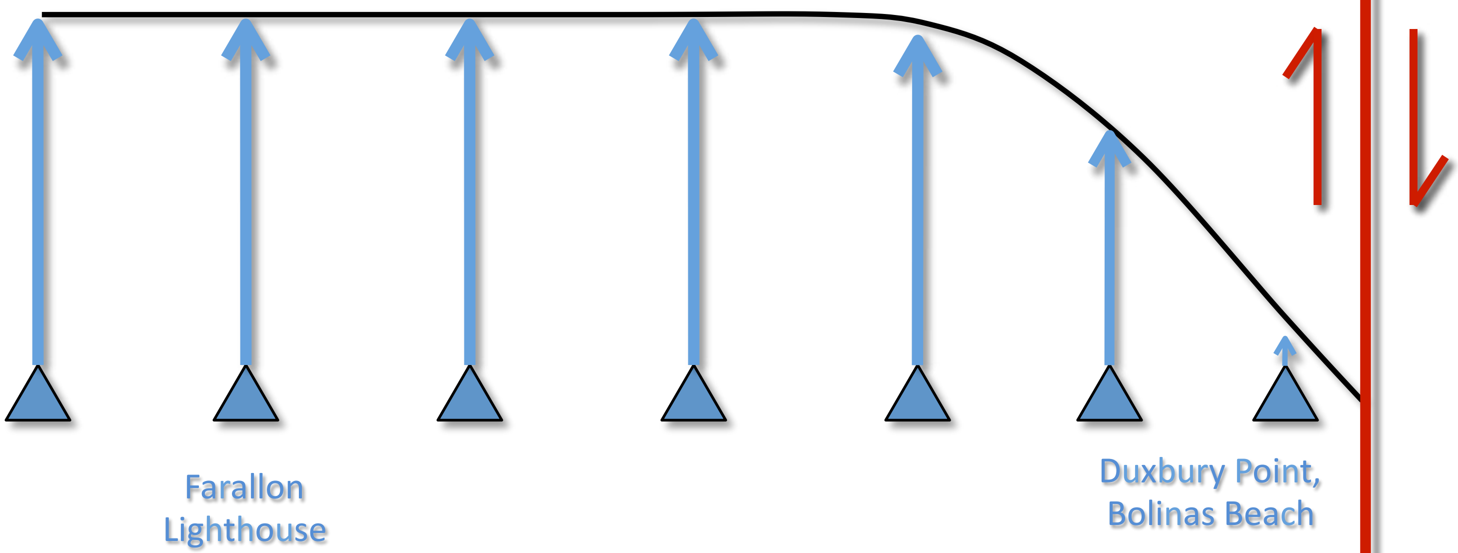
(iv) Rocks rebound to original undeformed shape



Farallon Escarpment
Farallon Island Light
Marin
San Francisco
Angel Island
Richmond
Vallejo
Napa
Berkeley
Oakland
Alameda
Daly City
Concord
Walnut Creek
San Leandro
Contra Costa
San Mateo
Hayward
Redwood City
Pleasanton
116
37
580
780
101
80
980
24
242
4
13
1
680
35
238
92
84

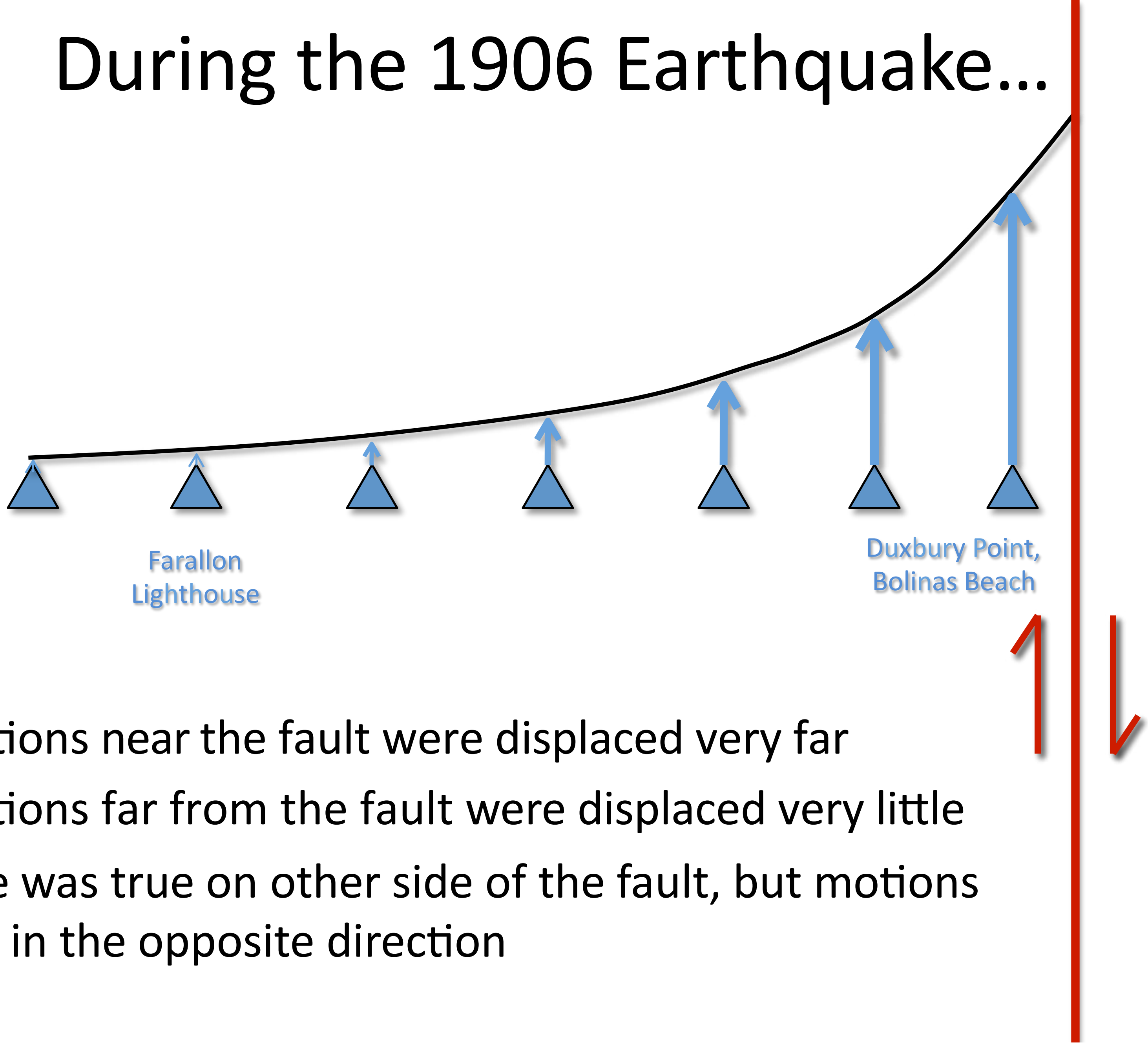

Farallon Escarpment
Farallon Island Light
Farallon Lighthouse
Duxbury Point, Bolinas Beach
Mill
San Francisco
11.42 mi
Imagery Date: May 31, 2007
© 2010 Google
Image © 2010 TerraMetrics
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
lat 37.811004° lon -122.848371° elev -178 ft
©2009
1

Before the 1906 Earthquake…



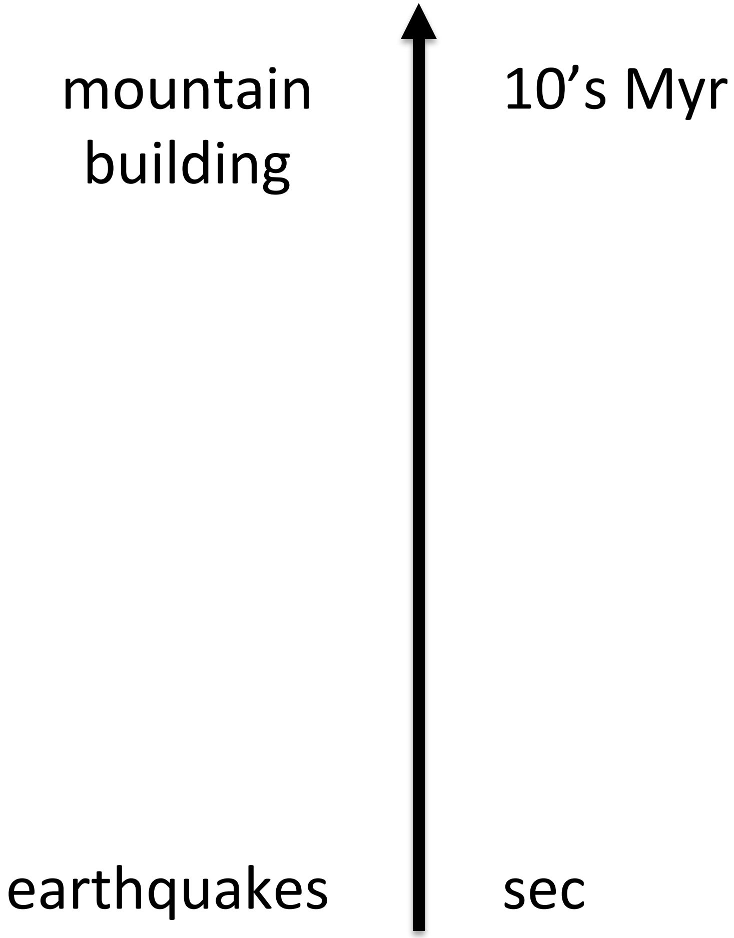
- Locations far from the fault were moving fast
- Locations near the fault were moving slow
- Same was true on other side of the fault, but motions were in the opposite direction

During the 1906 Earthquake…



- Locations near the fault were displaced very far
- Locations far from the fault were displaced very little
- Same was true on other side of the fault, but motions were in the opposite direction

Tectonic activities at different time scale

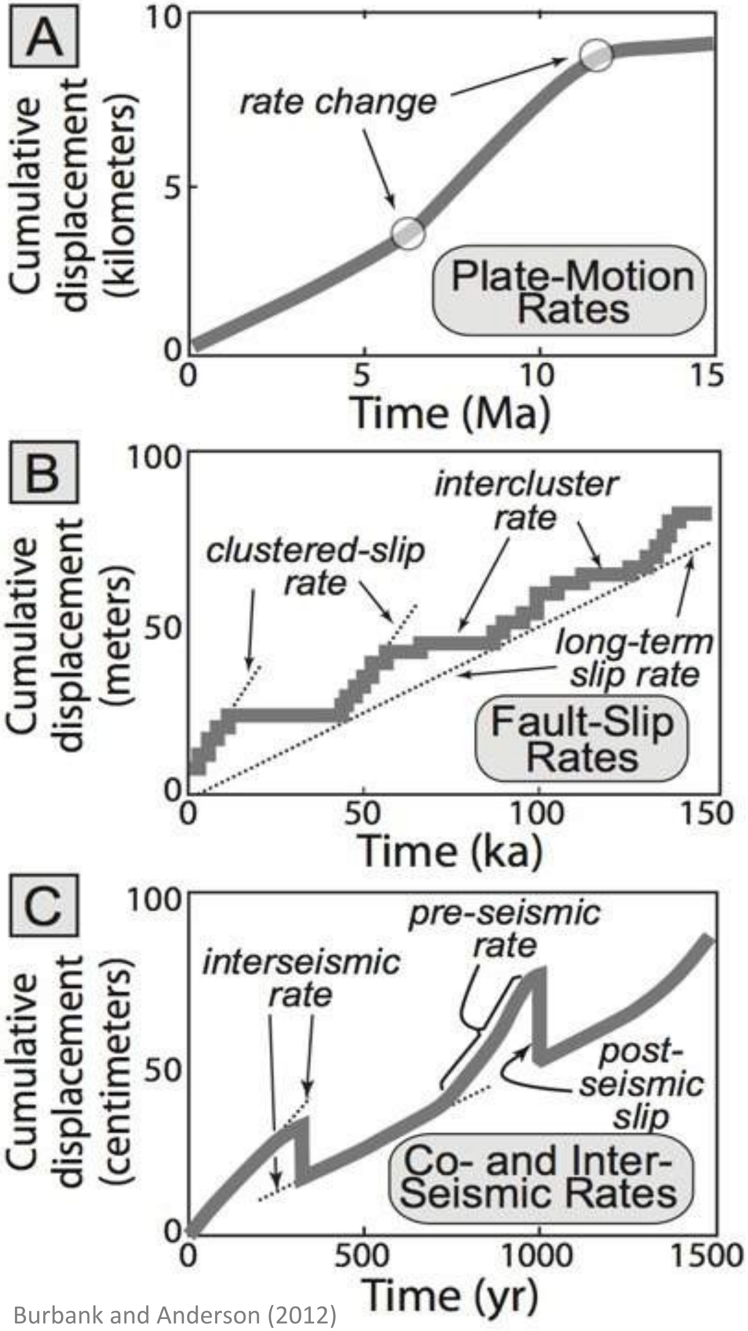


mountain building

10's Myr

earthquakes

sec



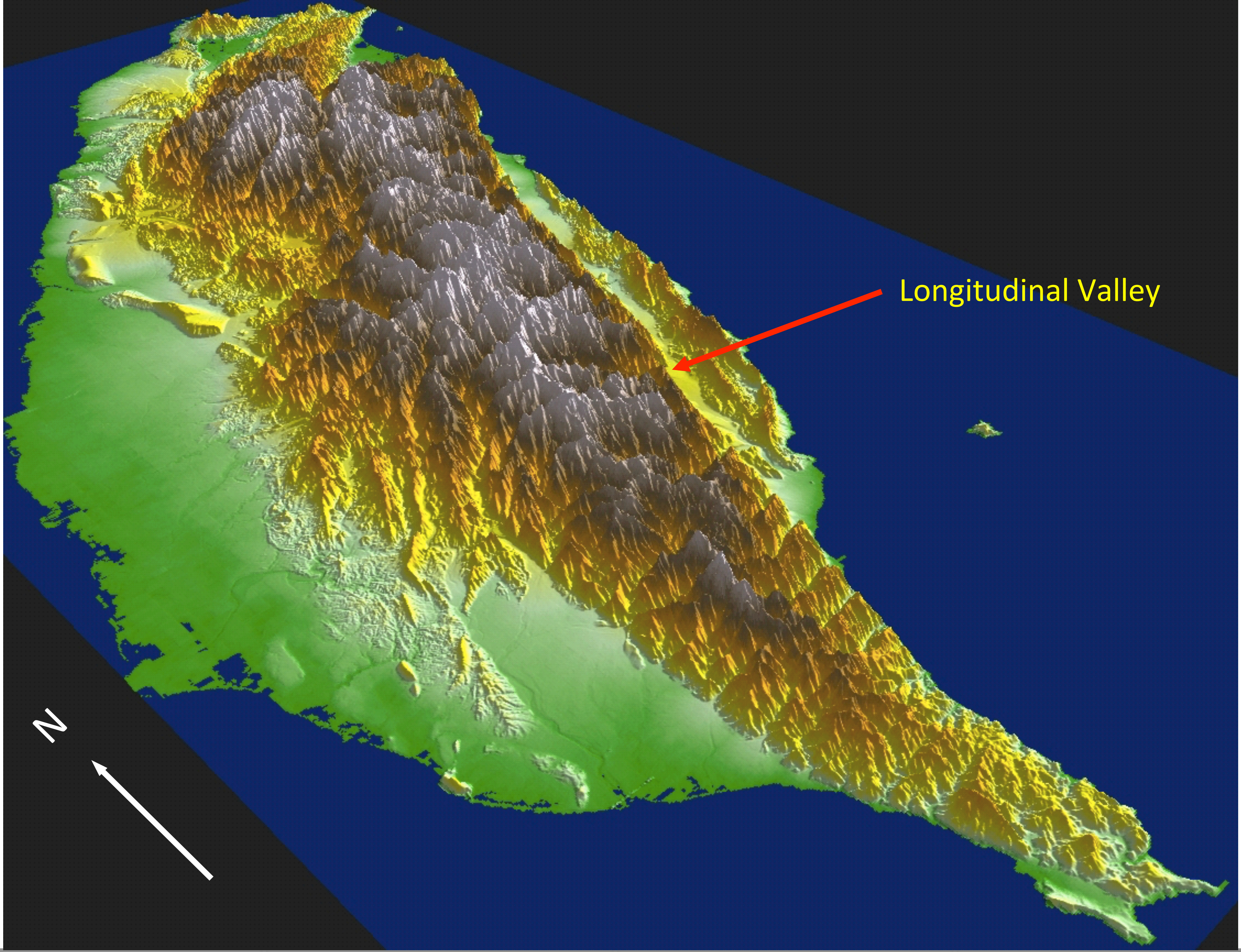
Burbank and Anderson (2012)

Outline

- Introduction
- Monitoring surface and topographic changes
- Analysis of deformation through earthquake cycle
- Future directions

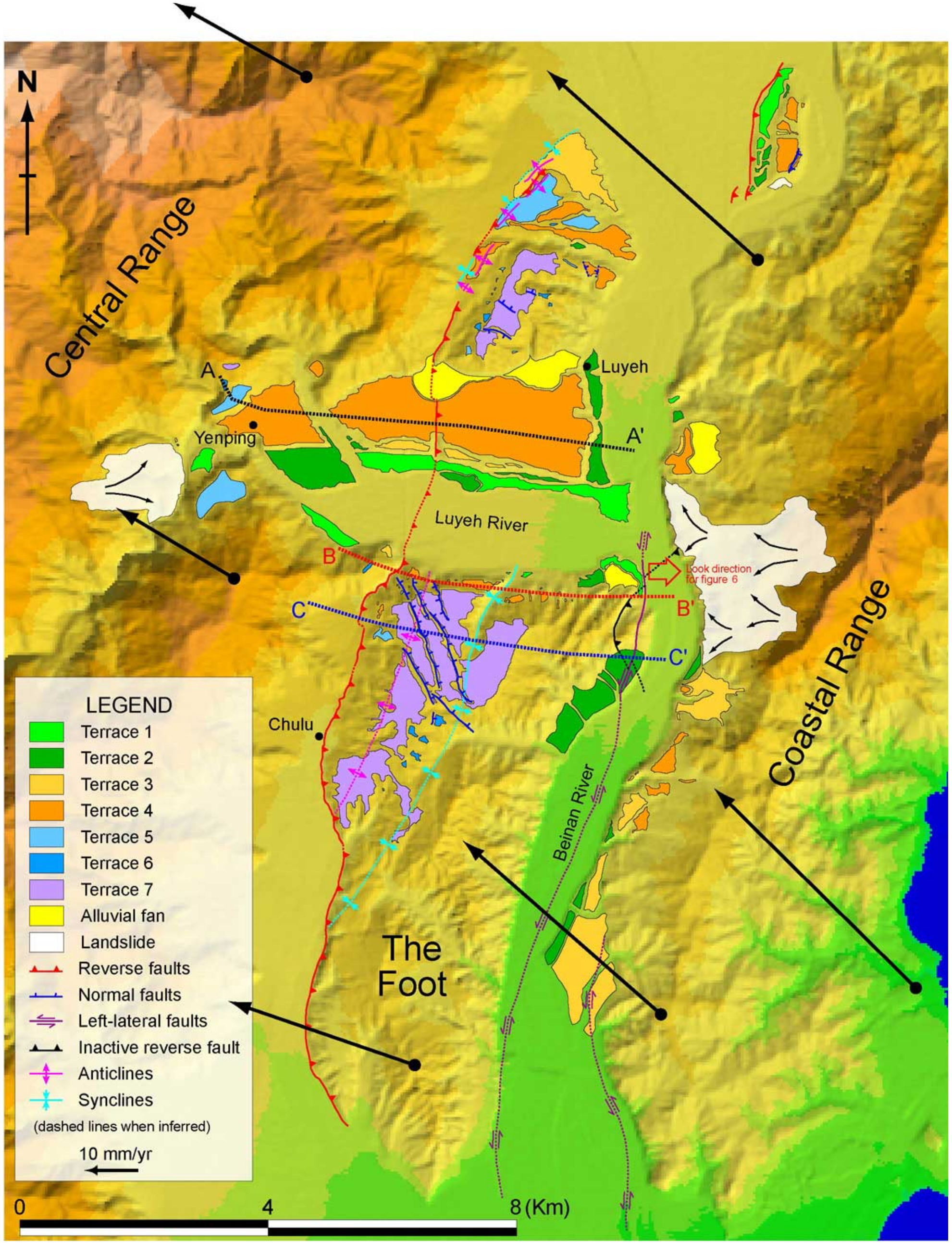
Observation and Monitoring Methods

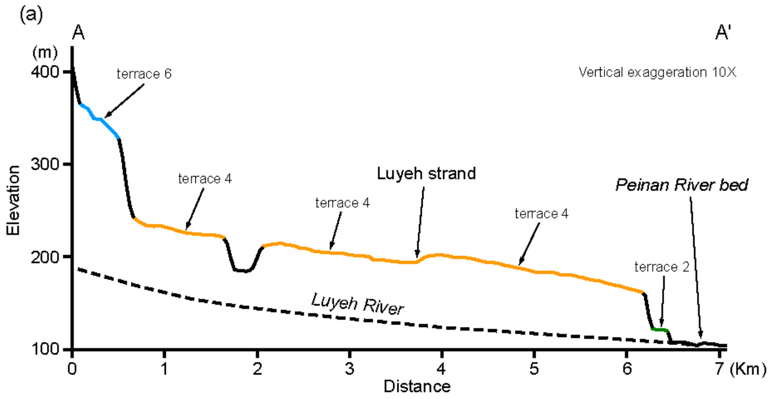
- Field investigation
  - Field survey
- Terrestrial geodesy
  - Leveling, triangulation, trilateration, etc.
- Space geodesy
  - GNSS, VLBI, etc.
- Remote sensing (imaging geodesy)
  - DEM, DEM change, InSAR, etc.
- Others
  - Gravity, seismic approach, ground resistance, etc.

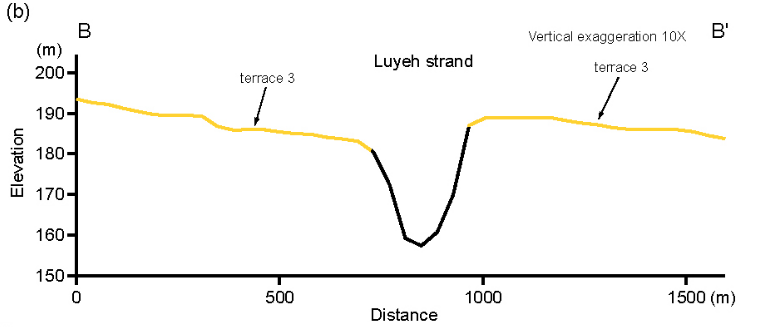


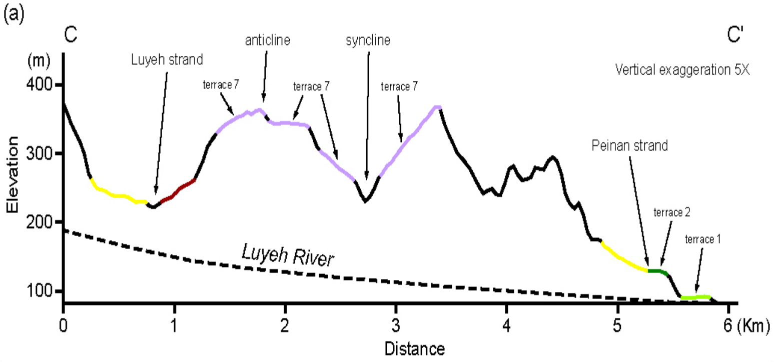
Longitudinal Valley
N

Field investigation & DEM/aerial photo analysis

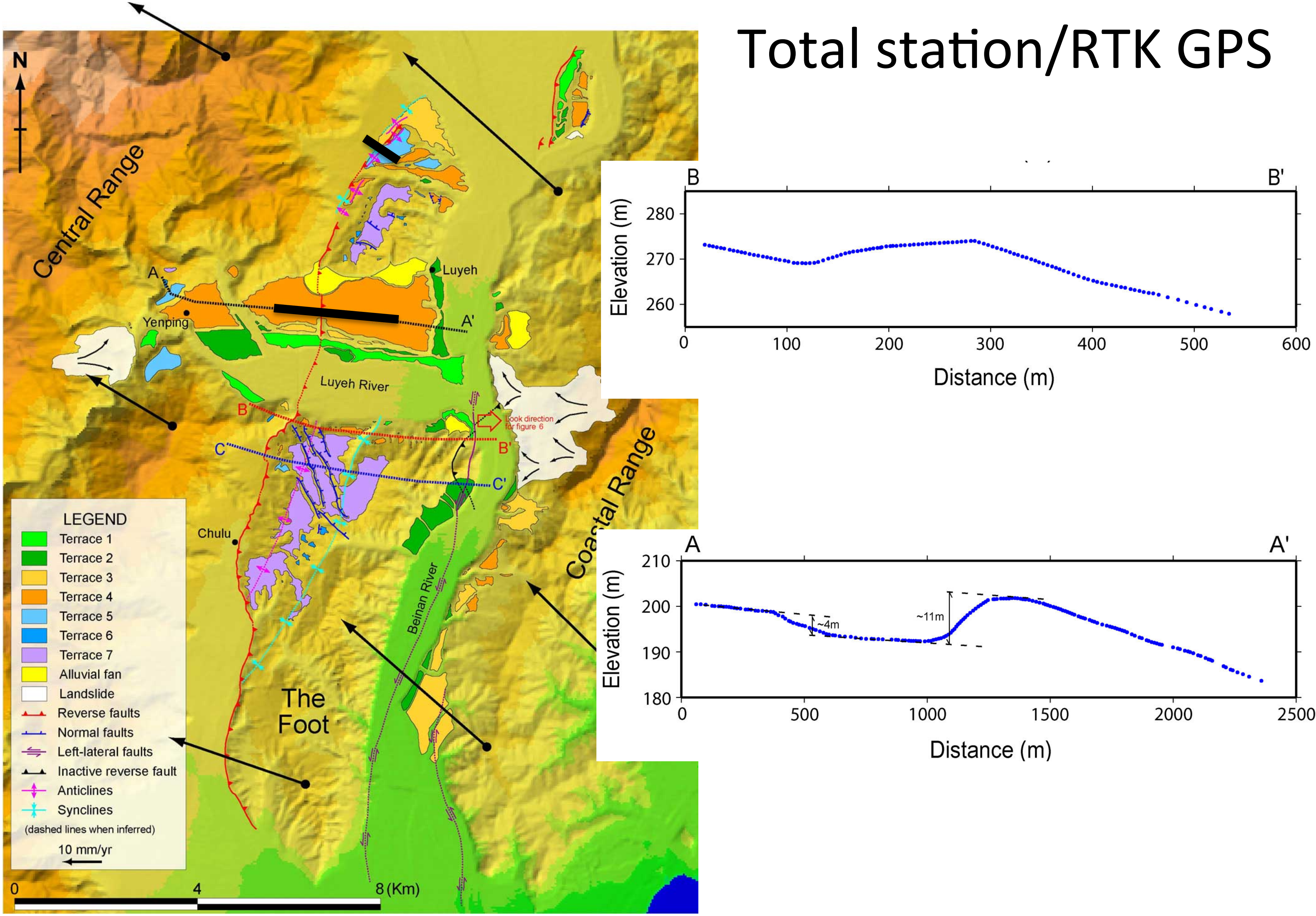




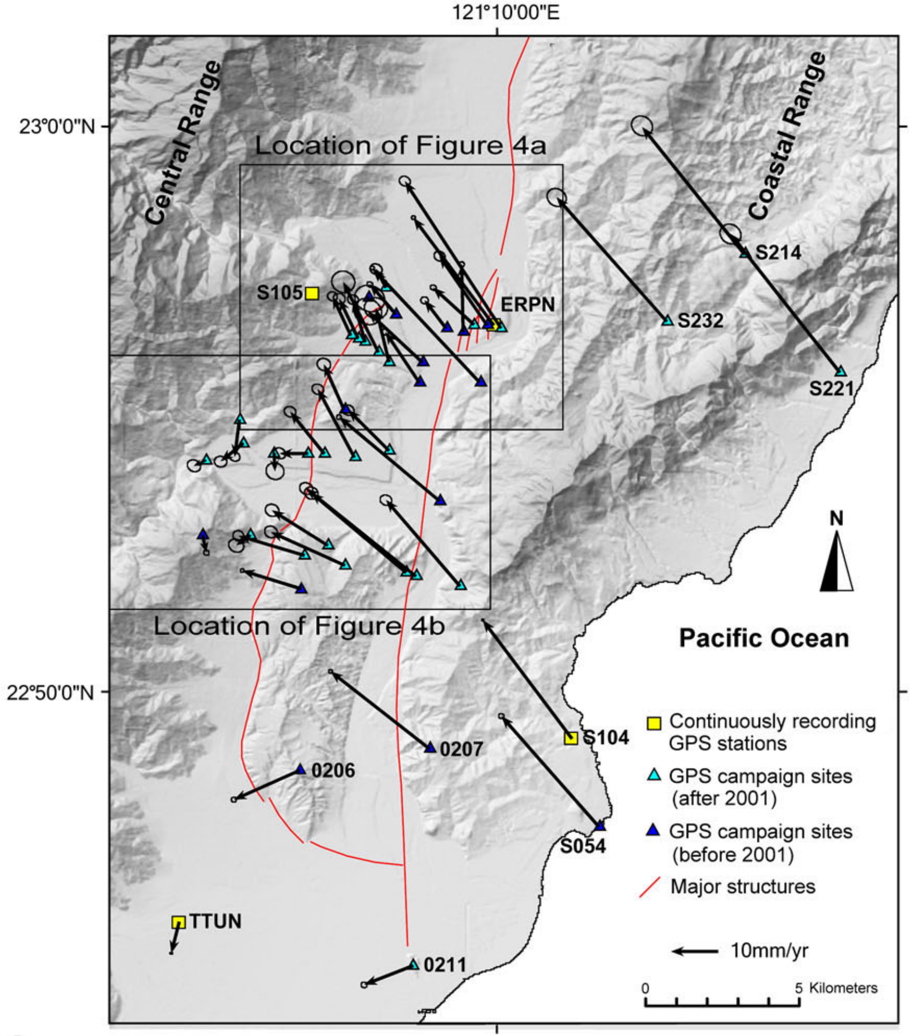


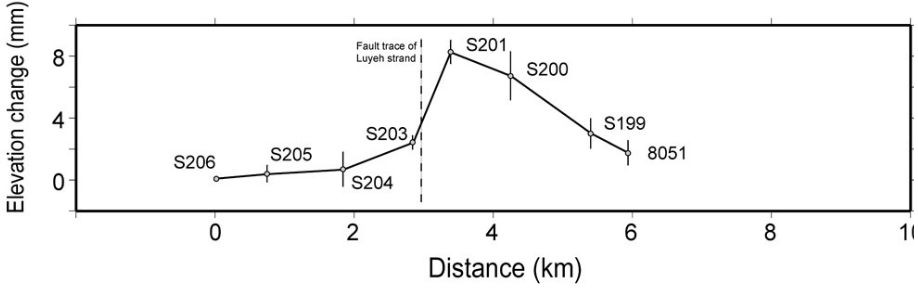


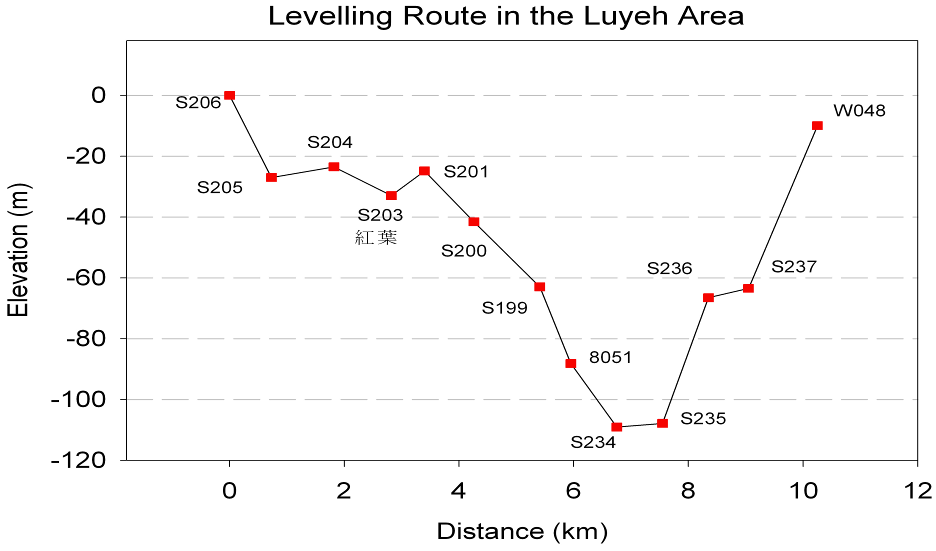
Total station/RTK GPS

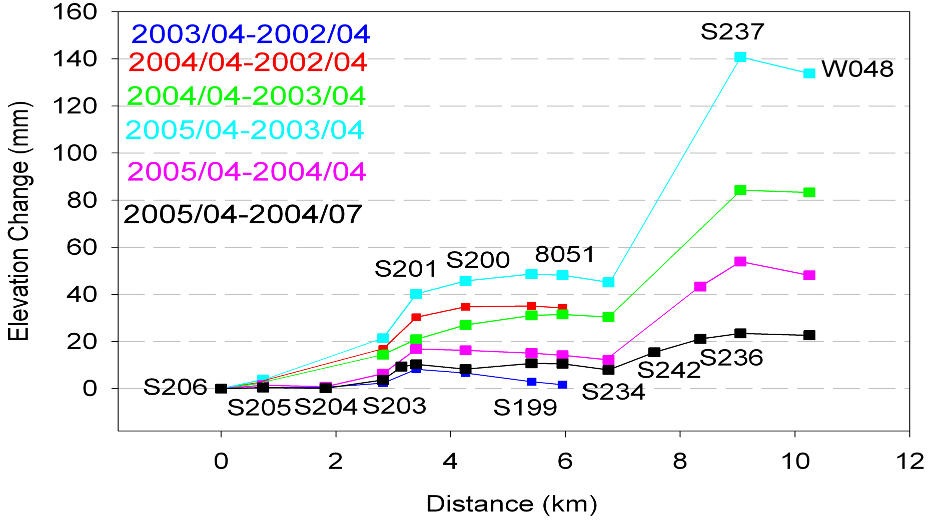


GPS and precise leveling

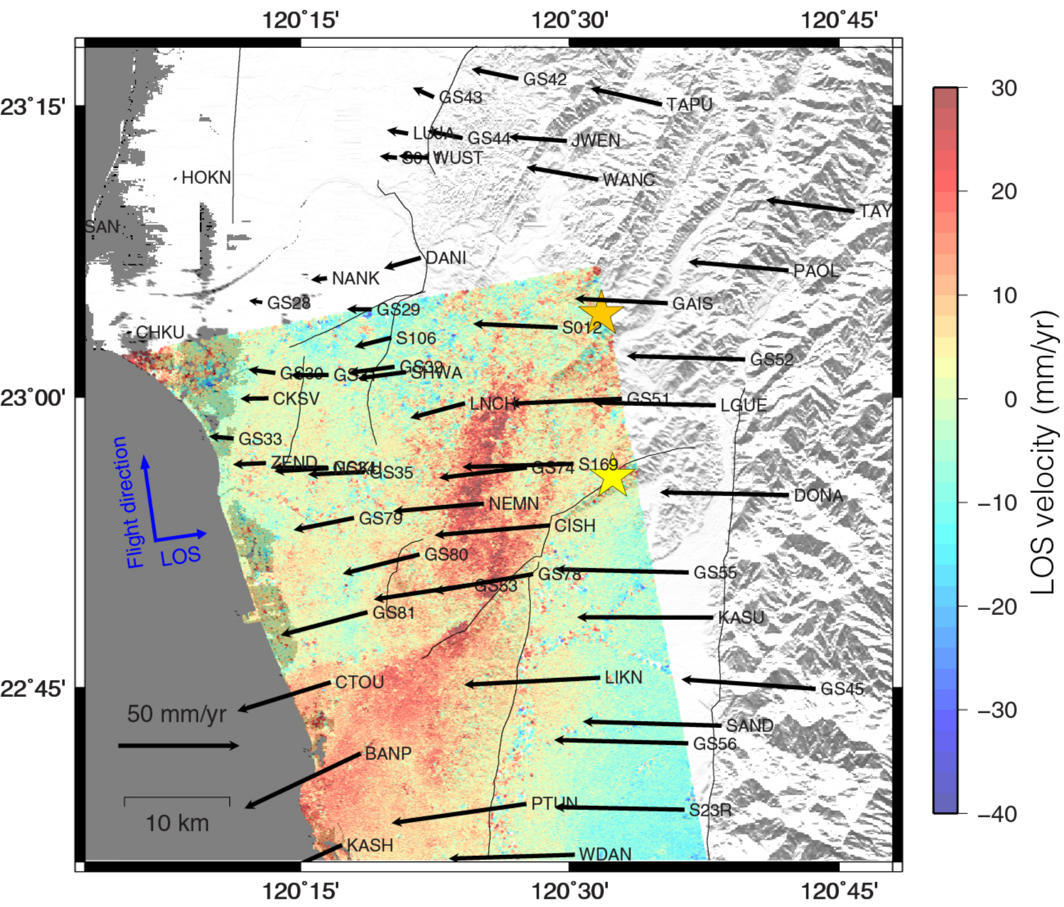






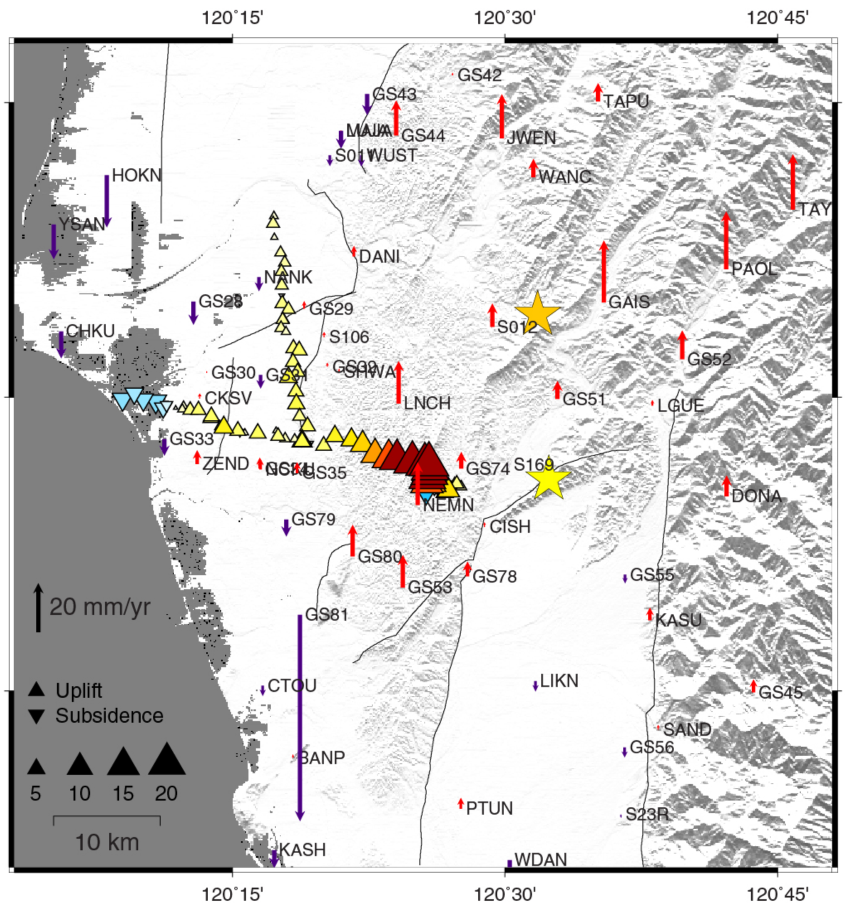


Southwestern Taiwan

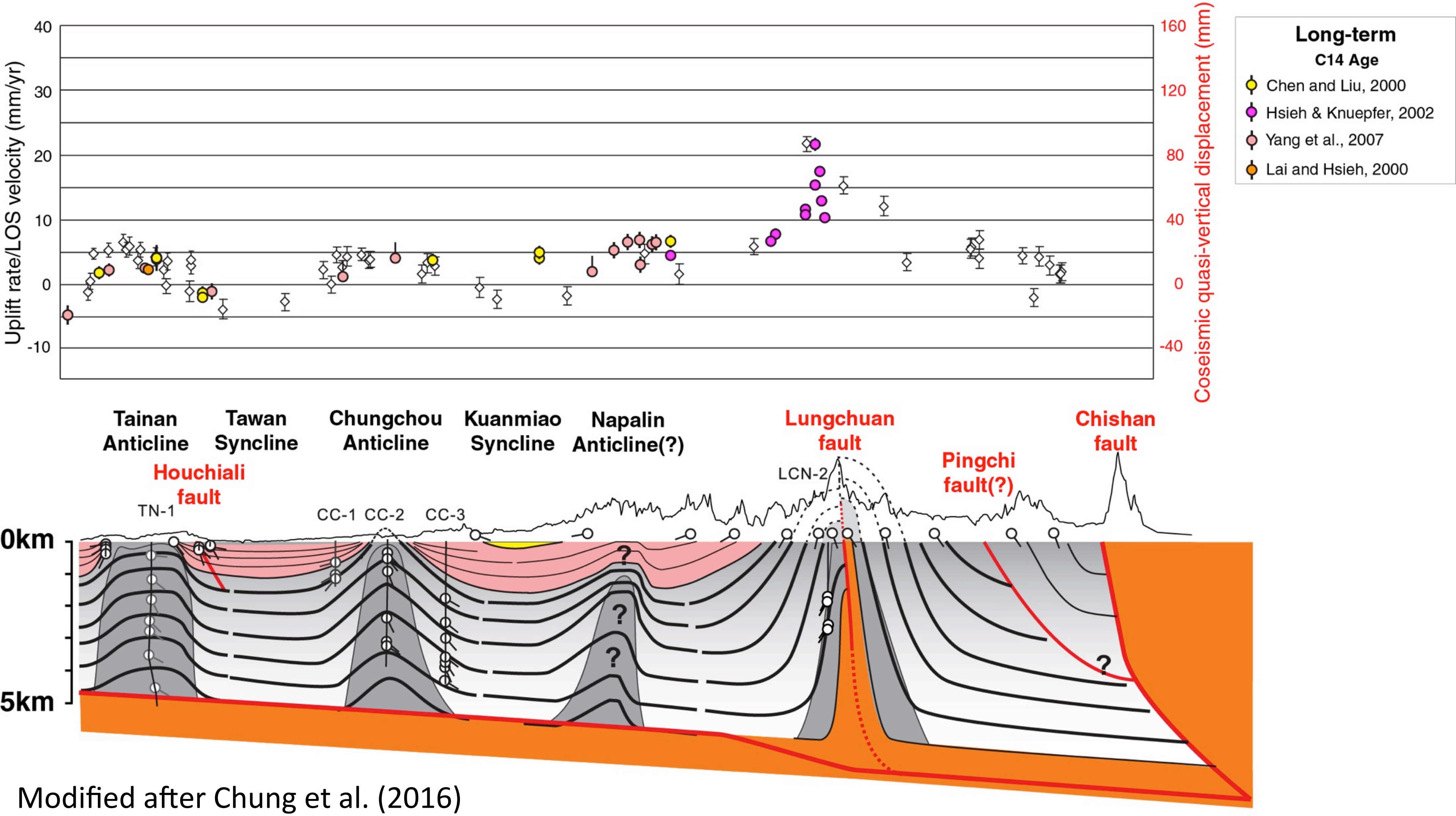


GPS Data from: GPS lab

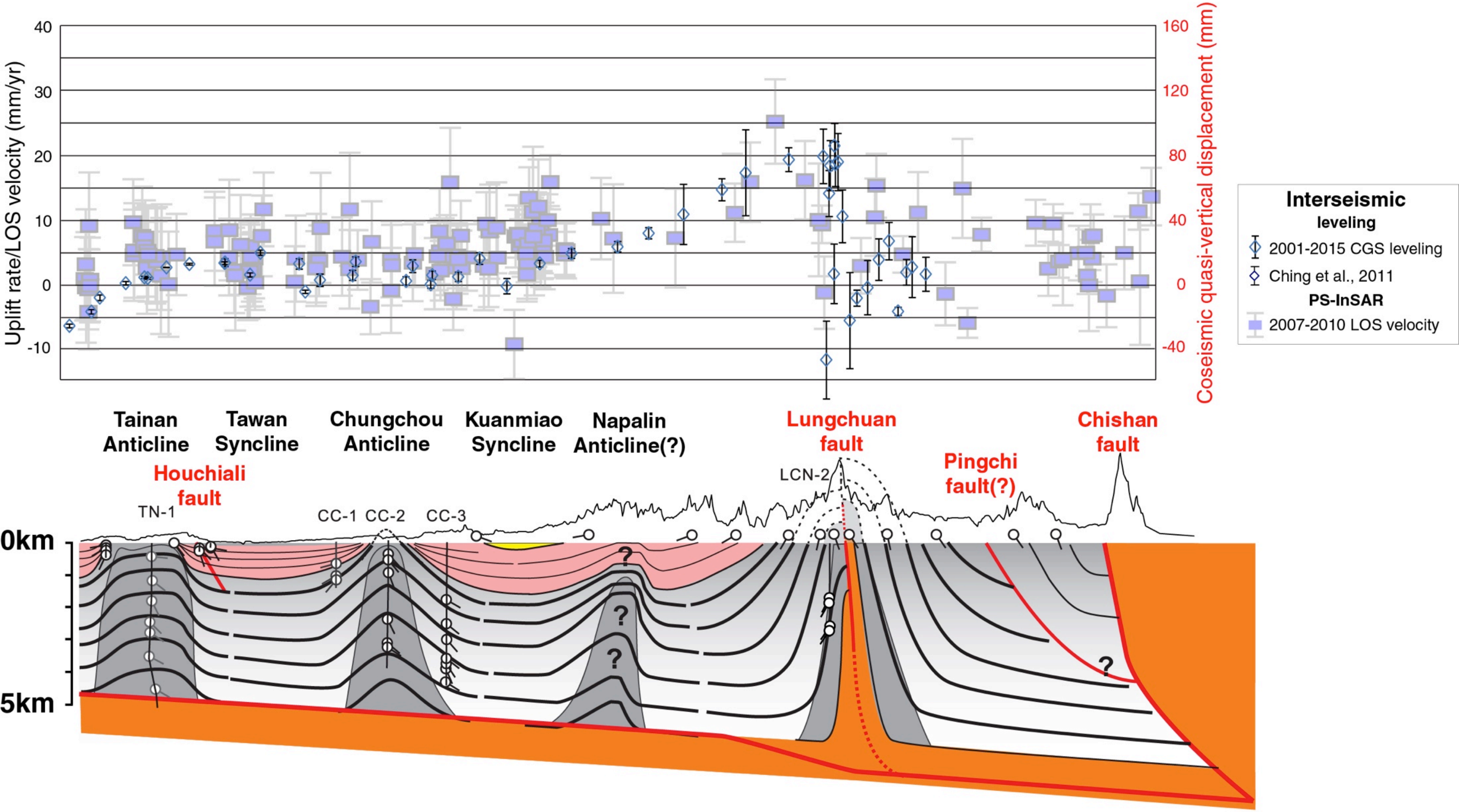
SAR image source: JAXA ALOS

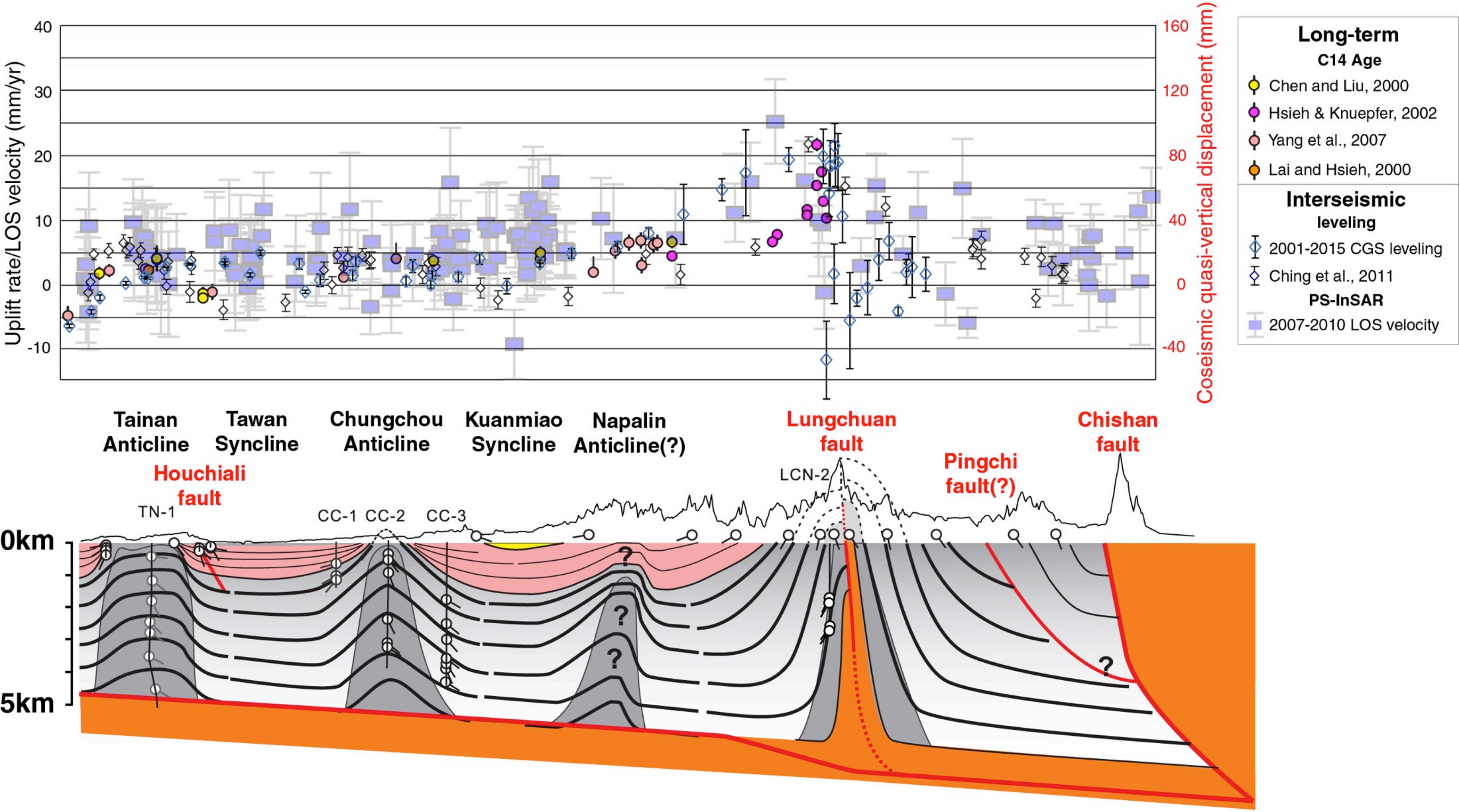


Leveling data source: CGS



Modified after Chung et al. (2016)


Uplift rate/LOS velocity (mm/yr)
40
30
20
10
0
-10
Coseismic quasi-vertical displacement (mm)
160
120
80
40
0
-40
Interseismic
leveling
2001-2015 CGS leveling
Ching et al., 2011
PS-InSAR
2007-2010 LOS velocity
Tainan Anticline
Tawan Syncline
Chungchou Anticline
Kuanmiao Syncline
Napalin Anticline(?)
Lungchuan fault
Chishan fault
Houchiali fault
Pingchi fault(?)
TN-1
CC-1
CC-2
CC-3
LCN-2
0km
5km
?
?
?
?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C14 Age
Chen and Liu, 2000
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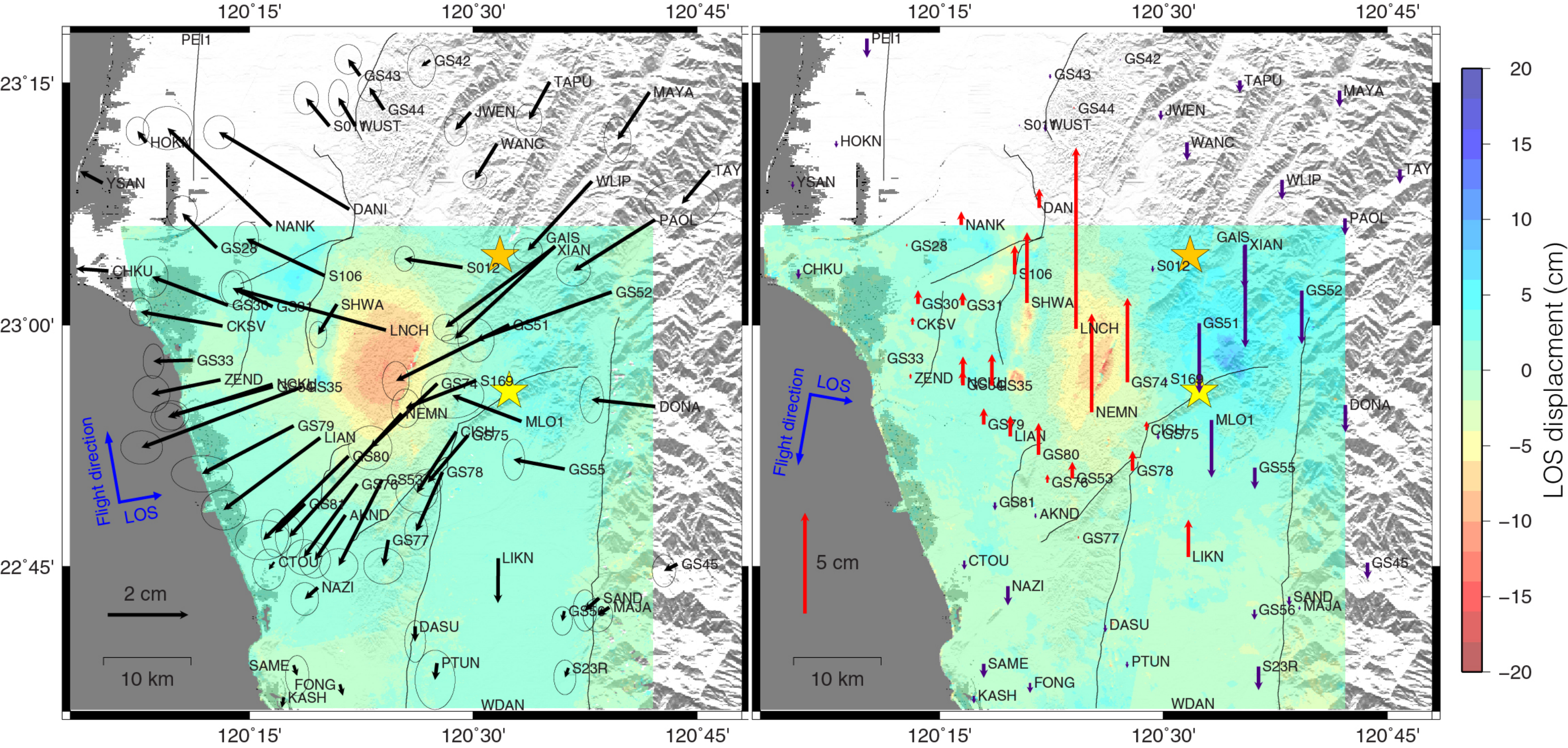
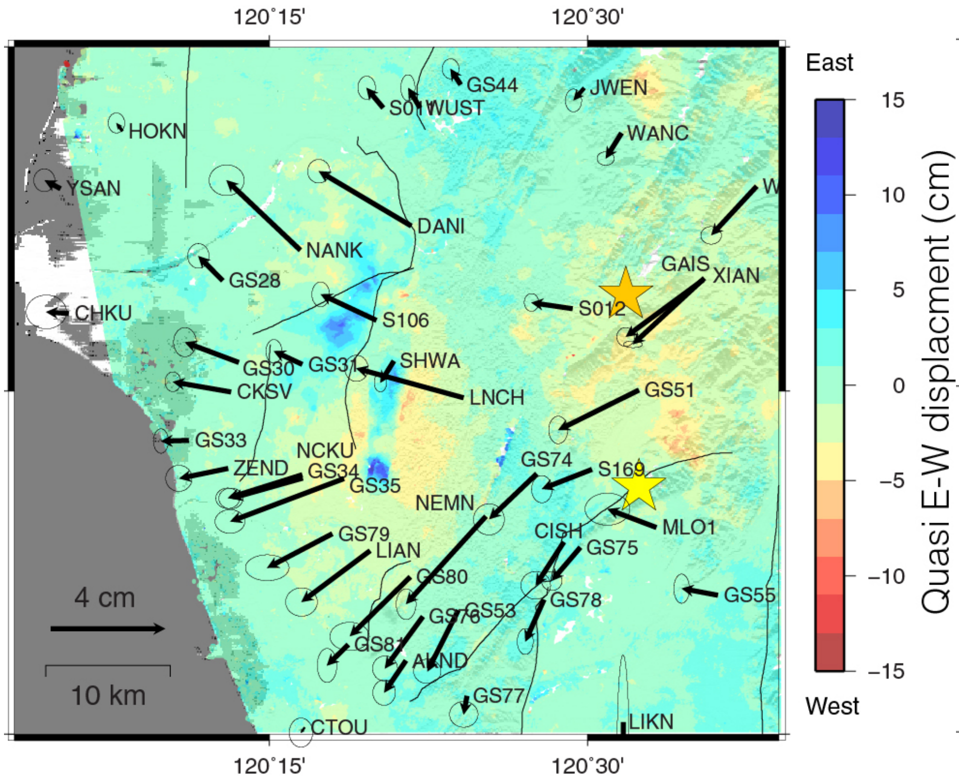
Meinong Earthquake

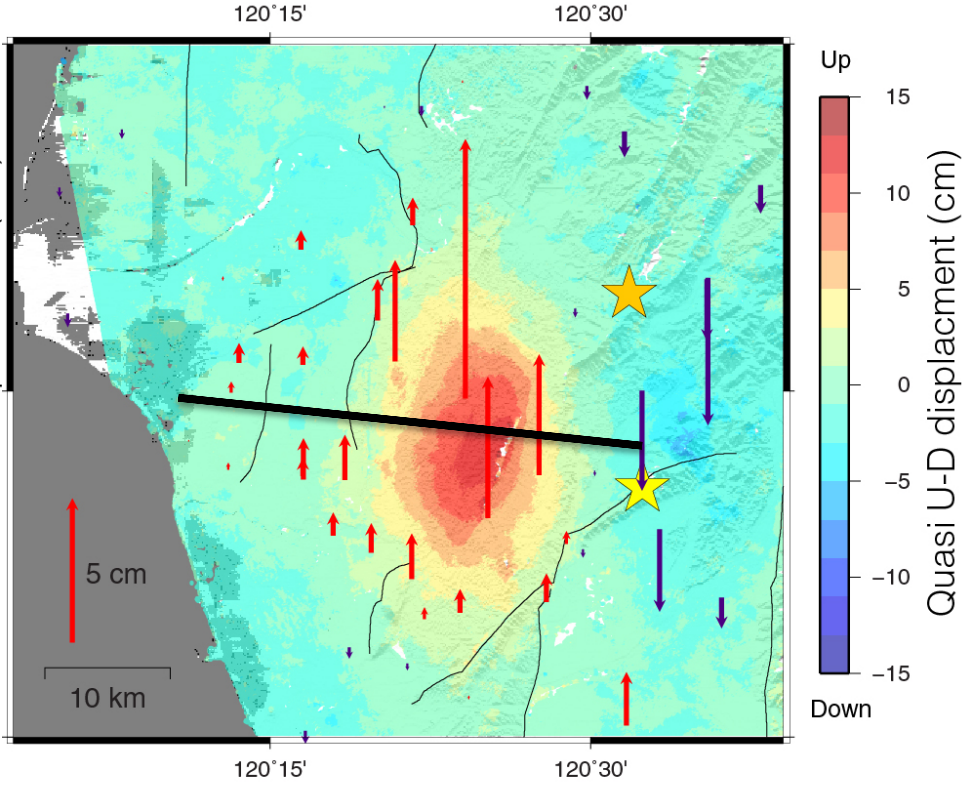


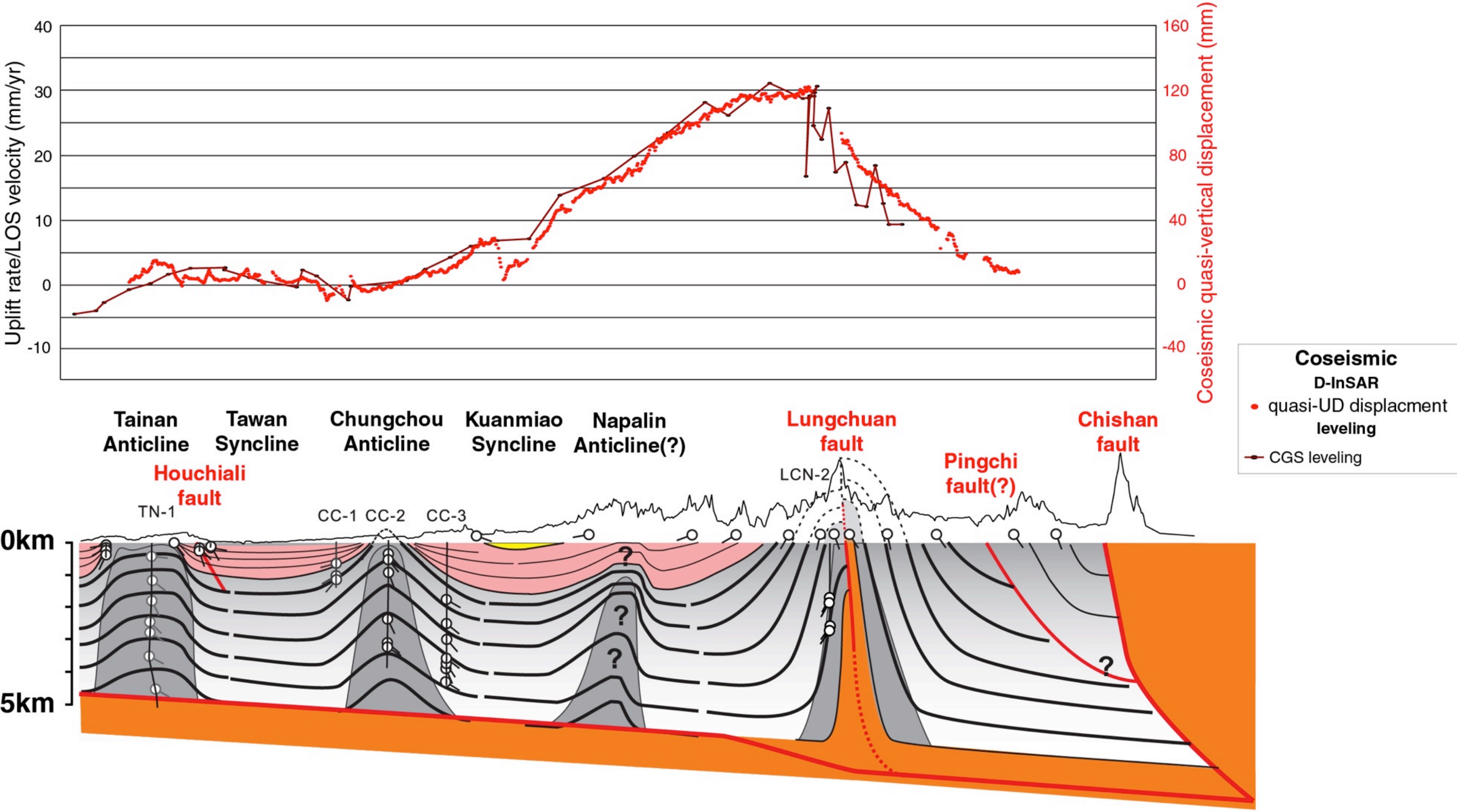
GPS Data source: CWB, CGS, NLSC, IESAS, NCKU
Processed by: CWB

SAR image sources: JAXA ALOS2

Meinong Earthquake



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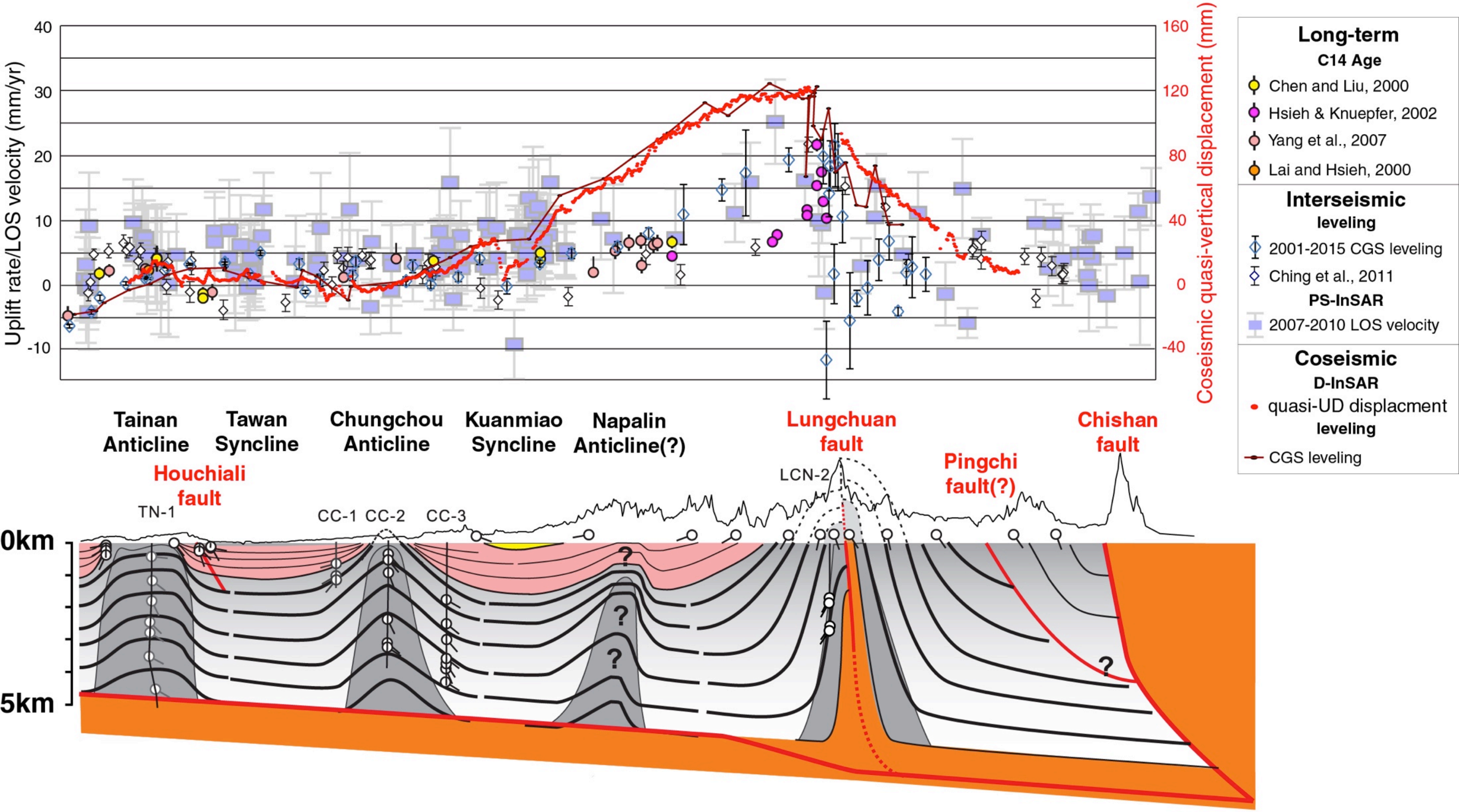
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?
?
?
0km
5km

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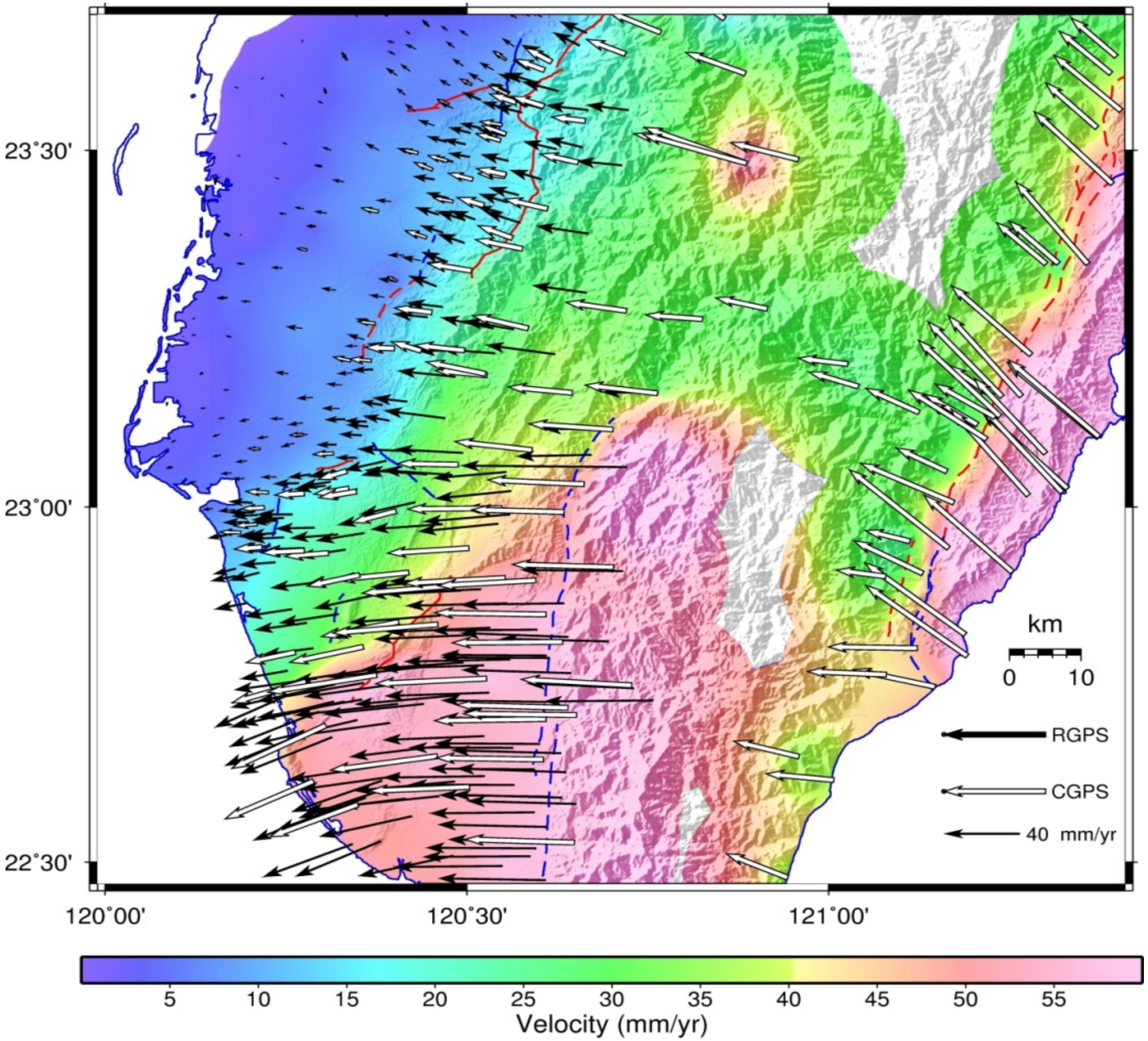
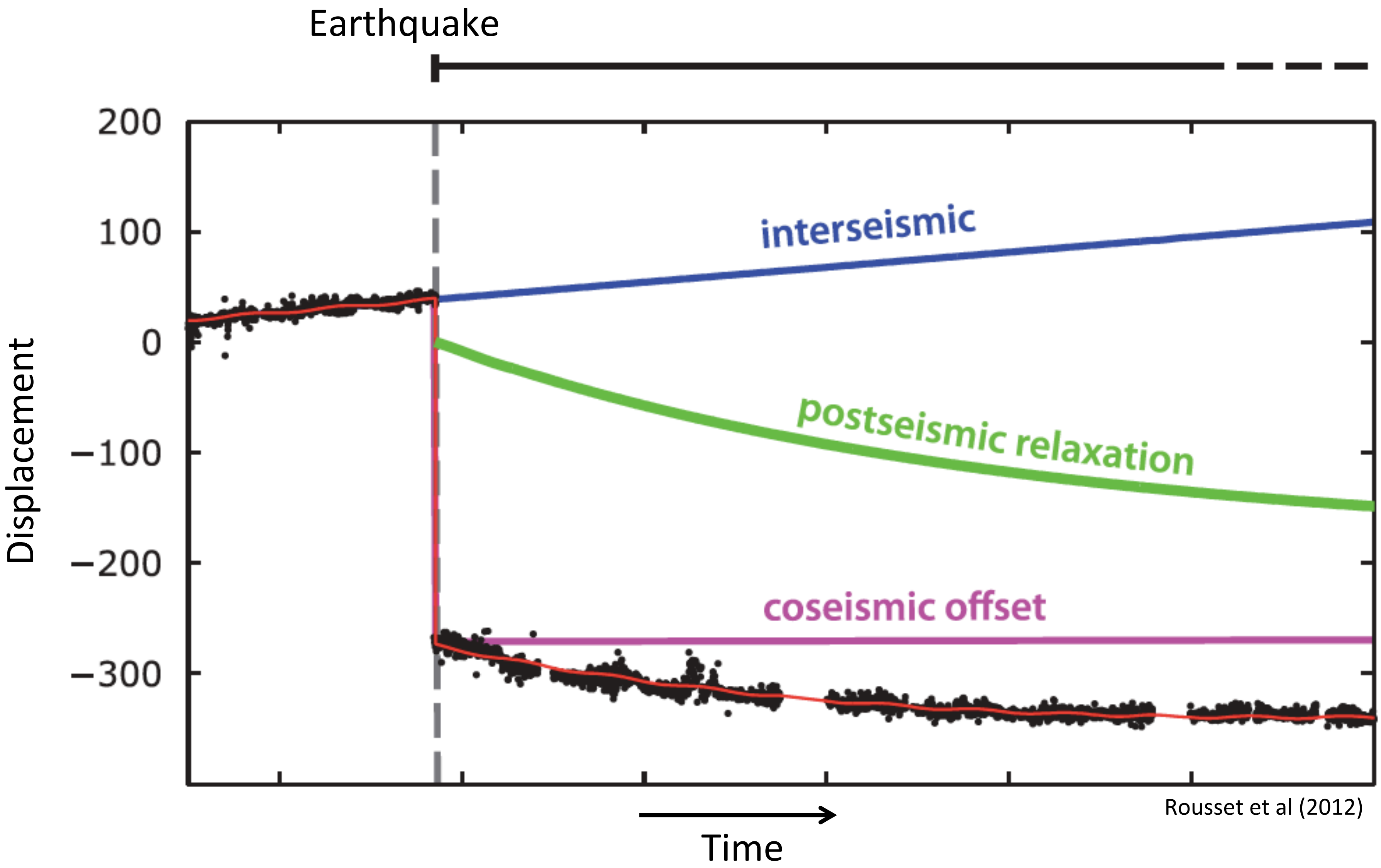
- Monitoring surface and topographic changes
- Analysis of deformation through earthquake cycle
- Future directions

How surface deformation looks like in space

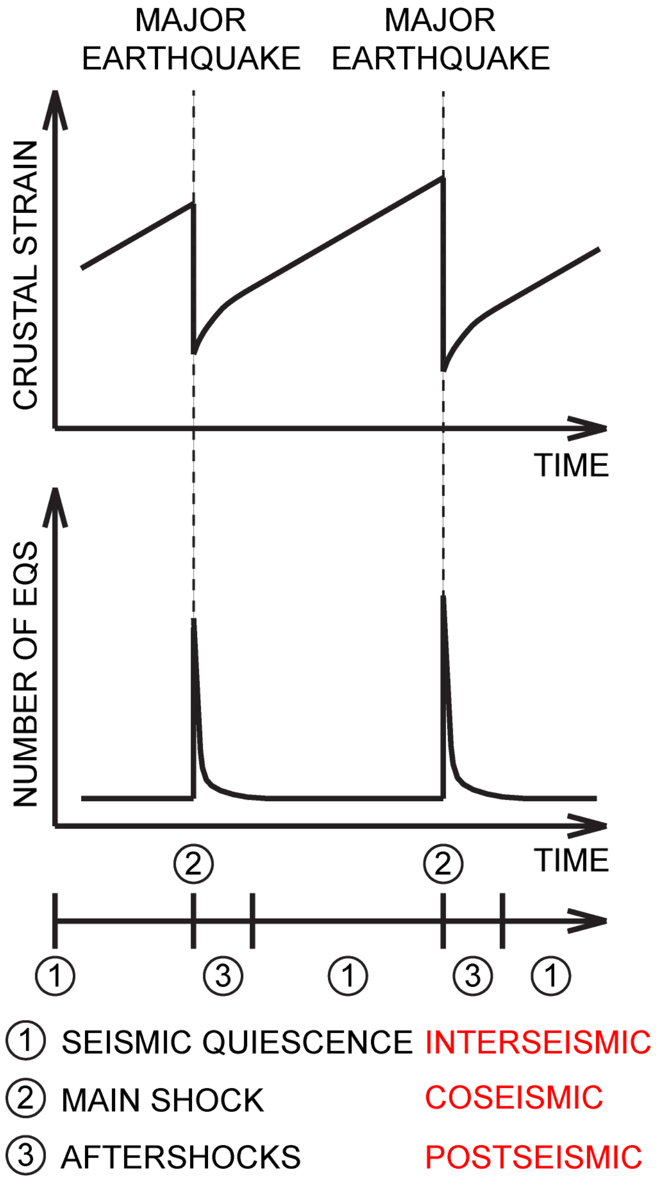


How surface deformation looks like in time



Rousset et al (2012)

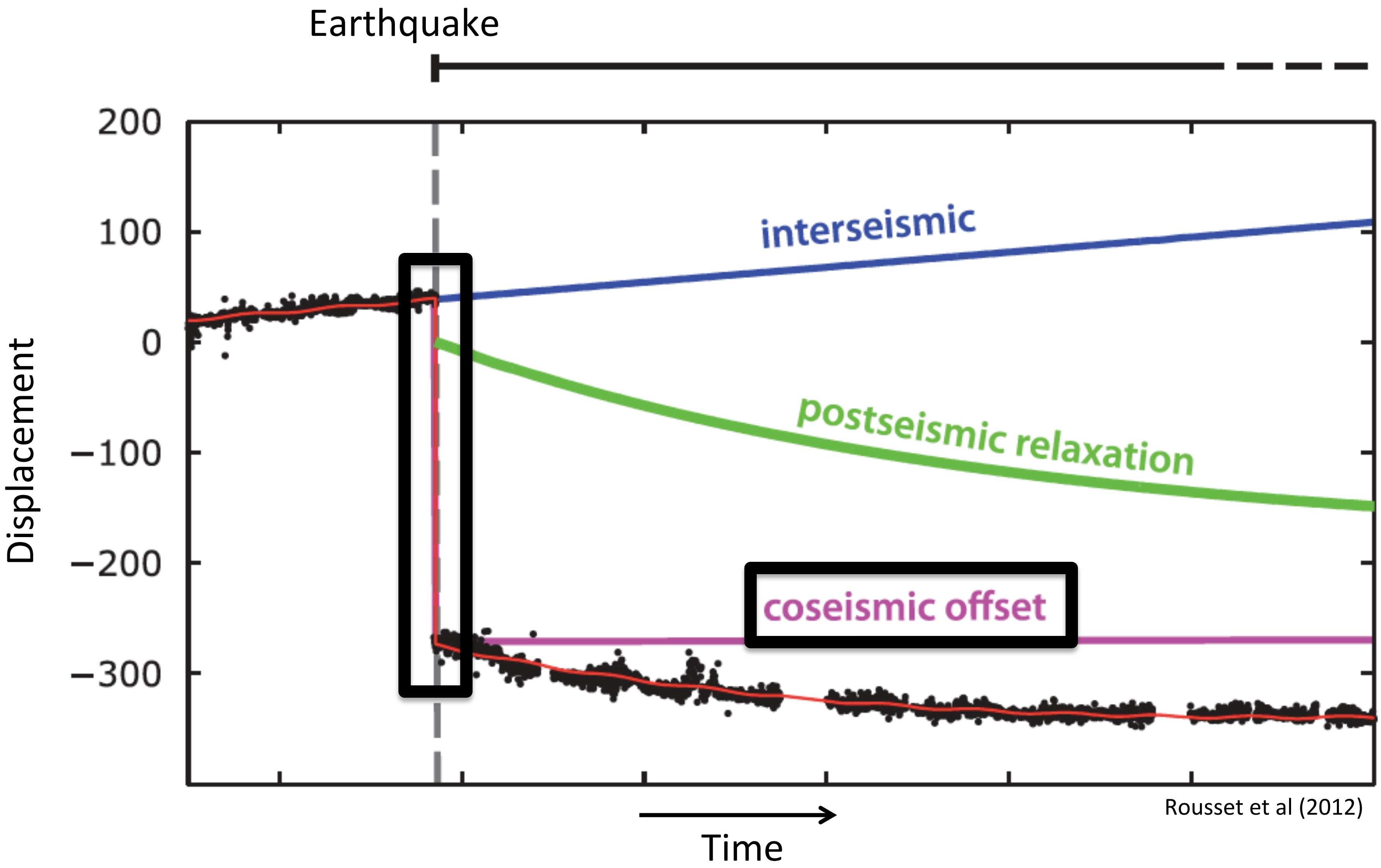
Stages of An Earthquake Cycle



- Coseismic period
  - The time during earthquakes
  - Seconds to minutes
- Postseismic period
  - The time after a large earthquake when anomalous deformation occurs
  - Days to years
- Interseismic period
  - The time between large earthquakes
  - Decades to millennia

Modified after Thatcher (1993)

How surface deformation looks like in time

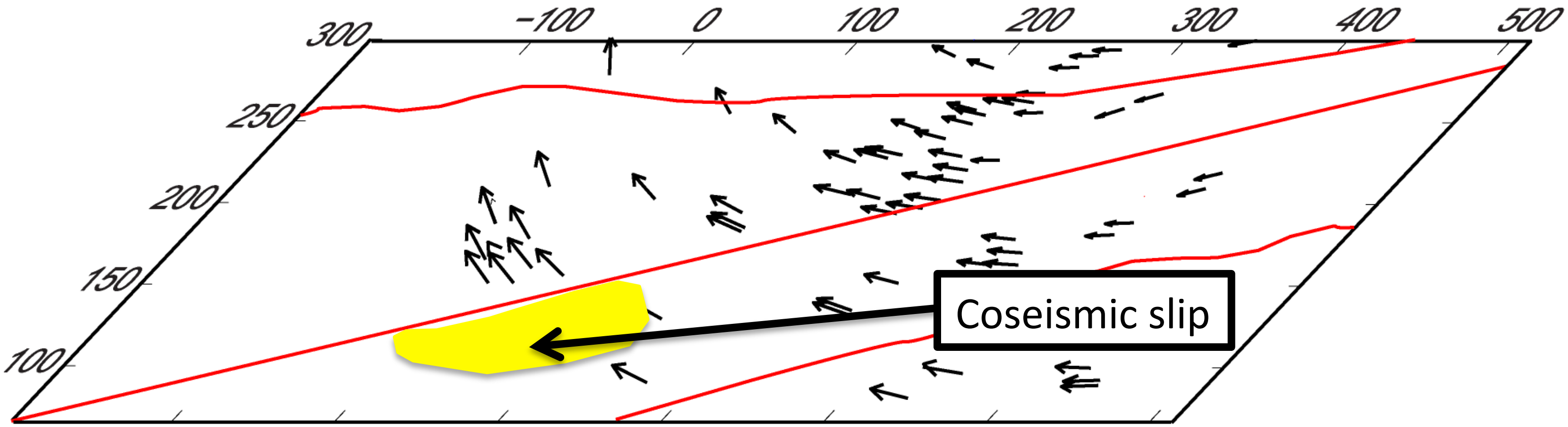


Rousset et al (2012)

Coseismic Deformation

- Large displacement close to the fault
- Displacements gradually decrease with distance
- Using geodetic data to estimate coseismic slip distribution and fault geometry
- Knowing slip distribution may help to infer
  - Rupture area and magnitude of the earthquake
  - Slip sense, fault motion, and structural architecture
  - Locked area on the fault and fault segmentation
  - Postseismic slip
  - Future earthquake scenario

Coseismic Deformation



Model Configuration

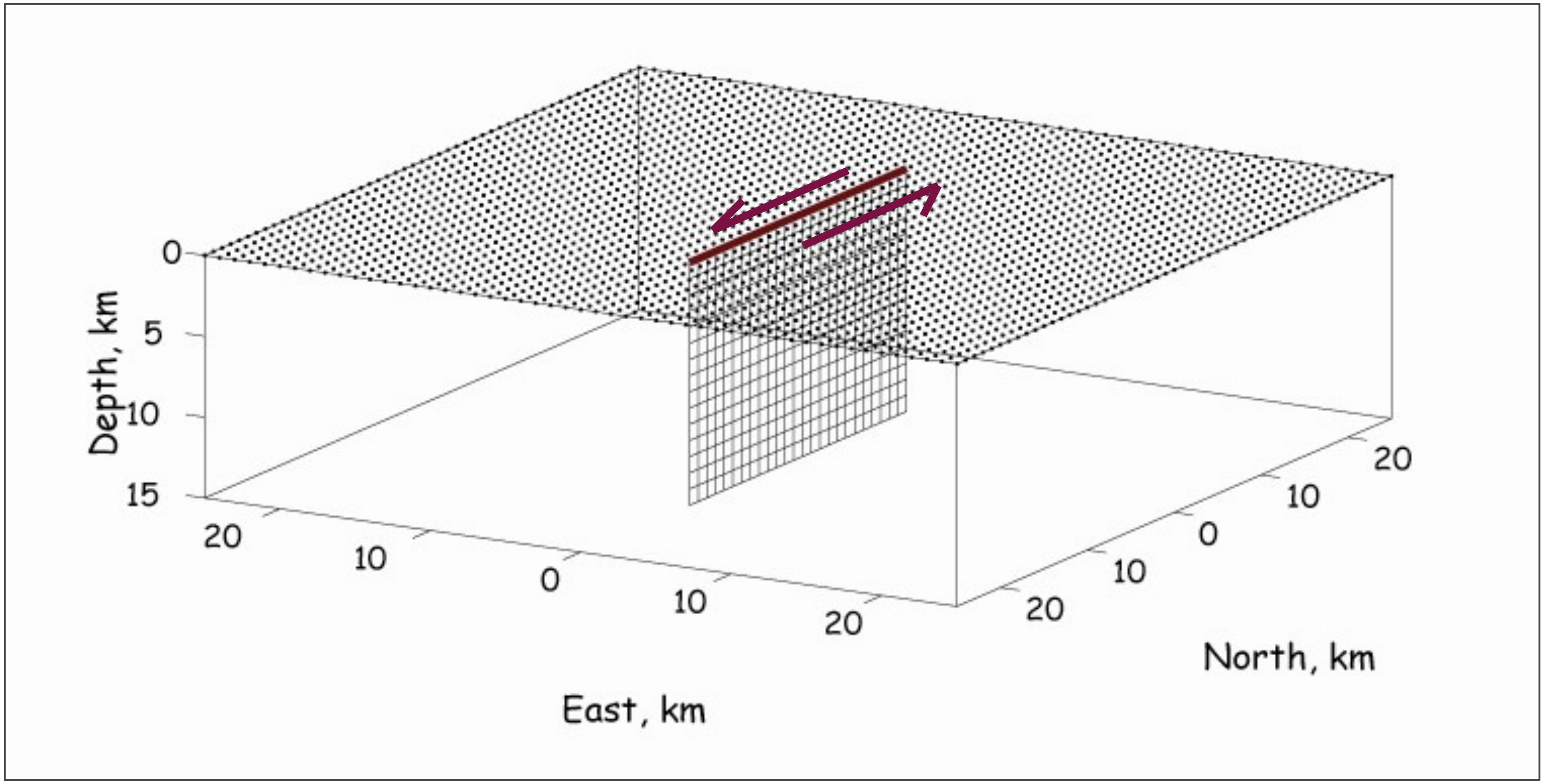
- Data: surface observations
  - GPS, seismic data, leveling, InSAR, etc.
- Need a model!
  - Using physical theories to relate surface changes to tectonic activities at depths
- Kinematic model: compute displacement due to dislocation (fault slip) in elastic half-space

$$\mathbf{d} = G_d \mathbf{s}$$

Surface observation Green's function Fault slip

Forward Model:

(Elastic Half Space, Layered Space, etc.)



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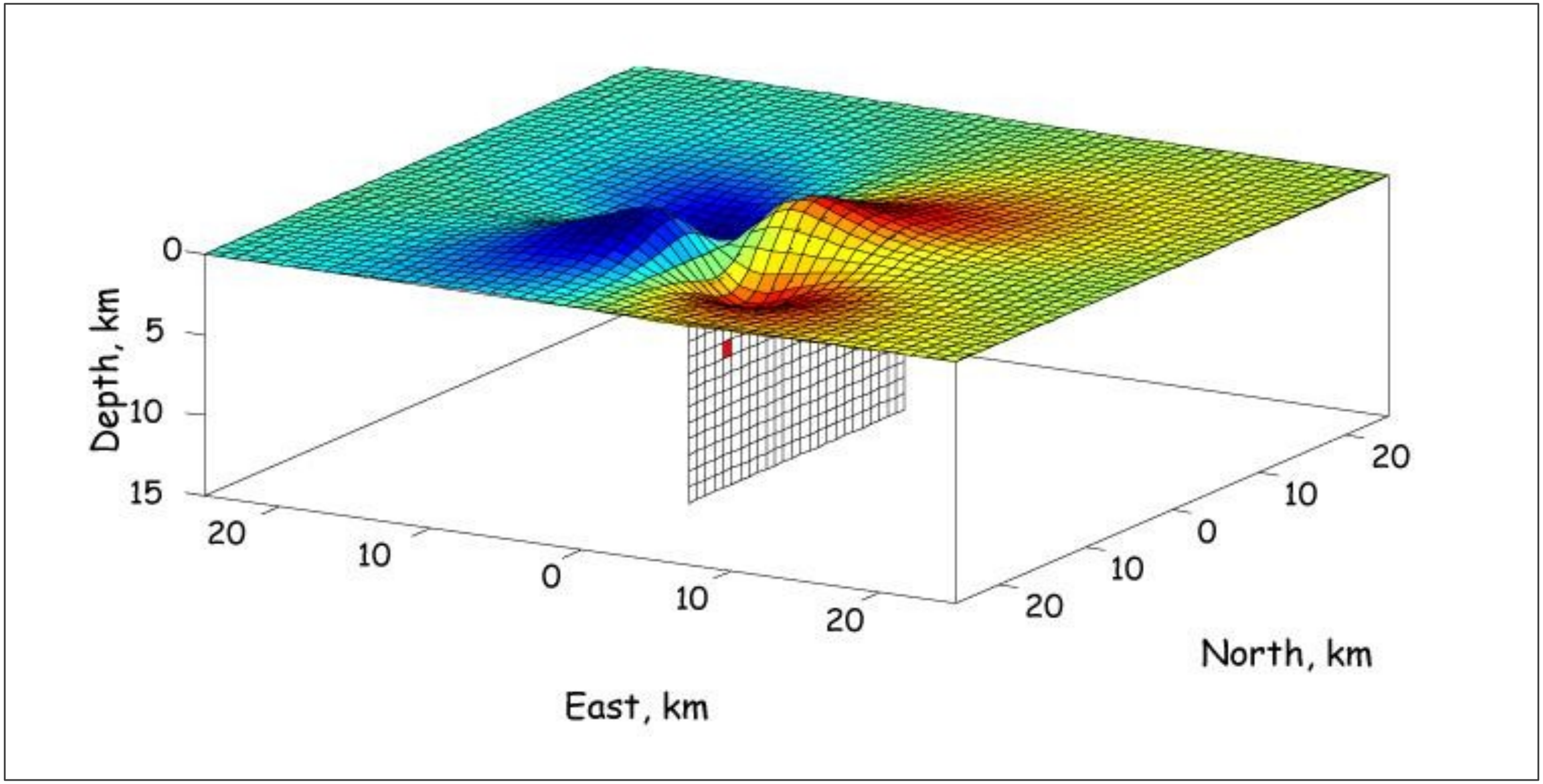

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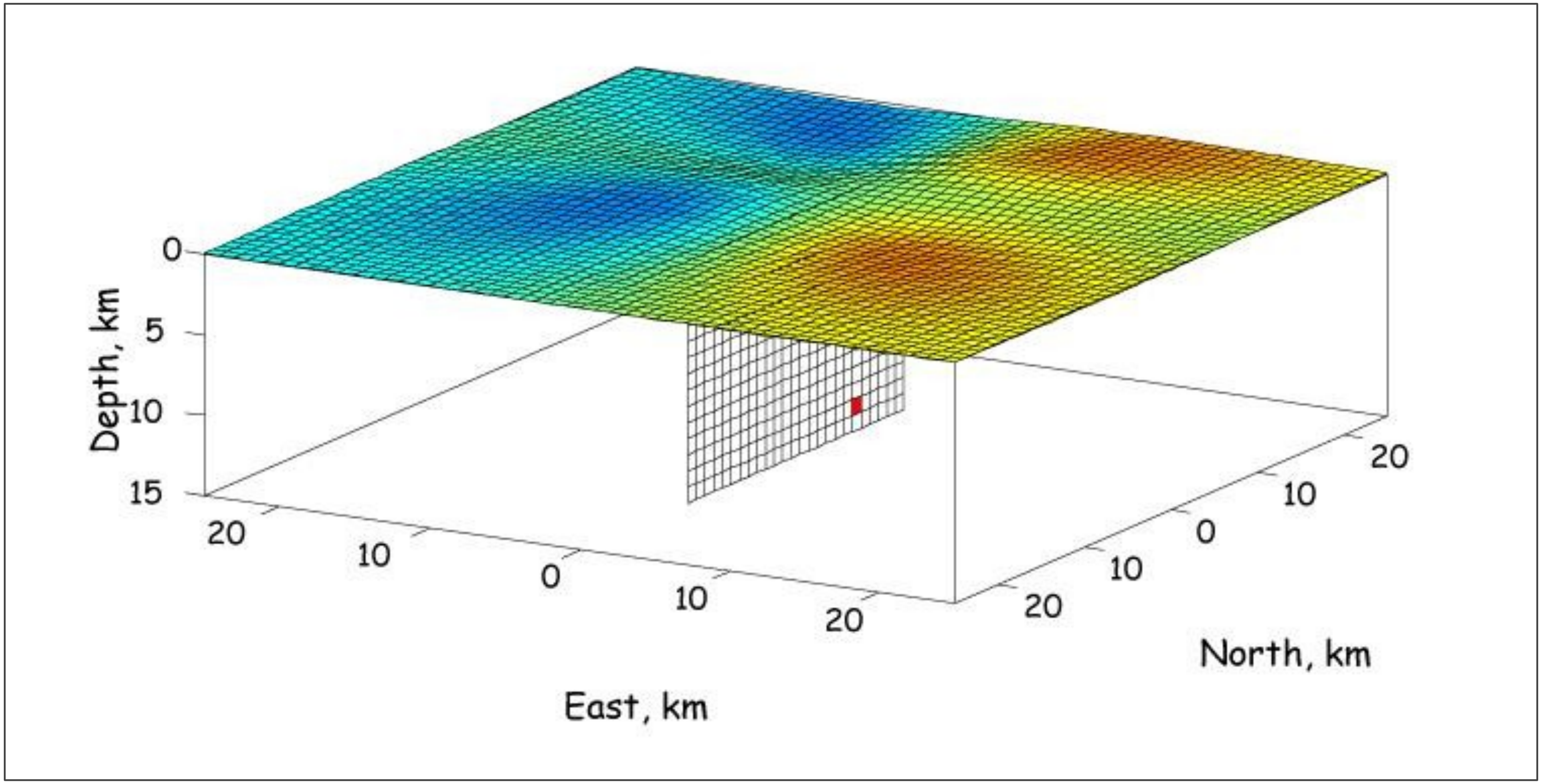

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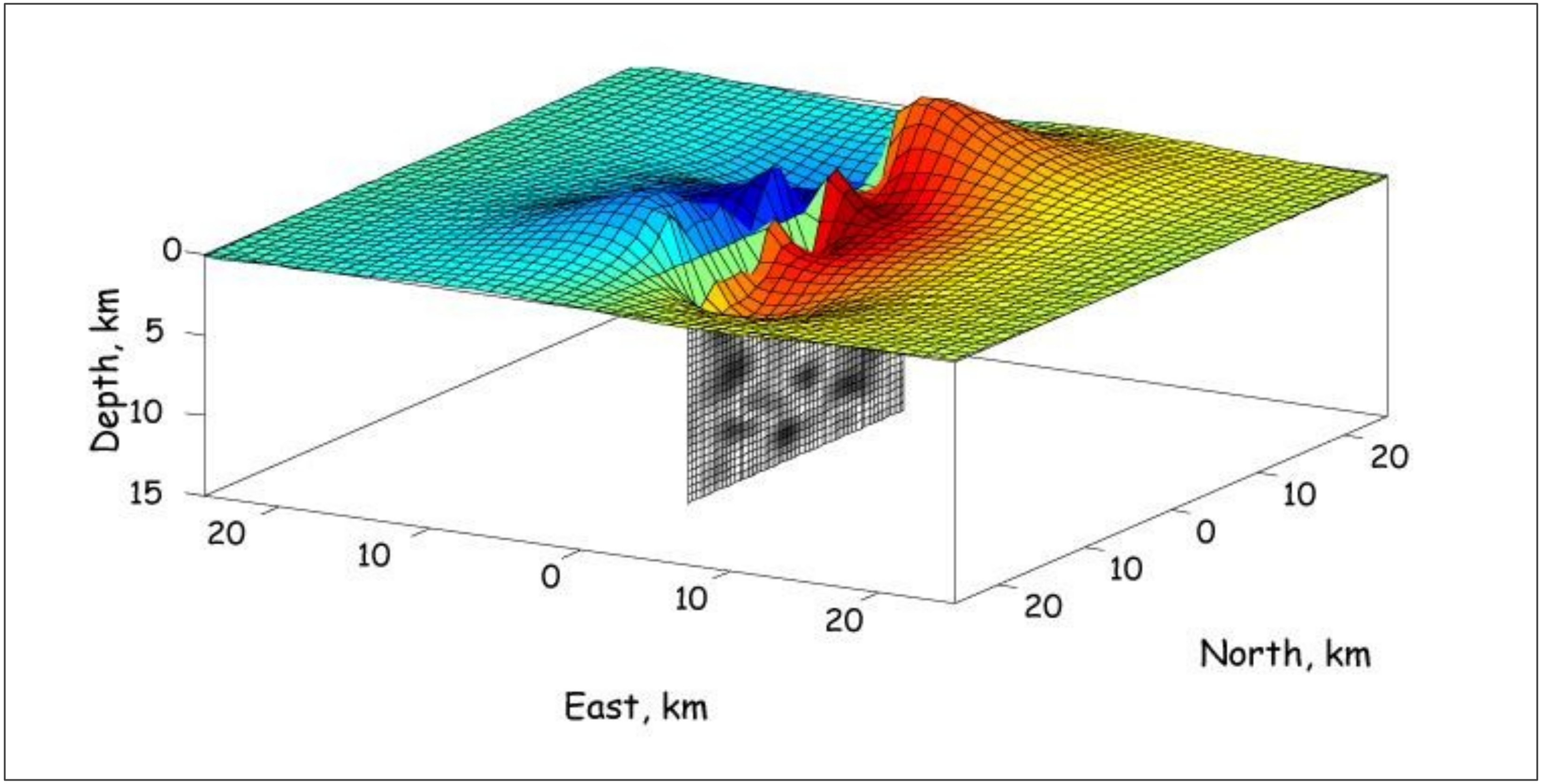
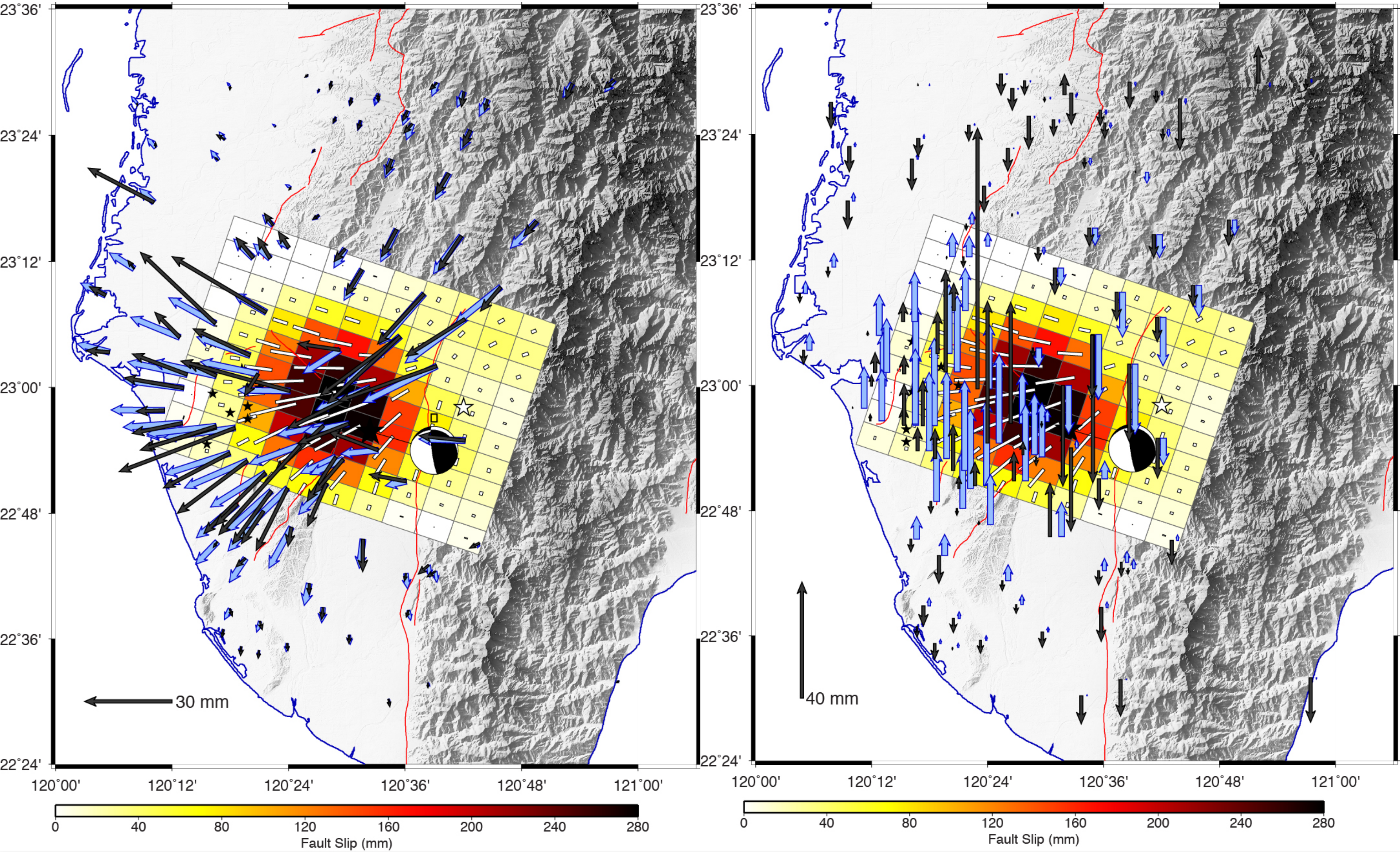
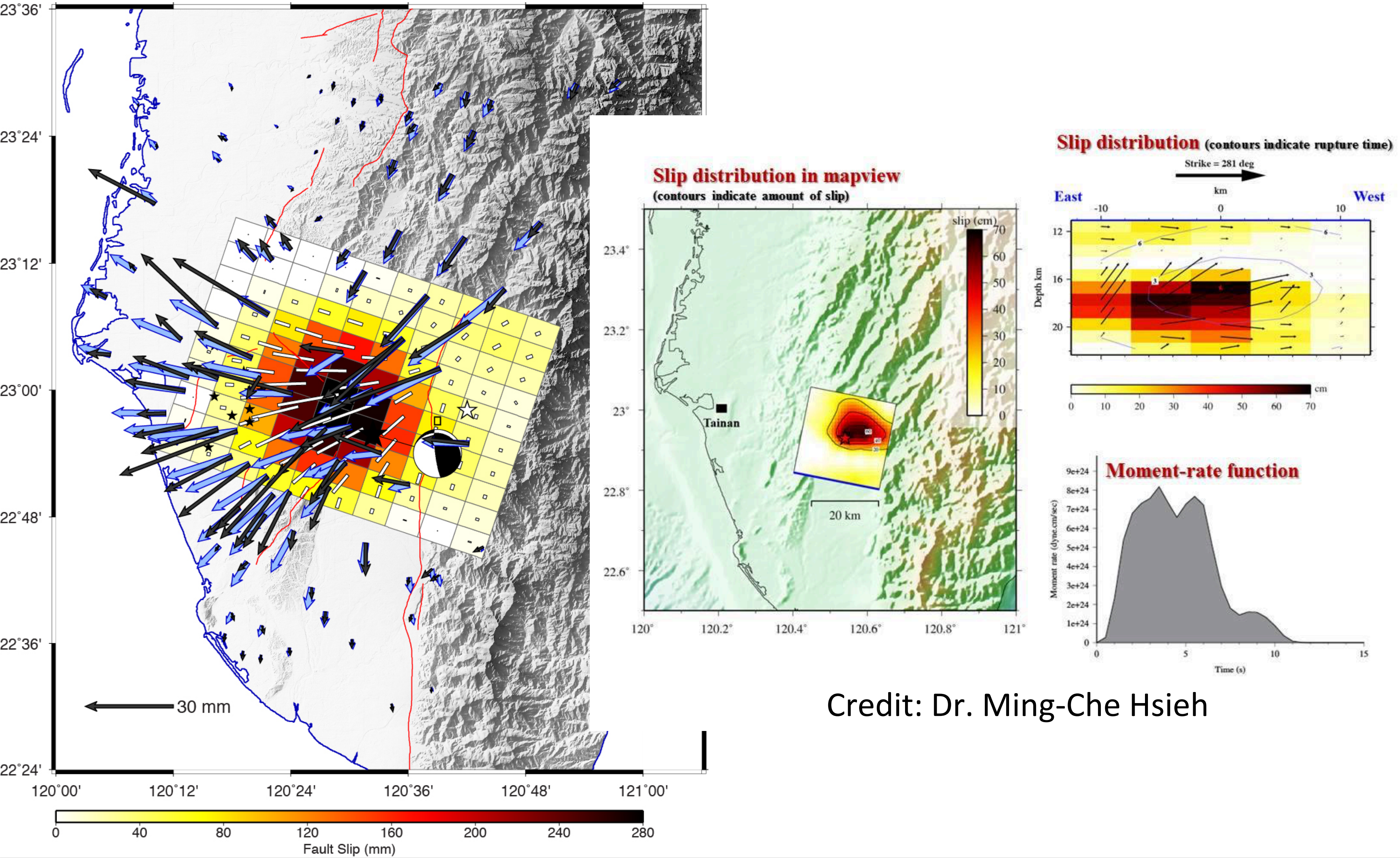


Total = ∑ all fault patches

2016 Meinong earthquake

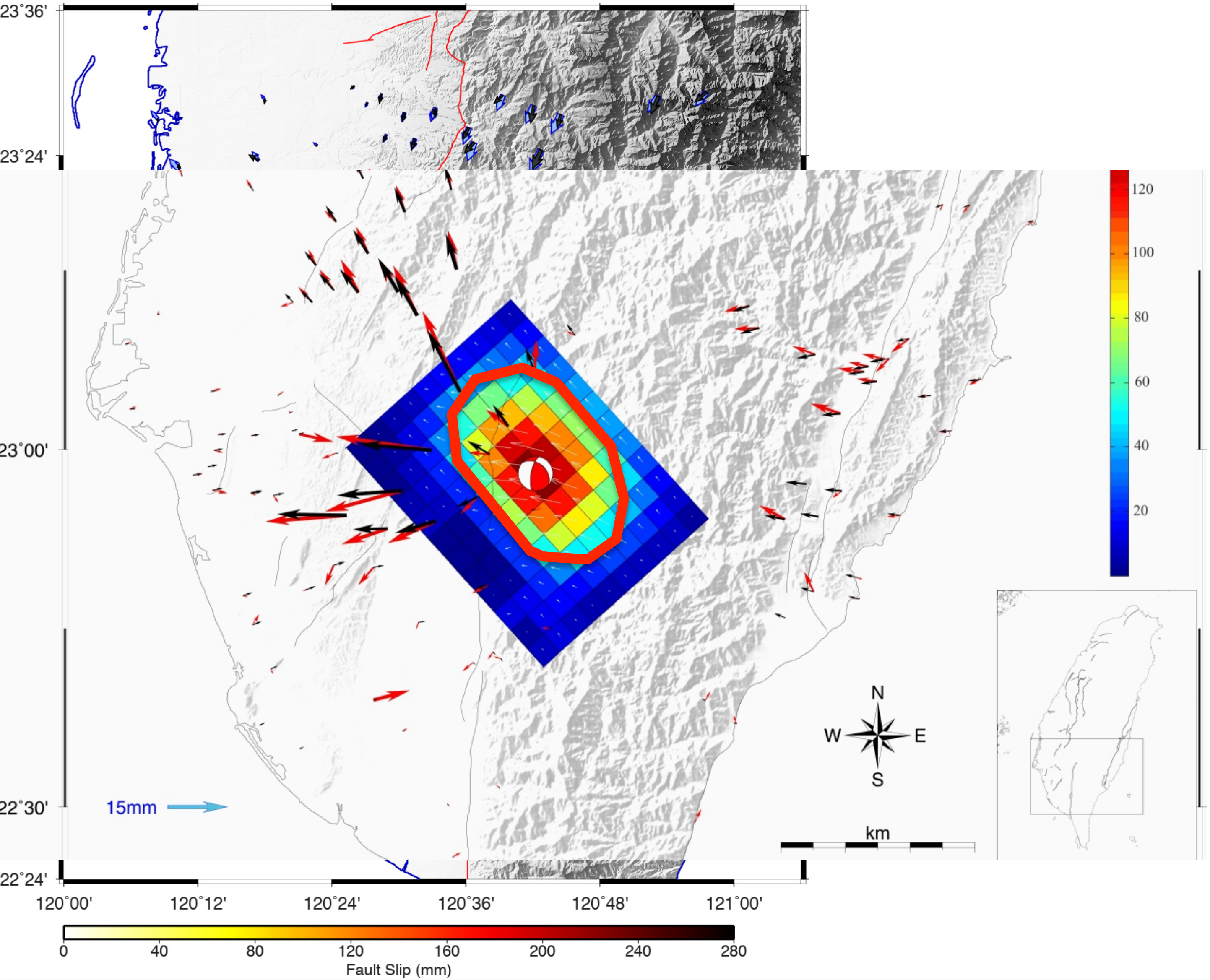


2016 Meinong earthquake



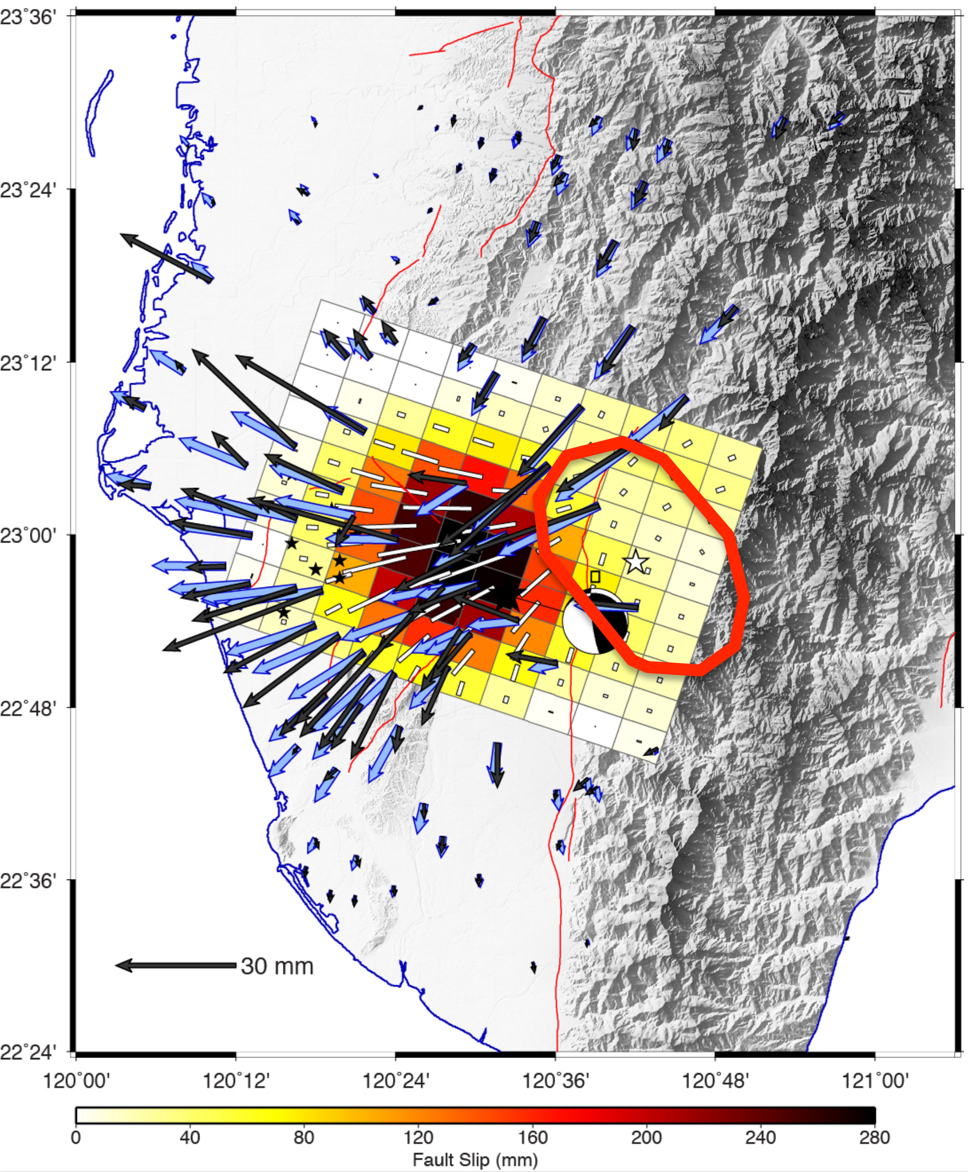
Credit: Dr. Ming-Che Hsieh

2016 Meinong earthquake

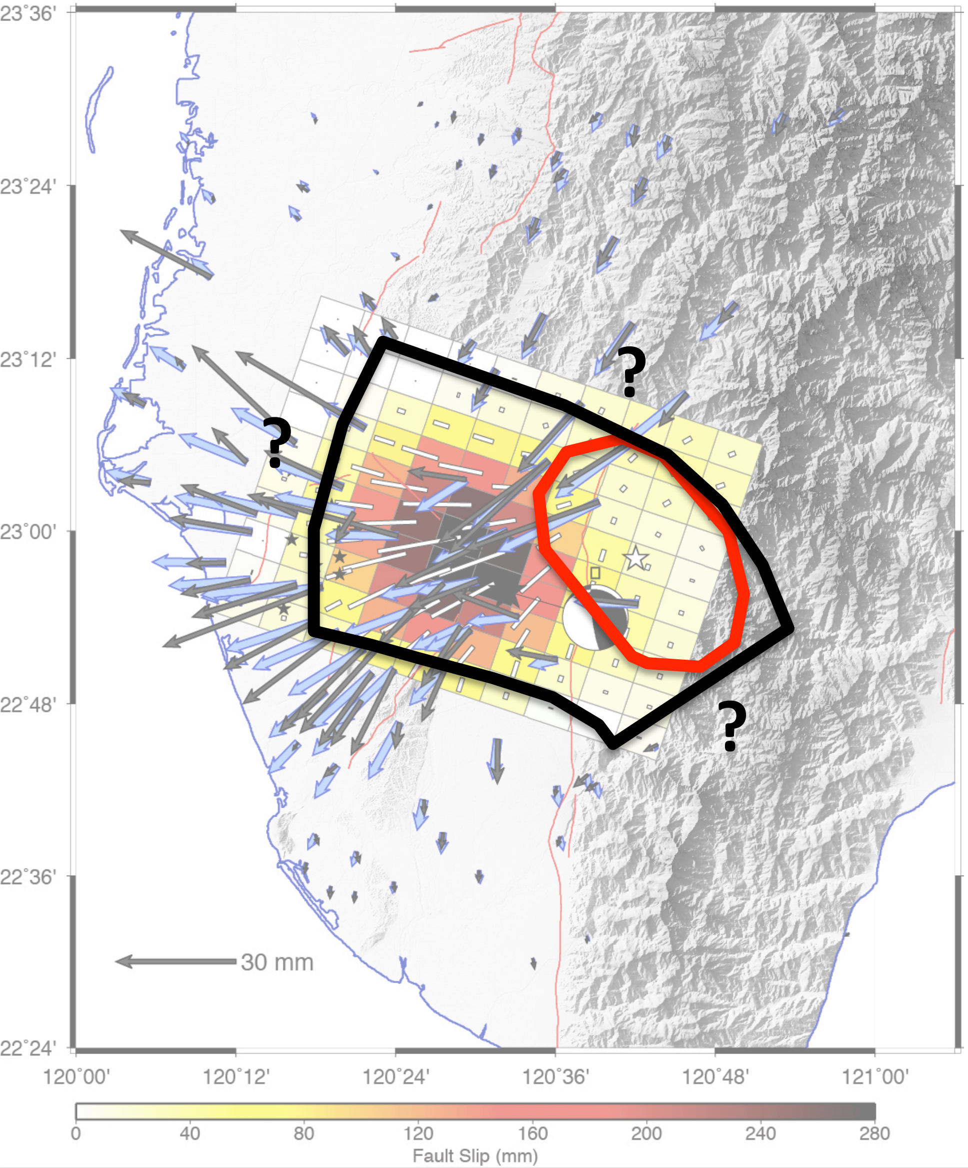


2010 Jiashiang earthquake

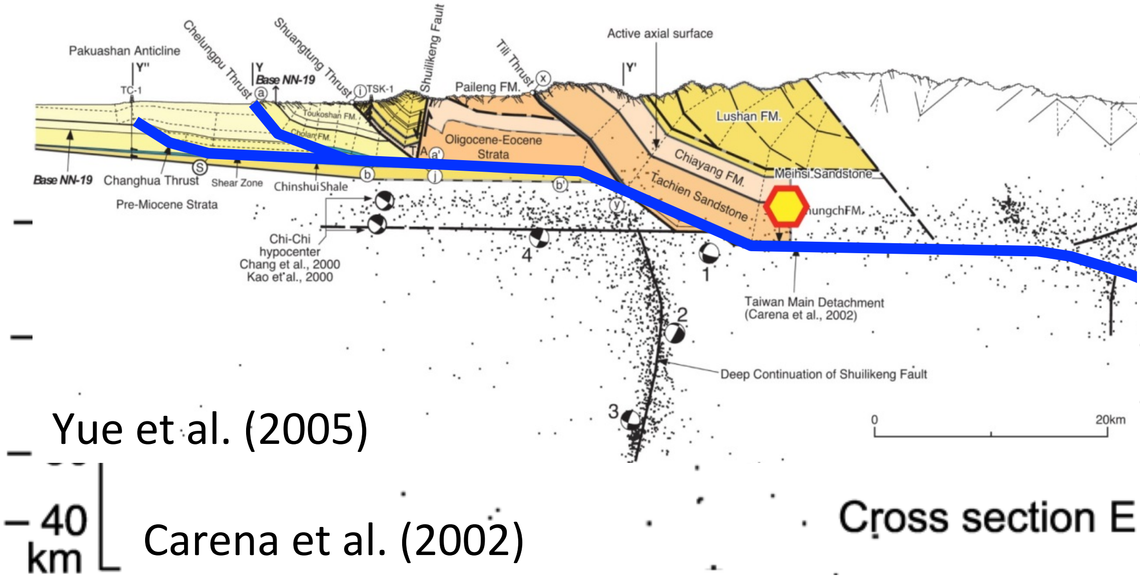
2016 Meinong earthquake



2016 Meinong earthquake

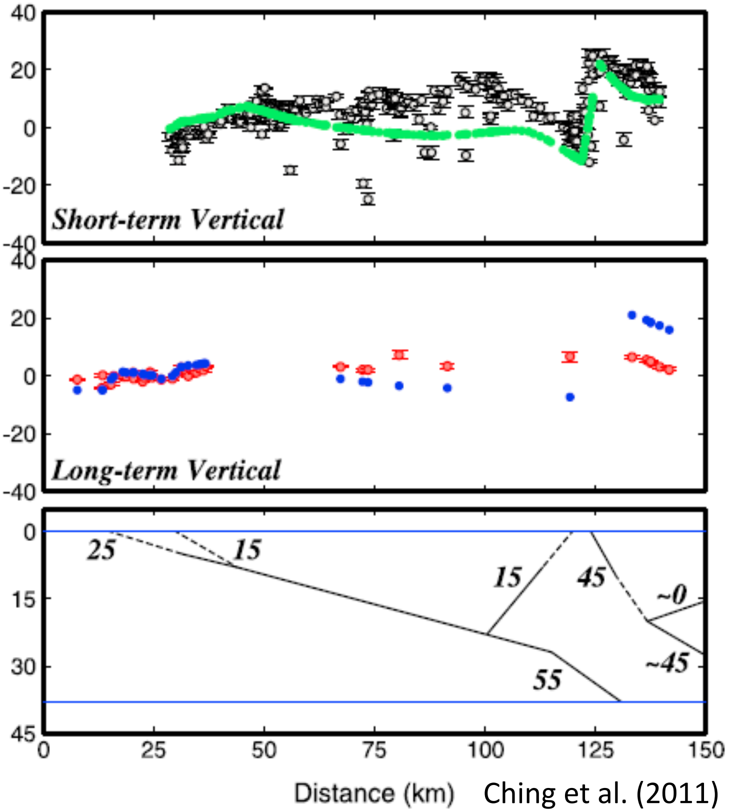


Thin-skinned Detachment Geometry



Yue et al. (2005)

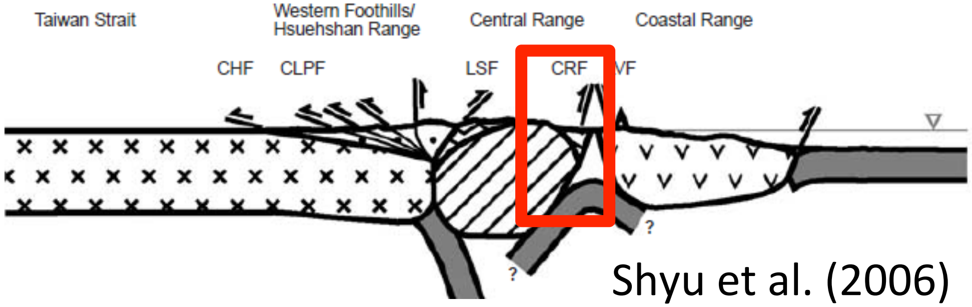
Carena et al. (2002)



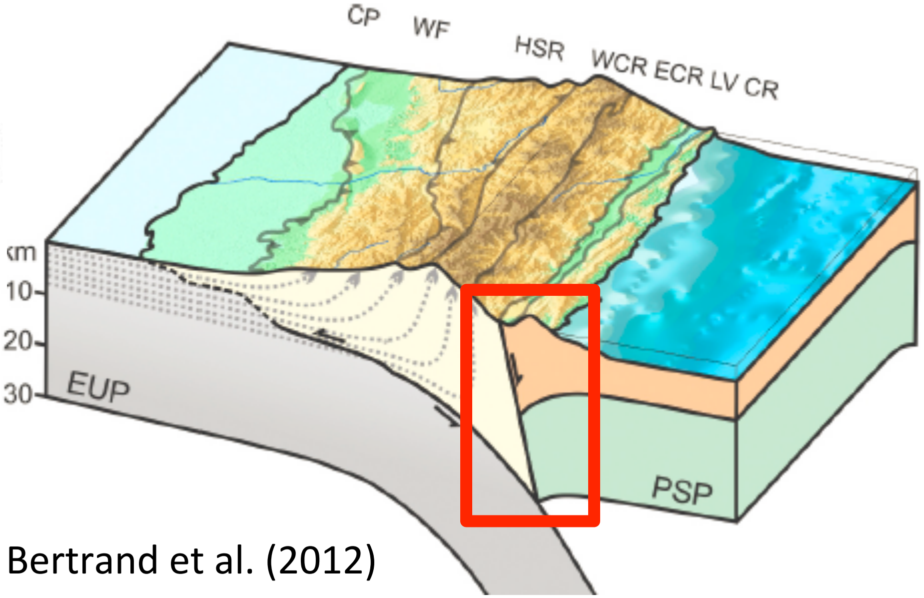
Ching et al. (2011)

- Mountains in Taiwan are deformed brittlely and detached above a shallow (~10 km) “detachment” or “décollment”
- Earthquakes are present in deeper depths and retrowedge
- High uplift rate cannot be simply explained by gently-dipping thin-skinned detachment

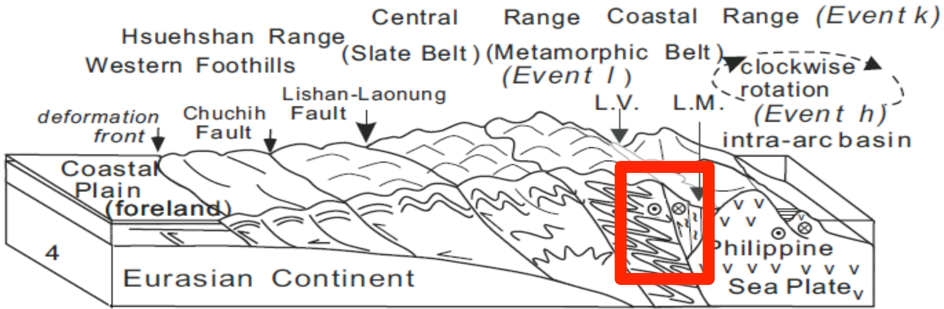
Unclear Central Range Fault Geometry



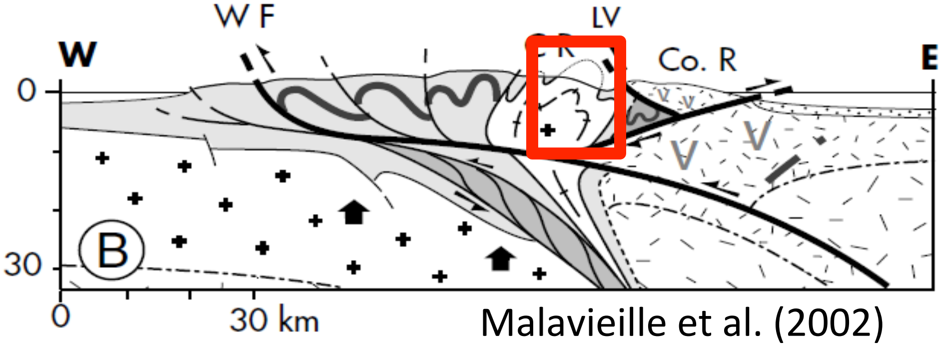
Shyu et al. (2006)



Bertrand et al. (2012)



Huang et al. (2006)



Malavieille et al. (2002)

Event 1: 1st Nantou EQ

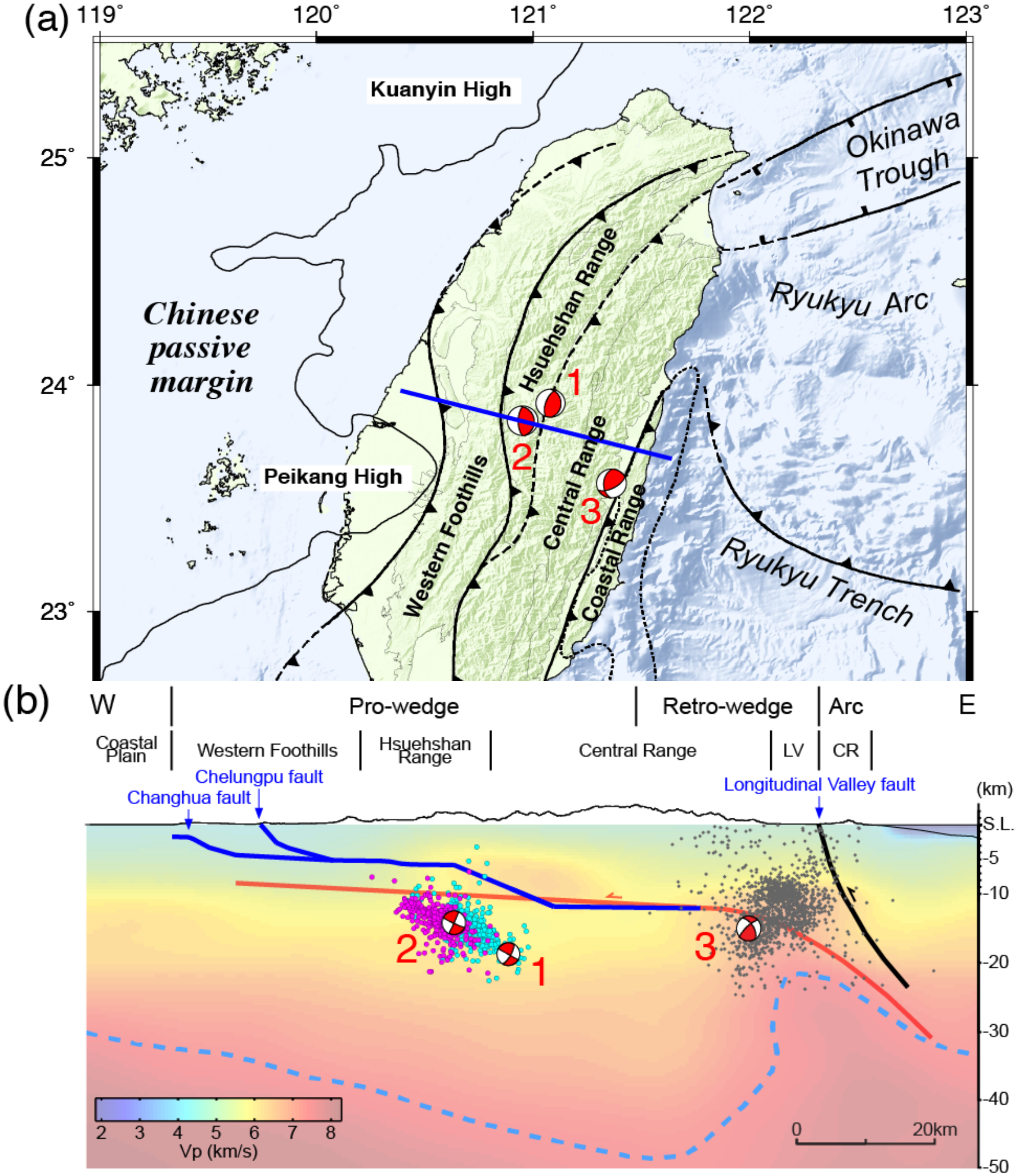
- 27 March 2013
- 19 km depth
- M 6.2

Event 2: 2nd Nantou EQ

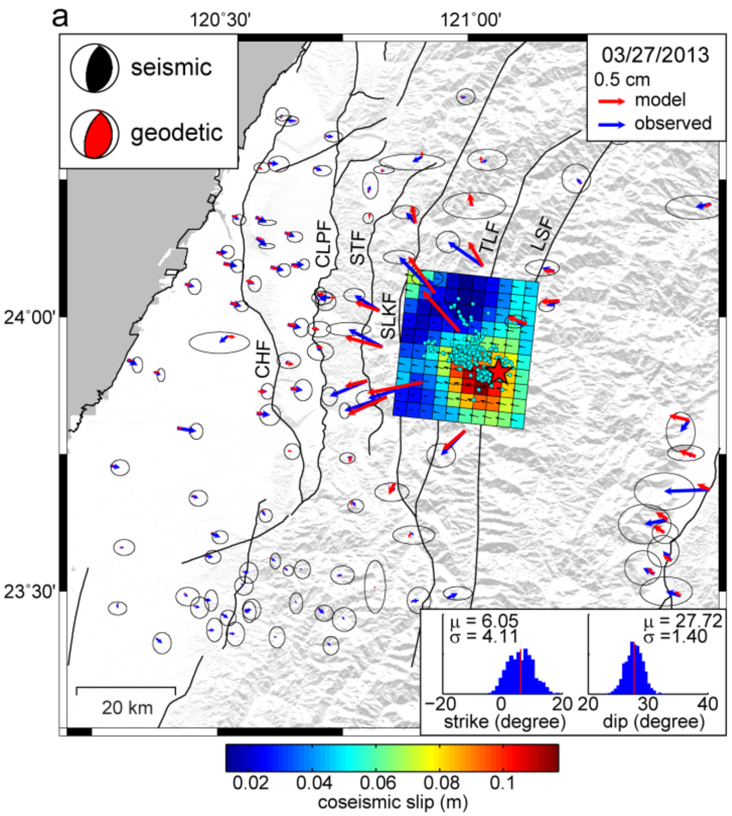
- 2 June 2013
- 14 km depth
- M 6.5

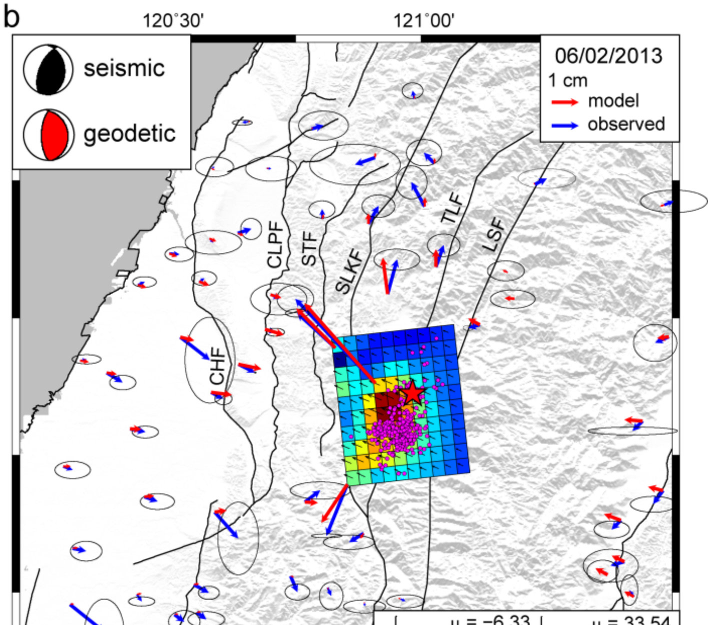
Event 3: Rueisuei EQ

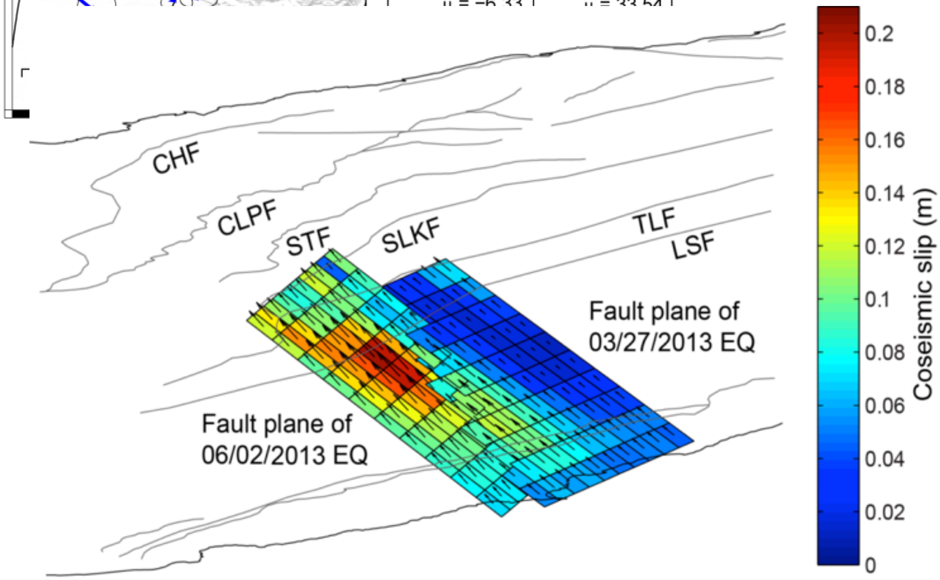
- 31 Oct 2013
- 15 km depth
- M 6.4



Nantou Earthquakes

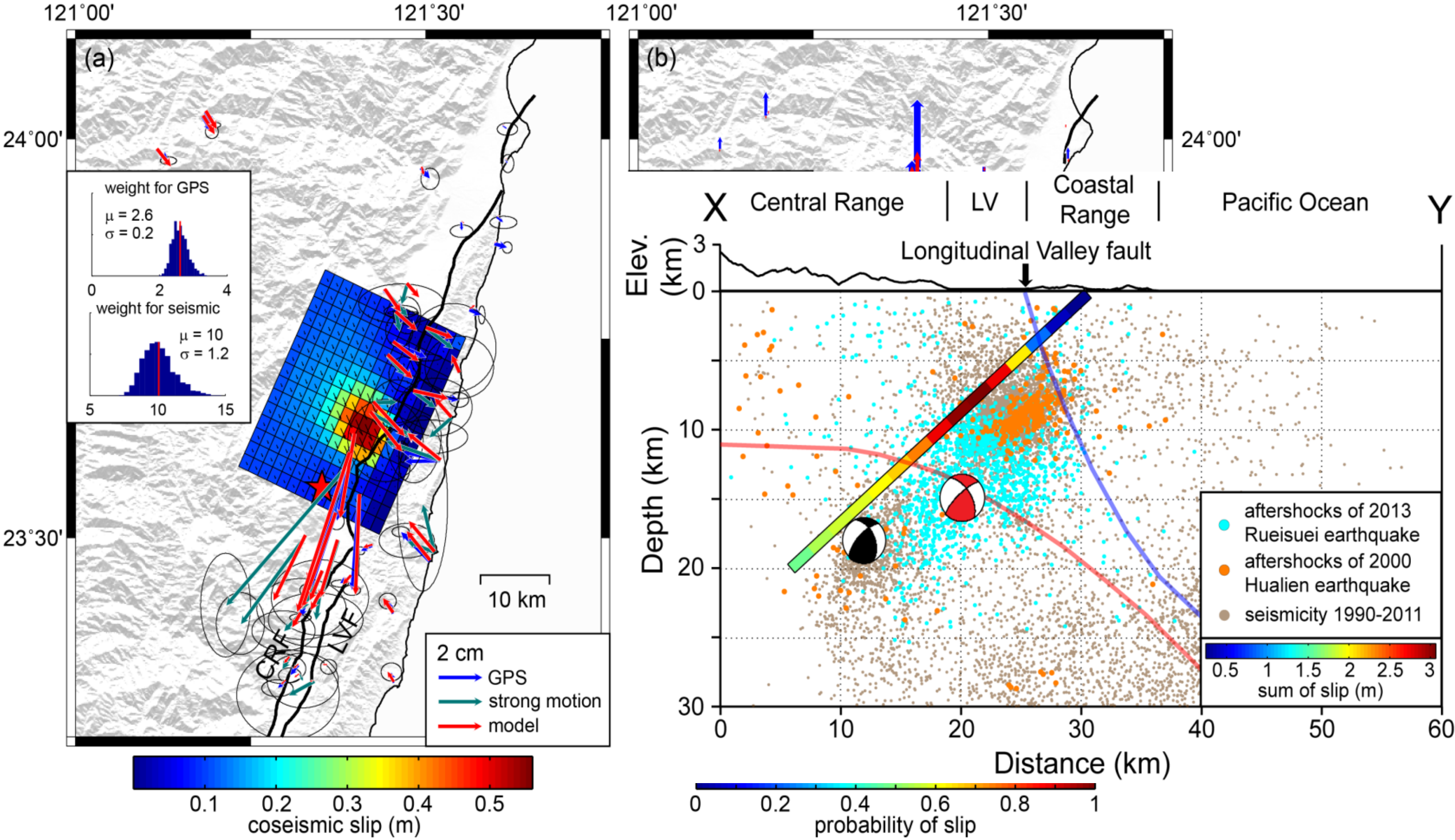




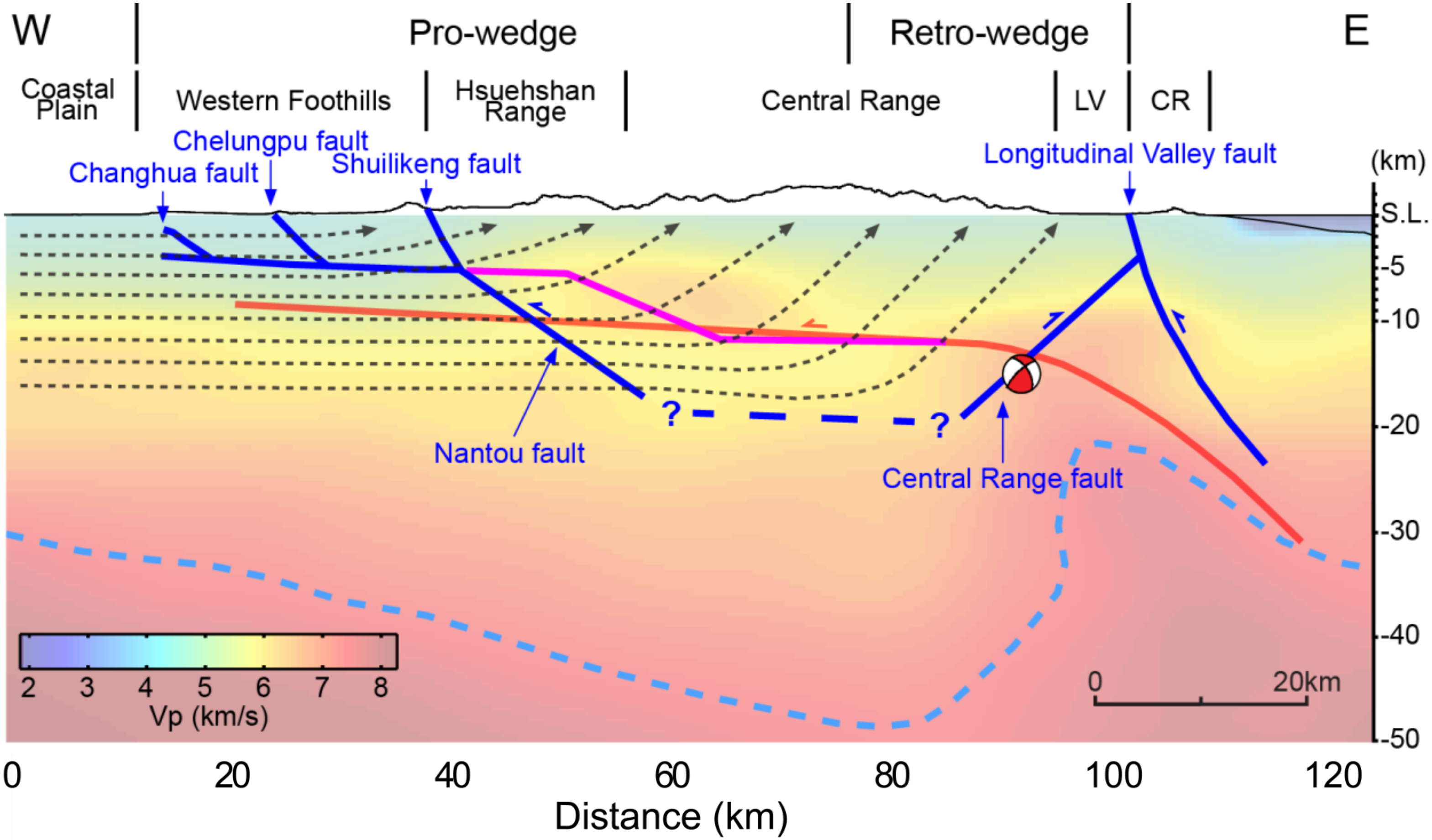


- Rupture at 5-19 km
- Two earthquakes on the same fault: Nantou fault
- Reveal a deep thrust fault

Rueisuei Earthquake

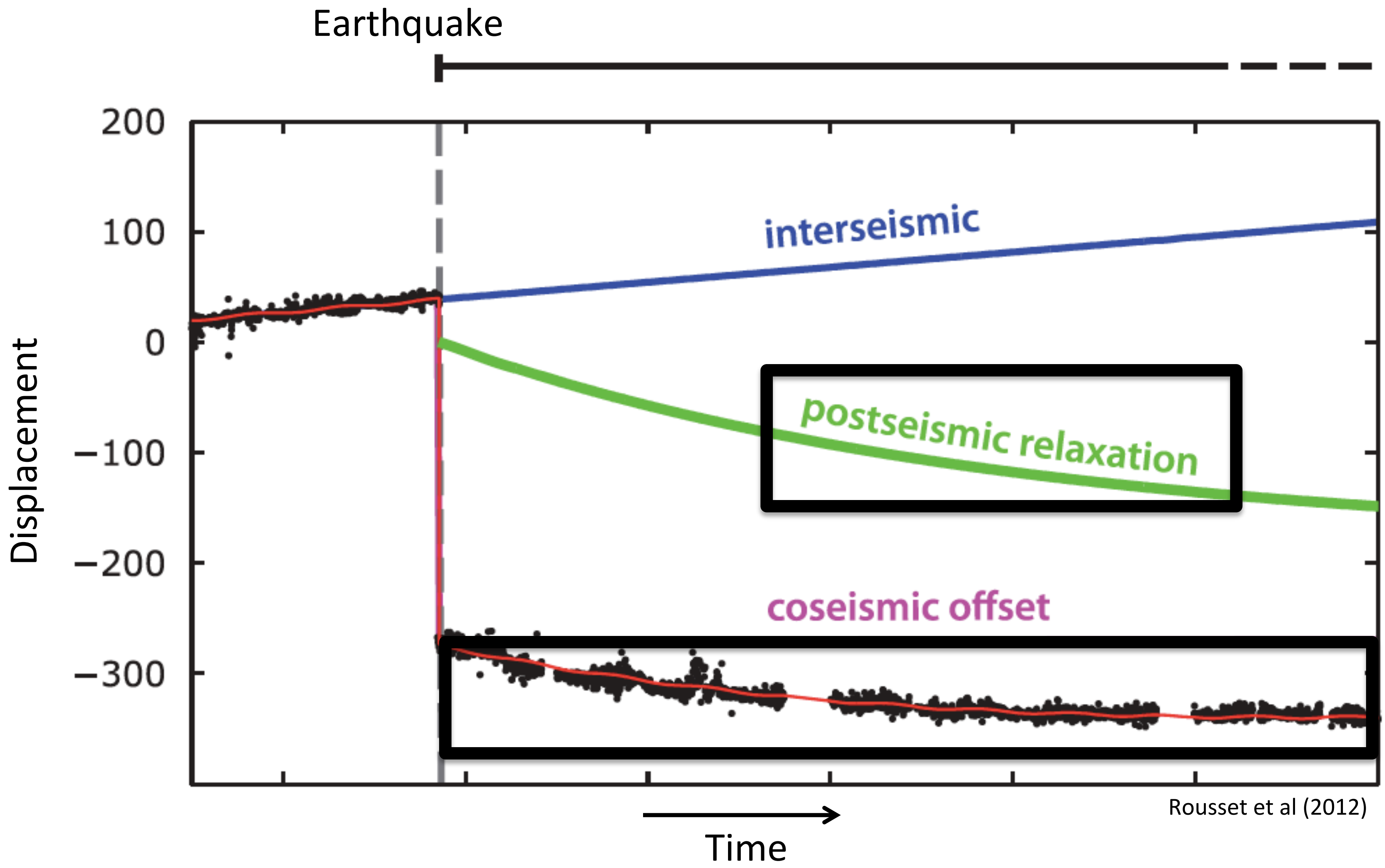


- Rupture at 4-15 km
- Reveal a west-dipping reverse fault, confirming the existence and geometry of the Central Range fault



- Newly identified Nantou fault and Central Range fault are reverse faults deeper than proposed thin-skinned detachment
- They may bound a doubly-vergent Taiwan orogenic wedge

How surface deformation looks like in time

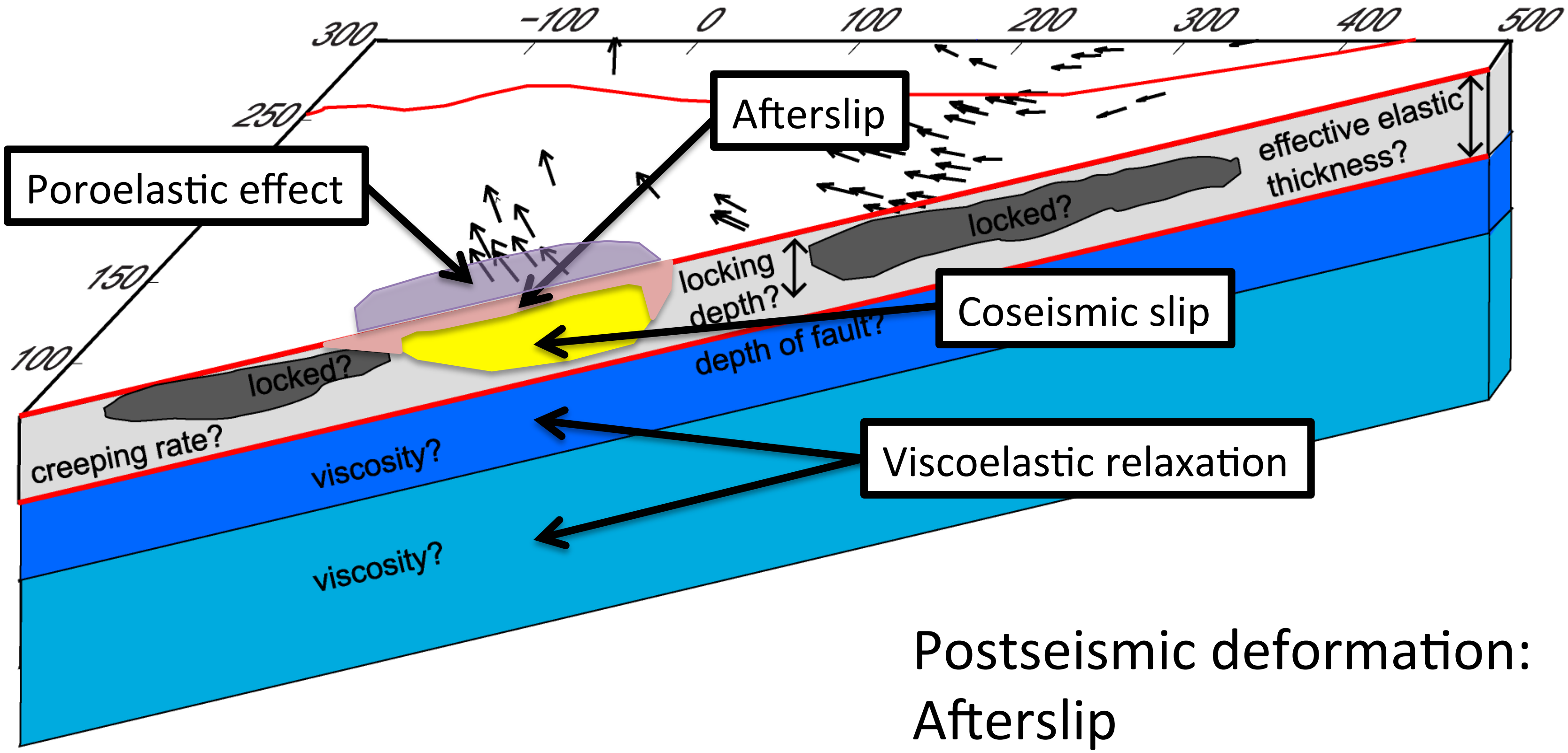


Rousset et al (2012)

Postseismic Deformation

- Three types of postseismic deformation
  - Afterslip: slow slip on the fault (days to years)
  - viscoelastic relaxation: response of viscous material to stress change of earthquake (depends on viscosity)
  - Poroelastic deformation: local to fault zone (days to months)
- postseismic deformation can help to infer
  - Slip evolution after earthquakes
  - Relationship with aftershocks
  - Frictional property from afterslip
  - Viscosity at depths from viscoelastic relaxation

Postseismic Deformation



Poroelastic effect

Afterslip

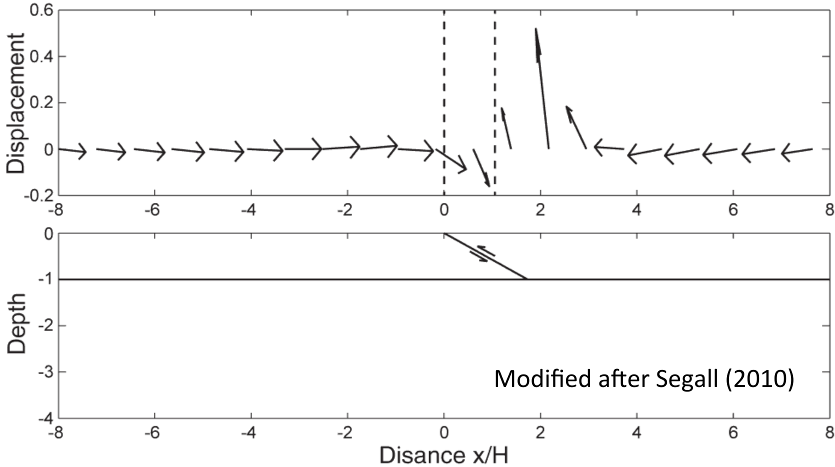
Coseismic slip

Viscoelastic relaxation

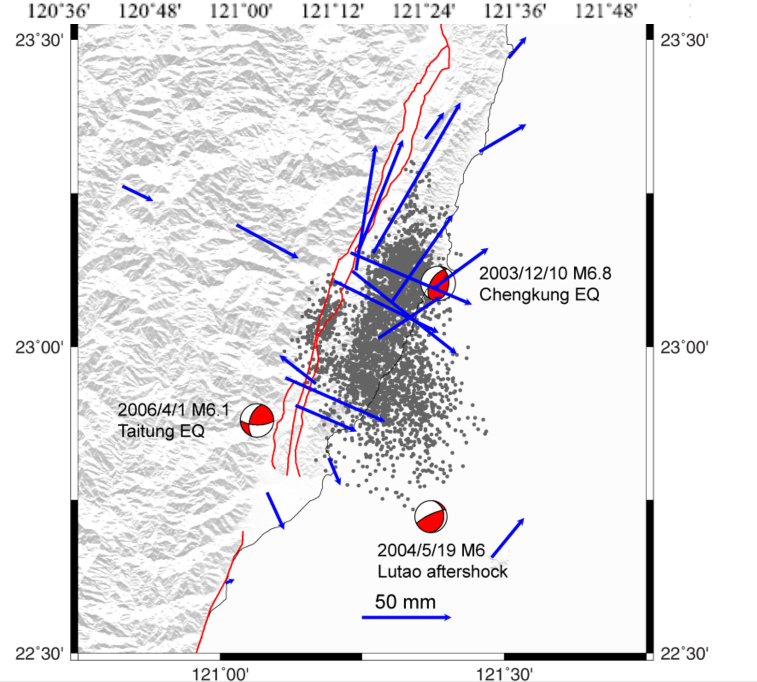
Postseismic deformation:
Afterslip
Poroelastic effect
Viscoelastic relaxation

Chengkung Earthquake

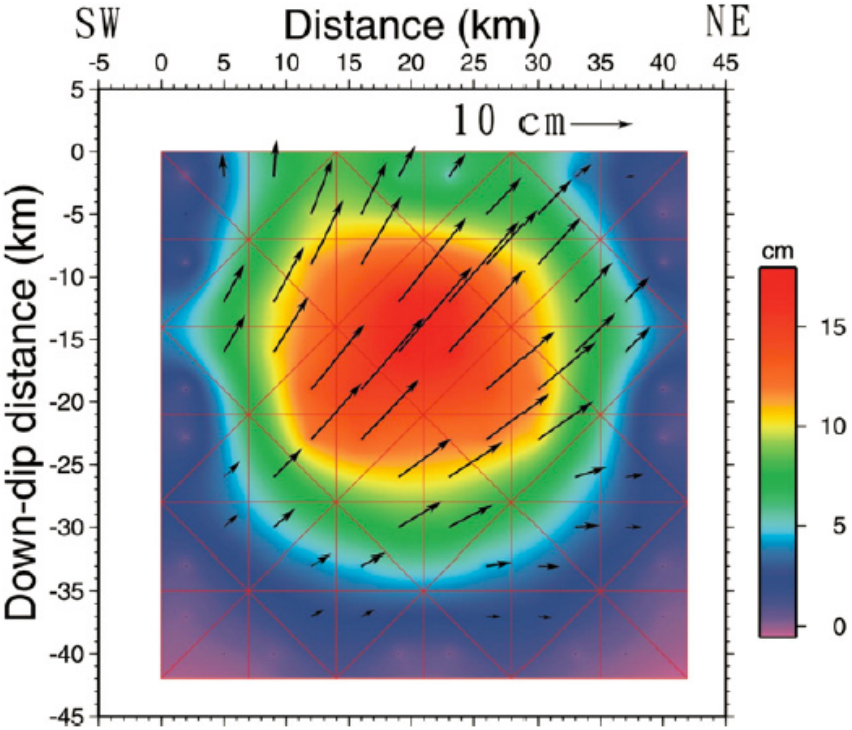
- 10 December 2013
- 22 km depth, M 6.8
- The largest earthquake since 1999 M7.6 Chi-Chi
- Occur on highly active Chihshang fault (a segment of Longitudinal Valley fault)
- Creeping at surface
- Well-constrained fault geometry
- Major coseismic slip at 15-25 km
- 2004/5/19 M6 Lutao aftershock
- Mainly afterslip



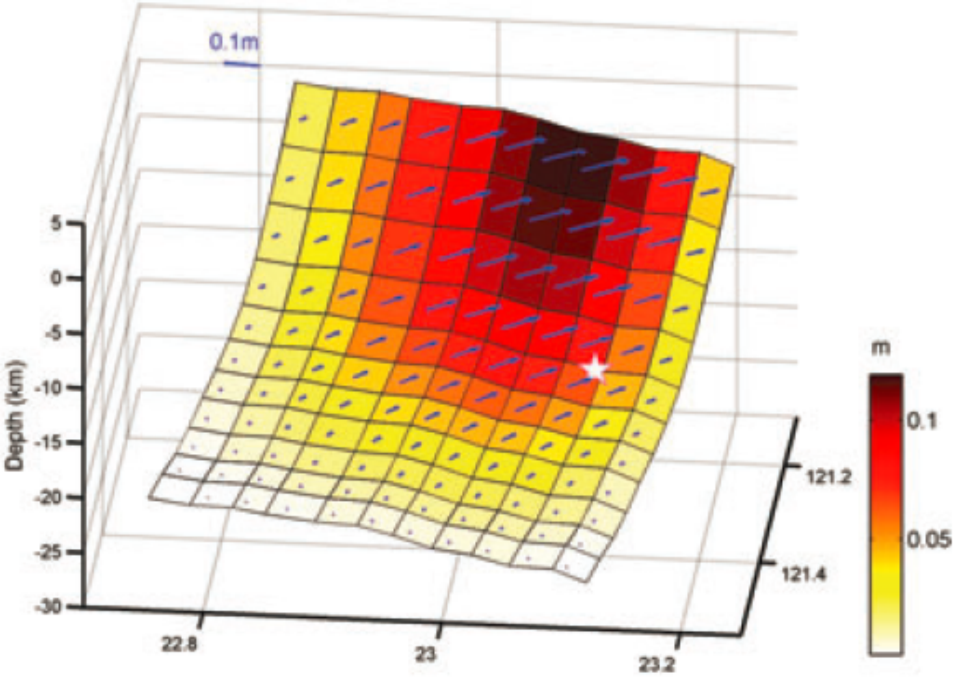
Postseismic displacements in vector form for a 30° dipping fault that cuts an elastic layer overlying a Maxwell half-space. t/tR = 4.



Afterslip Modeling



Cheng et al. (2009)

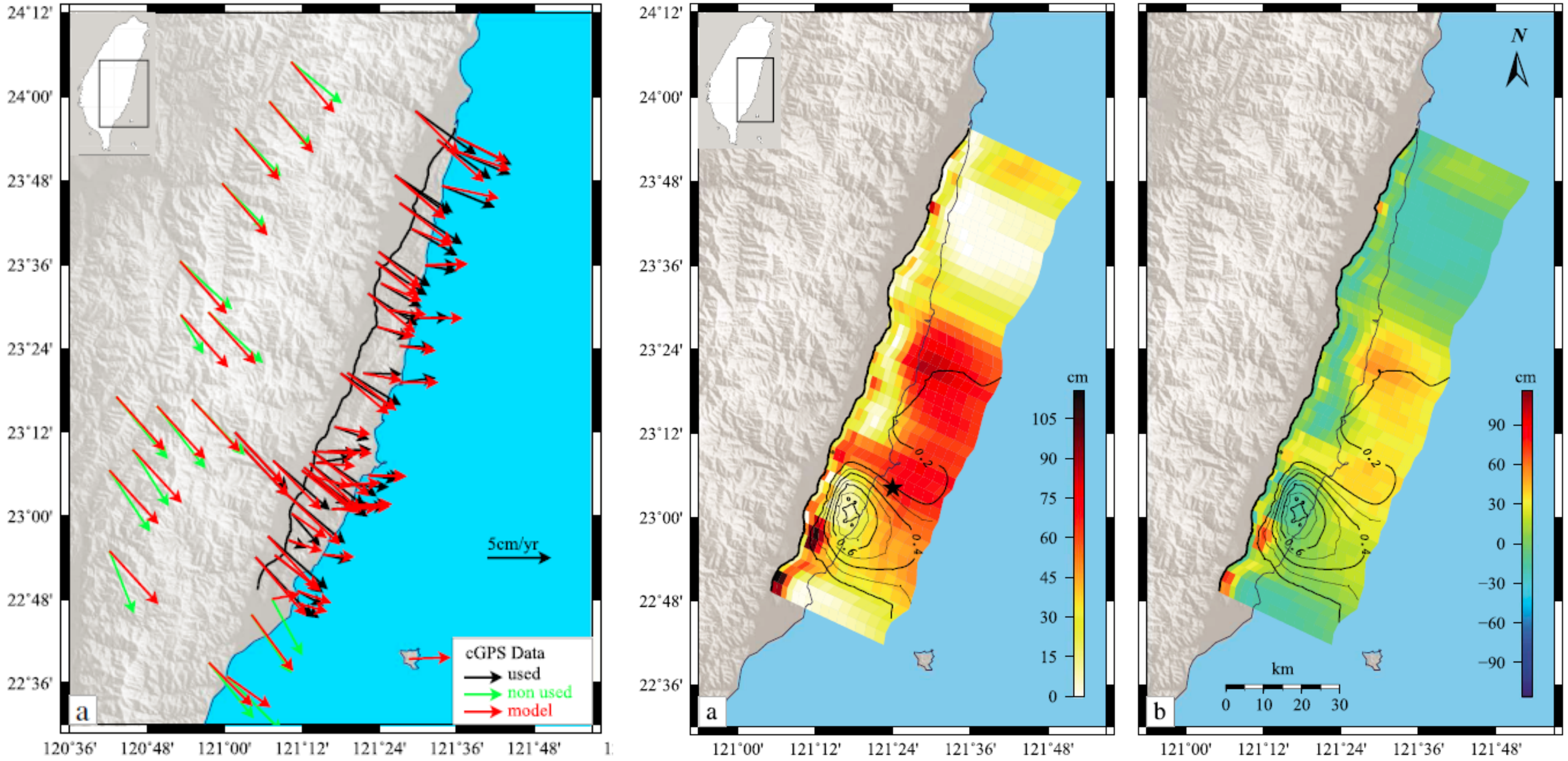


Hsu et al. (2009)

- ~100 days cumulative slip
- Major slip at 5-25 km

- 157 days cumulative slip
- Major slip at 0-10 km
- M 6.2, 13% of main shock

Afterslip Modeling

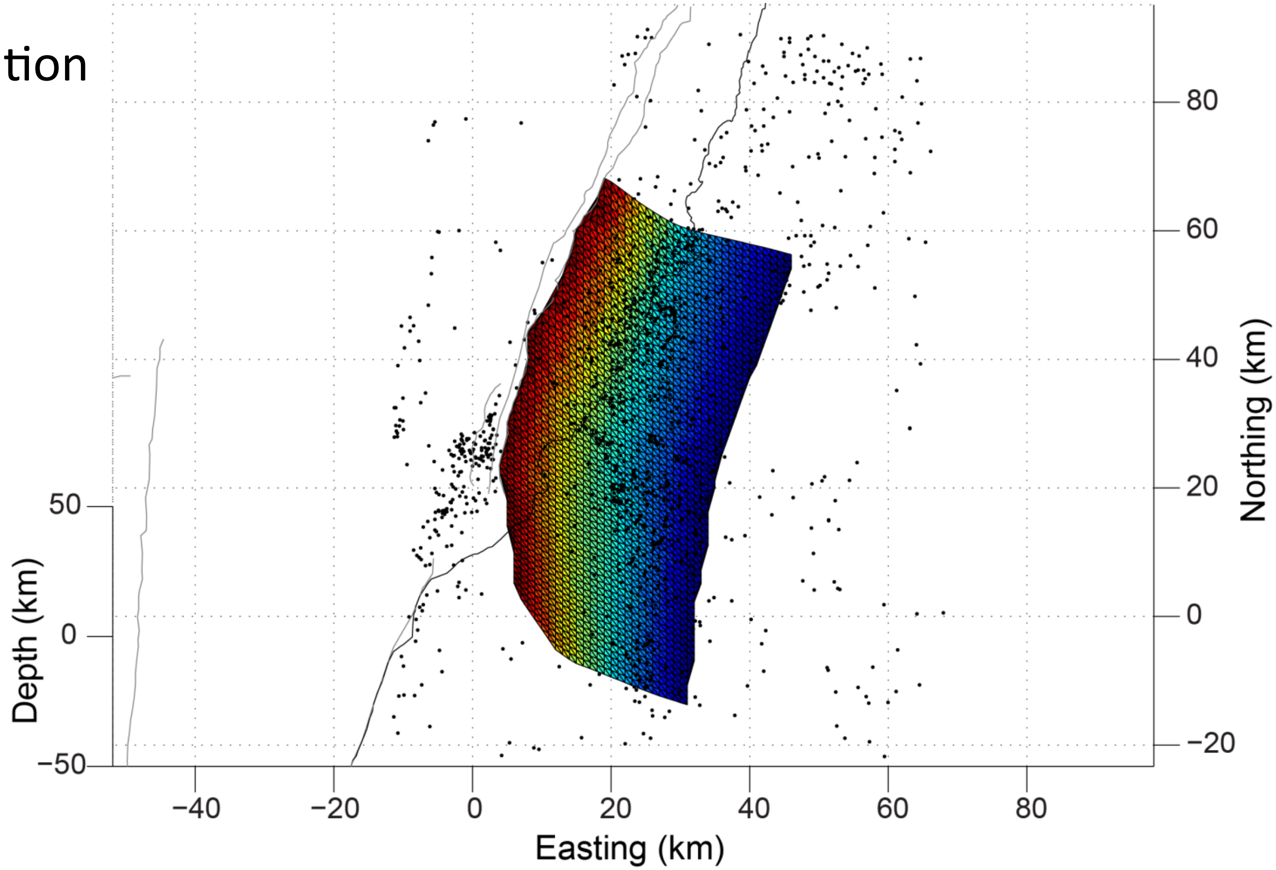


Thomas et al. (2014)

- ~7 years of slip (12/11/2003 – 11/26/2010)
- Up to 70 cm slip surrounding coseismic rupture area
- 1.53 X 10^{19} N m = M_w 6.7, 80% of main shock

Model fault geometry

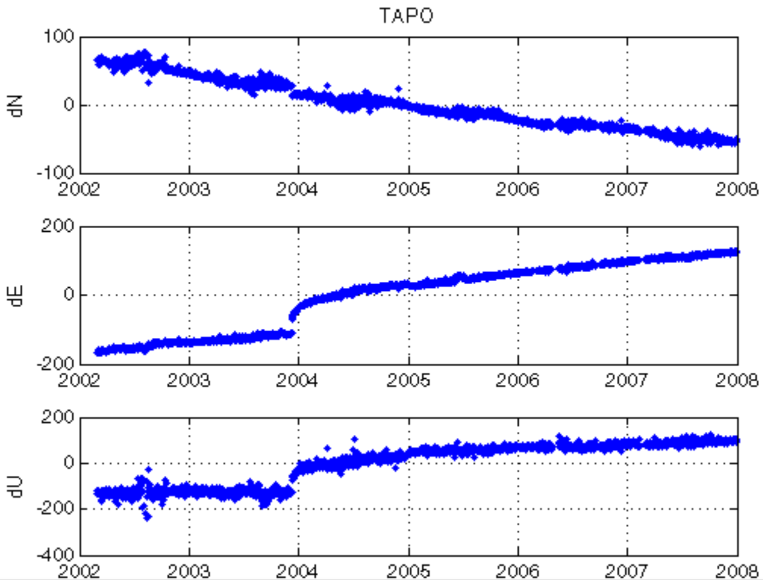
- Construct fault geometry based on relocated seismicity (Wu et al., 2008)
- Surface fault trace based on active fault map (Shyu et al., 2005)
- 1706 patches
- Triangular dislocation

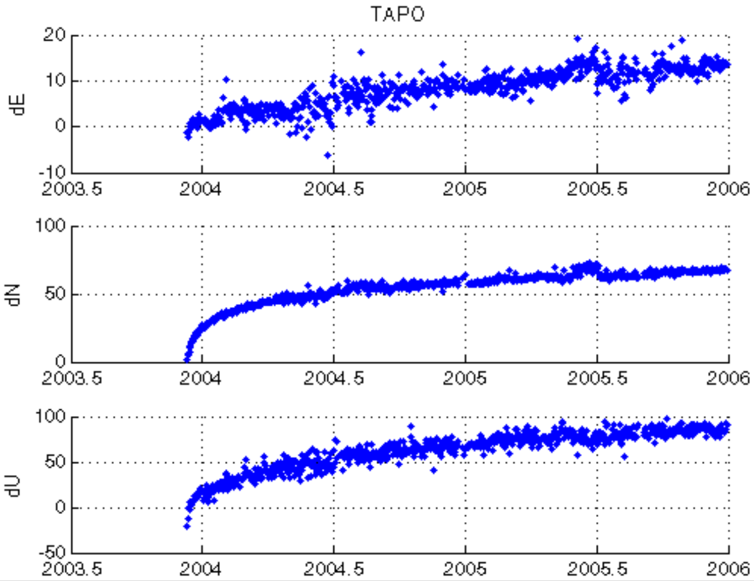


Surface deformation at postseismic stage

$$x(t) = x_0 + \underbrace{v_0 t}_{\text{Secular velocity}} + \underbrace{a_1 \sin(\omega t) + a_2 \cos(\omega t)}_{\text{Annual variations}} + \underbrace{b_1 \sin(2\omega t) + b_2 \cos(2\omega t)}_{\text{Semiannual variations}} + \underbrace{\sum_{i=1}^{Ns} s_i H(t - t_i)}_{\text{Coseismic displacement}} + \underbrace{p_1 \ln\left(1 + \frac{t + t_0}{p_2}\right)}_{\text{Postseismic deformation}}$$

- Time series from GPS lab, Institute of Earth Sciences, Academia Sinica
- 23 continuous GPS stations
- Remove secular, seasonal, coseismic displacement, antenna change, and common model errors
- Bayesian/MCMC metropolis method to search optimal P_2





Inverse Method

- Modified Network Inverse Filter (Fukuda et al., 2014)
- General NIF observation equation

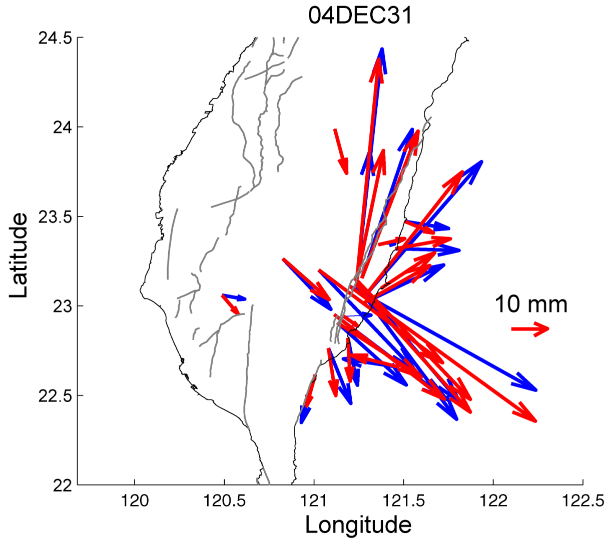
$$\underbrace{\mathbf{u}(\mathbf{x},t)}_{\text{Observation}} = \int_A \underbrace{\mathbf{G}(\mathbf{x},\boldsymbol{\xi})}_{\text{Green's function}} \underbrace{\mathbf{s}(\boldsymbol{\xi},t)d\boldsymbol{\xi}}_{\text{Slip}} + \underbrace{\mathcal{L}(\mathbf{x},t)}_{\text{Local bench-mark motion (temporally correlated)}} + \underbrace{\mathbf{e}(\mathbf{x},t)}_{\text{Observation error (random)}}$$

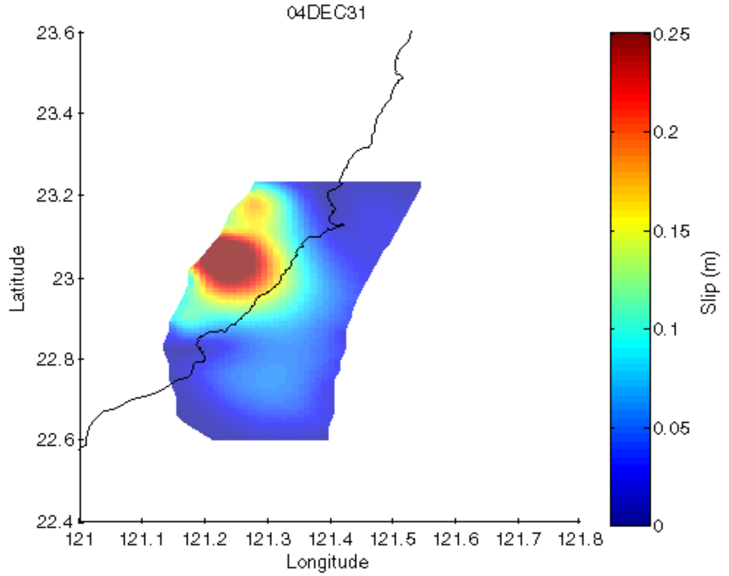
- Temporal evolution of slip rate

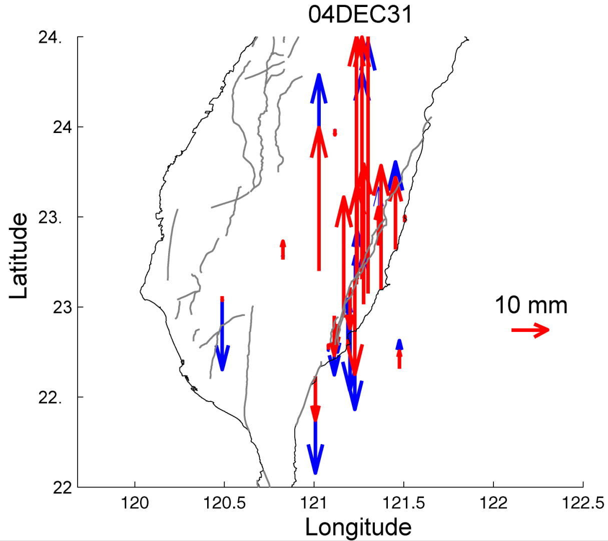
$$\dot{s}(\boldsymbol{\xi},t+\Delta t) = \dot{s}(\boldsymbol{\xi},t) + v_t, \qquad v_t \sim N(0,\alpha^2\Delta t)$$

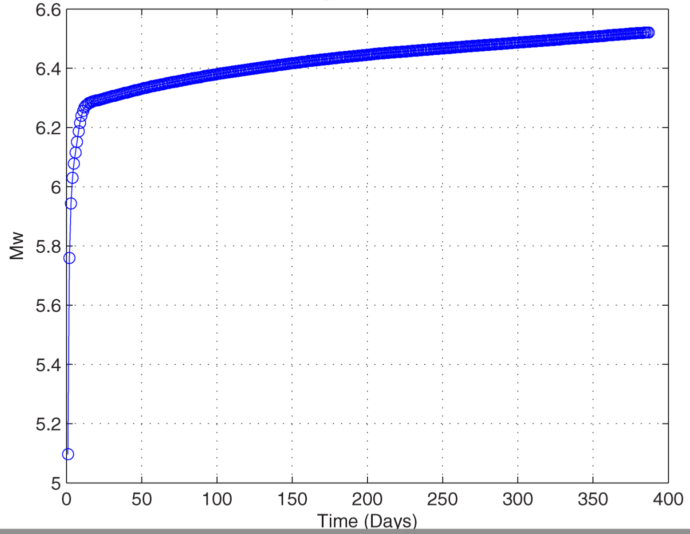
  - Temporal smoothing of slip rate is controlled by α^2
  - α^2 is usually assumed to be constant (constant smoothing)
  - In this method, we estimate time-dependent α^2, which improves temporal resolution

Spatiotemporal Modeling

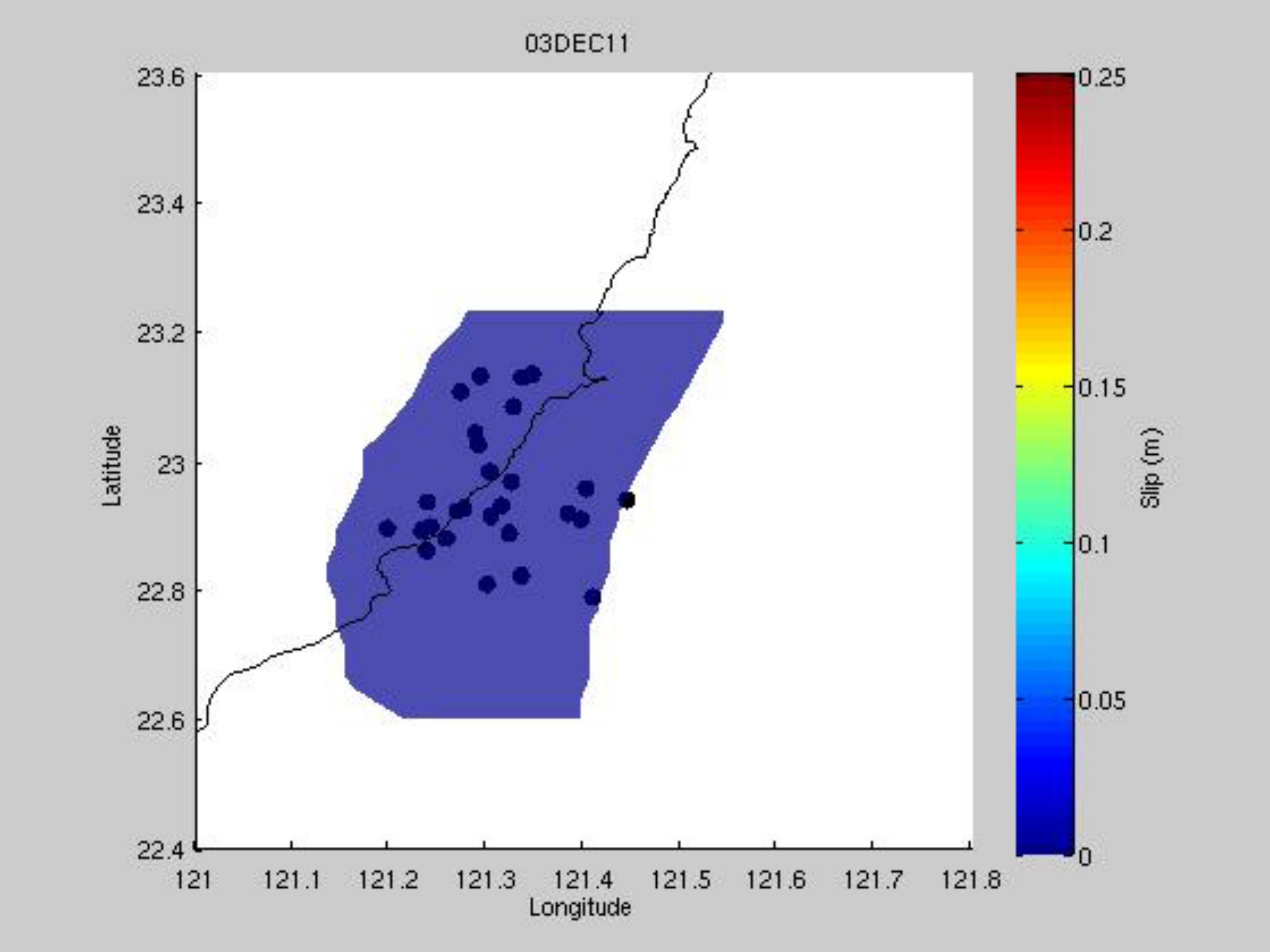




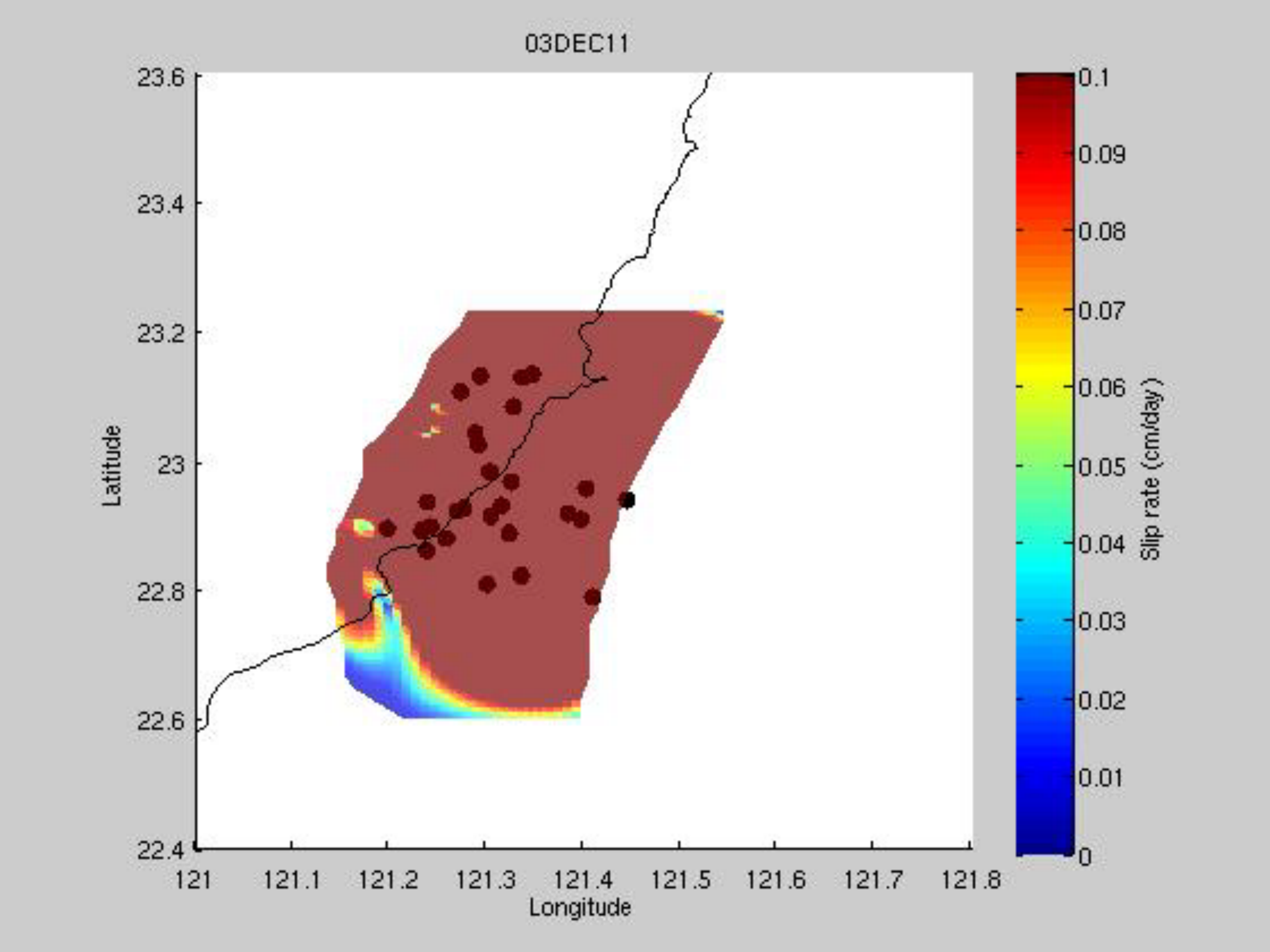




Cumulative Slip Evolution



Slip Rate Evolution



Fault Frictional Property

- Rate and state fault friction

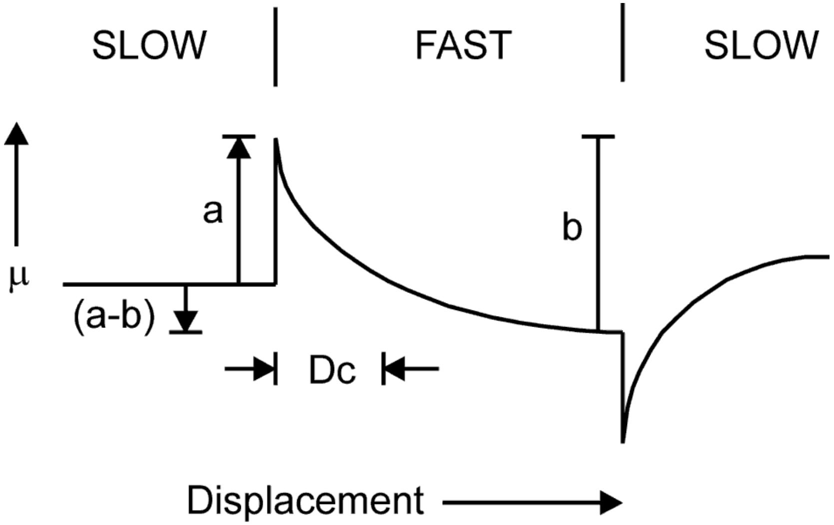
$$\tau_{ss} = \tau_* + (a-b)\sigma_{eff} \ln\left(\frac{V}{V_*}\right)$$

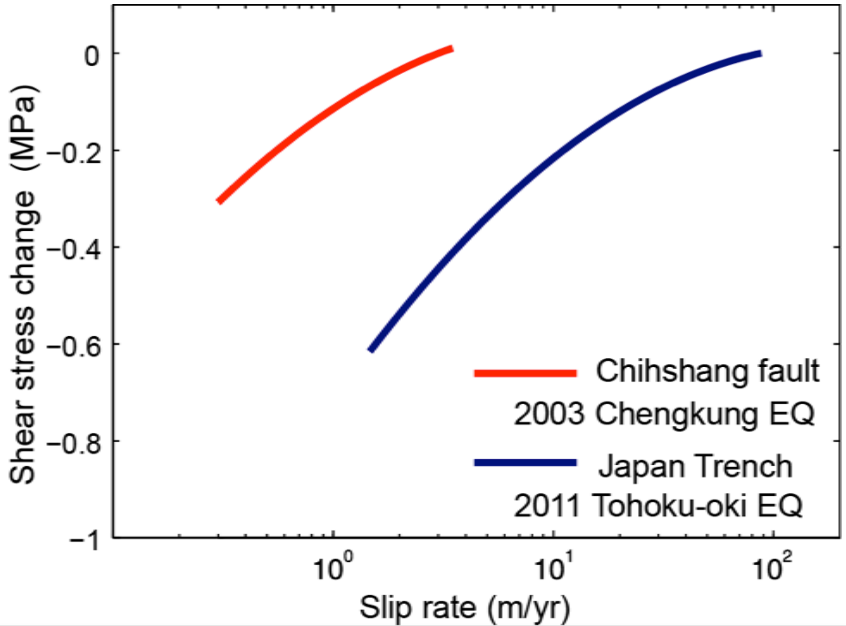
a-b > 0 : velocity strengthening

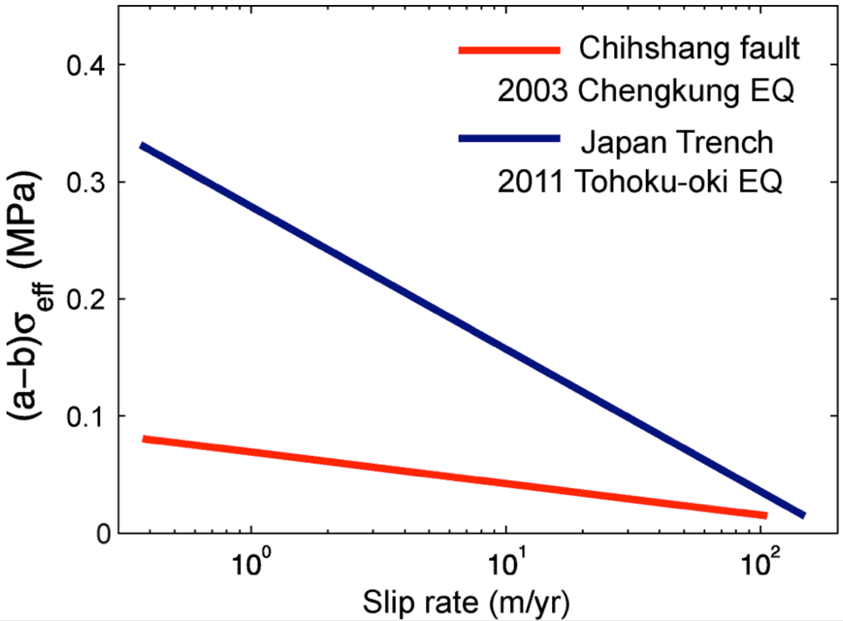
stable, creeping area

a-b < 0 : velocity weakening

unstable, rupture area

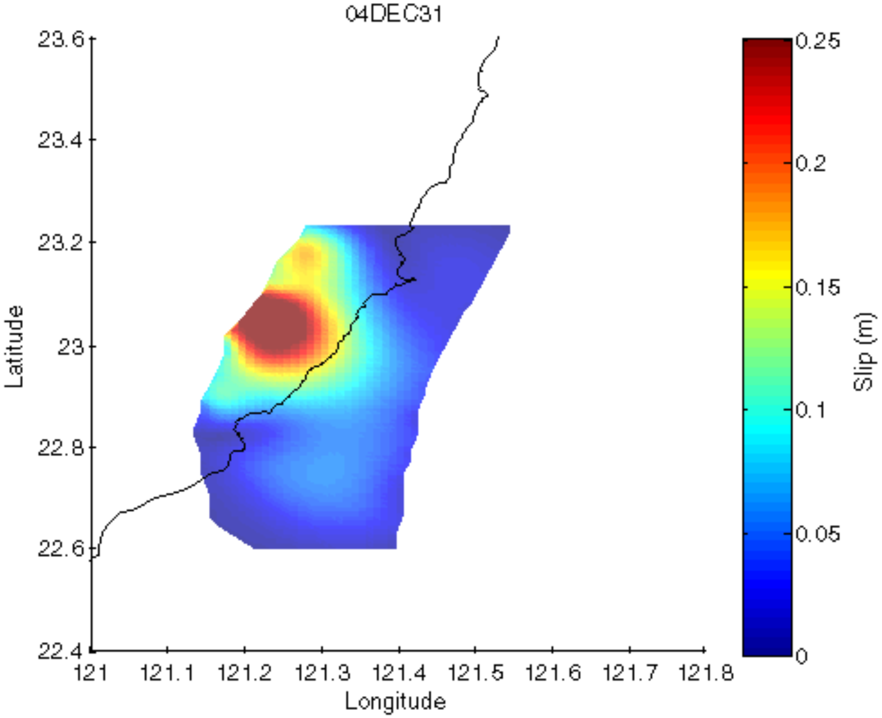




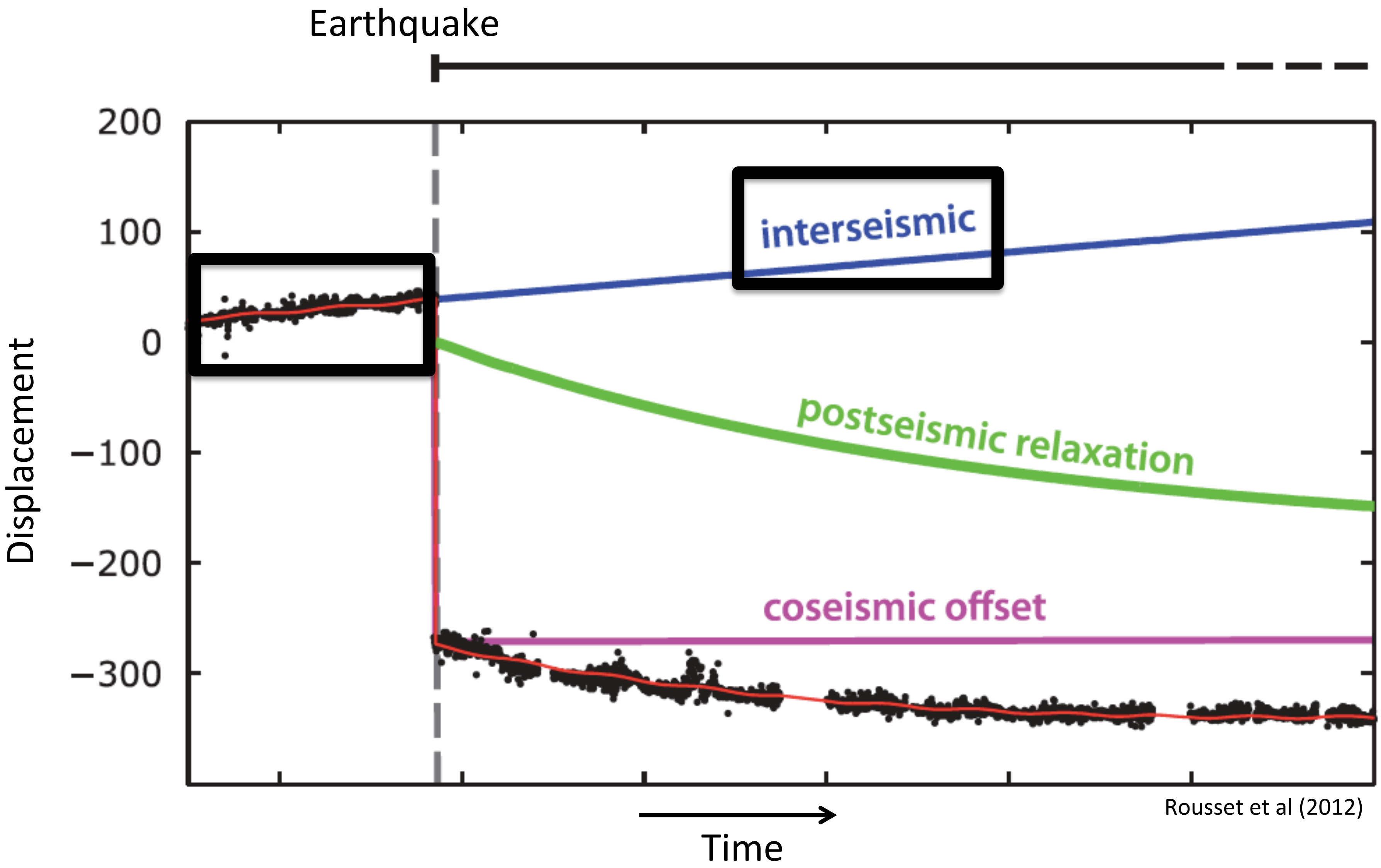


Chengkung Earthquake Afterslip

- Major afterslip is at shallow depth (0-10 km) between Chihshang and Guanshan
- Magnitude of accumulative afterslip within one year is ~ 6.5
- Minor afterslip area is at deeper depths offshore of Taitung, consistent with the area of M6 Lutao earthquake
- Aftershocks occur around the fringe of slip area
- Estimated frictional property shows velocity strengthening, consistent with shallow creep of the Chihshang fault



How topographic change looks like in time

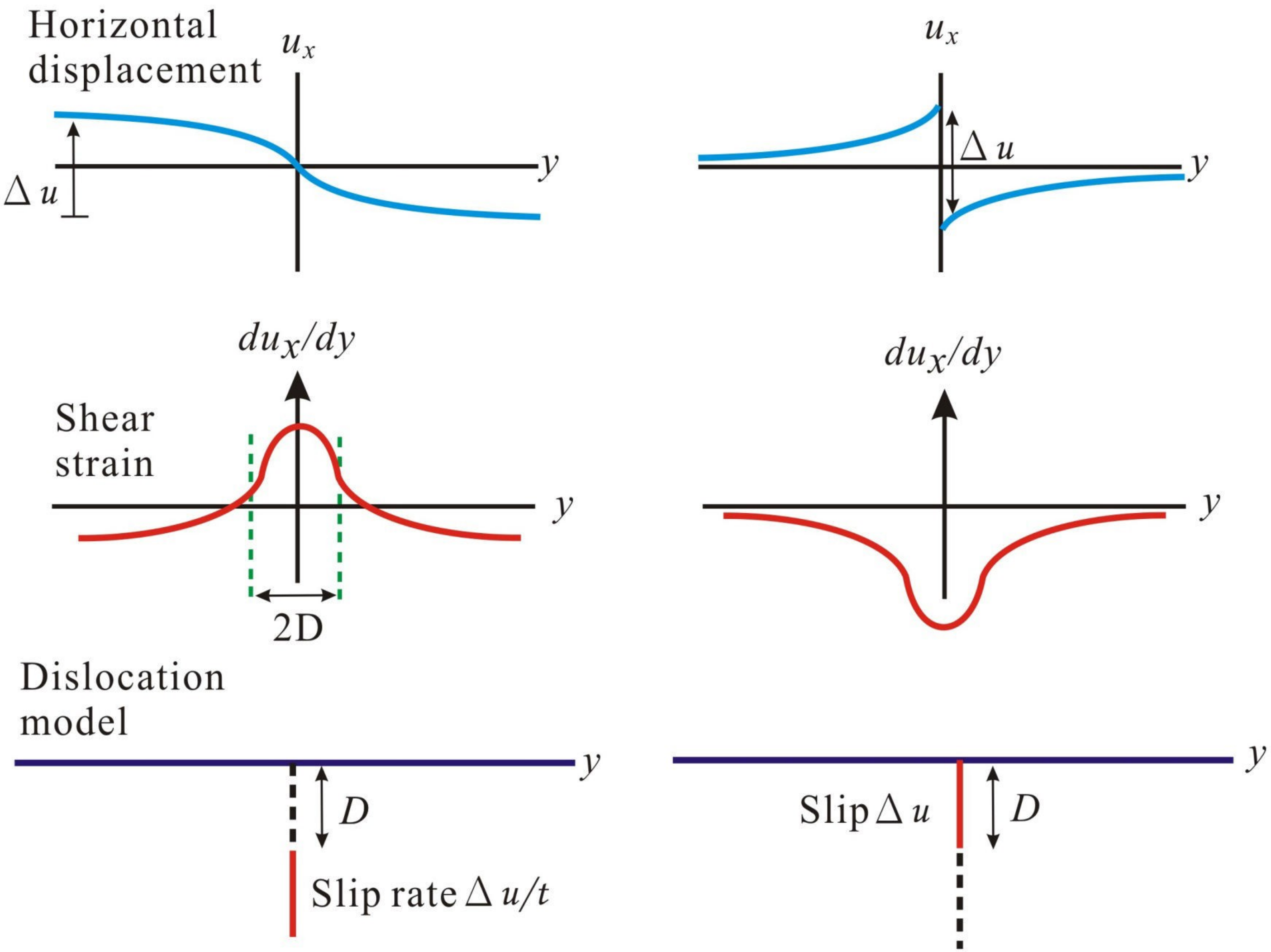


Rousset et al (2012)

Interseismic Deformation

- Faults are locked at some depth during interseismic period to store elastic energy
- Need a model: cannot infer fault slip rates directly from geodetic data
- Geodetic rate: estimated fault slip rates using geodetic data
- Knowing fault slip rates can help to infer
  - Strain partitioning and determine major faults
  - Recurrence interval, possible slip, and seismic potential

Elastic Rebound Model

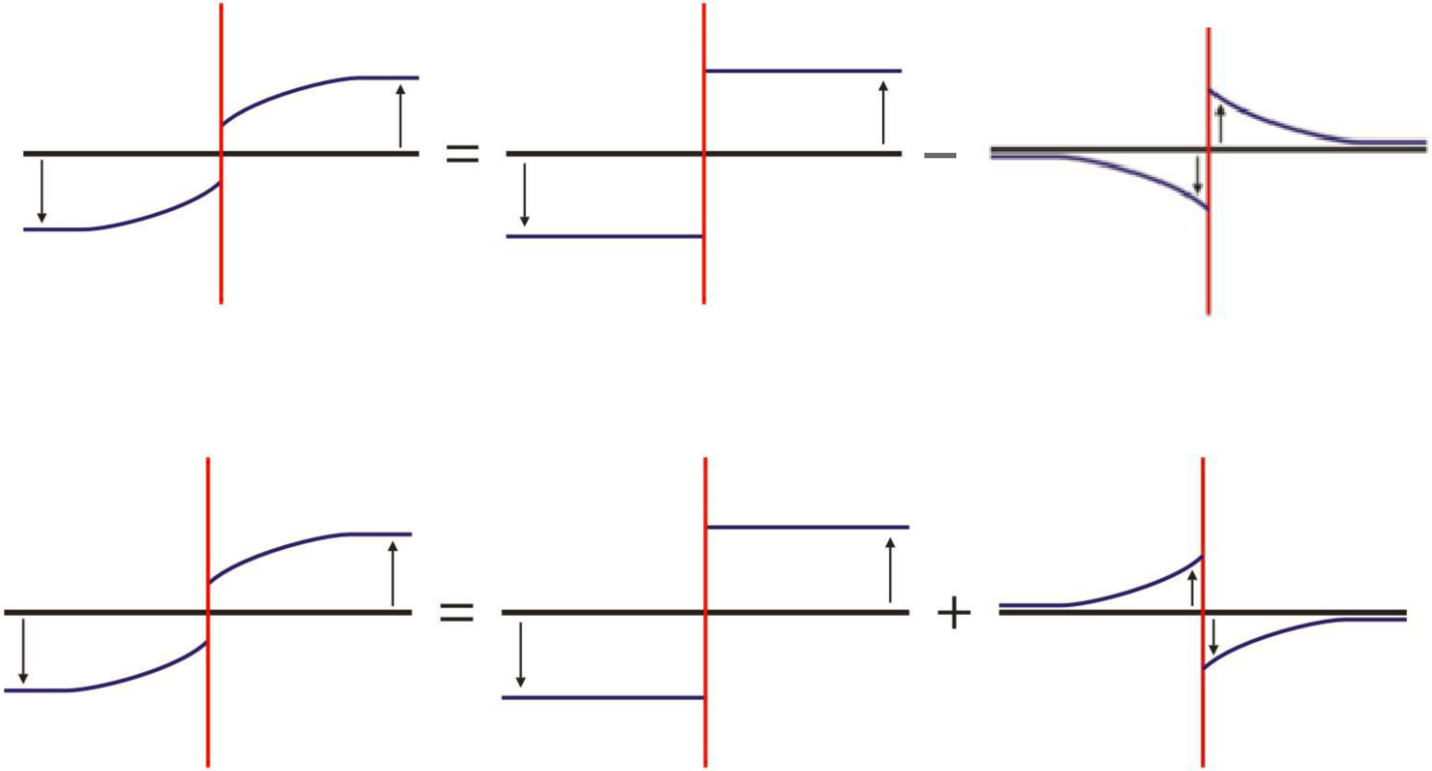


Block Model

Interseismic displacement

Long-term Block motion

Coseismic displacement

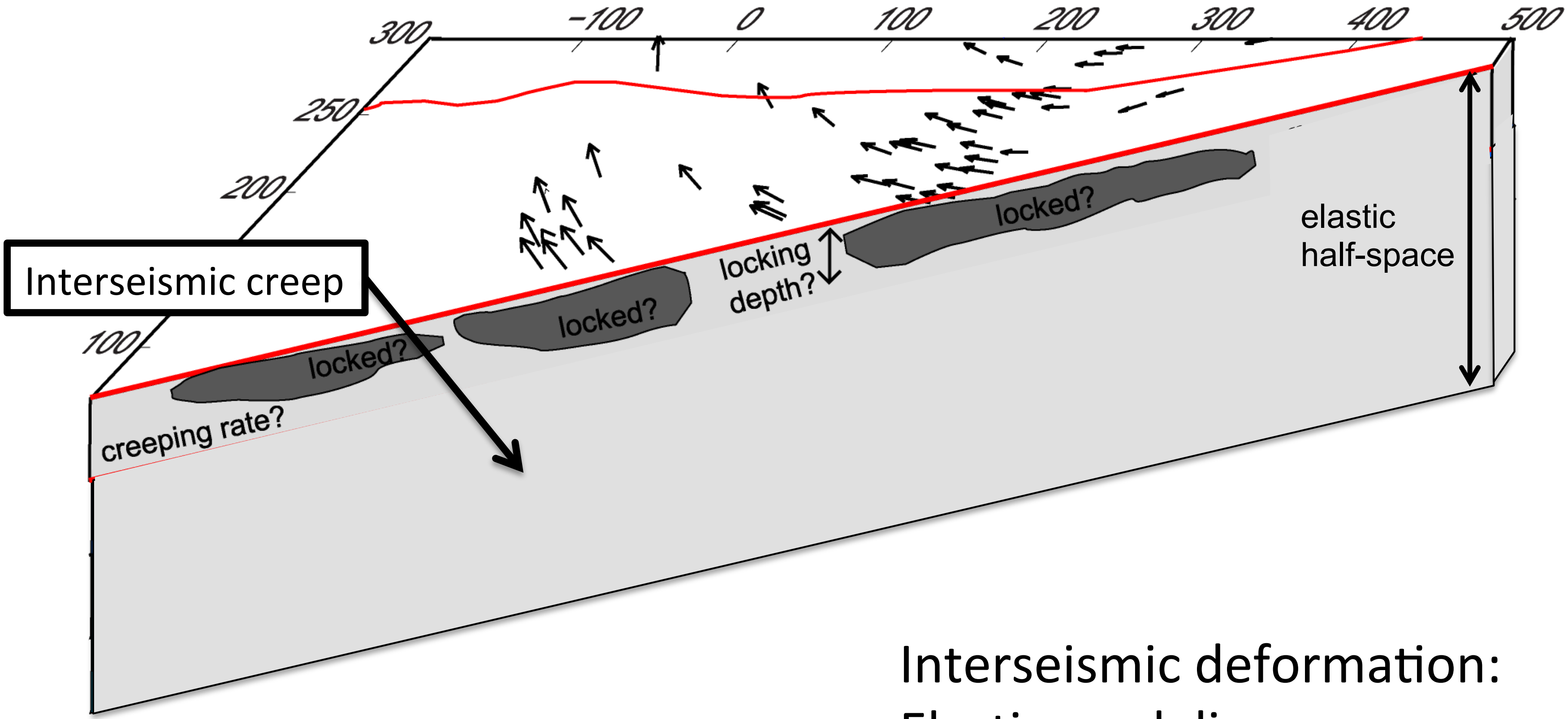


Interseismic displacement

Long-term Block motion

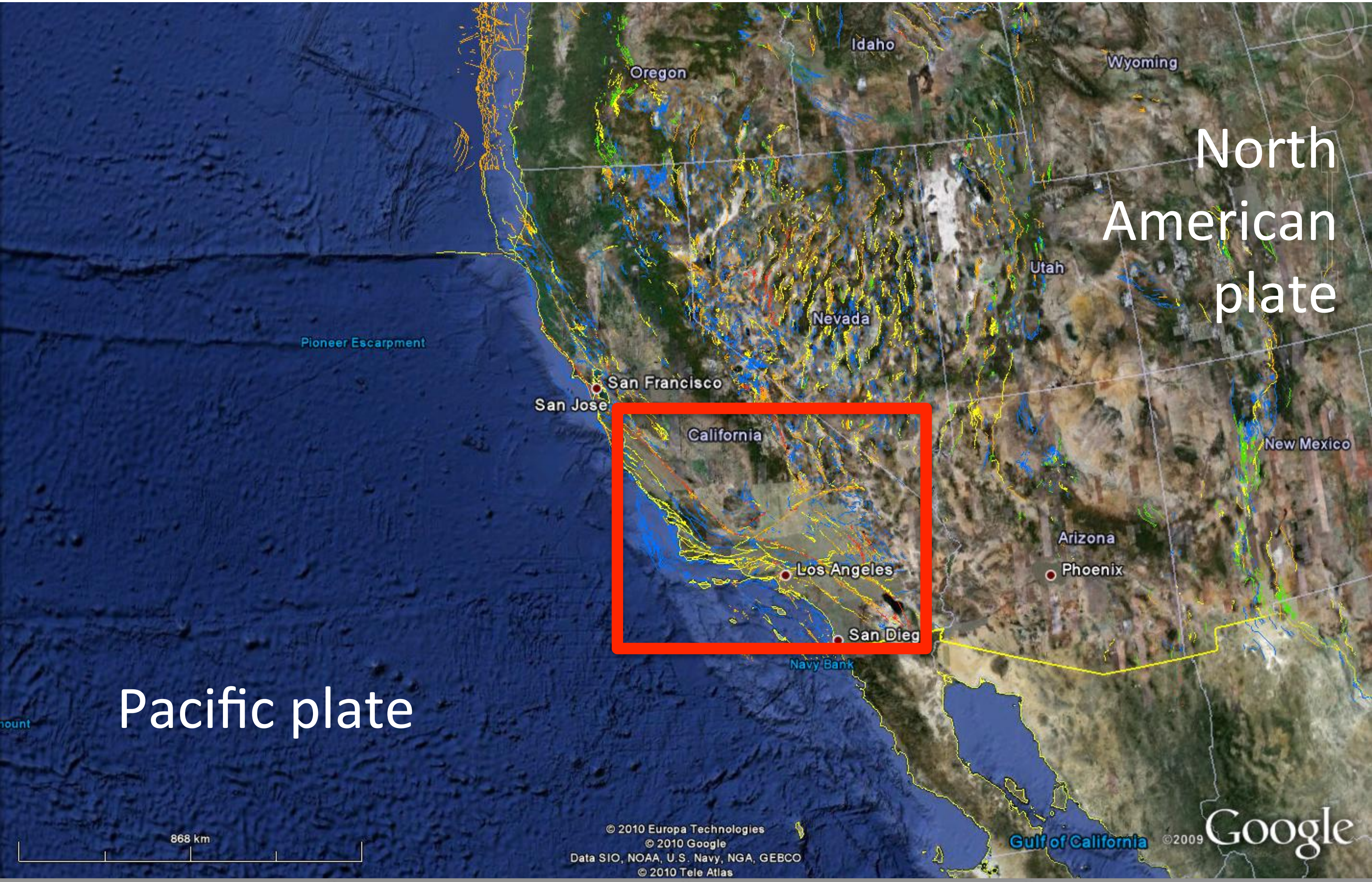
“Backslip” model

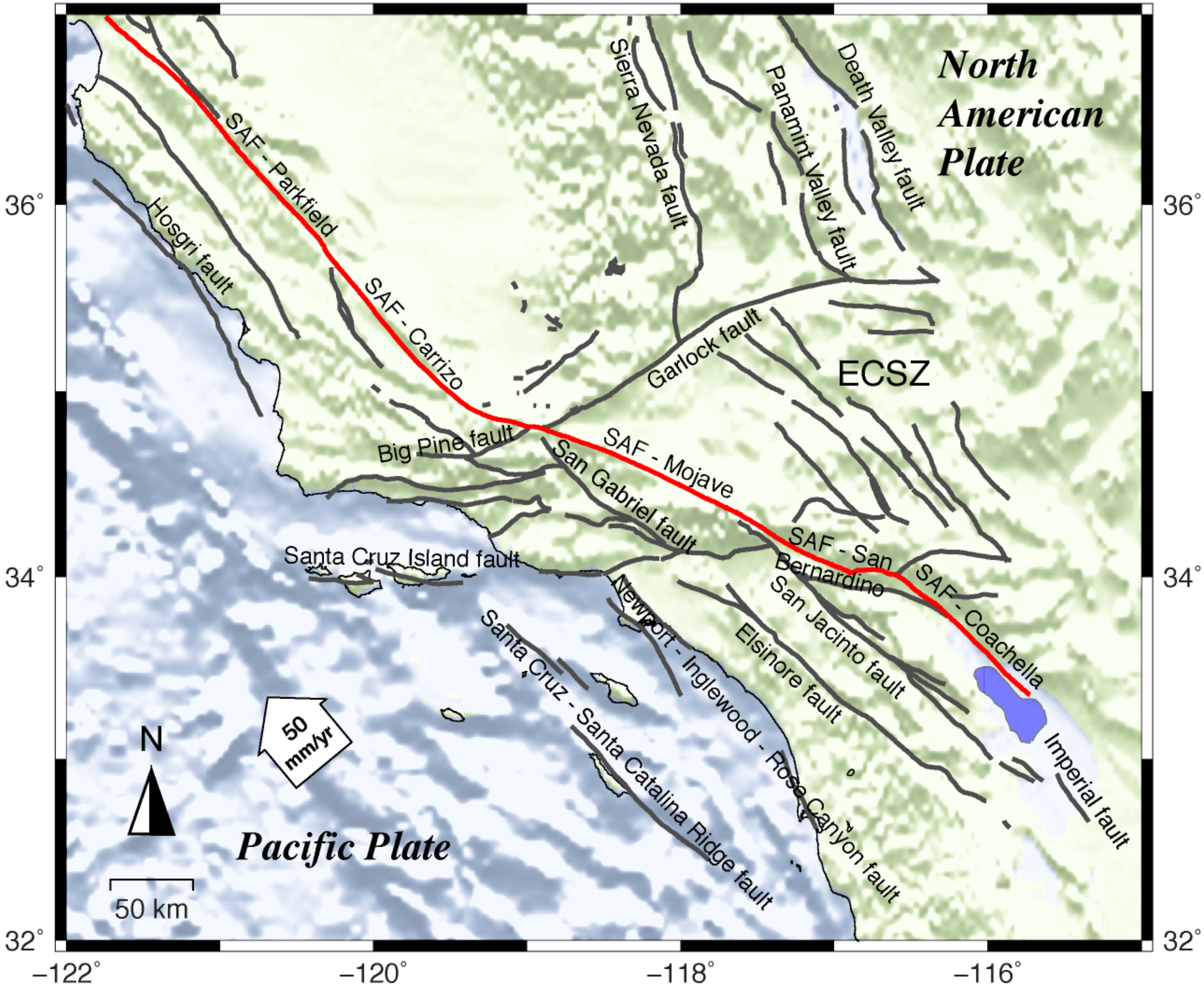
Conceptual Lithospheric structure



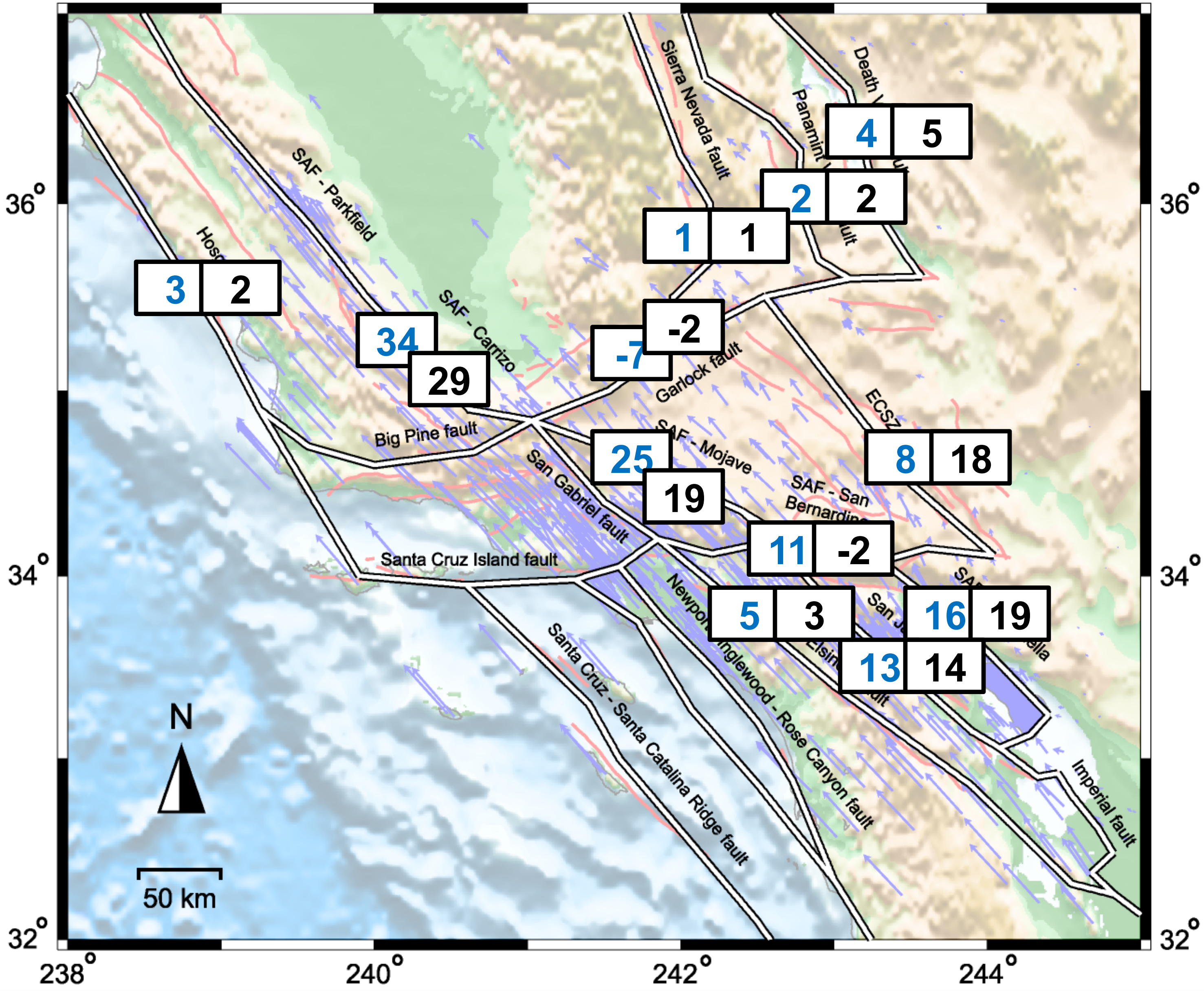
Interseismic deformation:
Elastic modeling

To access seismic potential in California

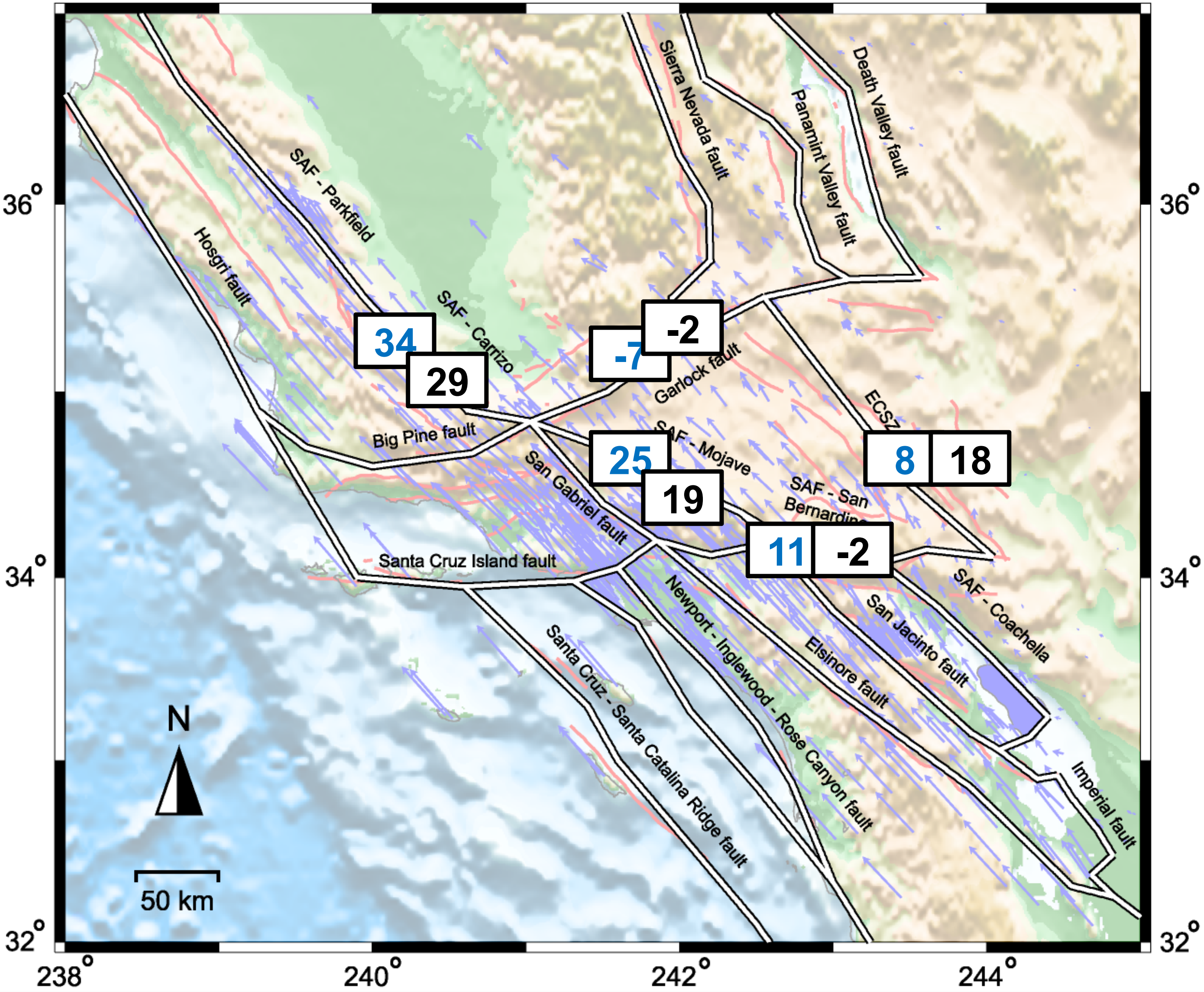



North American Plate
Pacific Plate
SAF - Parkfield
SAF - Carrizo
SAF - Mojave
SAF - San Bernardino
SAF - Coachella
Hosgri fault
Sierra Nevada fault
Panamint Valley fault
Death Valley fault
Garlock fault
ECSZ
Big Pine fault
San Gabriel fault
Santa Cruz Island fault
Newport - Inglewood - Rose Canyon fault
Elsinore fault
San Jacinto fault
Imperial fault
Santa Cruz - Santa Catalina Ridge fault
50 mm/yr
N
50 km
36°
34°
32°
−122°
−120°
−118°
−116°

Geologic rates (mm/yr) Geodetic rates (mm/yr)

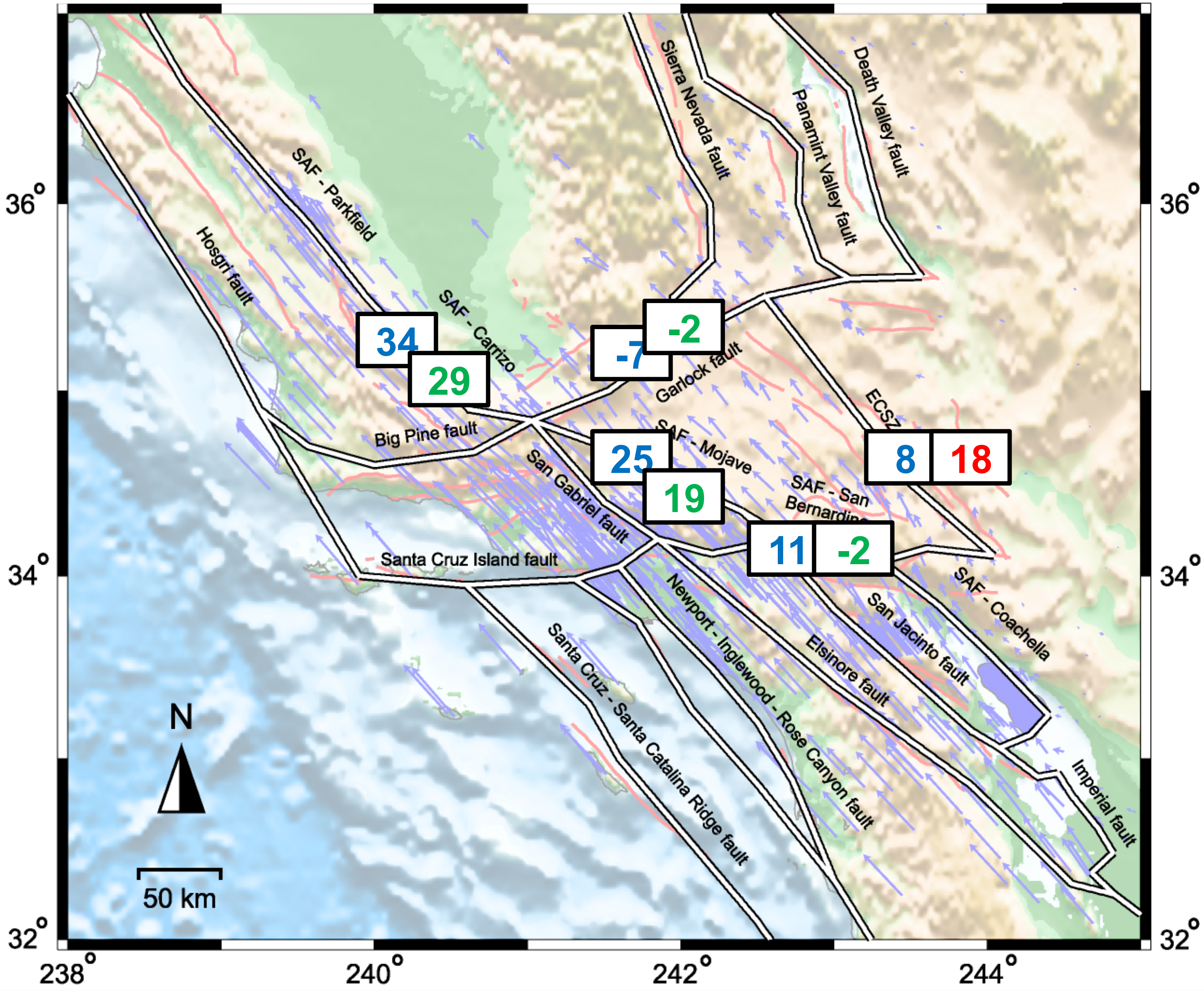


Slip rate discrepancies

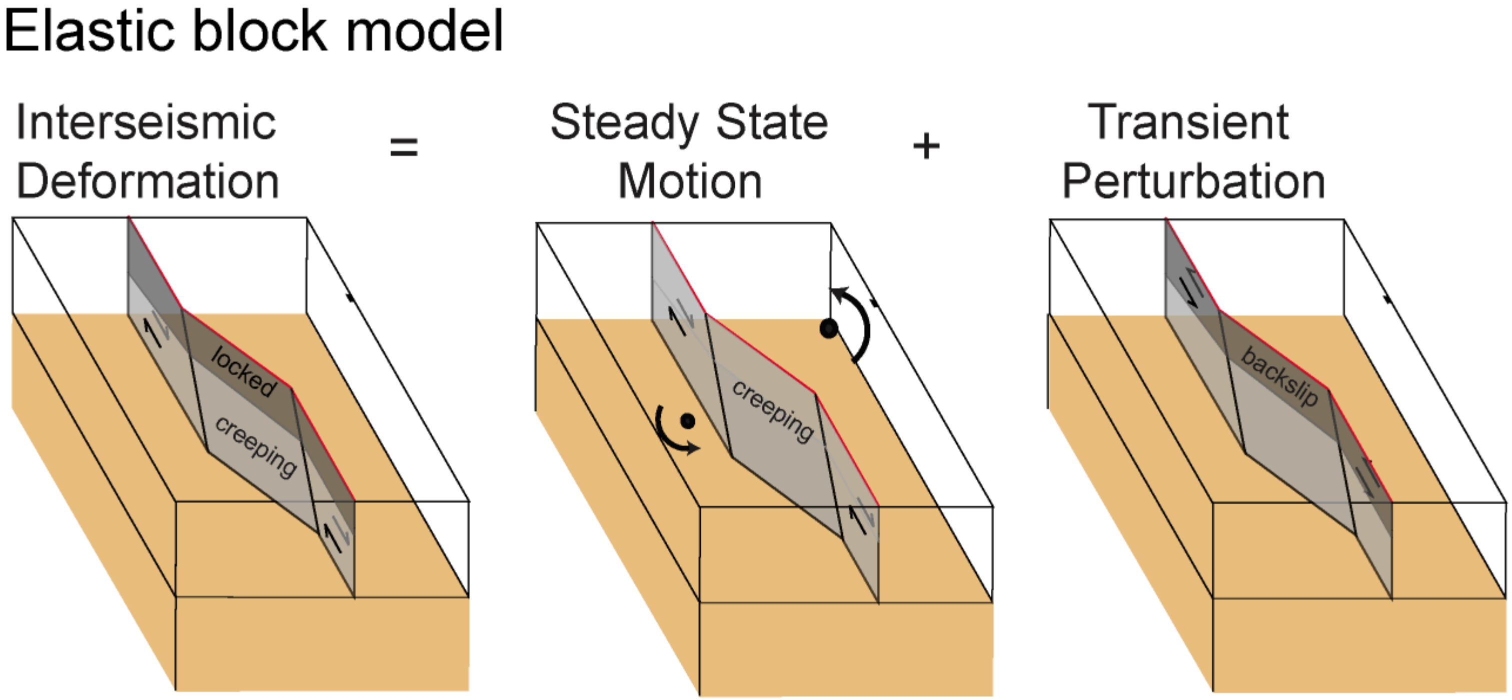


Geodetic rates underestimate

Geodetic rates overestimate



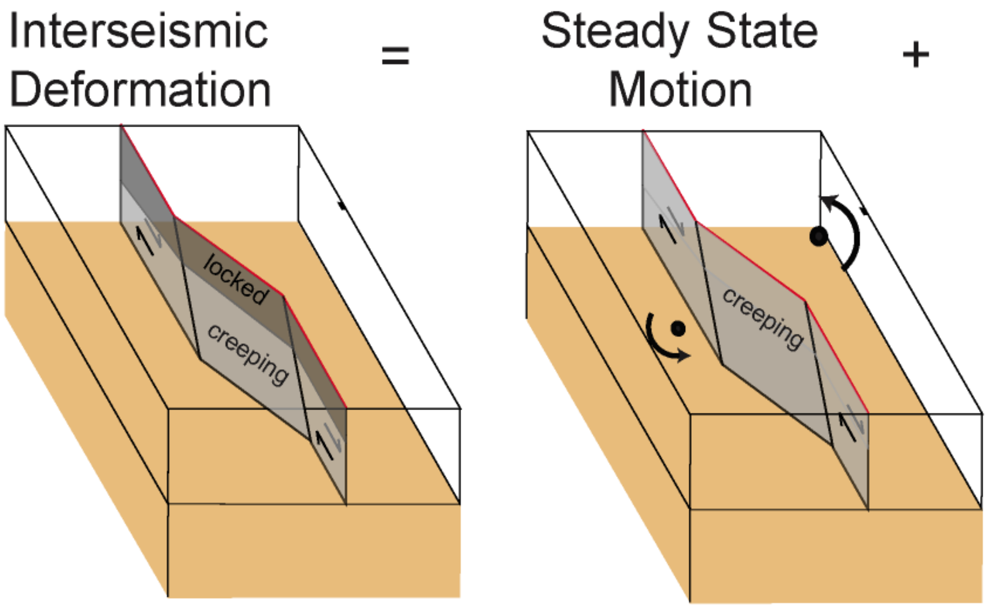
Geodetic rates: Elastic Block Model



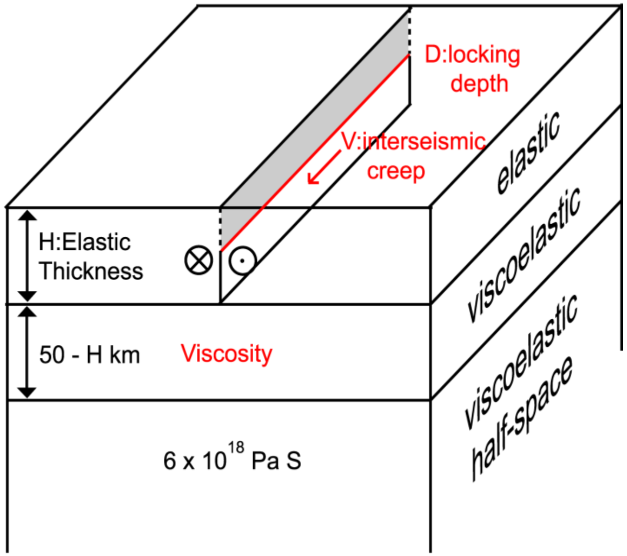
Present-day geodetic data	"Steady-state component"	"Transient component"
GPS velocities	Block rotation on Earth surface	Elastic strain accumulation

Improving Transient Component

Elastic block model



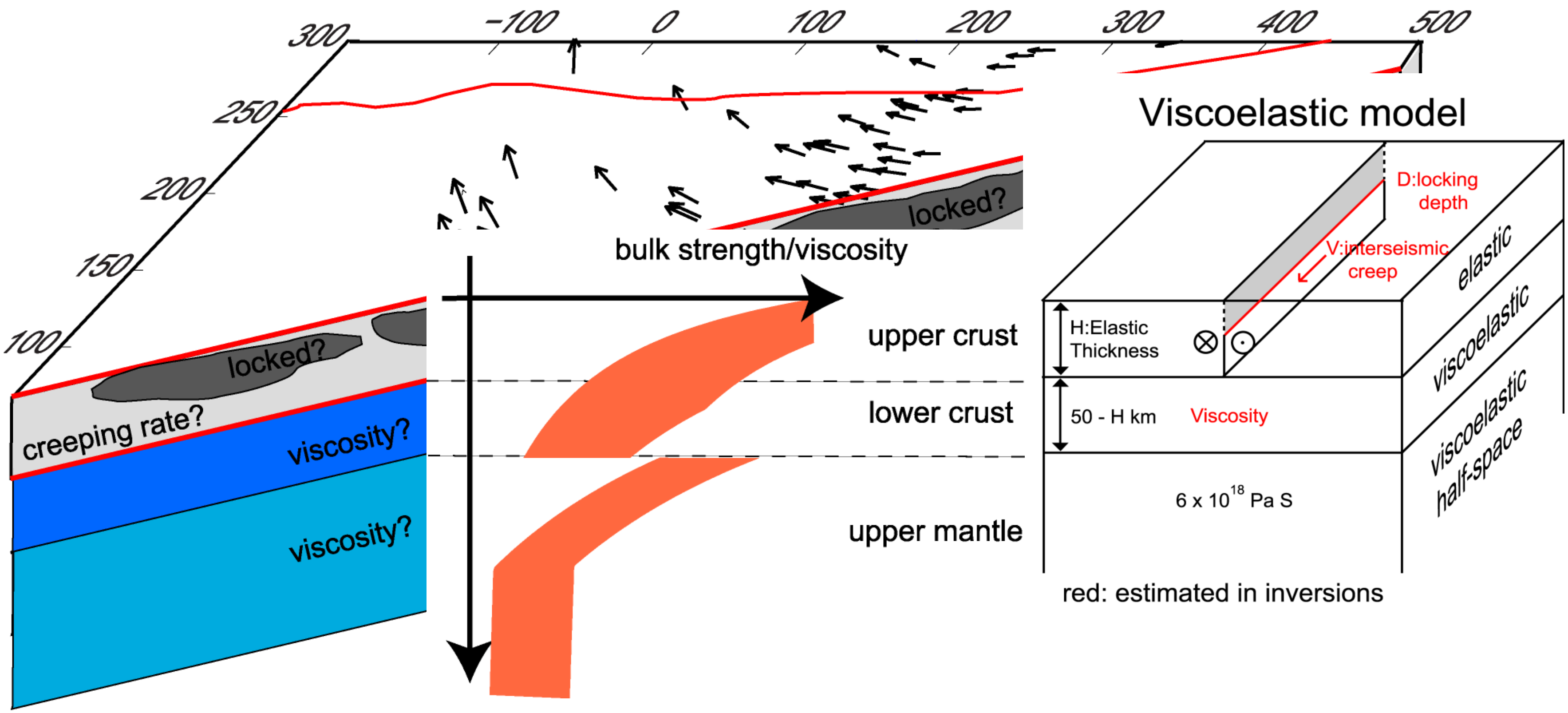
Viscoelastic model



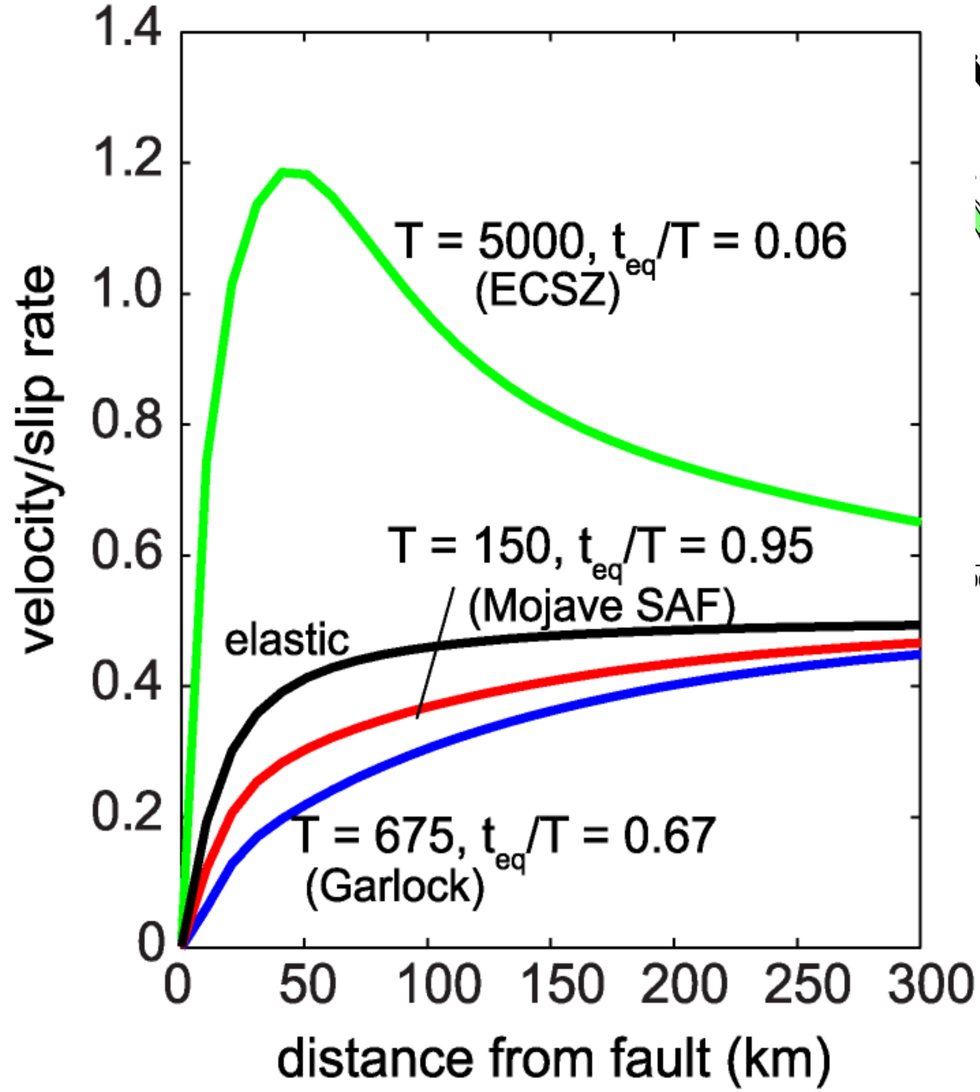
red: estimated in inversions

- Elastic half-space
- Elastic strain accumulation
- Cannot simulate time-varying deformation due to earthquakes and rheology at depths

Viscoelastic layered model

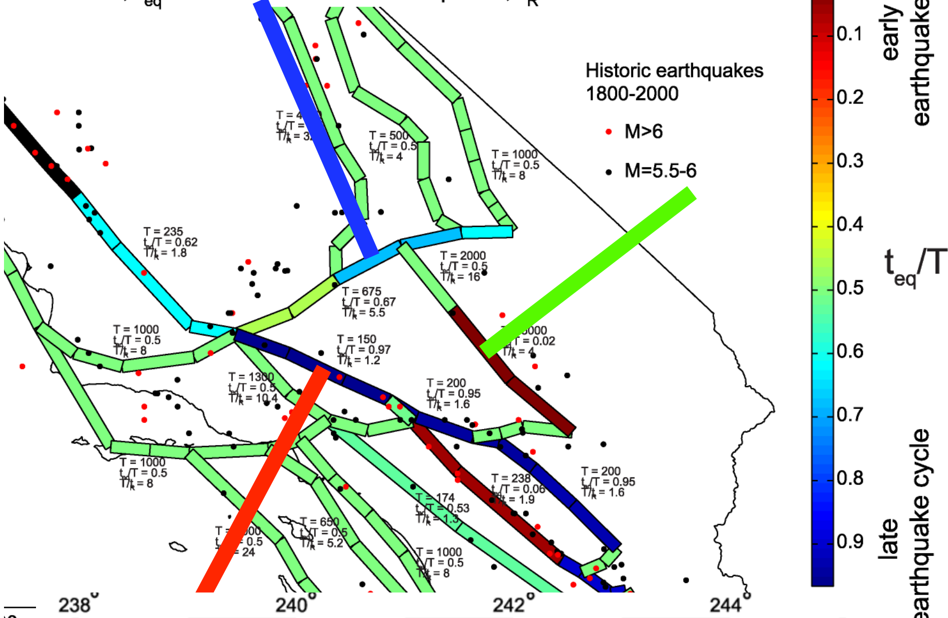


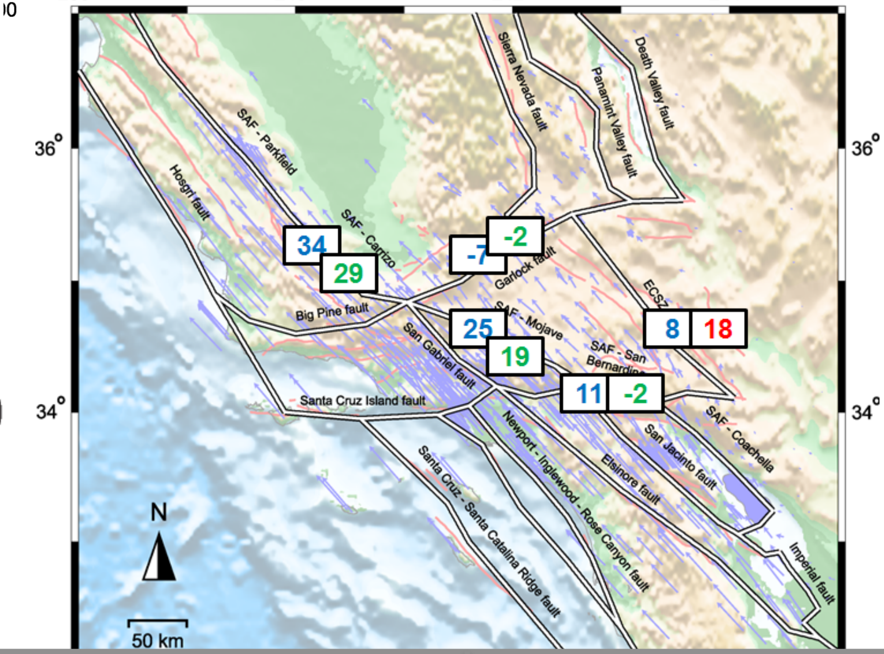
- Time-varying interseismic creep below locking depth
- Impose viscosity for lower crust and upper mantle



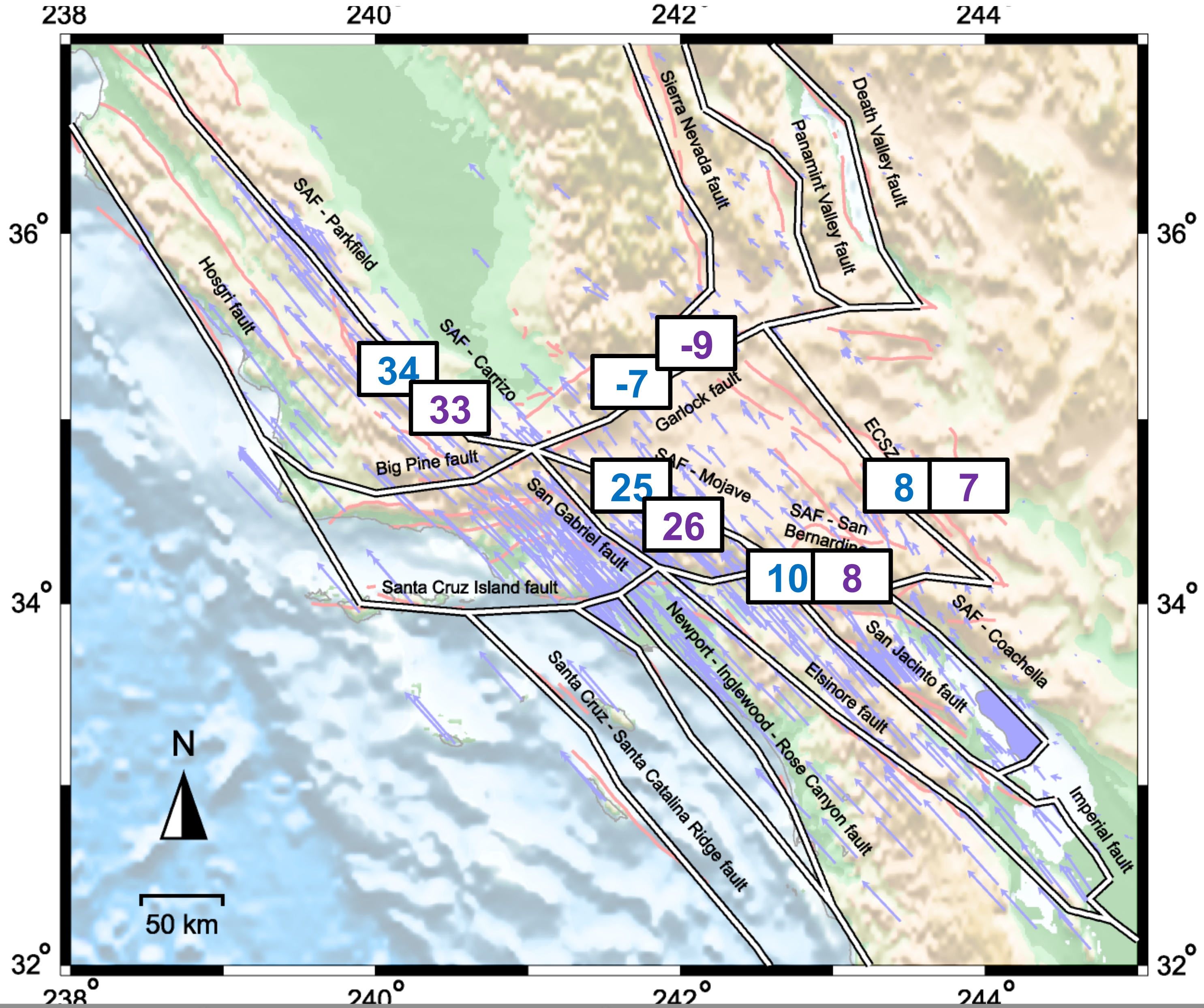
Rupture segments and assumed earthquake timing

T = recurrence interval, t_{eq} = time since last earthquake, t_R = relaxation time

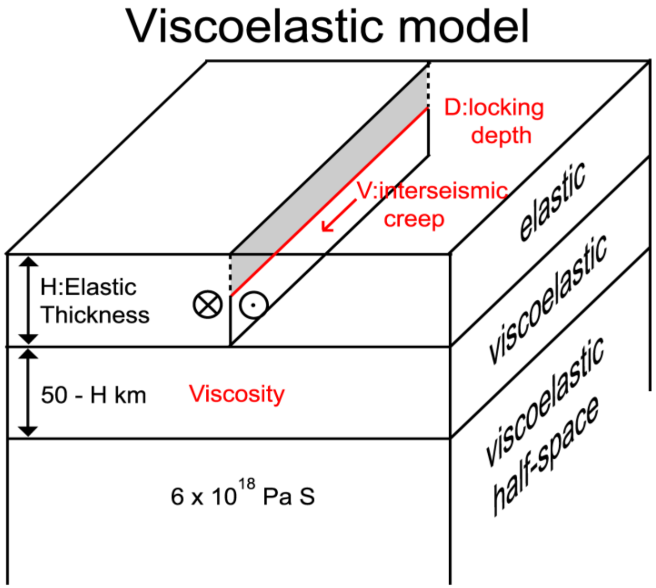




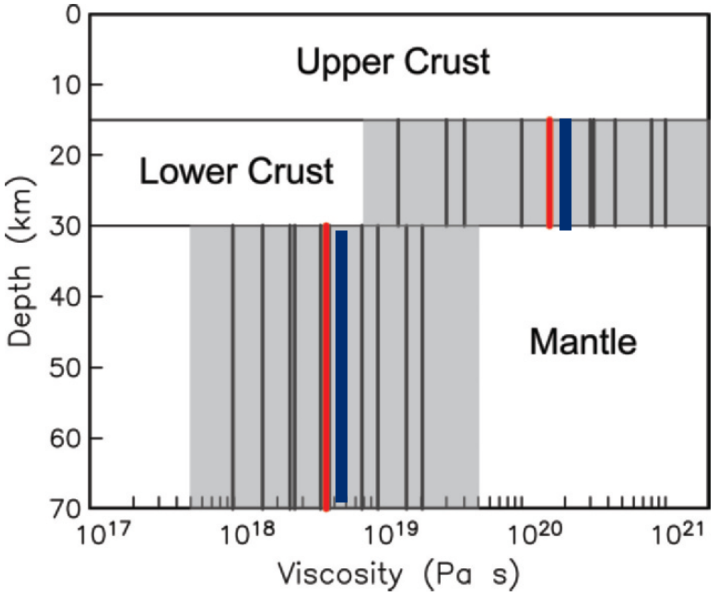
Geologic rates (mm/yr) Geodetic rates (mm/yr)



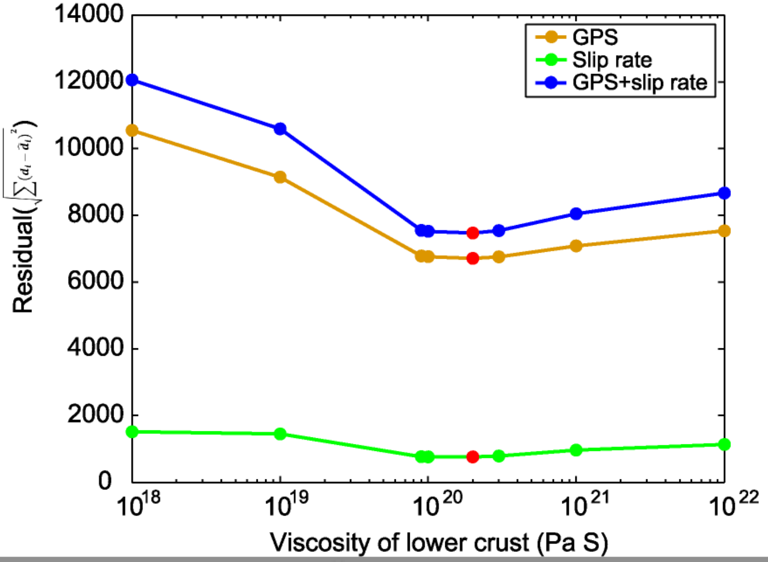
Locking Depth and Viscosity of the Lower Crust



red: estimated in inversions



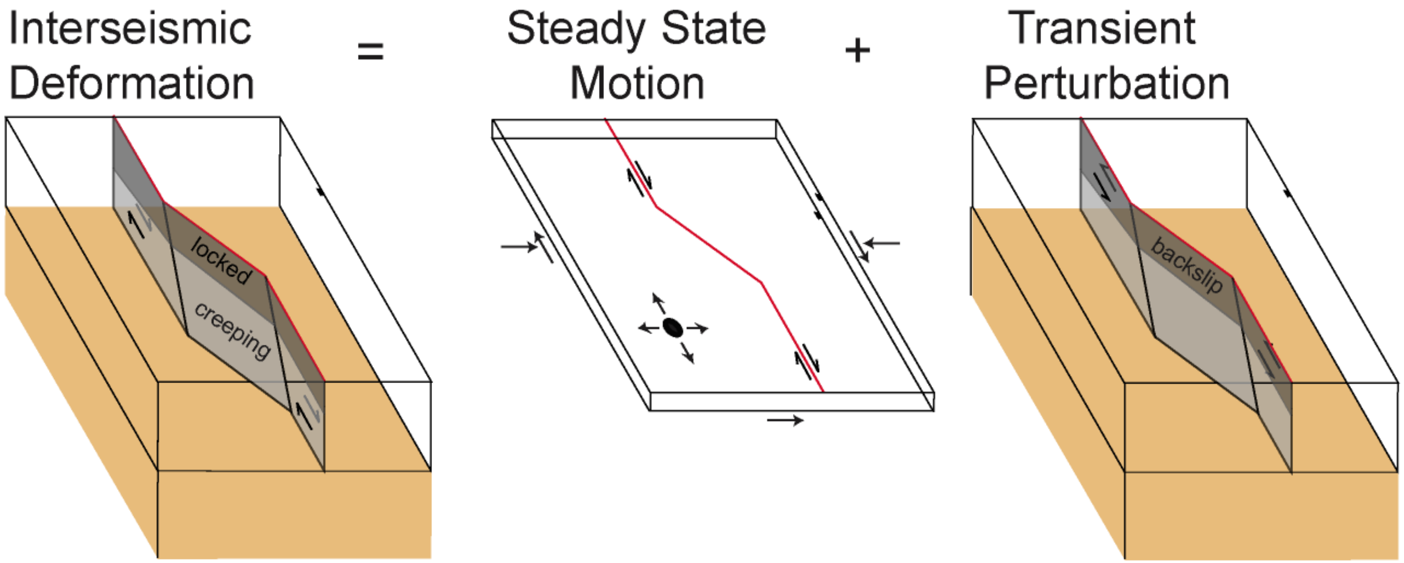
Thatcher and Pollitz (2008)



- Fixed upper mantle viscosity
- Grid search for lower crust viscosity
- Minimum residual at 2X10^{20} Pa S

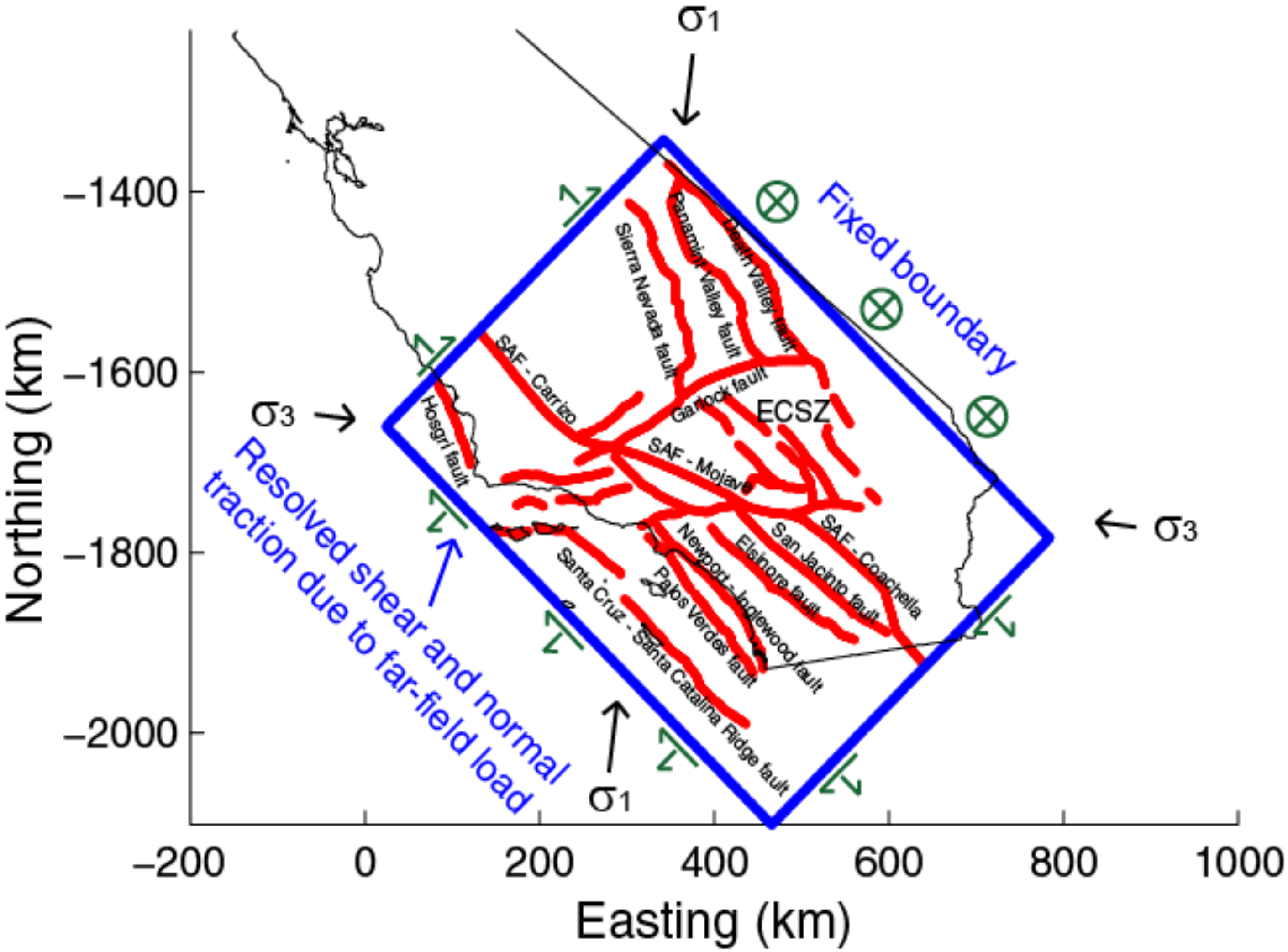
Improving Steady State Component

Elastic block model



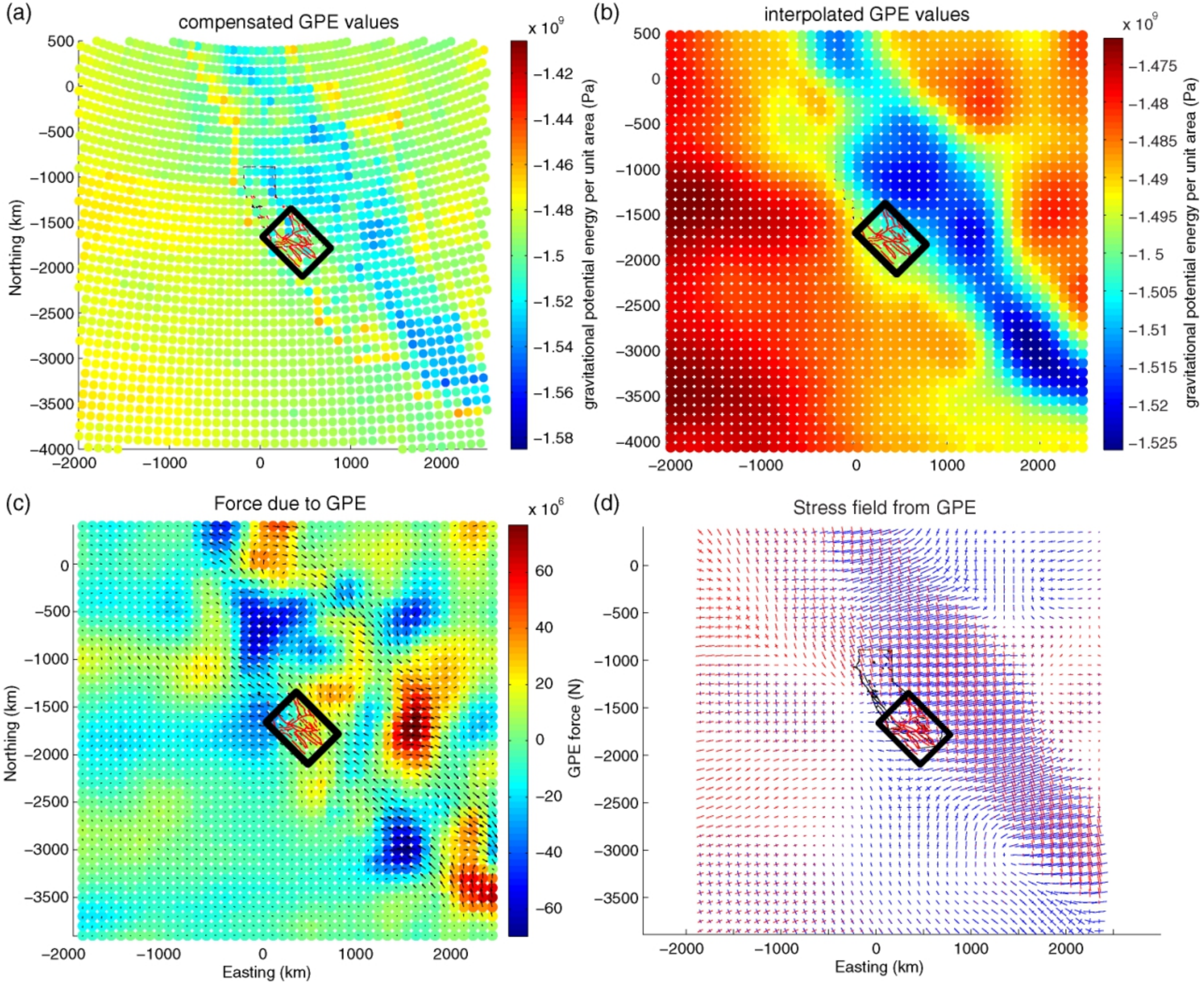
- Kinematic relationship
- Identifying block rotation by fitting GPS velocities
- No physics and rheology

Geodynamic Model

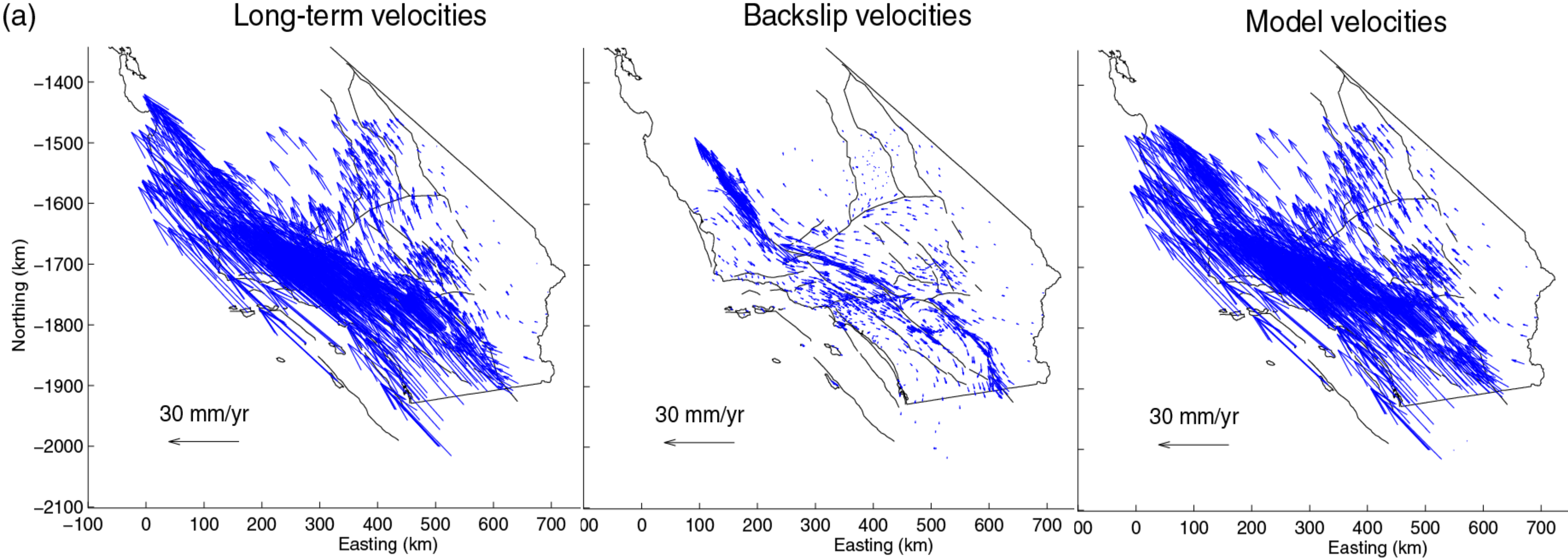


Mechanical model allows deformation under applied stresses

Topographic stresses



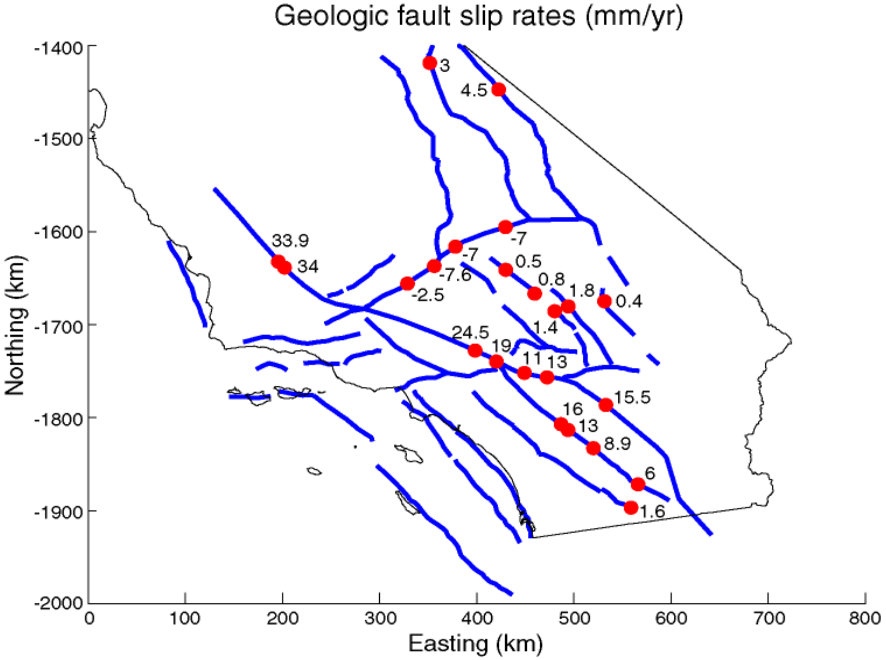
Model surface velocities

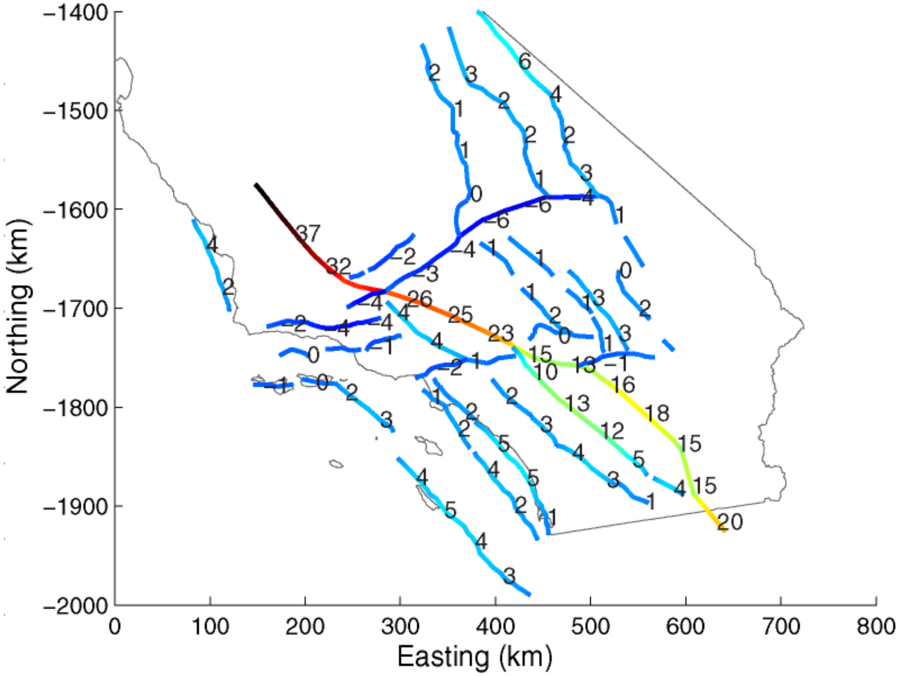


“Steady-state component”

“Transient component”

Present-day geodetic data





- Optimal far-field stress: ~22 MPa
- Optimal lithospheric viscosity: > 10^{27} Pa S
- Imposed shear stress due to topography: ~8 MPa

Interseismic Crustal Deformation Model

- Interseismic models are not only data dependent but also highly **model dependent**
- Working towards incorporating more physics
- Need to carefully choose geological/mechanical constraints

Outline

- Introduction
- Monitoring surface and topographic changes
- Analysis of deformation through earthquake cycle
- Future directions

Moving forward

- New data – new opportunities!
- Repeat time weeks (days!) not months-years
- Advances in modeling tools, inversion approaches, data analysis
- New challenges

Sciencecartoonsplus.com

"AH, FOR THE GOOD OLD DAYS WHEN GEOLOGISTS WORKED OUTDOORS."

Future Research Tasks

- Spatiotemporal surface monitoring by using geodesy and remote sensing
- Integrating multidisciplinary data (geology – geodesy – geophysics)
- Spatiotemporal analysis
- Real-time/fast interaction

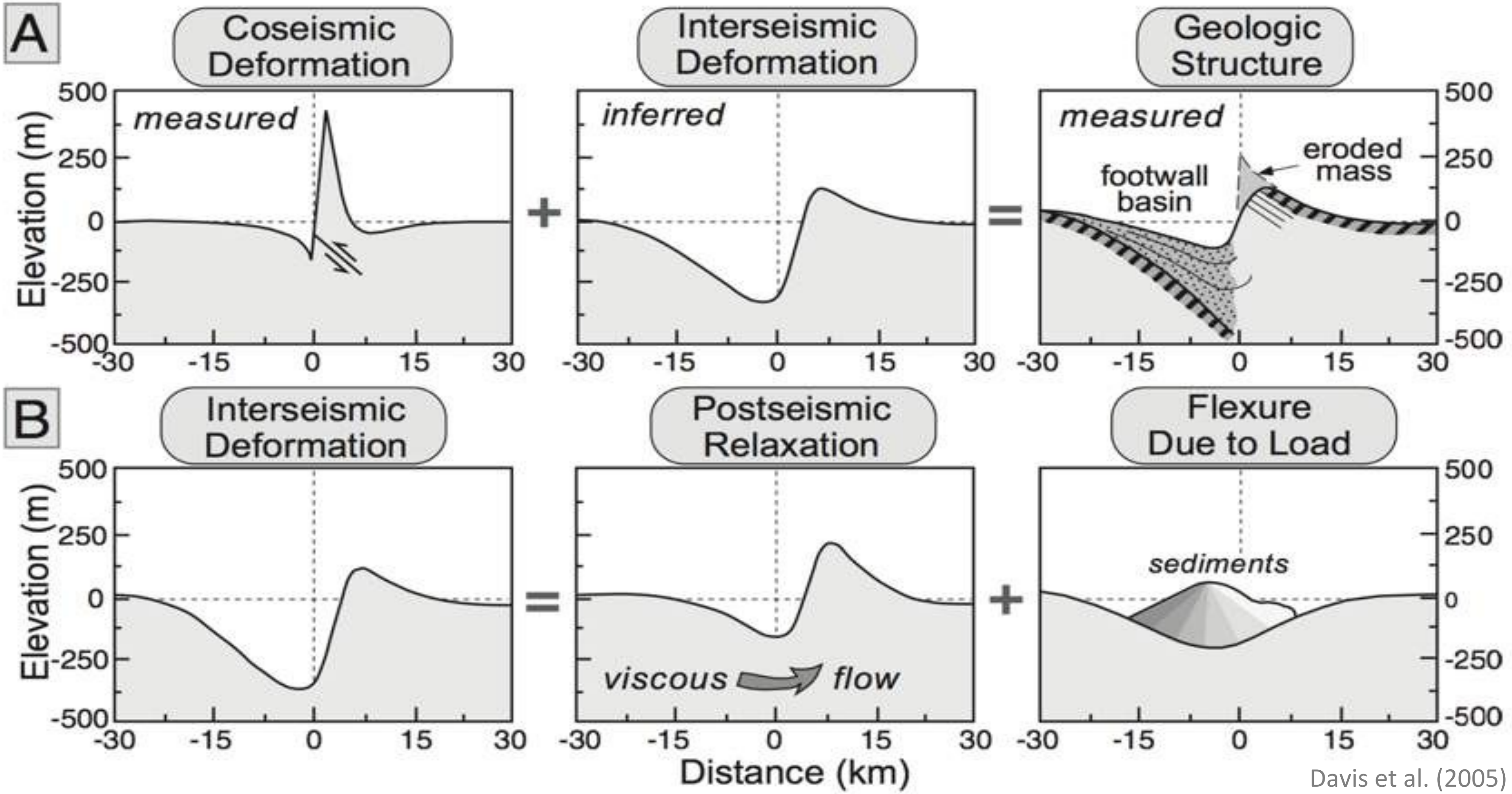
Future Research Directions

- Mechanical constrained earthquake cycle surface deformation
- Surface process, topographic evolution and mountain building
- Using geotechniques for surface and environmental monitoring

Thank you!

Courtesy of Dr. Hao-Tsu Chu

Corresponding topographic changes



Davis et al. (2005)

Time-dependent Layered Model

- Elastic models tend to under-predict/over-predict slip rates for faults in late/early earthquake cycle

- Fault slip rate discrepancies can be reconciled using viscoelastic layered model

- The viscosity estimate is consistent with other estimates of lower crust/upper mantle in western U.S.

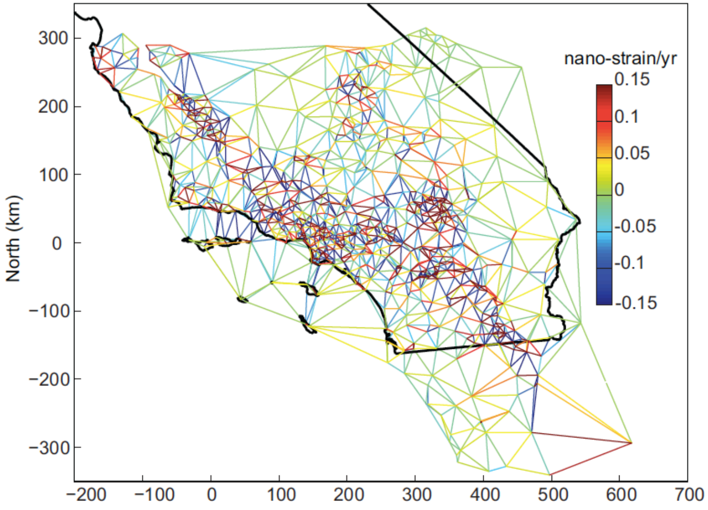
Dynamic thin-sheet model

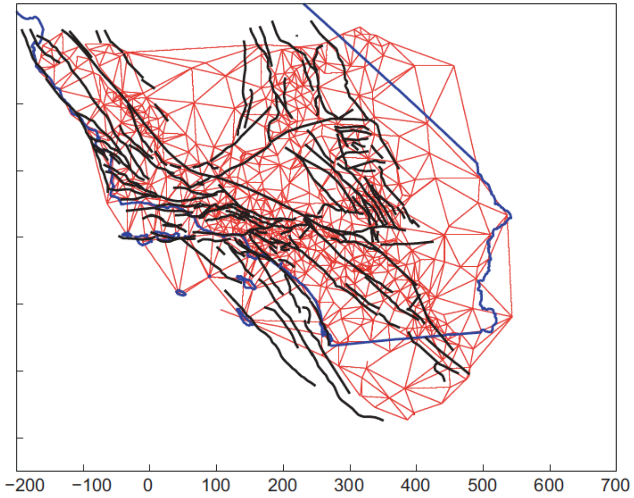
- With imposed tectonic forces and given fault geometry, the viscoelastic thin-sheet model predicts fault slip rates consistent with geologic rates

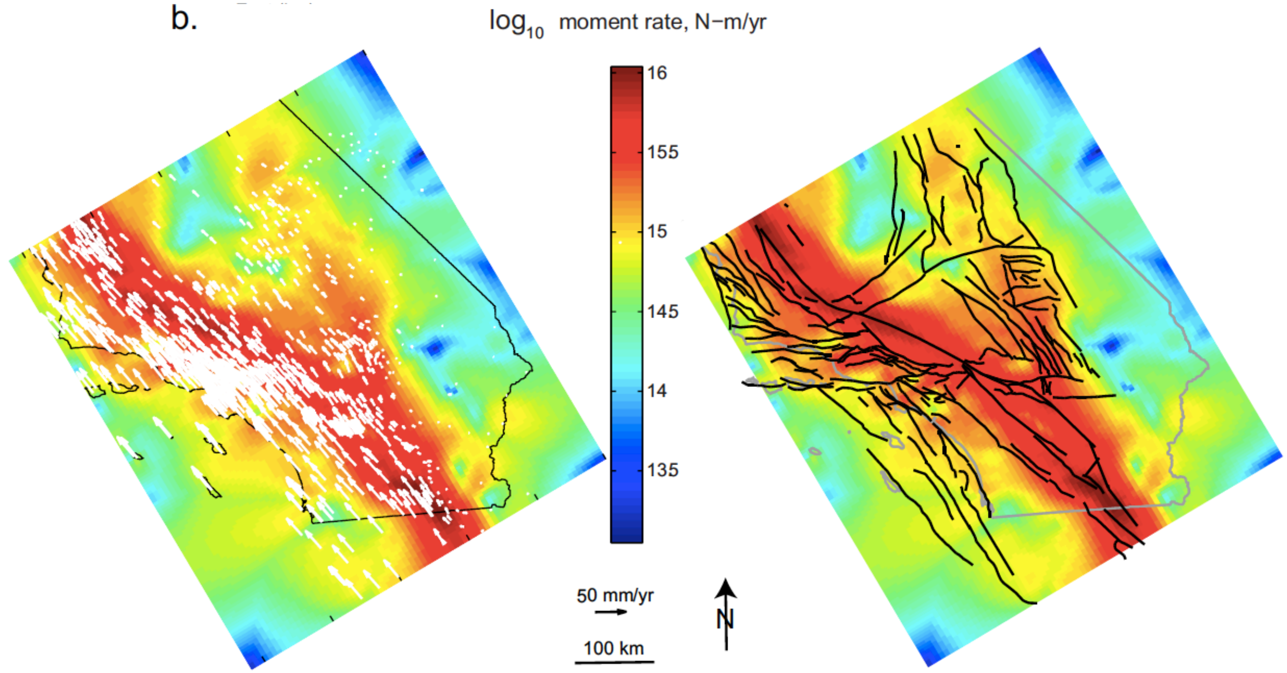
- The current fault movement is well-controlled by the tectonic loads in this region

- The estimated far-field loading is consistent with tectonic stress in the lithosphere

Regional Deformation Model





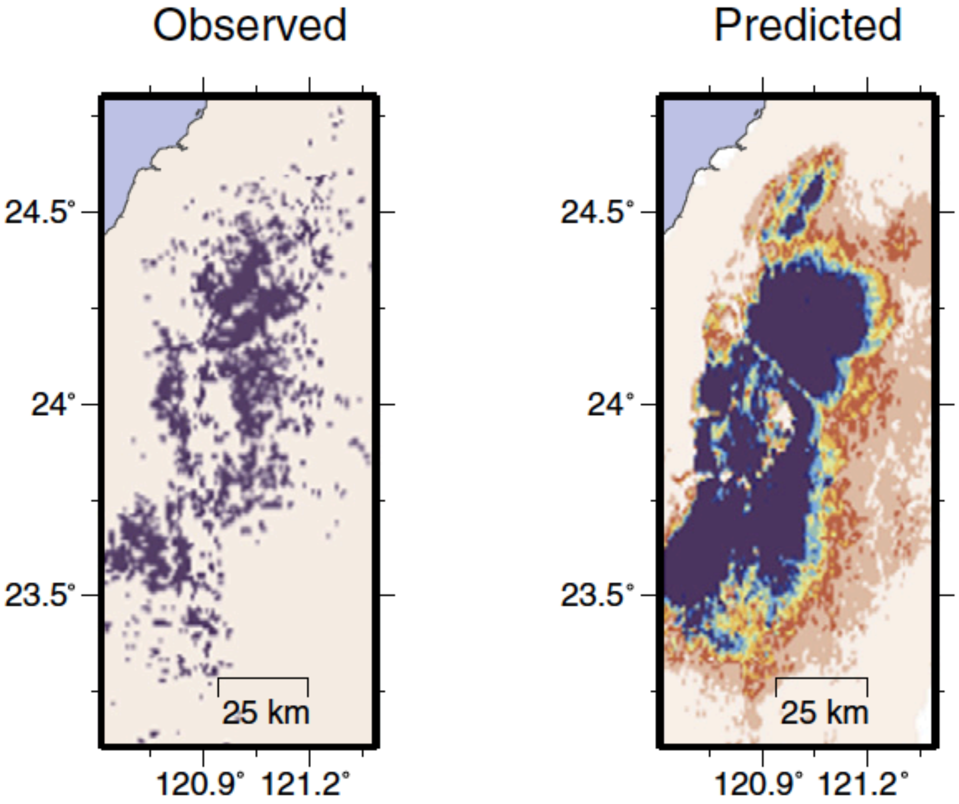


Real-time Earthquake Report

- Focal mechanism: CWB, RMT, gCAP, BATS, Auto BATS, FMNEAR
- Wave propagation: ROS
- Seismic scale: Palert

- Fast/real-time fault solution: coseismic slip and postseismic afterslip
- Real-time assessment for earthquake response: displacement, rupture, landslide, liquefaction, and crowd-sourcing

Real-time Earthquake Report



Nowicki et al. (2014)

- Predict possible locations of triggered landslide and liquefaction
- GIS based analysis
- Crowd-sourcing via mobile device and social media
- Prompt Assessment of Global Earthquakes for response (PAGER)

- Collaborators:
  - Anna Nowicki, Indiana University
  - David J Wald, U.S. Geological Survey
  - Bing Sheng Wu, Nanyang Technological University

Assessing seismic potential

- Taiwan Earthquake Model (TEM): seismic hazard map from Probabilistic Seismic Hazard Analysis (PSHA)

- Short-term slip rates, creeping, and asperities
- Future earthquake scenarios
- Time-dependent PSHA
- Predict earthquake cycle processes