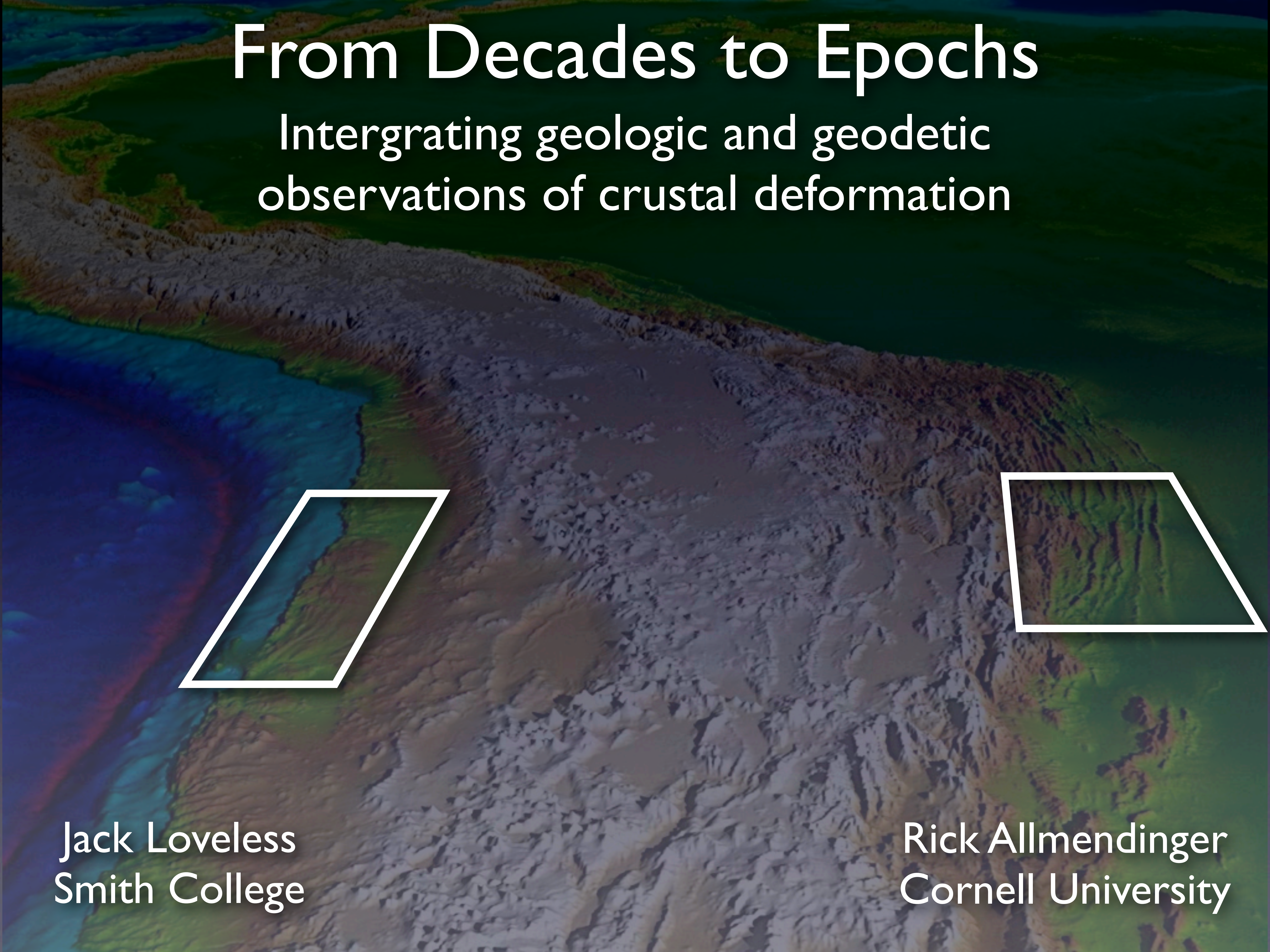
From Decades to Epochs

Intergrating geologic and geodetic observations of crustal deformation



Jack Loveless
Smith College

Rick Allmendinger
Cornell University

Comparing Geodetic & Geologic Rates

- Strain analysis
  - Nothing more than the gradients in the displacement/velocity fields
  - Good for regional analysis, not so good for individual faults
- Elastic block modeling
  - Based on active fault maps
  - Provides a prediction of fault slip rates
  - Faults can only terminate against other faults

Calculating Strain from a Displacement Field

displacement

position

$$u_i = t_i + \frac{\partial u_i}{\partial X_j} X_j = t_i + e_{ij} X_j$$

displacement gradient tensor

In 1D, e_{ij} is just the extension:

$$e = \frac{\Delta u}{\Delta X} = \frac{l_{final} - l_{initial}}{l_{initial}}$$

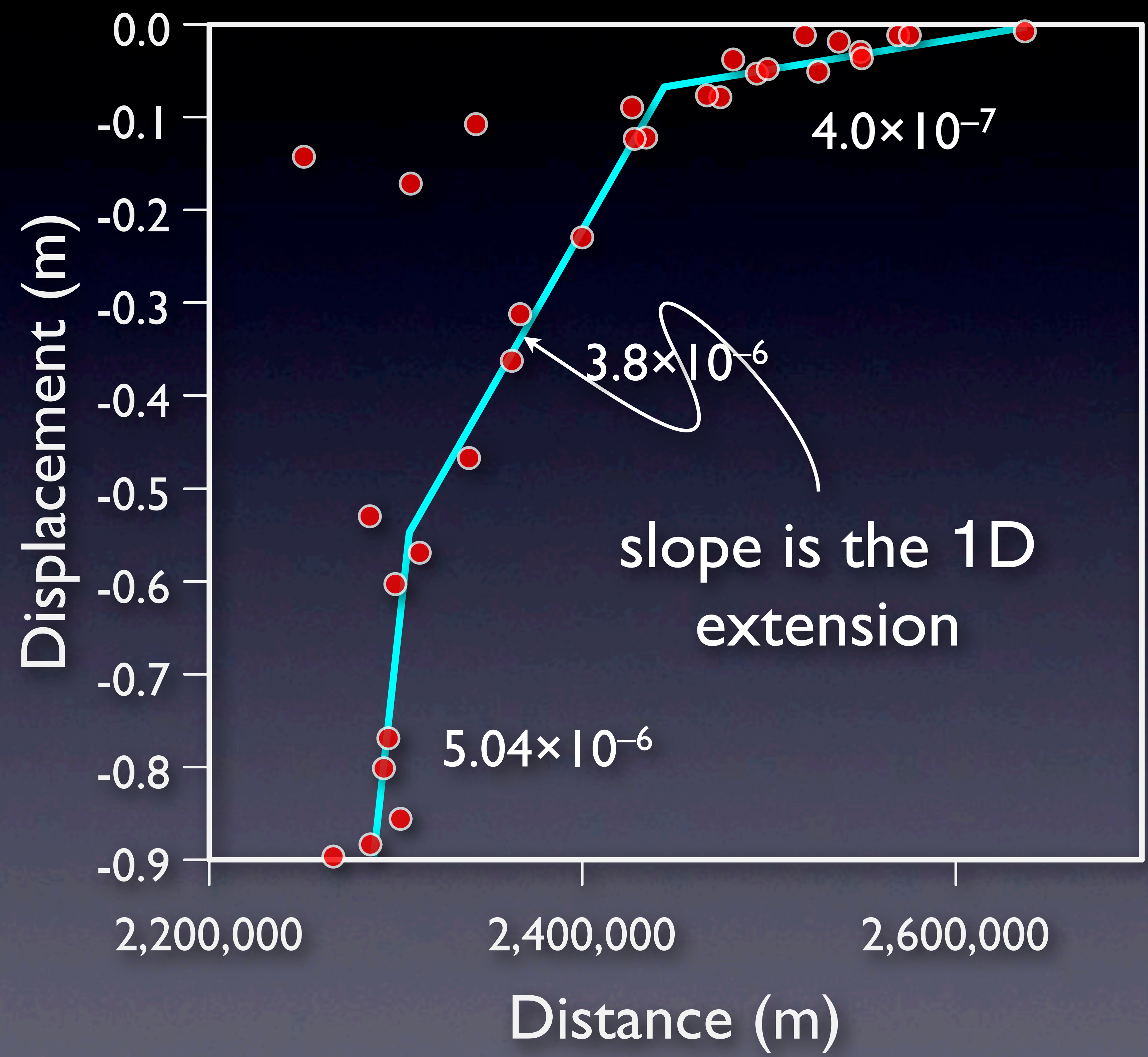
Strain From Displacement Vectors

1D Transect

rotate coordinate system so it parallels the mean vector

vectors from Klotz et al (1999)

Strain From Displacement Vectors



Strain From Displacement Vectors

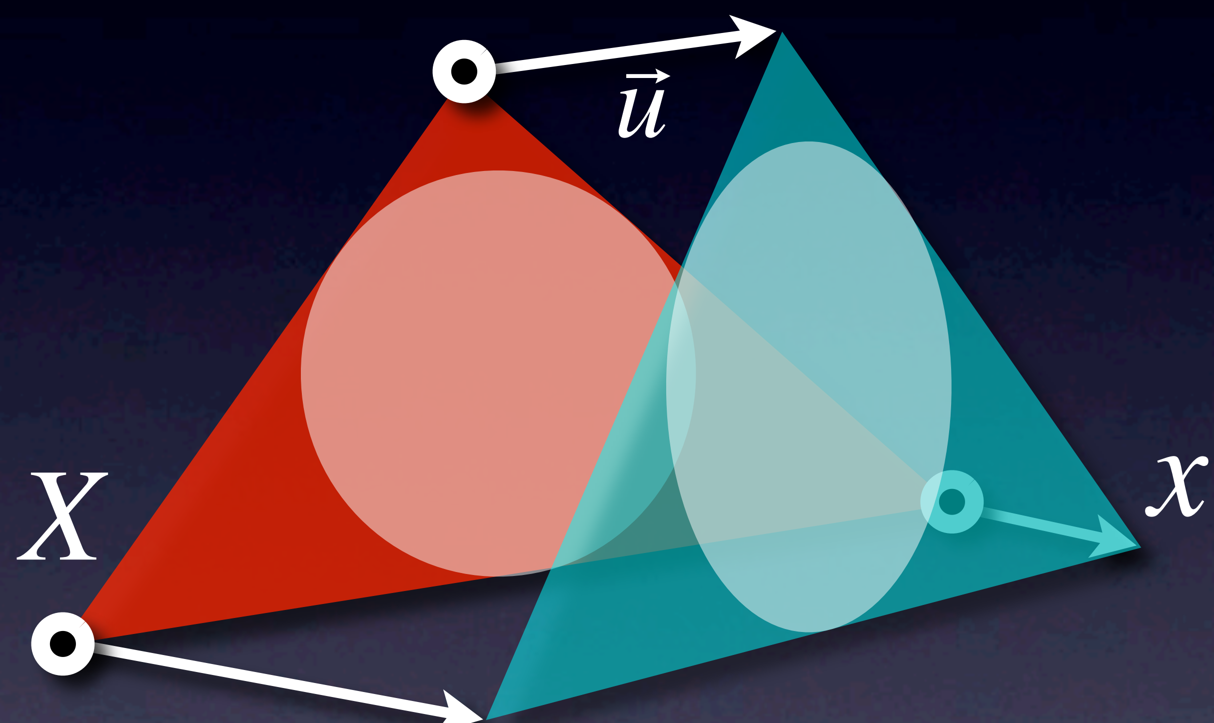
these secondary gradients often explain why major structures are not ⊥ to displacement vectors

but, there are gradients ⊥ to the transect, too!

The Inverse Problem

knowns

$$u_i = t_i + e_{ij} X_j$$



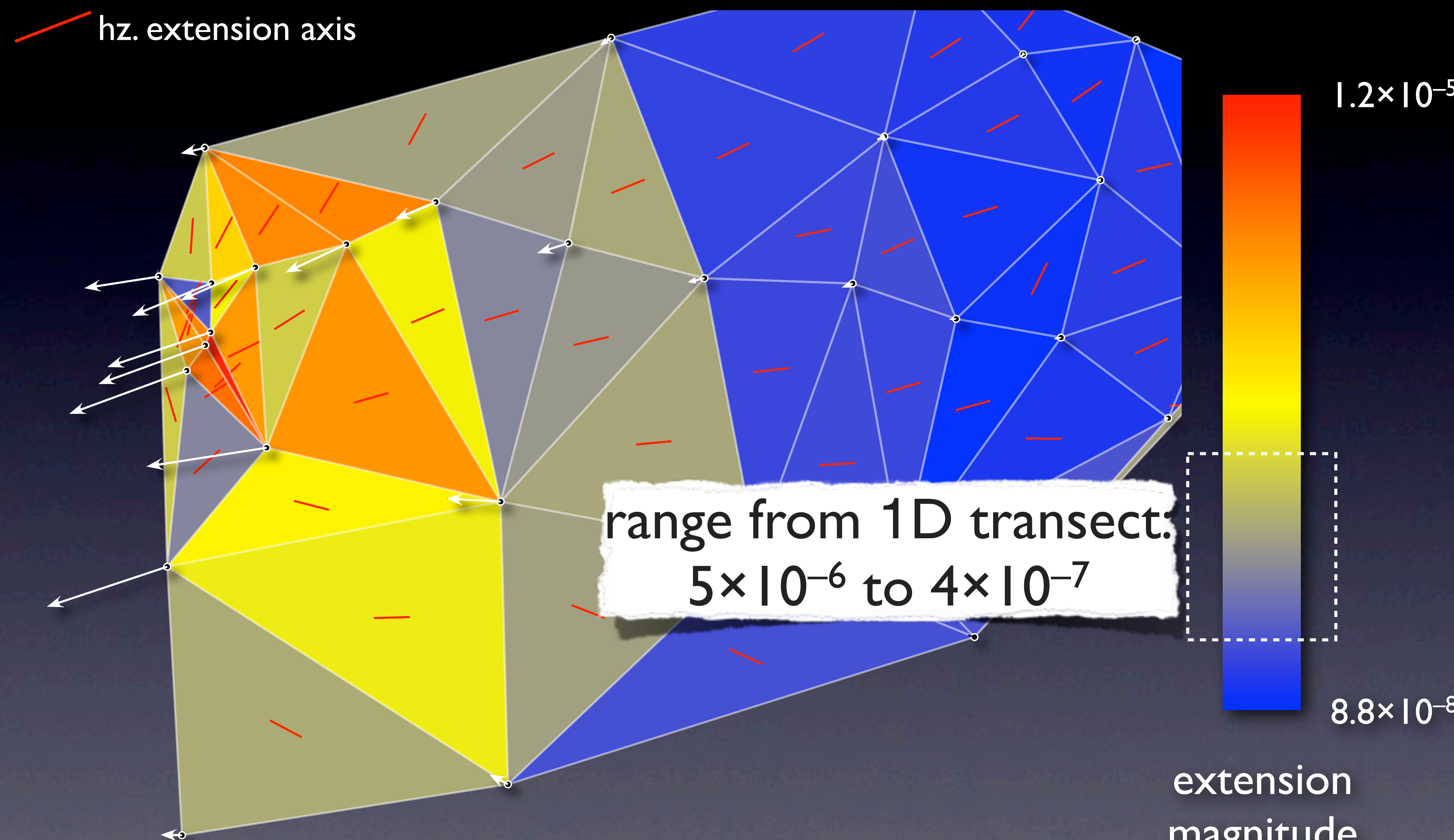
solve for the 6 unknowns

$$\begin{bmatrix} {}^1u_1 \\ {}^1u_2 \\ {}^2u_1 \\ {}^2u_2 \\ \cdots \\ \cdots \\ {}^nu_1 \\ {}^nu_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & {}^1X_1 & {}^1X_2 & 0 & 0 \\ 0 & 1 & 0 & 0 & {}^1X_1 & {}^1X_2 \\ 1 & 0 & {}^2X_1 & {}^2X_2 & 0 & 0 \\ 0 & 1 & 0 & 0 & {}^2X_1 & {}^2X_2 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & 0 & {}^nX_1 & {}^nX_2 & 0 & 0 \\ 0 & 1 & 0 & 0 & {}^nX_1 & {}^nX_2 \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ e_{11} \\ e_{12} \\ e_{21} \\ e_{22} \end{bmatrix}$$

each station & vector gives two equations

$n \geq 3$ (in 2D)

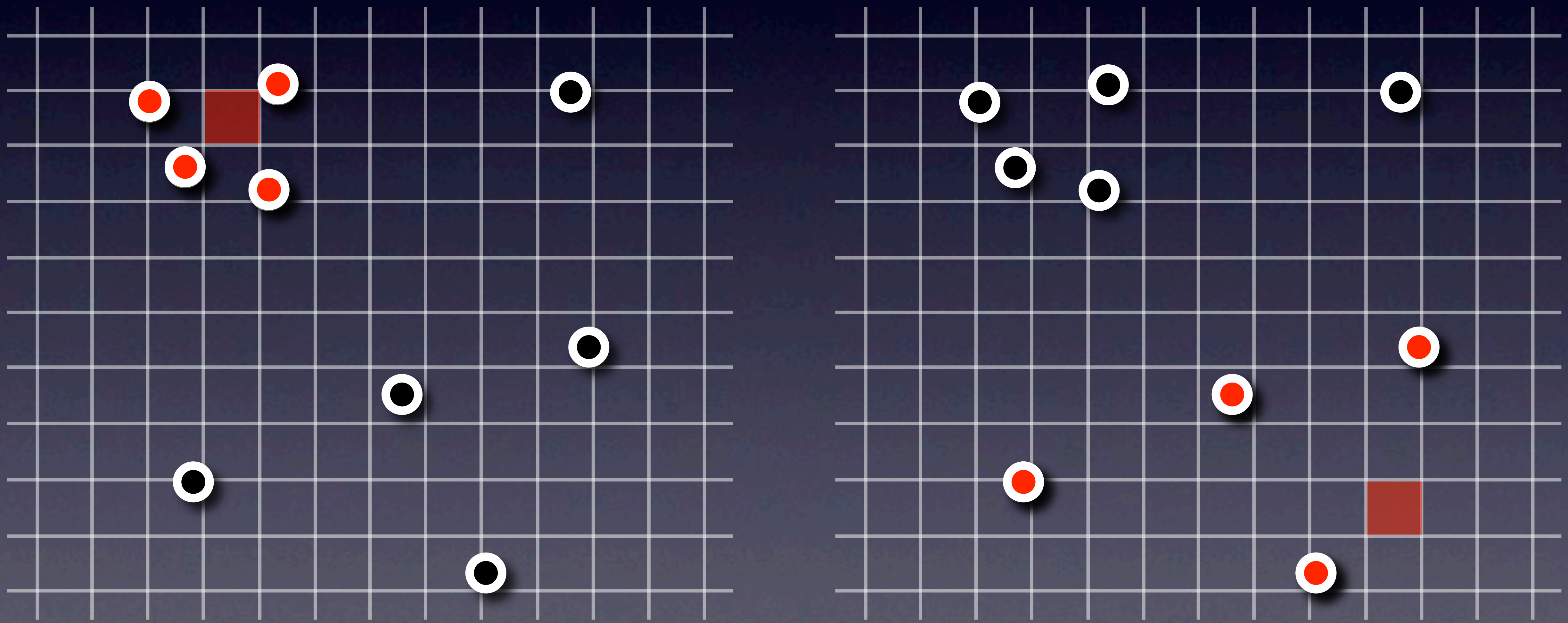
Strain From Displacement Vectors



2D — Delaunay Triangulation

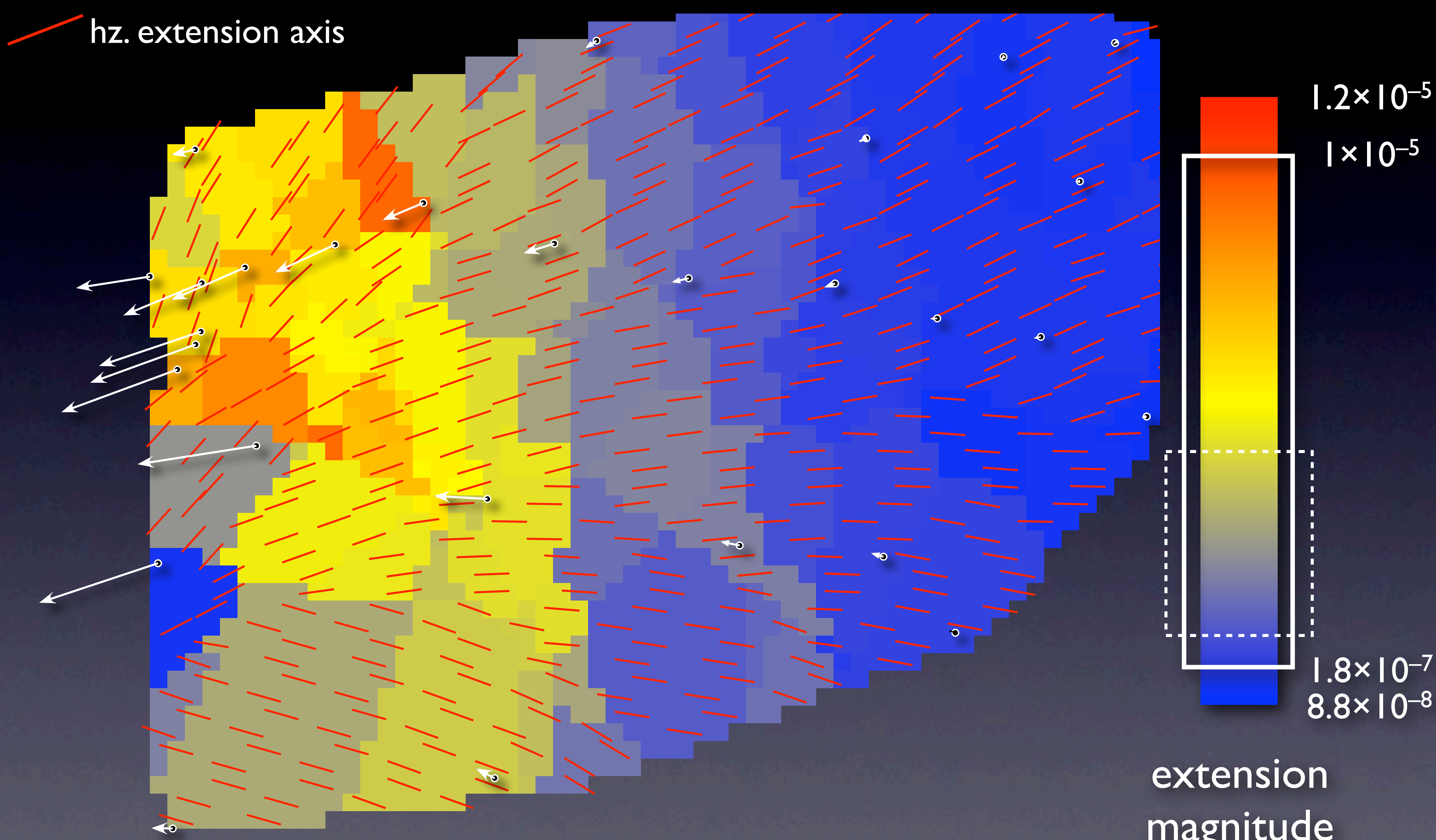
Calculate a regularly-spaced velocity gradient field from irregularly spaced data

Strategy 1: Nearest Neighbors (e.g., n = 4)



each grid node has different spatial significance!

Strain From Displacement Vectors

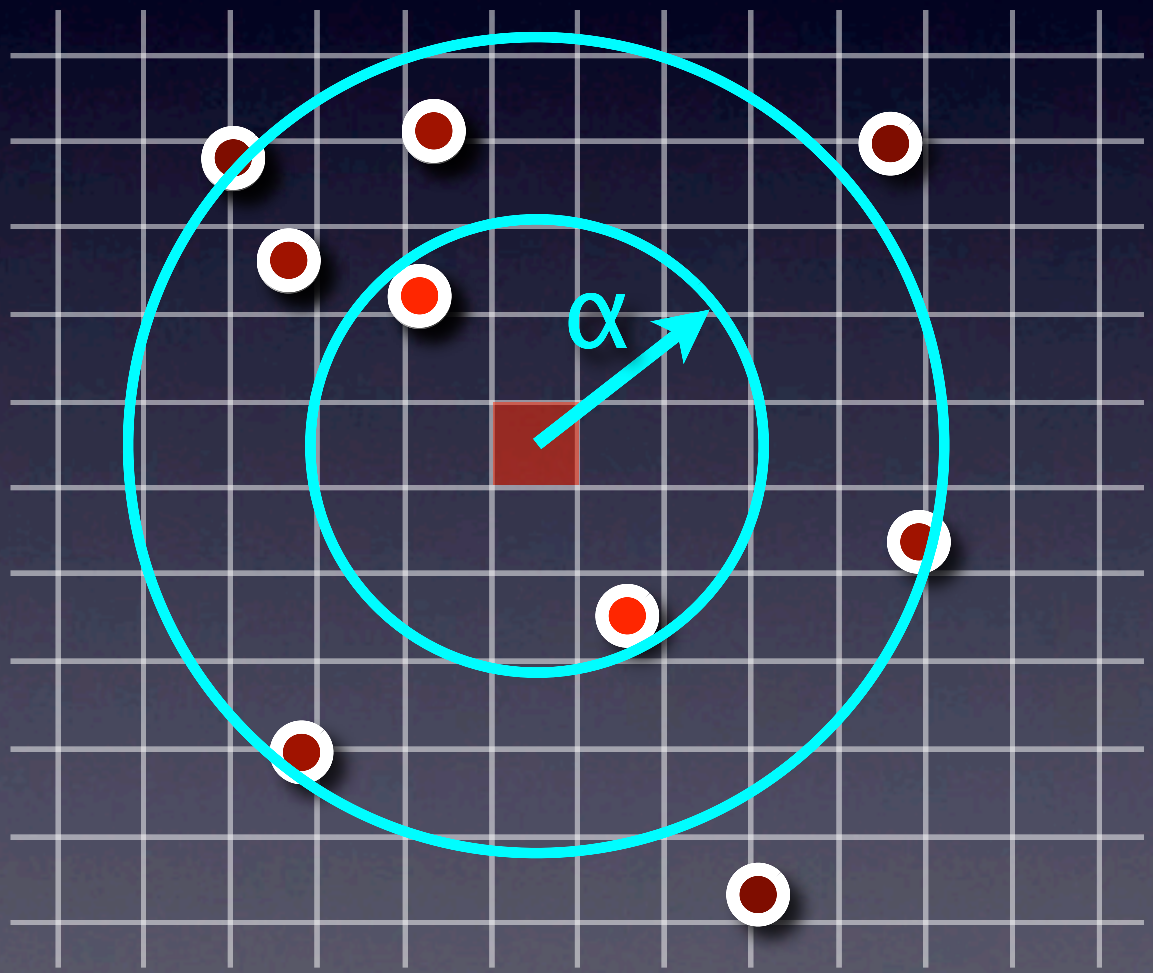


2D — Nearest Neighbor Least Squares

n = 6

Calculate a regularly-spaced velocity gradient field from irregularly spaced data

Strategy 2: Distance Weighted (Shen et al., 1996)



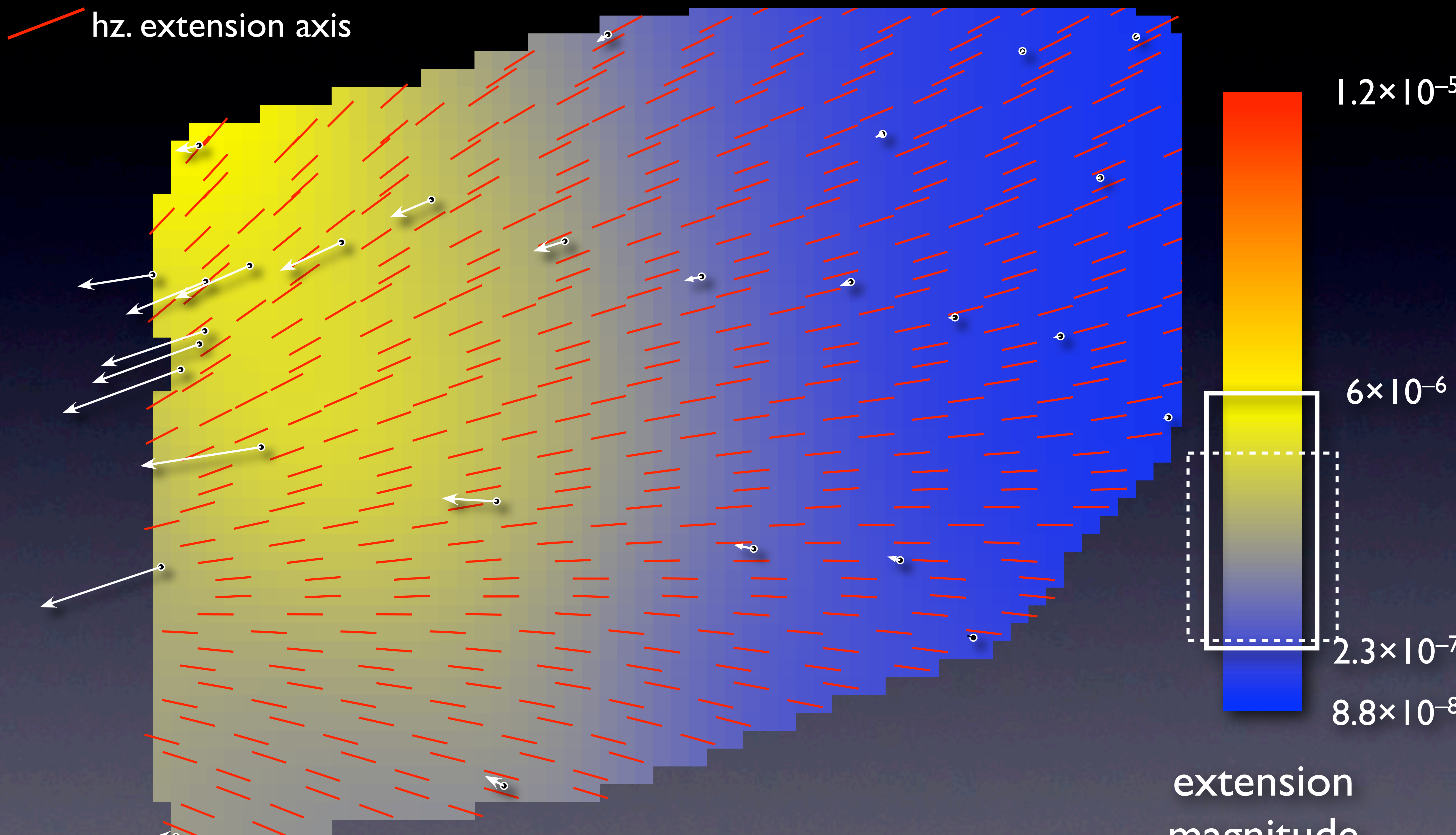
spatial variation is smoothed out

- all stations used in calculation for each grid node
- contribution of each station weighted by distance from node
- use a weighted least squares solution (Menke, 1984):

$$\mathbf{m} = \left[\mathbf{G}^{\mathbf{T}}\mathbf{W}\mathbf{G}\right]^{-1}\mathbf{G}^{\mathbf{T}}\mathbf{W}\mathbf{d}$$

$$\mathbf{W} = \exp\left(\frac{-dist^2}{2\alpha^2}\right)$$

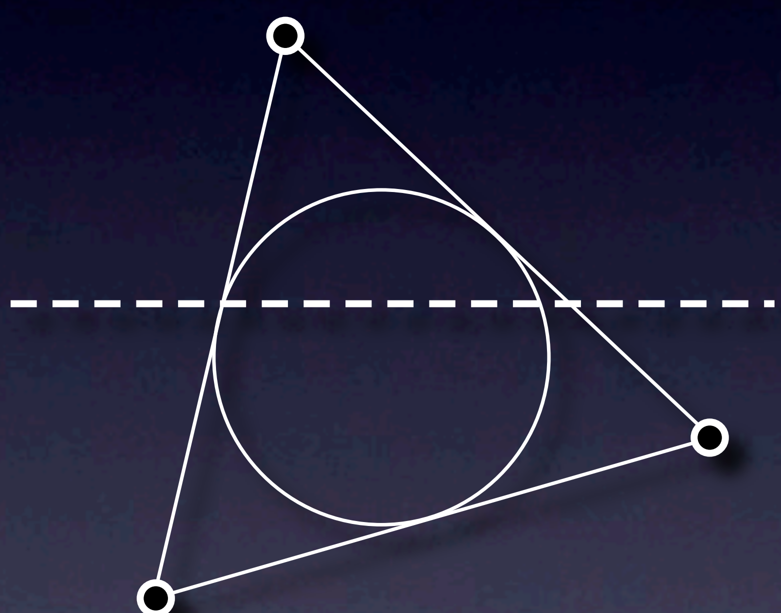
Strain From Displacement Vectors



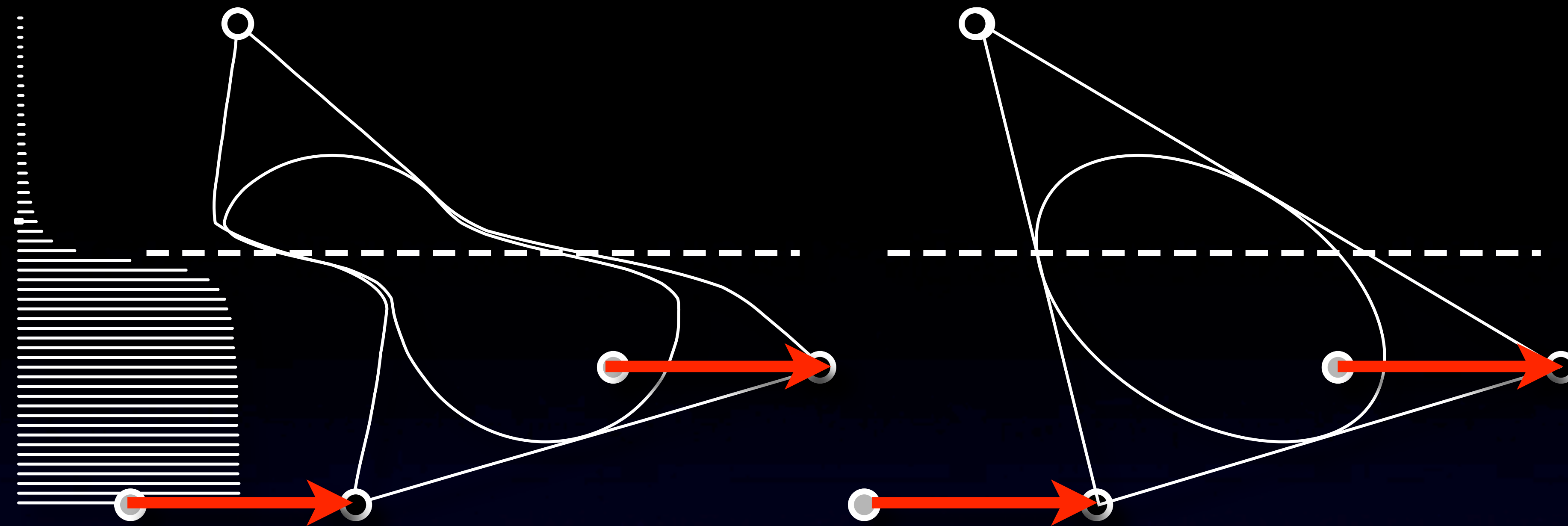
2D — Distance Weighted

$$\mathbf{m}=\left[\mathbf{G^TWG}\right]^{-1}\mathbf{G^TWd} \quad \textit{where} \quad \mathbf{W}=\exp\left(\frac{-dist^2}{2\alpha^2}\right)$$

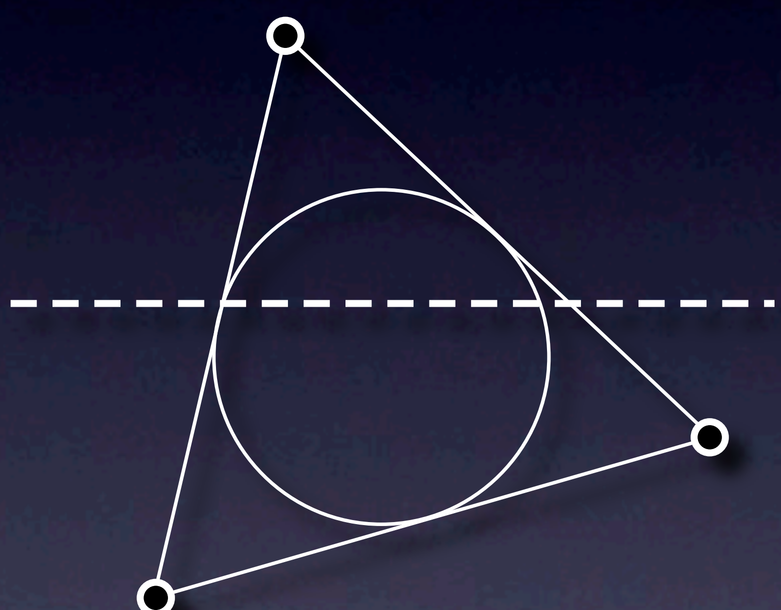
Strain & Faulting



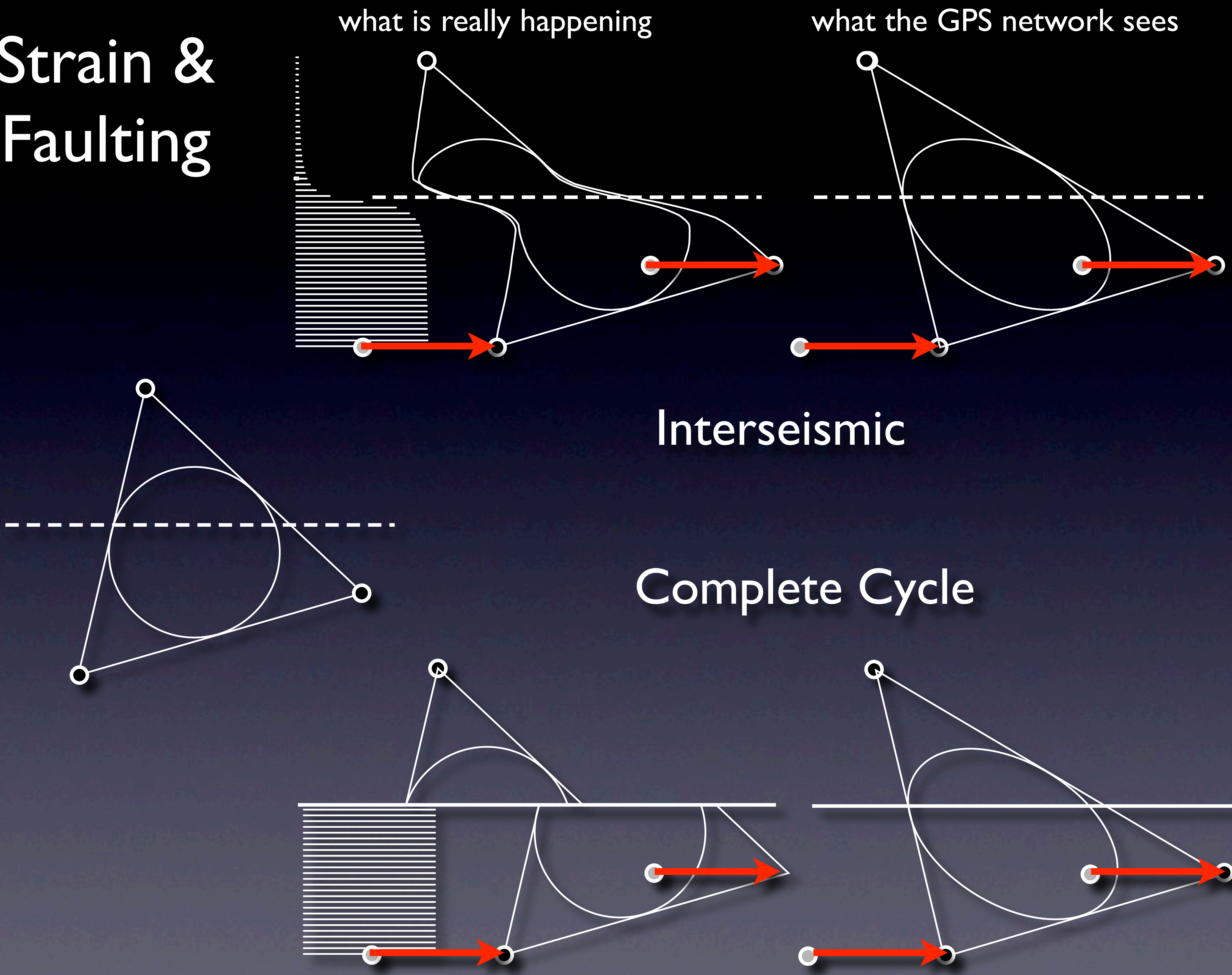
Strain & Faulting



Interseismic



Strain & Faulting



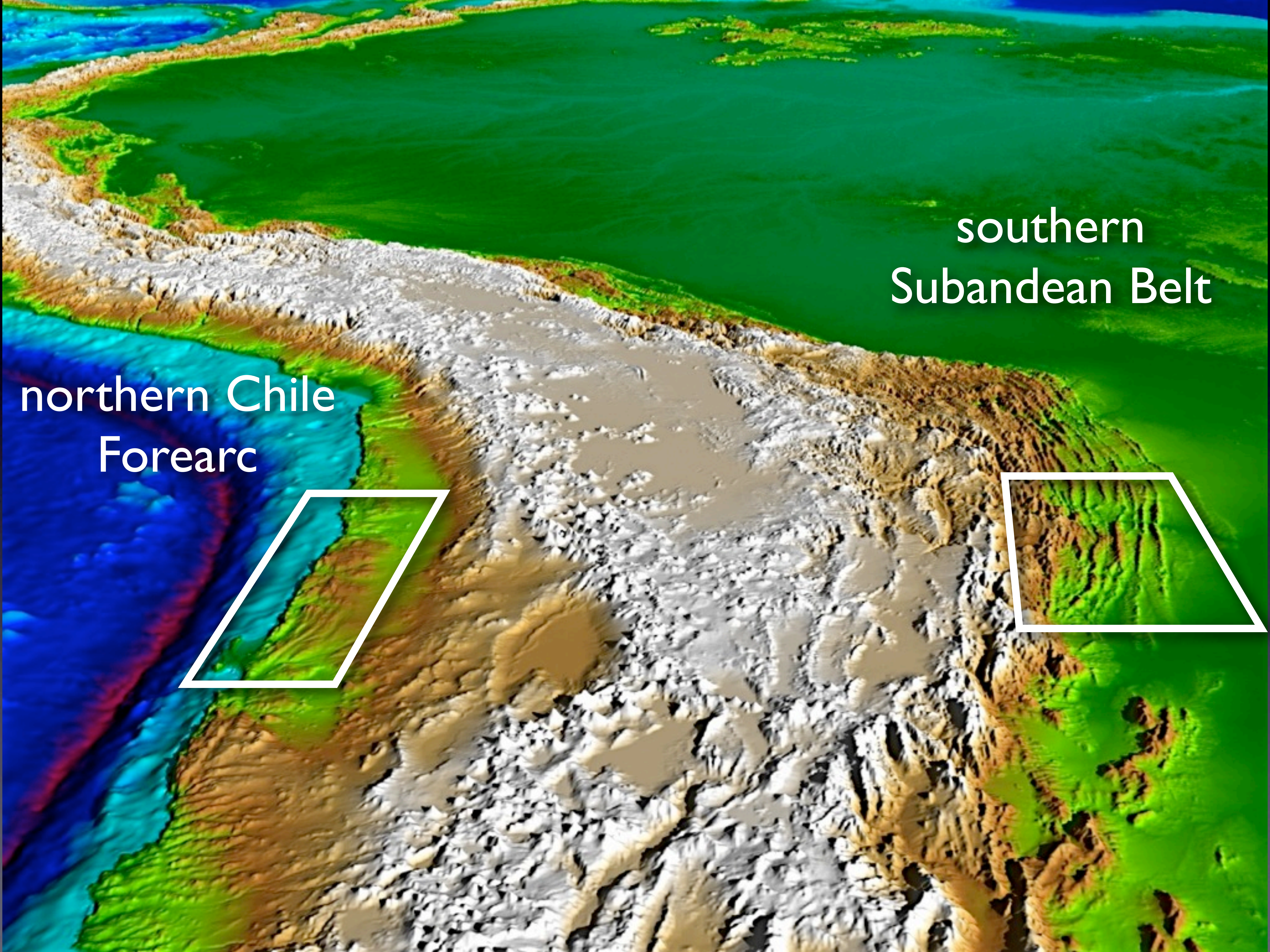
Interseismic

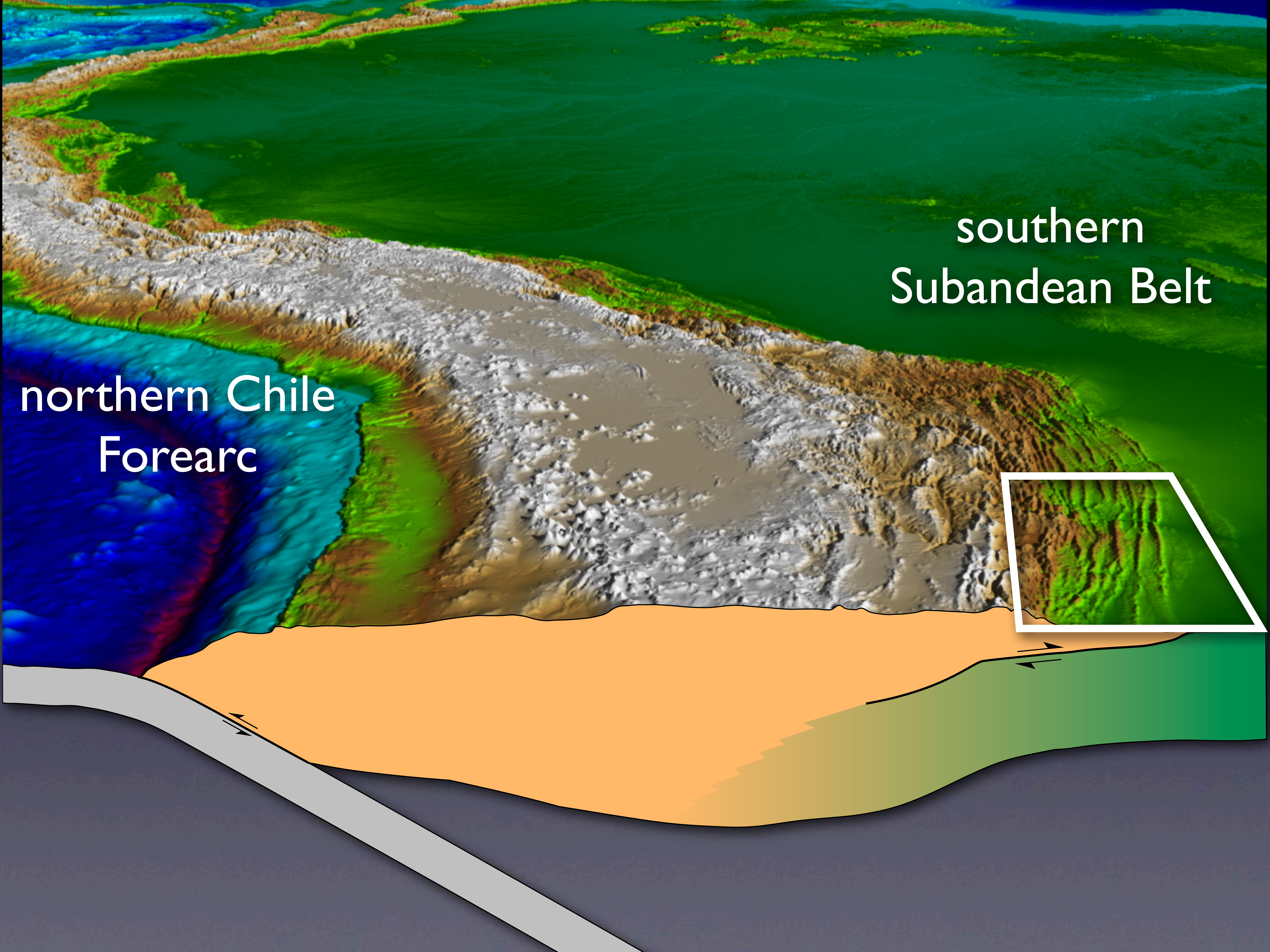
Complete Cycle

Interseismic and Long Term Strain

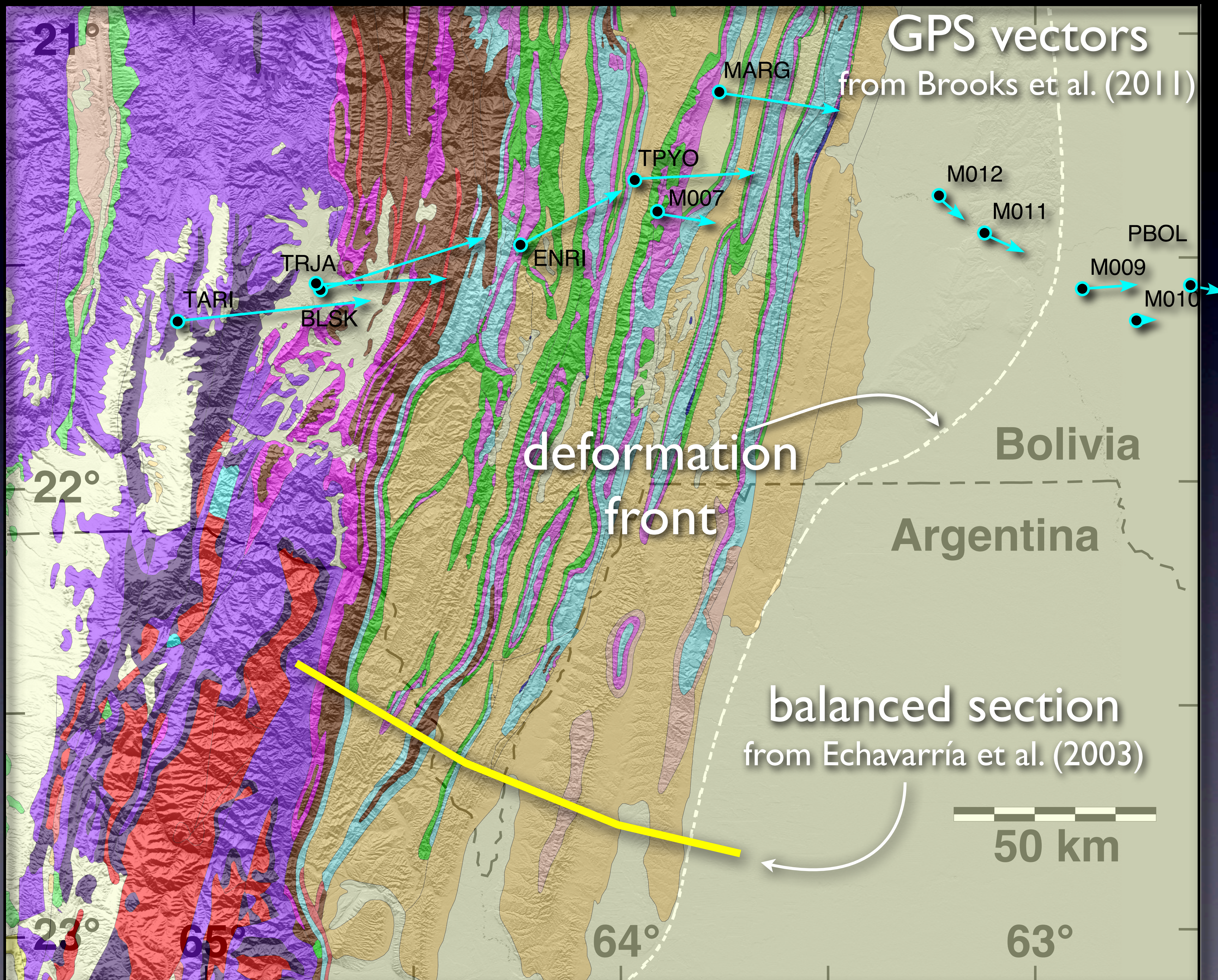
- Geodetic strain during the interseismic part of the seismic cycle should match the long term geologic strain (where networks cross major faults)

- Need very dense networks to differentiate between creeping faults and those that are locked interseismically

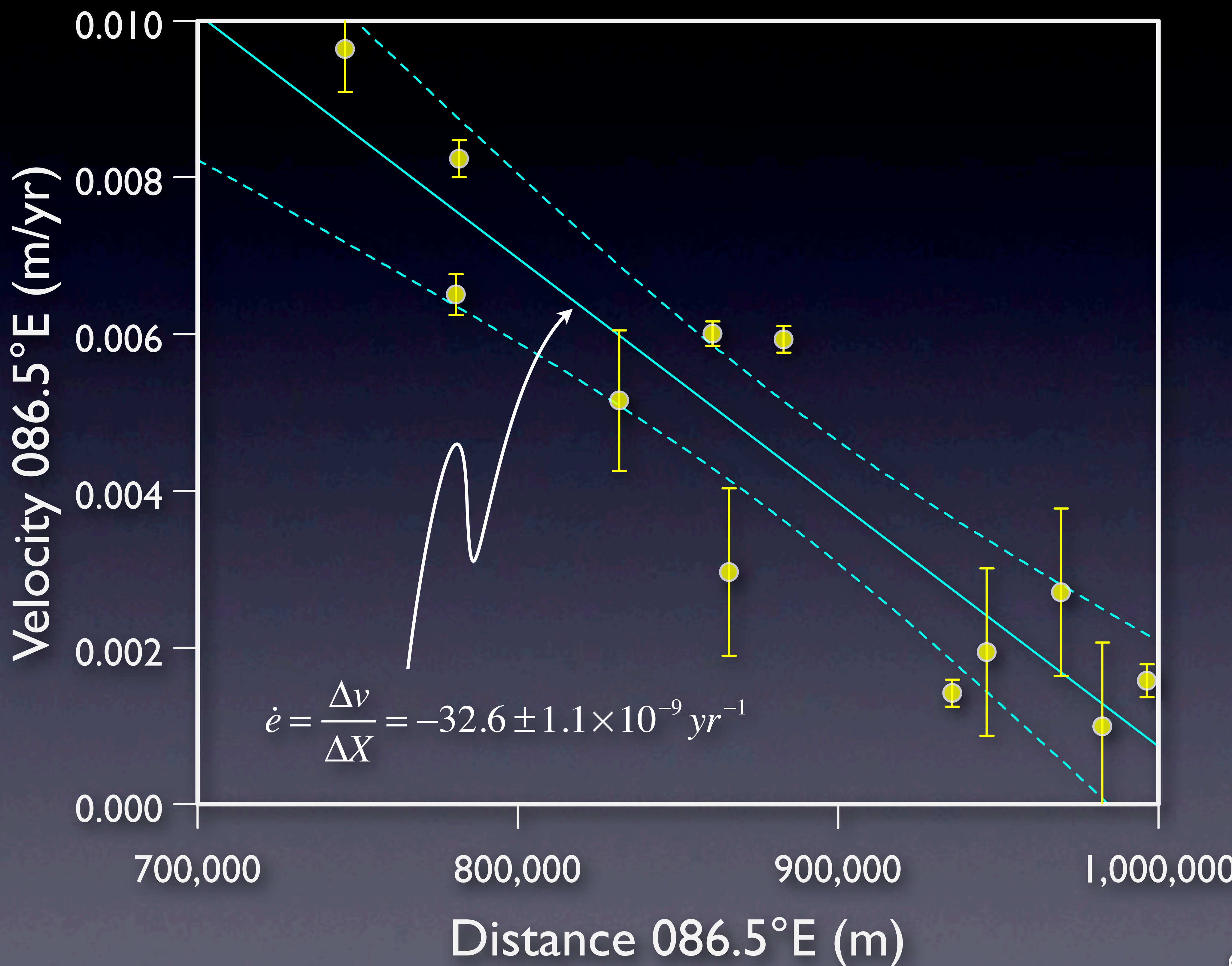

southern
Subandean Belt
northern Chile
Forearc


southern
Subandean Belt
northern Chile
Forearc

Southern Subandean Thrust Belt

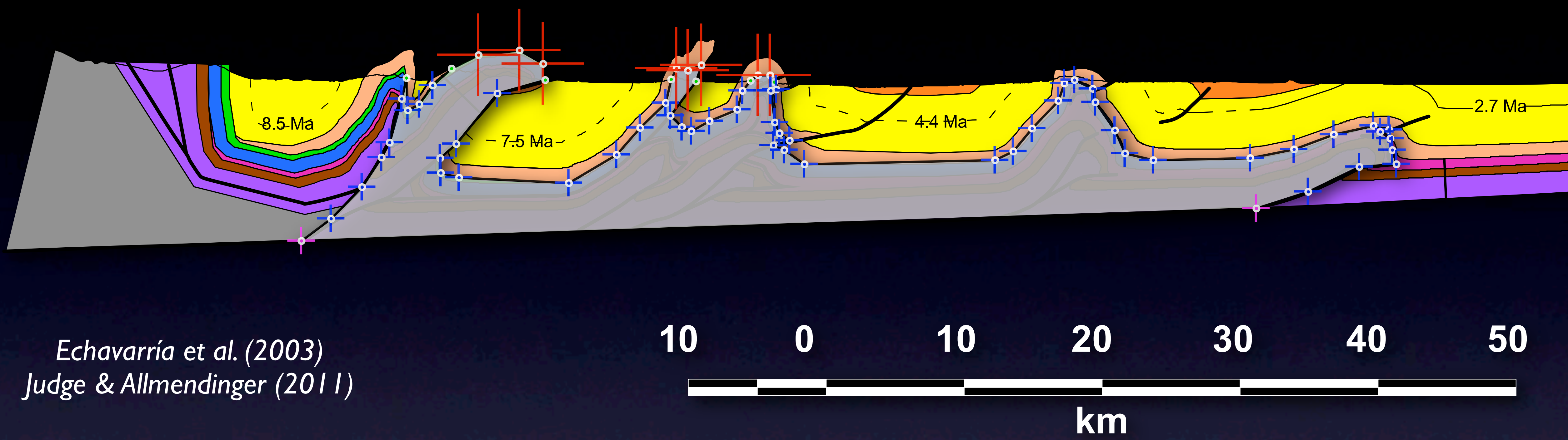


Subandean GPS Interseismic Strain Rate



GPS data from Brooks et al. (2011)

Subandean Balanced Section

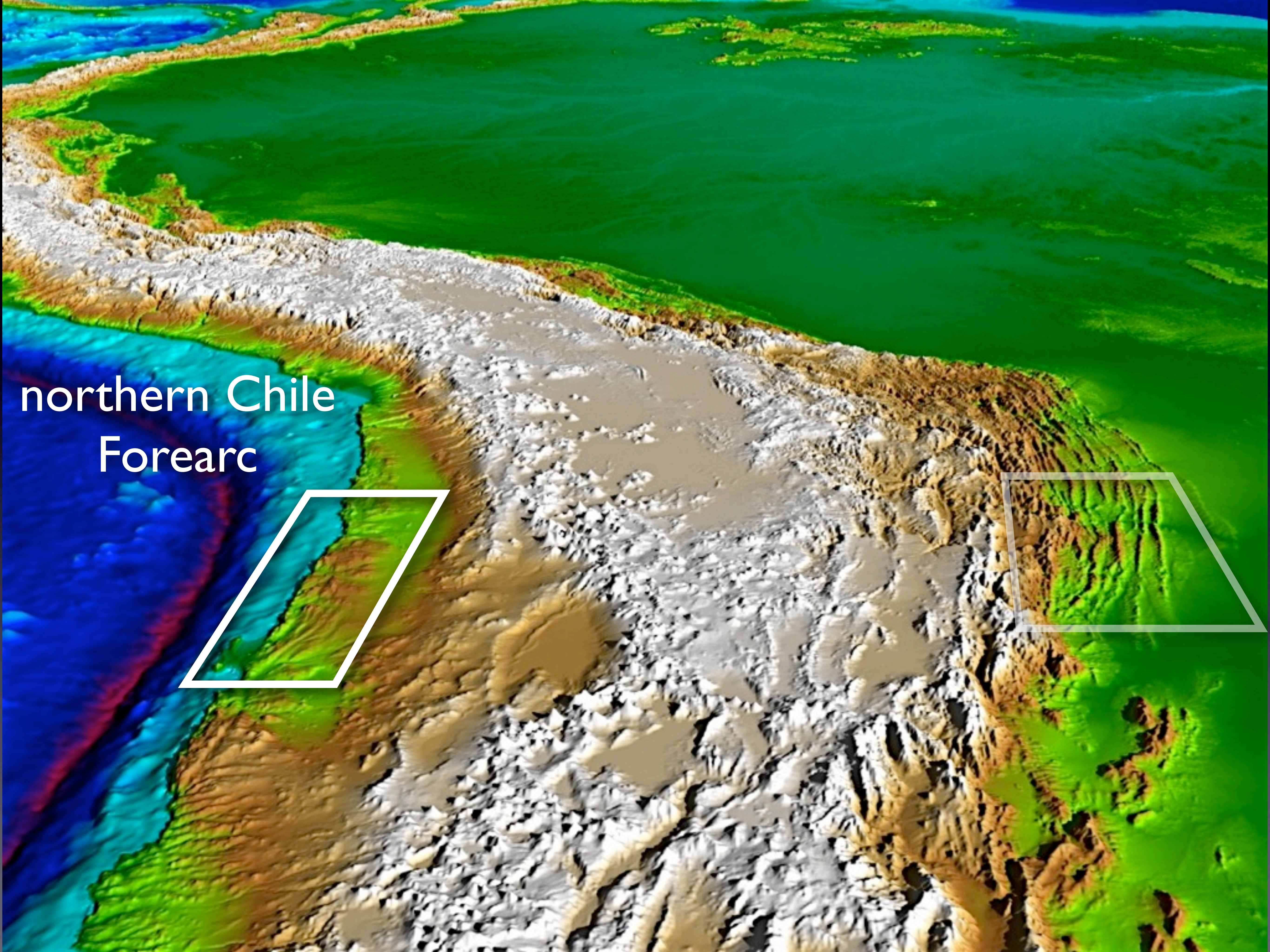


Echavarría et al. (2003)
Judge & Allmendinger (2011)

		Error	
		Gaussian	Maximum
Shortening:	49.58	± 18.71	90.48
Shortening percent:	38.39	± 8.97	43.76

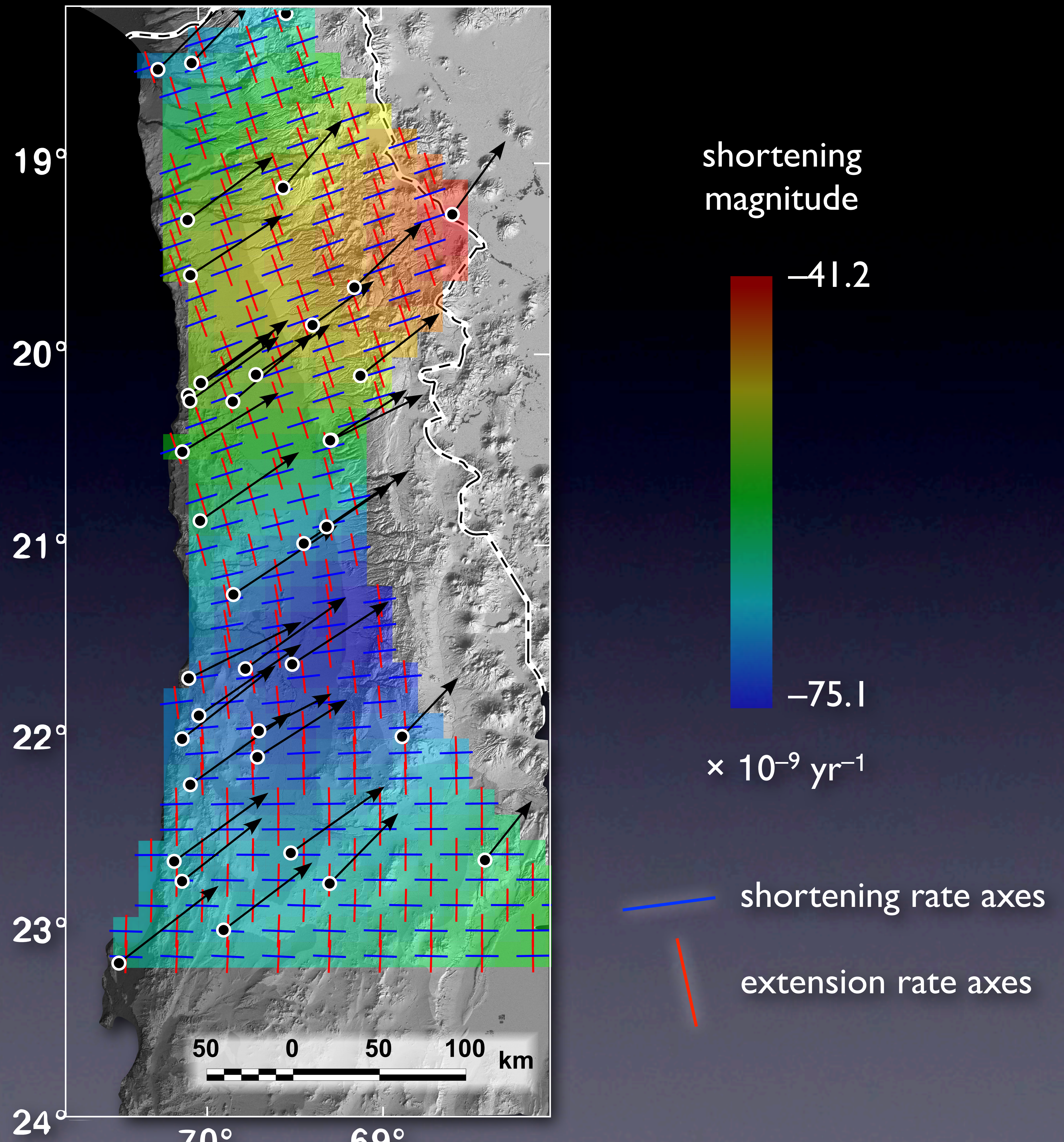
Geology: $-38.4 \pm 9 \times 10^{-9}\ yr^{-1}$ for 10 Ma

GPS: $-32.6 \pm 1.1 \times 10^{-9}\ yr^{-1}$ for 10 yr


northern Chile
Forearc

Interplate Seismicity Since 1900

Northern Chile cGPS

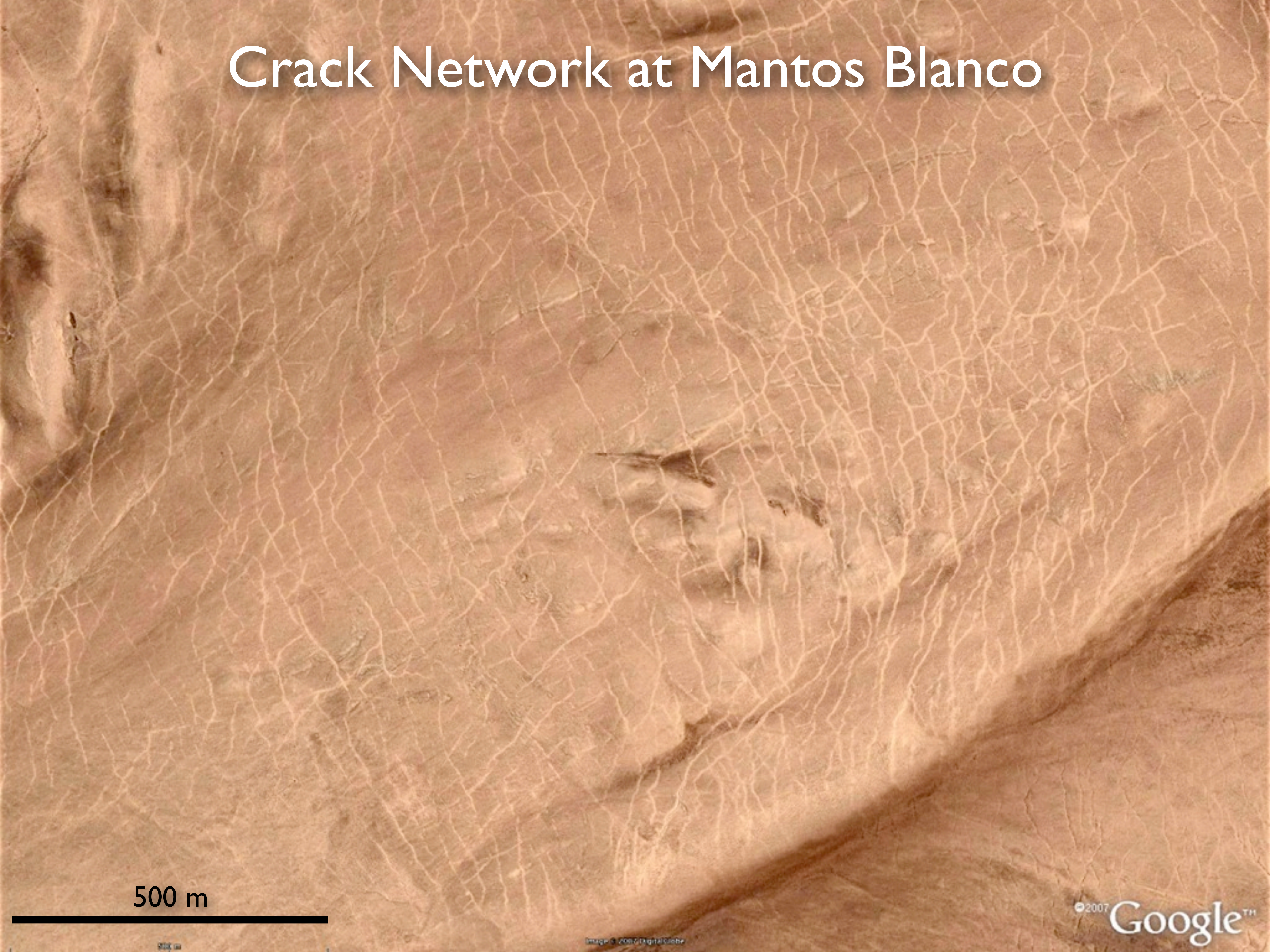


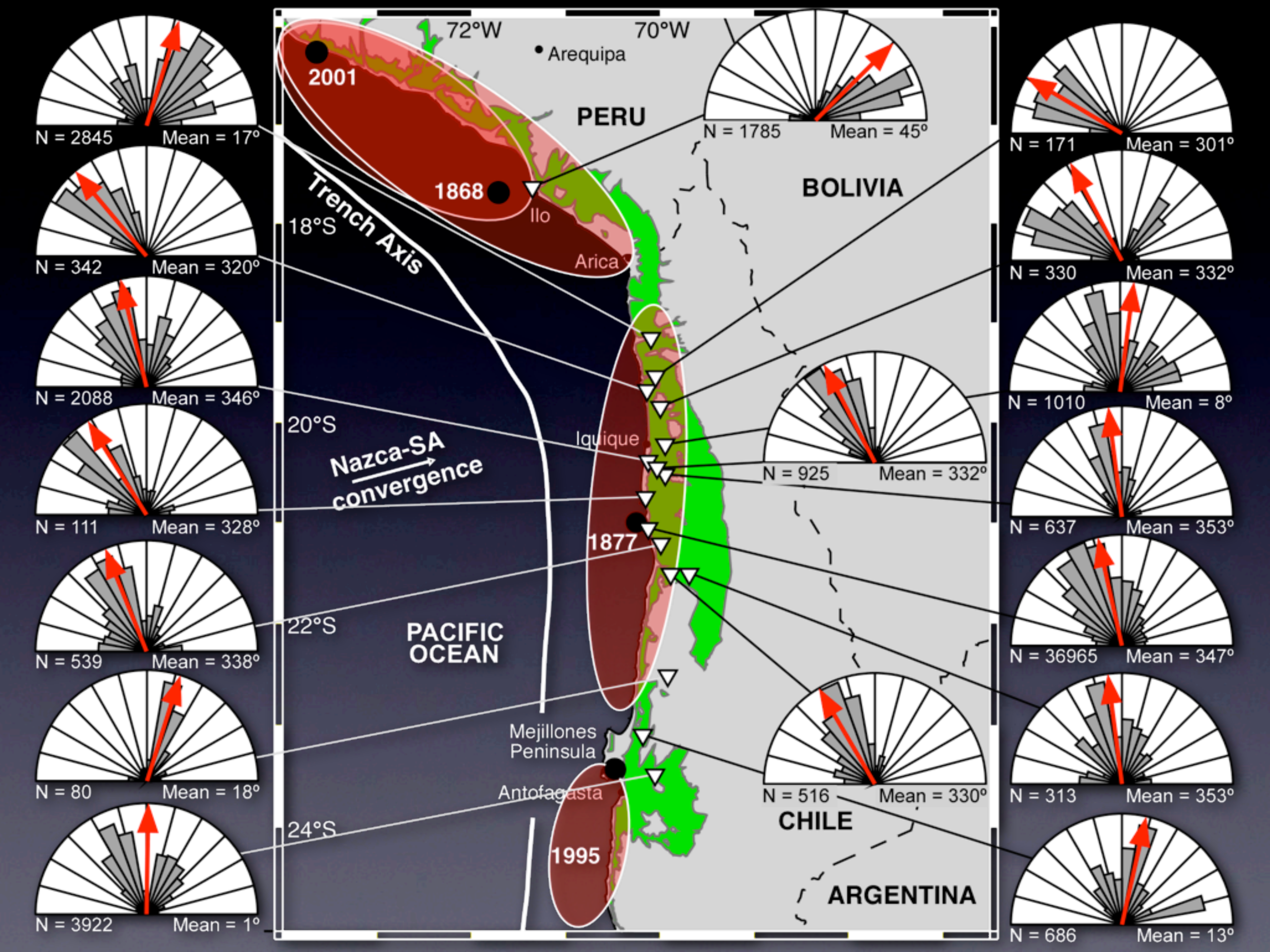
cGPS stations from Caltech, IRD, & IPGP

Coastal Cordillera near Antofagasta

Caleta Herradura—Mejillones Peninsula

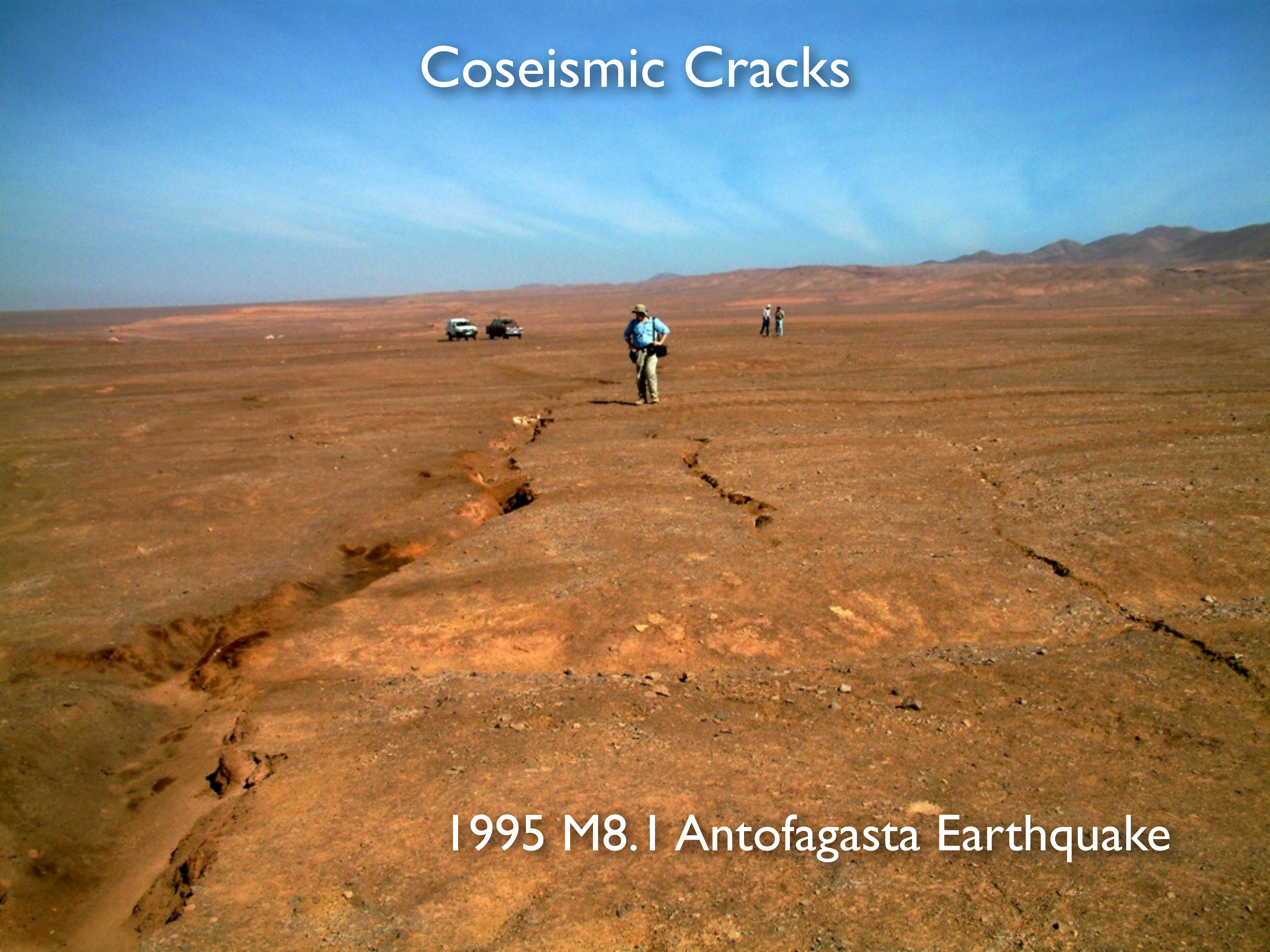
Crack Network at Mantos Blanco




N = 2845 Mean = 17º
N = 342 Mean = 320º
N = 2088 Mean = 346º
N = 111 Mean = 328º
N = 539 Mean = 338º
N = 80 Mean = 18º
N = 3922 Mean = 1º
72°W
70°W
Arequipa
2001
PERU
1868
Ilo
Arica
Trench Axis
18°S
BOLIVIA
20°S
Iquique
Nazca-SA convergence
1877
22°S
PACIFIC OCEAN
Mejillones Peninsula
Antofagasta
24°S
1995
CHILE
ARGENTINA
N = 1785 Mean = 45º
N = 925 Mean = 332º
N = 516 Mean = 330º
N = 171 Mean = 301º
N = 330 Mean = 332º
N = 1010 Mean = 8º
N = 637 Mean = 353º
N = 36965 Mean = 347º
N = 313 Mean = 353º
N = 686 Mean = 13º

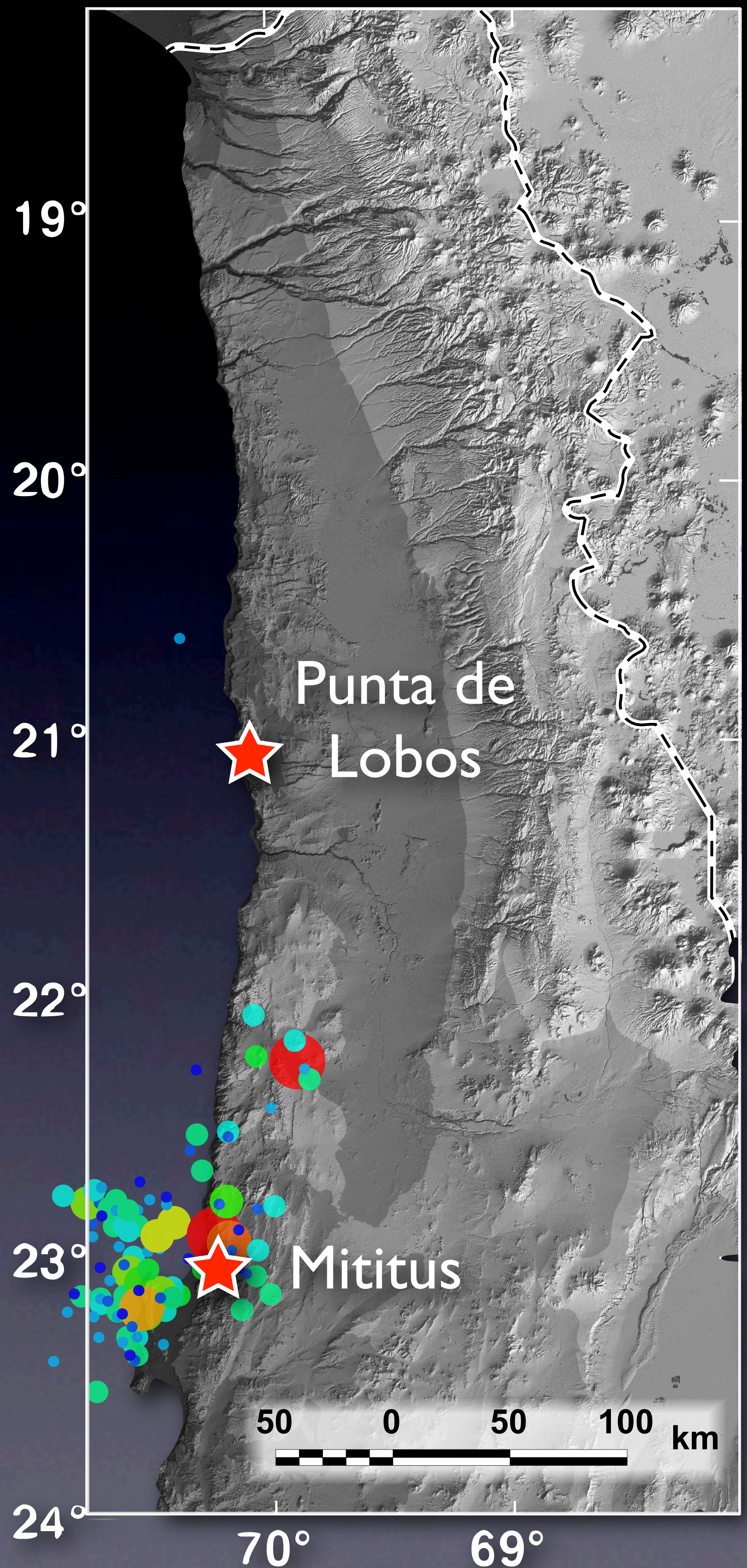
Crack in Bedrock

Coseismic Cracks



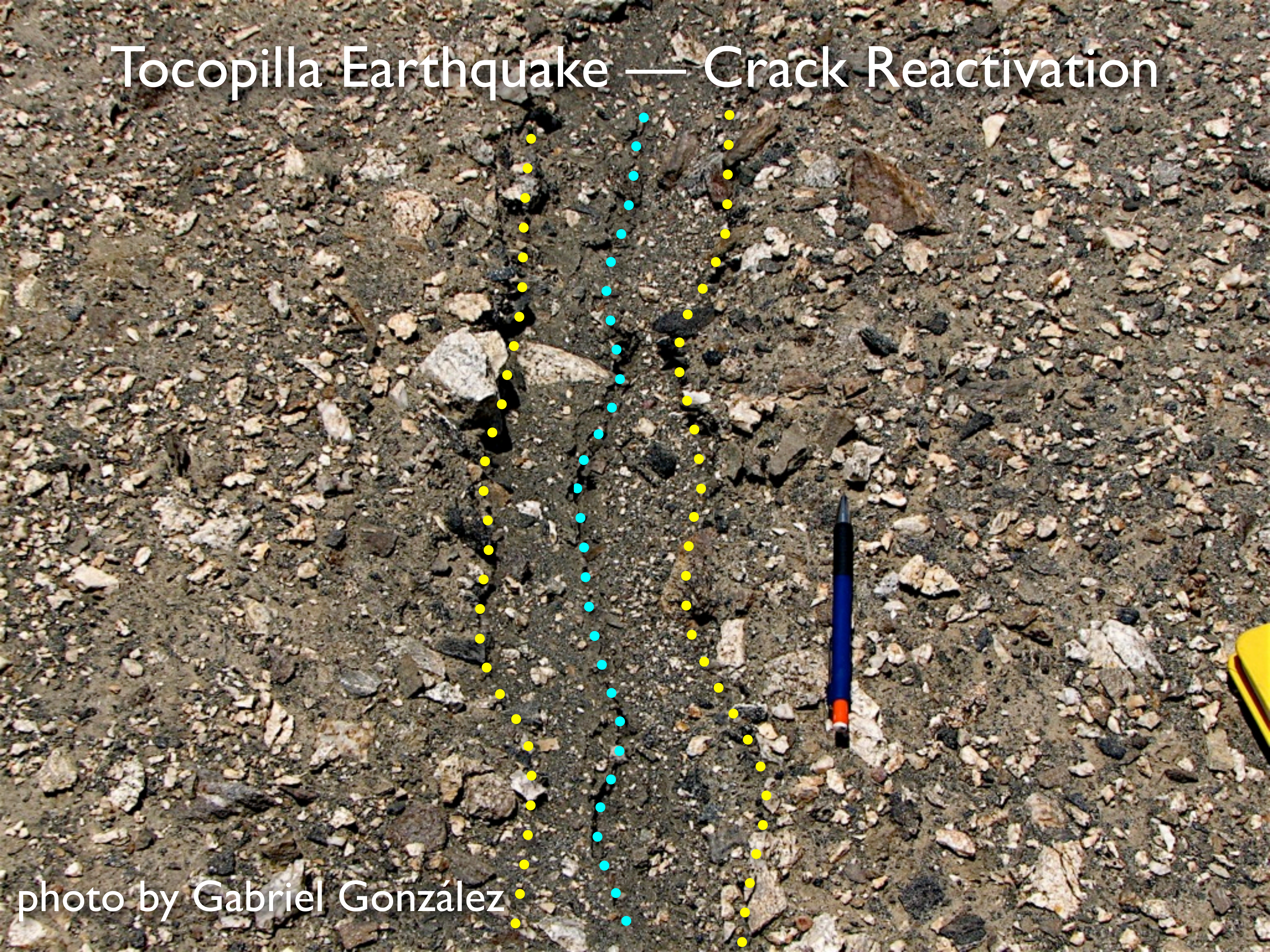
1995 M8.1 Antofagasta Earthquake

Crack Study Areas

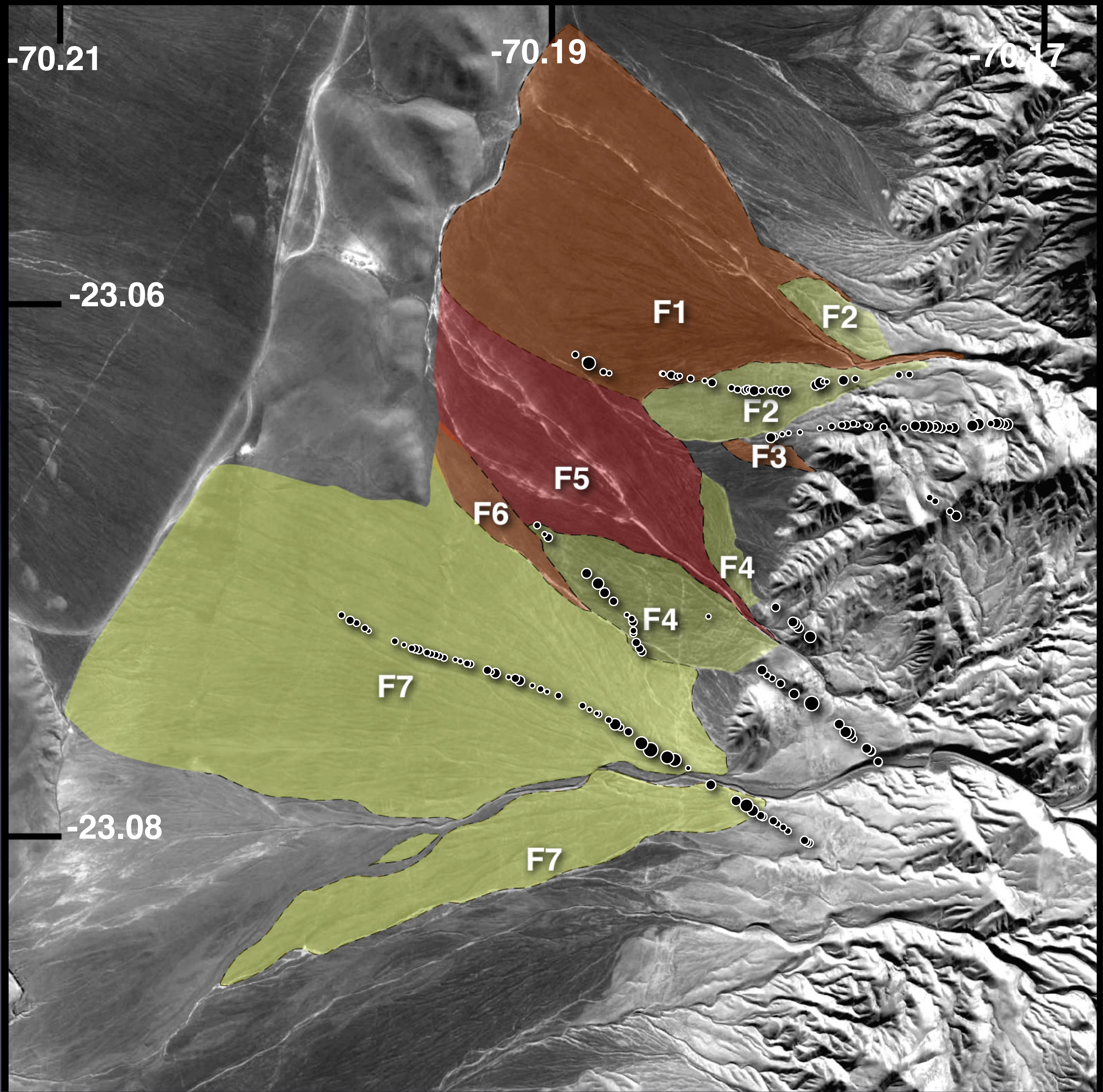


2007 M_w7.7 Tocopilla aftershocks

Coseismic Cracks — M7.7 Tocopilla 2007

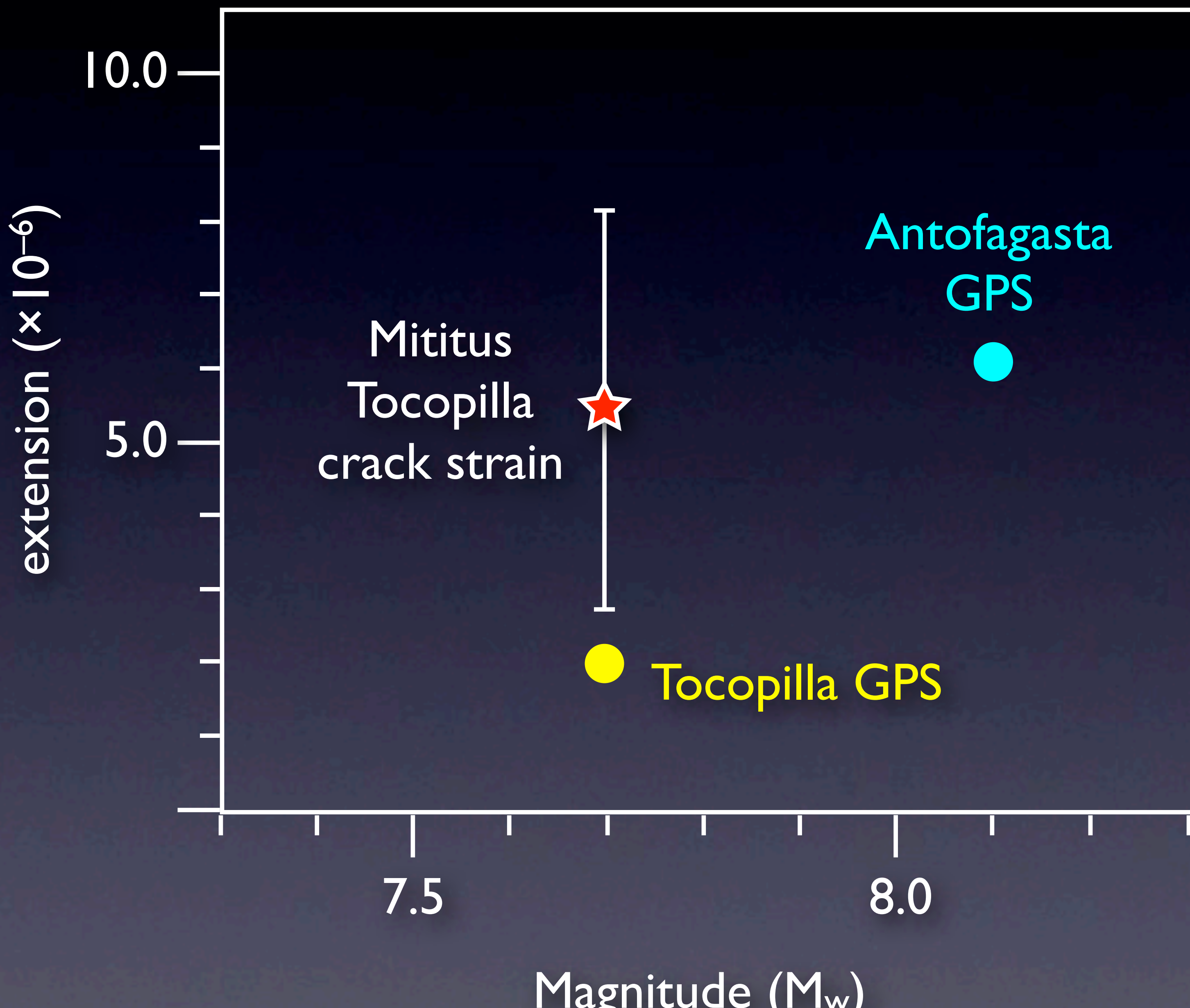

Tocopilla Earthquake — Crack Reactivation
photo by Gabriel González

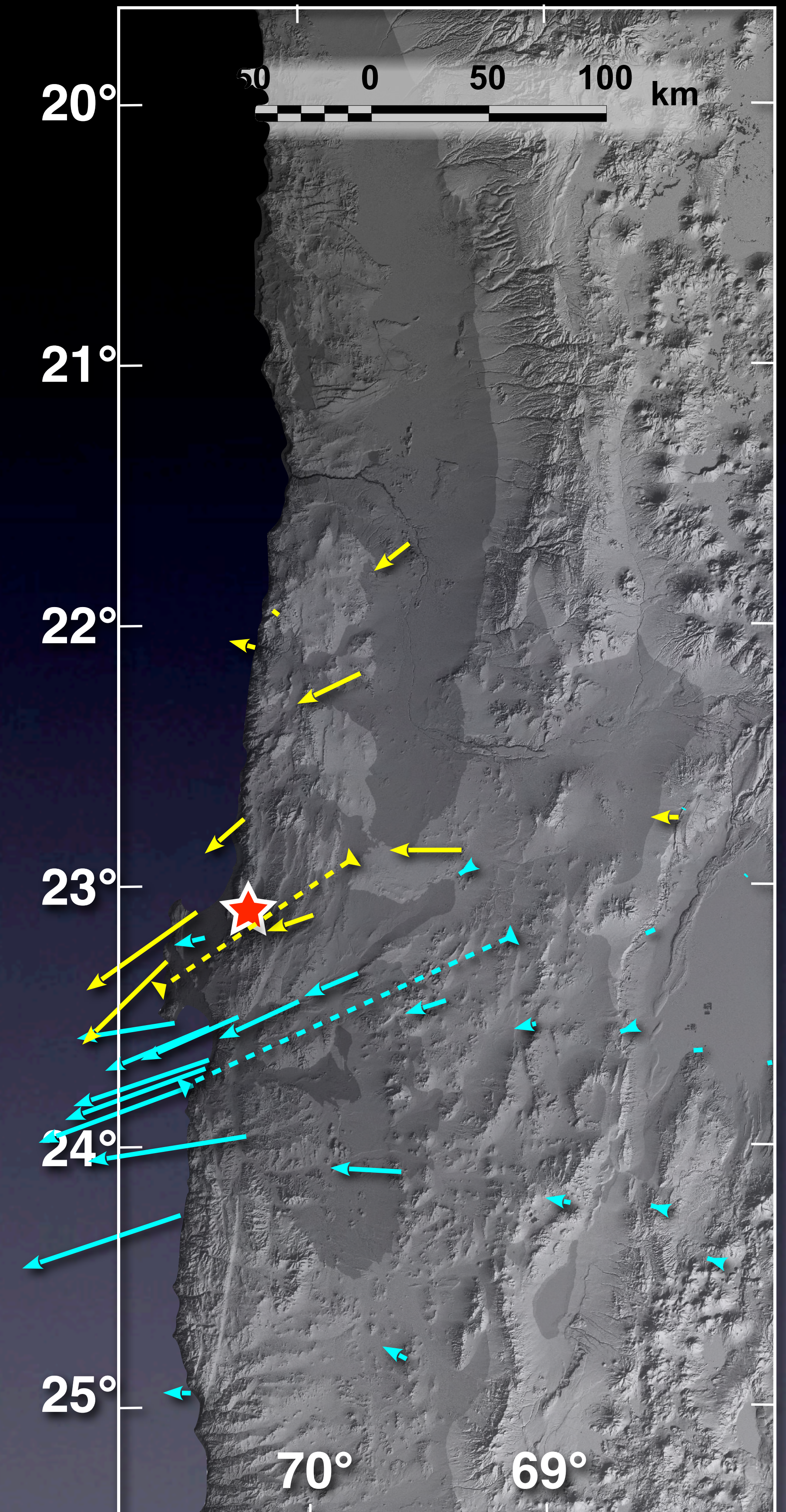
Mititus Area — Northern Part



Baker (2012)

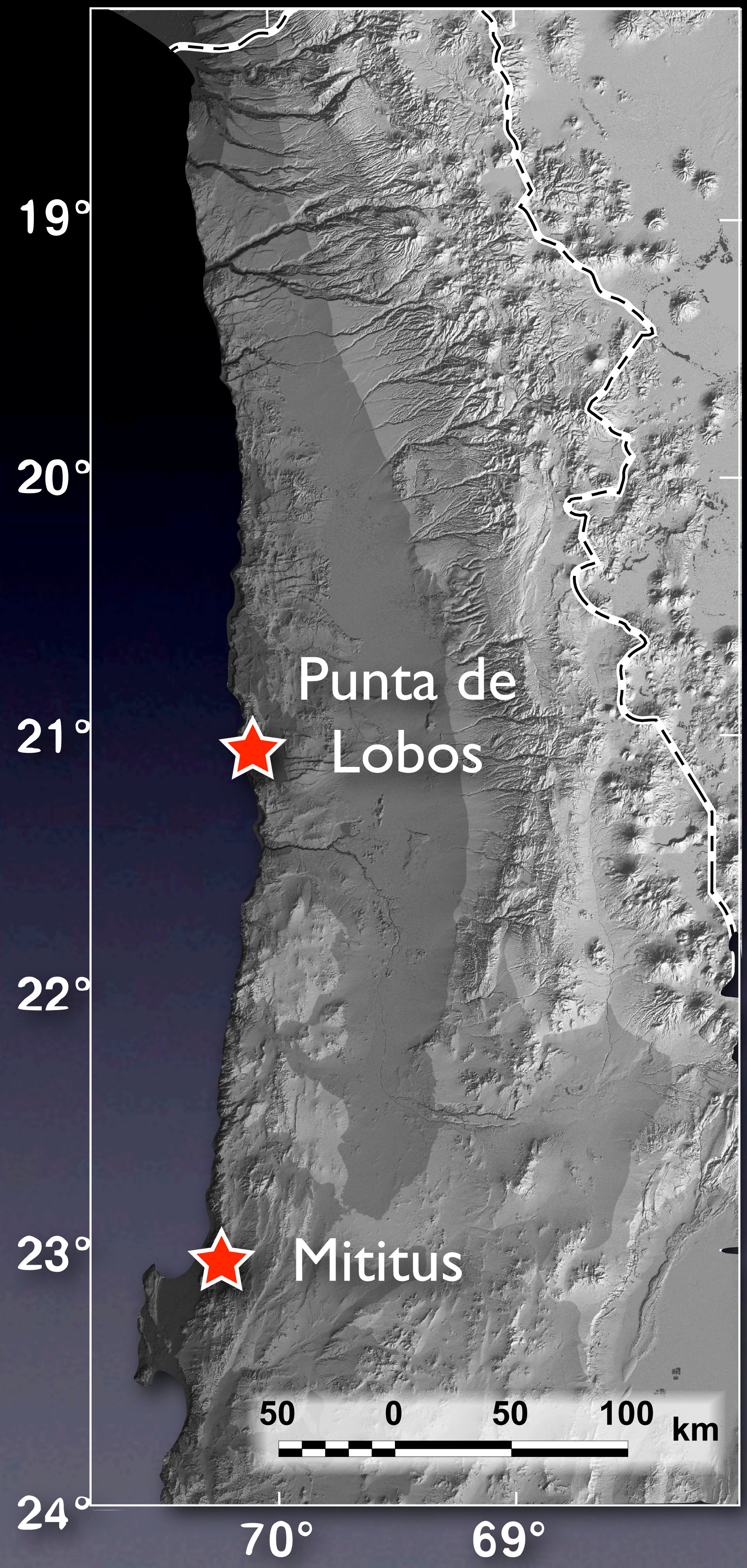
Coseismic Geodetic Strain & Crack Strain





Baker et al. (submitted)

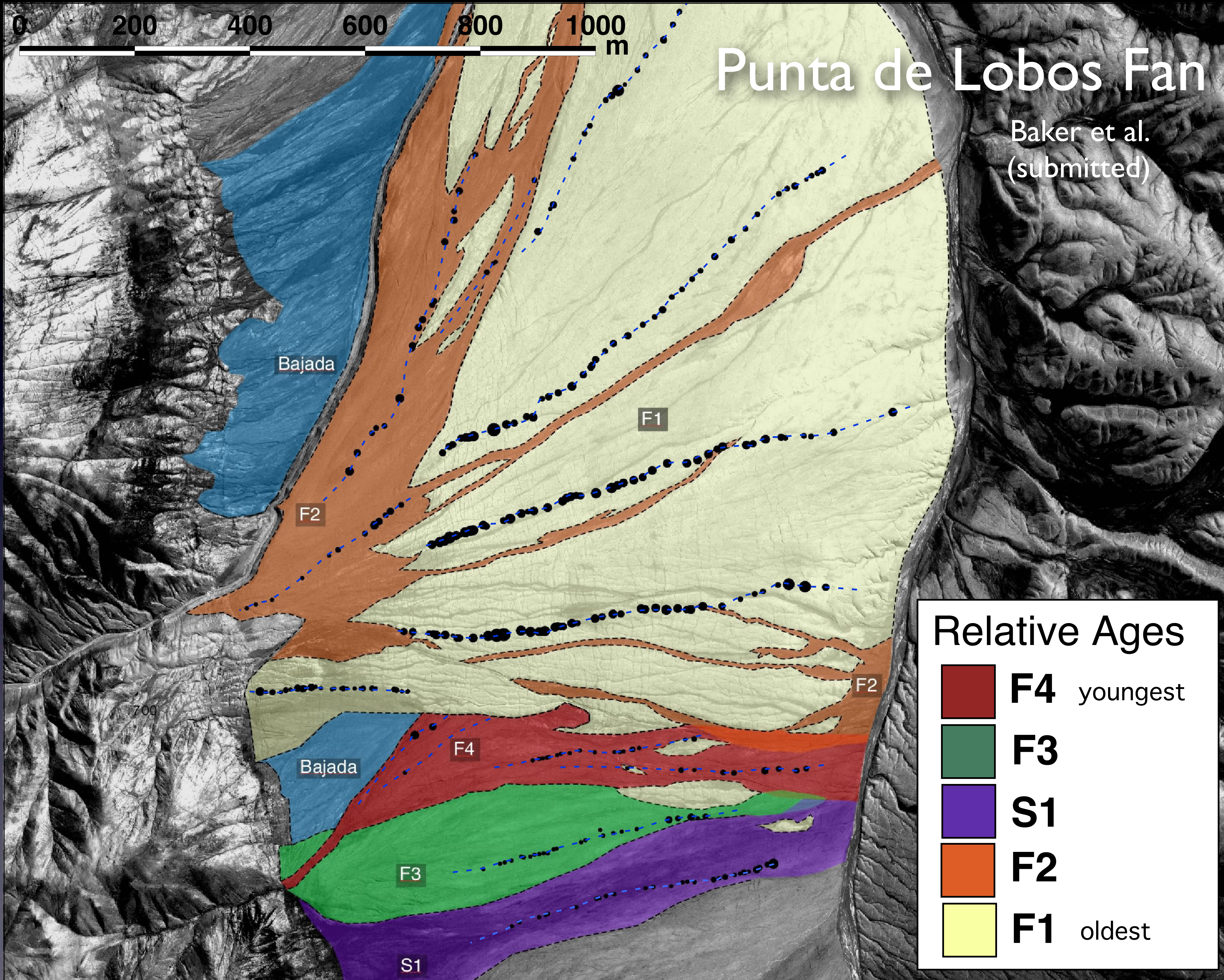
Crack Study Areas




0
200
400
600
800
1000
m
Punta de Lobos Fan
Image © 2010 DigitalGlobe

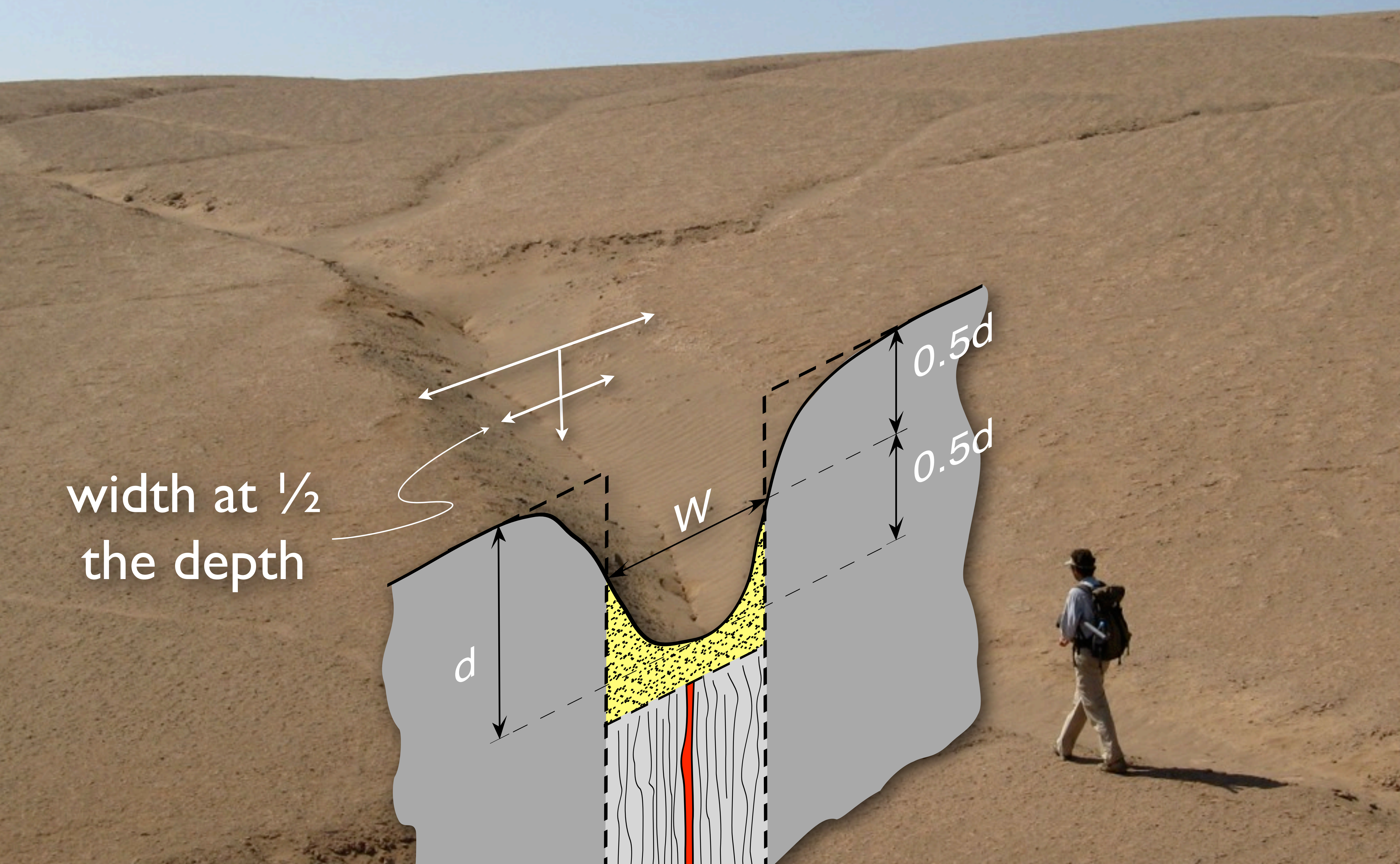

Punta de Lobos Fan


~200,000 yr surface
~800,000 yr surface

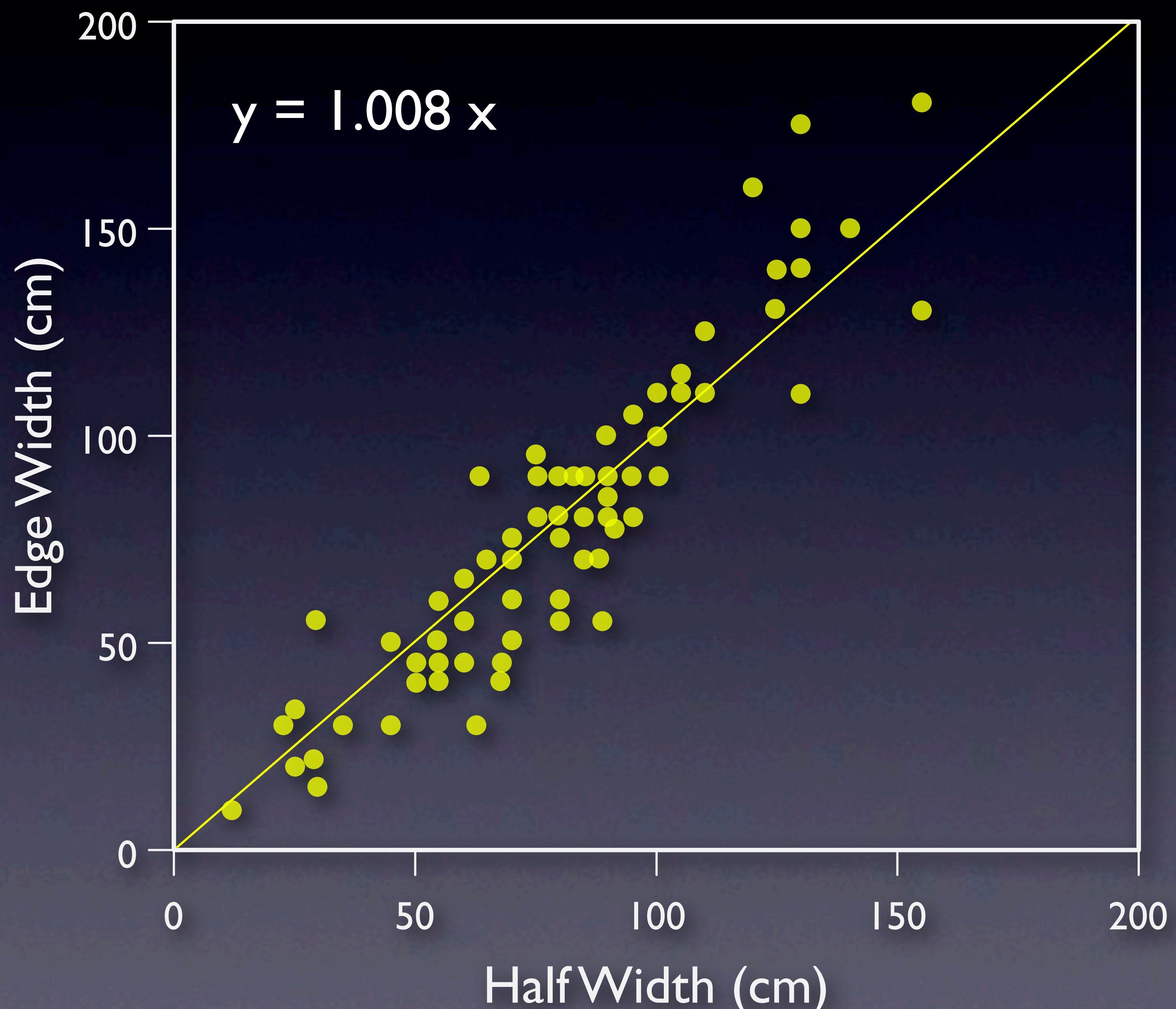


Punta de Lobos Fan
Baker et al.
(submitted)
0
200
400
600
800
1000
m
Bajada
F2
F1
F2
Bajada
F4
F3
S1
700
Relative Ages
F4 youngest
F3
S1
F2
F1 oldest

Estimating Crack Opening

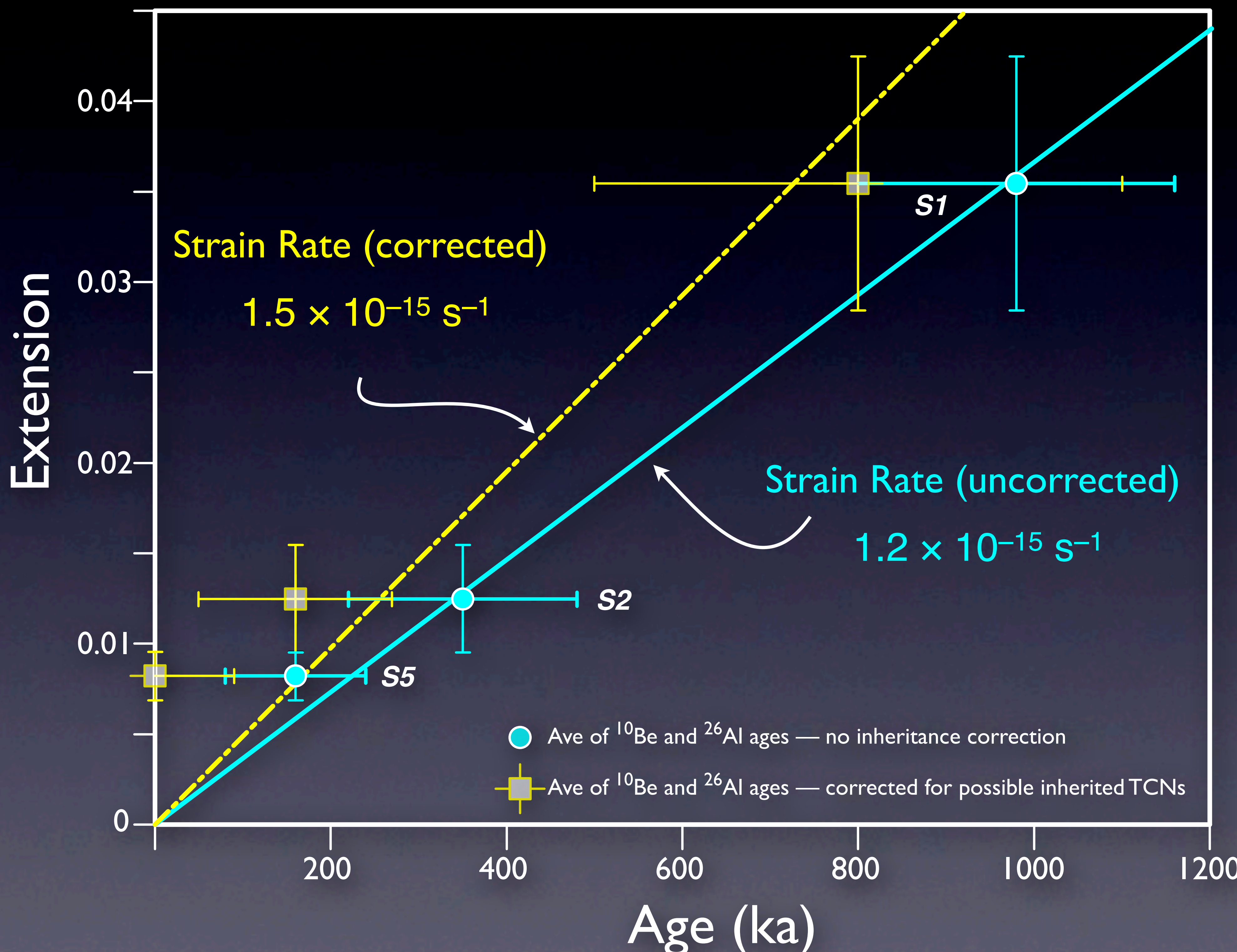


Estimating Crack Width



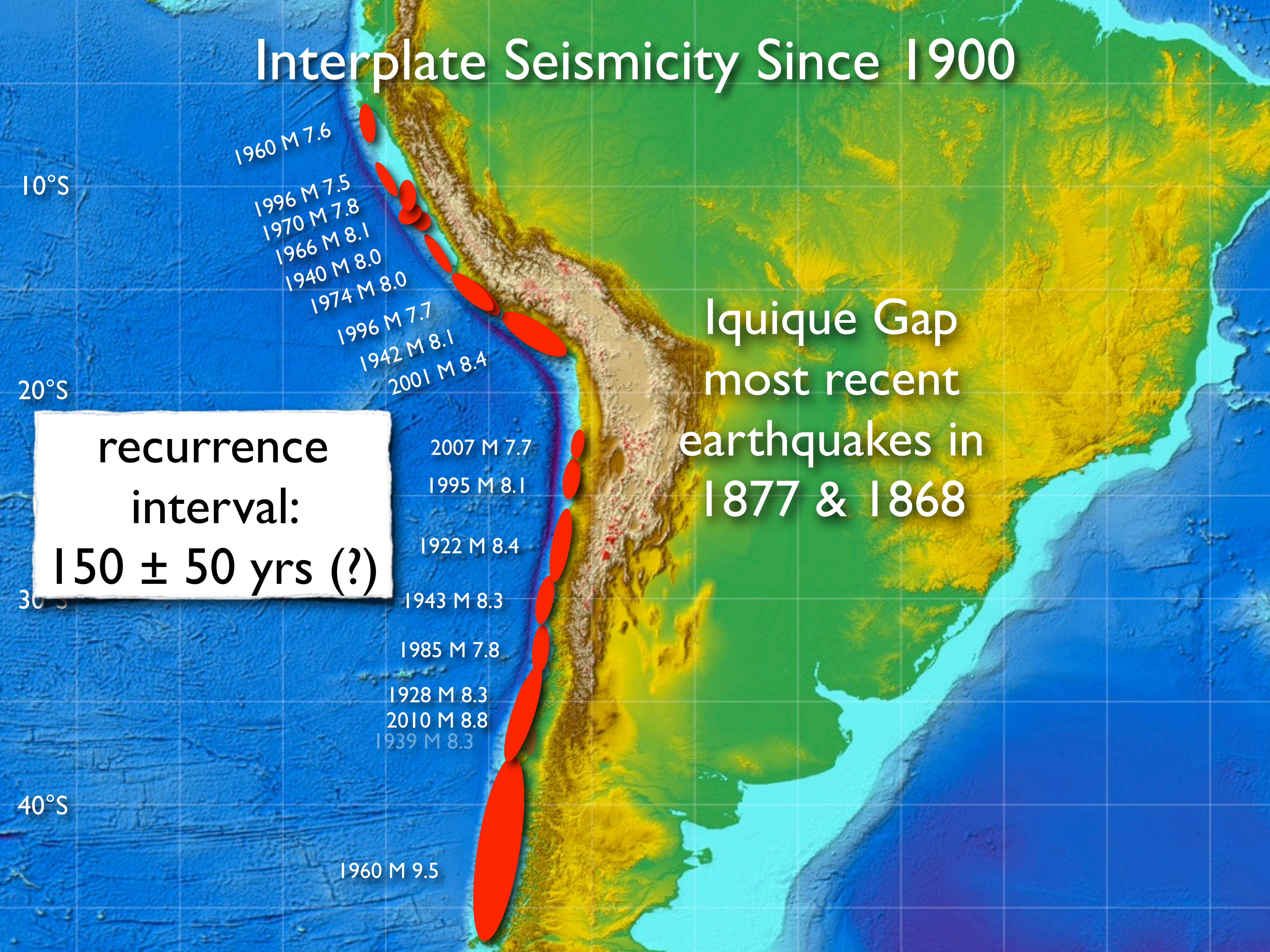
Amanda Baker et al. (submitted)

Strain Rates due to Cracking



Baker et al. (submitted)

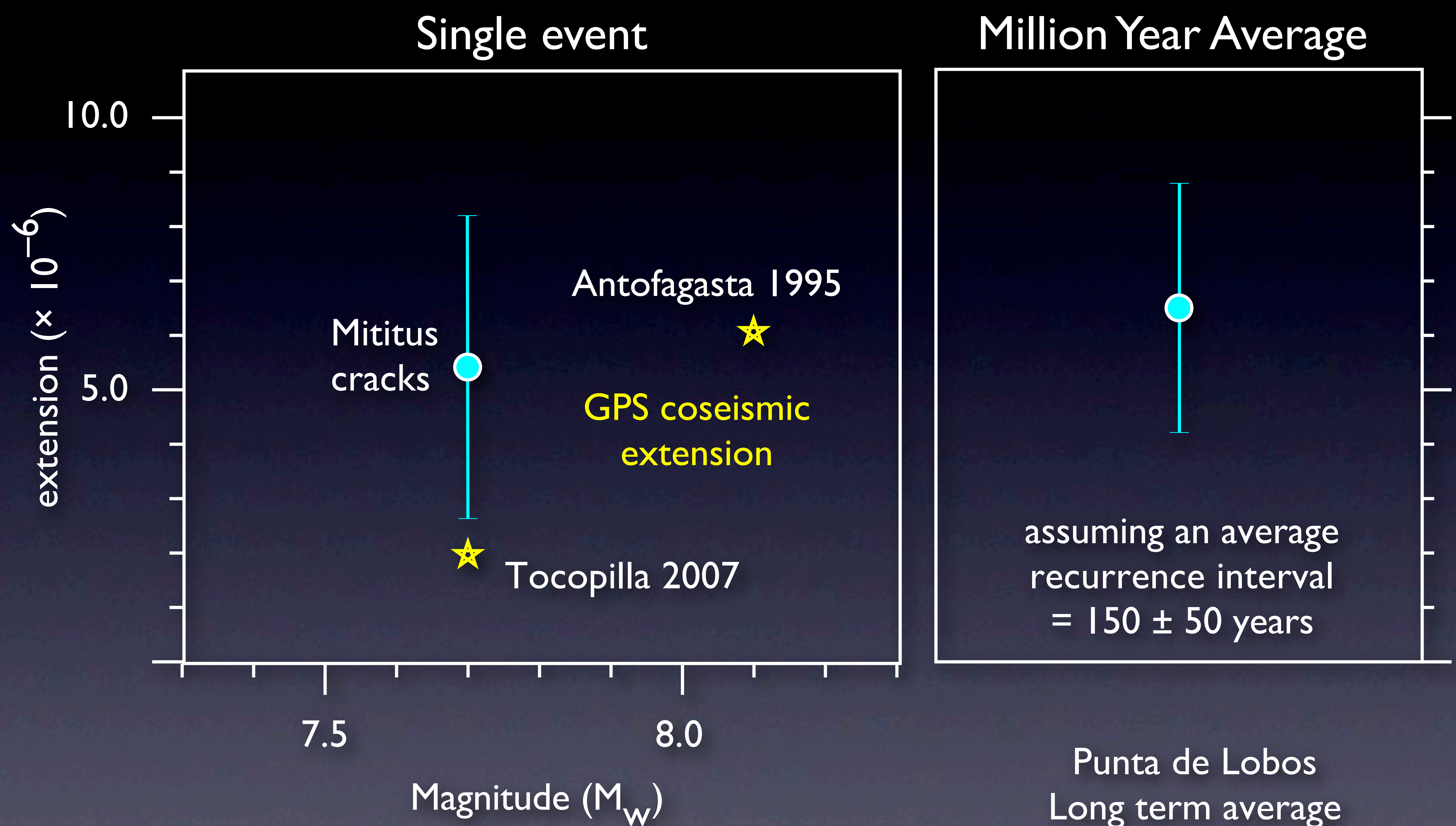
Interplate Seismicity Since 1900



recurrence interval: 150 ± 50 yrs (?)

Iquique Gap most recent earthquakes in 1877 & 1868

Coseismic Geodetic Strain & Crack Strain



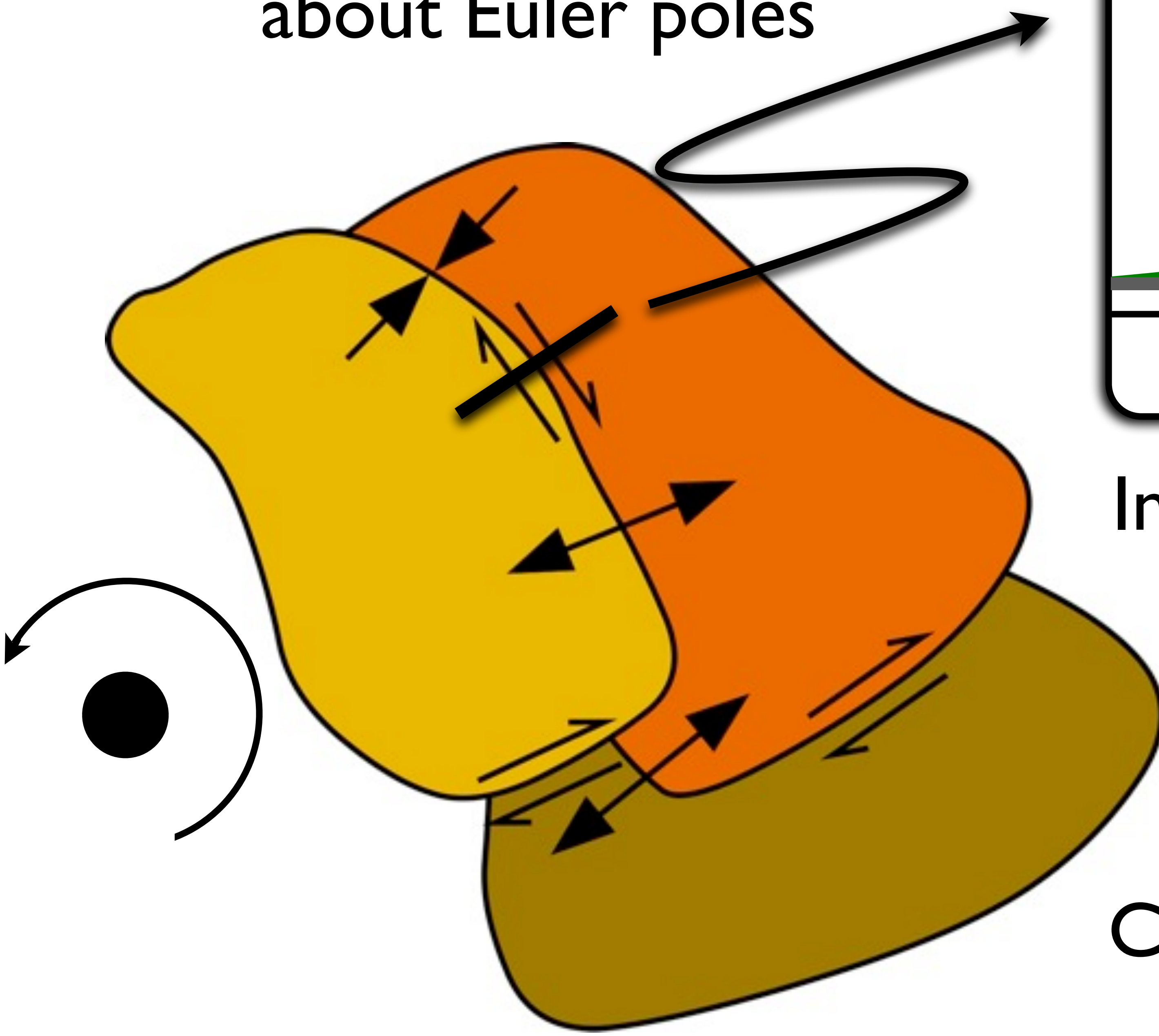
Baker et al. (submitted)

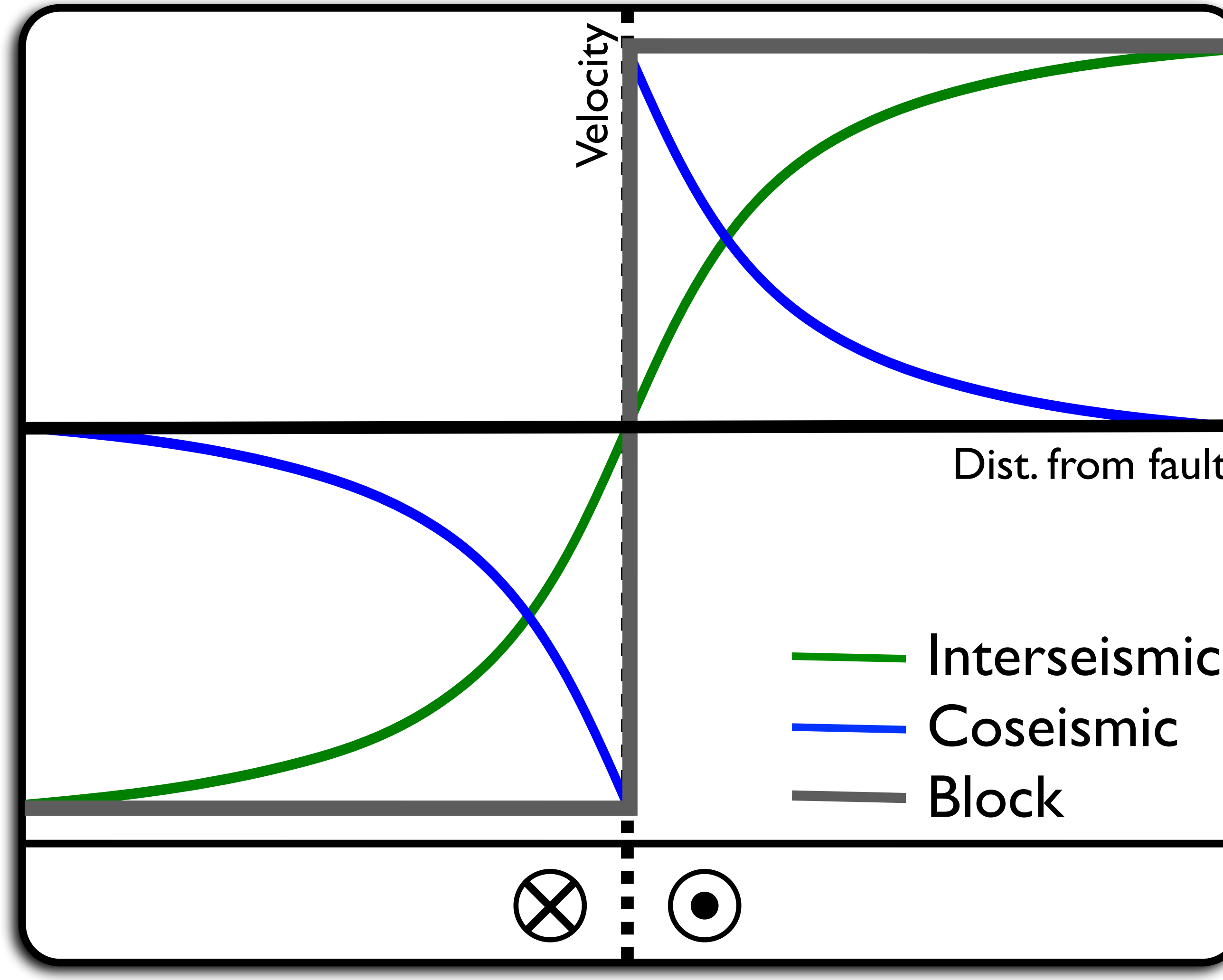
How much “elastic” rebound is permanent?

- Permanent crack strain is same order of magnitude as geodetic strain
- For a single event (Tocopilla 2007), permanent crack strain accounts for at very least ~15% of geodetic strain
- Both cracks and GPS sample the surface strain
- Implications for Reid model elastic rebound

Interseismic elastic block modeling

Block interactions described by rotation about Euler poles



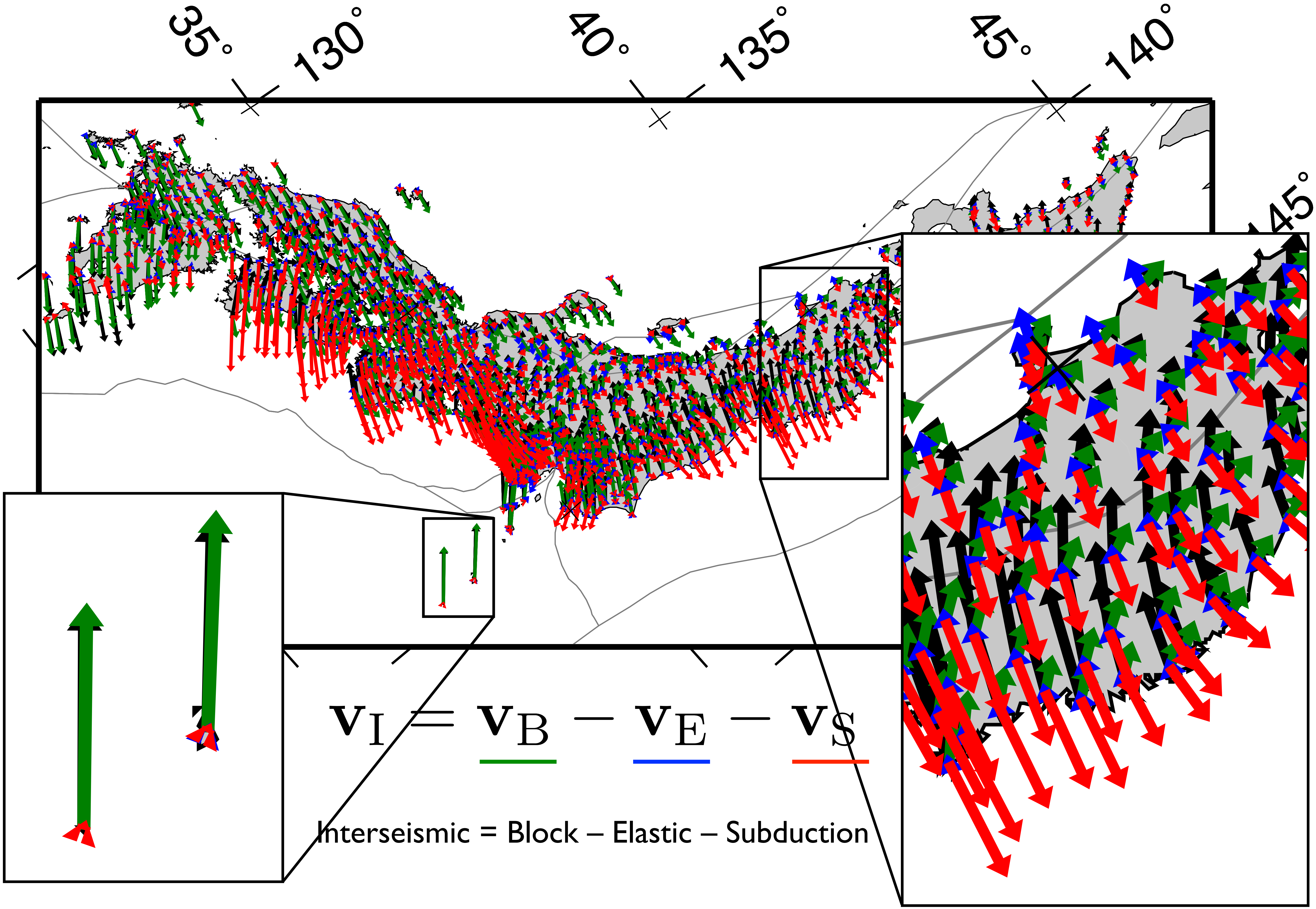


Interseismic = Block - Coseismic

Subtraction of coseismic: <u>Coseismic Slip Deficit</u>

Consideration of block motion + elastic effects → <u>Block Model</u>

Elastic block modeling: Velocity decomposition



$$\mathbf{v}_{\mathrm{I}} = \underline{\mathbf{v}_{\mathrm{B}}} - \underline{\mathbf{v}_{\mathrm{E}}} - \underline{\mathbf{v}_{\mathrm{S}}}$$

Interseismic = Block – Elastic – Subduction

Constructing the block geometry

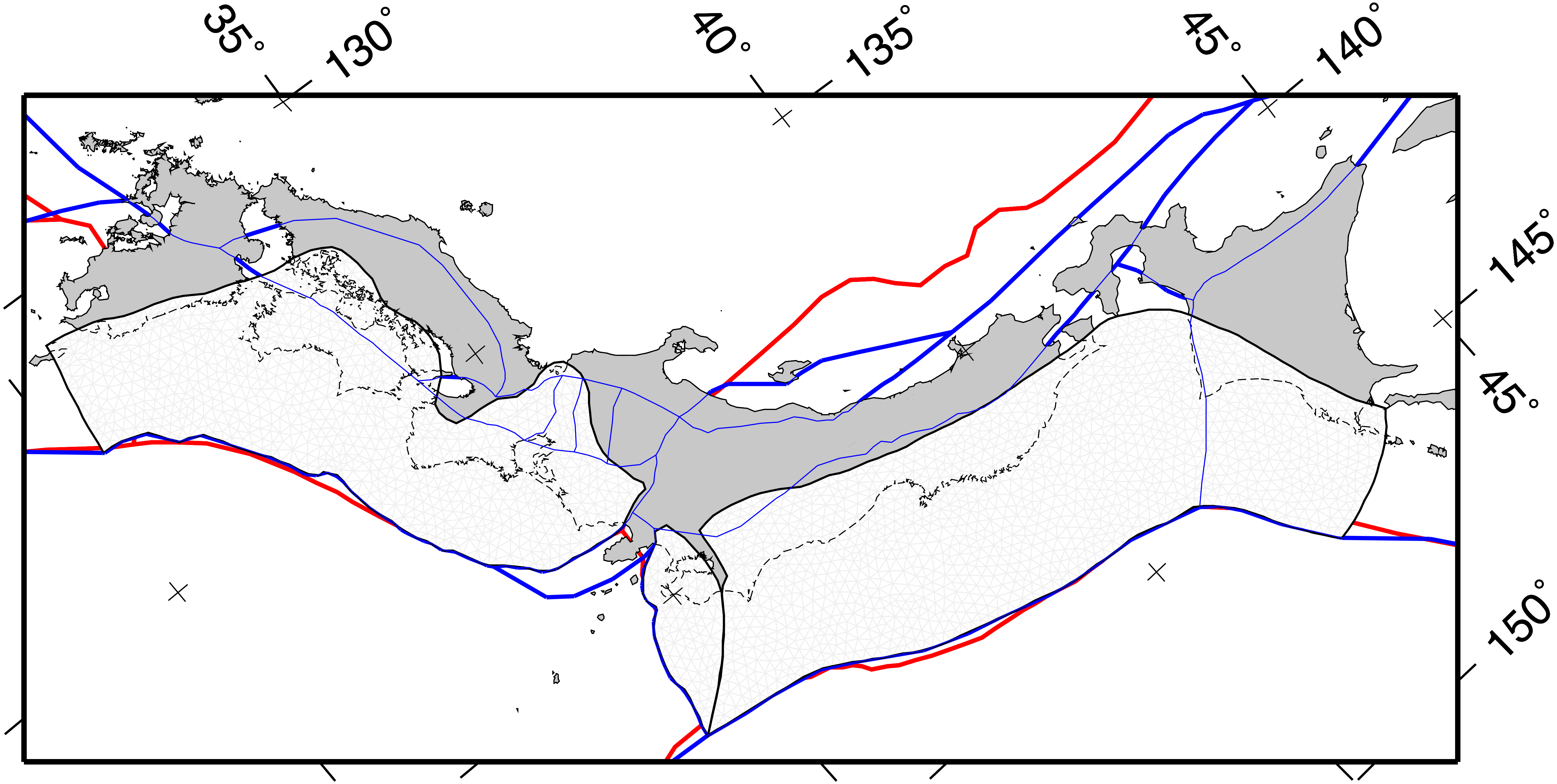
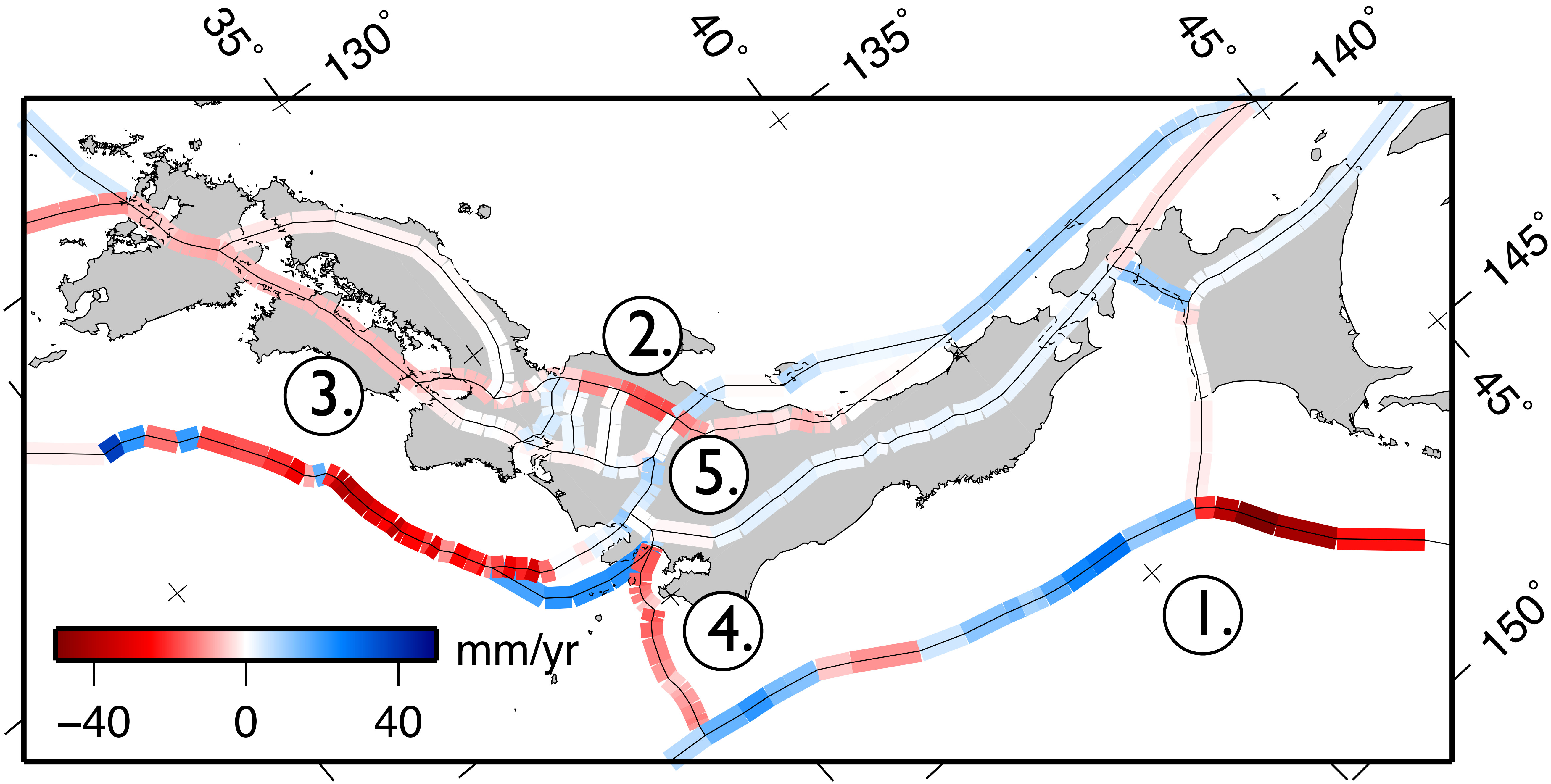


Plate boundaries ⟶ Active fault traces ⟶ Block geometry

e.g., Bird, *G*[3], 2003

Digital Active Fault Map of Japan,
AIST online active fault database

Estimated strike-slip rates

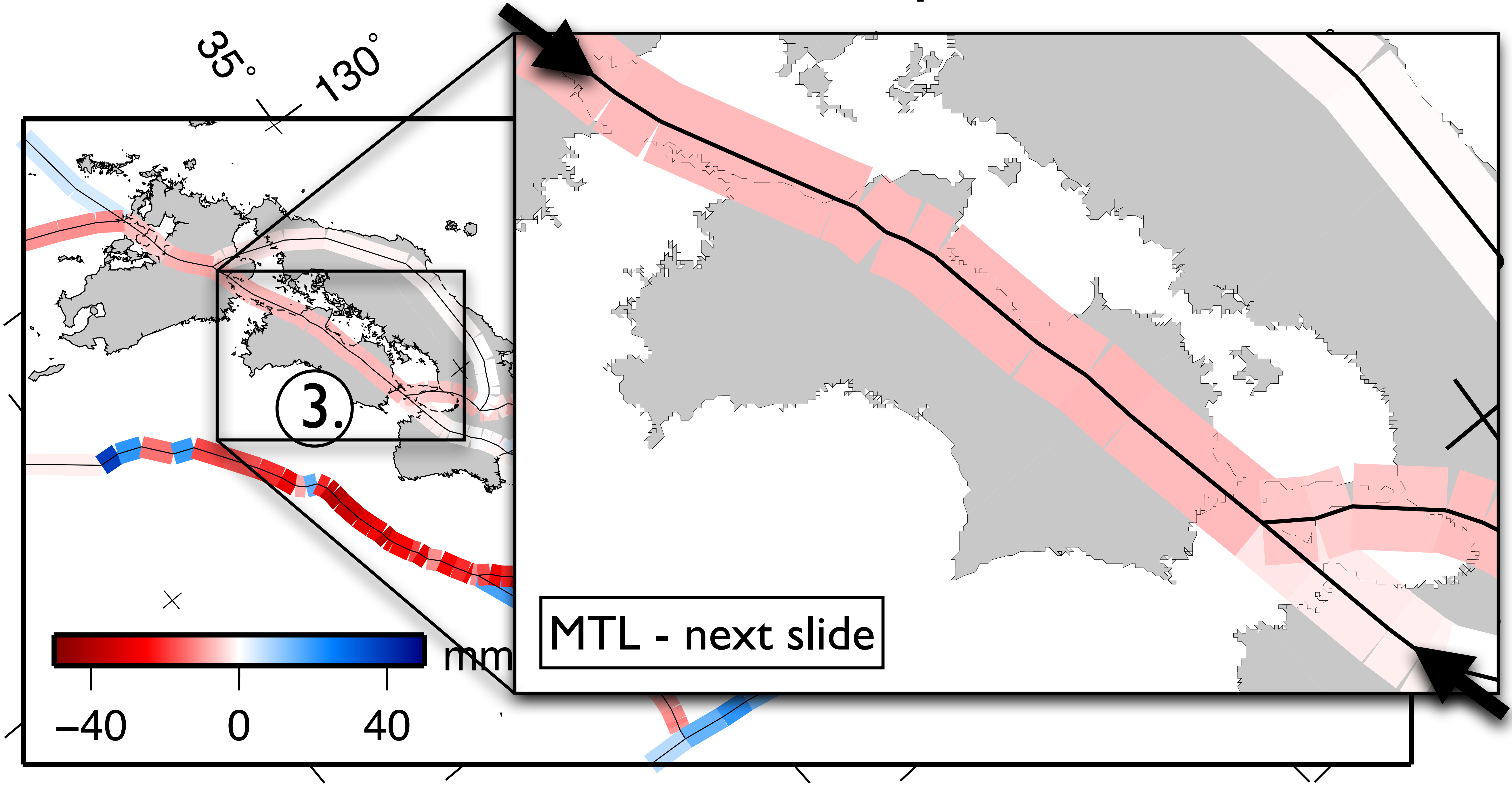


Right-lateral

Left-lateral

1. Sign depends on strike of trench
2. ~15 mm/yr R-L on NKTZ
3. ~7 mm/yr R-L on MTL, ~22 mm/yr at Nankai
4. ~17 mm/yr R-L at Sagami Trough
5. Up to 10 mm/yr L-L on ISTL

Estimated strike-slip rates



Right-lateral

Left-lateral

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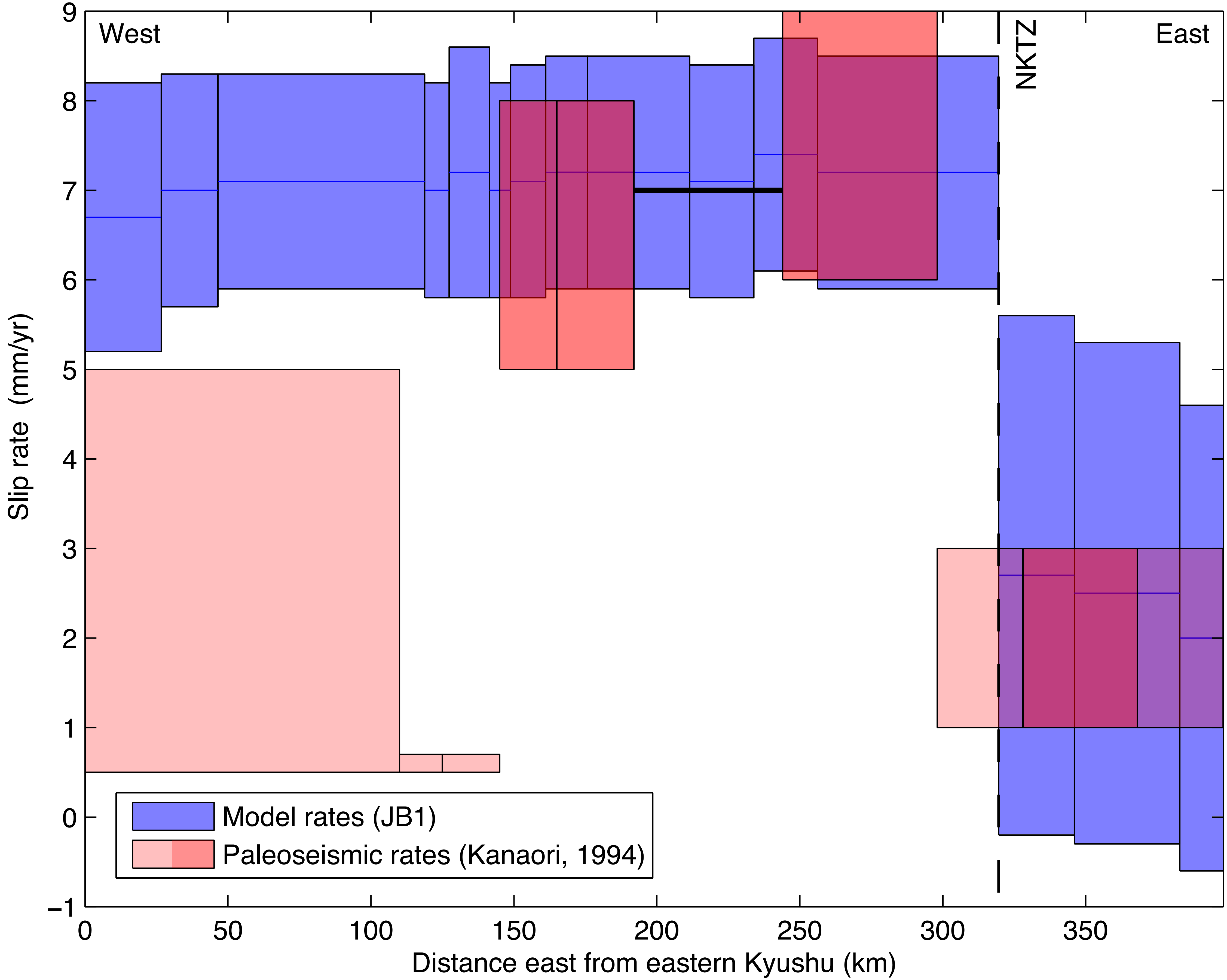
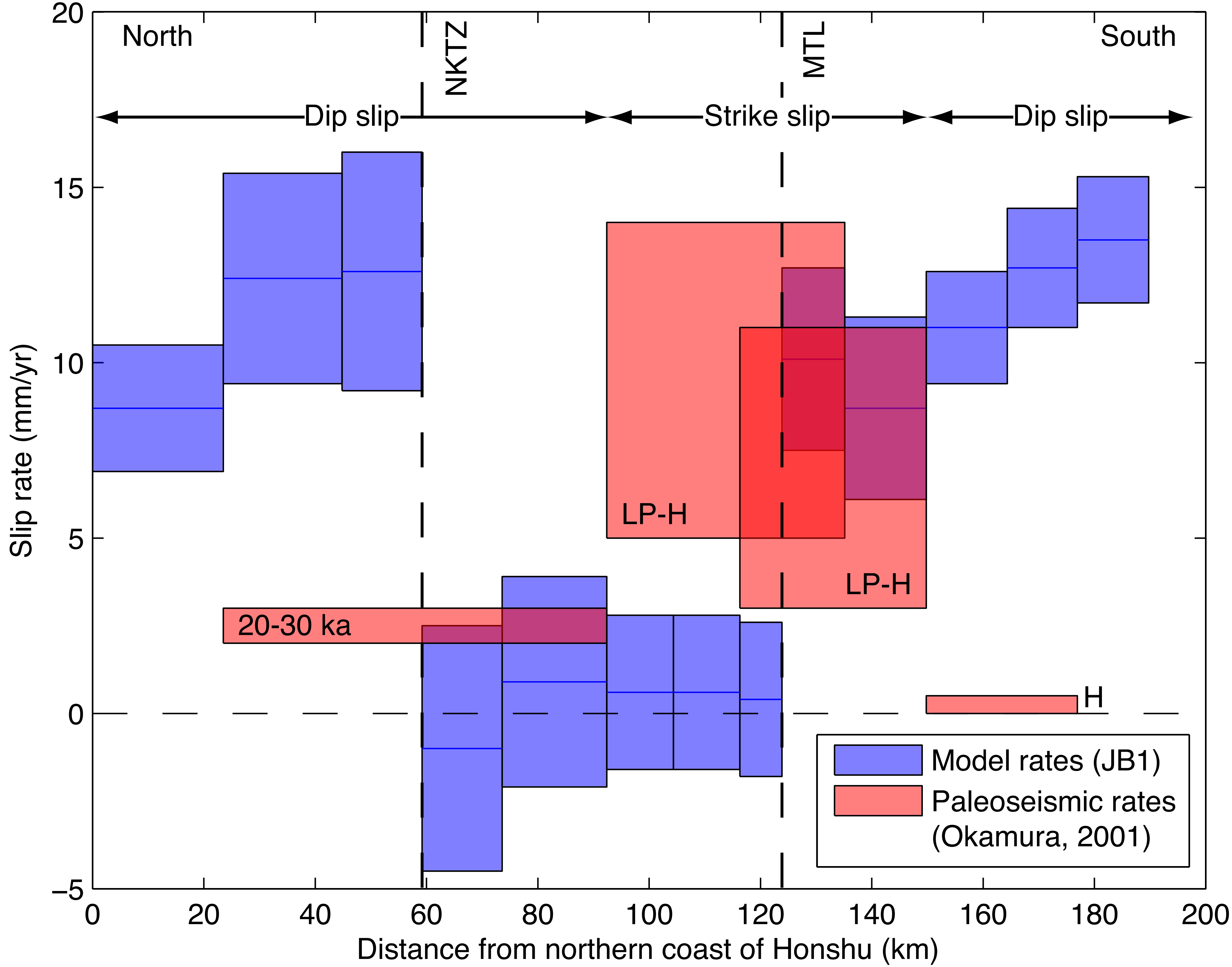
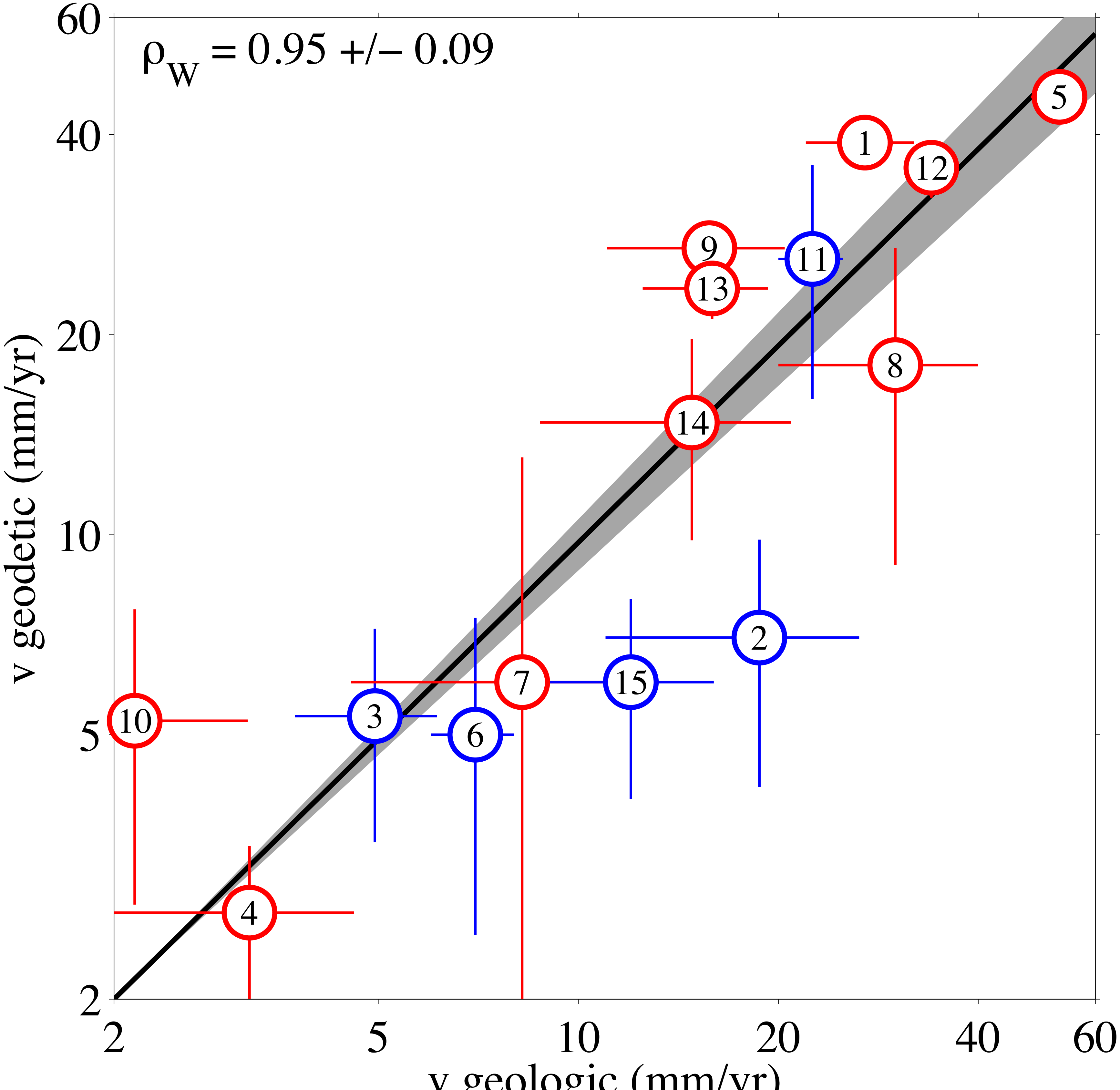
Fault slip through time: MTL



Fault slip through time: ISTL



Geodetic vs. geologic slip rates worldwide



1) Alpine
2) Altyn Tagh
3) Dead Sea
4) Elsinore
5) Fairweather
6) Garlock
7) Karakoram
8) SAF-Mojave
9) North Anatolian
10) Owens Valley
11) Philippine
12) SAF-Carrizo
13) SAF-Indio
14) San Jacinto
15) Haiyuan

Red = right-lateral
Blue = left-lateral

Meade et al., *In prep.*

Consistency in deformation through time

- Examples of remarkable consistency in style and rate over times scales 10 yr – 10 Myr
- Discrepancies in rates bring about interesting questions:
  - Changing fault system geometry
  - Shifting locus of deformation
  - Transient rheologies
  - "Retrograde" coseismic deformation
  - Anomalous individual events that deviate from "average" behavior
- Elastic models are at best generalizations and slip models derived from them represent average behavior

Integrating geodesy and geology in courses

- Geodetic observations record active tectonics — discuss current events, newly formed/activated structures
- Geologic observations are of the end product of deformational processes
- Strain rate calculations are subject to length-scale issues and are better suited to interpreting regional deformation rather than individual fault processes
- Elastic models — for determining slip rates, slip areas, interseismic coupling, etc. — are oversimplified but often do a good job at interpreting geodetic observations
- Geologists can document the actual mechanisms by which geodetically observed strain occurs
- Big remaining question: how to integrate the seismic cycle over time to produce mountains?

Possible activities

- Calculate 1-D velocity gradients "by hand"
- Use StrainSim to calculate 2-D strain
  - Compare patterns of 2-D strain with patterns of faulting
  - Compare dilitation with uplift/subsidence
  - Compare relative magnitudes of strain with published fault slip rates
  - Compare principal strain axes with fault orientations
- Fit fault-parallel GPS velocities with screw dislocation model to estimate slip rate and locking depth