De la cartographie au suivi temporel: Apport de l’interférométrie Radar pour une exploration mécanique du glissement asismique

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25 Novembre 2014

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S. Minson

Et Aussi:

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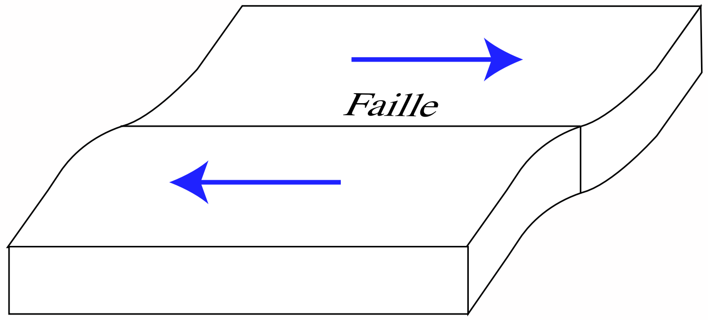
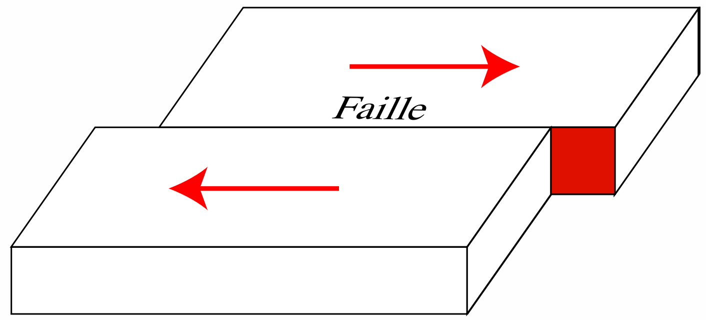
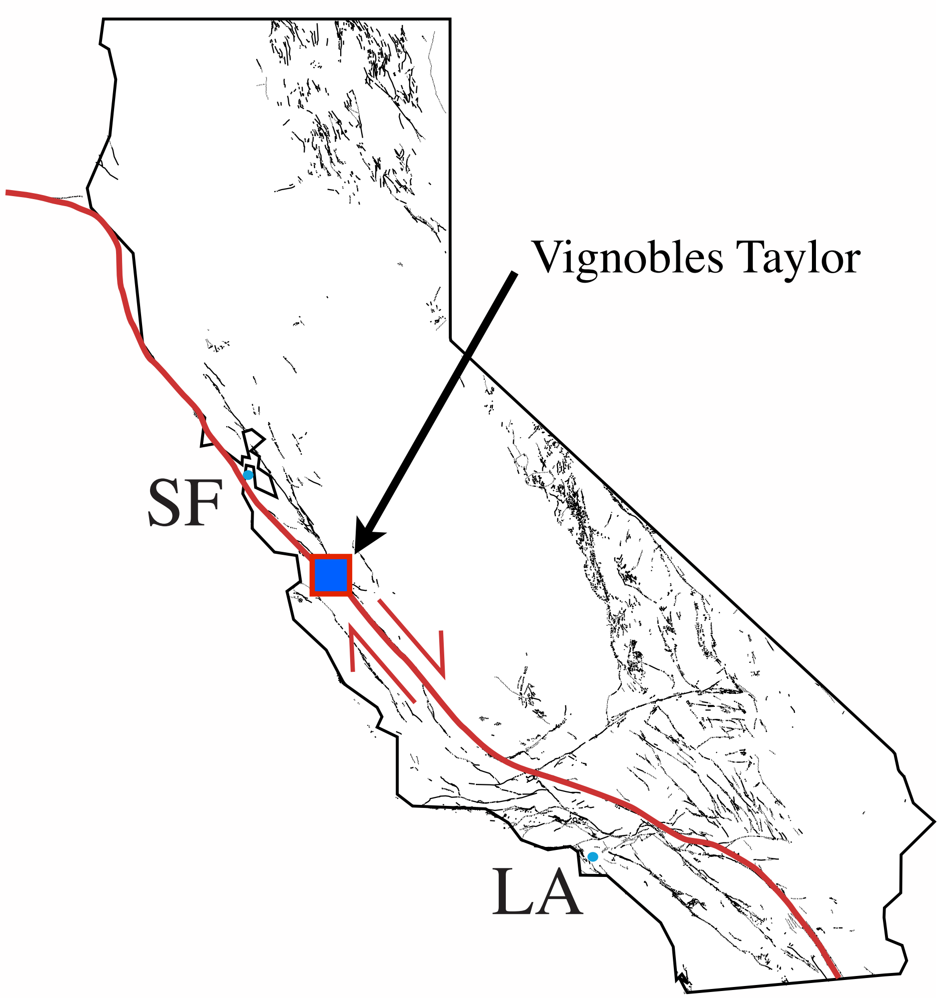
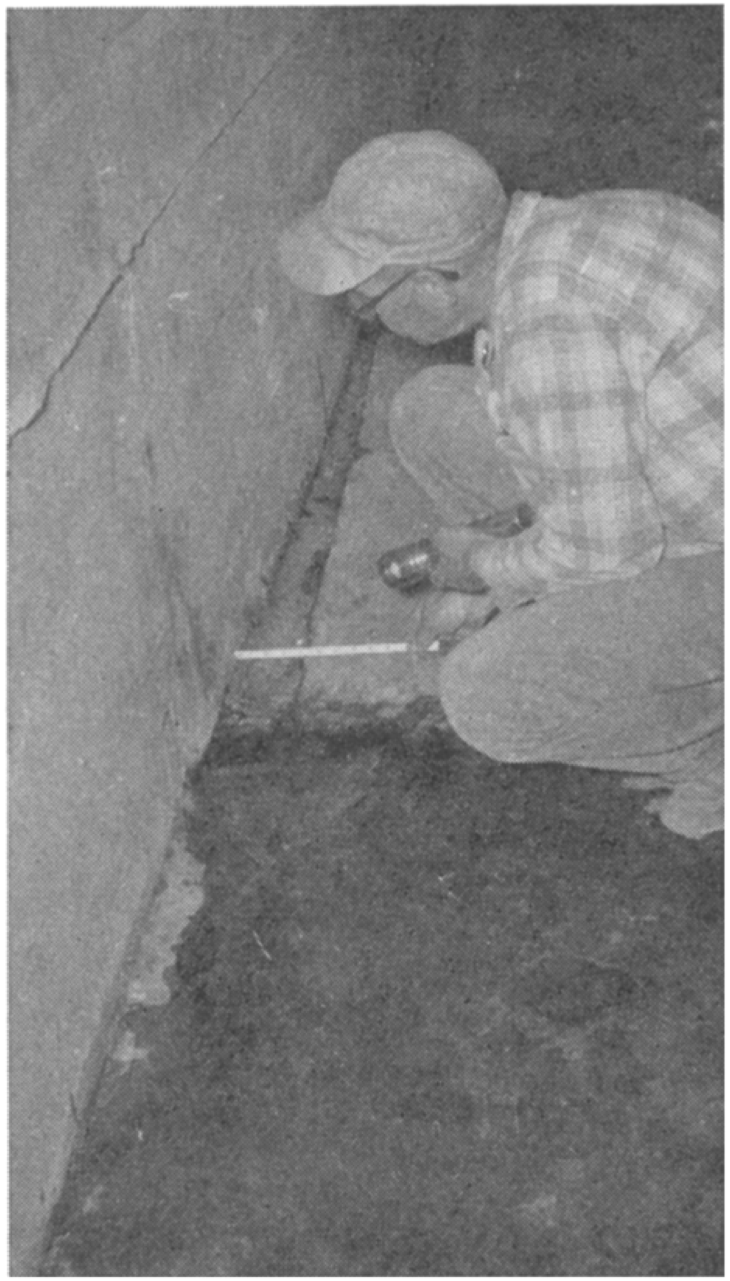
Z.-K. Shen (UCLA)
G. Peltzer (UCLA)
M. Aivazis

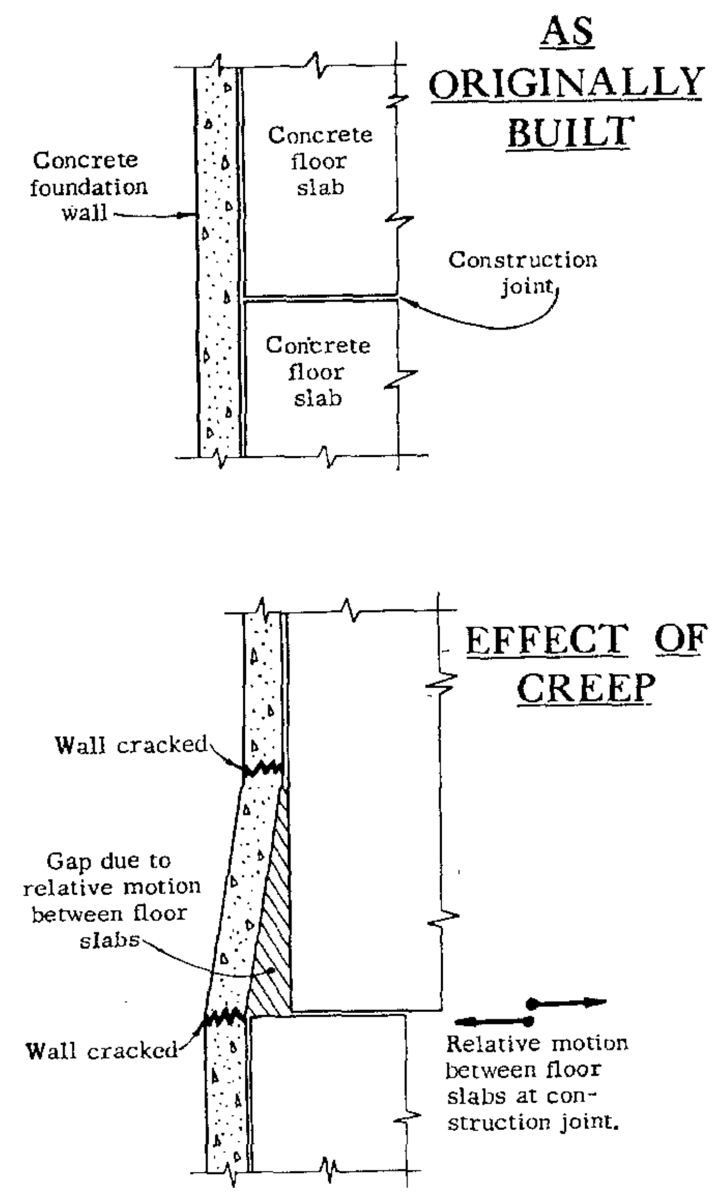
First evidences





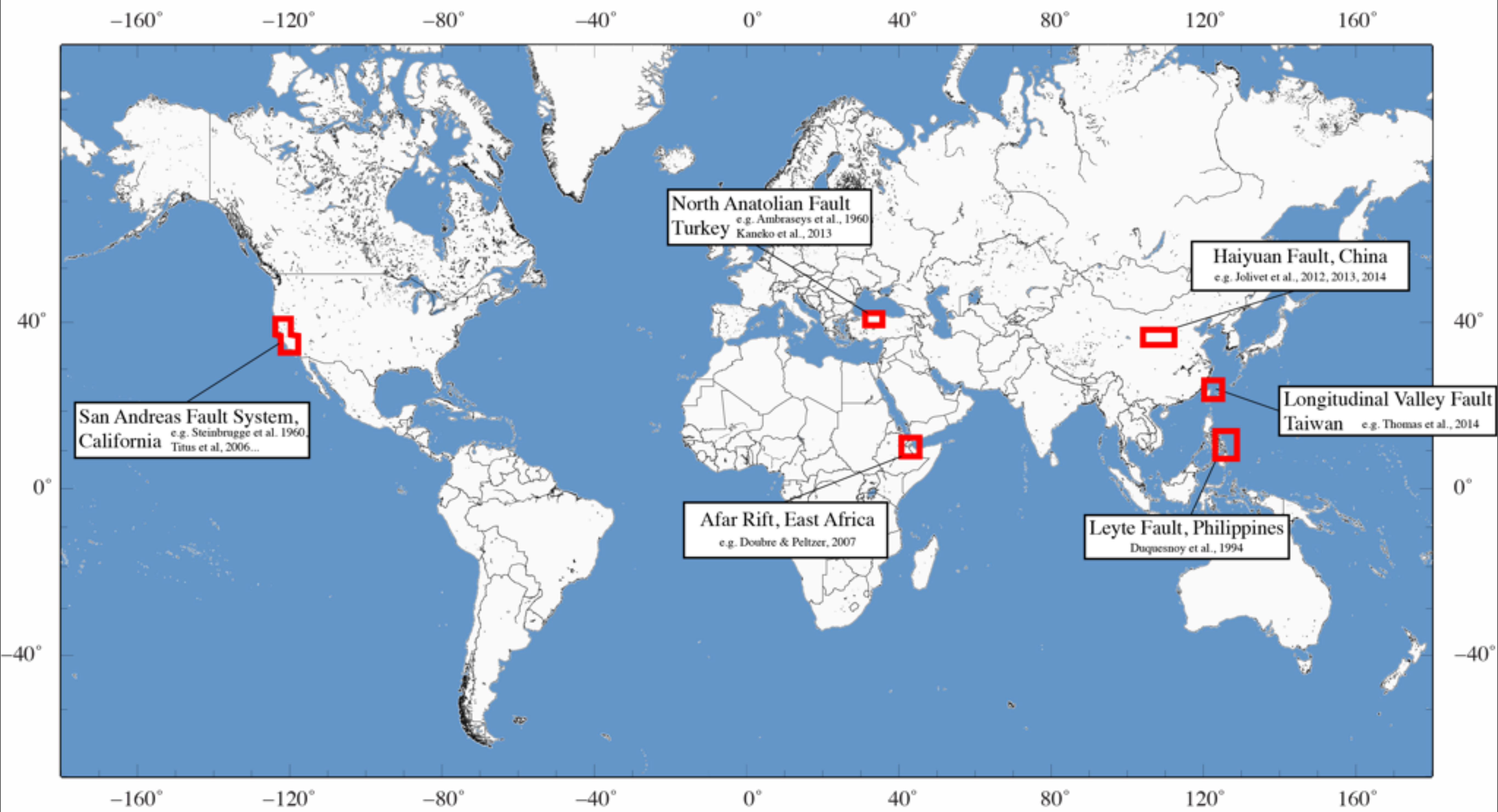






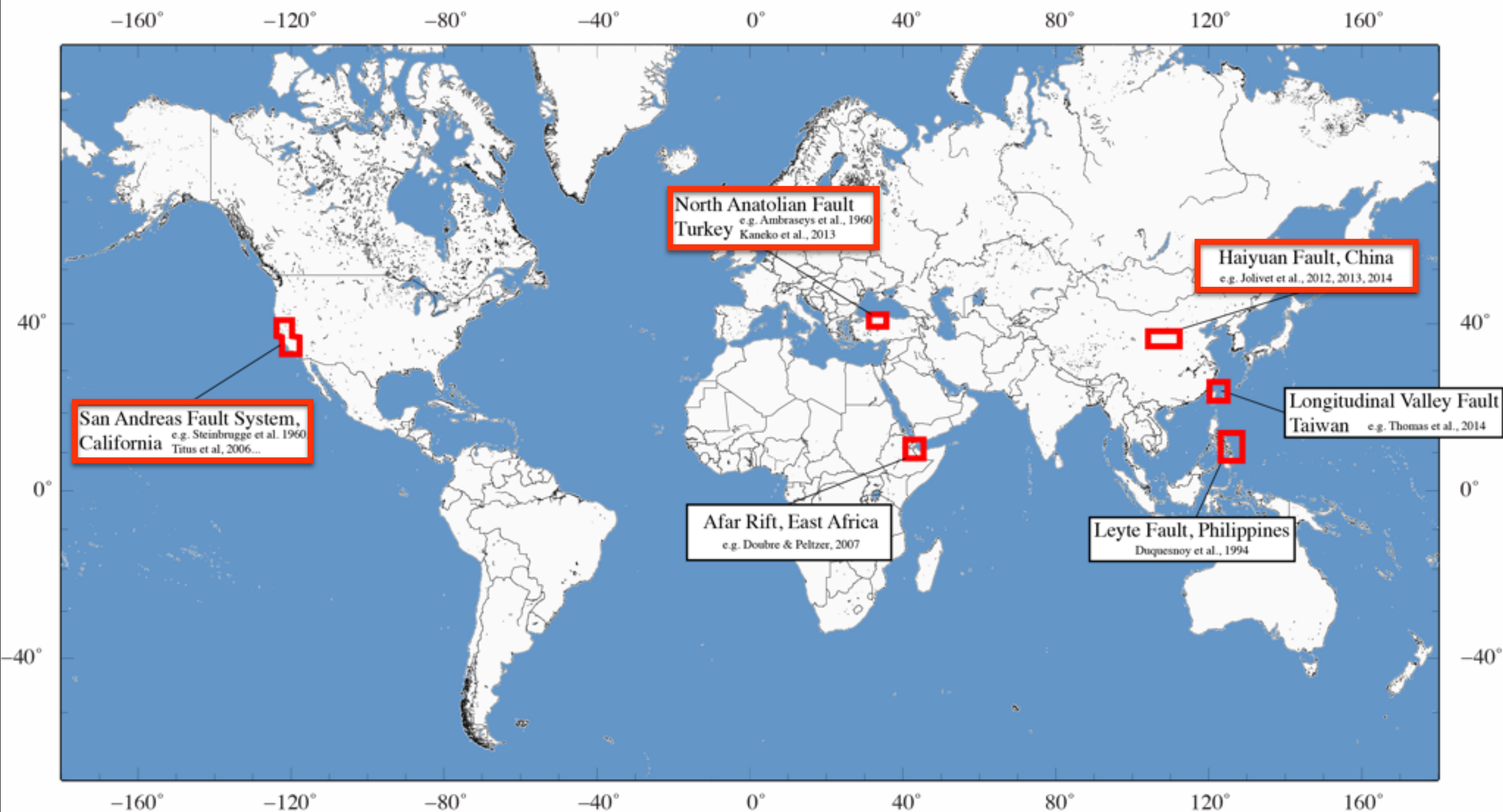
Steinbrugge et al 1960

Worldwide



−160°
−120°
−80°
−40°
0°
40°
80°
120°
160°
40°
0°
−40°
North Anatolian Fault
Turkey e.g. Ambraseys et al., 1960 Kaneko et al., 2013
Haiyuan Fault, China
e.g. Jolivet et al., 2012, 2013, 2014
San Andreas Fault System, California e.g. Steinbrugge et al. 1960, Titus et al, 2006...
Longitudinal Valley Fault
Taiwan e.g. Thomas et al., 2014
Afar Rift, East Africa
e.g. Doubre & Peltzer, 2007
Leyte Fault, Philippines
Duquesnoy et al., 1994

Worldwide



–160° –120° –80° –40° 0° 40° 80° 120° 160°
40° 0° –40°
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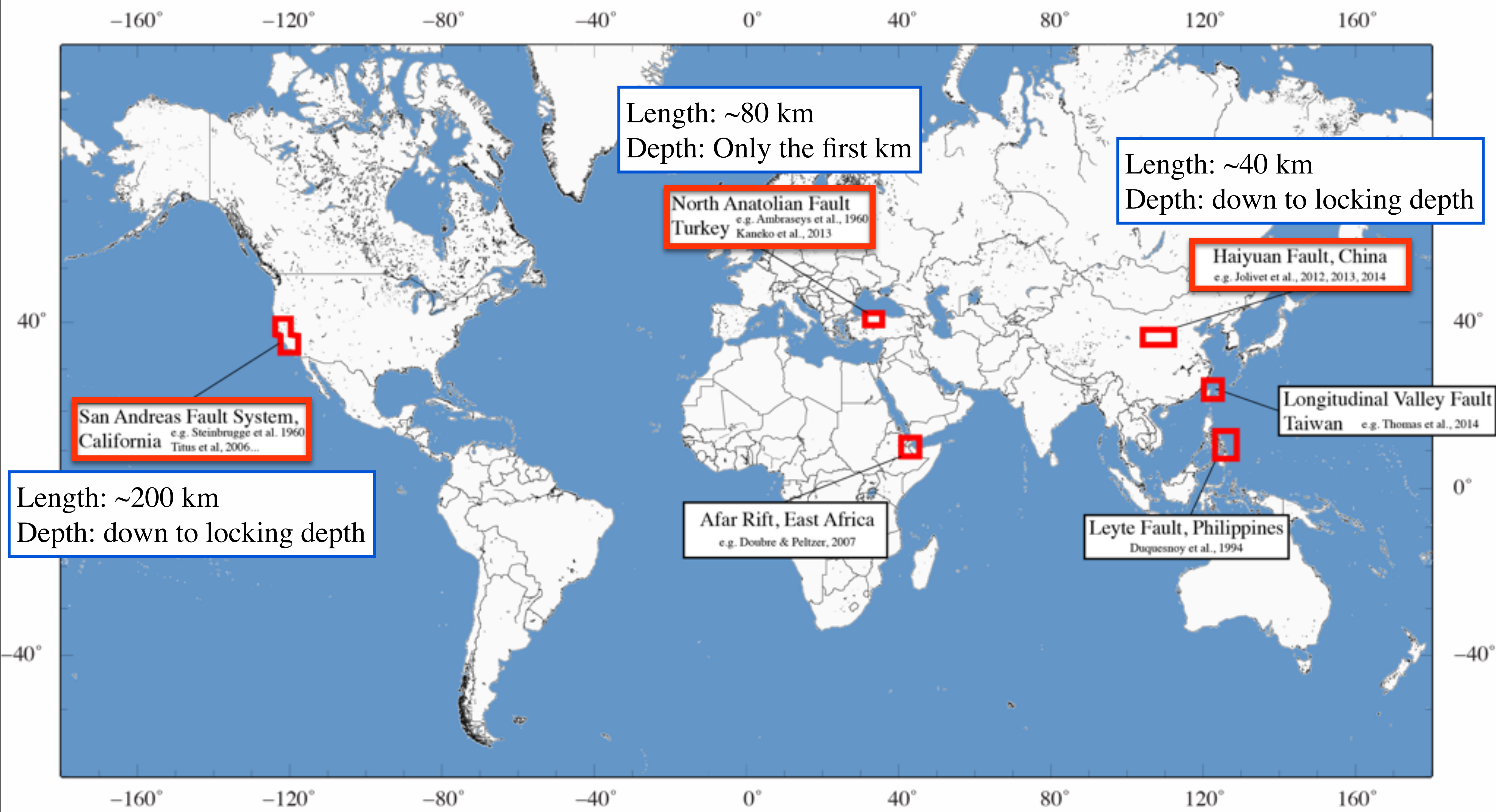
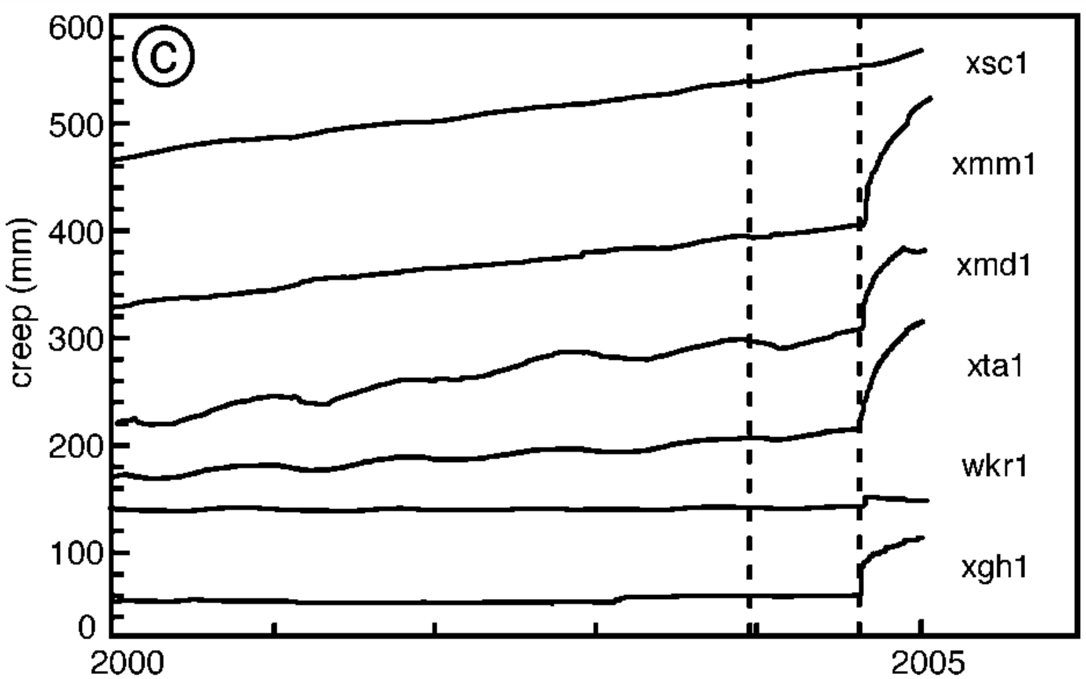
Variable spatial scales

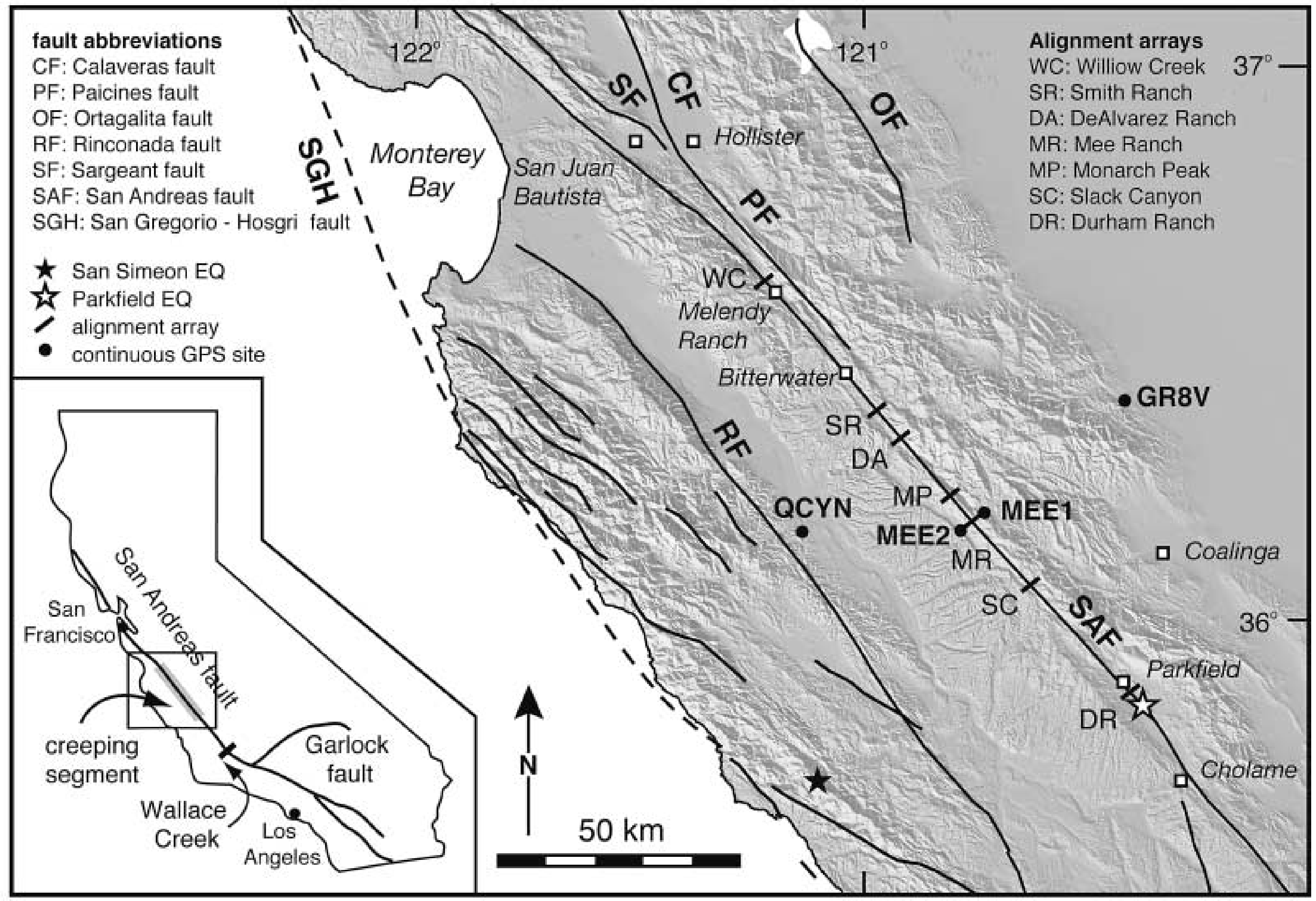


USGS website

A wide variety of behaviours



Titus et al., 2006



A large variety of temporal behaviours, from permanent aseismic sliding to episodic events and periodic oscillations

Creep and the Earthquake Cycle

1. Affects the budget of slip where it occurs
2. Related to the initiation of some earthquakes
3. Influences the propagation and arrest of ruptures

Creep and the Earthquake Cycle

Where?

1. Affects the budget of slip where it occurs
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When?

Creep and the Earthquake Cycle

1. Affects the budget of slip where it occurs
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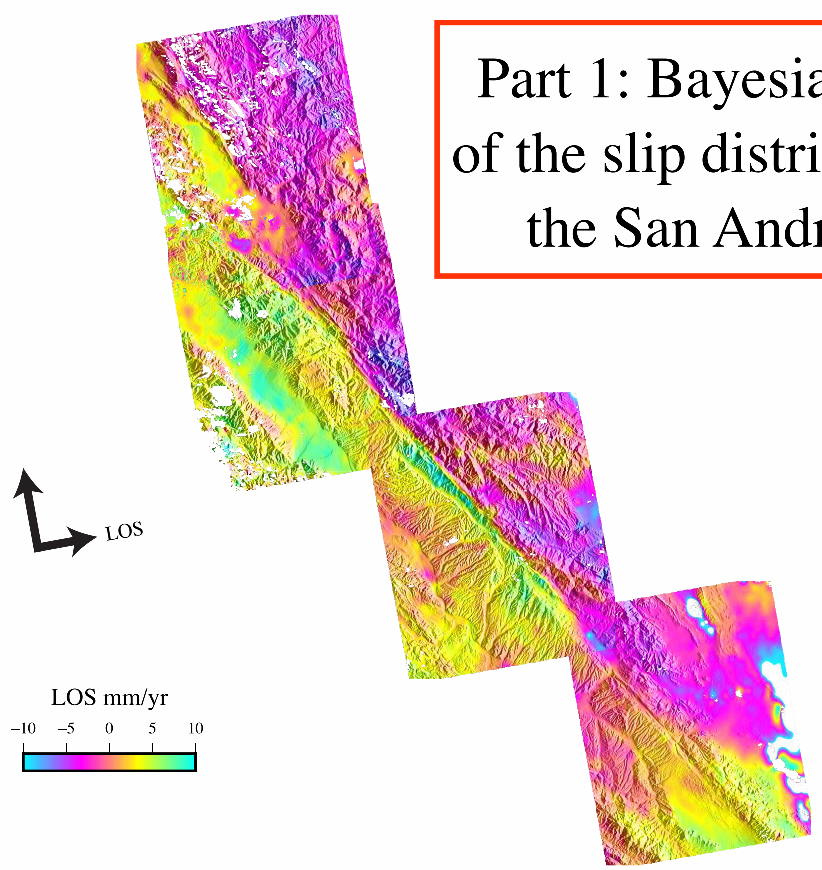
Where?

When?

Mapping creep along active faults using InSAR



Part 1: Bayesian sampling of the slip distribution along the San Andreas Fault

Creep and the Earthquake Cycle

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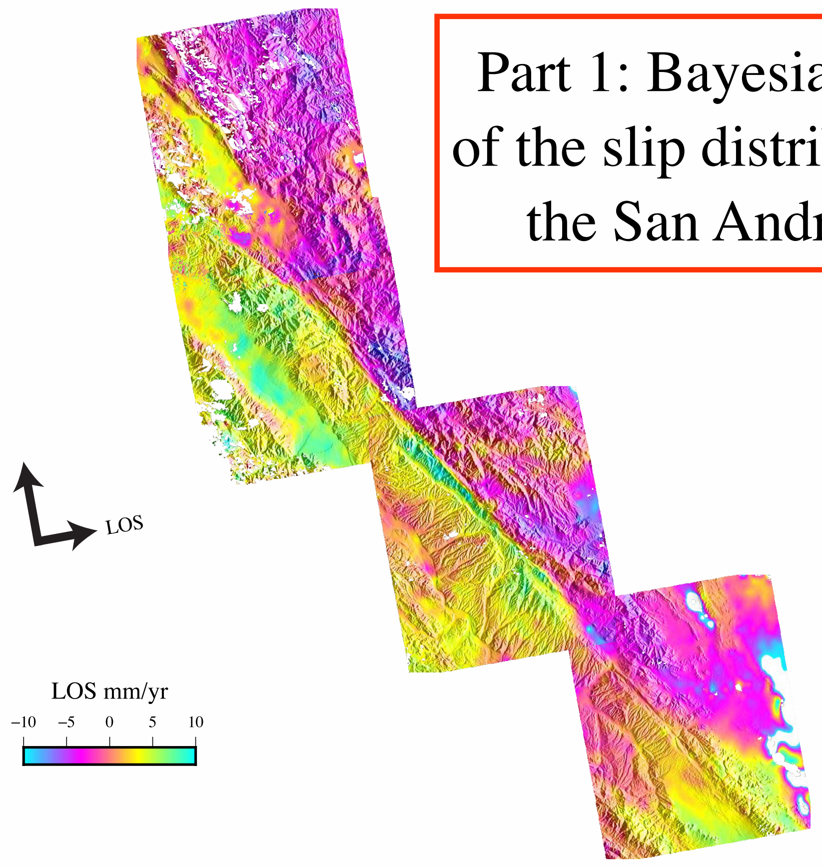
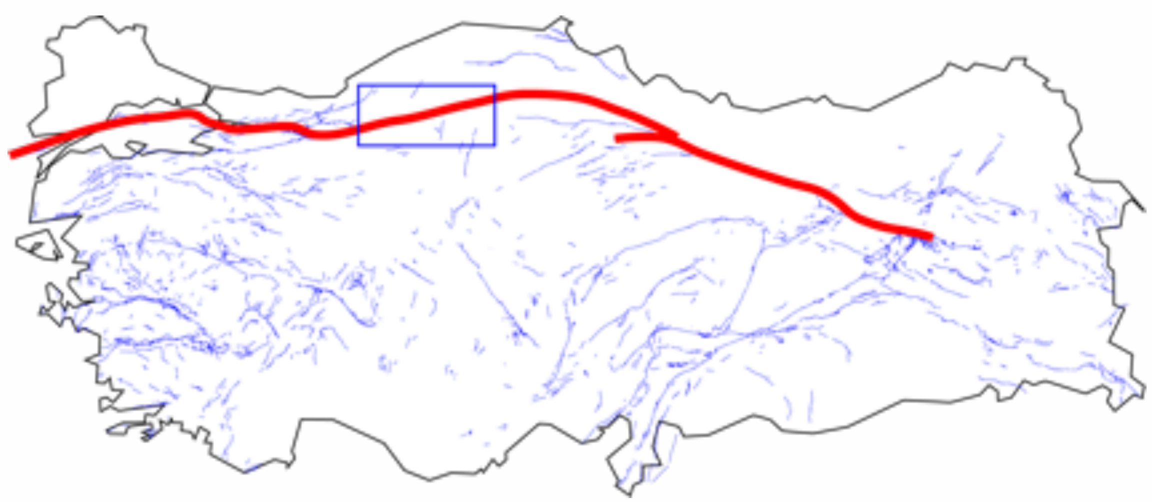


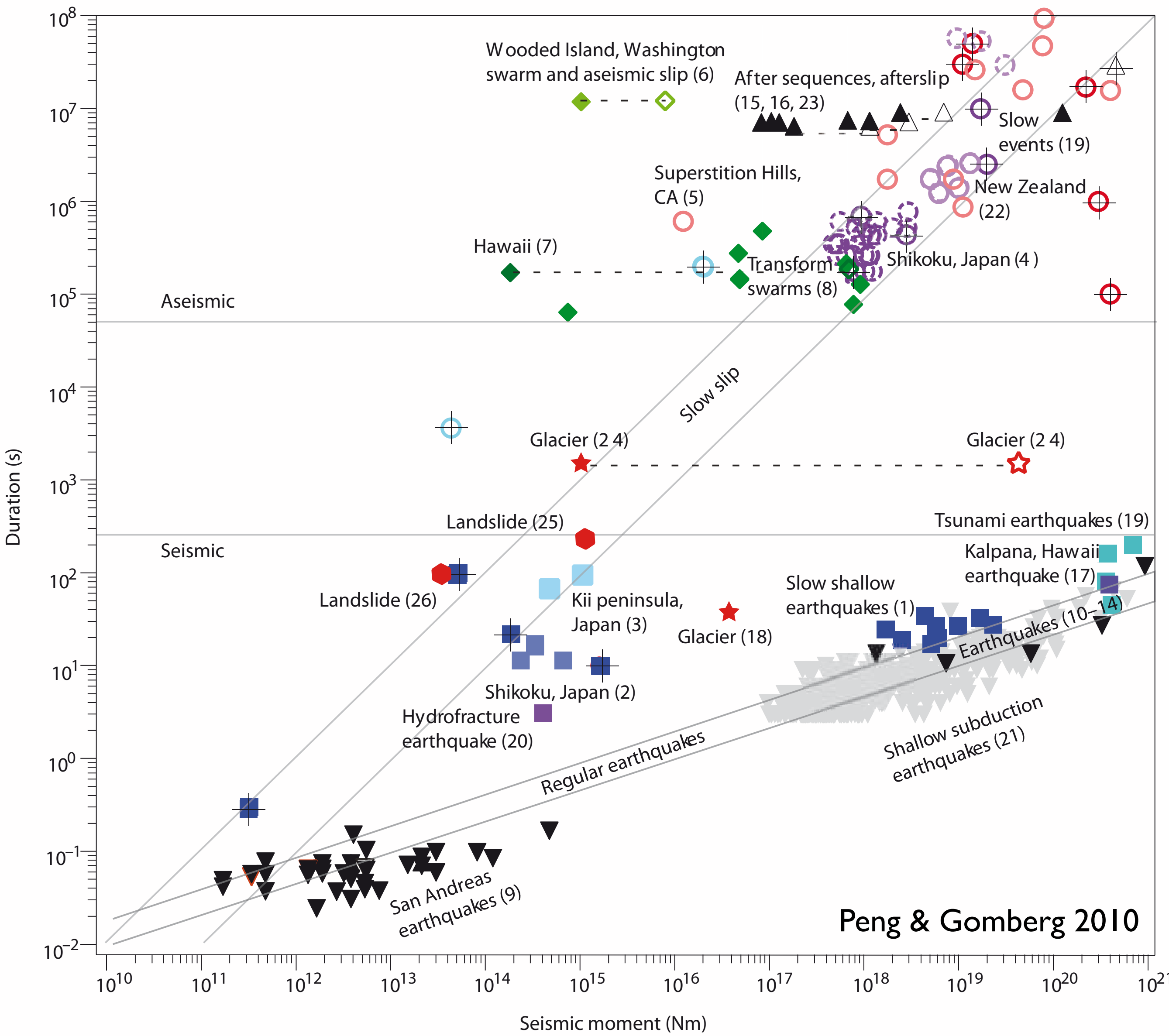
Part 1: Bayesian sampling of the slip distribution along the San Andreas Fault

Monitoring temporal variations of aseismic slip using InSAR

Part 2: the North Anatolian fault creeping segment imaged by short repeat time Radar satellites



Creep and the Earthquake Cycle



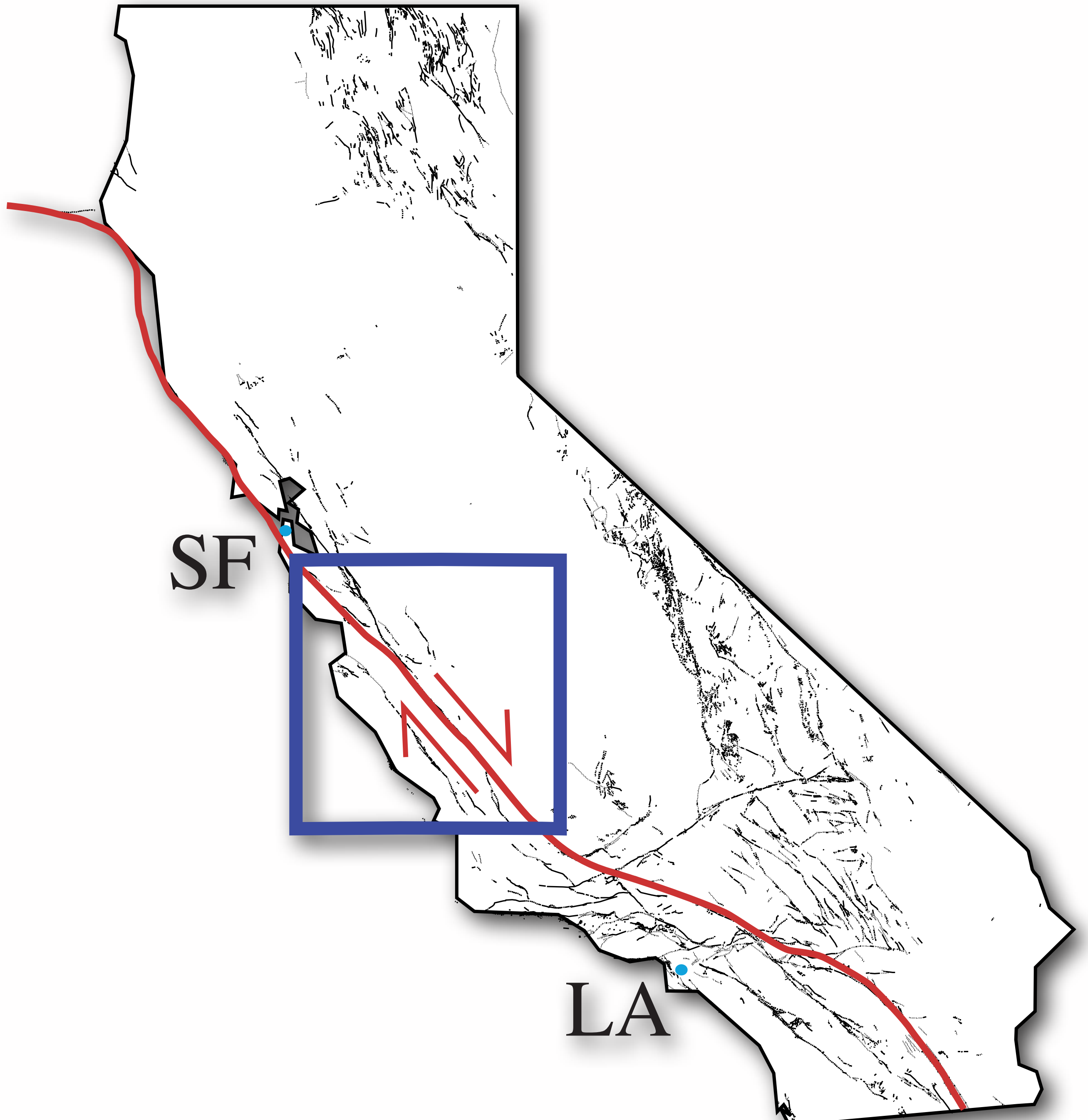
Creep occurs where fault rheology favours stable behaviour (i.e. slip- or rate-strengthening)

Earthquakes occur where fault rheology favours unstable behaviour (i.e. slip- or rate-weakening)

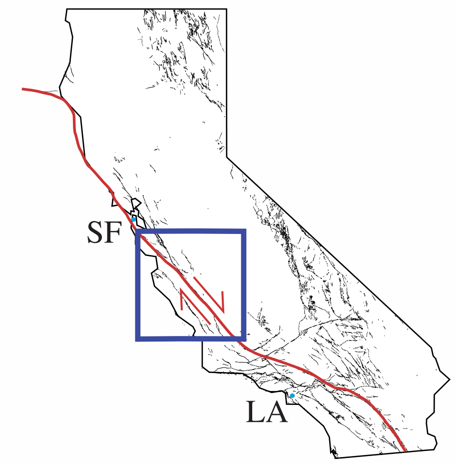
Bi-modal behaviour or continuum of modes of slip, from the earthquake to aseismic sliding?

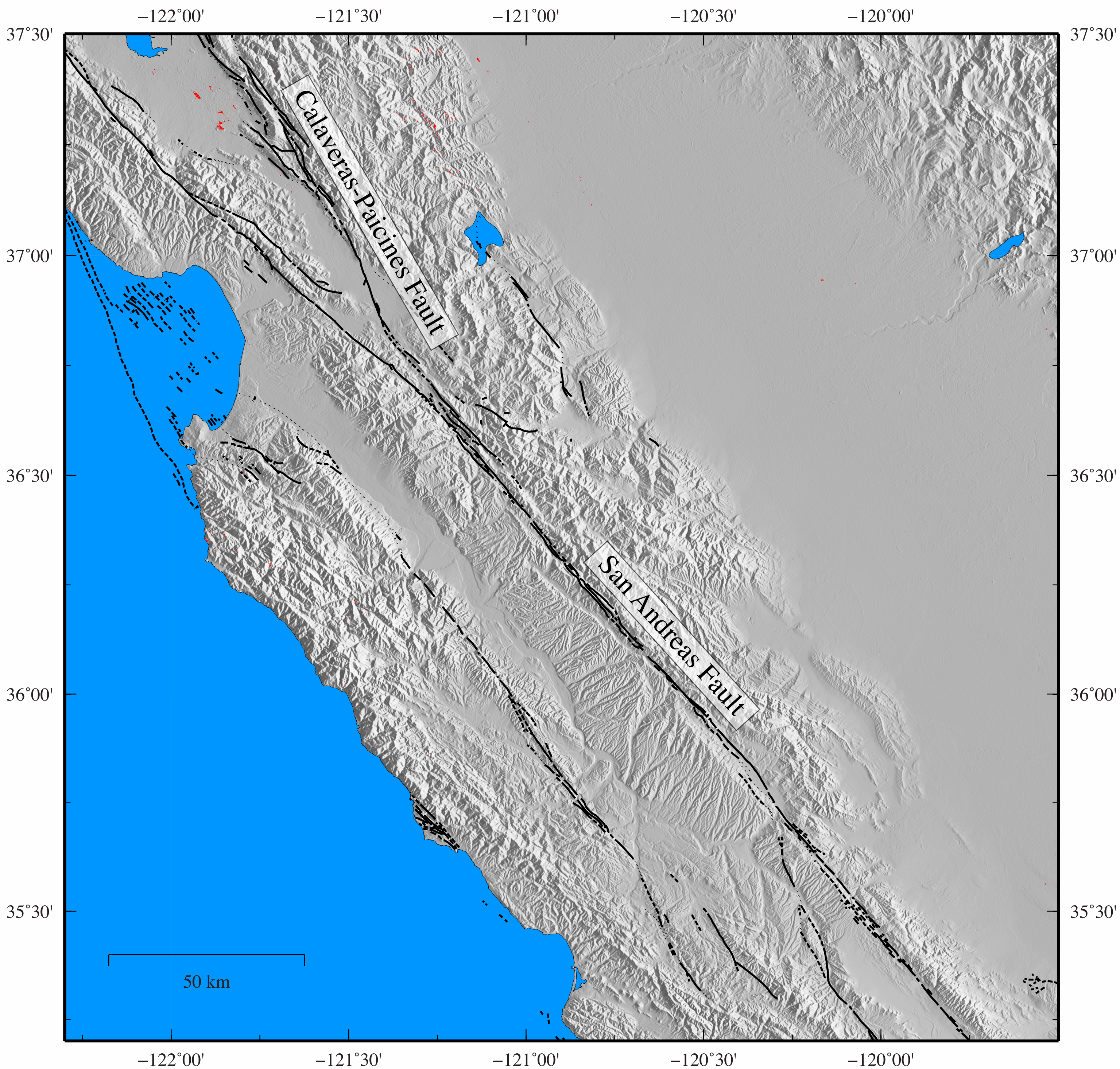
Part 3: Exploring the influence of fault geometry on aseismic slip from InSAR data.

Part 1: Bayesian sampling of the slip distribution along the San Andreas Fault



Seismotectonic Setting





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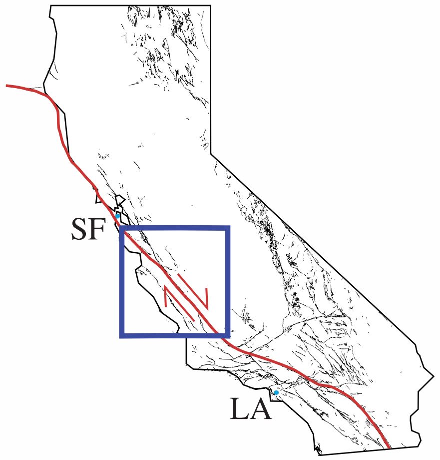
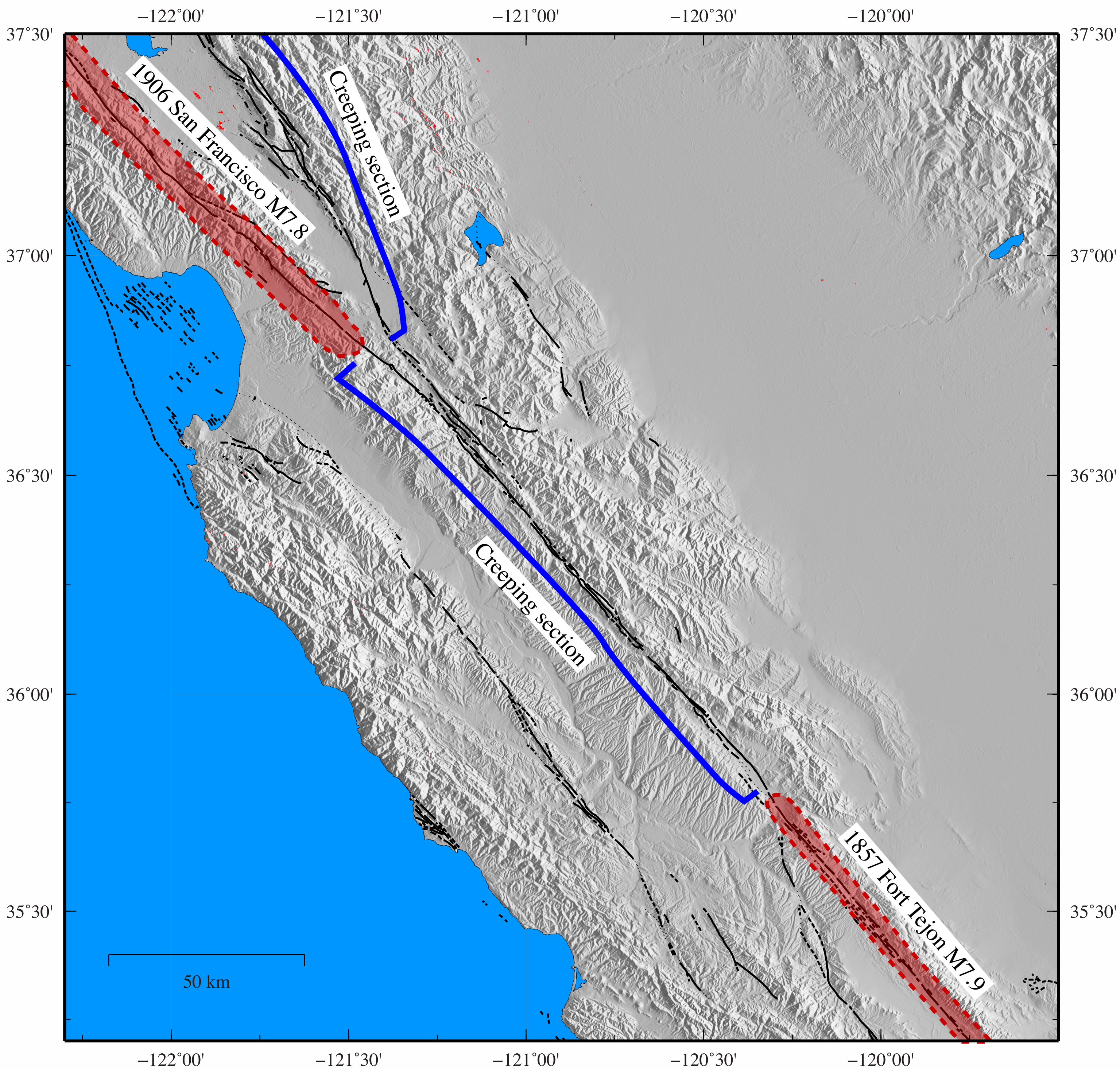
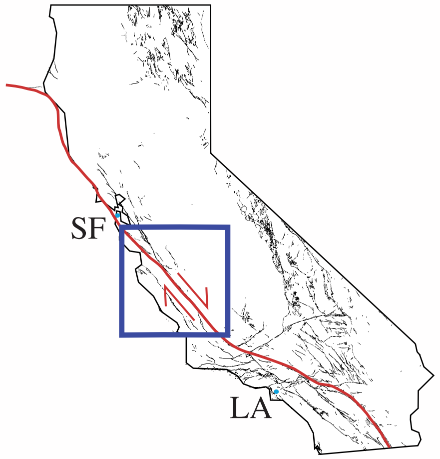
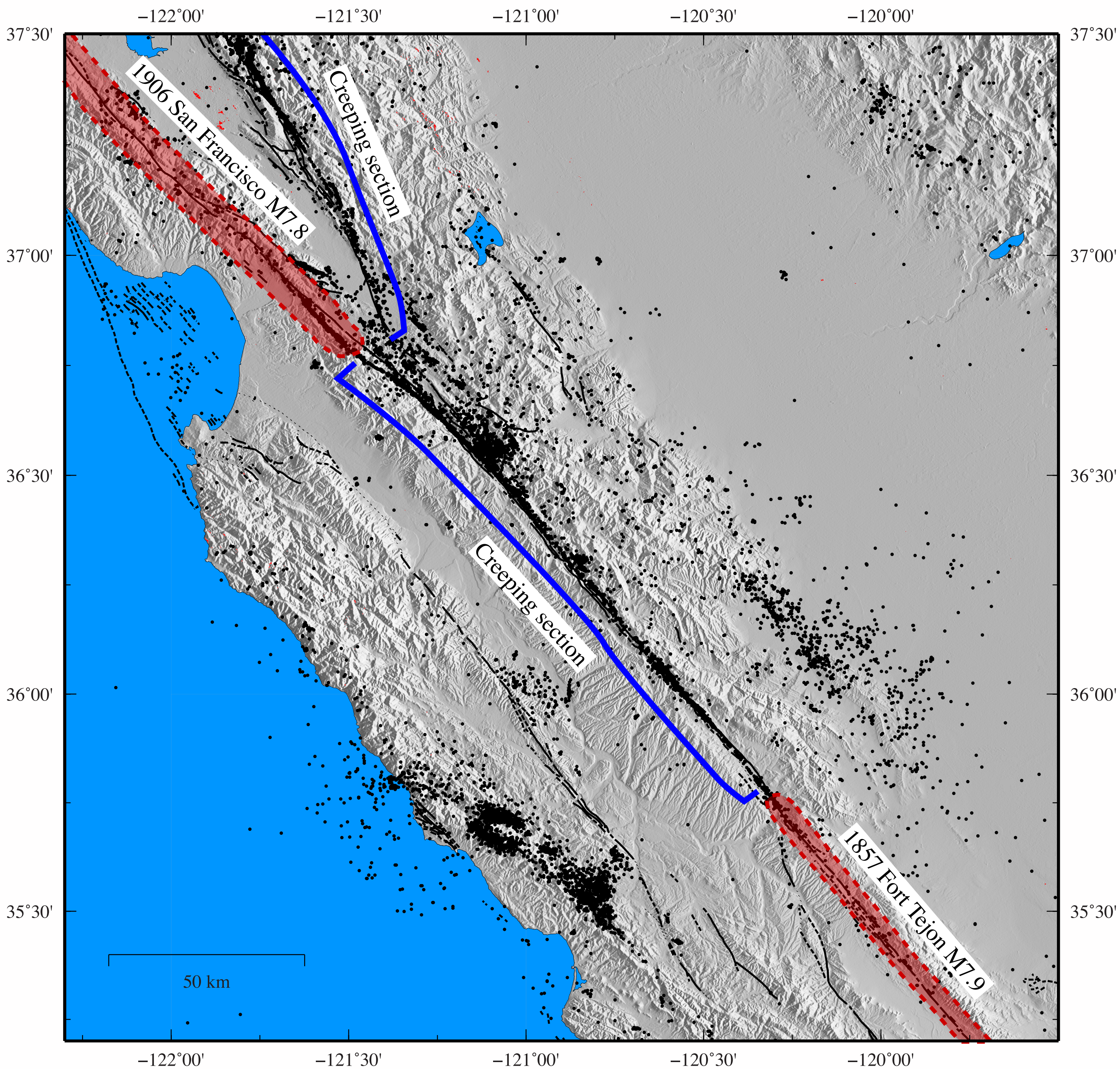




150 km-long Creeping section in between 2 historic M7.8 earthquake rupture traces

Seismotectonic Setting



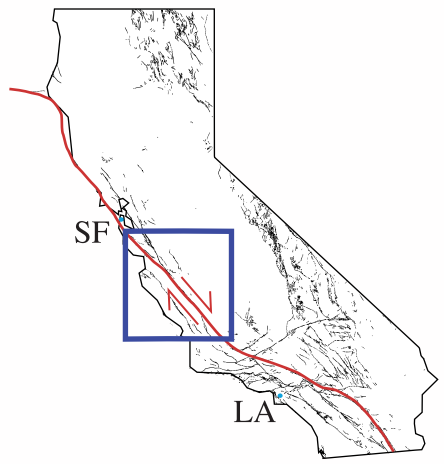


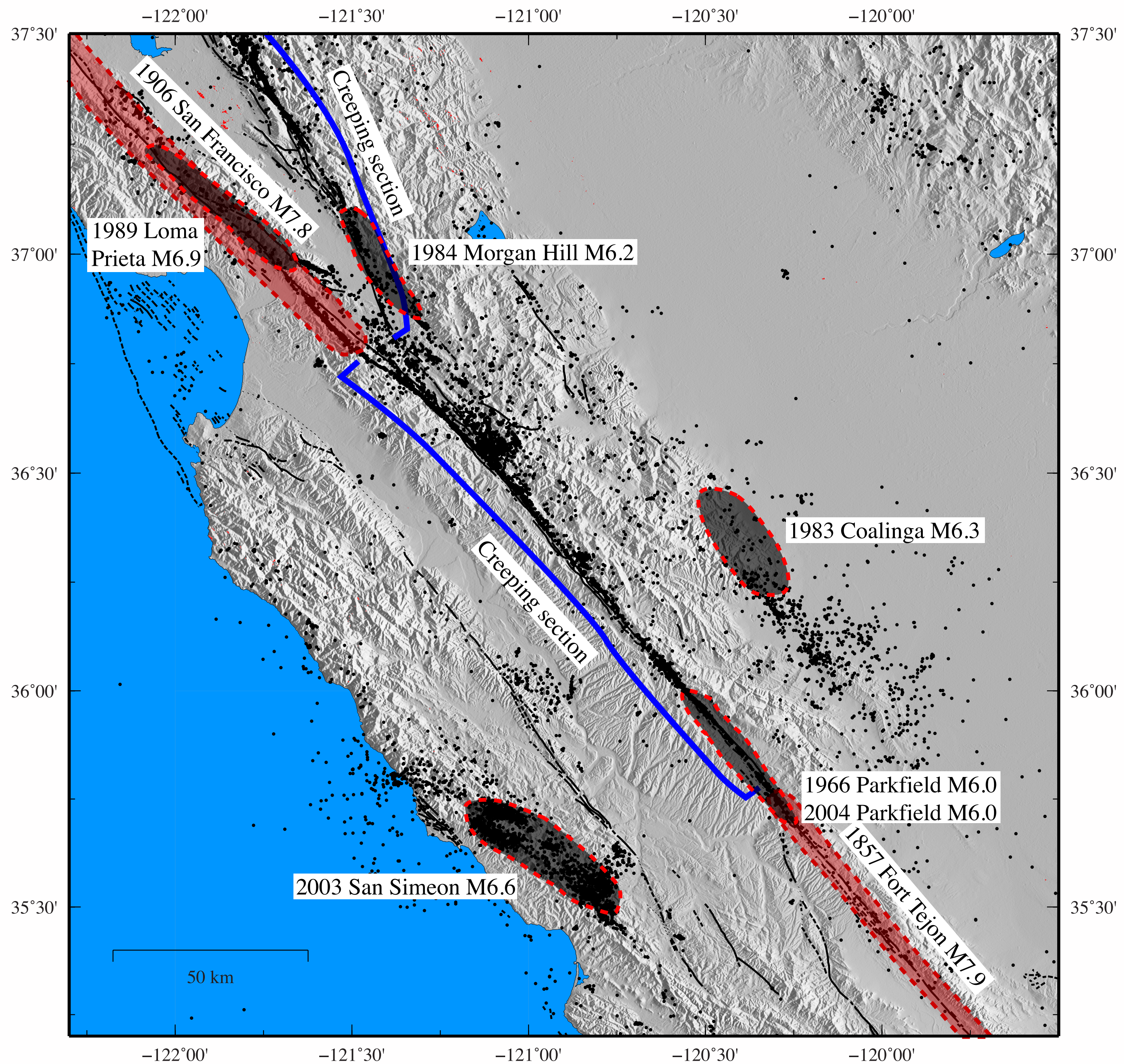
Waldhauser F. and Schaff D. P. (2005, 2008)

150 km-long Creeping section in between 2 historic M7.8 earthquake rupture traces

Strong Micro-seismic activity along the creeping sections (M<4 2006 -2010)

Seismotectonic Setting





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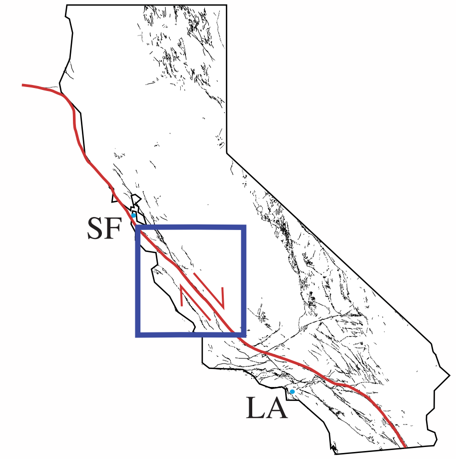

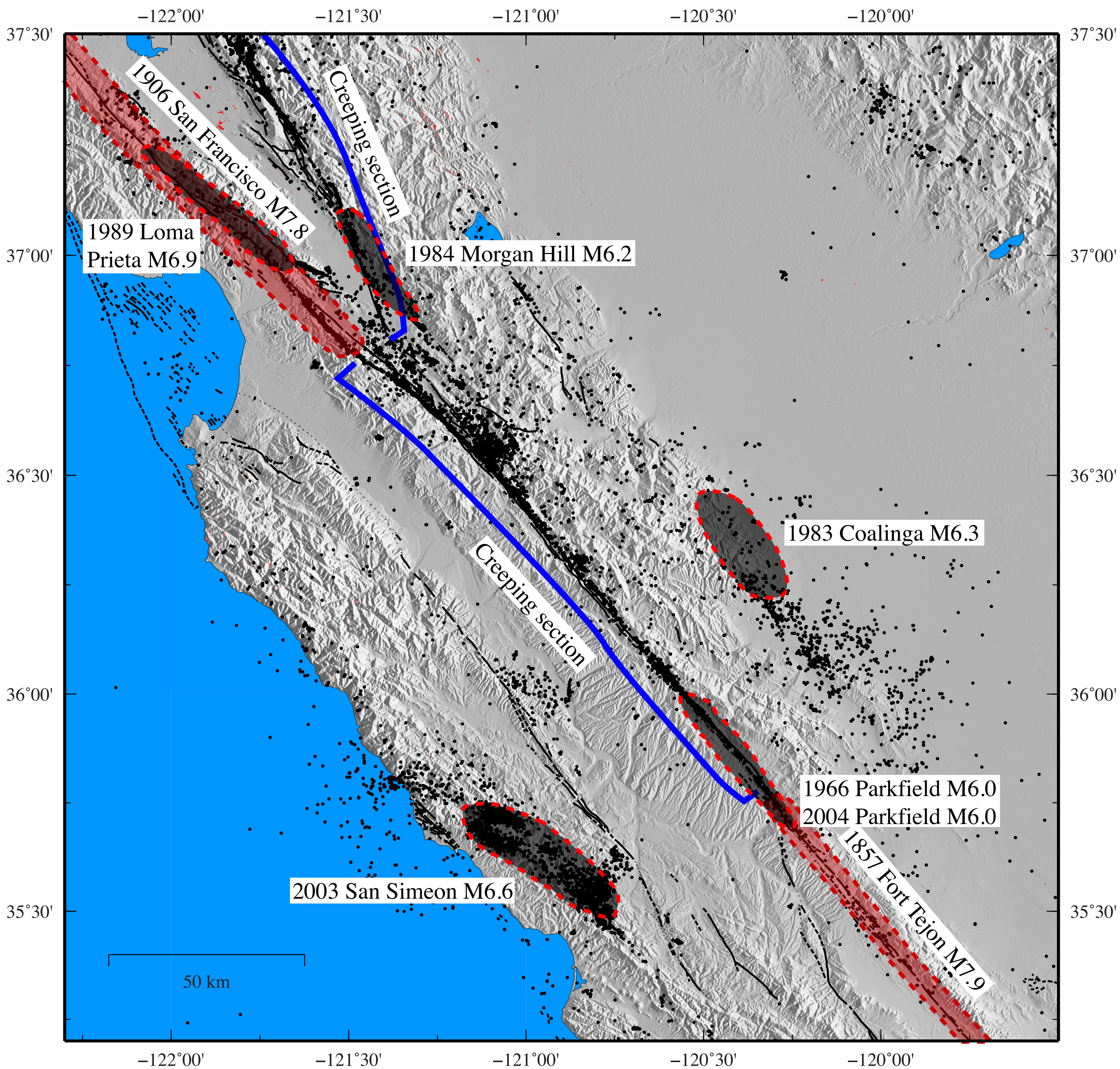

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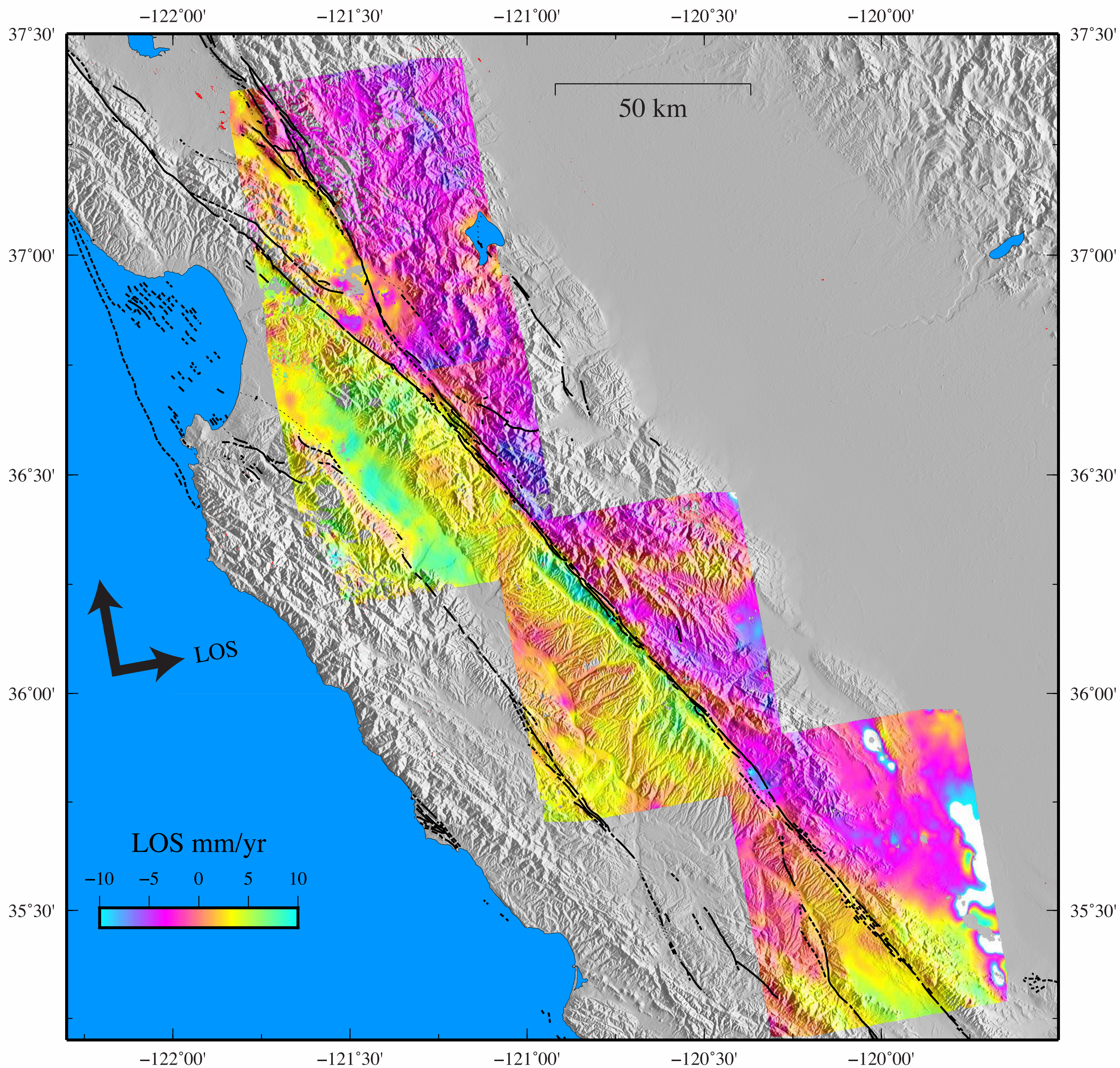
Slip Deficit Buildup rate?
Variability along strike?

Seismotectonic Setting

ALOS Data (L-Band)



Time Series 2006 -> 2010

Multiscale empirical atmospheric correction (Lin et al., 2010)

Multiscale Interferometric Time-Series (MInTS, Hetland et al., 2010)

1. Interferograms -> Wavelet
2. Velocity + Seasonal Term
3. Wavelet -> Velocity Map

Seismotectonic Setting

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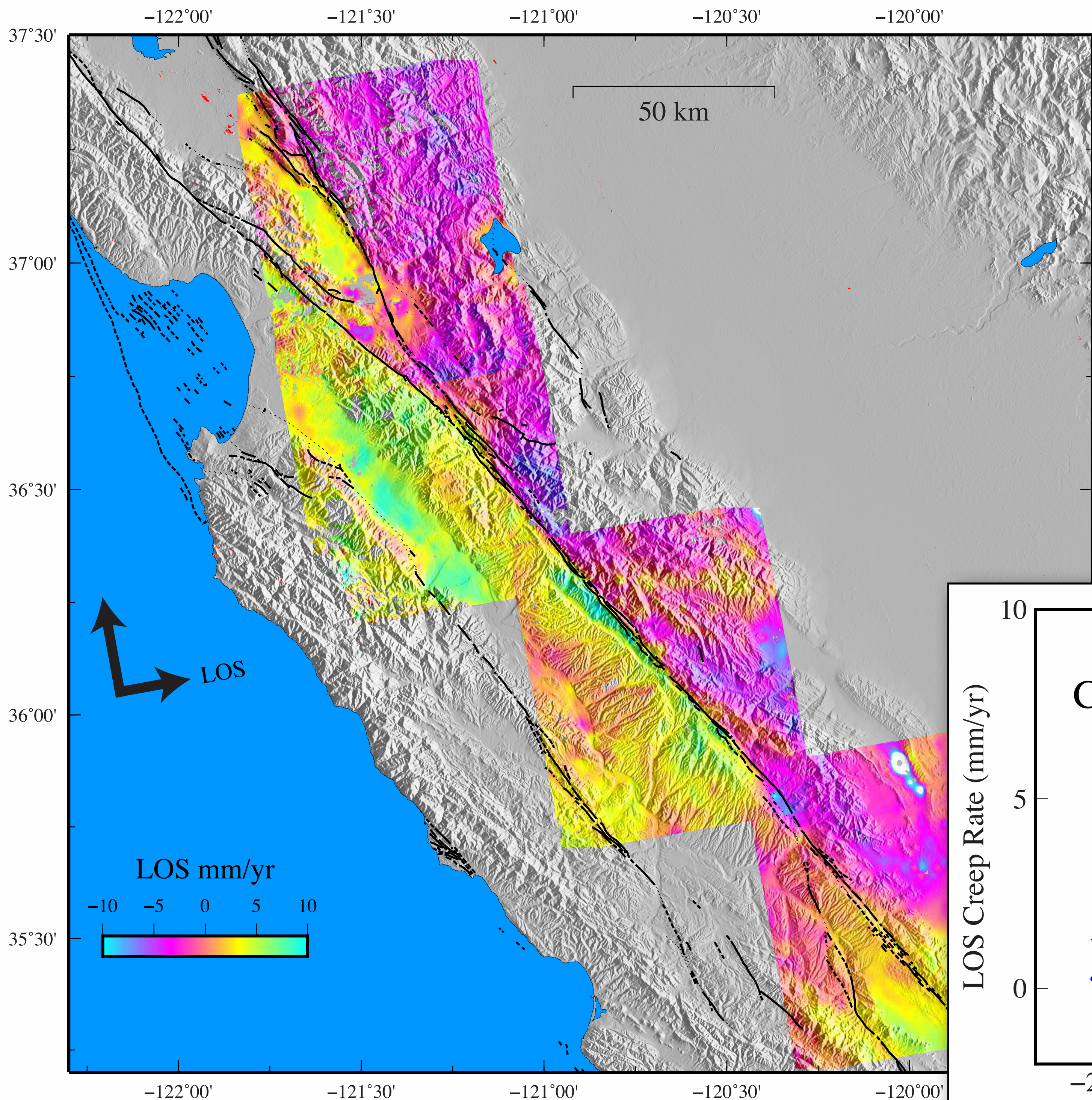

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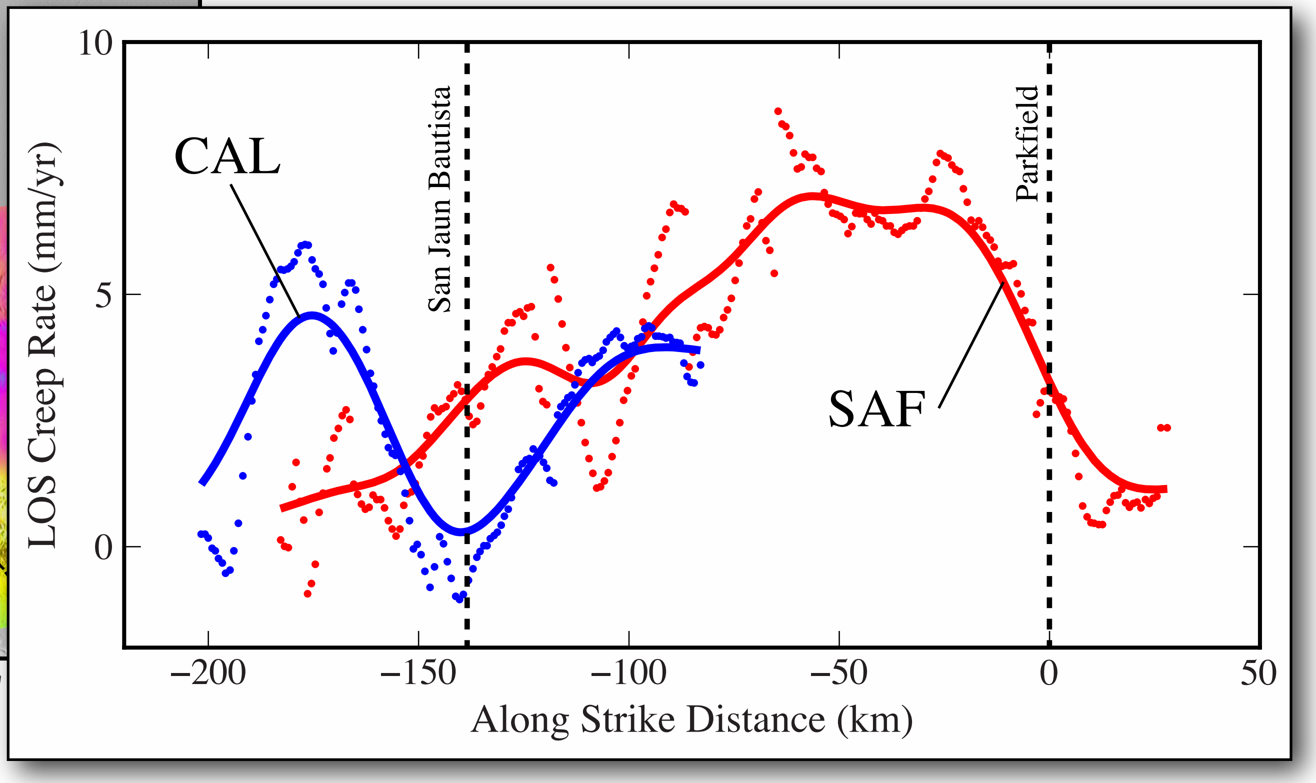
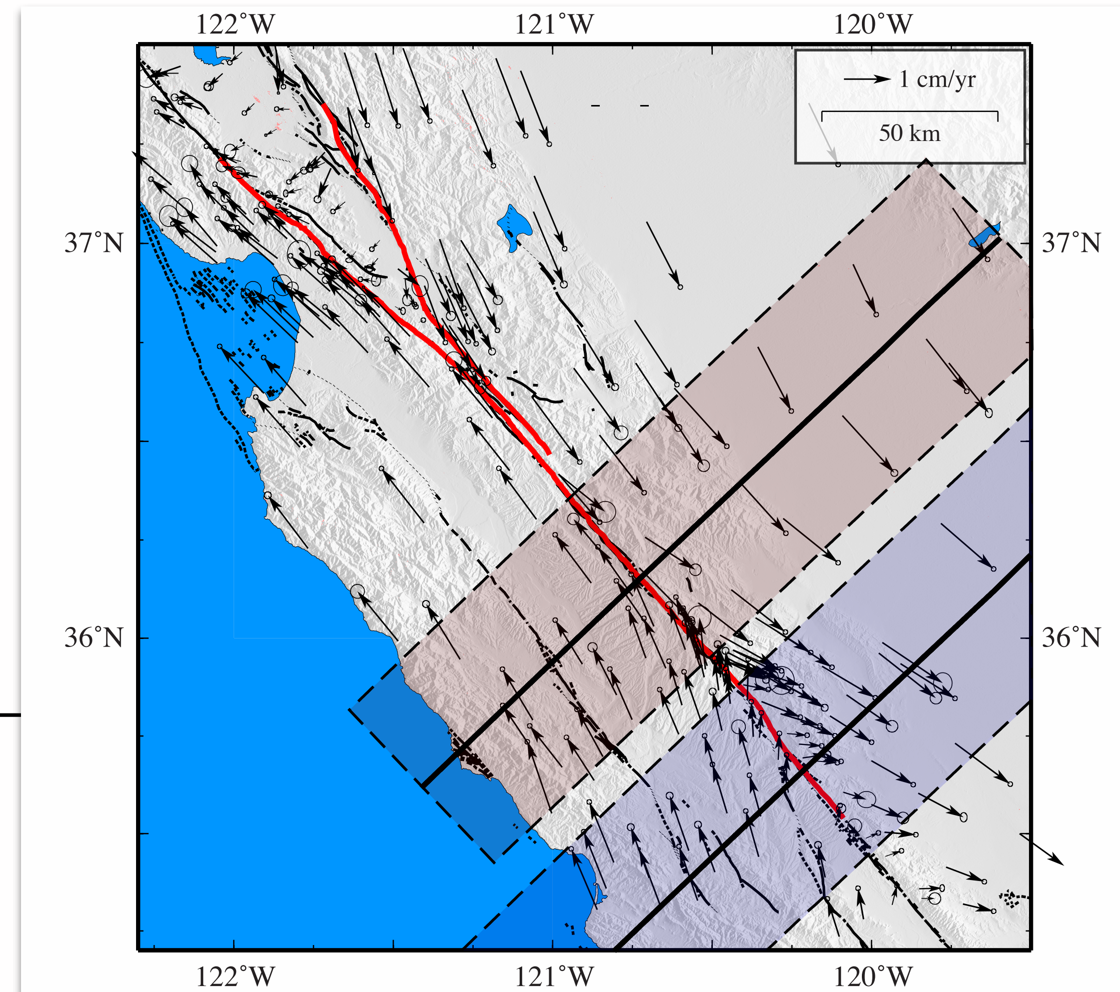
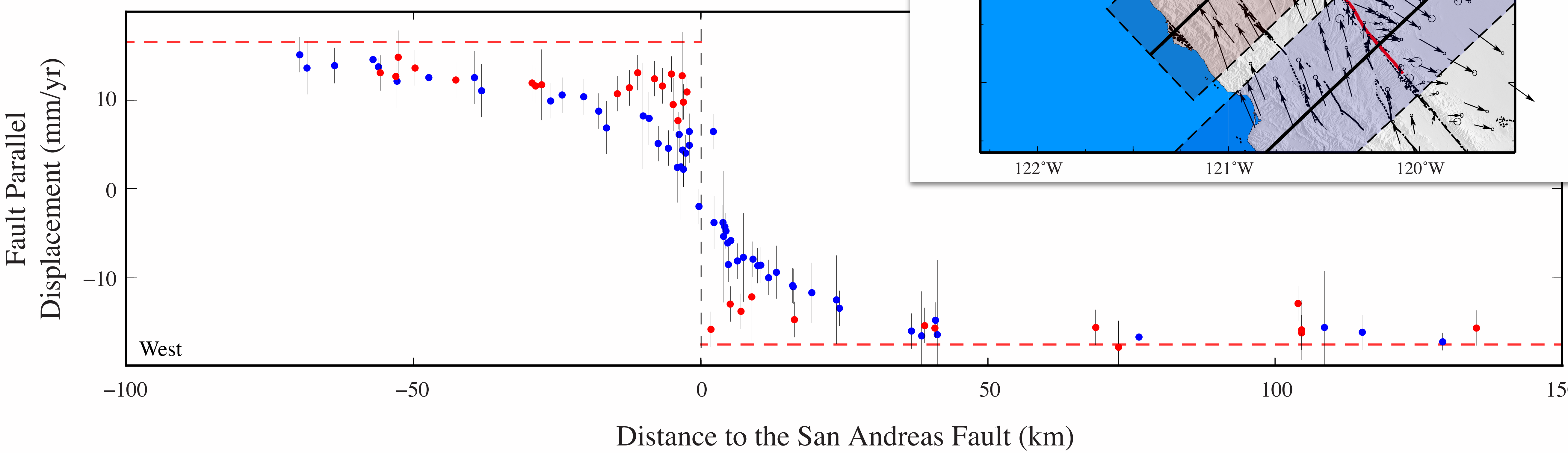


GPS Velocity Field

United Western US Crustal Motion Map
(Z.-K. Shen)

Campaign data from UNAVCO, SCEC, NCEDC and USGS data centers
Period: 1993 - 2011
Common mode errors estimated
Extract the Velocity from Time Series and Campaign sites





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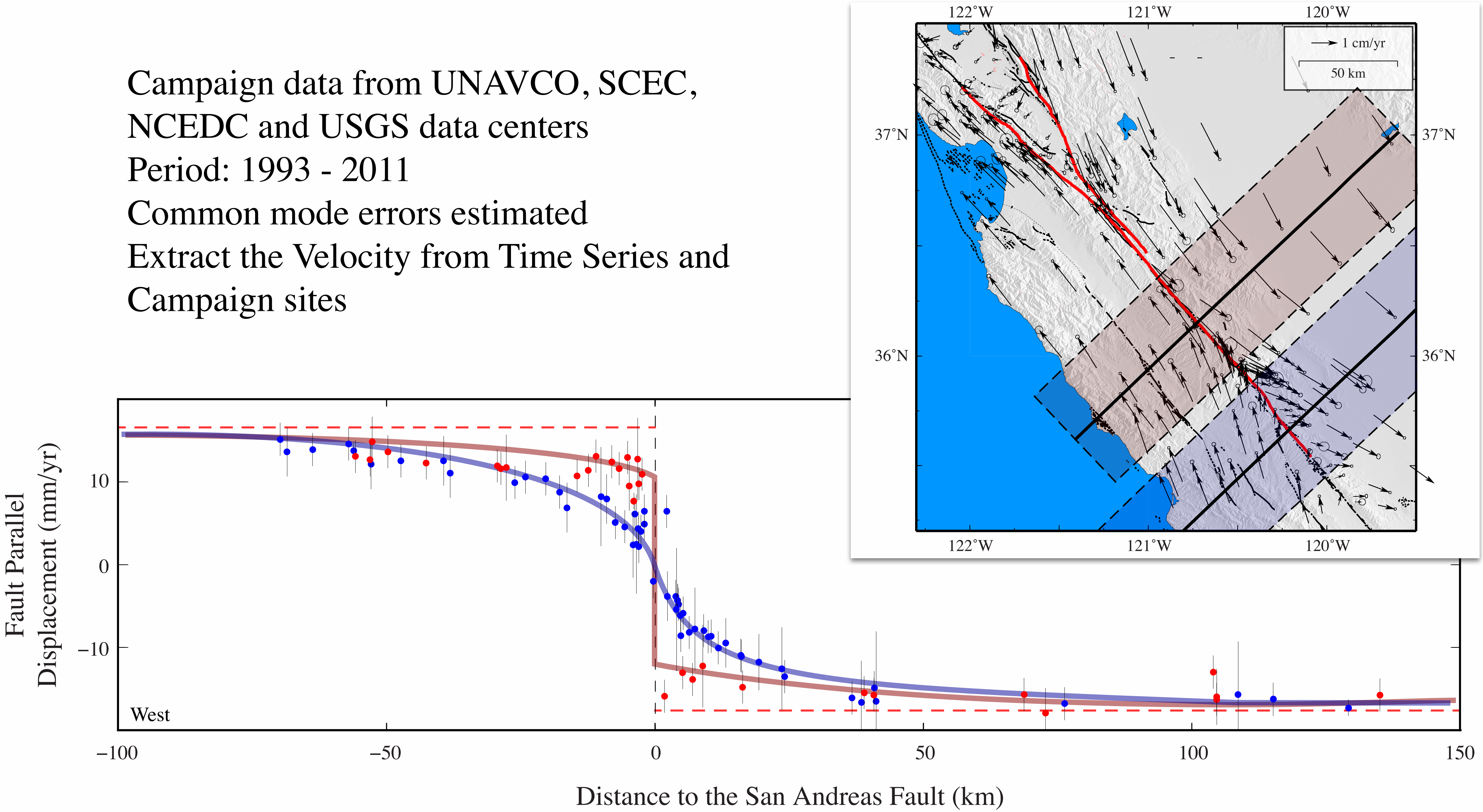
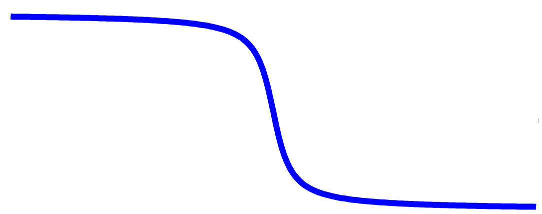


Model Parameterization

<u>Conceptual Model:</u>

Interseismic Loading



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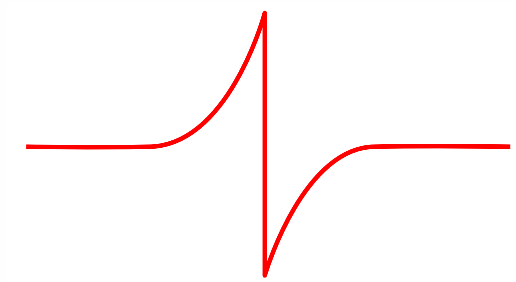
Shallow Creep



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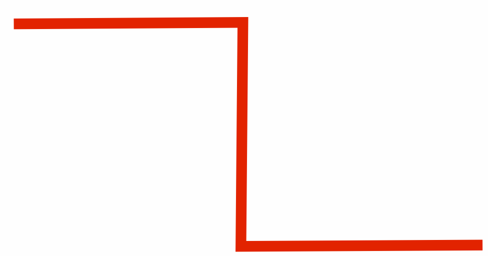
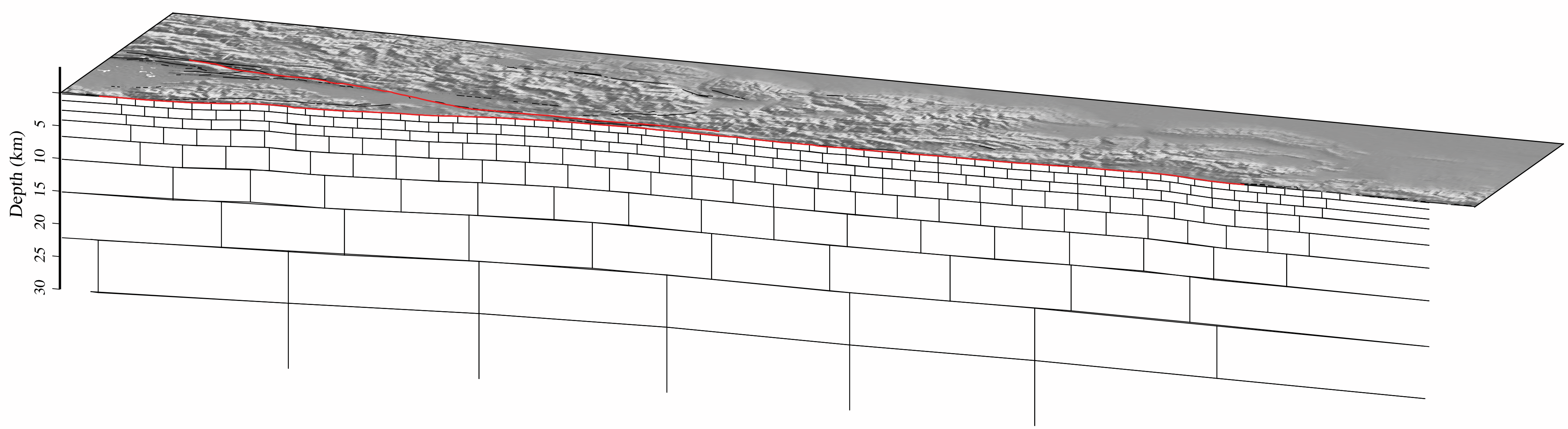


Surface Displacement



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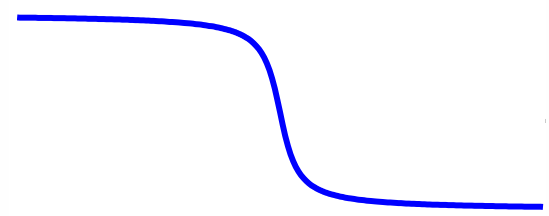

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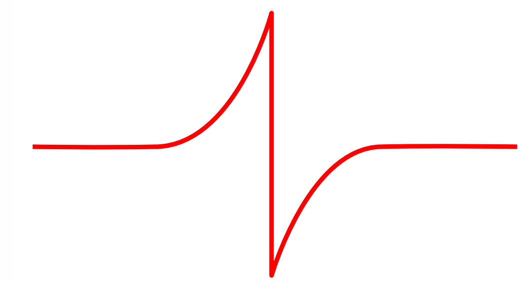

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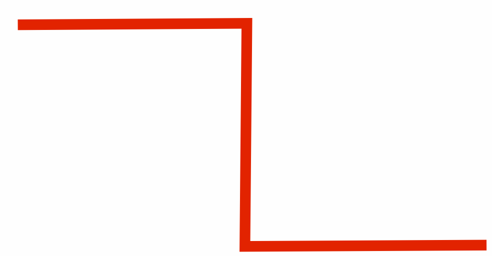

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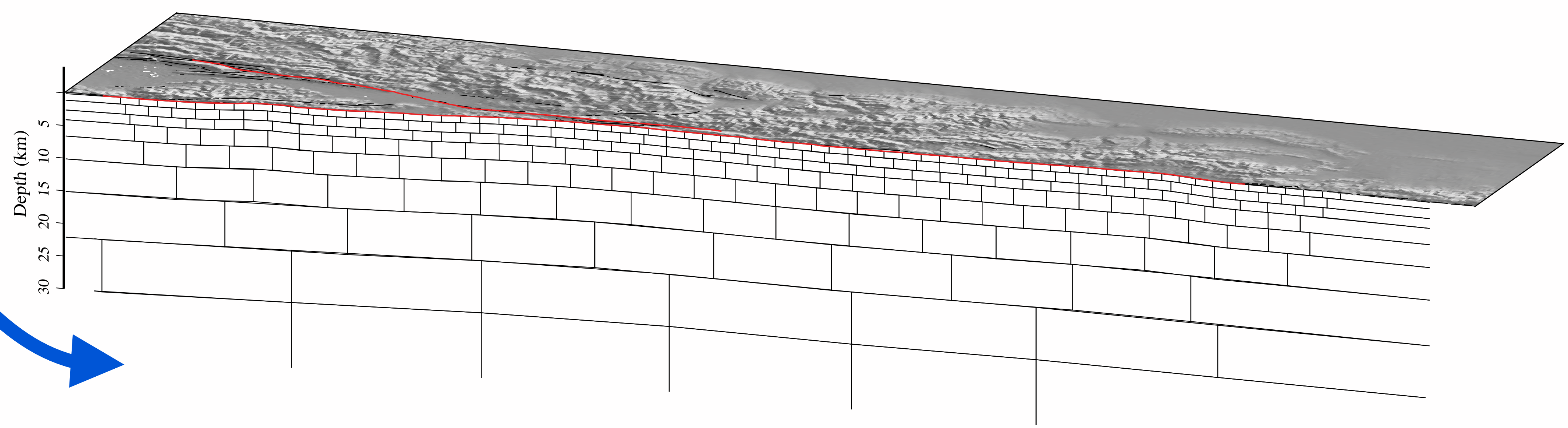

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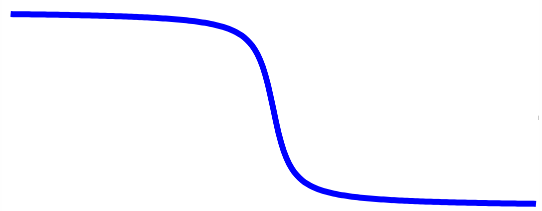

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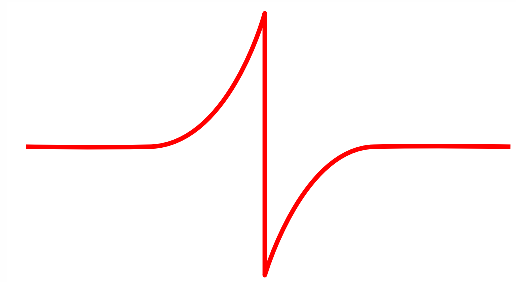

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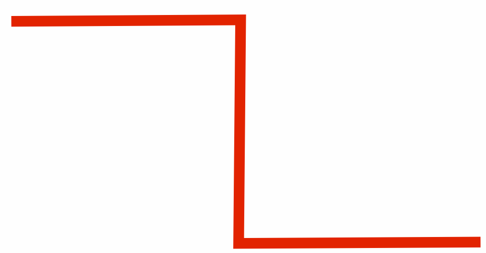

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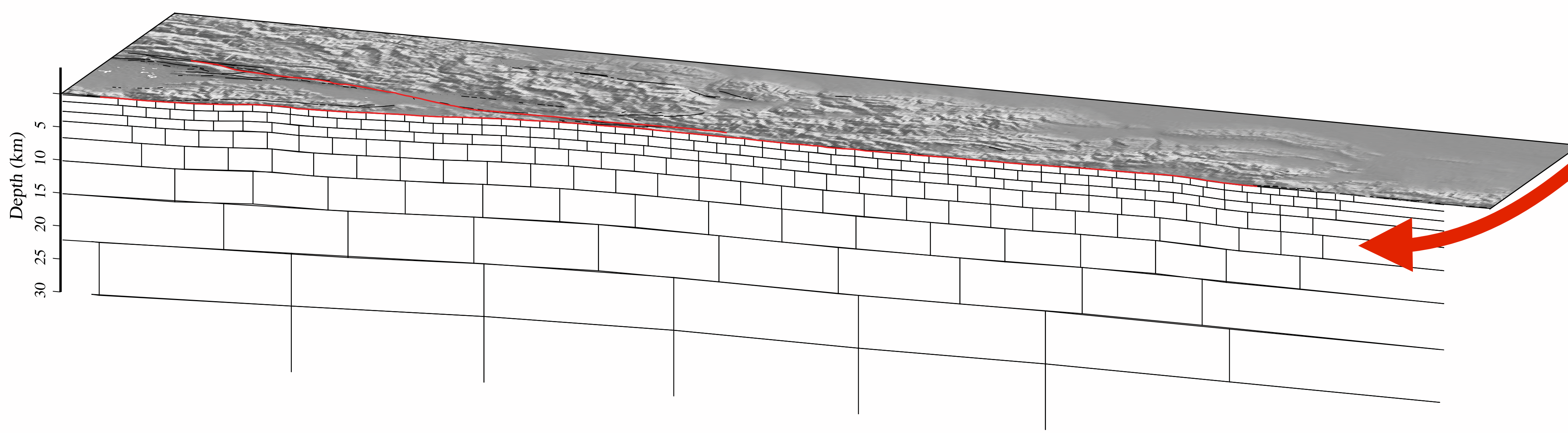
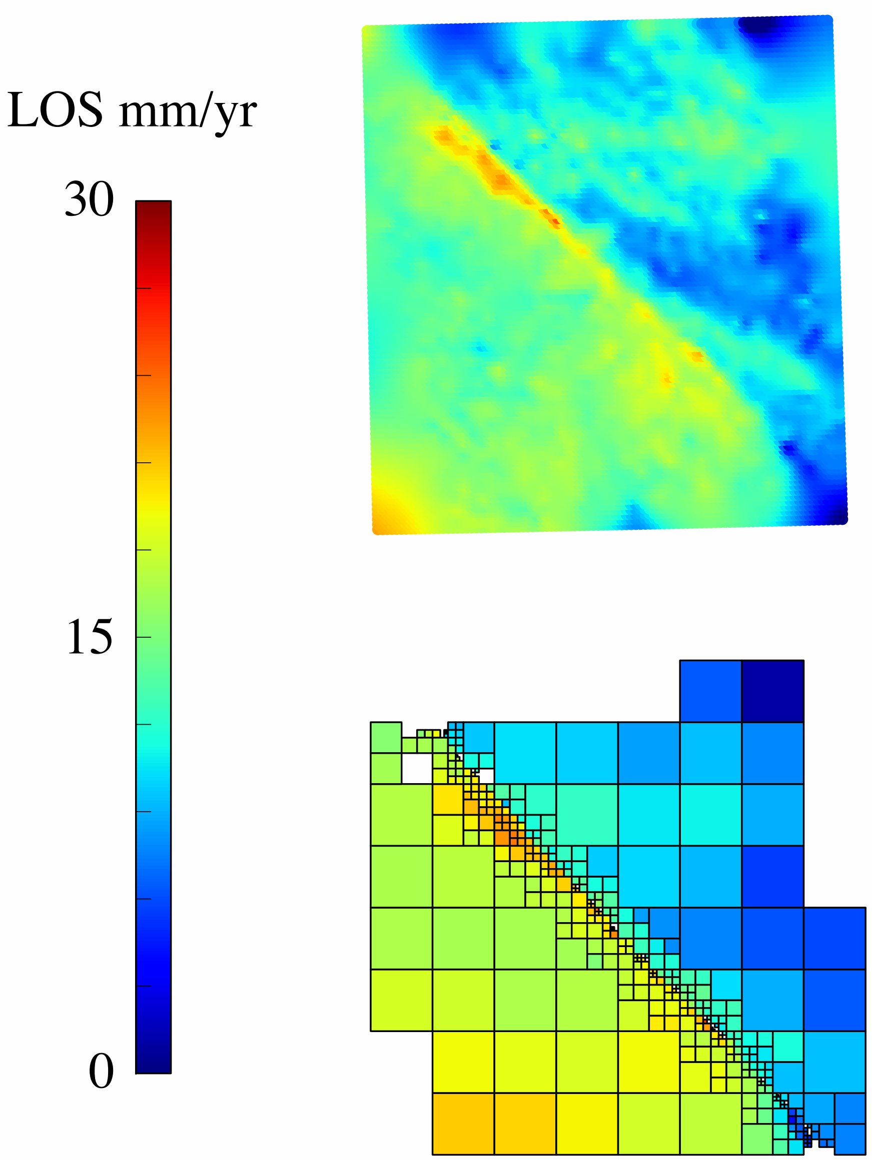


Inversion Strategy

$$\mathbf{d} = \mathbf{G}\mathbf{m}$$

Resolution-based
Quadtree downsampling

- Shallow slip (strike + dip)
- Deep slip (strike)
- Nuisance Parameters



Lohman and Simons, 2005

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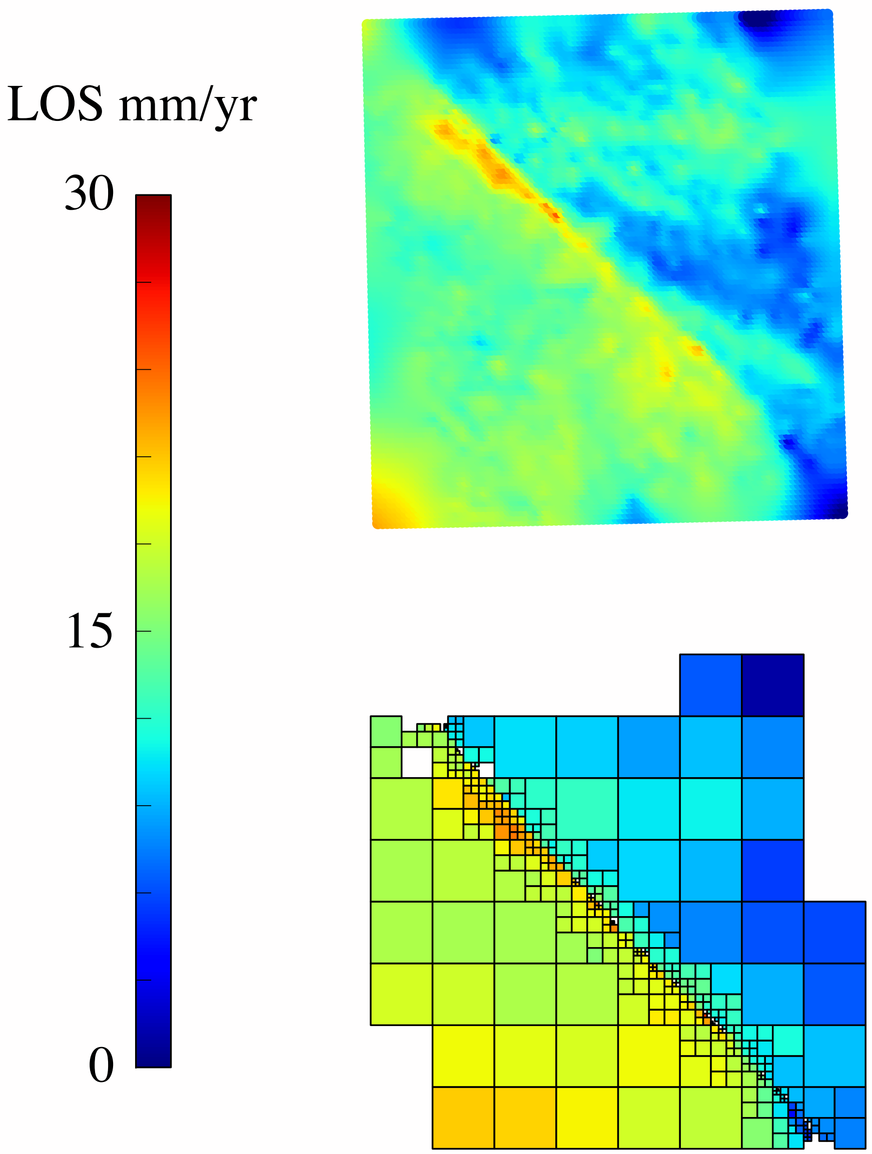

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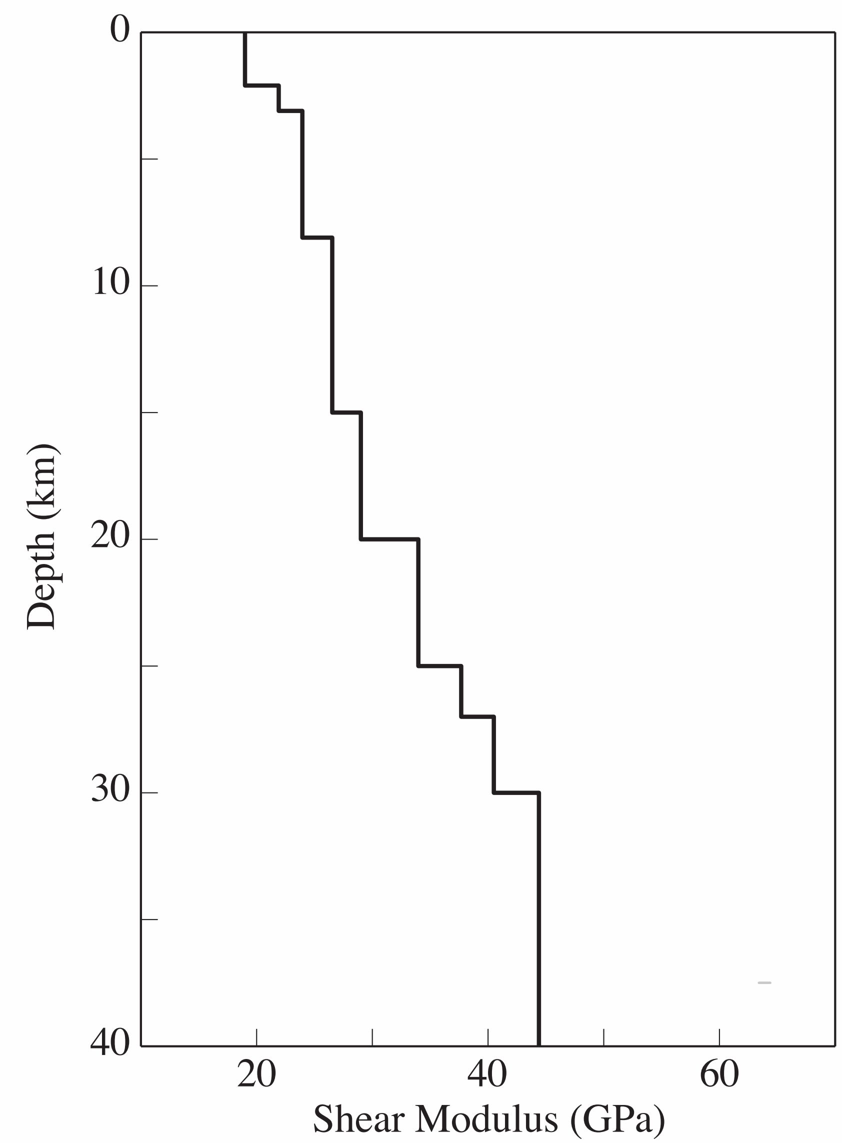

Elastic Semi-Infinite
Stratified Half-Space
(EDKS Software)

Velocity structure derived from Lin, Thurber et al 2010 BSSA

Density structure derived from Christensen and Mooney, 1995, JGR

Bayesian Sampling and Error Model

$$p(\mathbf{m}|\mathbf{d}_{\text{obs}}) \propto p(\mathbf{m}) \exp\left[-\frac{1}{2}(\mathbf{d}-\mathbf{Gm})^T \mathbf{C}_\chi^{-1}(\mathbf{d}-\mathbf{Gm})\right]$$

Posterior PDF $\propto$ Prior PDF $\times$ Likelihood

Bayesian Sampling and Error Model

$$p(\mathbf{m}|\mathbf{d}_{\text{obs}}) \propto p(\mathbf{m}) \exp\left[-\frac{1}{2}(\mathbf{d}-\mathbf{G}\mathbf{m})^T \mathbf{C}_\chi^{-1} (\mathbf{d}-\mathbf{G}\mathbf{m}) \right]$$

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Positivity on strike-slip parameters (Uniform)

Gaussian centered on 0 on dip-slip parameters

Uniform prior on the "nuisance" parameters

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Combines the data and the associated covariances

As we do not have smoothing, we need an accurate description of errors to not overfit the data

$$\mathbf{C}_\chi = \mathbf{C}_d + \mathbf{C}_p$$

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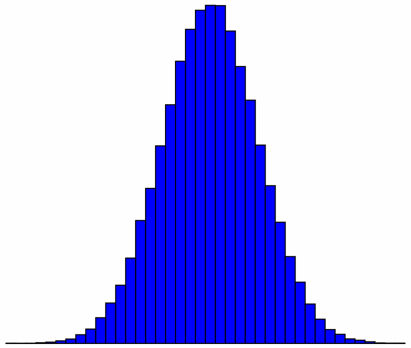
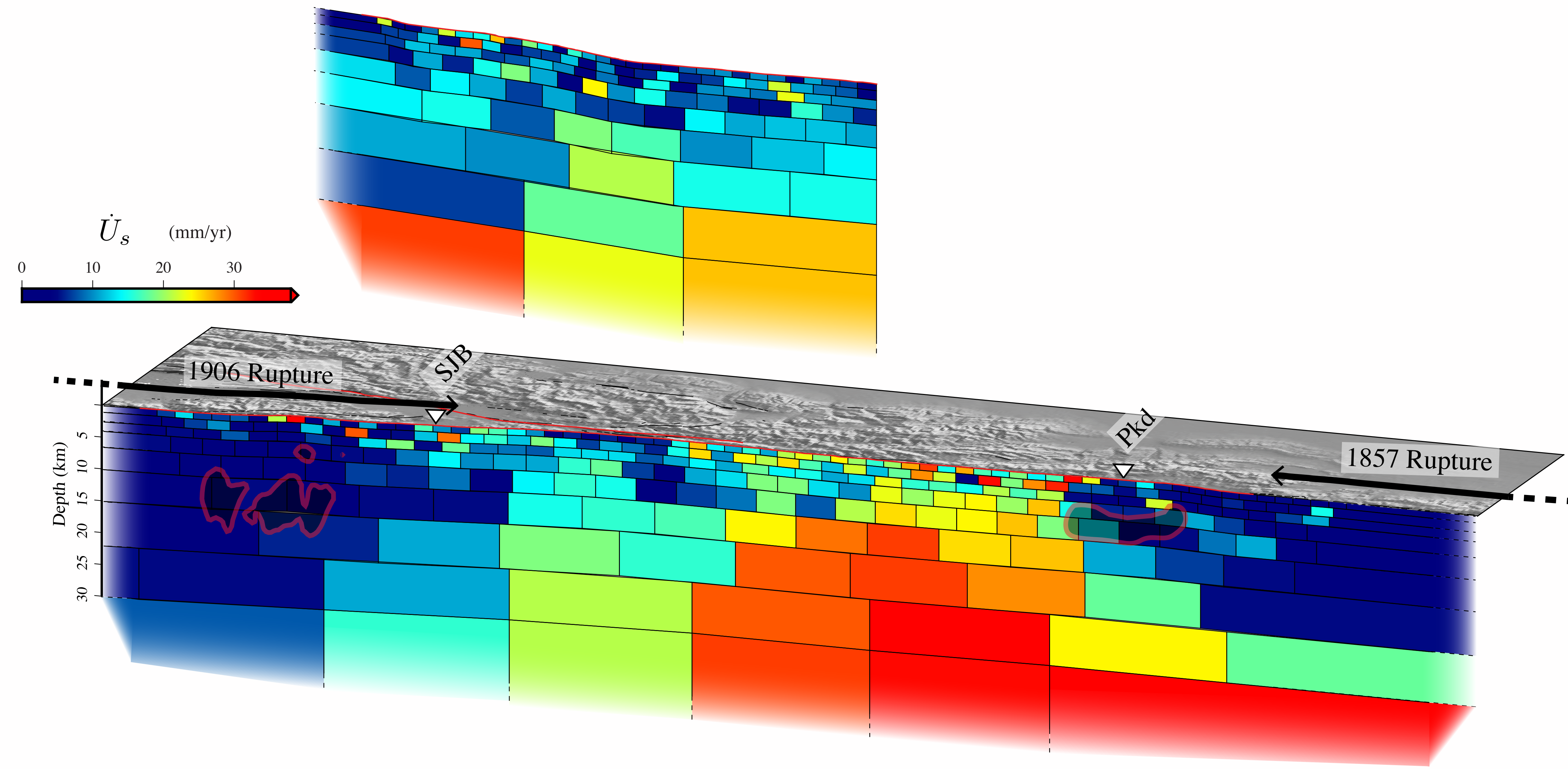


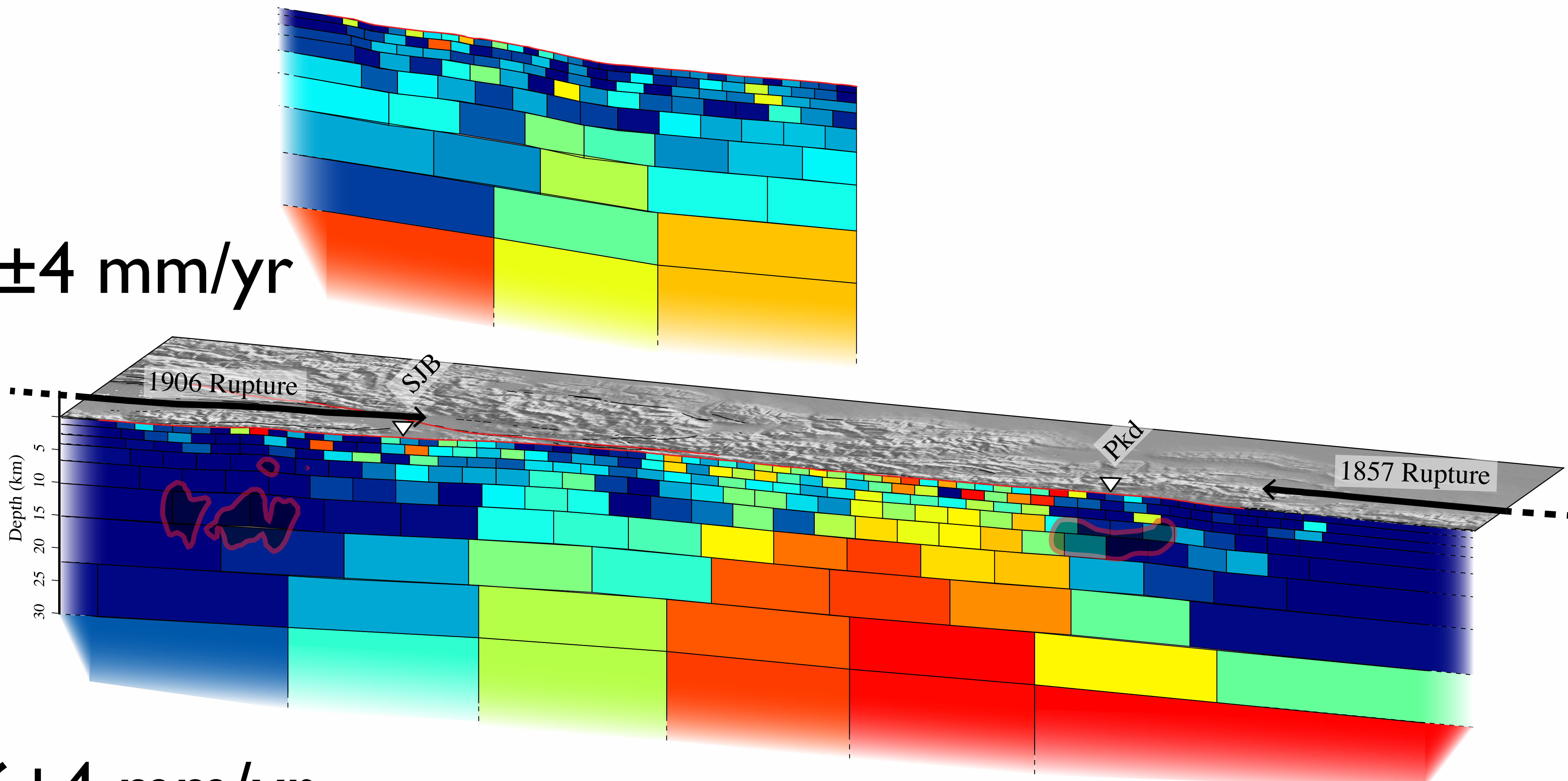
The PDF of the model allowed by the data and their associated errors

Maximum Likelihood Model



Maximum Likelihood Model

26±4 mm/yr

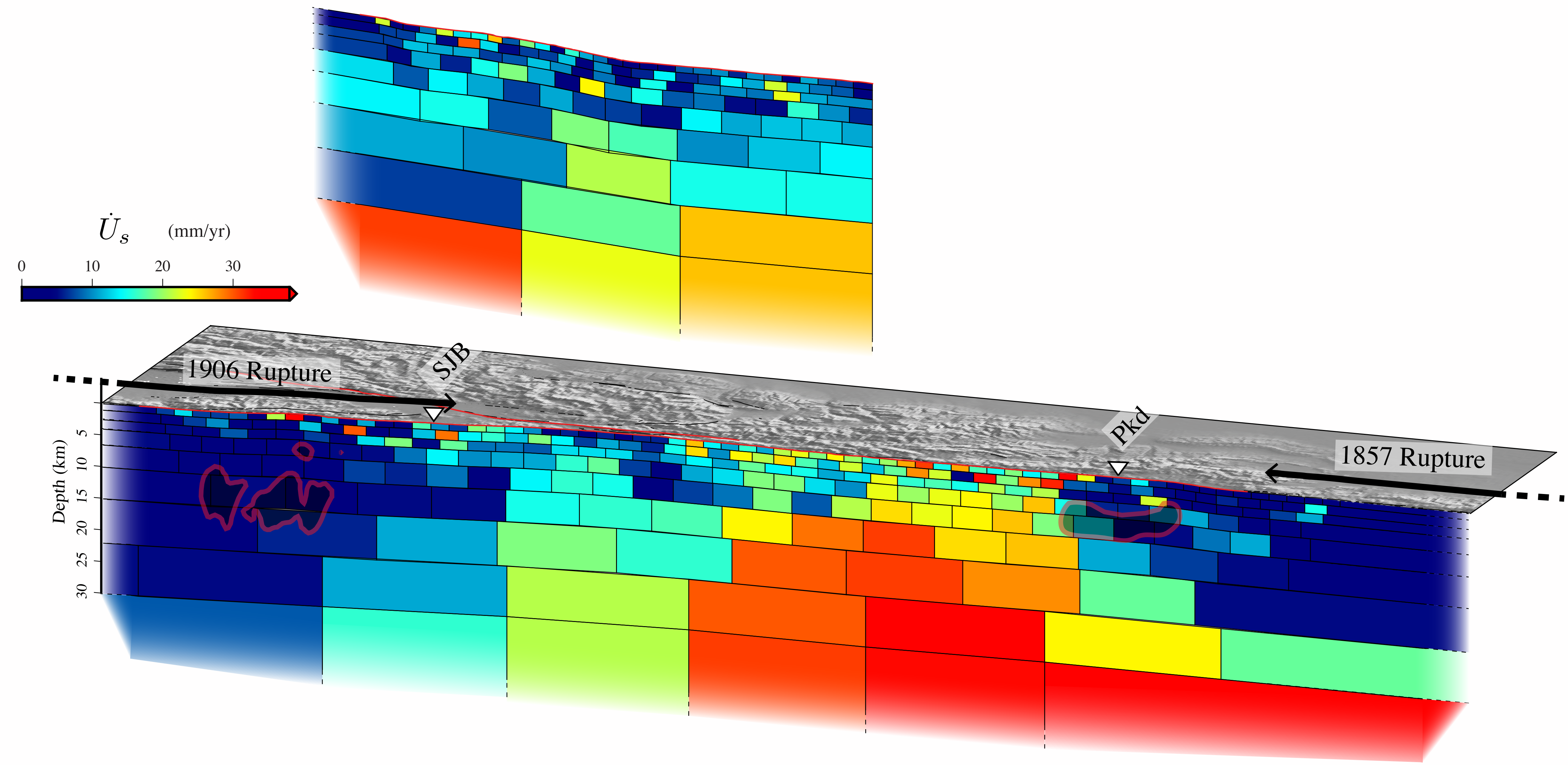


16±4 mm/yr

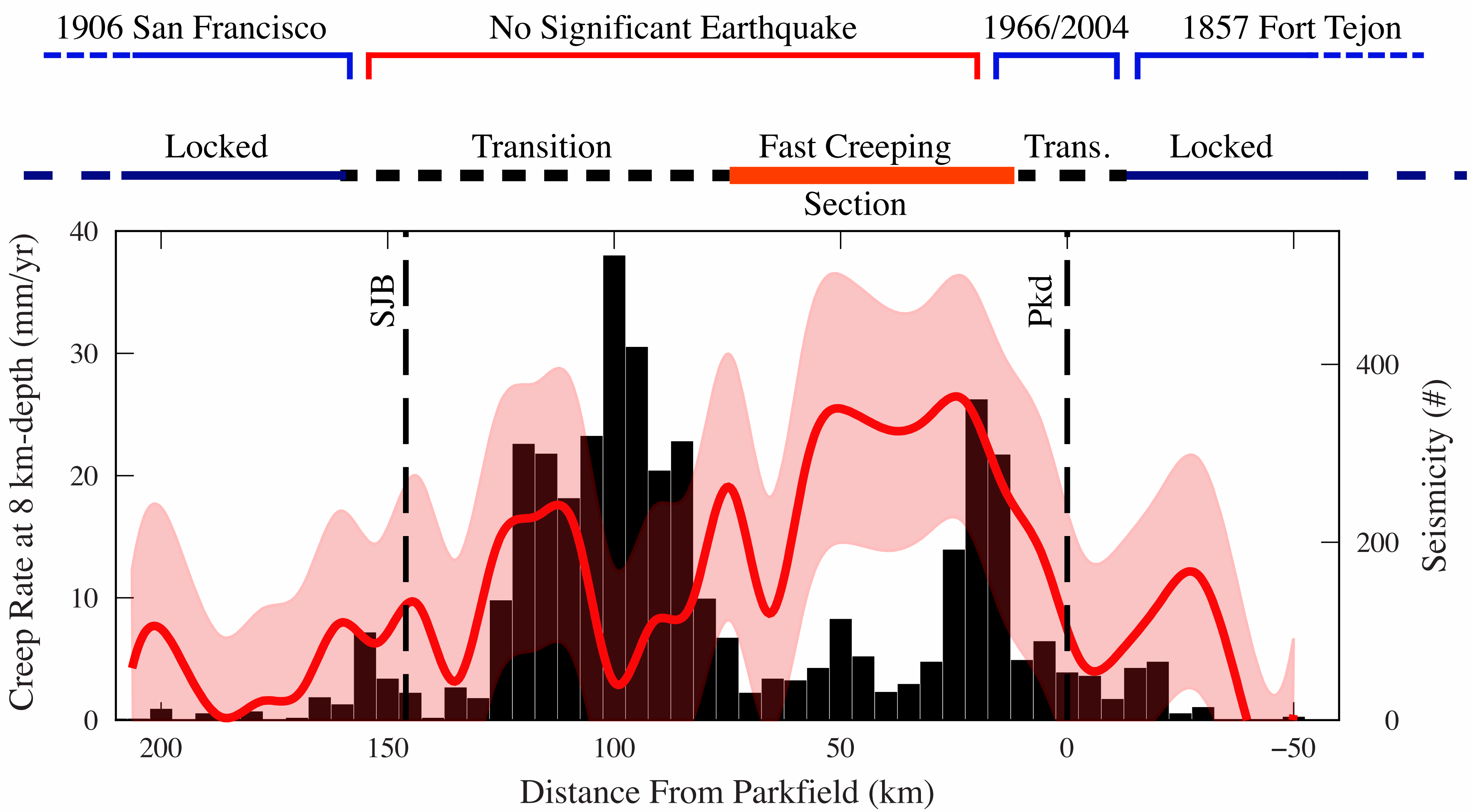
36±2 mm/yr

Constant deep loading rate along-strike with partitioning on sub-parallel structures

Maximum Likelihood Model



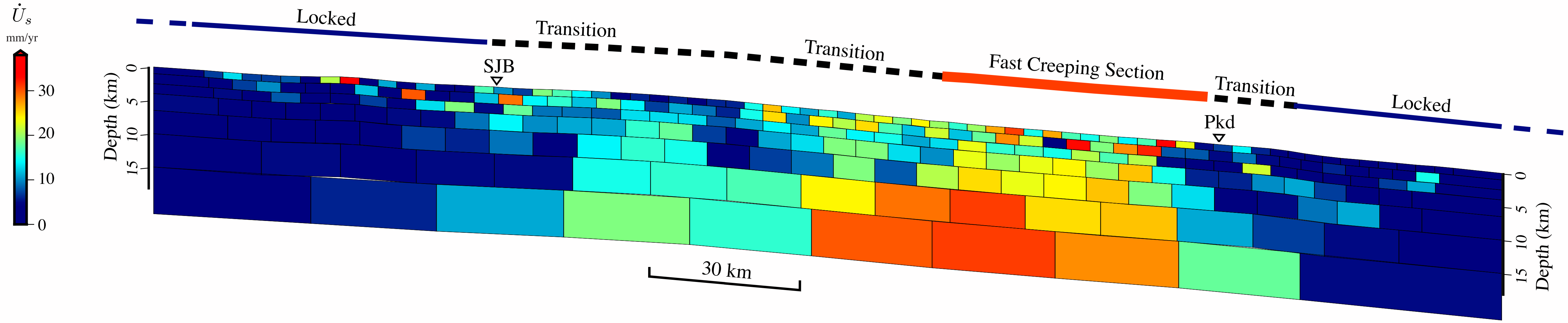
Along-Strike variations of creep



Transitioning from Fast Creeping to Locked through "rough" fault zones

Microseismicity: Waldhauser F. and Schaff D. P. (2005, 2008)

Identifying Asperities and Creeping segments: How robust?



Because we sample the distribution of possible models, we can derive probabilistic answers to simple questions

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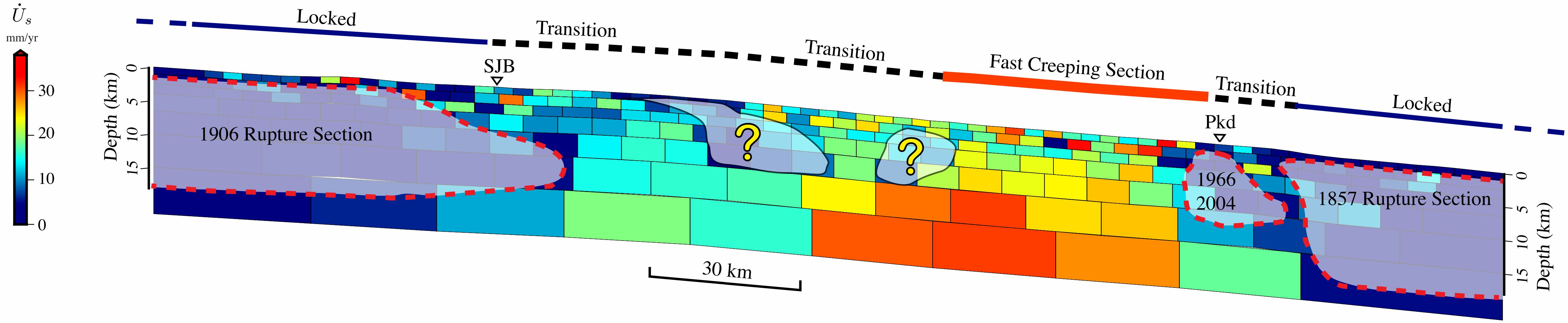

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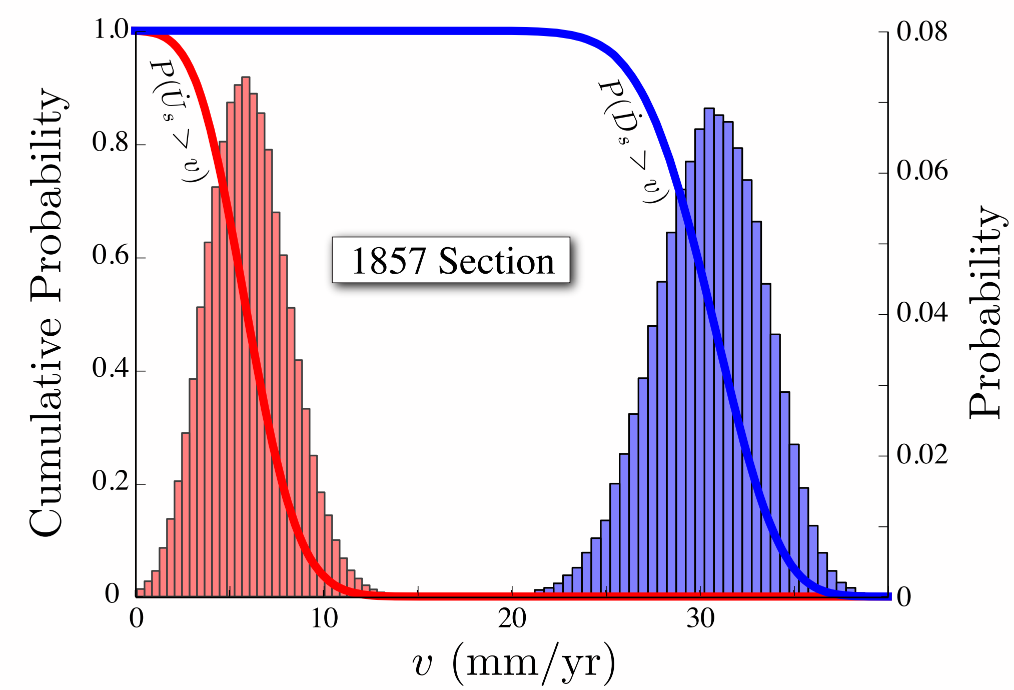

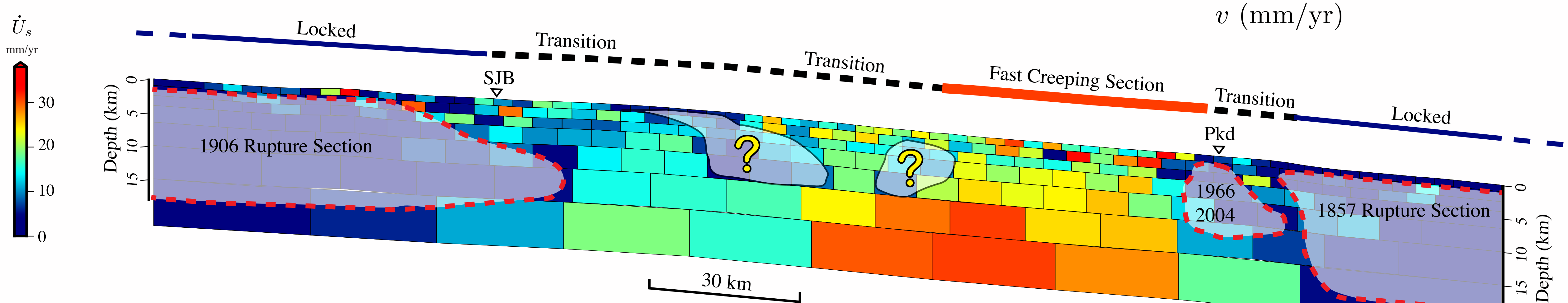

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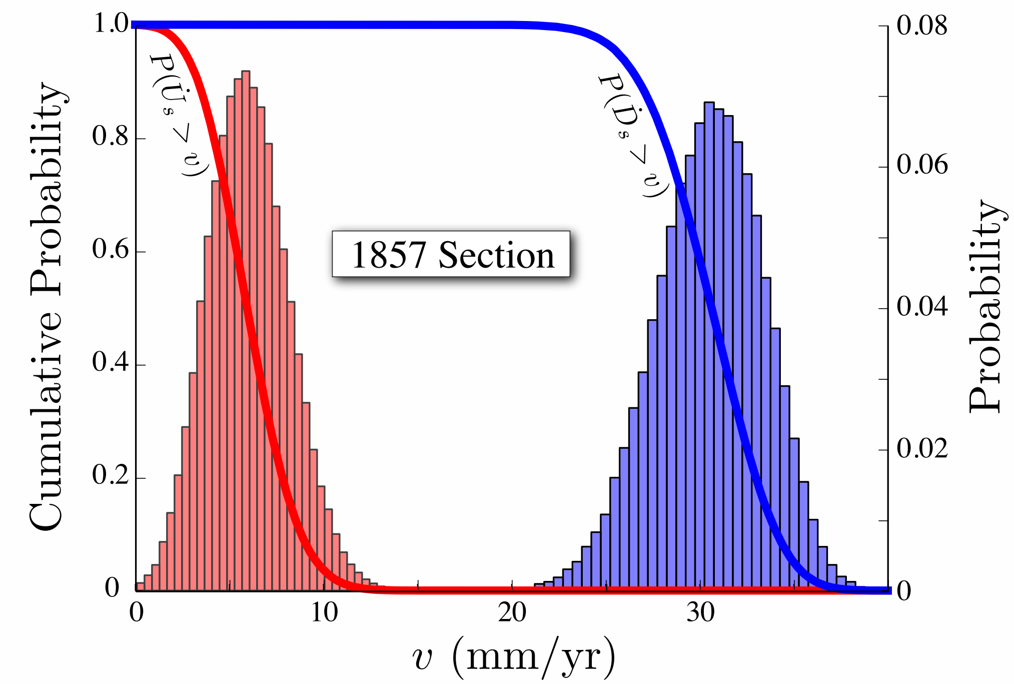
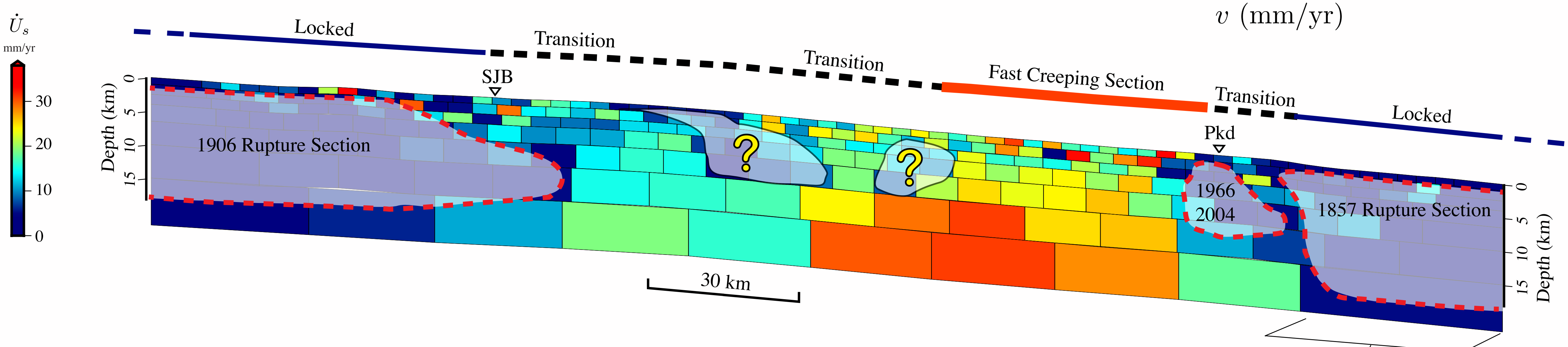
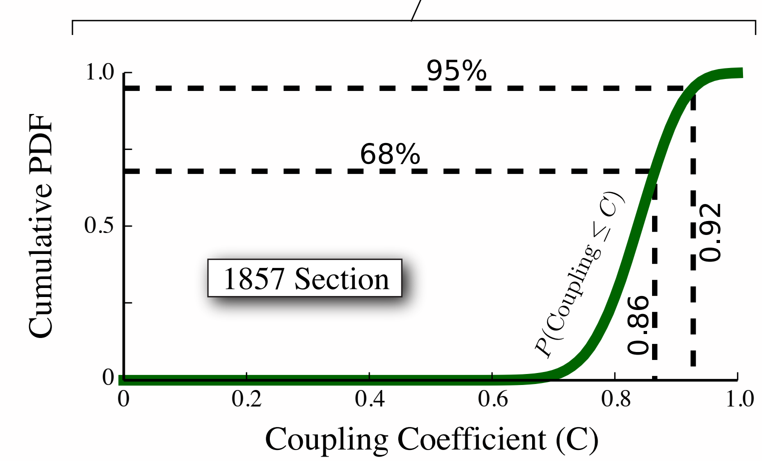


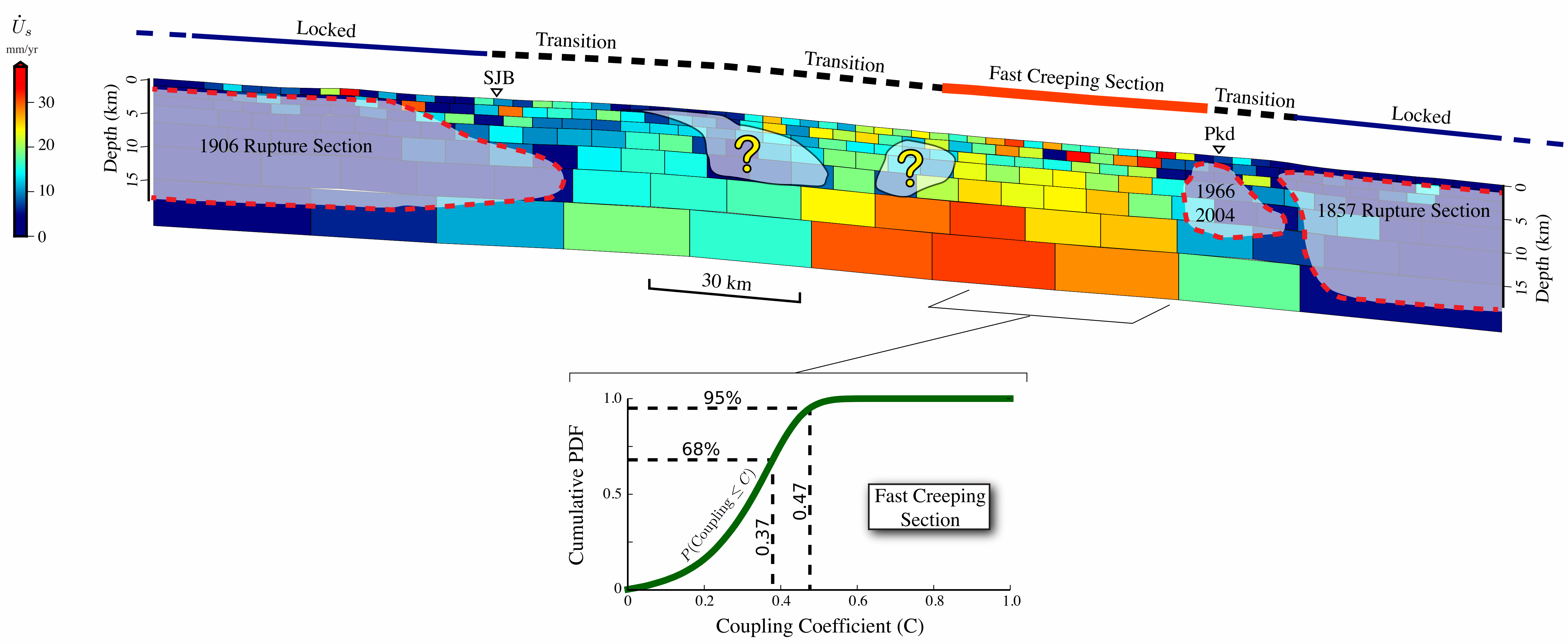




The probability that fault coupling is lower than 0.7 is 0
(i.e. there is a 100% chance that coupling is higher)

Identifying Asperities and Creeping segments: How robust?

- There is 50% chance that coupling is lower than 0.5 along the creeping segment
- There is 50% chance that the slip deficit is higher than 1 cm/yr !!



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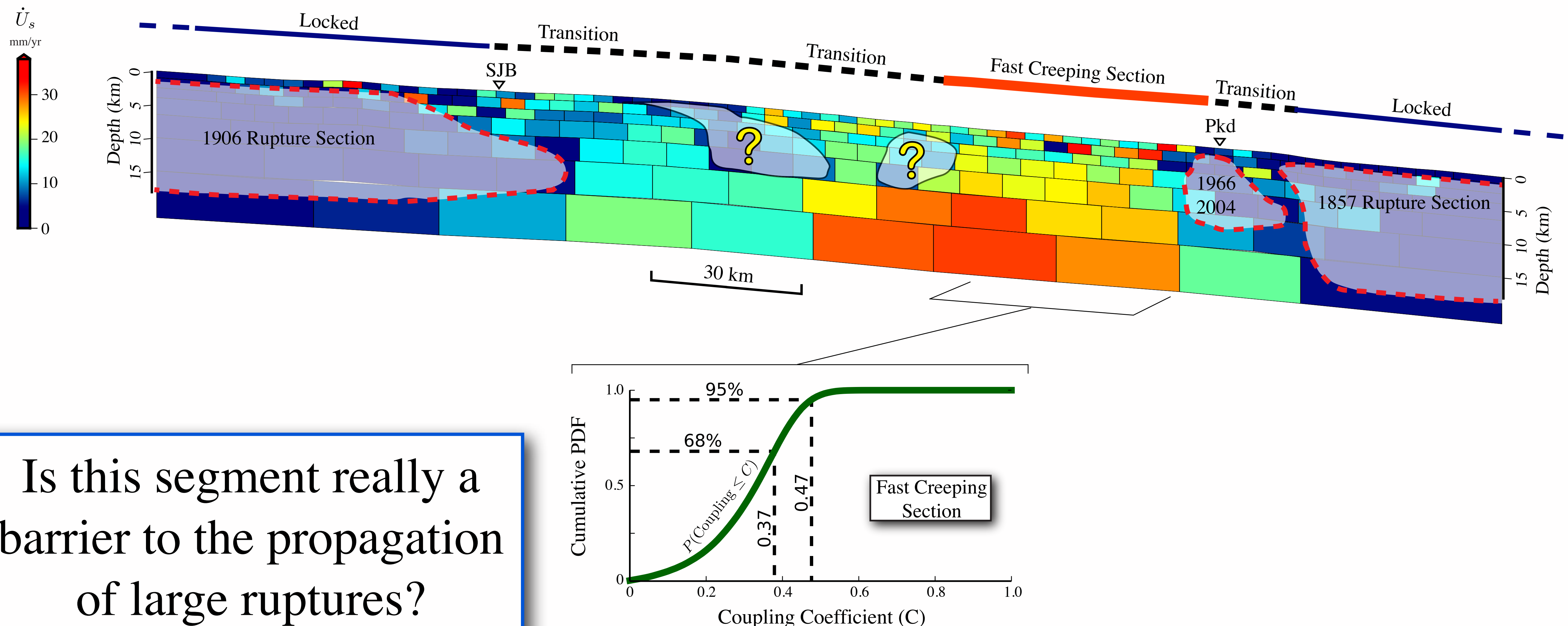
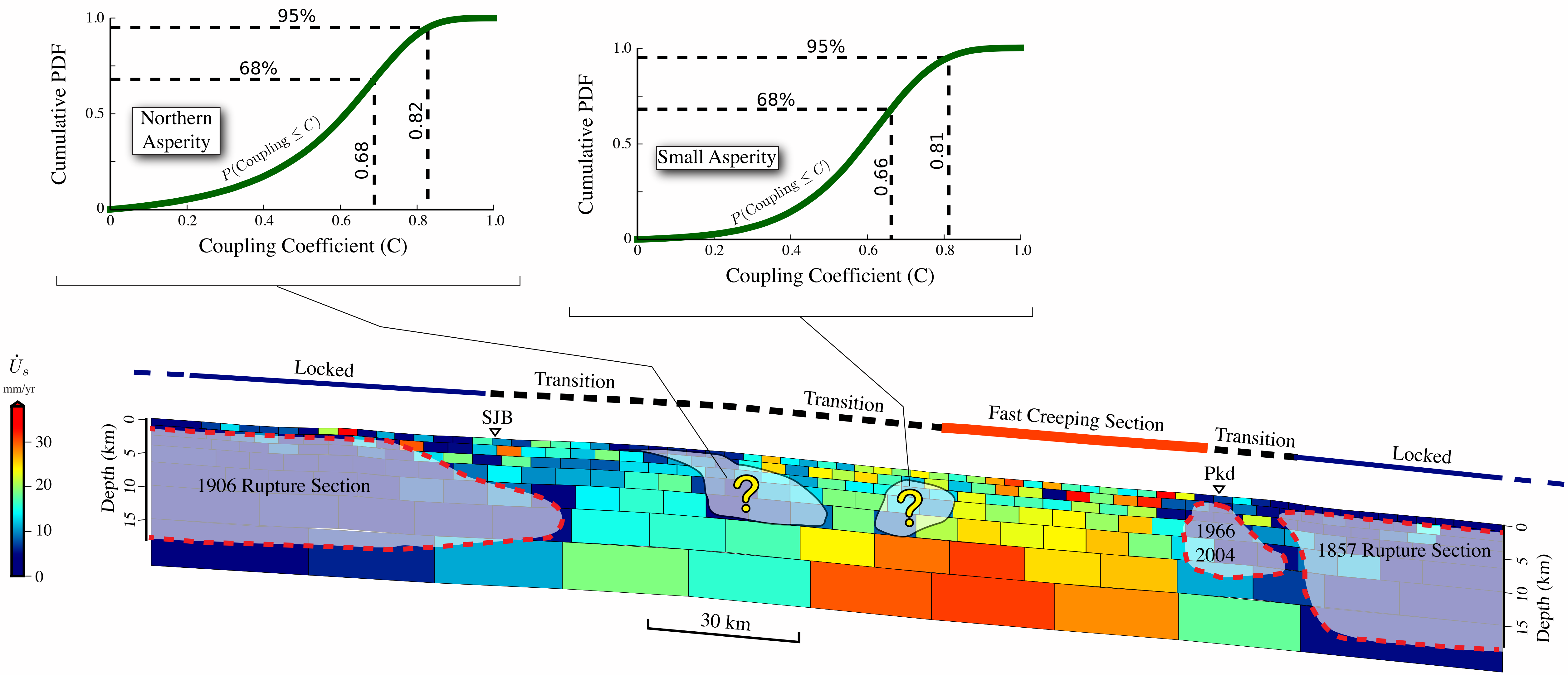


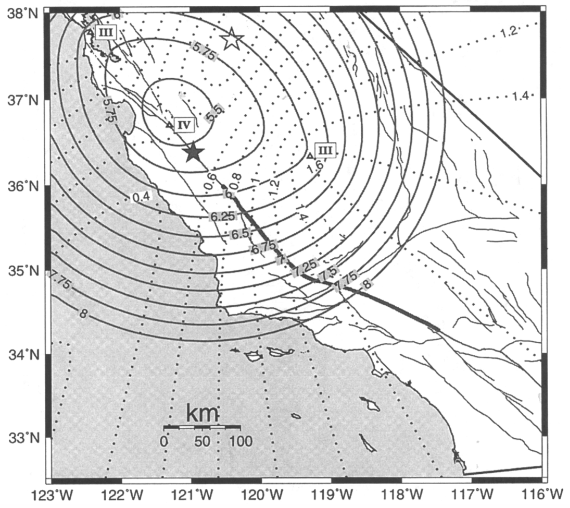
Is this segment really a barrier to the propagation of large ruptures?

Relationship with 1857 M7.9 Fort Tejon ?



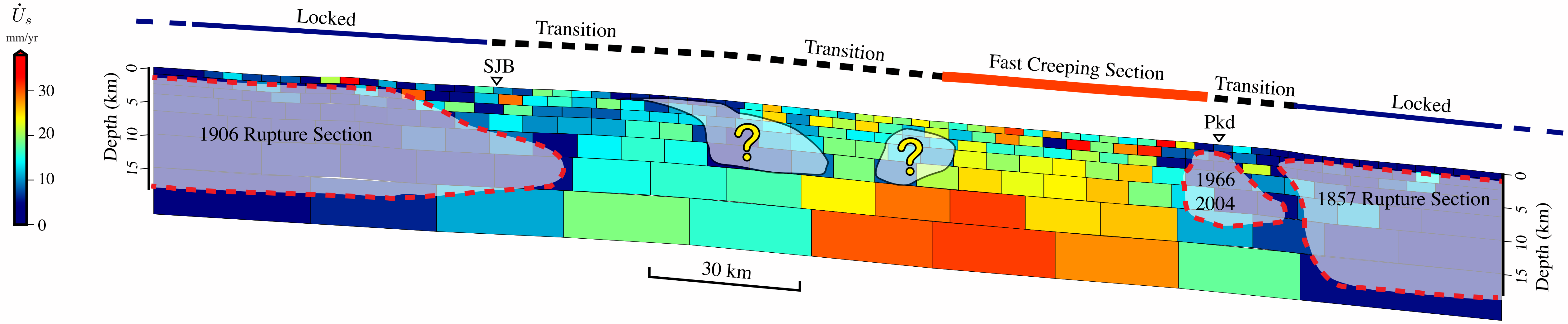
For both asperities, 70% chance that slip deficit exceeds 12 mm/yr

Relationship with 1857 M7.9 Fort Tejon ?



3 significant size foreshocks (M~5-6):

- "pre-dawn" 4h before (north)
- "dawn" 2h before (north)
- "sunrise" 1h before (Parkfield)



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Candidates for the seismic asperities that ruptured during the sequence of 1857 foreshocks

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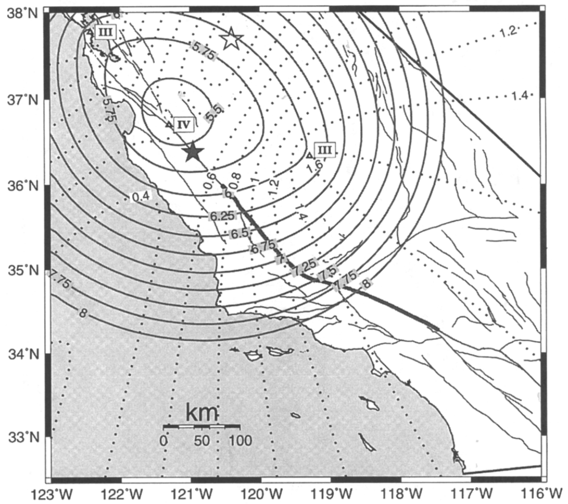

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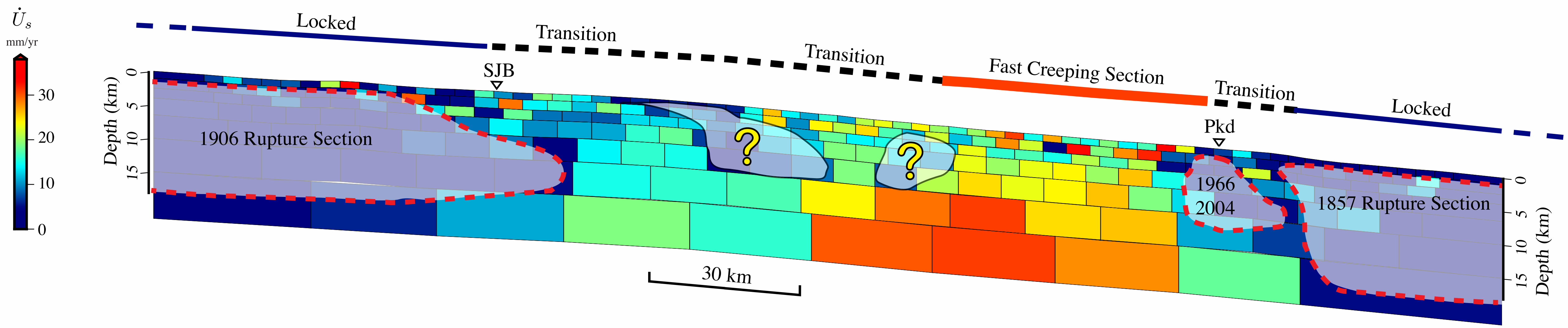

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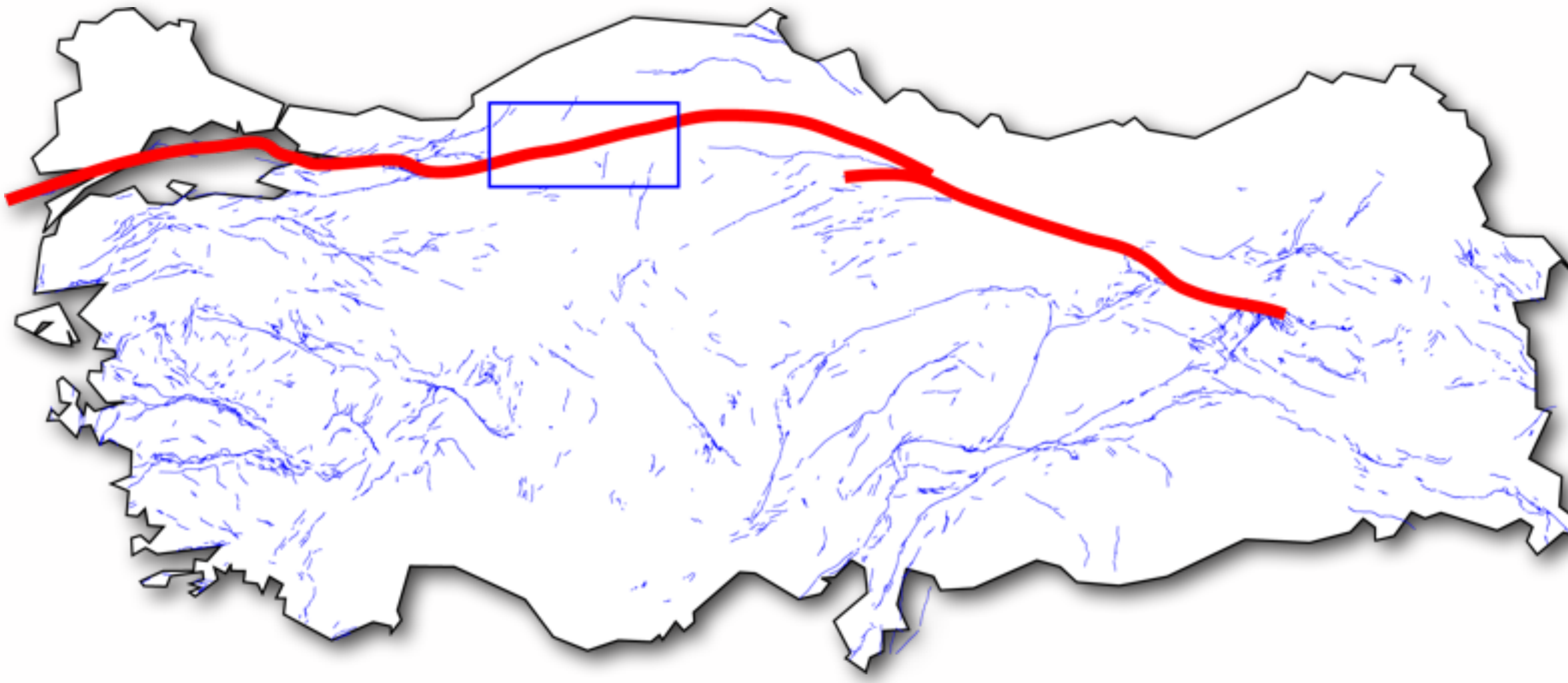
Candidates for the seismic asperities that ruptured during the sequence of 1857 foreshocks

A possible underlying creep rate increase prior to the nucleation of the 1857 M7.9 earthquake

Part 2: the North Anatolian fault creeping segment imaged by short repeat time Radar satellites



PhD: Baptiste Rousset, Grenoble + CalTech

Seismotectonic setting

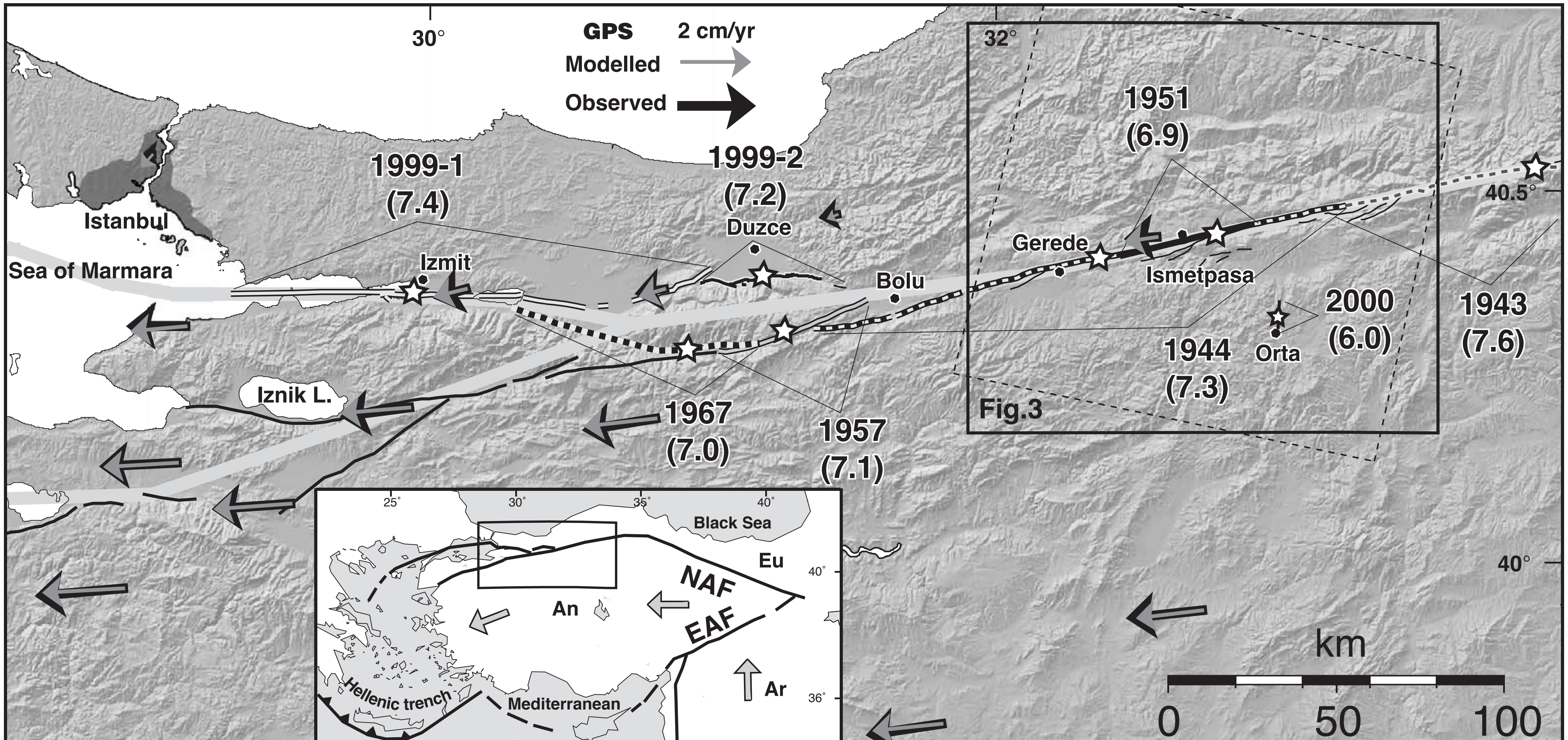
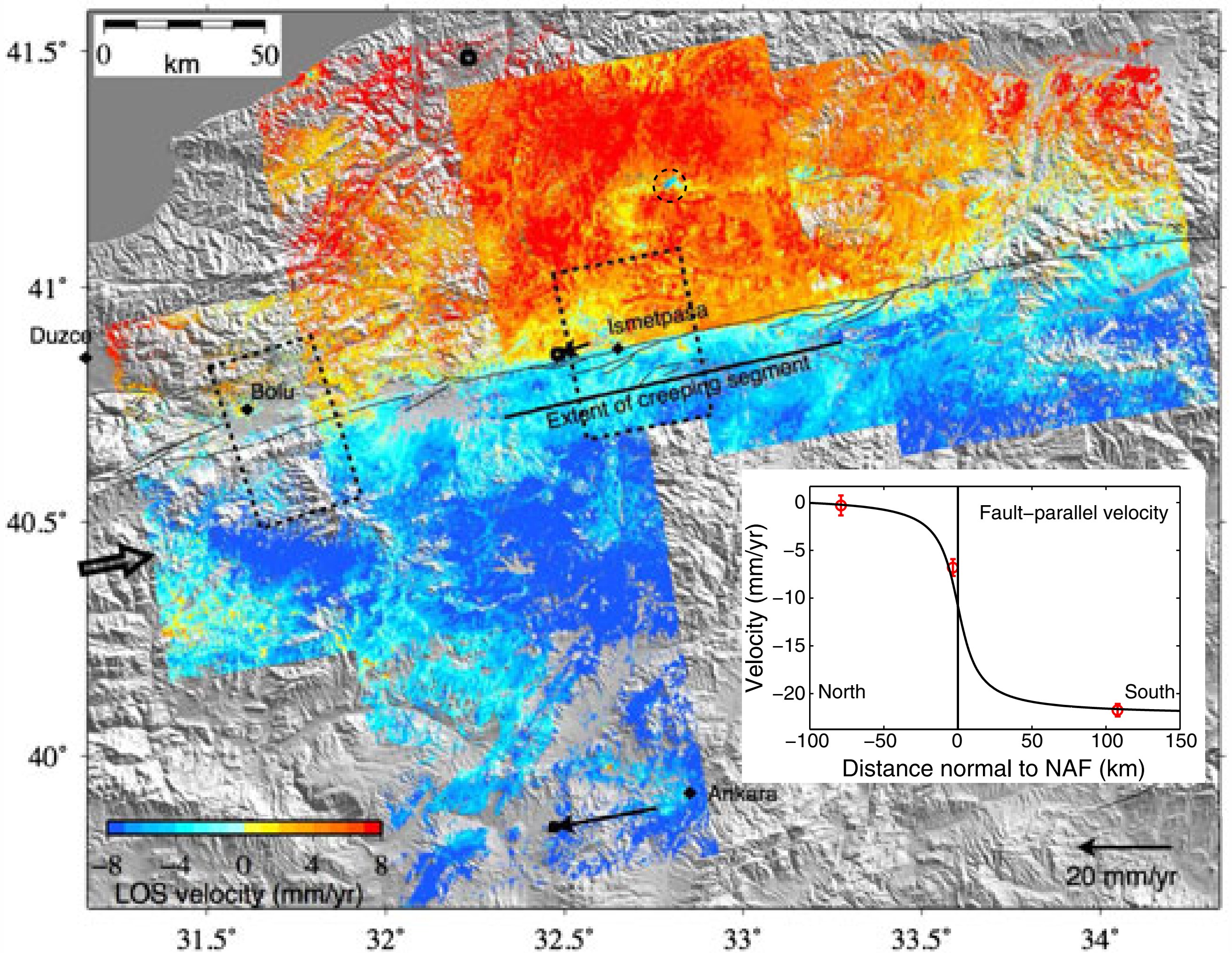


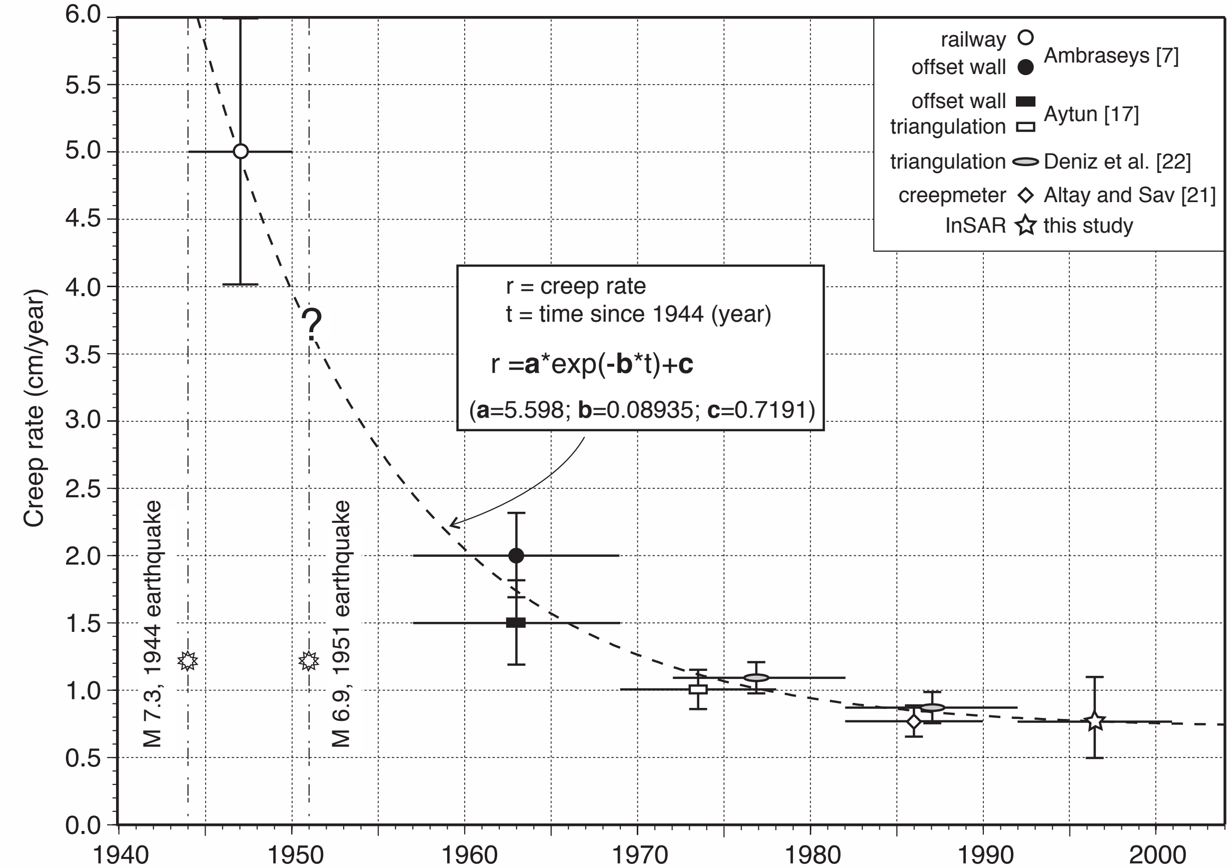
Fig. 1. Map of the North Anatolian Fault (NAF) in the Sea of Marmara region [20] with the rupture segments of the large earthquakes that occurred in the last century. Arrows are GPS observed and modeled vectors relative to the Eurasian plate [16]. The dashed rectangle is the ERS image frame. The inset map shows the schematic plate configurations (Eu=Eurasia, Ar=Arabia, An=Anatolia, EAF=East Anatolian Fault).

Çakir et al, 2005, EPSL

Seismotectonic setting



Kaneko et al, 2012, JGR



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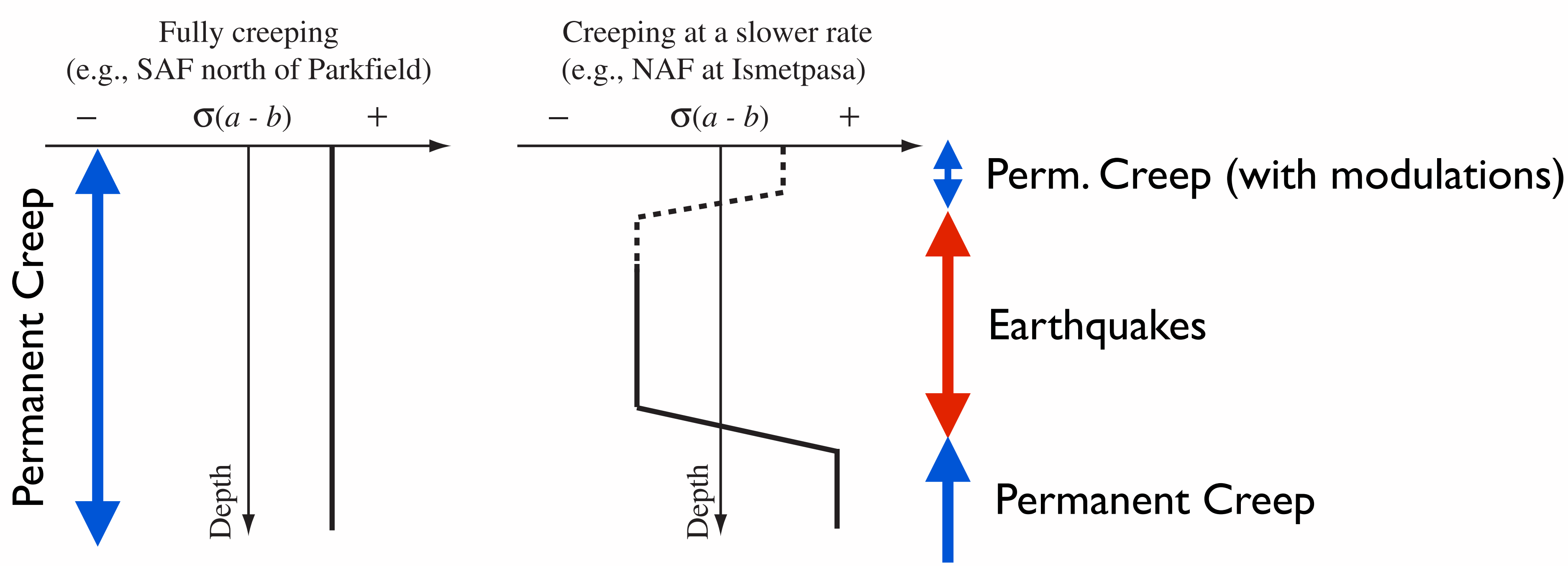
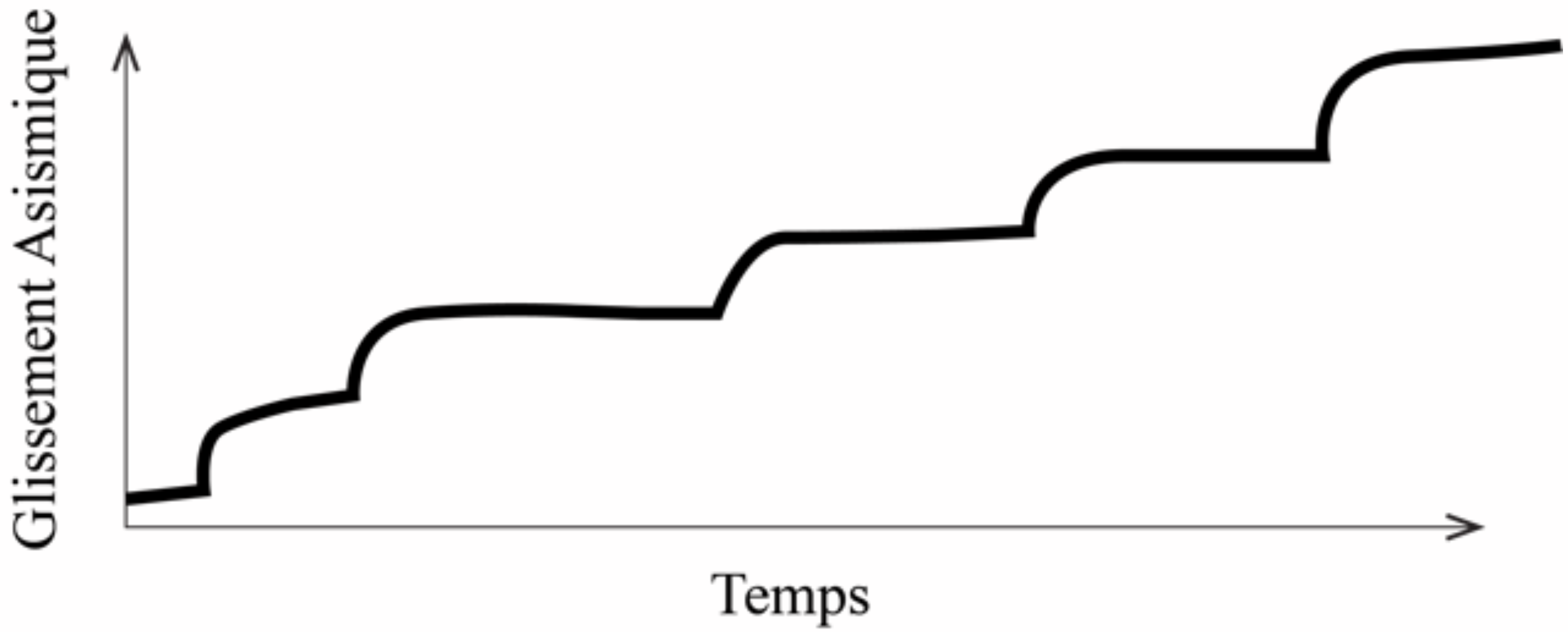


InSAR as we know it…



10 years ago: first cGPS stations revealed “slow earthquakes”

Cannot be detected with the loose traditional sampling we have with ERS-1/2, Envisat, RSAT-1/2, ALOS…

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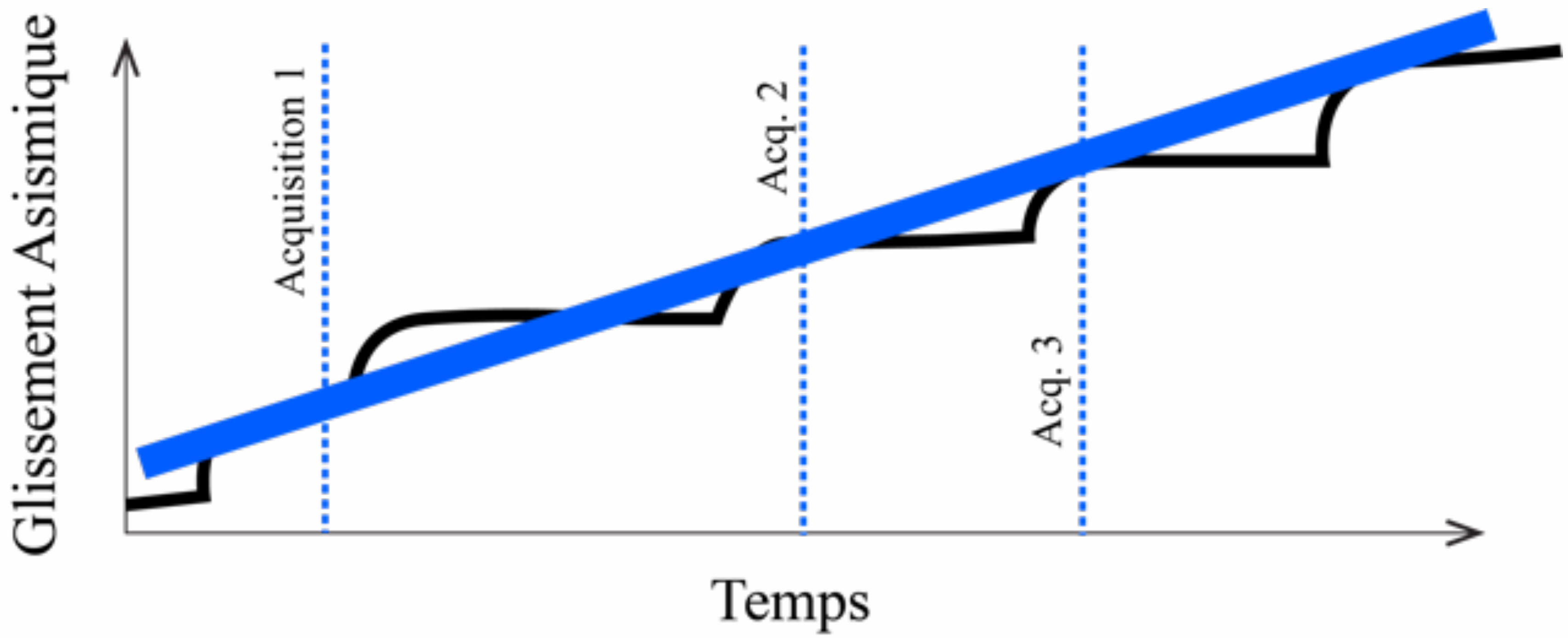

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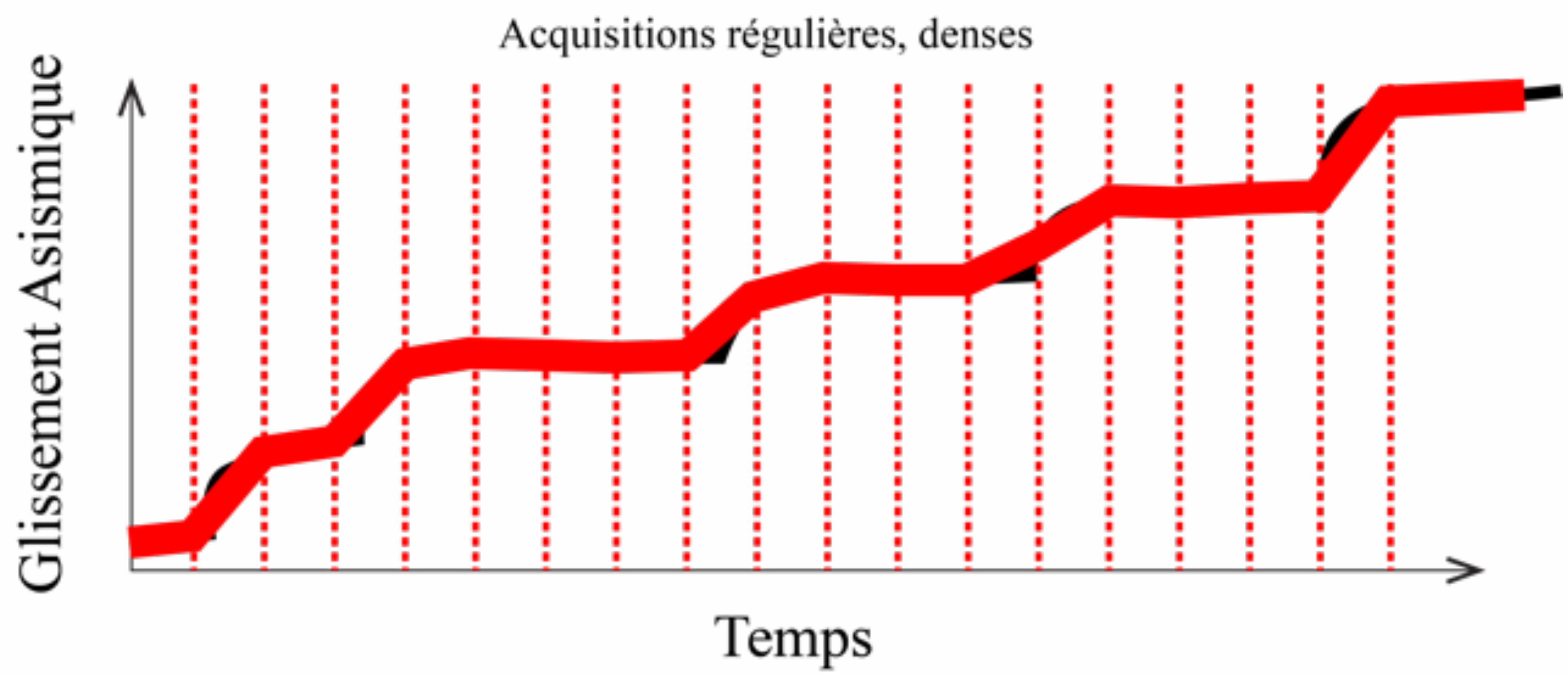
InSAR as it became…

New constellations with short repeat time:
Sentinel 1/2 (6 days), Cosmo SkyMed (1-12 days), TSX (1-12 days)



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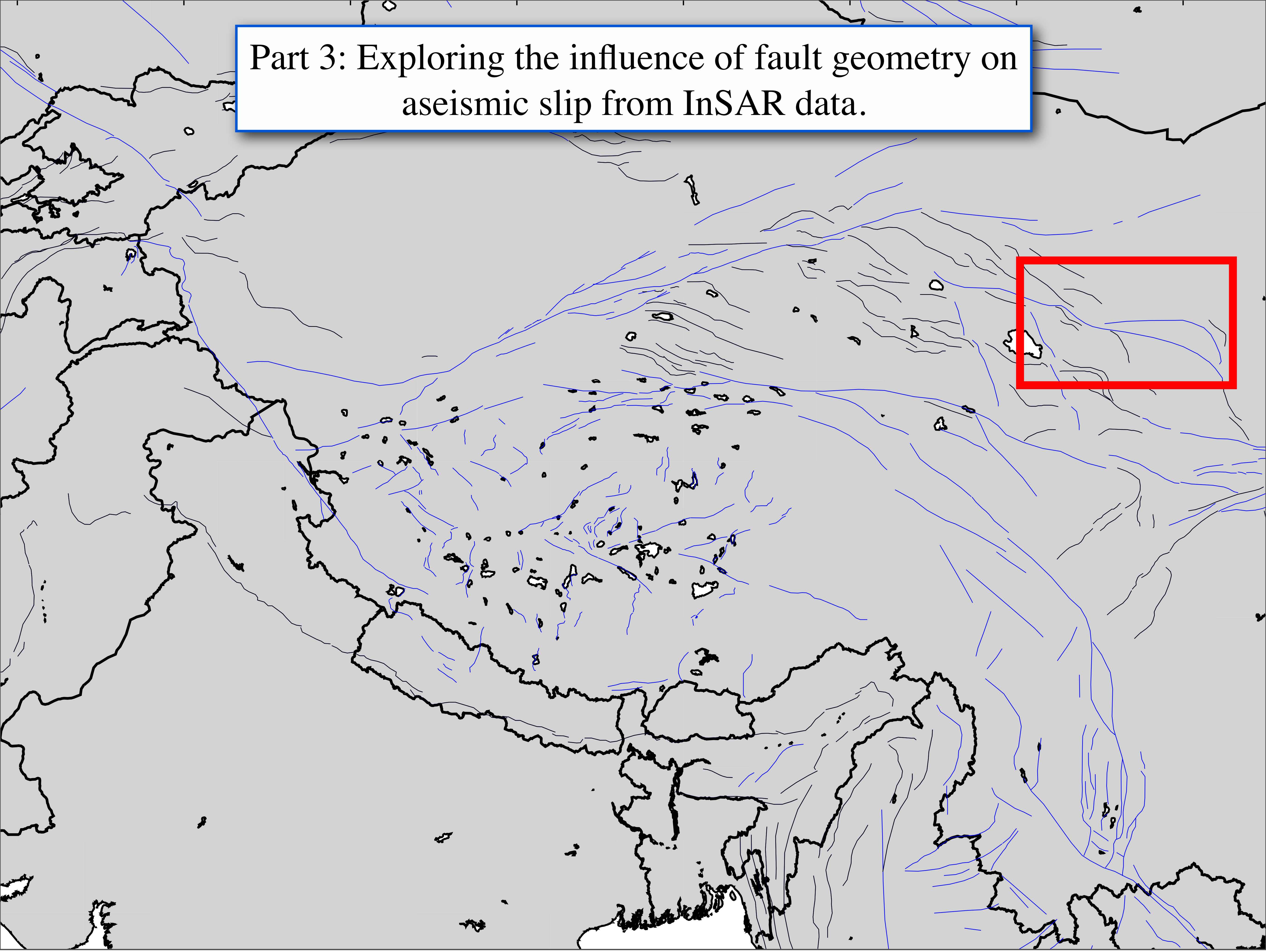
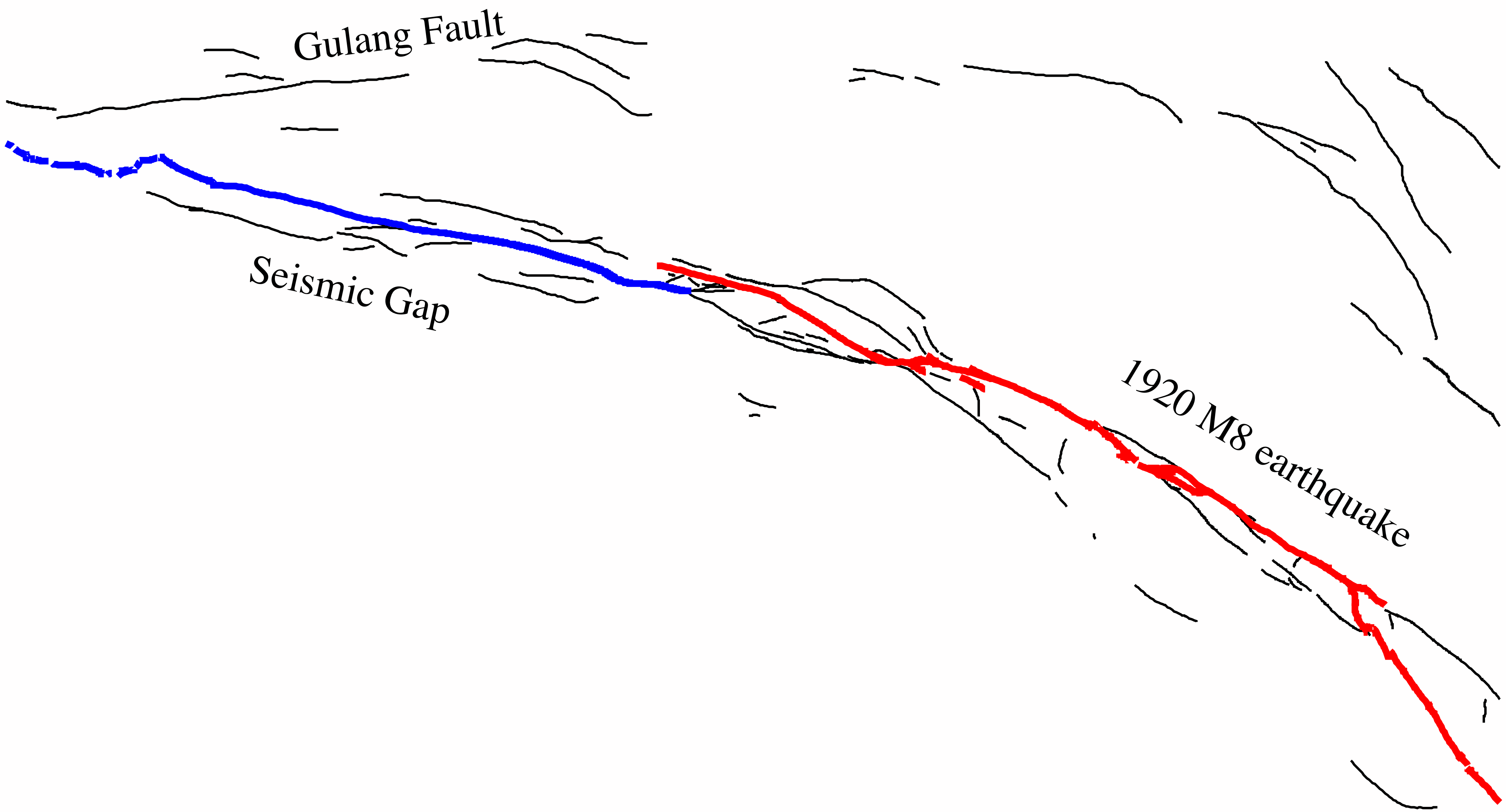
Time Series of CSK data over the NAF

I removed this part because it is Baptiste work and it has not been published yet...
Sorry...

Part 3: Exploring the influence of fault geometry on aseismic slip from InSAR data.



Aseismic slip along the Haiyuan fault



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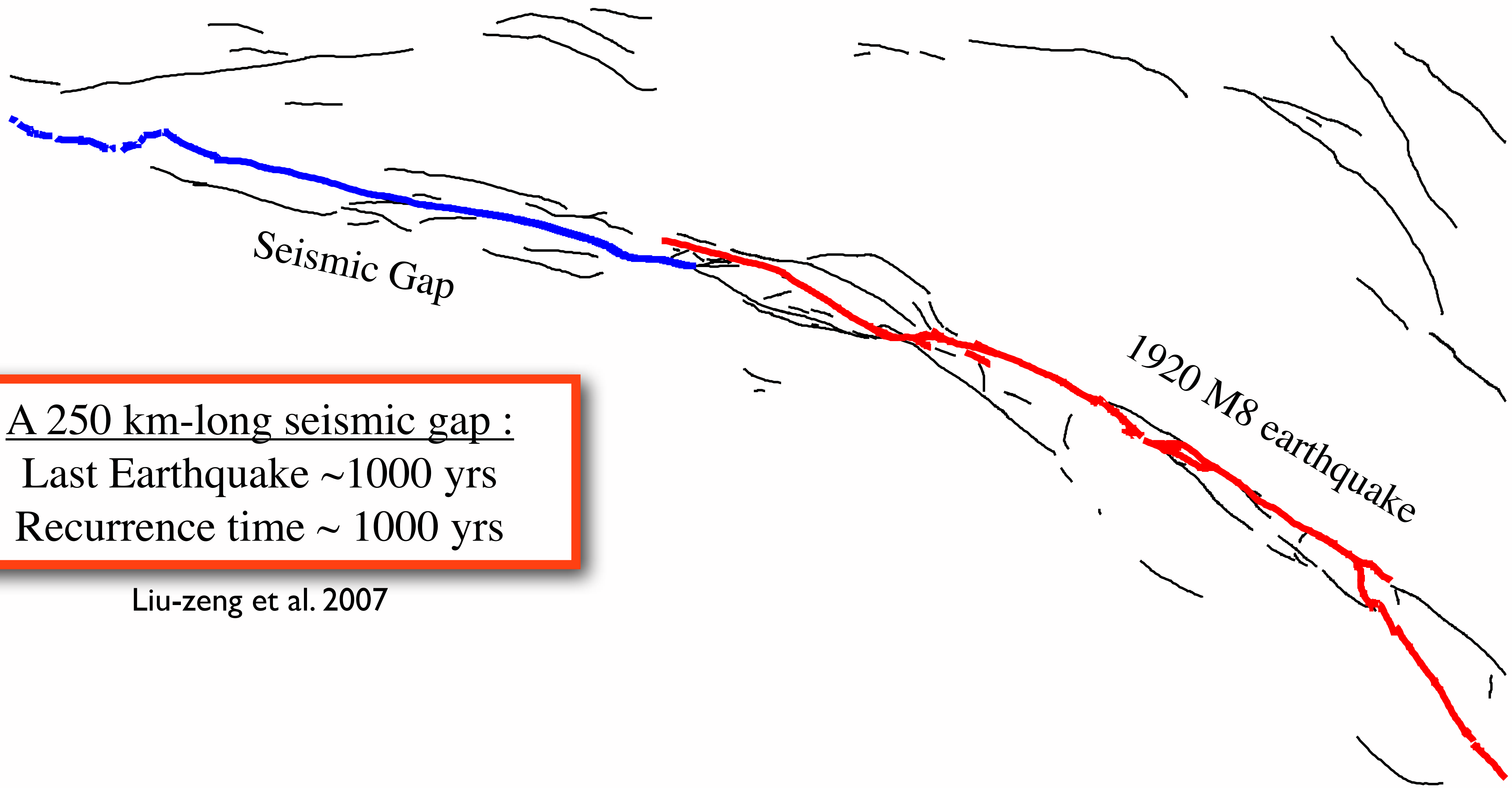
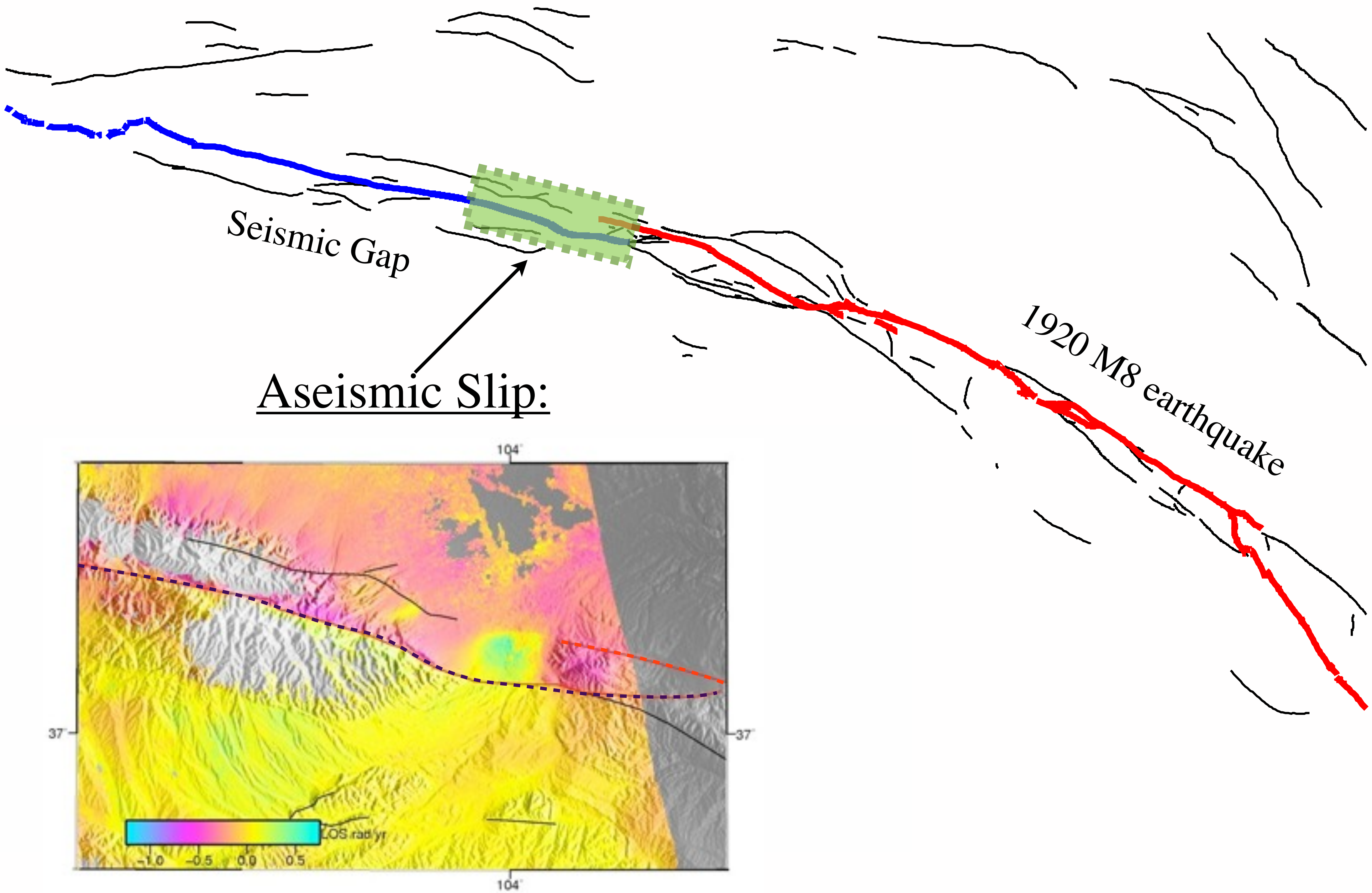


A 250 km-long seismic gap :
Last Earthquake ~1000 yrs
Recurrence time ~ 1000 yrs

Liu-zeng et al. 2007

Aseismic slip along the Haiyuan fault



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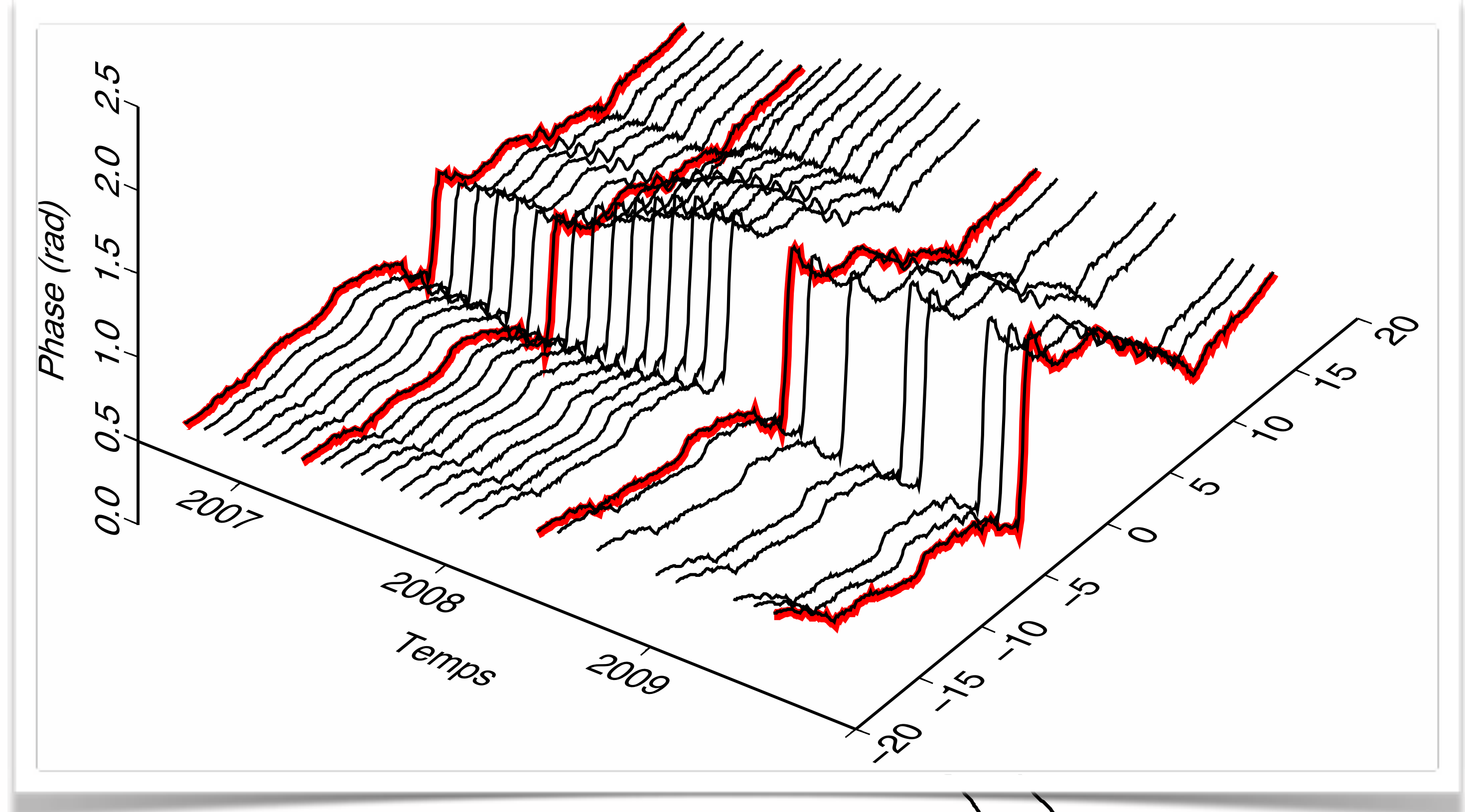
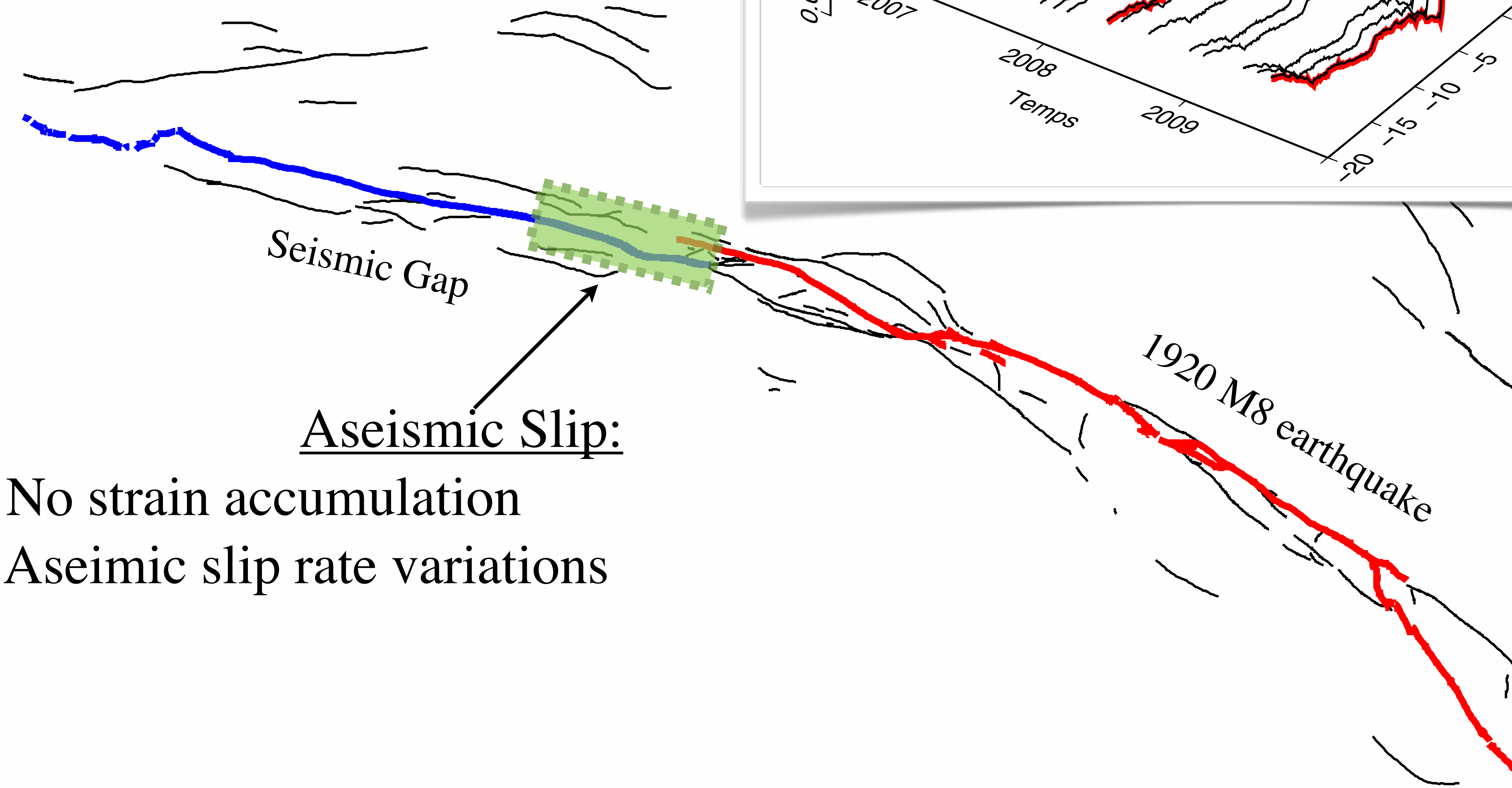




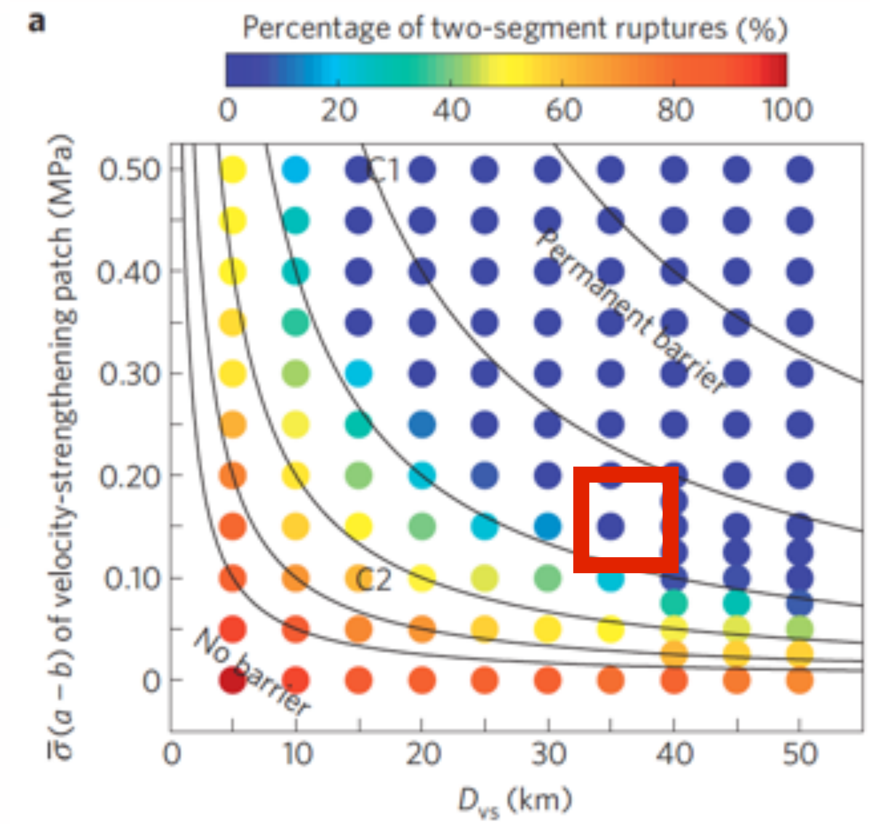
<u>Aseismic Slip:</u>

- No strain accumulation
- Aseimic slip rate variations

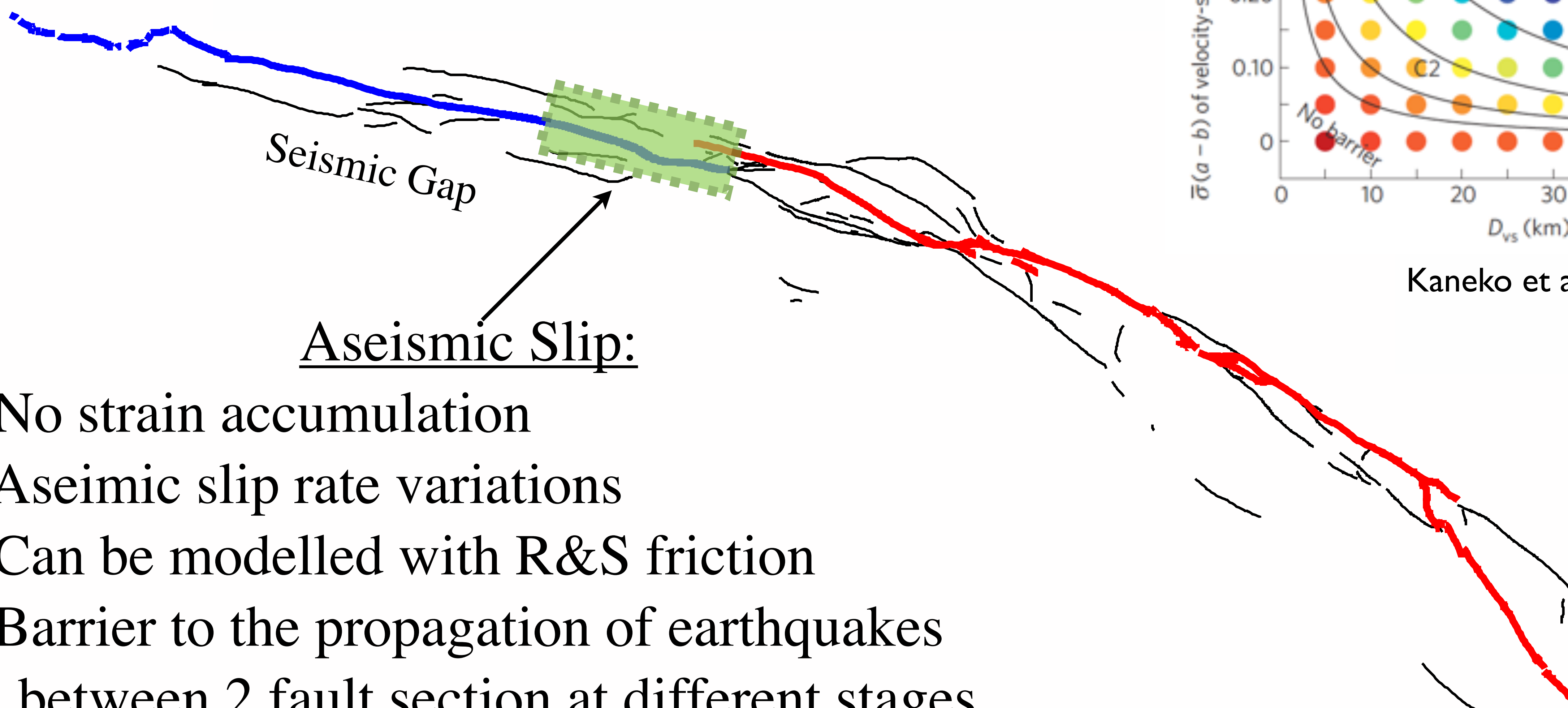
Aseismic slip along the Haiyuan fault

$$(a - b) \sim 2e - 3$$

$$\sigma_n \sim 50 - 100 \ \mathrm{MPa}$$



Kaneko et al 2010



<u>Aseismic Slip:</u>

- No strain accumulation
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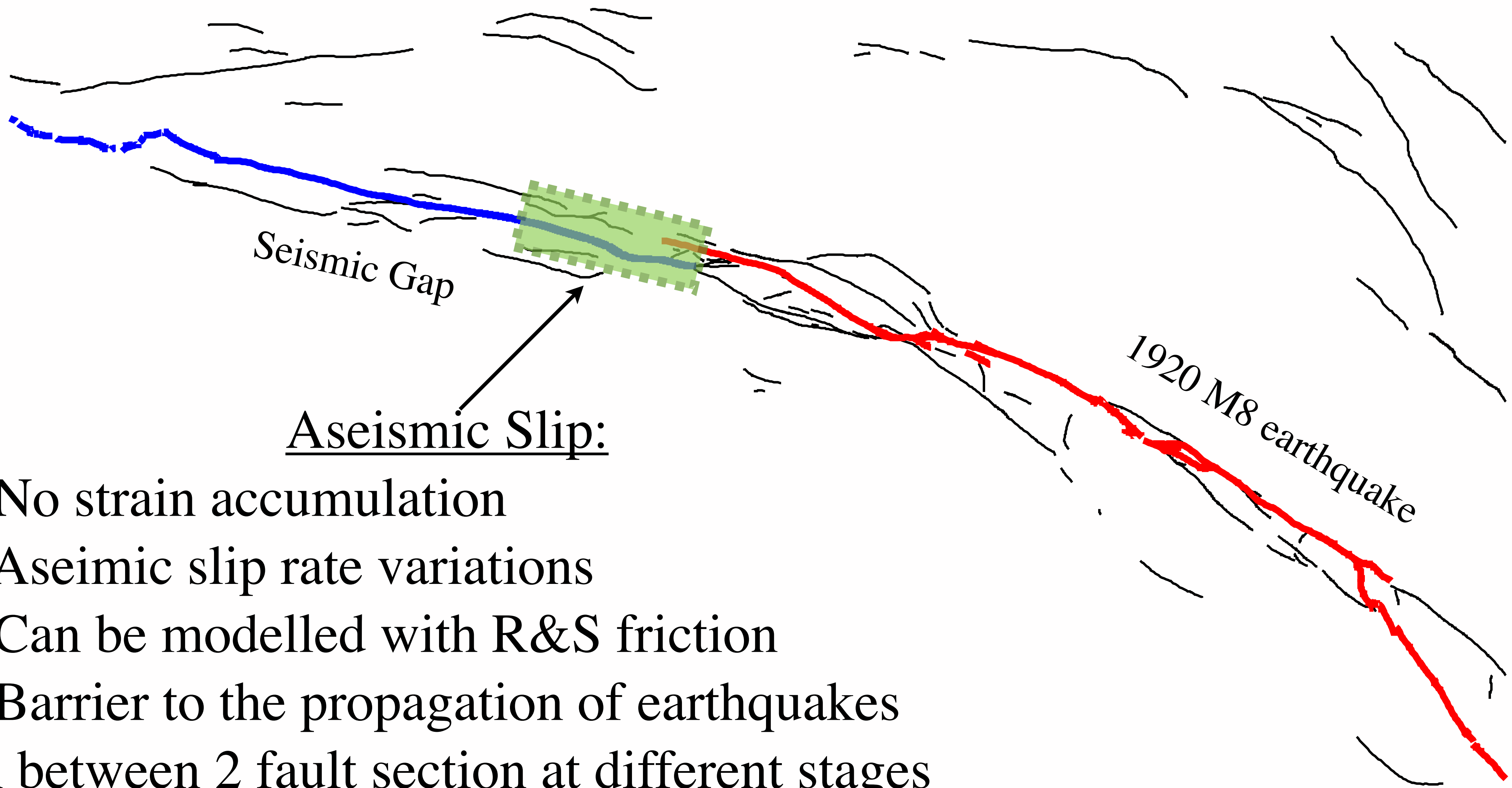
- Can be modelled with R&S friction
- Barrier to the propagation of earthquakes in between 2 fault section at different stages of the earthquake cycle

Aseismic slip along the Haiyuan fault

What is the physics at stake behind aseismic slip?



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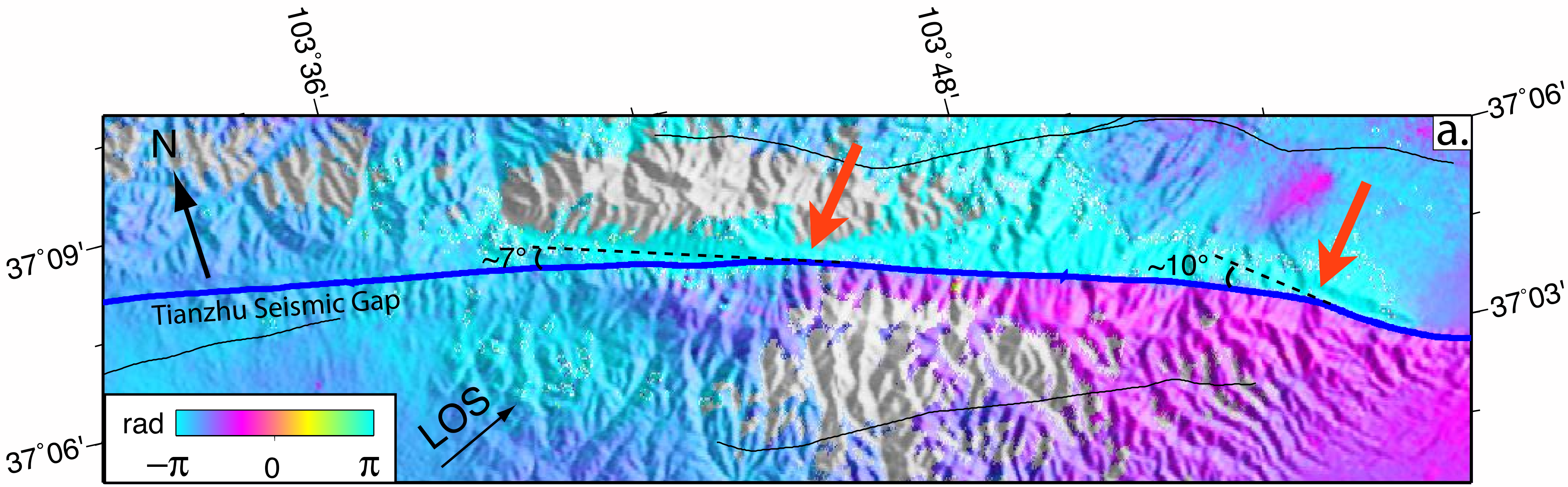
Fault geometry and aseismic slip



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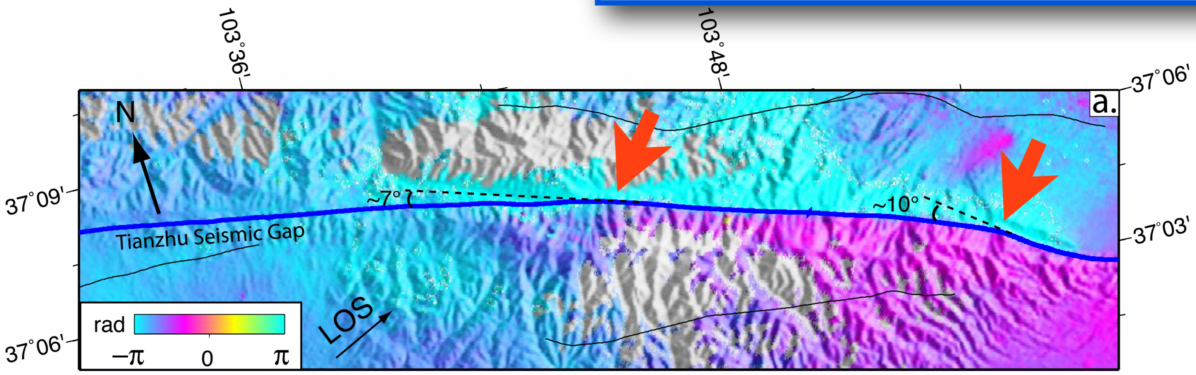
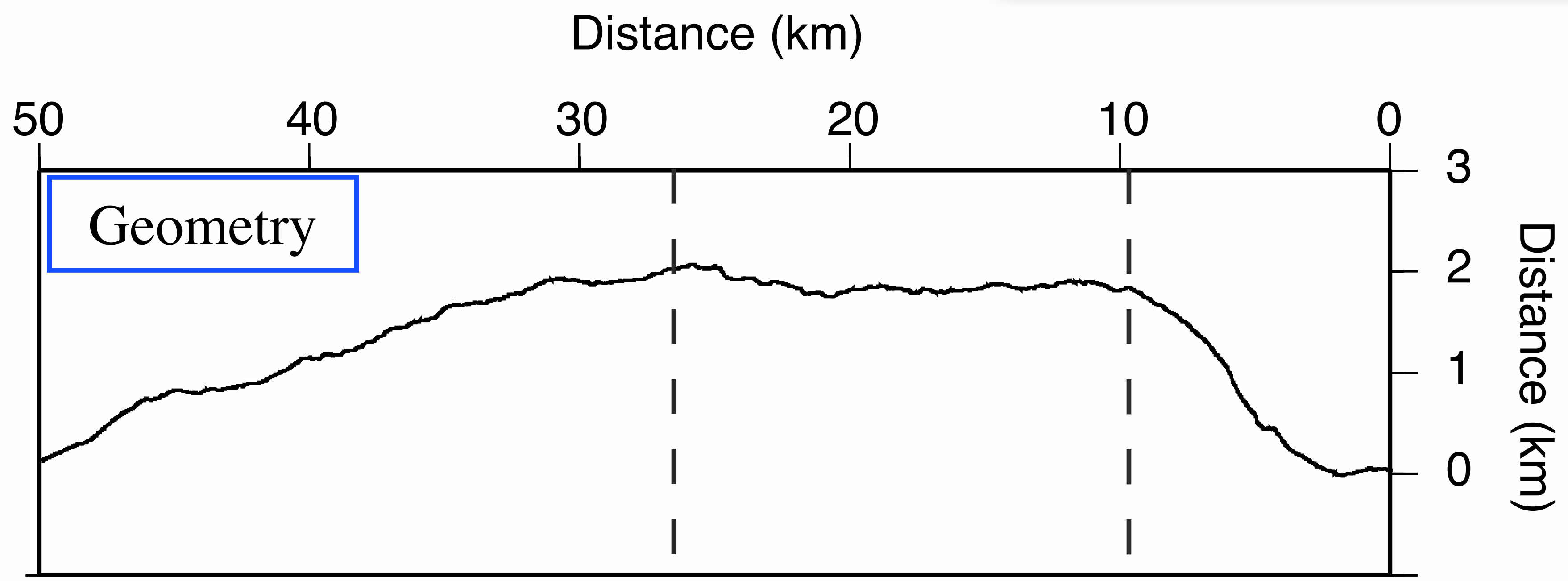


First Order Segmentation:
Three Segments



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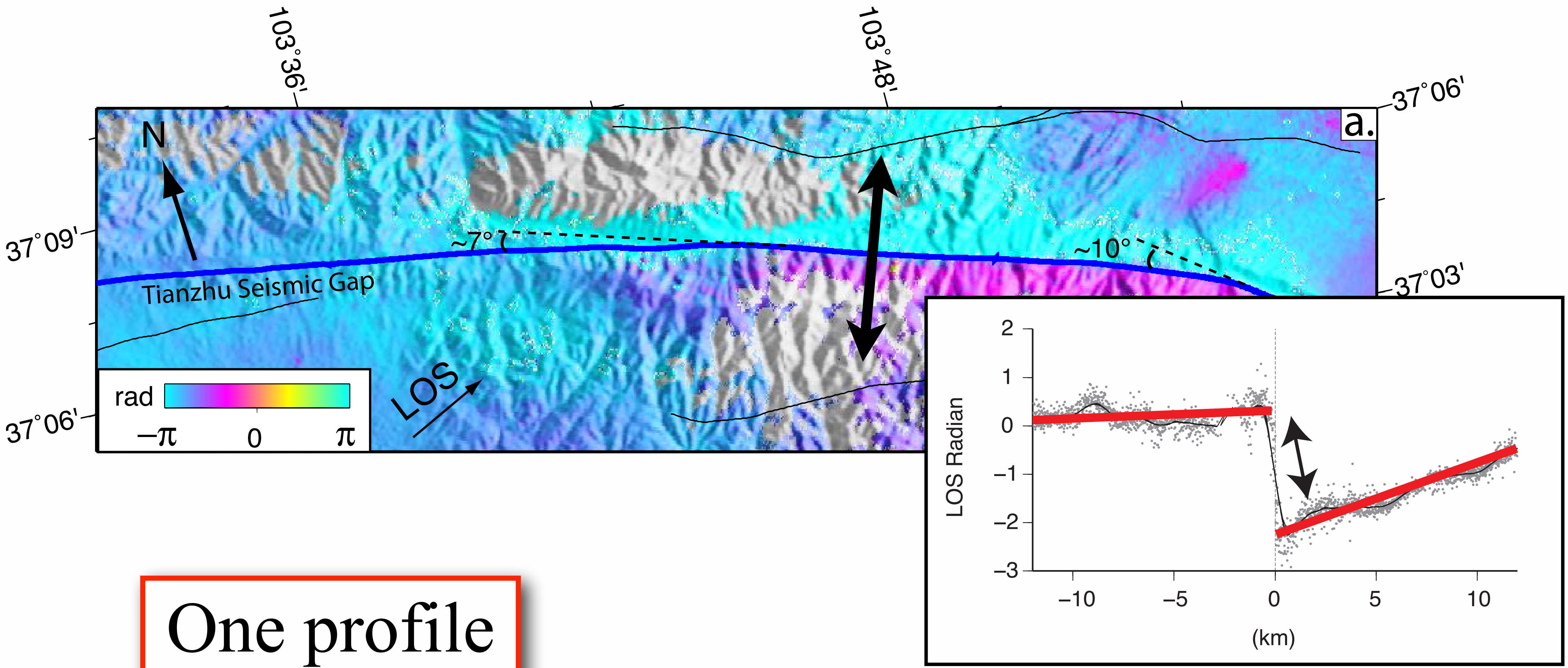
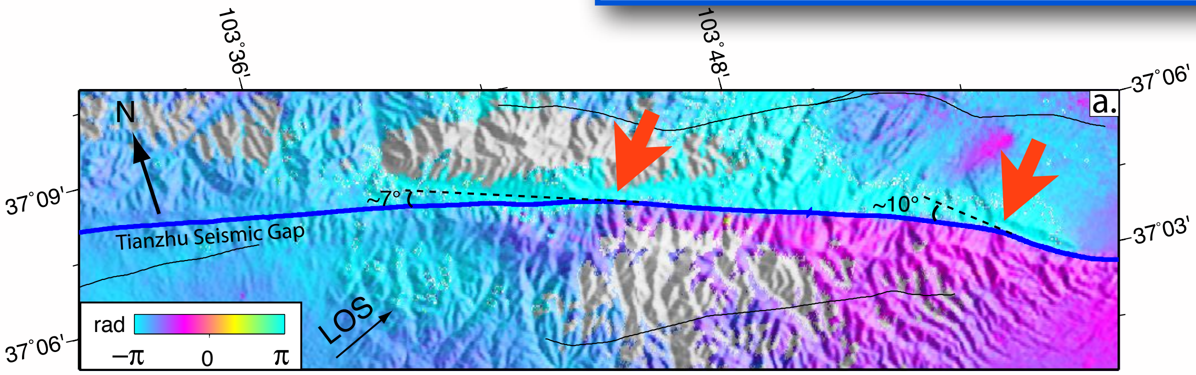


One profile every 45 m

Fault geometry and aseismic slip



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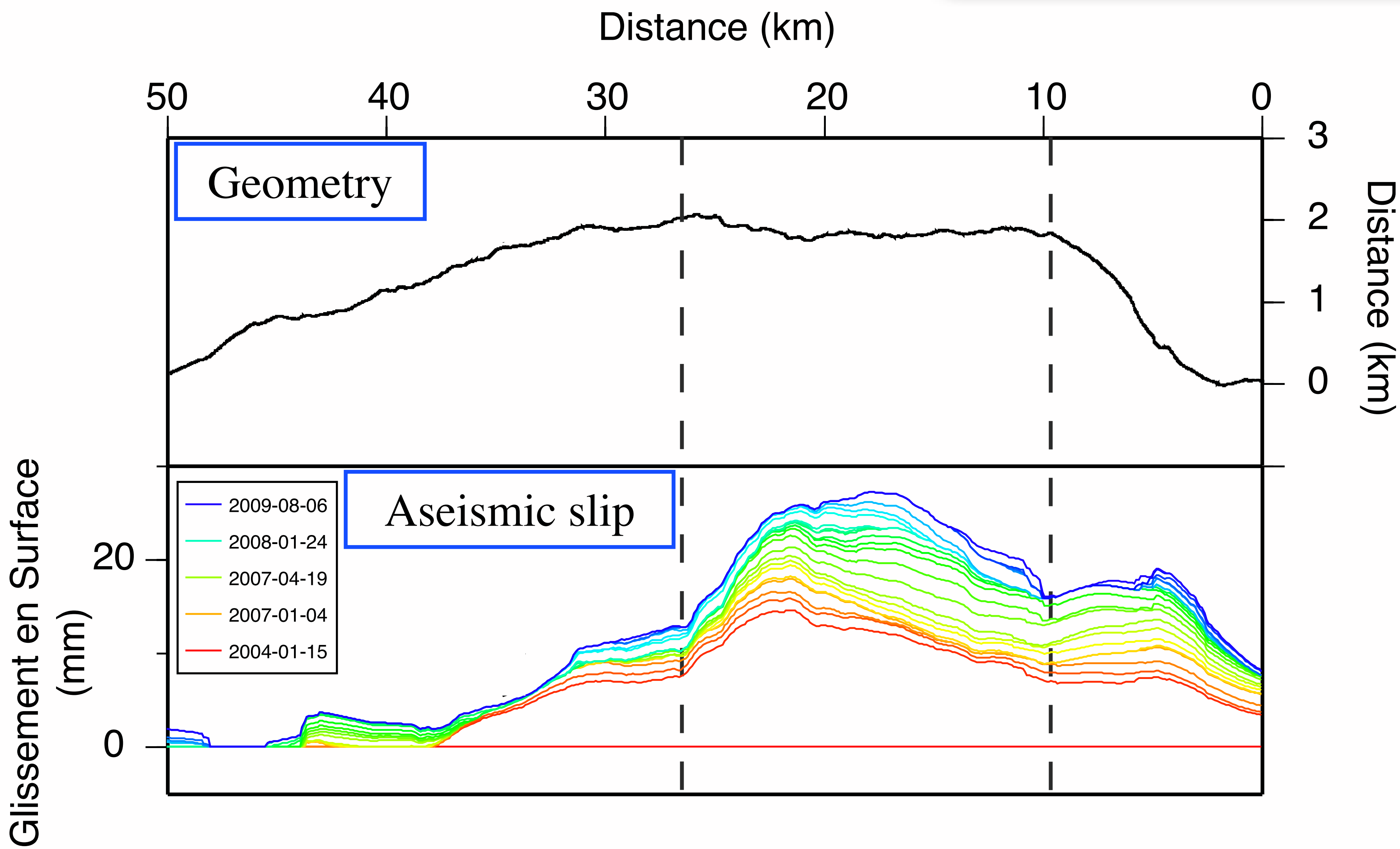
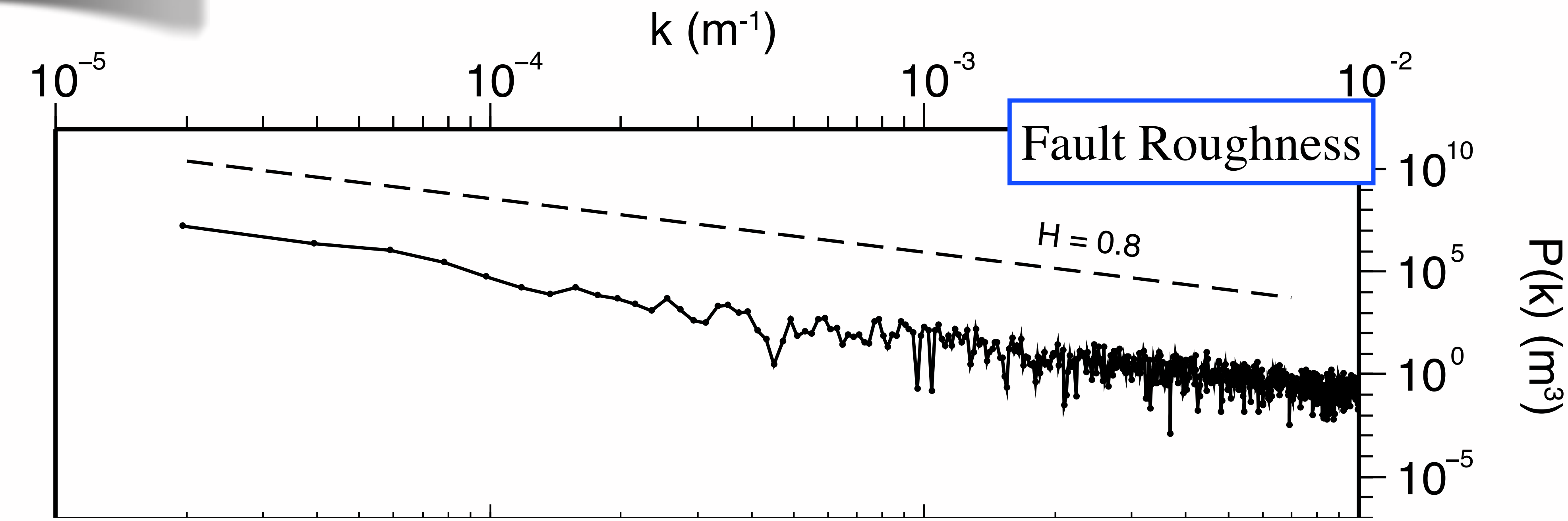


Fault geometry and aseismic slip

Fourier Power Spectrum

$$P(k) \sim k^{-1-2H}$$



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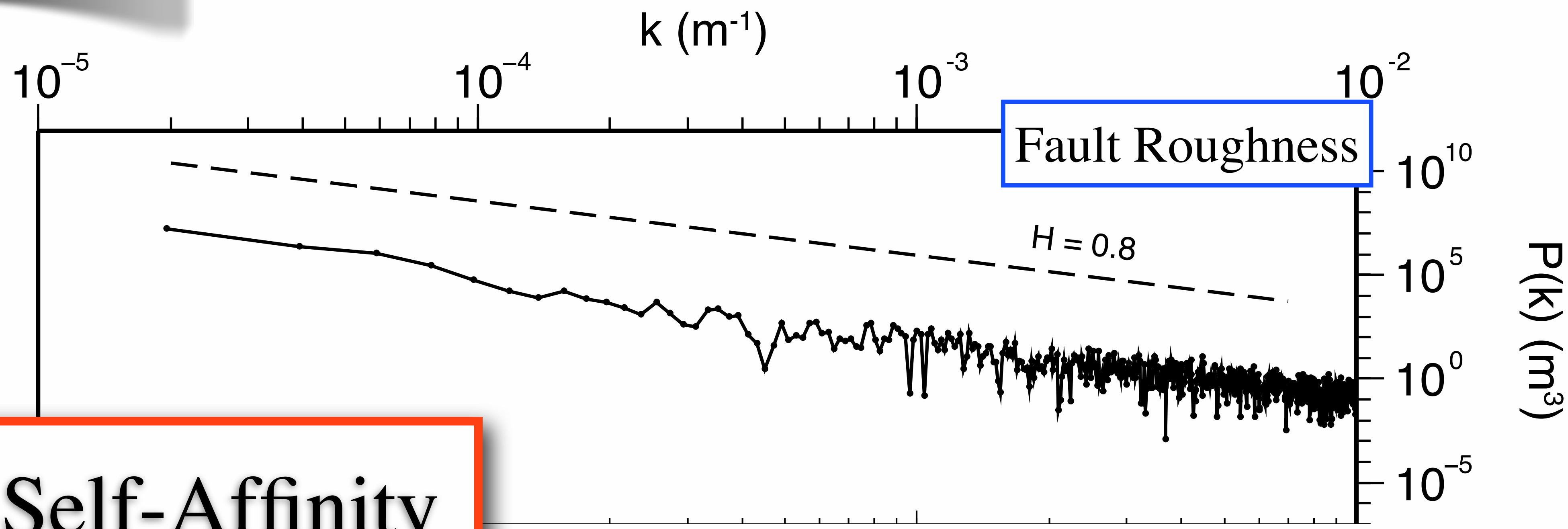
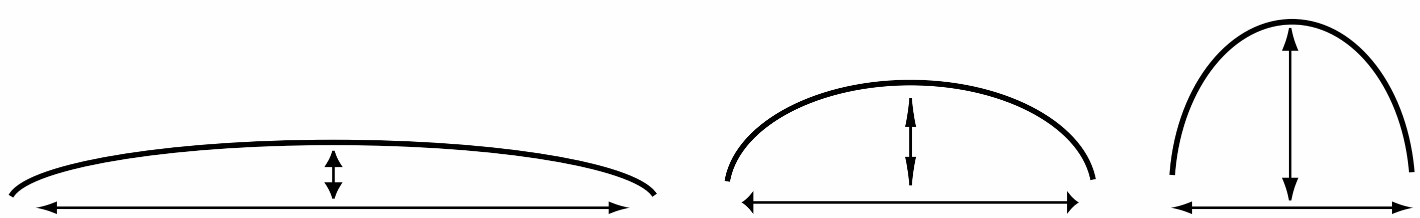


Self-Affinity



Fault geometry and aseismic slip

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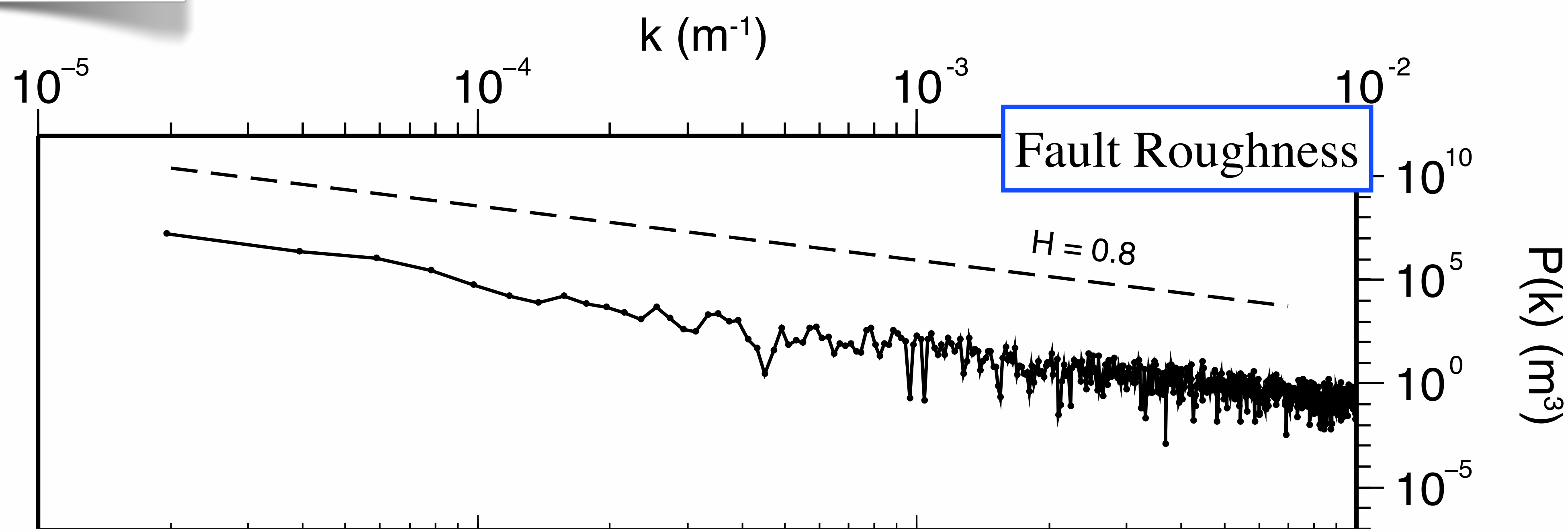
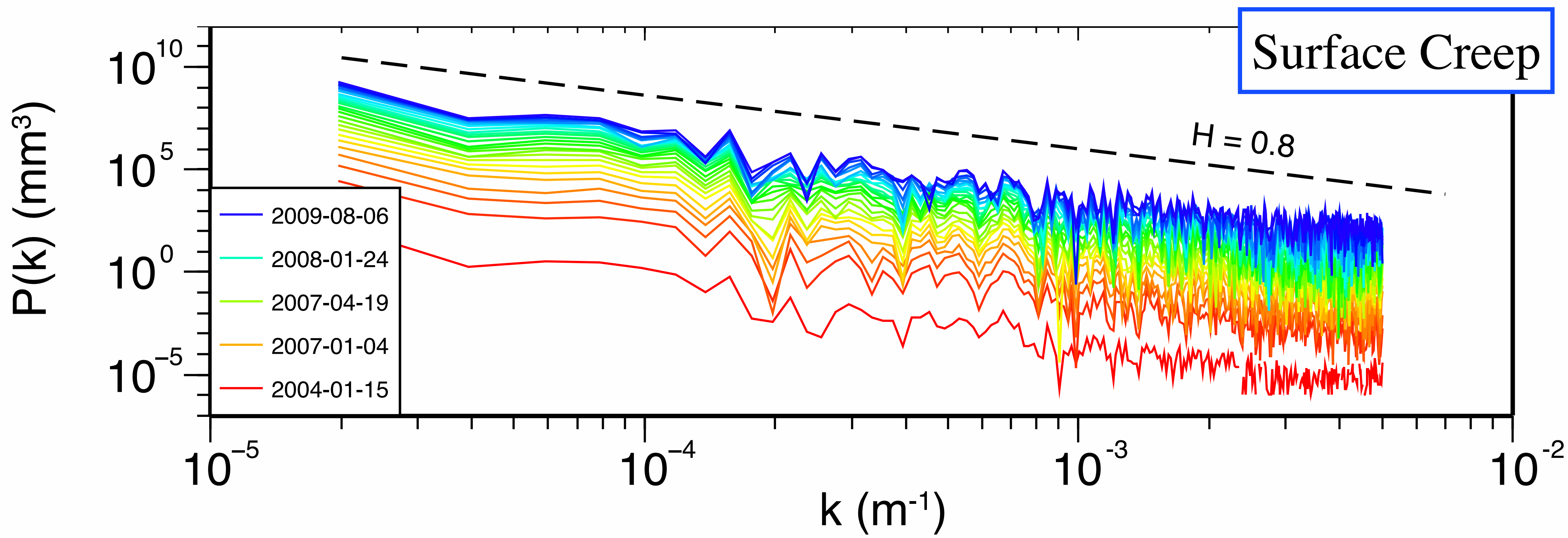


Bulk properties of the crust control the fault geometry, through long distance interactions

e.g. Candela et al 2011

Fault geometry and aseismic slip

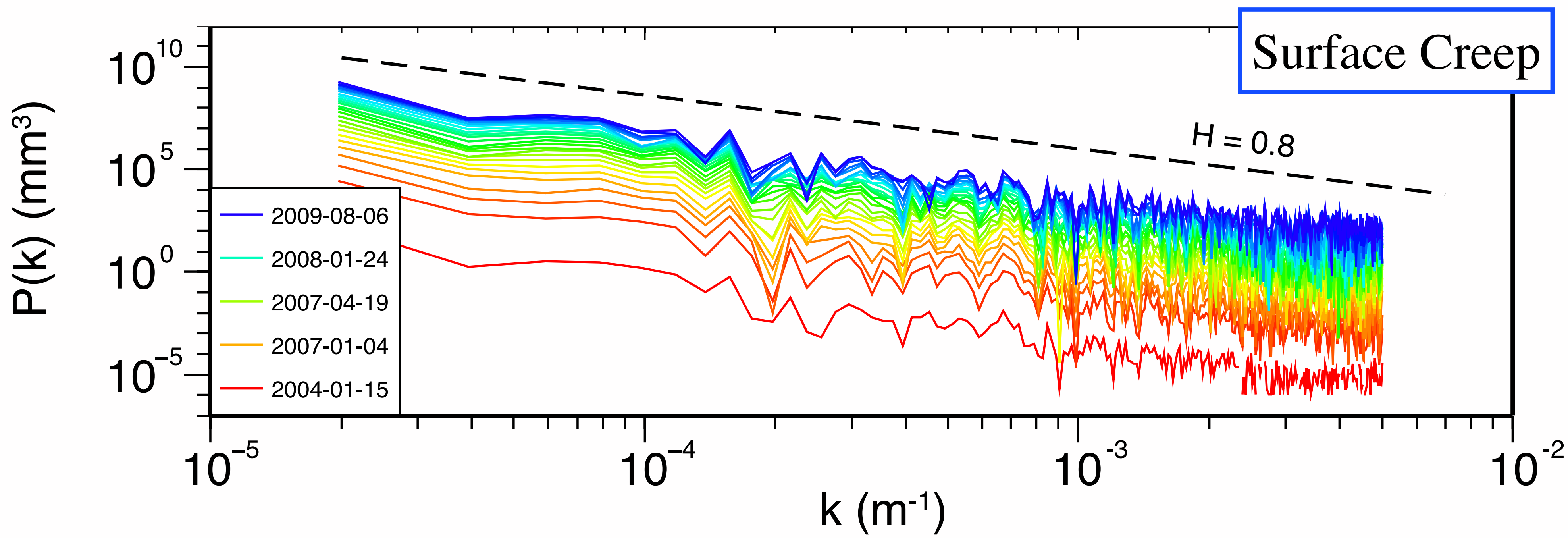
$$P(k) \sim k^{-1-2H}$$



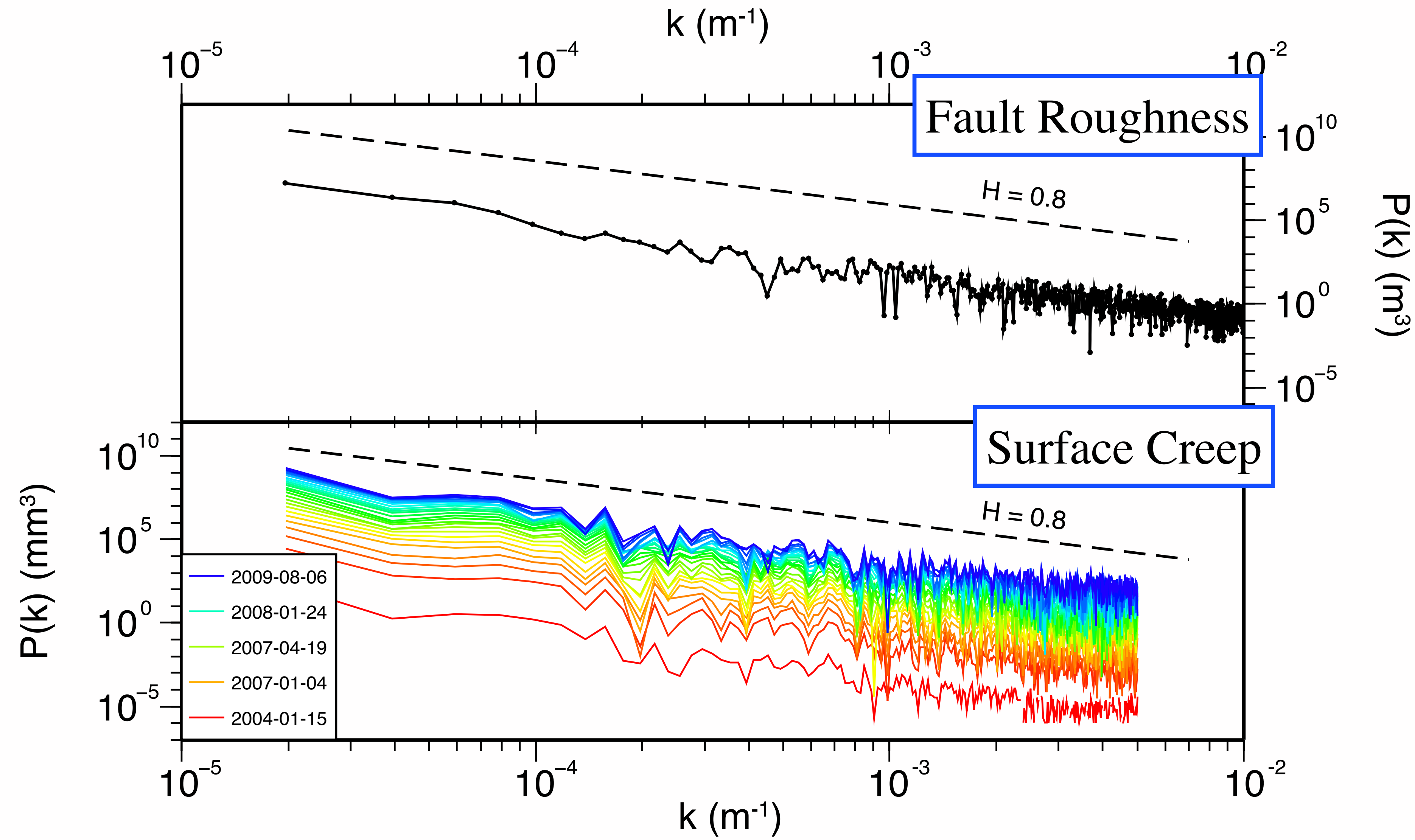
Fault geometry and aseismic slip

$$P(k) \sim k^{-1-2H}$$

Slip is organized in bursts



Fault geometry and aseismic slip



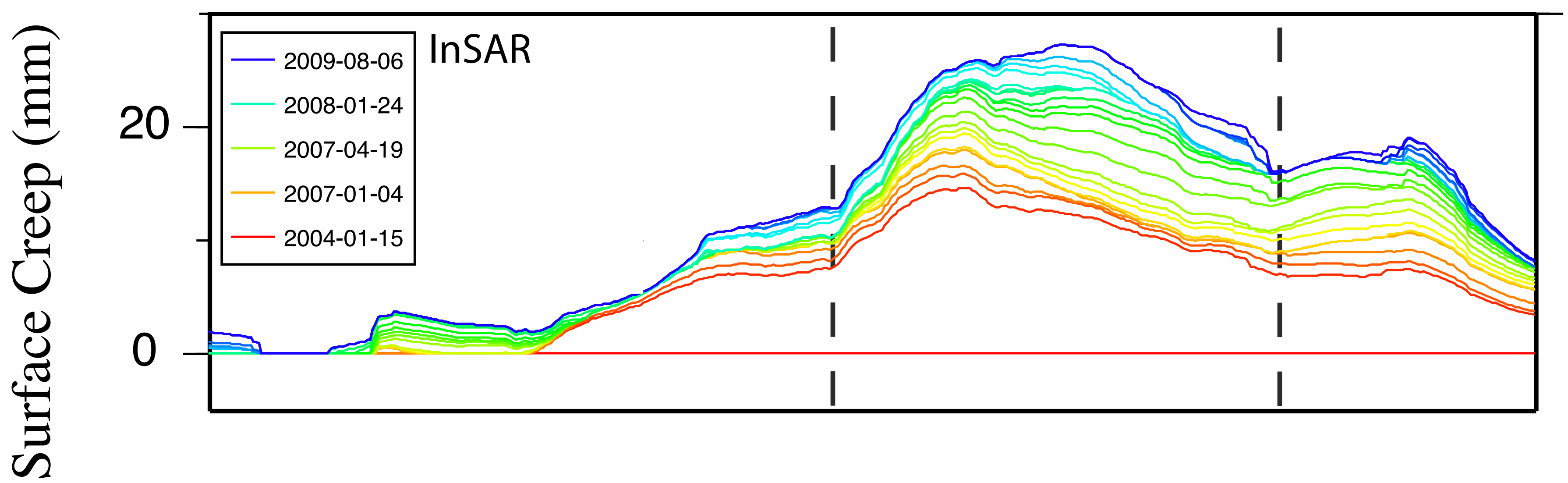
A similar power law:

Aseismic slip occurs on geometrical asperities

This power law is constant through time:

Geometrical asperities are “permanent” (at least for the 5 years period)

Temporal behaviour of aseismic slip



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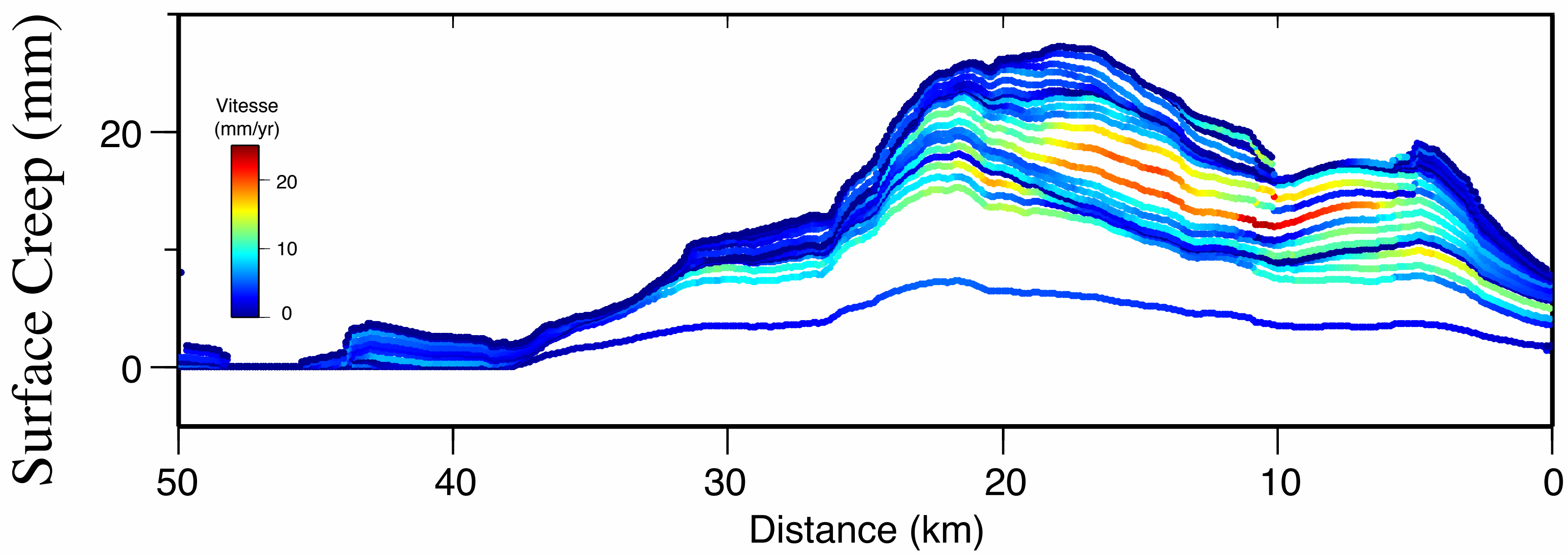

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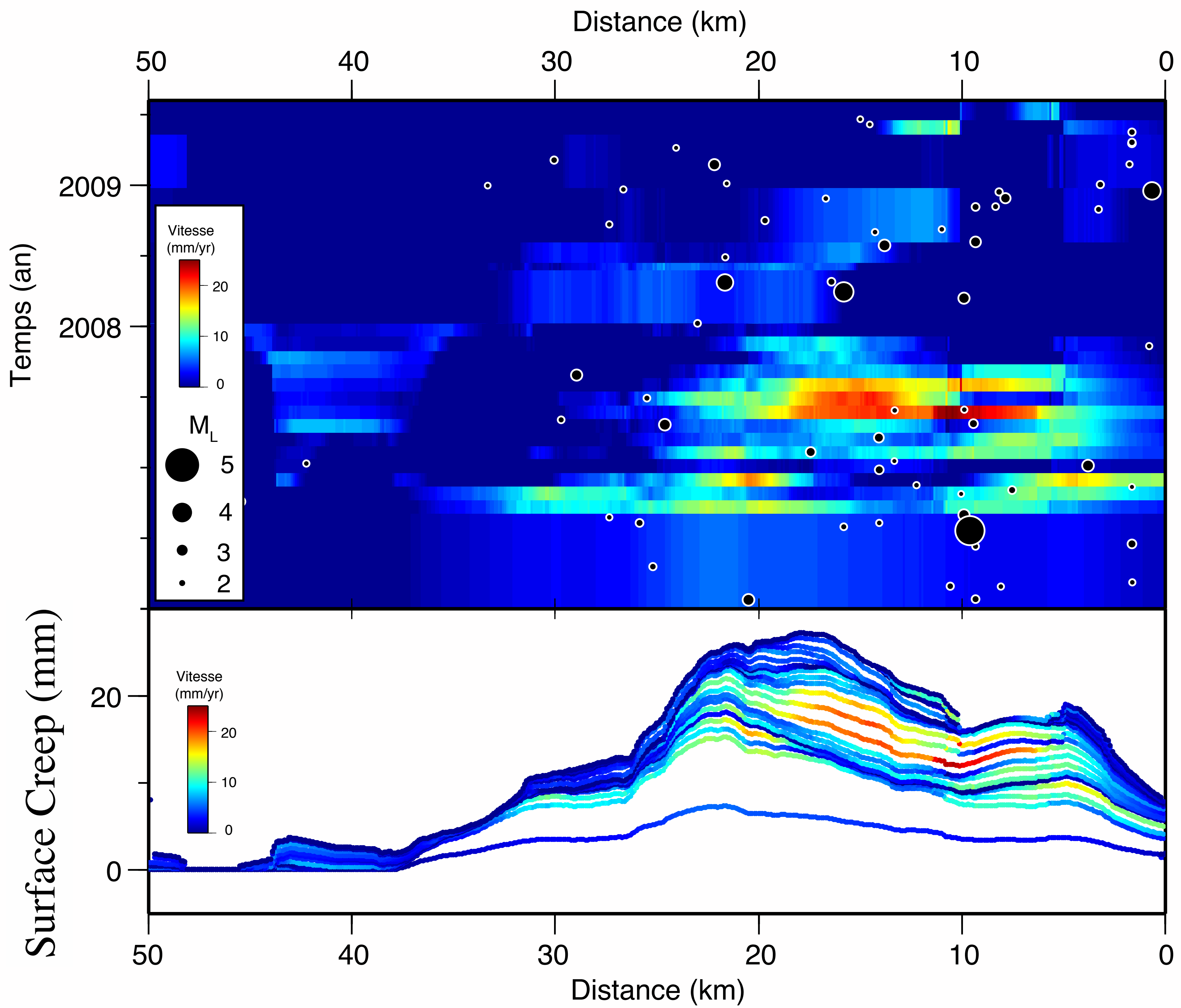

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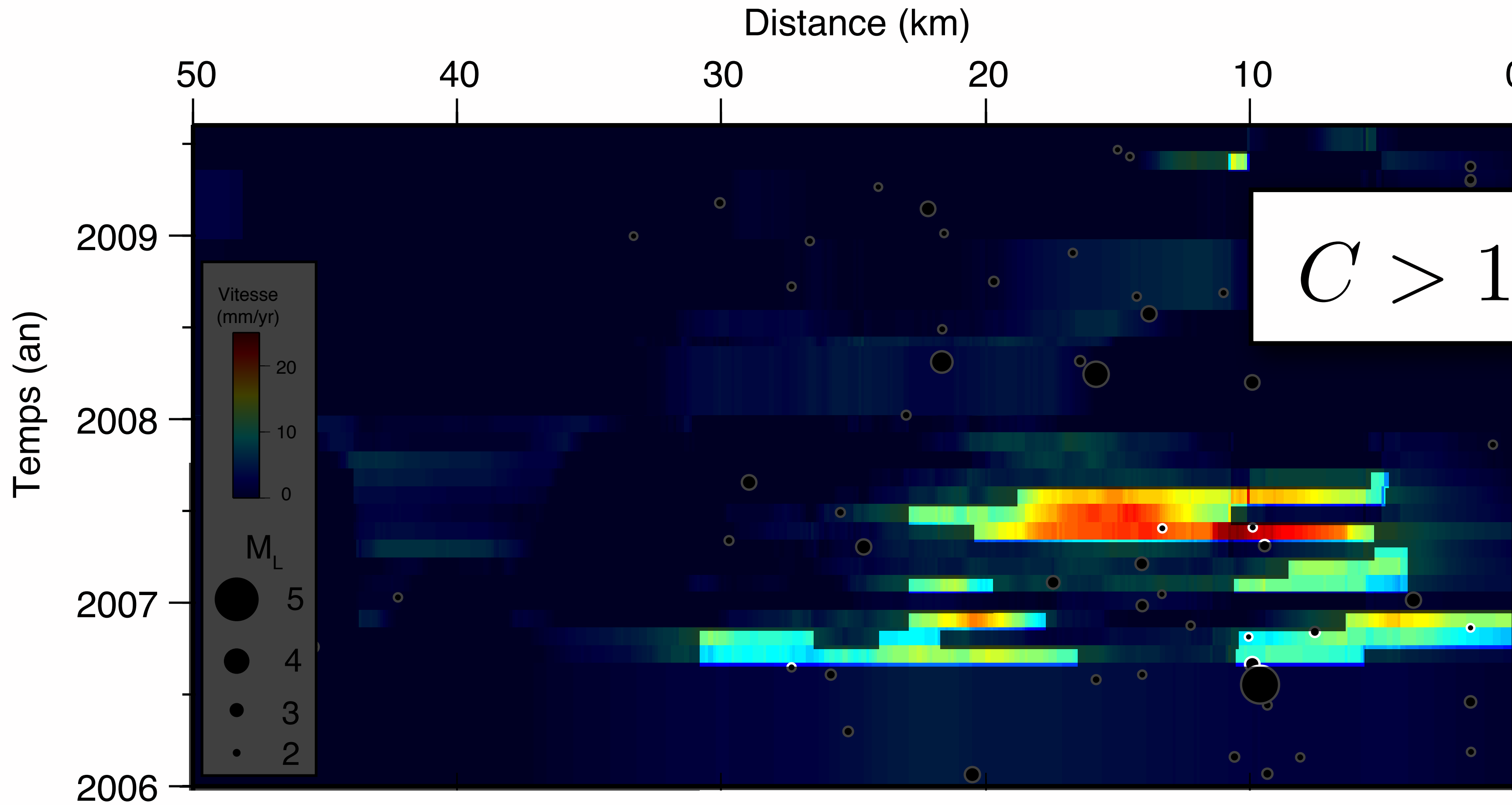
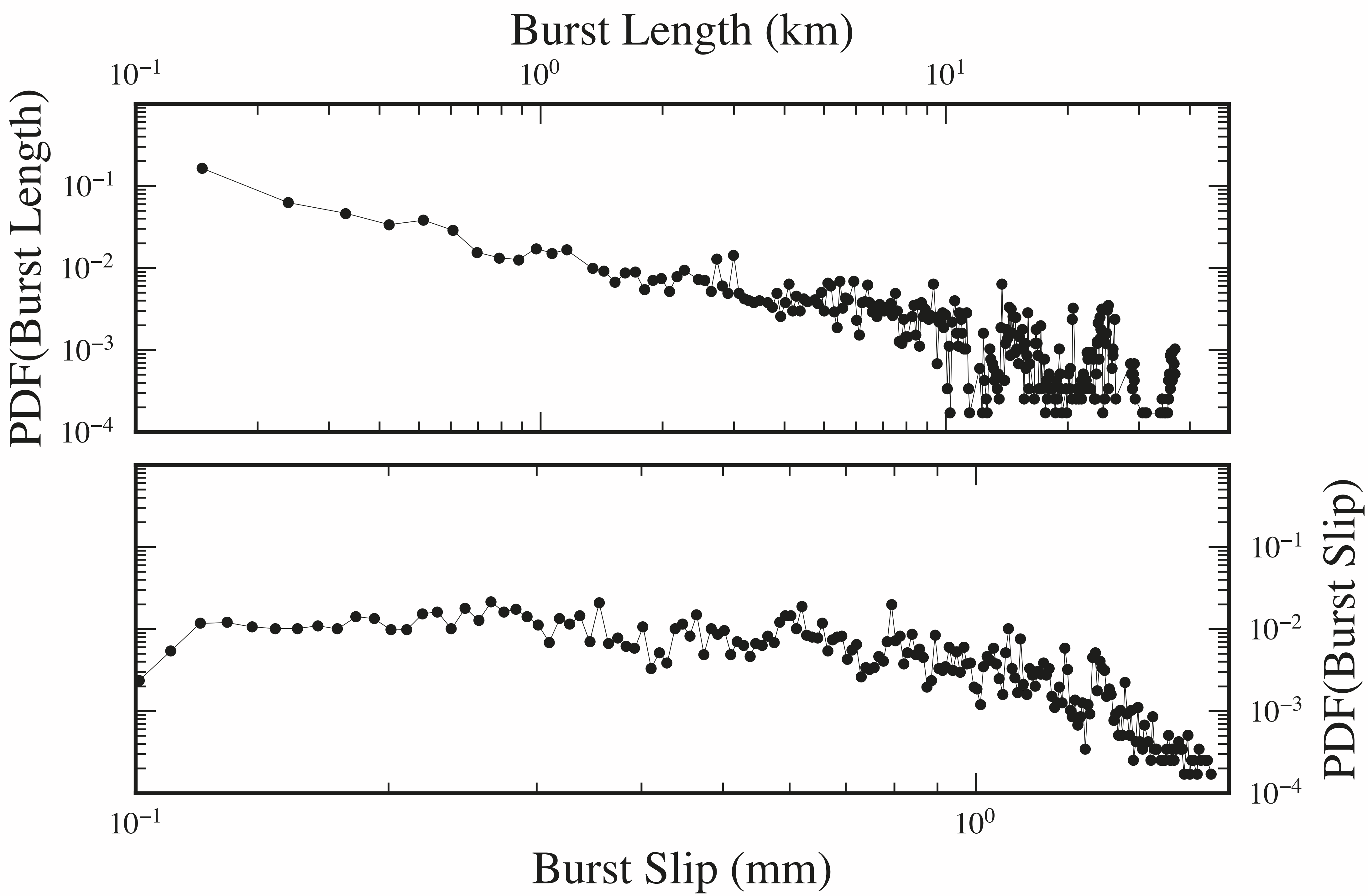


$$C > 11 \text{ mm.an}^{-1}$$

Burst: Segment where the velocity is higher than C

C varies from 1 to 15 mm/yr

Temporal behaviour of bursts of aseismic slip



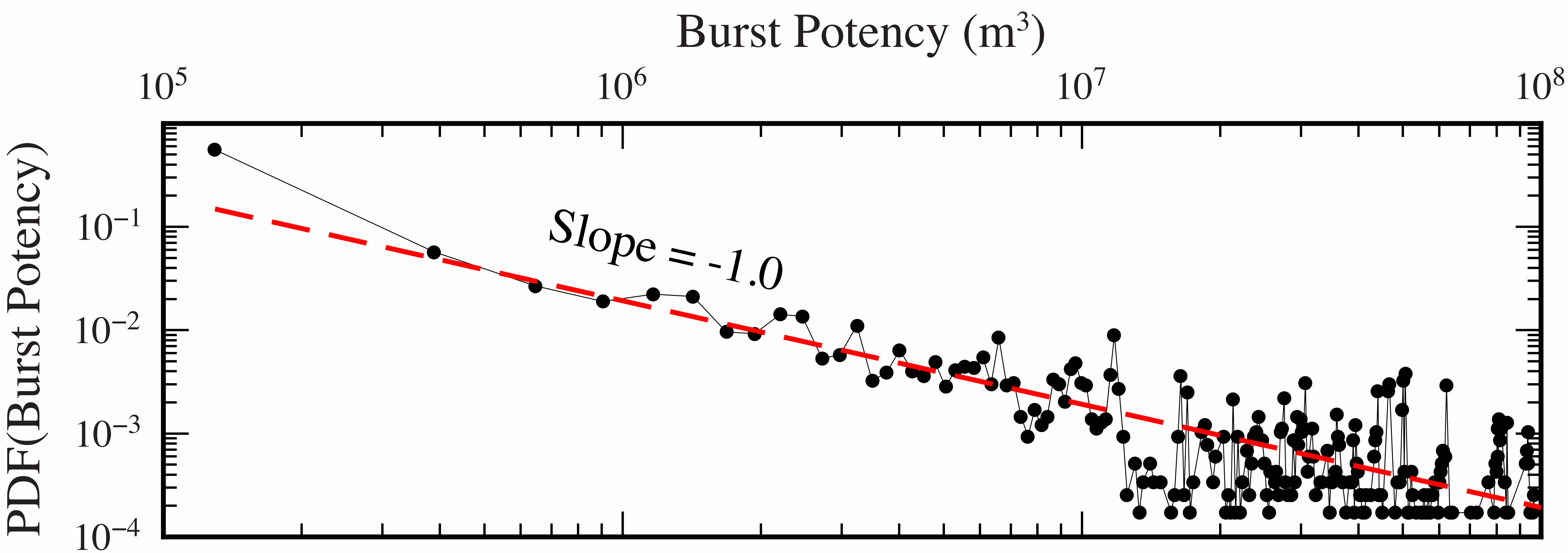
Temporal behaviour of bursts of aseismic slip

Seismic Moment:

$$M_0 = \mu SD$$

Seismic Potency:

$$P = SD$$



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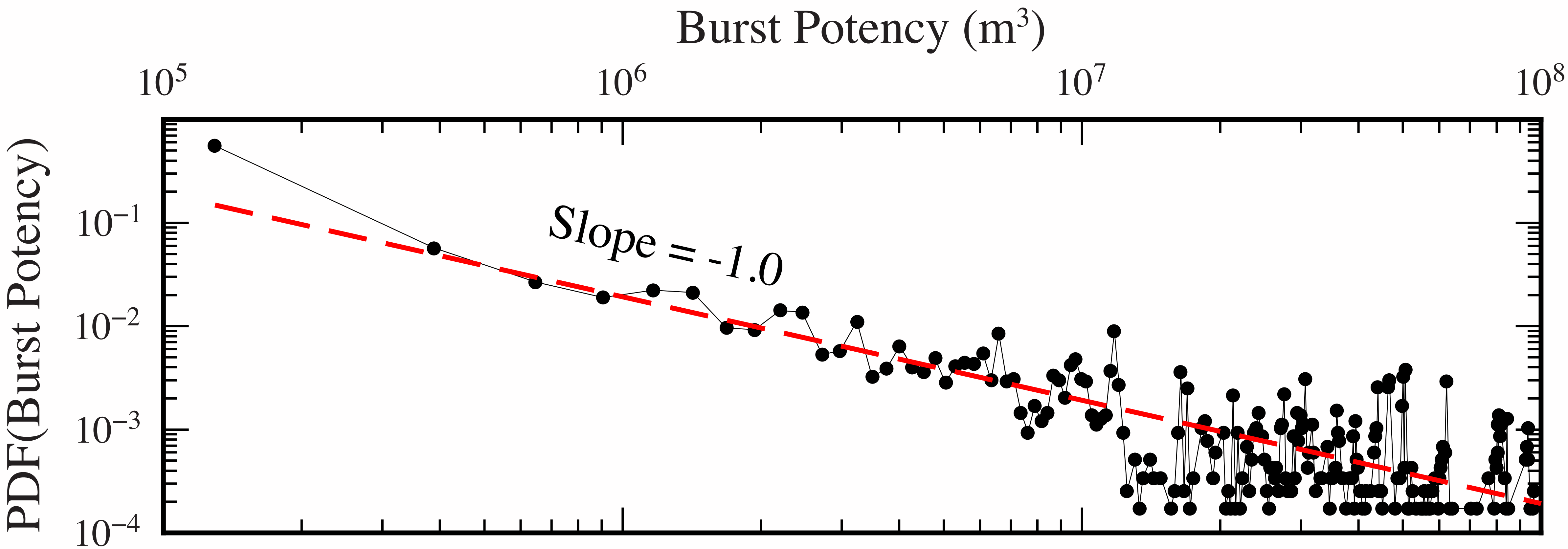
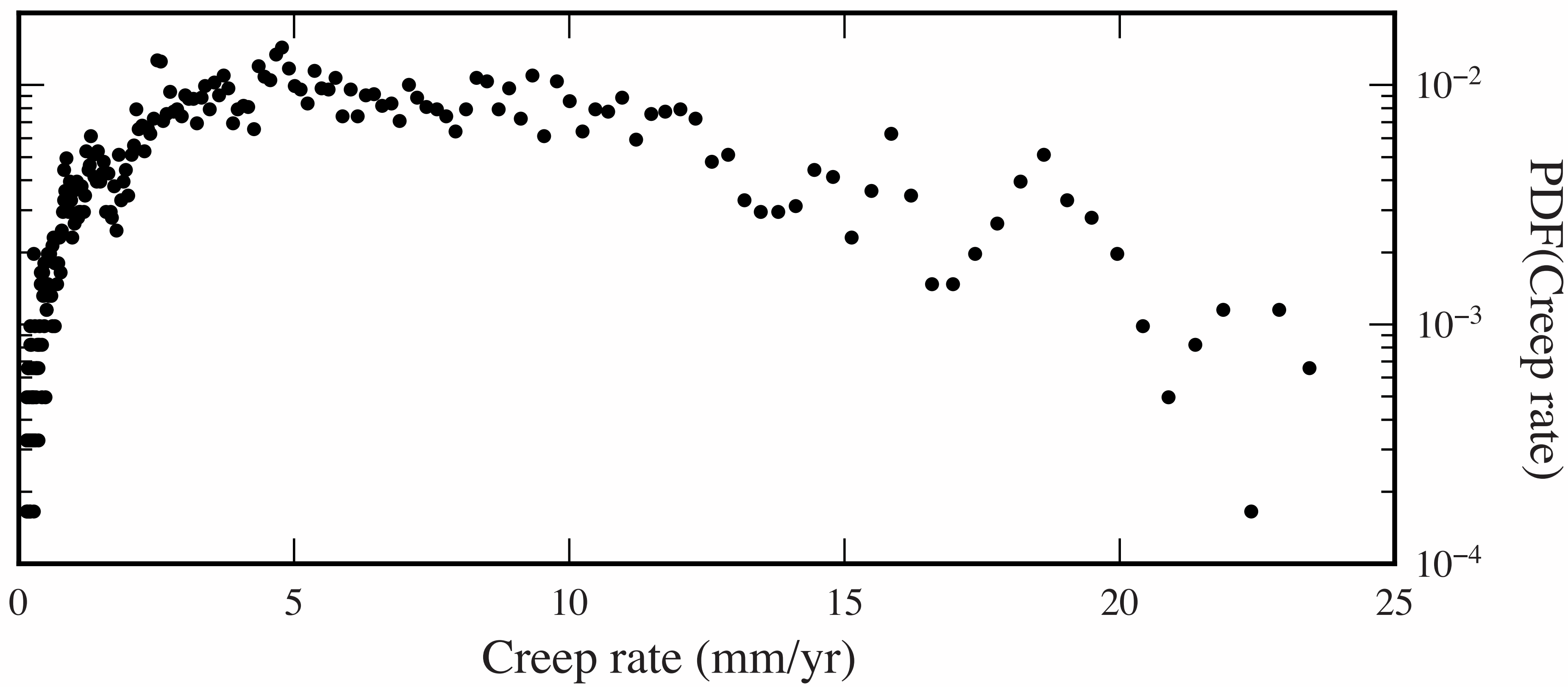


This law is similar to the Gutemberg-Richter law for earthquakes

Temporal behaviour of bursts of aseismic slip



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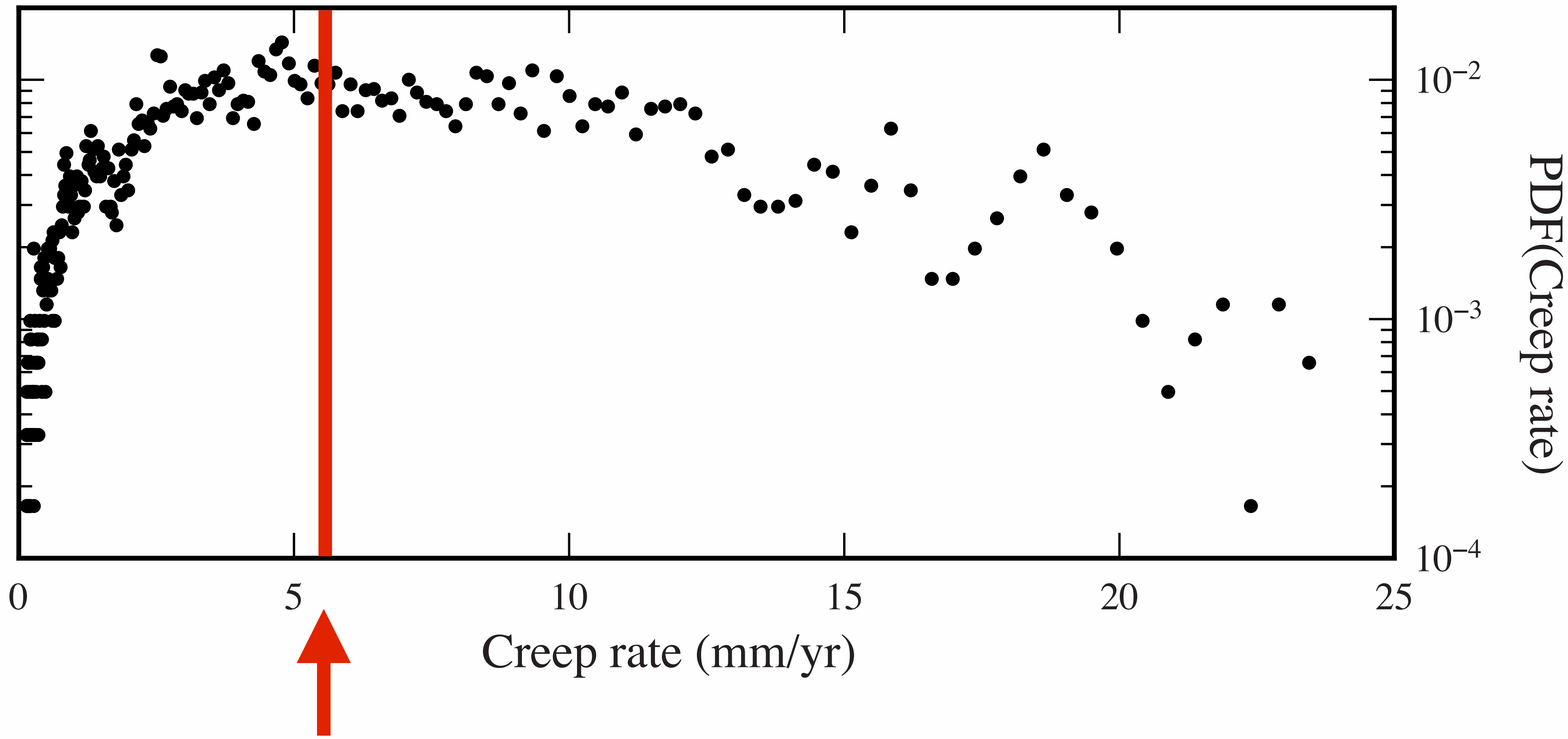
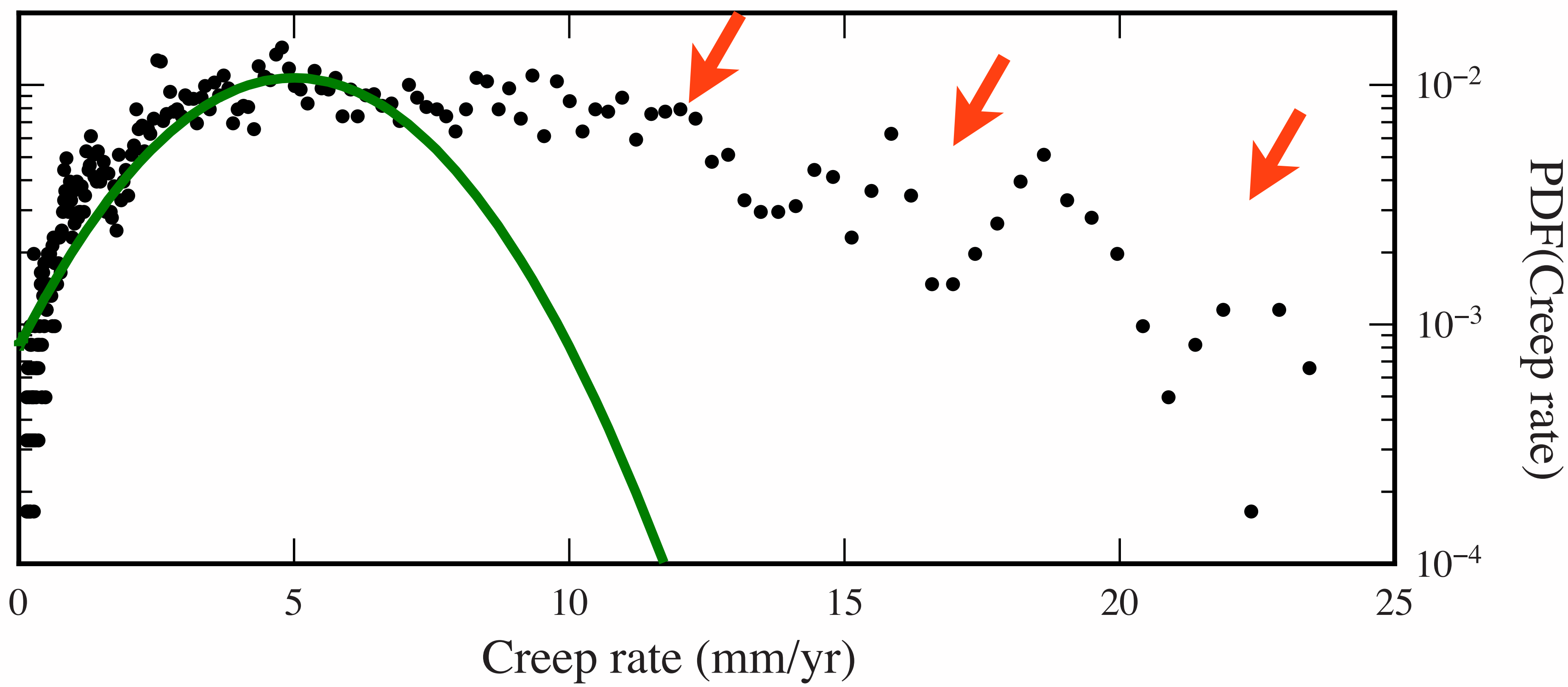


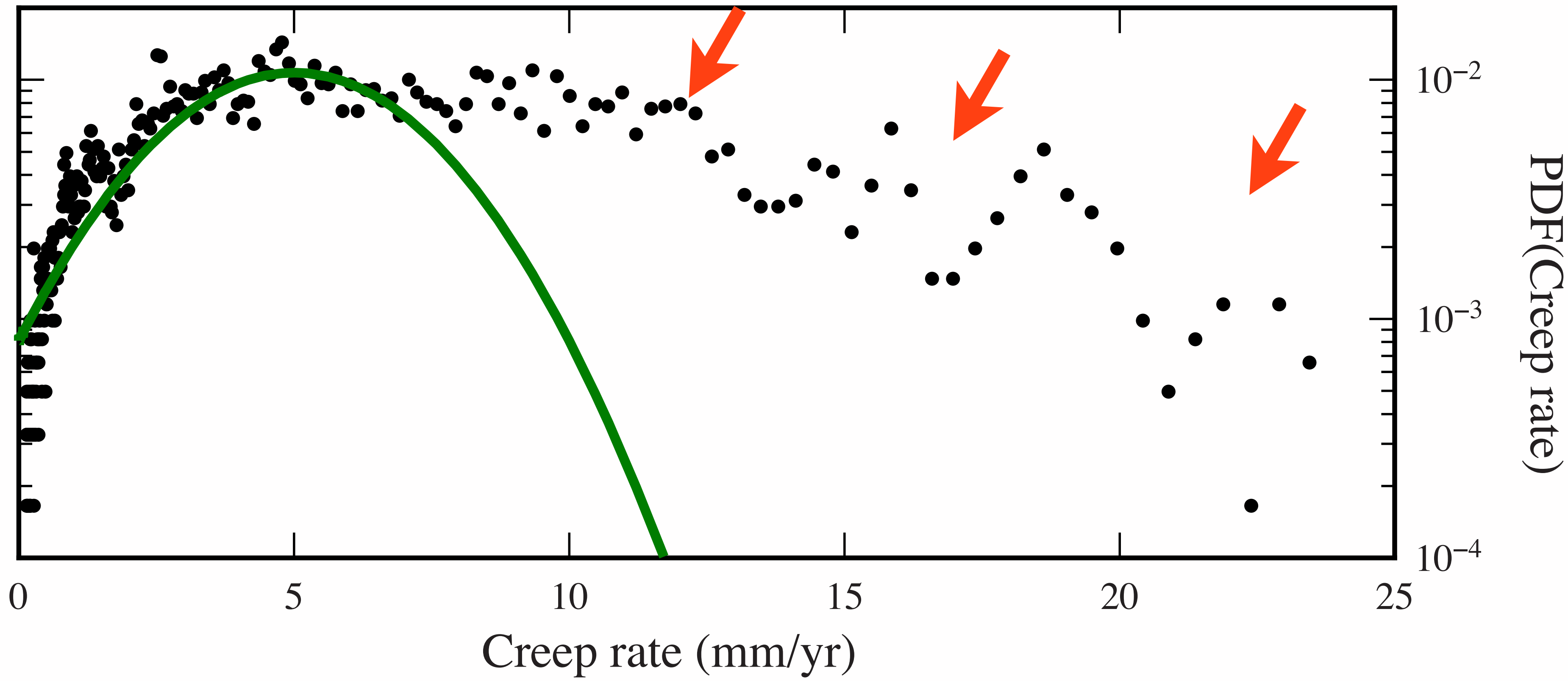
Centered on 6 mm/yr
(i.e. equal to the average
creep and loading rate)

Temporal behaviour of bursts of aseismic slip



→ Avalanche-like mechanism

Temporal behaviour of bursts of aseismic slip



→ Avalanche-like mechanism

We see a cascade of events

Creep Bursts cascades, like aftershocks do

Temporal behaviour of bursts of aseismic slip

- Creep spatial and temporal behaviour is influenced by the fault geometry.
- The creep bursts size (magnitude?) follows a power-law, like small earthquakes.
- Avalanche-like behaviour, like aftershocks.

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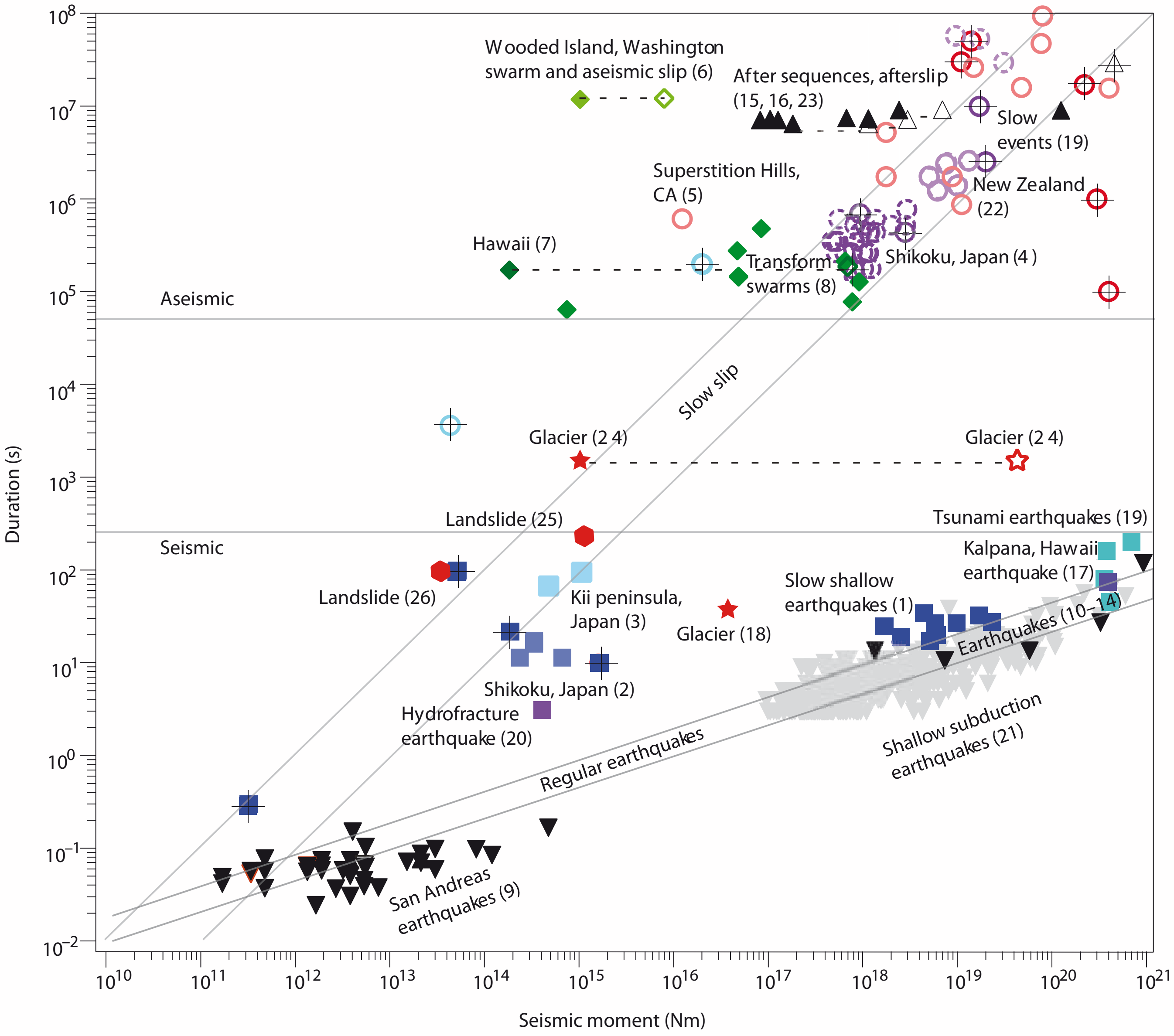

Bi-modal behaviour or continuum of modes of slip, from the earthquake to aseismic sliding?

Temporal behaviour of bursts of aseismic slip

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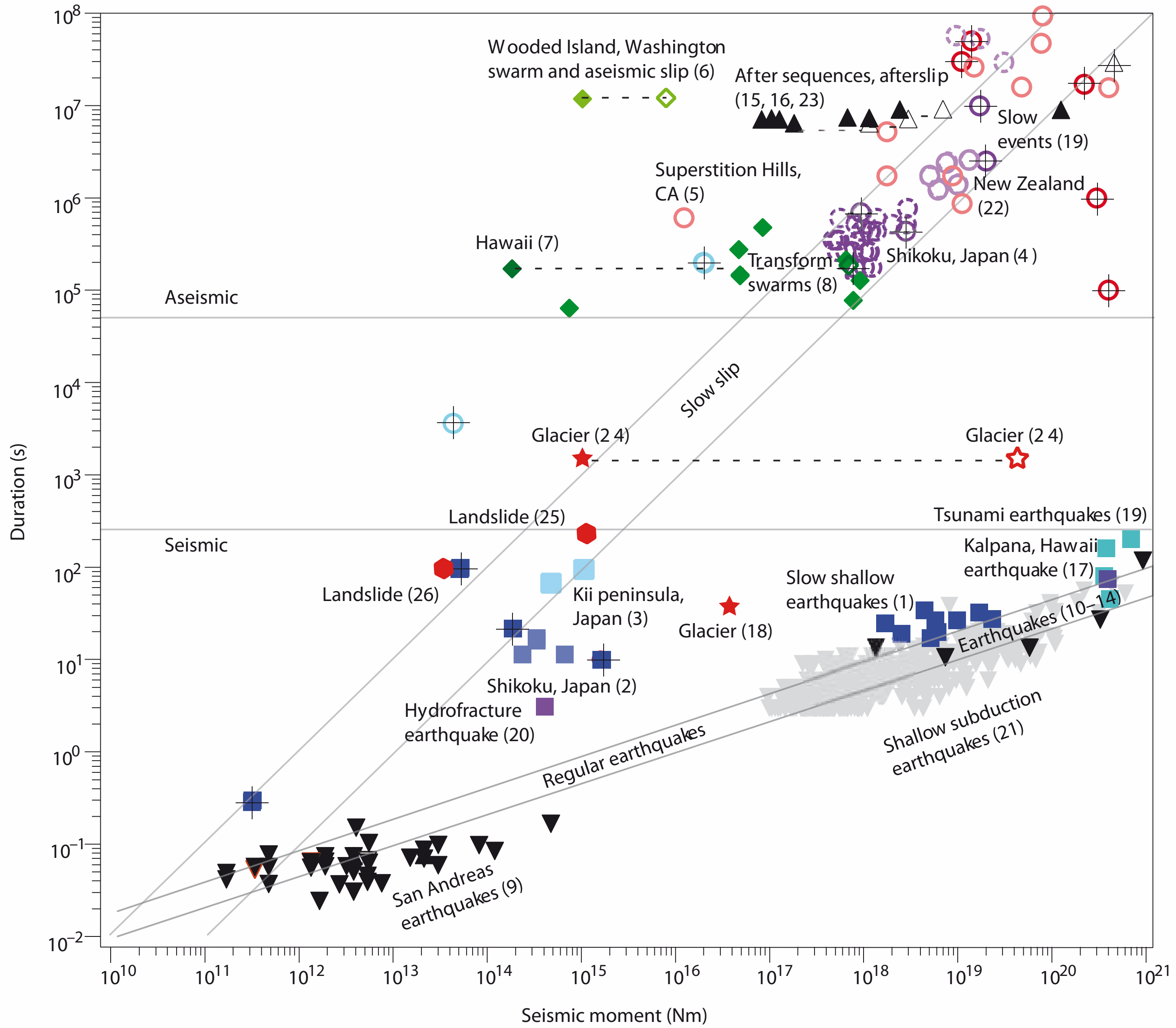


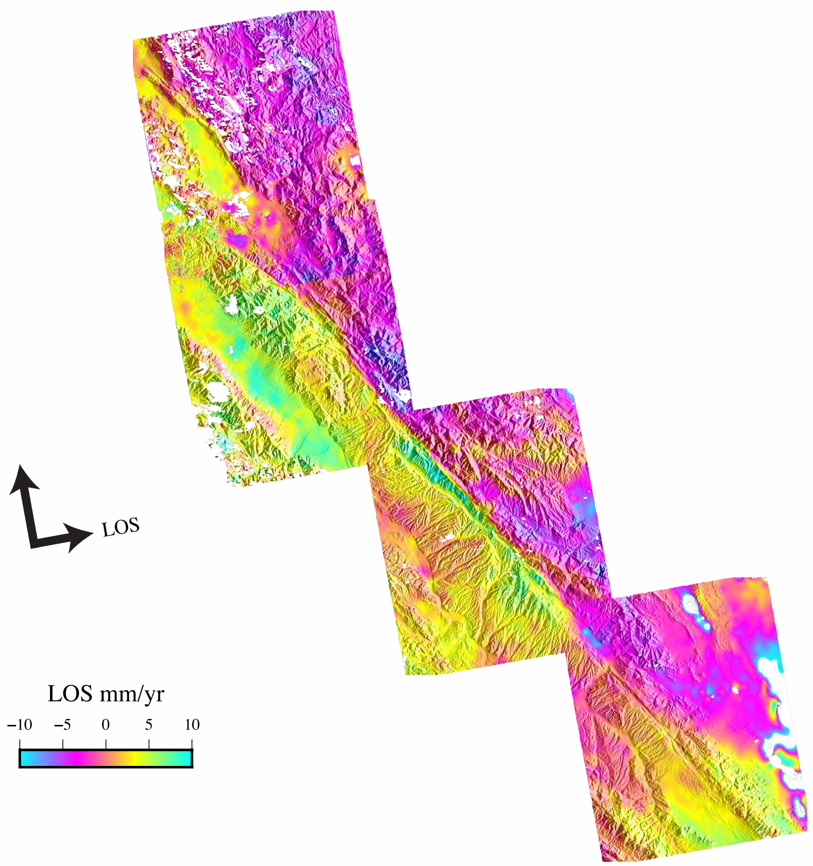
Bi-modal behaviour or continuum of modes of slip, from the earthquake to aseismic sliding?

Continuum from aseismic slip to earthquakes

Conclusions - Perspectives

Mapping creep along active faults using InSAR

Systematically quantify fault coupling along active boundaries.
Identify locked and creeping patches.
Relate to the past (and future) seismic history of the fault



Monitoring temporal variations of aseismic slip using InSAR

New constellations are in place.
Short repeat time will shed a new light on creeping segments (dynamic evolution)
Systematic monitoring of creeping faults on continental settings

Extracting possible mechanical behaviours from InSAR images

Using these new data sets to explore possible new interpretations, refine models and explain the interplay between seismic and aseismic behaviour