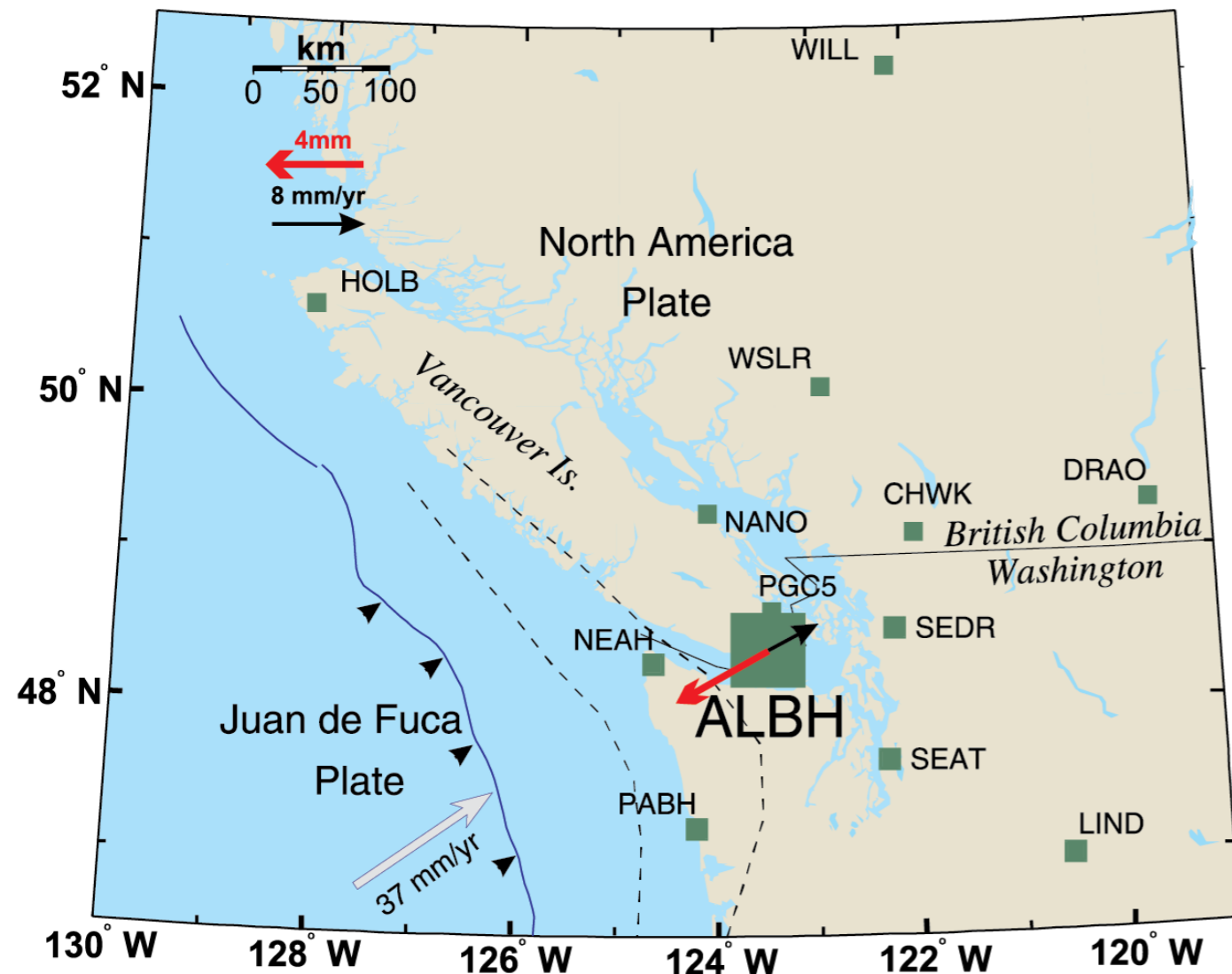


The transient and intermittent nature of slow slip

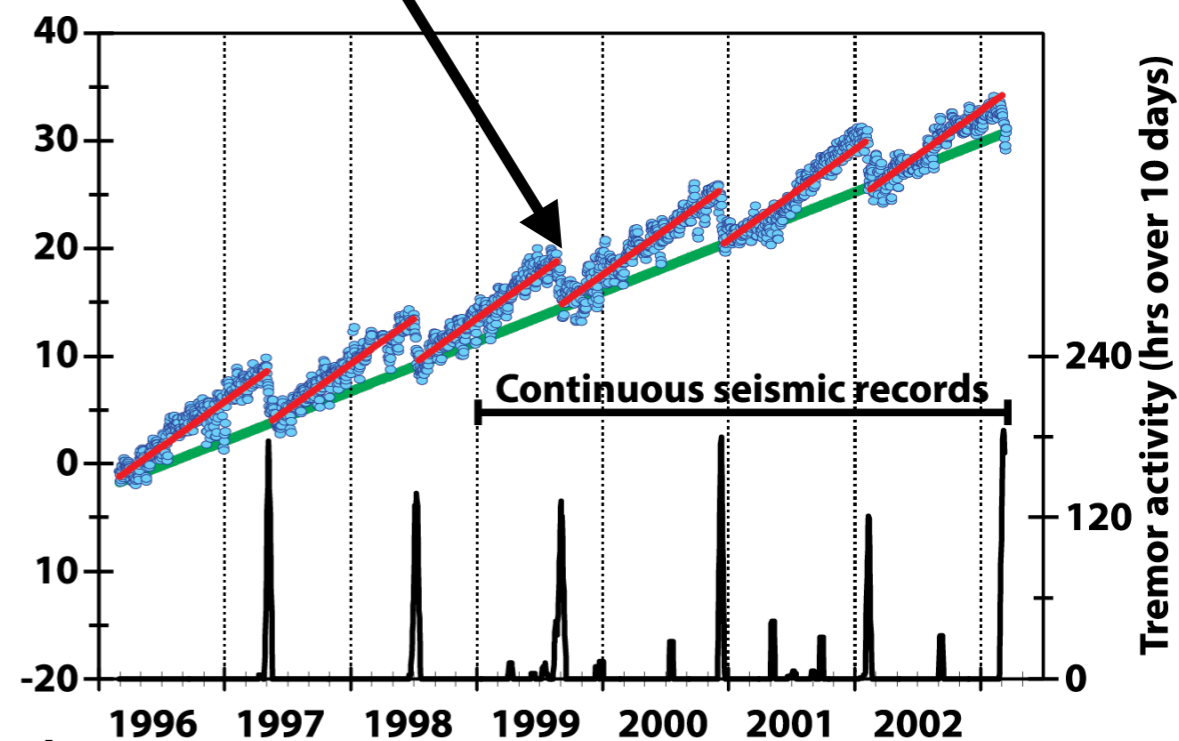
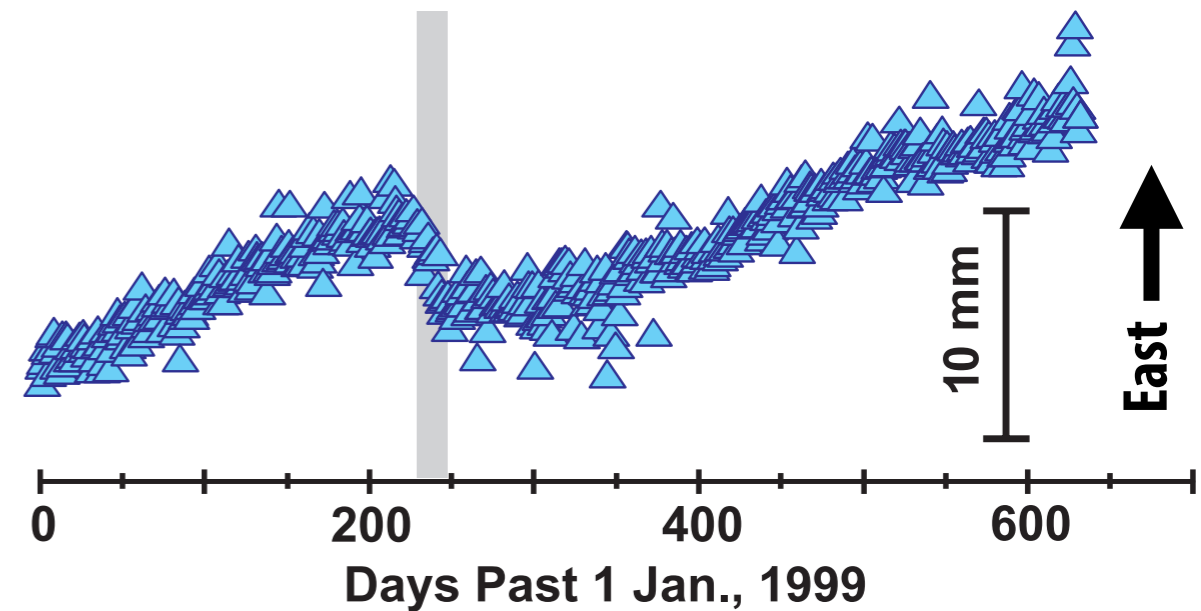
William Frank

University of Southern California

Slow-slip events (SSEs)

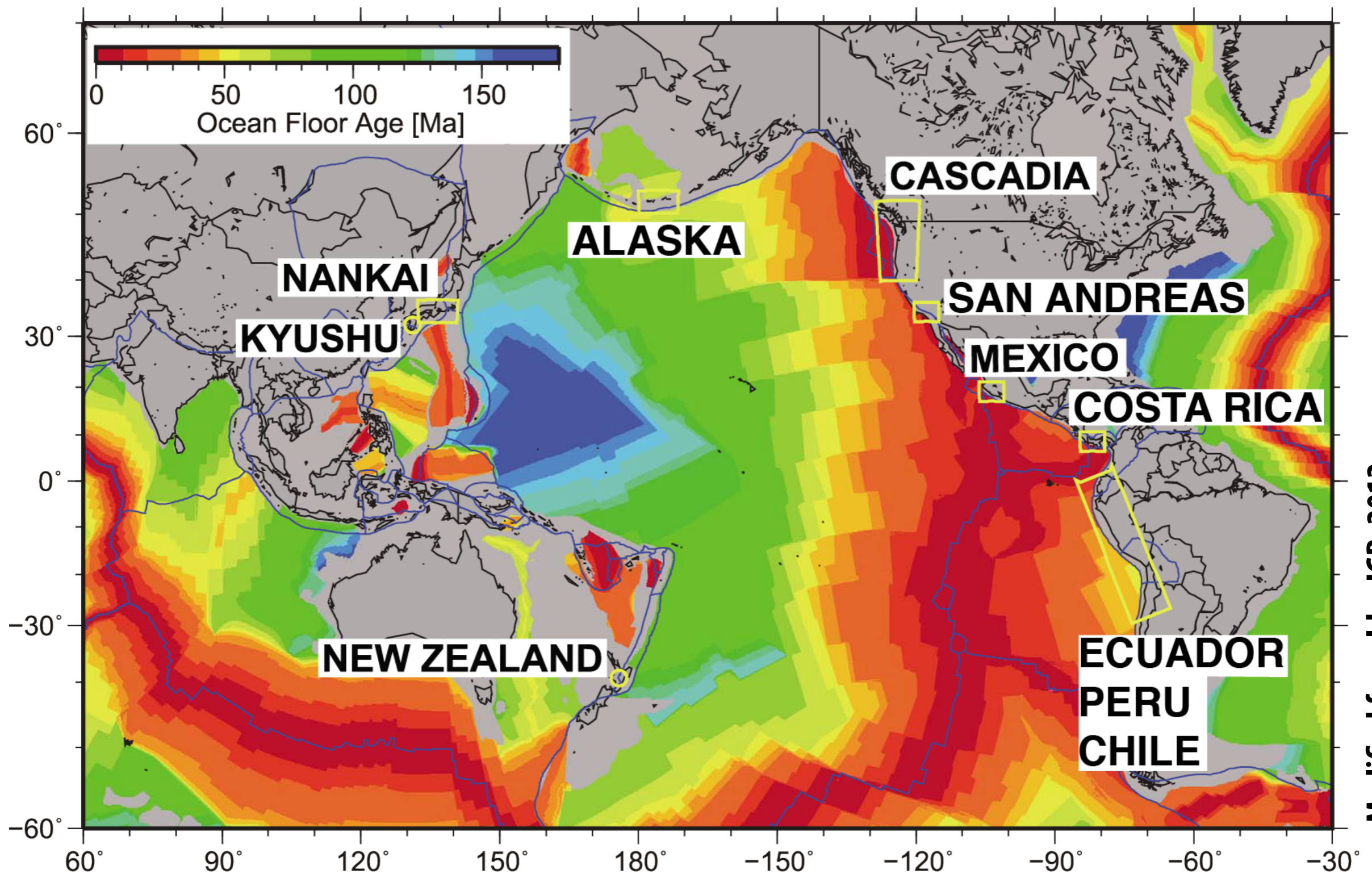


Modified from Dragert et al., Science, 2001



- ▶ New mode of aseismic transient **release**
- ▶ Lasts from several days to weeks to months
- ▶ Can release as much built-up tectonic stress as a major earthquake

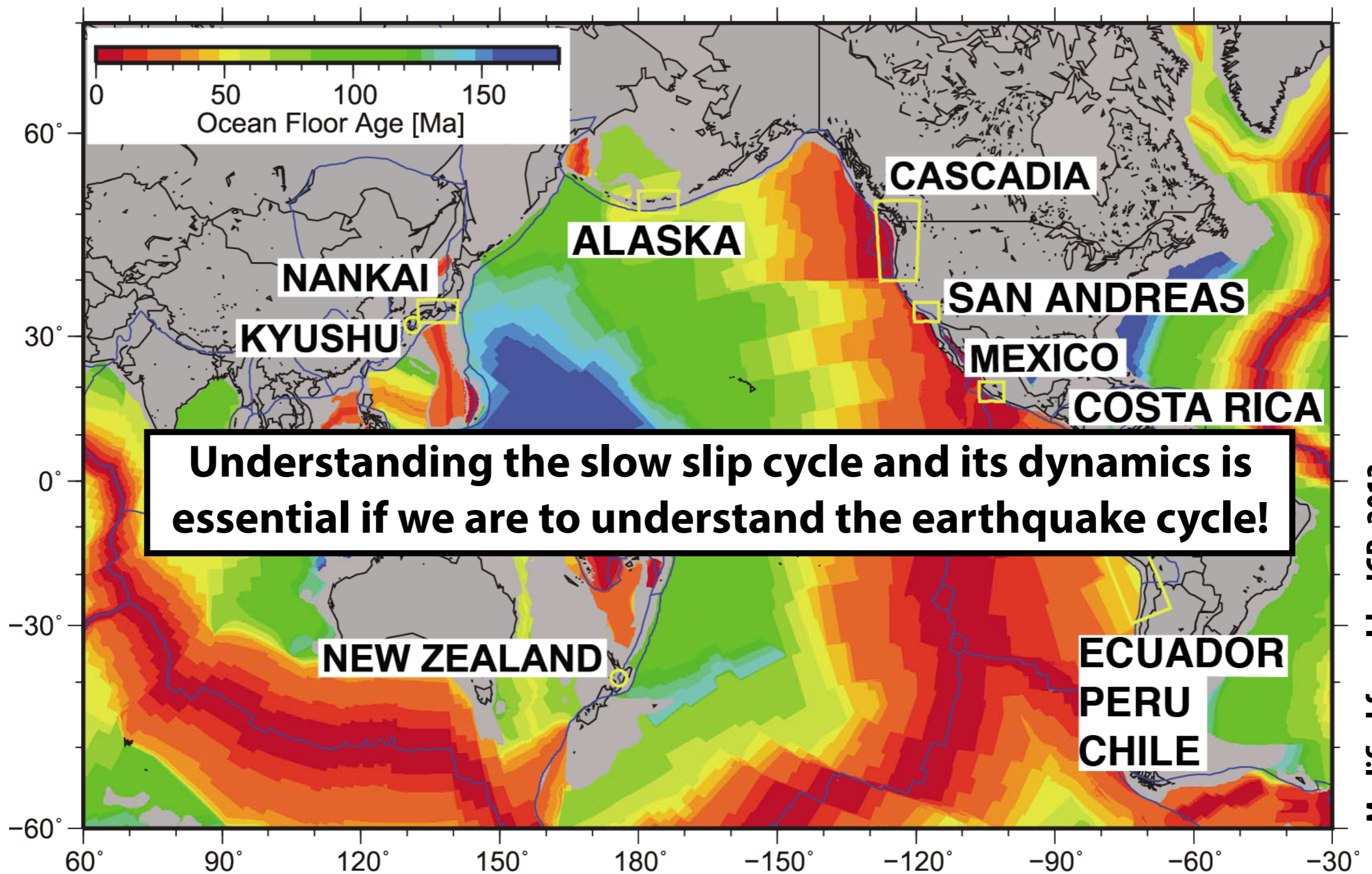
Slow slip is where big earthquakes happen



Modified from Ide, JGR, 2012

Slow slip must play some role in the earthquake cycle!

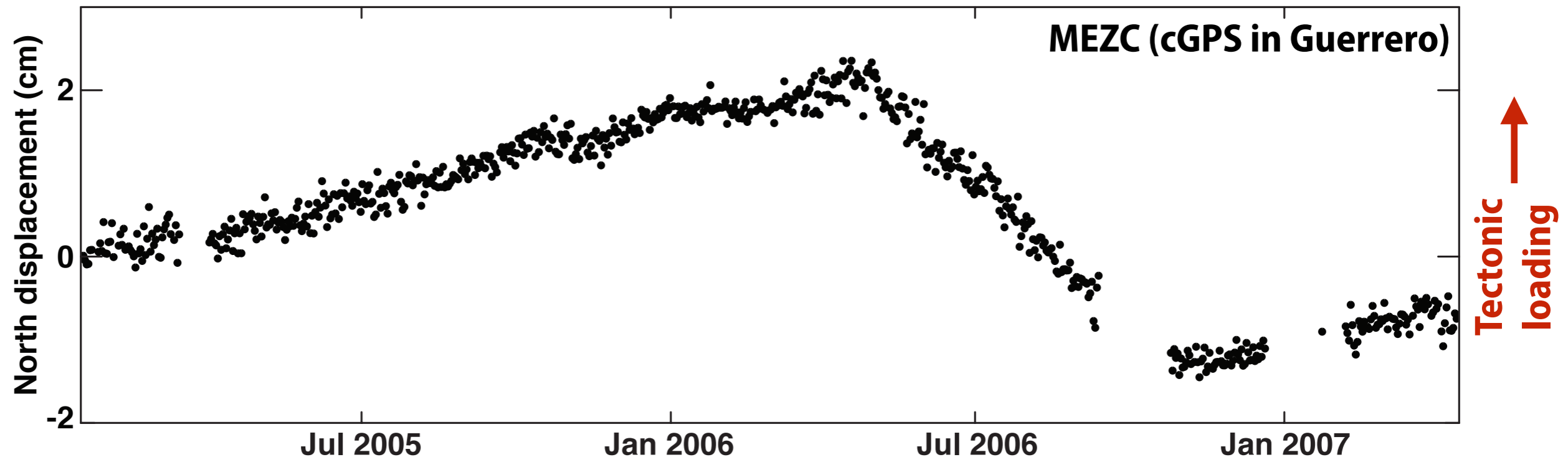
Slow slip is where big earthquakes happen



Modified from Ide, JGR, 2012

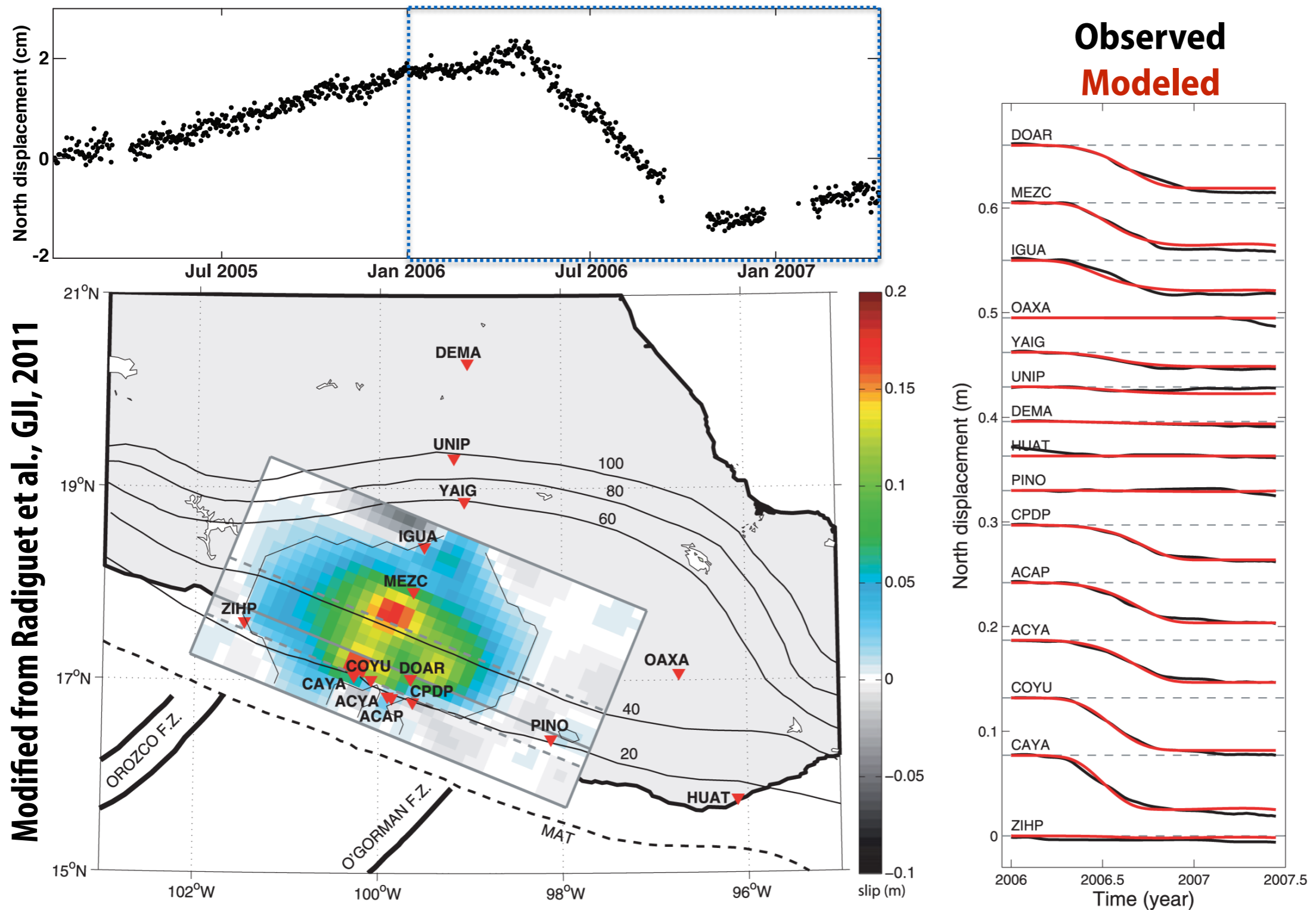
Slow slip must play some role in the earthquake cycle!

Geodesy is our tool to directly constrain slow slip



- ▶ No direct seismic radiation
- ▶ Mainly cGPS (although also tilt- and strain-meters)
- ▶ Point observations integrate elastic response over wide area
 - ▶ Spatiotemporal resolving power dependent on network density
- ▶ Position solutions sampled daily with error of several mm

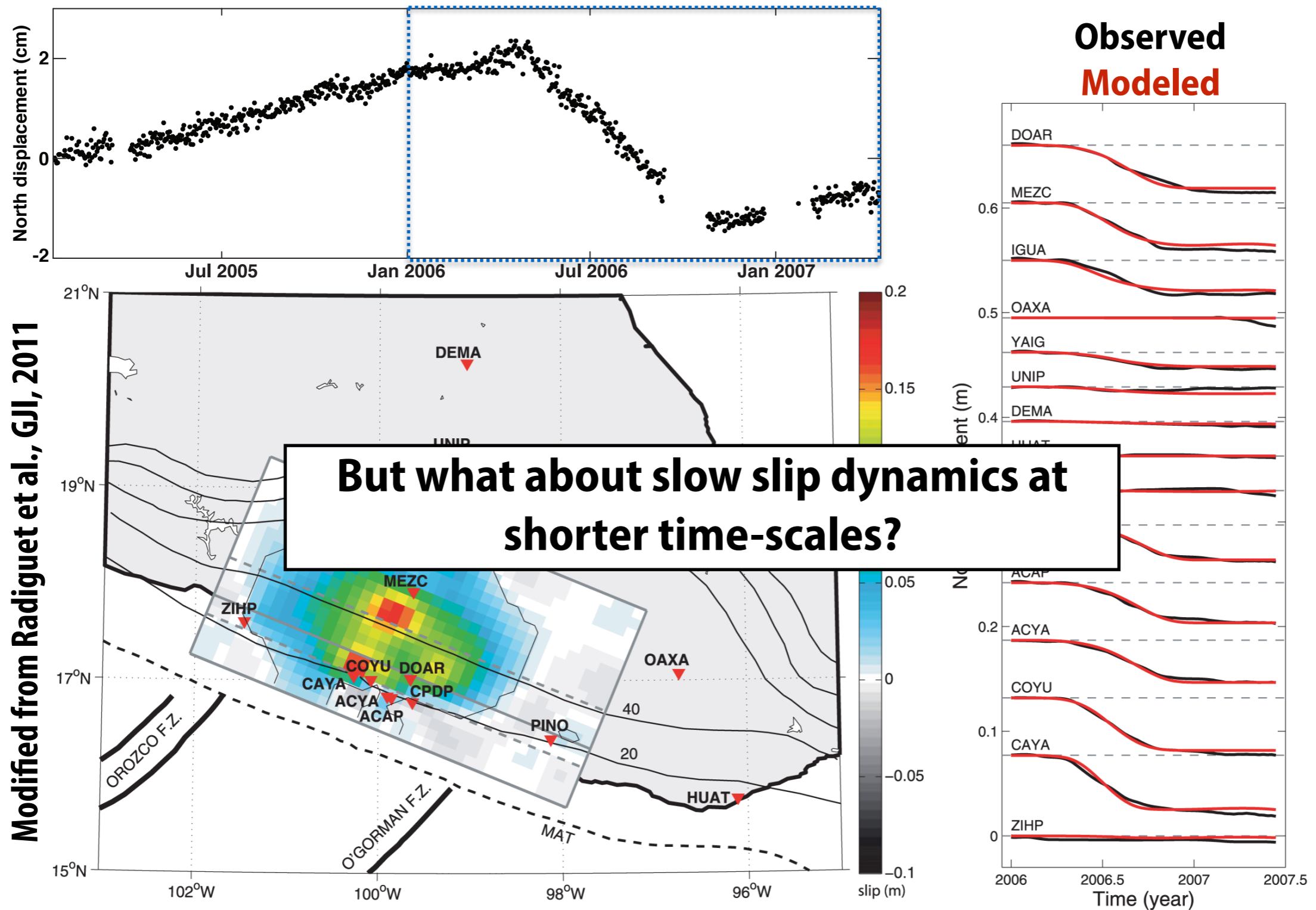
Geodetic image of a M_w 7.5 slow slip event



Modified from Radiquet et al., GJI, 2011

- ▶ Six-month long rupture
- ▶ Smooth, continuous
- ▶ Long-period (>30-day) deformation well constrained

Geodetic image of a M_w 7.5 slow slip event

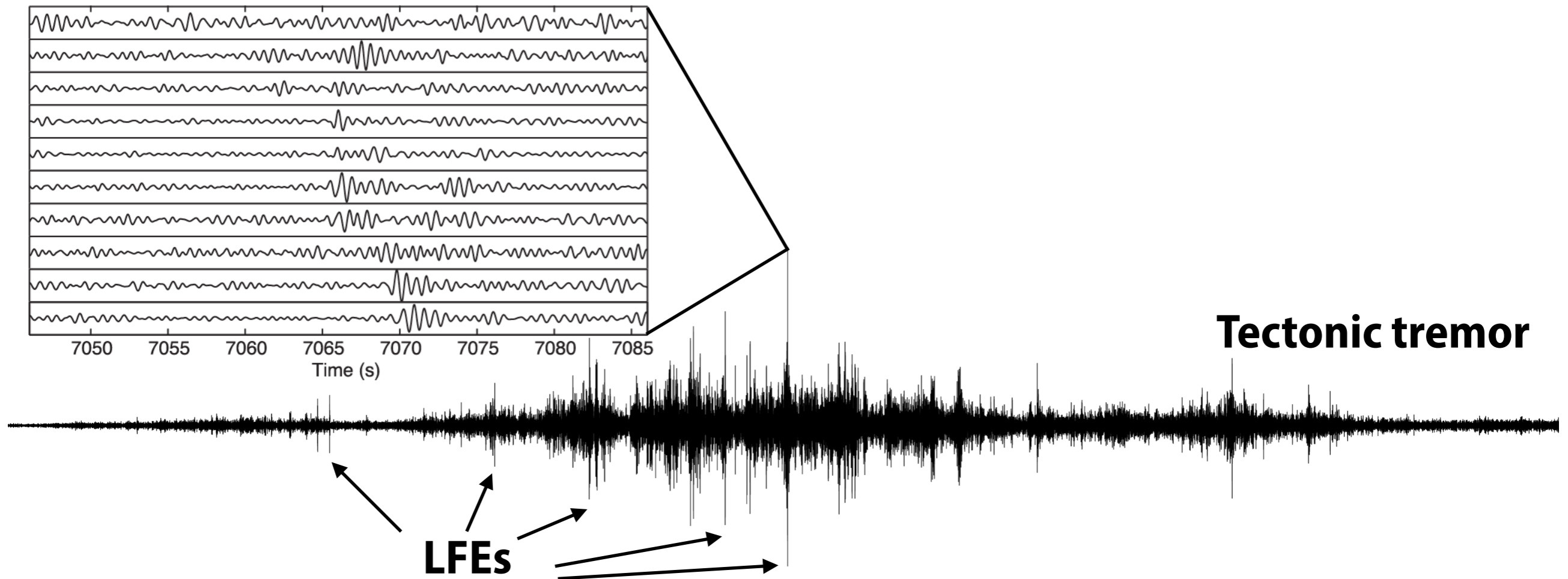


Modified from Radiquet et al., GJI, 2011

- ▶ Six-month long rupture
- ▶ Smooth, continuous
- ▶ Long-period (>30-day) deformation well constrained

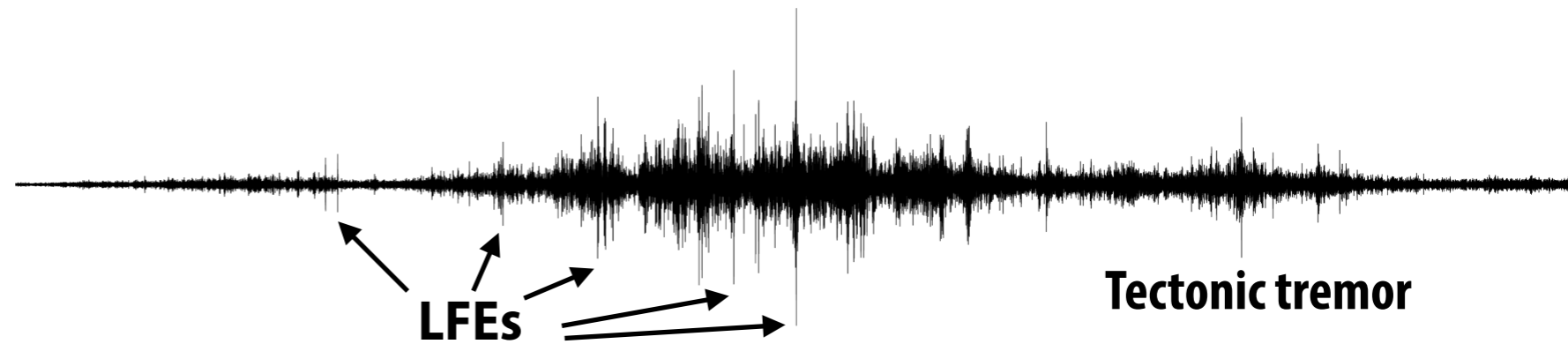
Slow seismicity: Low-frequency earthquakes (LFEs)

Modified from Frank and Shapiro, GJI, 2014

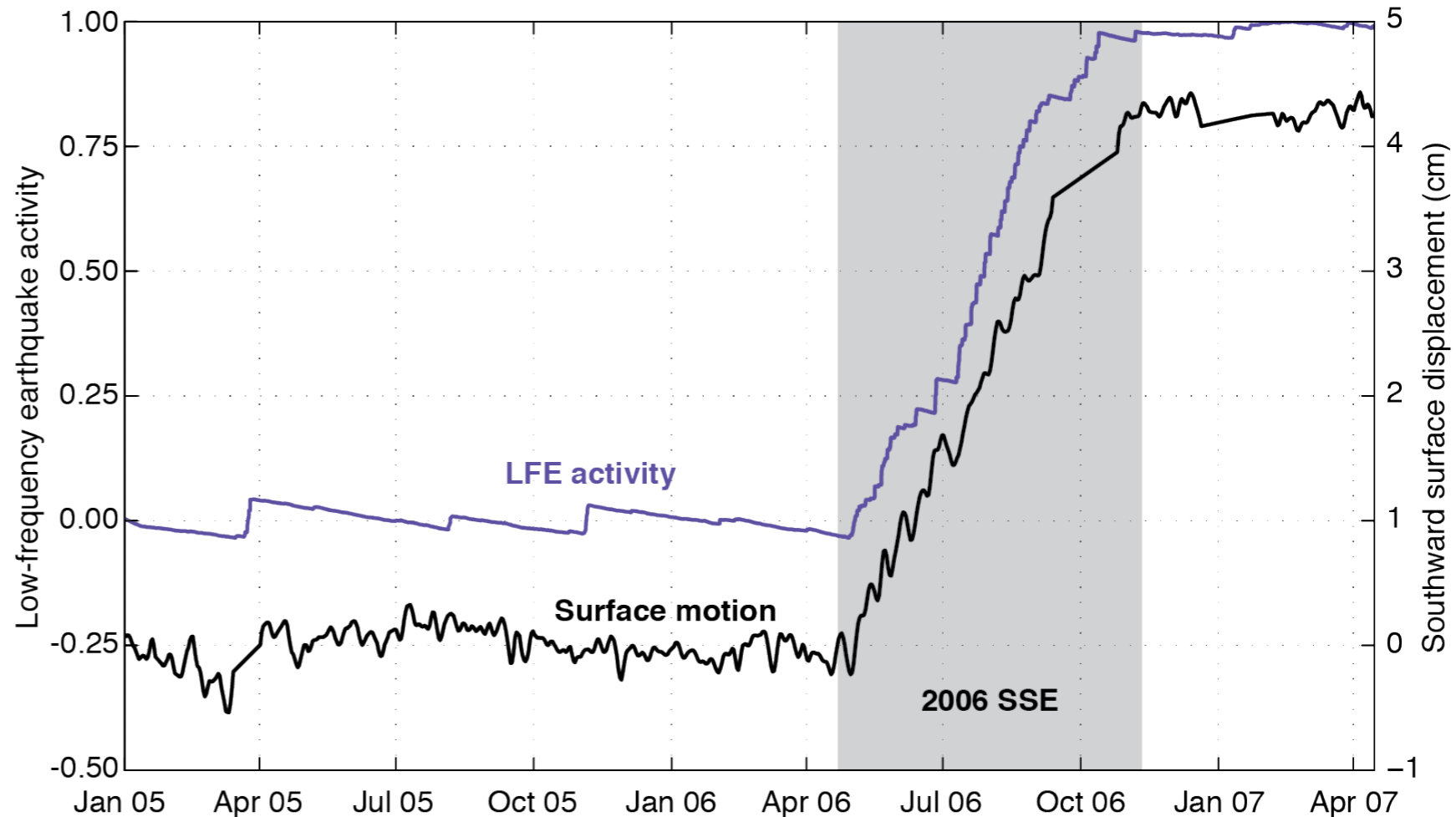


- ▶ Small, impulsive, **repetitive** seismic events on the plate interface
- ▶ Correlated with slow slip in both time and space

Low-frequency earthquakes as a proxy for slow slip

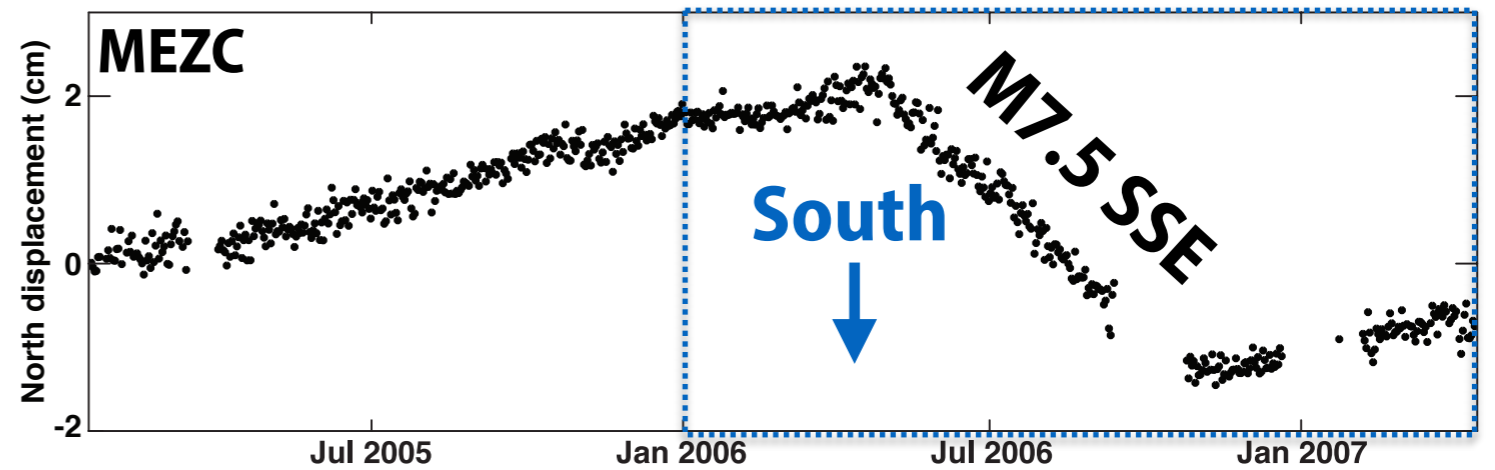


- ▶ Bursts of LFEs occur during slow slip (Frank et al., Sci. Adv., 2016)
- ▶ LFEs are a spatio-temporally precise proxy for slow slip!

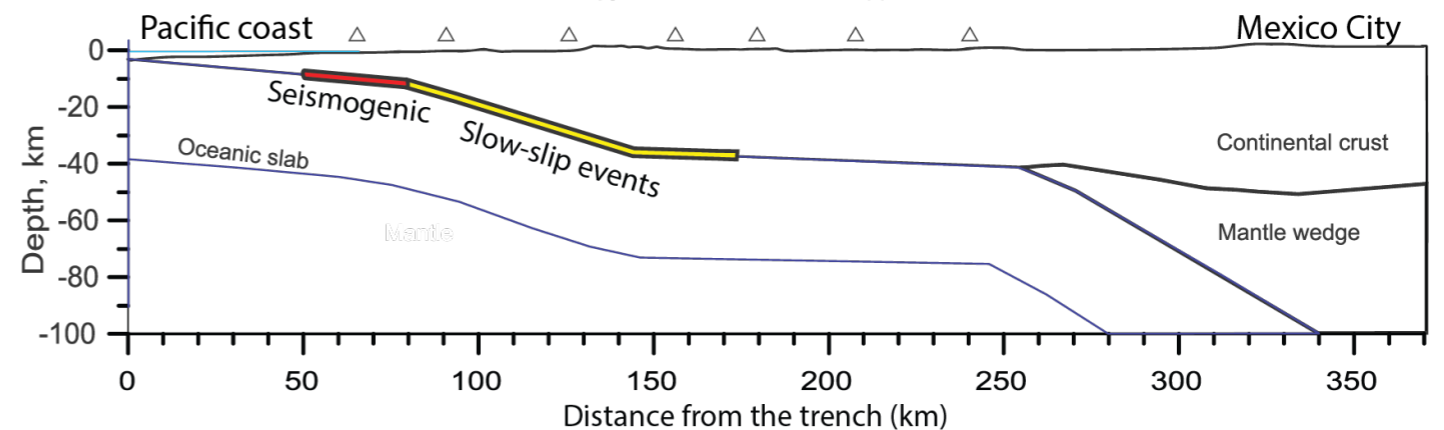
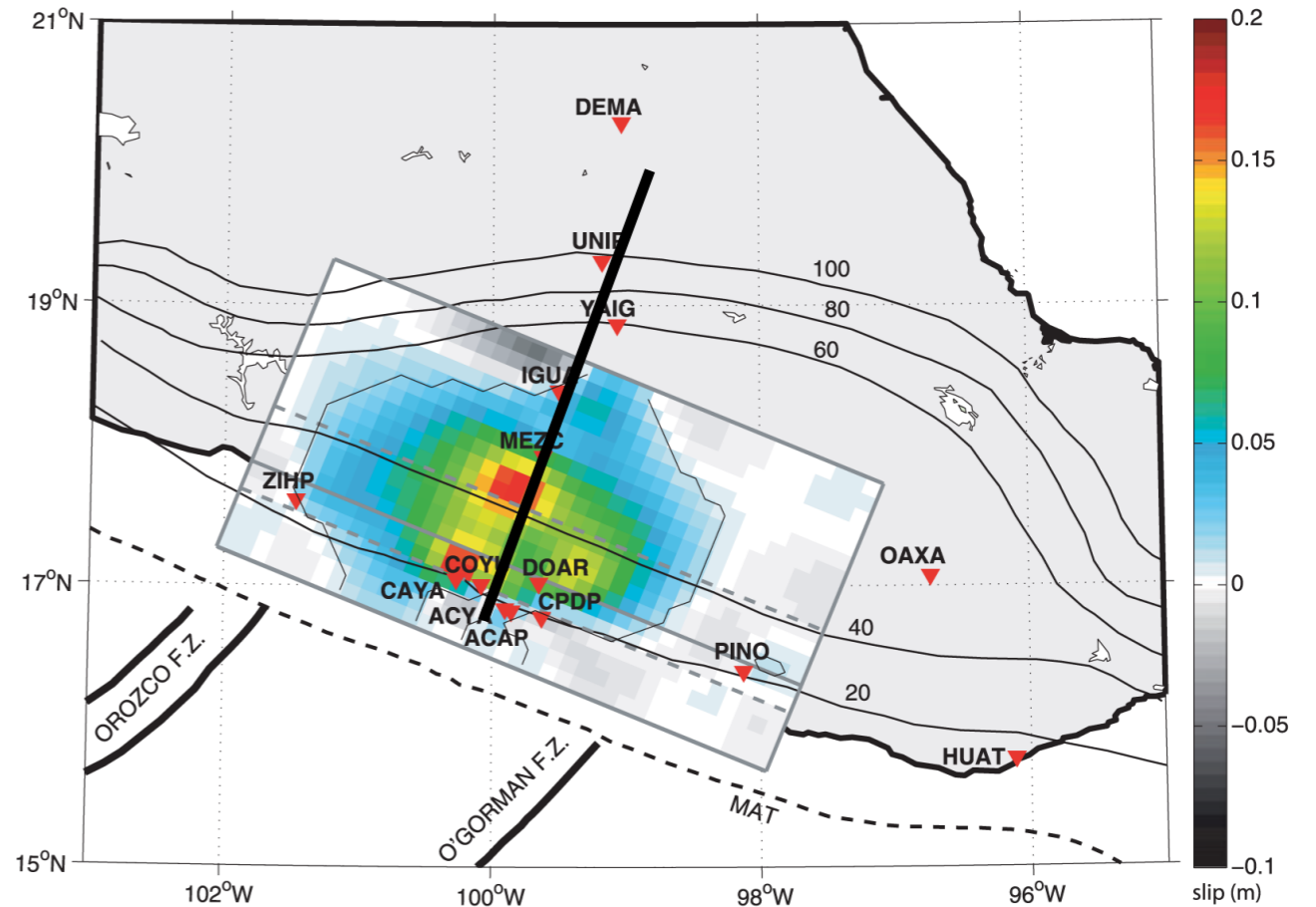


Modified from Frank et al., EPSL, 2015

Slow slip in Guerrero



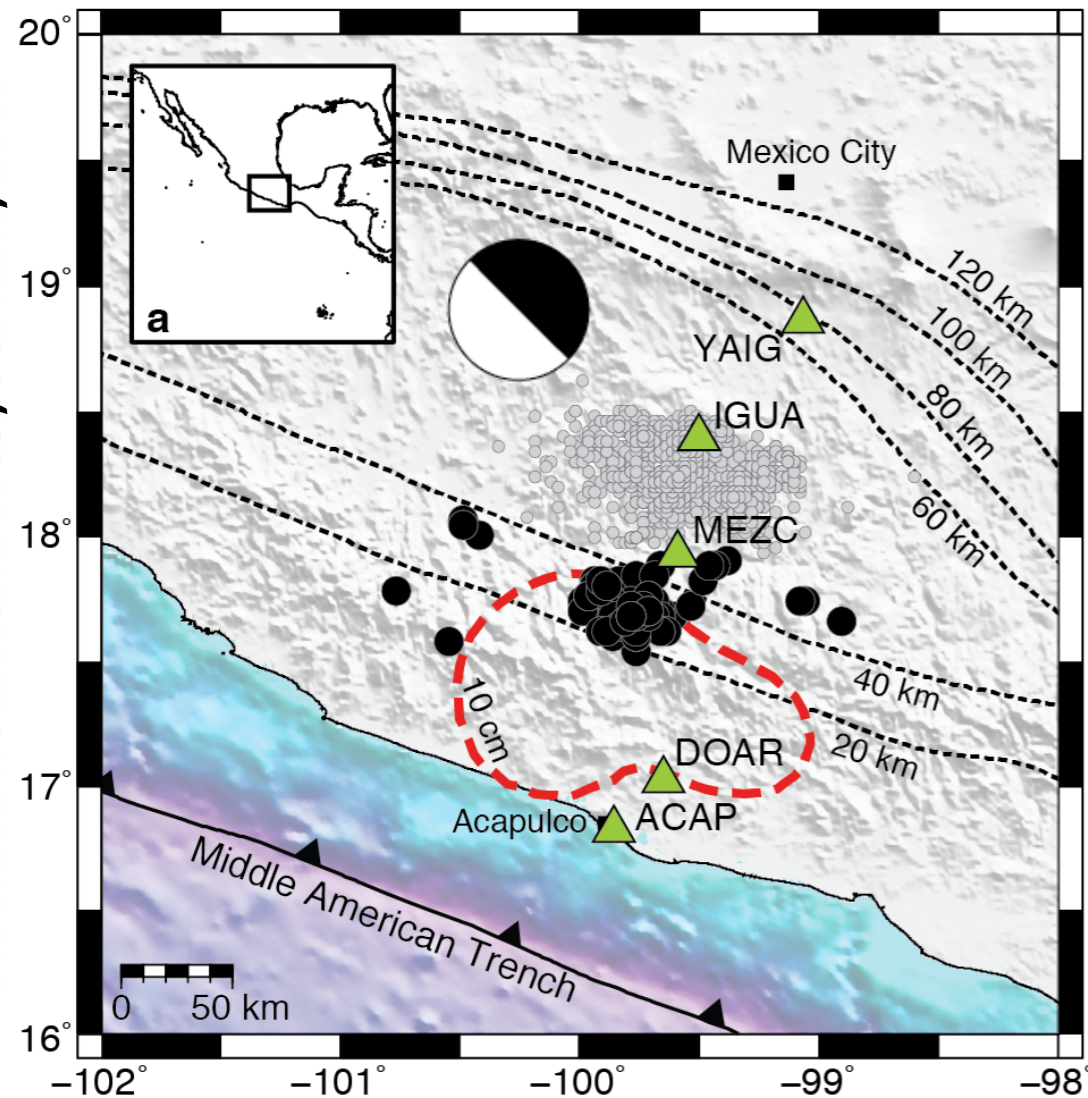
- ▶ Flat slab subduction
 - ▶ Natural control on pressure
- ▶ Major M7.5 slow slip events every 4 years
- ▶ Tectonic release to the **South**



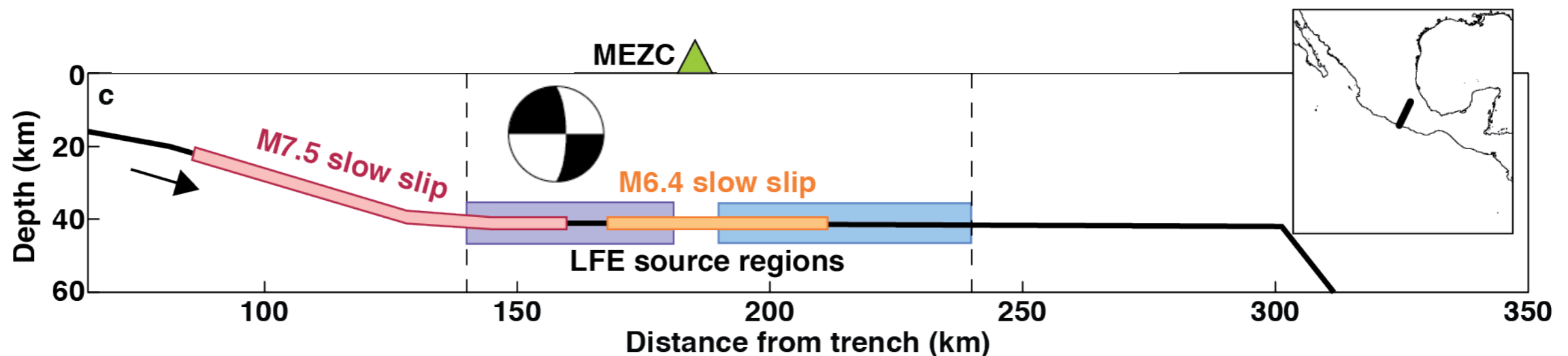
Modified from Radigue et al., GJI, 2011

Low-frequency earthquakes in Guerrero

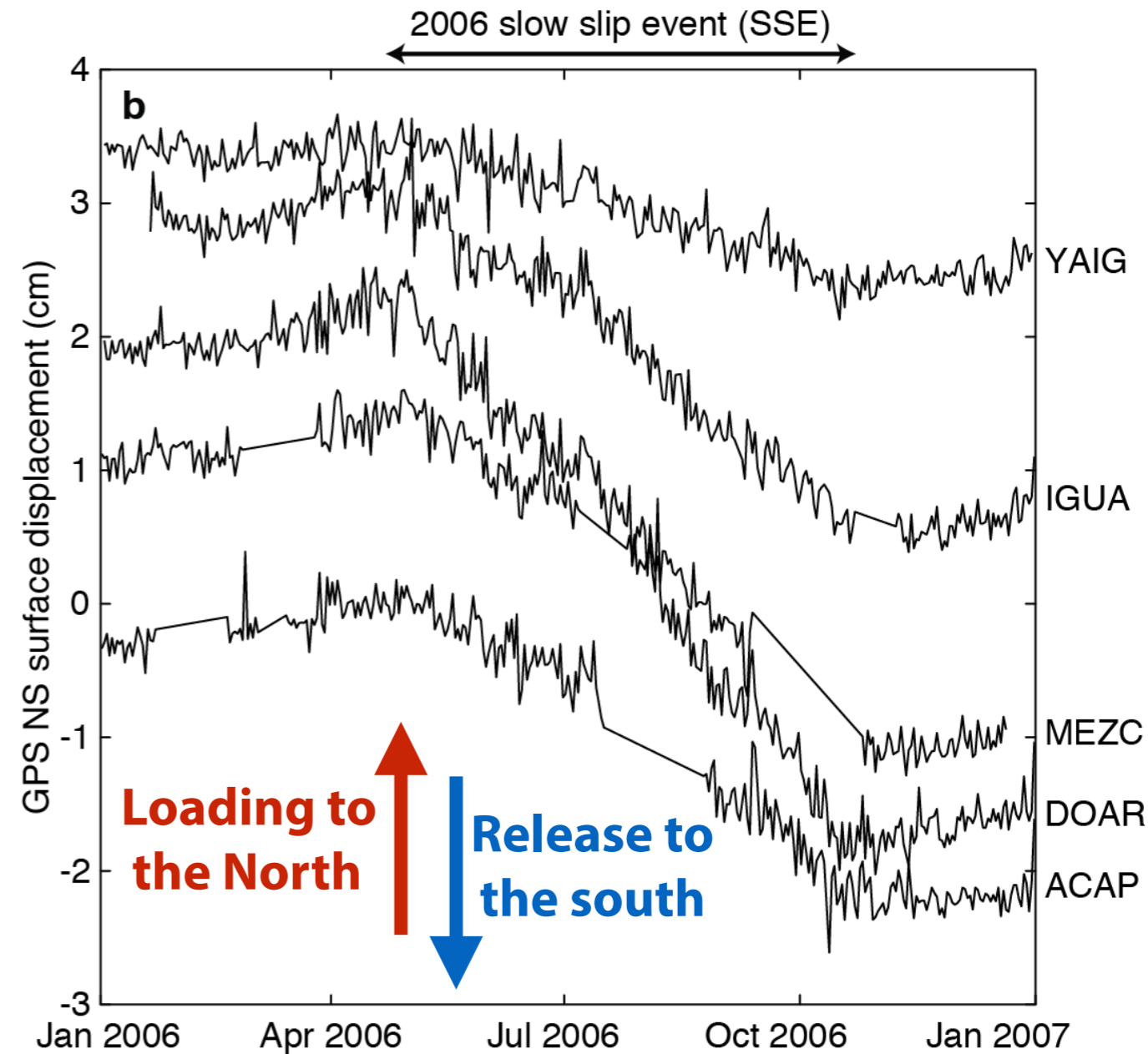
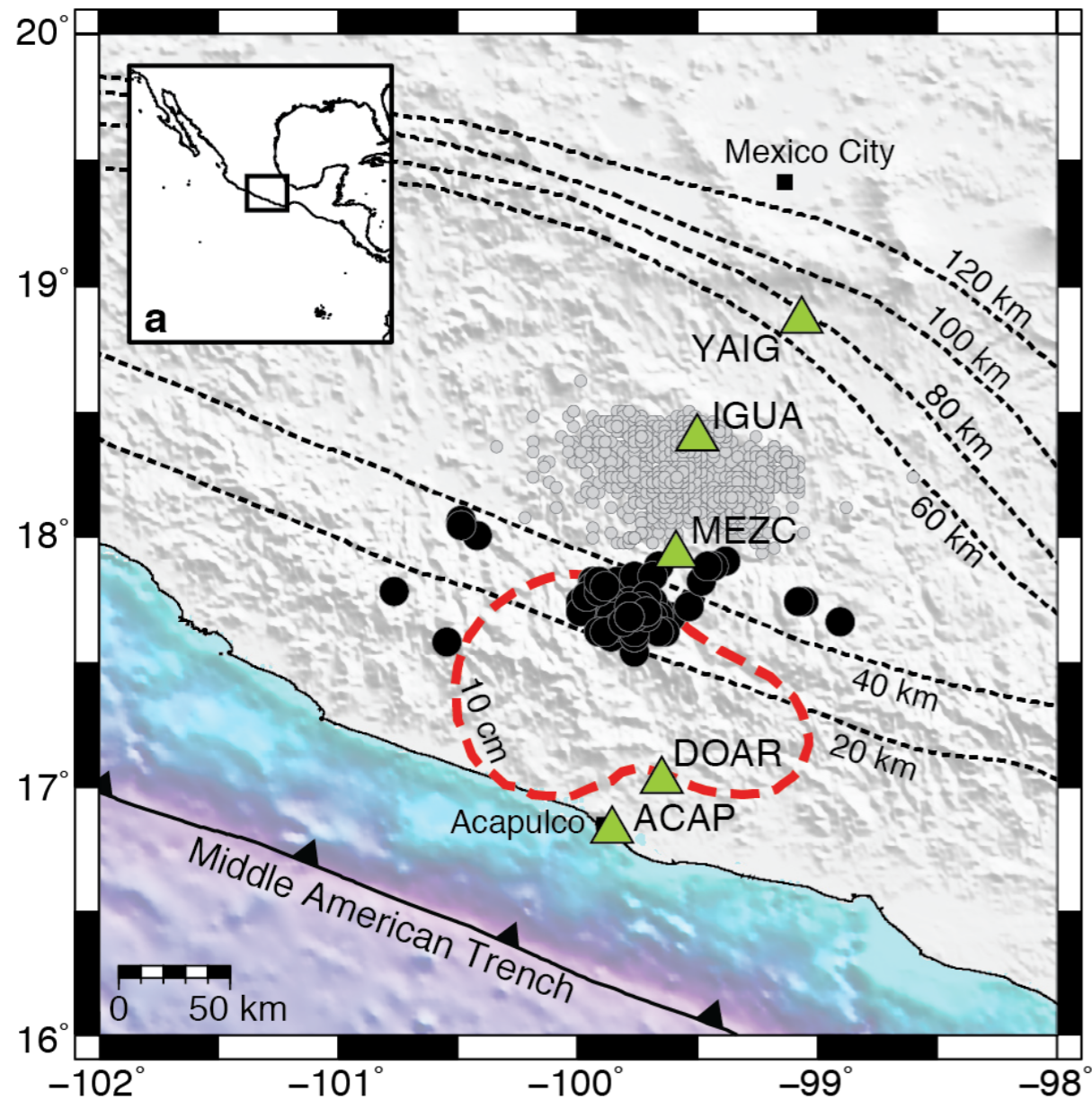
Modified from Frank et al., Sci. Adv., 2018



- ▶ 2.5-year catalog contains 1,849,486 LFEs
 - ▶ 1120 unique spatial sources
- ▶ Shearing focal mechanism on plate interface
- ▶ Precise locations reveal multiple LFE source regions
- ▶ **Updip** LFE activity strongly correlated with geodetically-observed slow slip



2006 M7.5 slow slip through the lens of LFEs

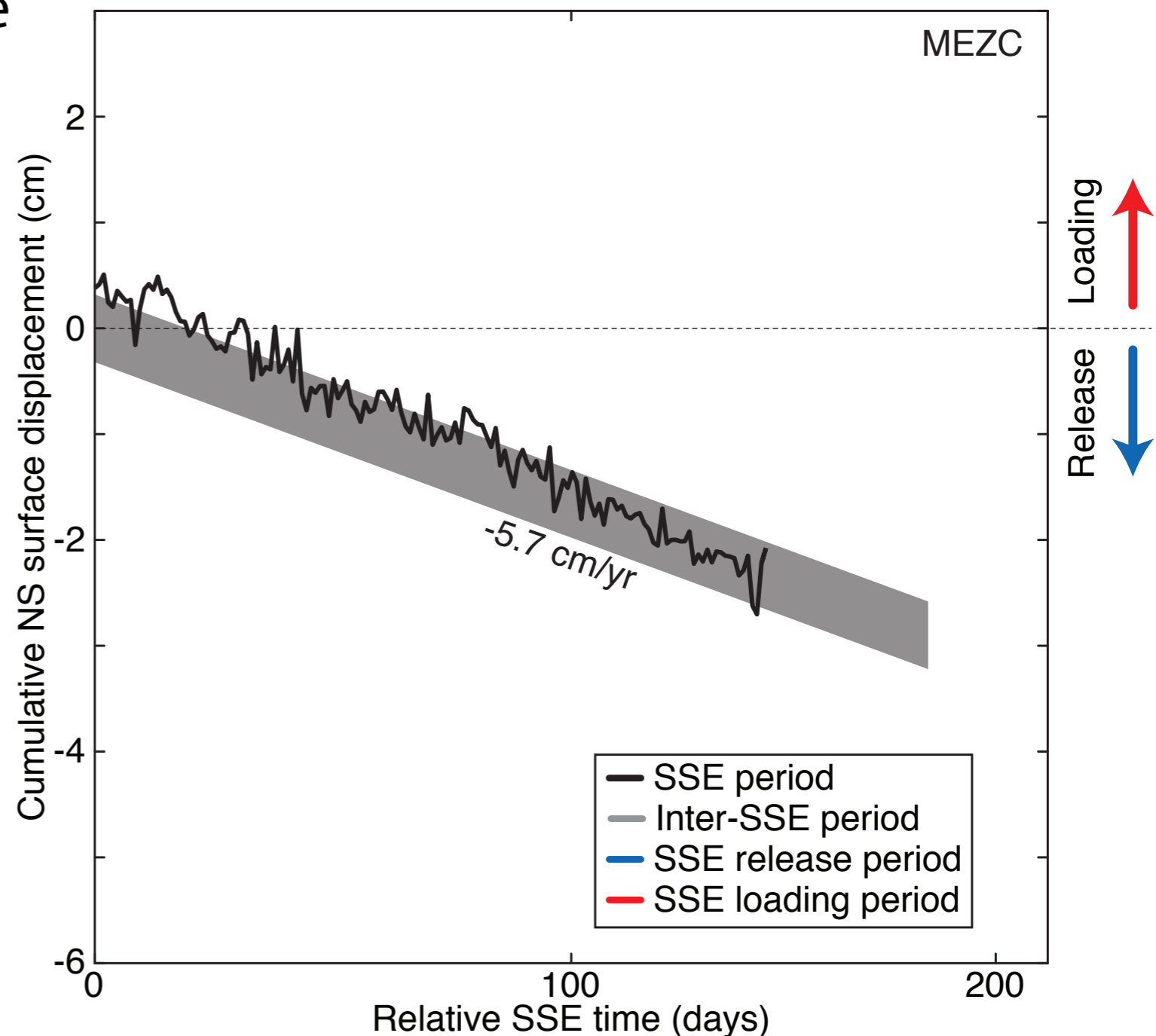
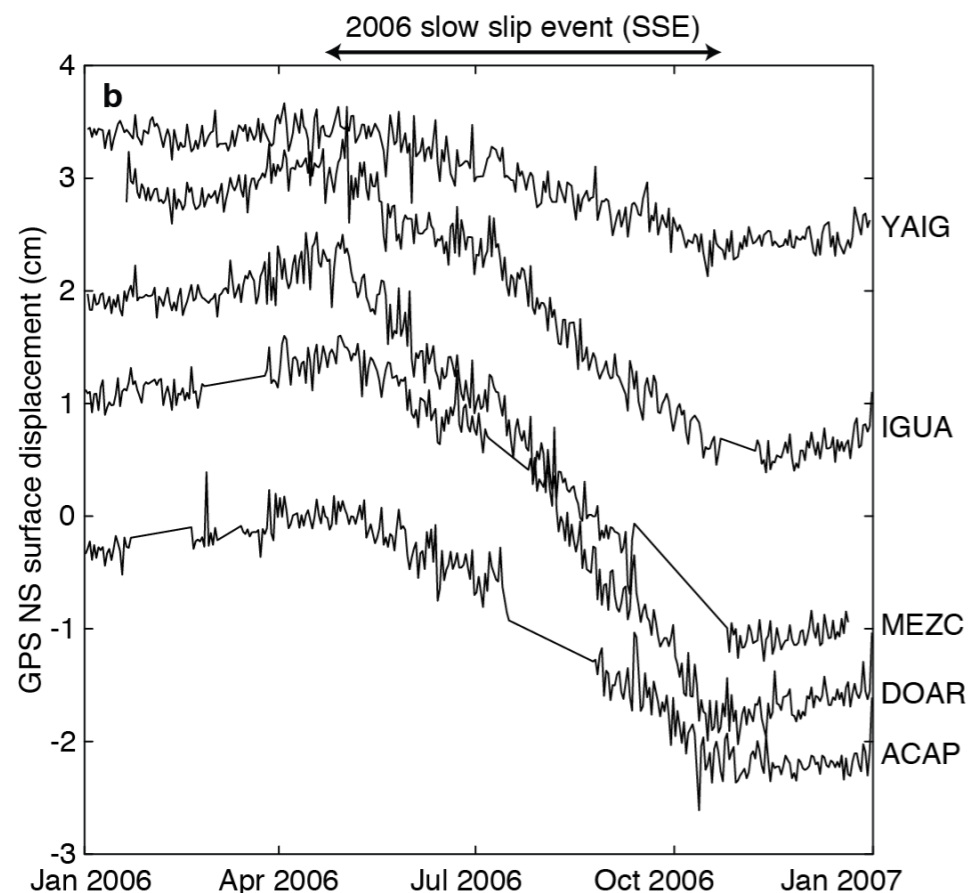


Modified from Frank et al., *Sci. Adv.*, 2018

- ▶ Slow slip at the interface concentrated in the **updip zone**

Long-period displacement during a M7.5 slow slip event

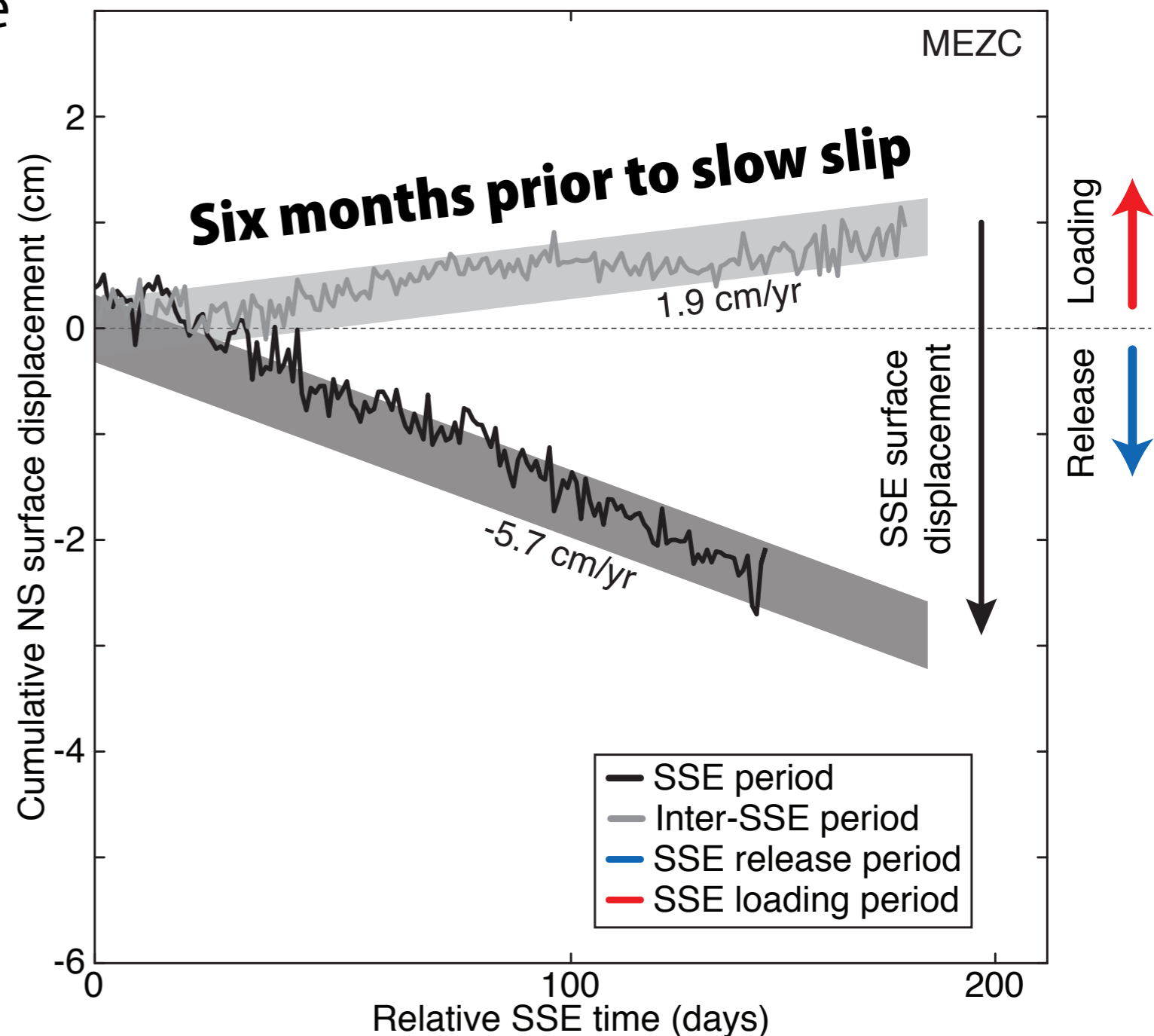
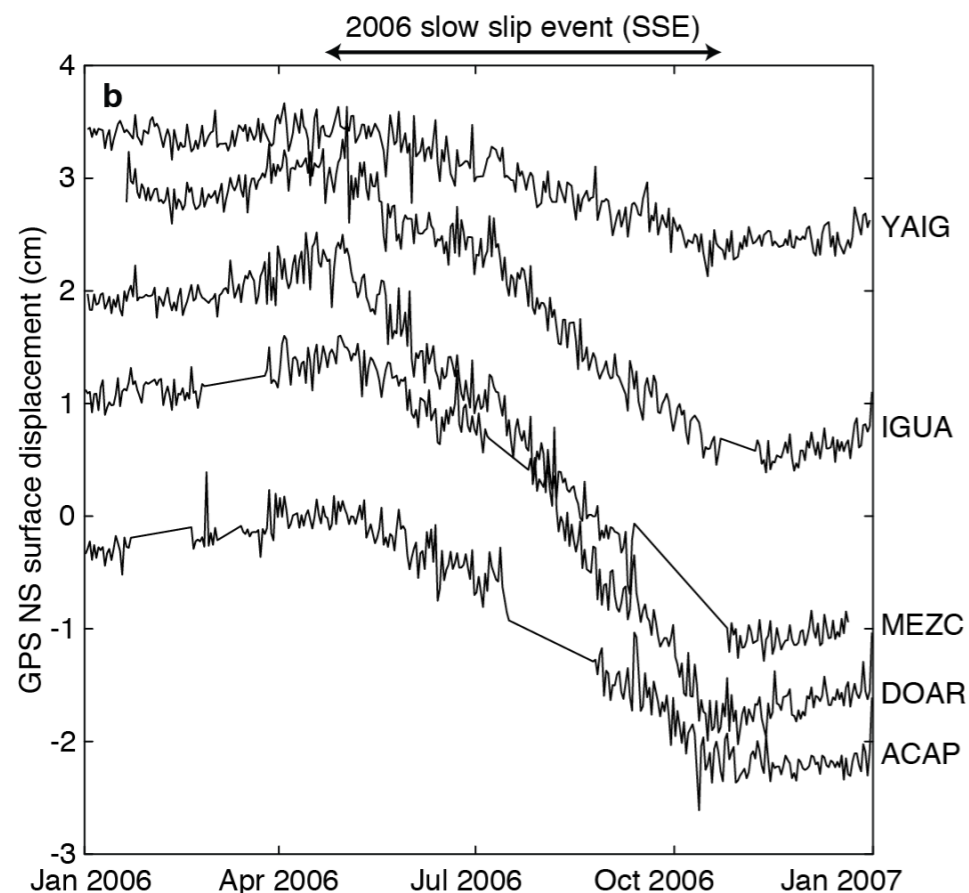
- ▶ Monotonic motion towards the **South**
- ▶ Continuous six-month **release**



Modified from Frank et al., Sci. Adv., 2018

Long-period displacement during a M7.5 slow slip event

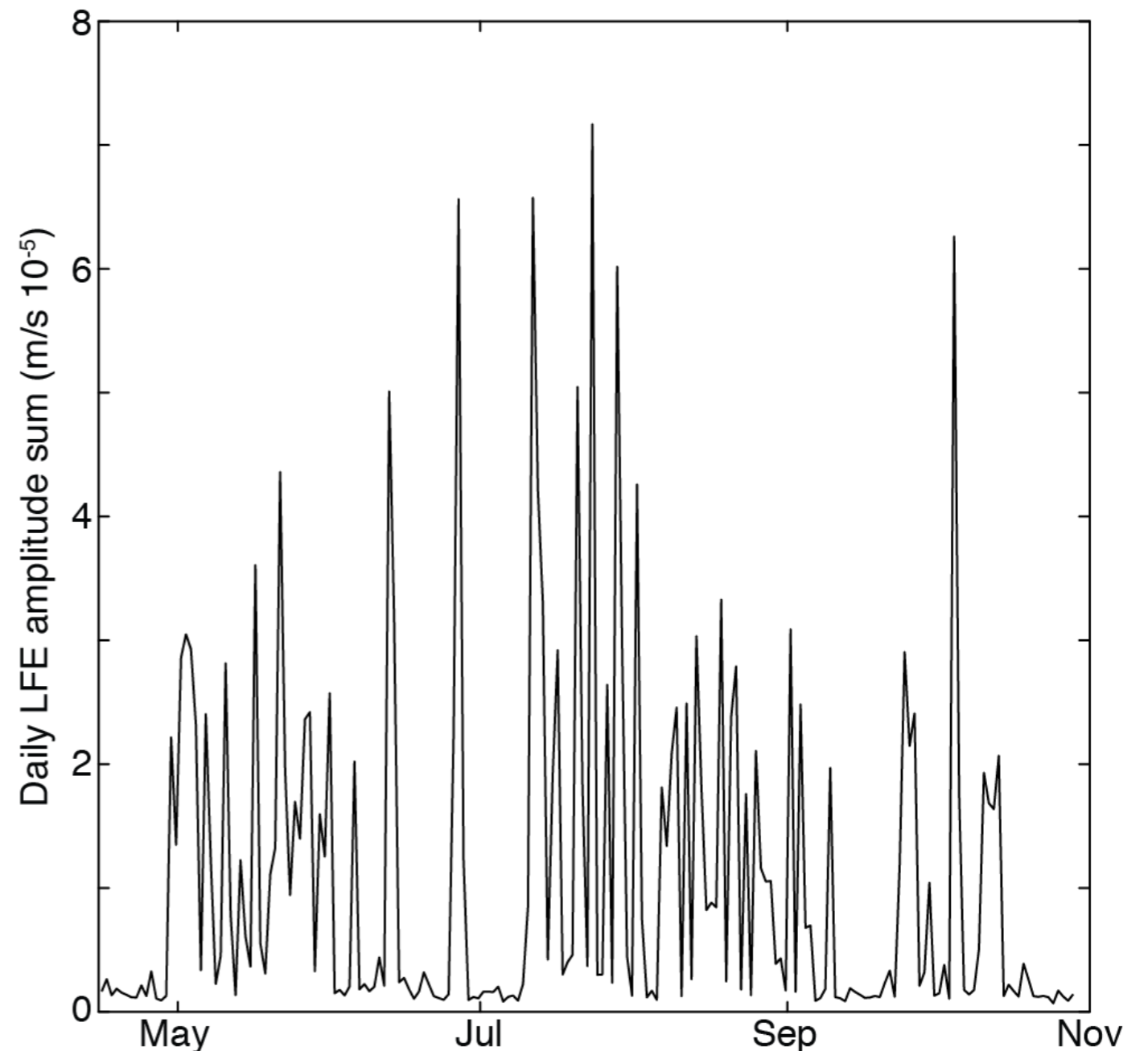
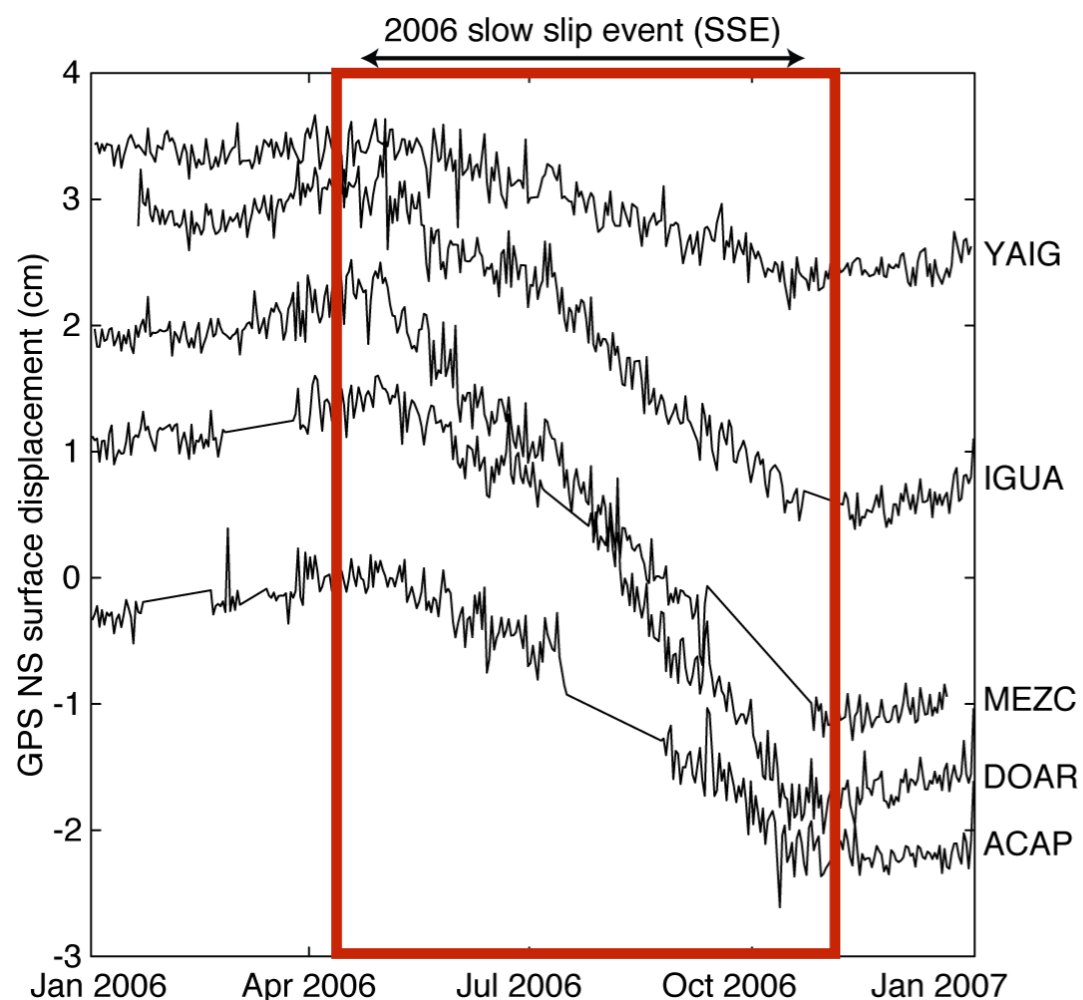
- ▶ Monotonic motion towards the **South**
- ▶ Continuous six-month **release**
- ▶ About ~ 3.85 cm displacement (after correcting for data gaps)



Modified from Frank et al., Sci. Adv., 2018

Quantifying LFE activity

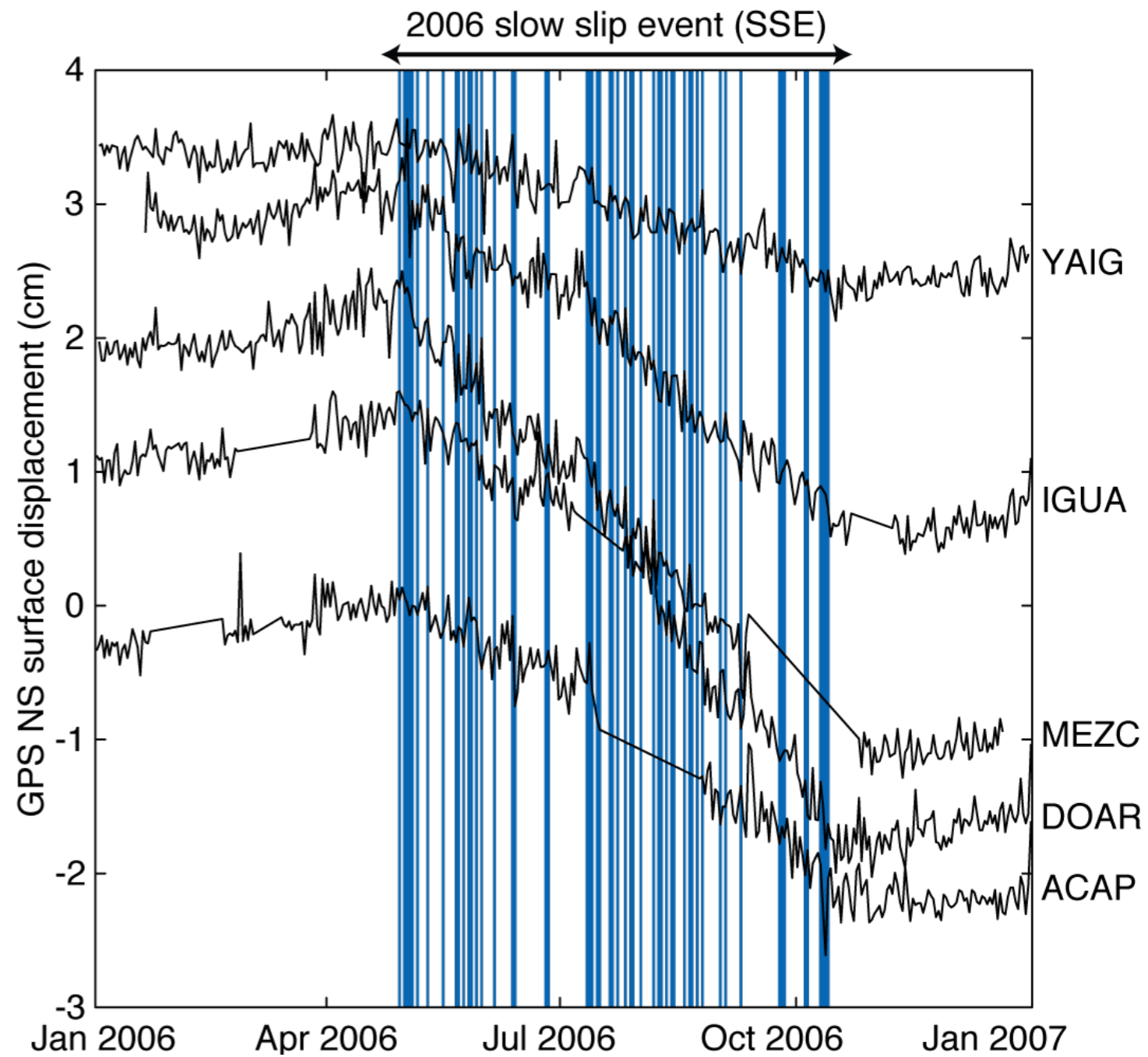
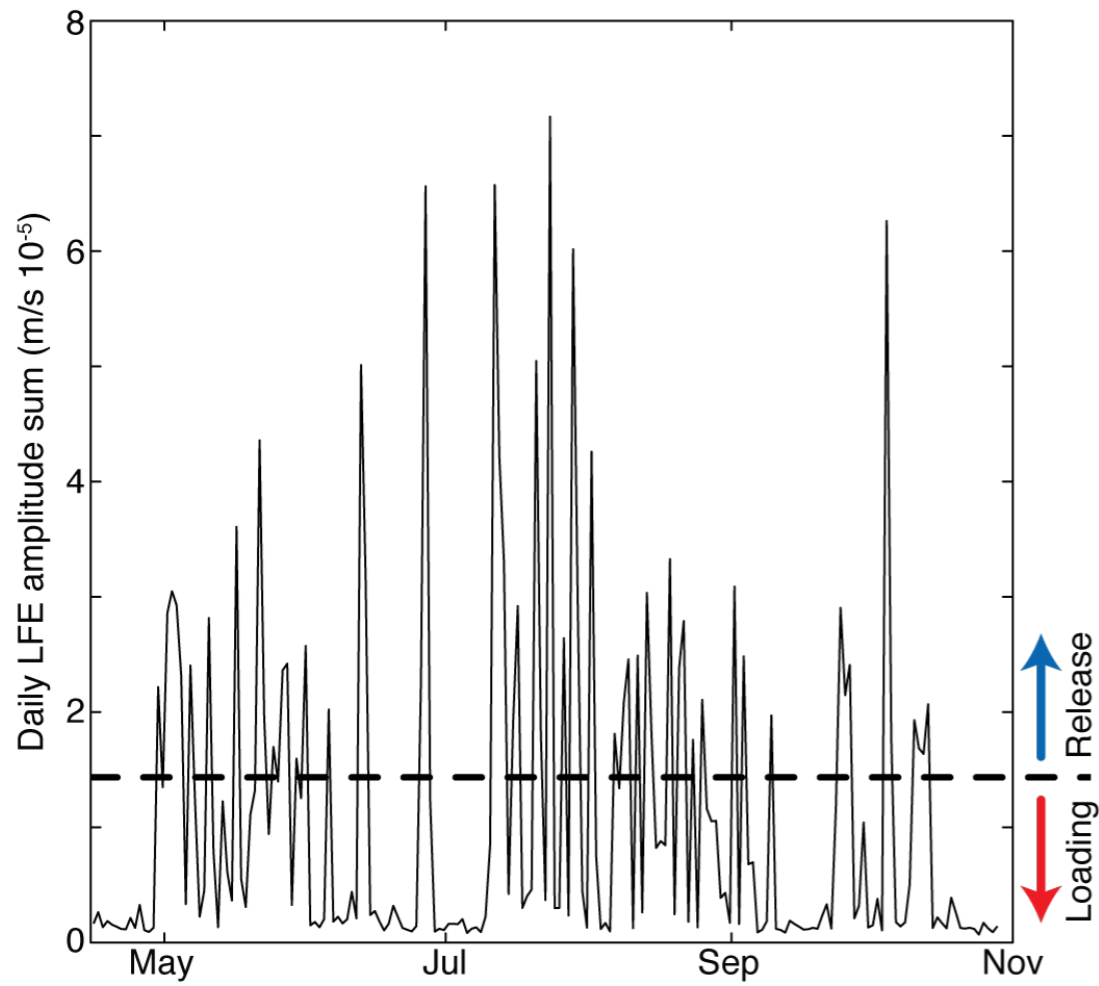
- ▶ Focus on updip LFE sources closest to slow slip
- ▶ Quantify on a daily time scale
 - ▶ Same time scale as GPS!
- ▶ $N_{\text{LFEs}} \times \text{median}[\text{amplitude}]$



Intermittent LFE activity during slow slip

Hypothesis: high LFE activity = **slow slip transient**

- ▶ Seismicity > threshold, **tectonic release**
- ▶ Seismicity < threshold, **tectonic loading**

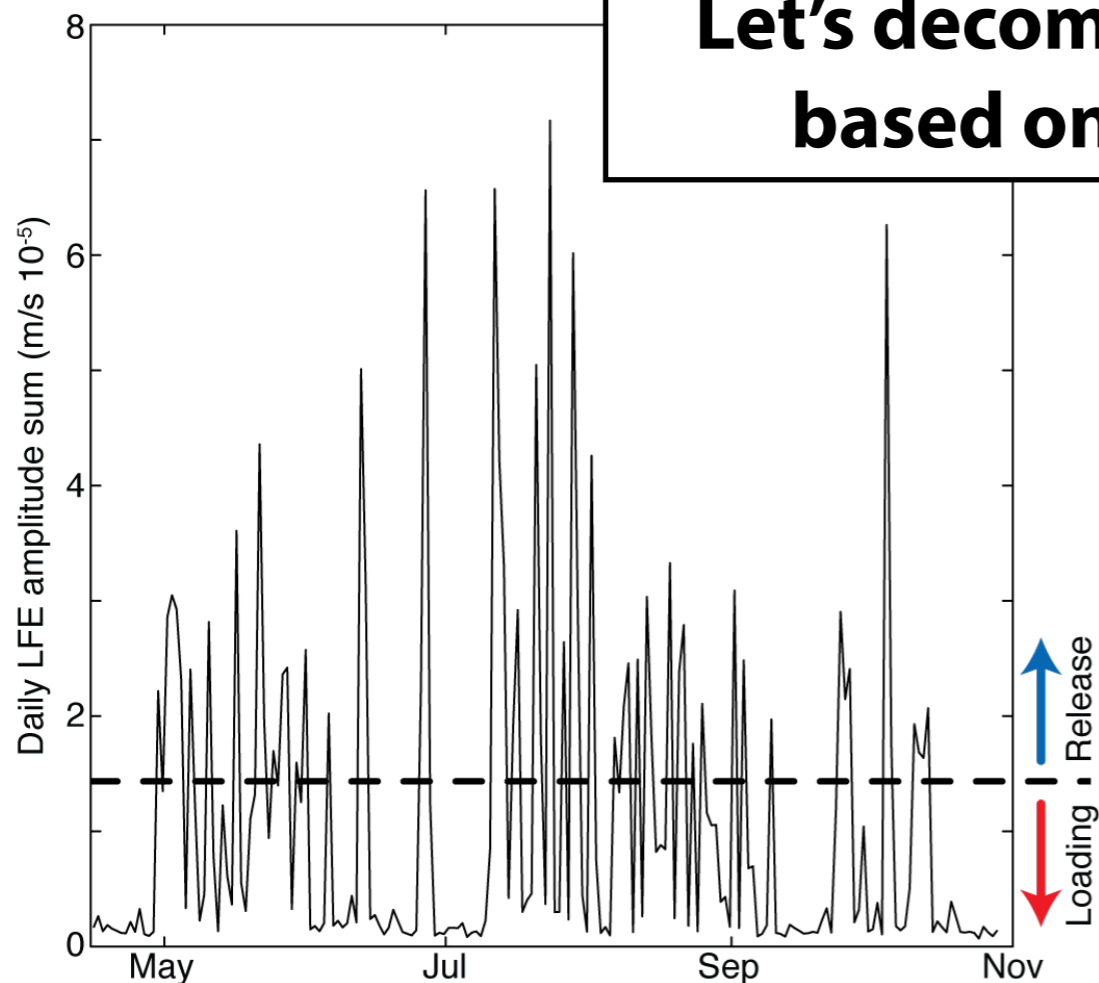


Modified from Frank et al., *Sci. Adv.*, 2018

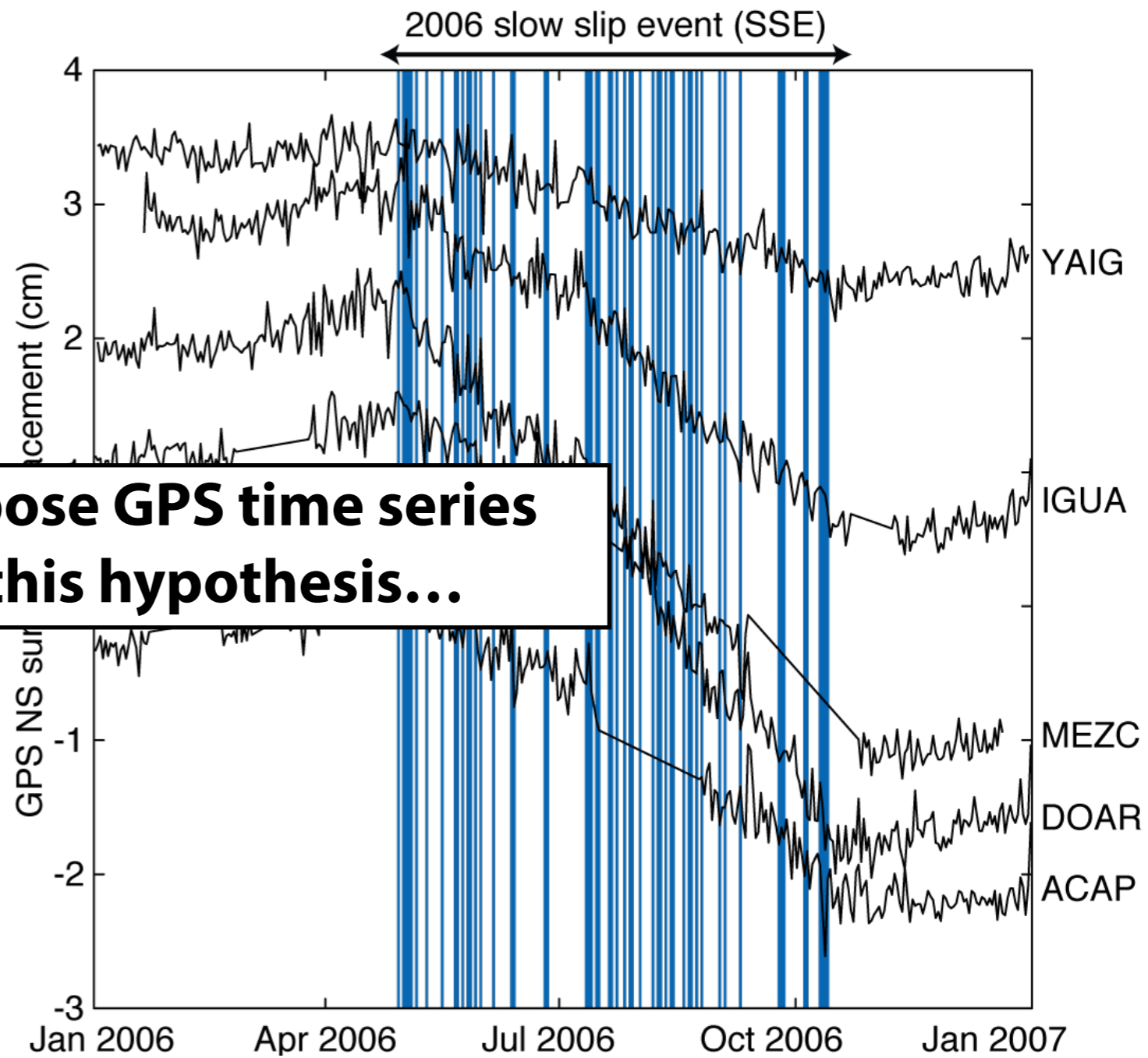
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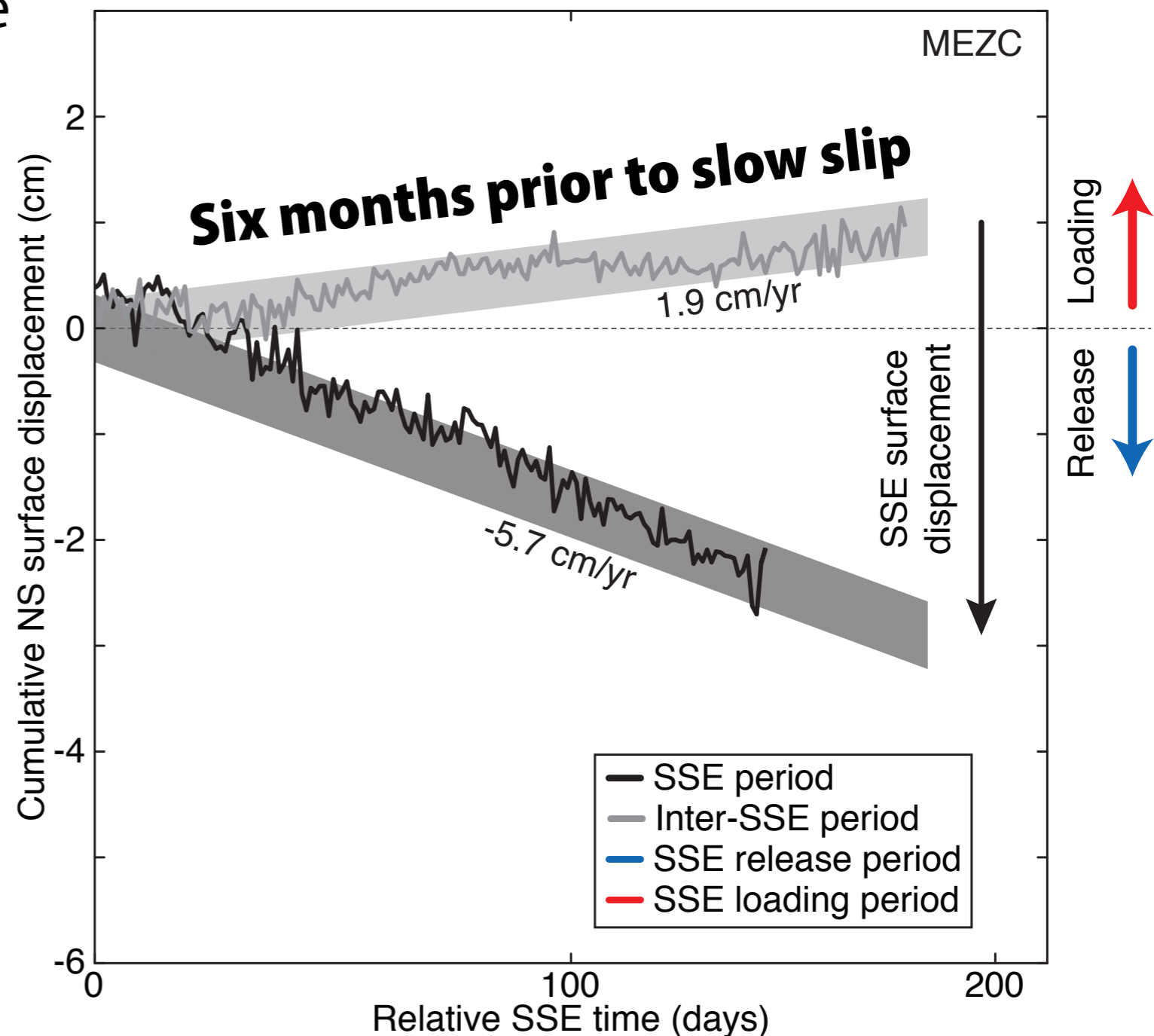
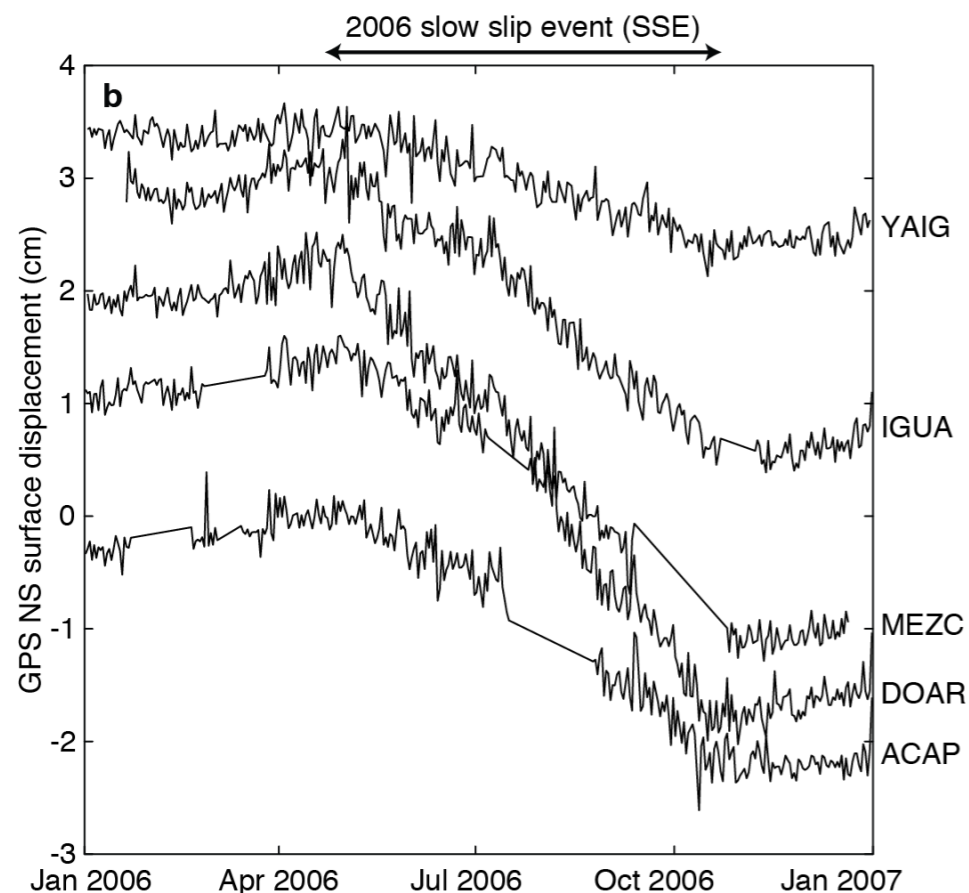
Let's decompose GPS time series based on this hypothesis...



Modified from Frank et al., *Sci. Adv.*, 2018

Long-period displacement during a M7.5 slow slip event

- ▶ Monotonic motion towards the **South**
- ▶ Continuous six-month **release**
- ▶ About ~ 3.85 cm displacement (after correcting for data gaps)

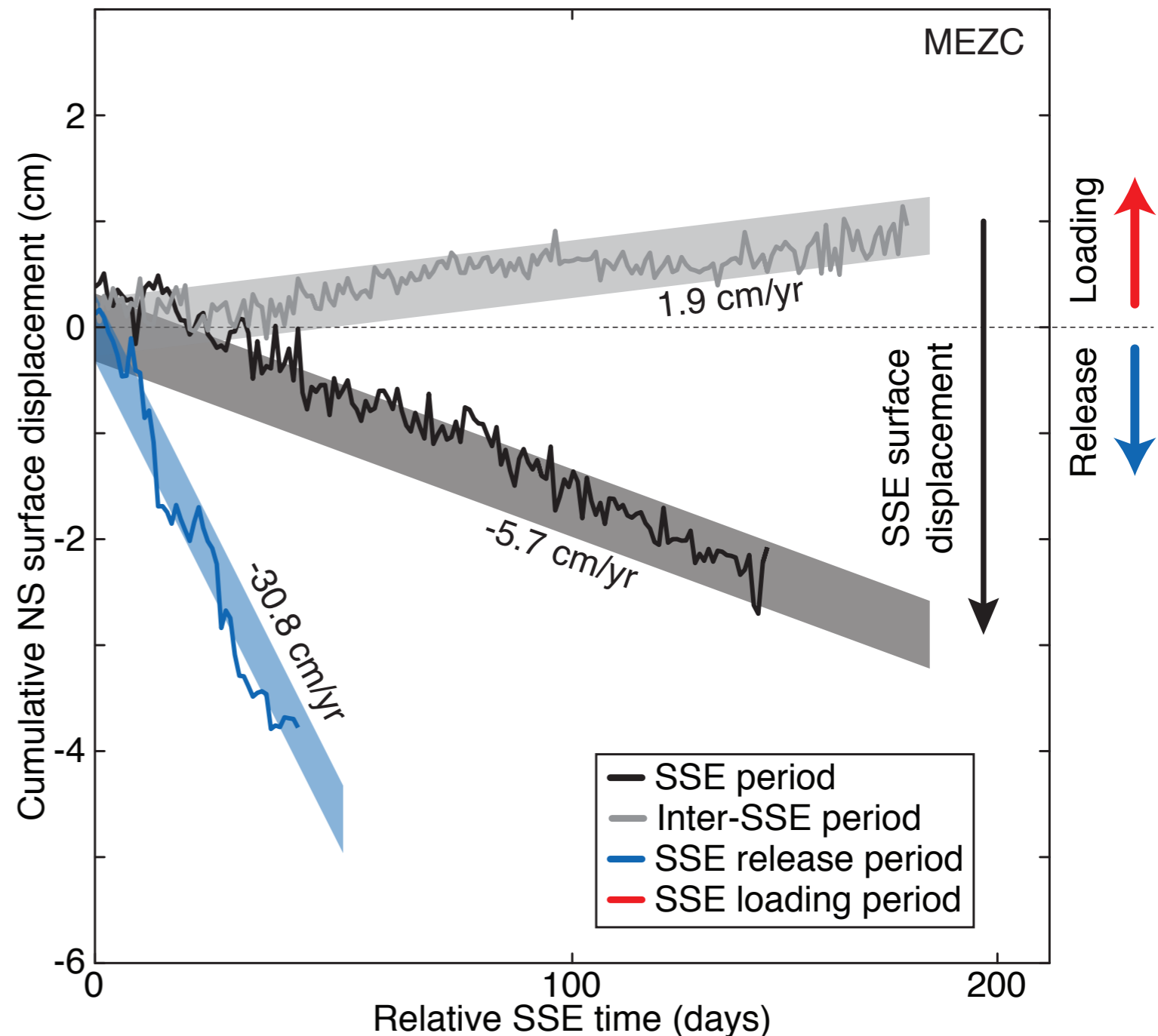
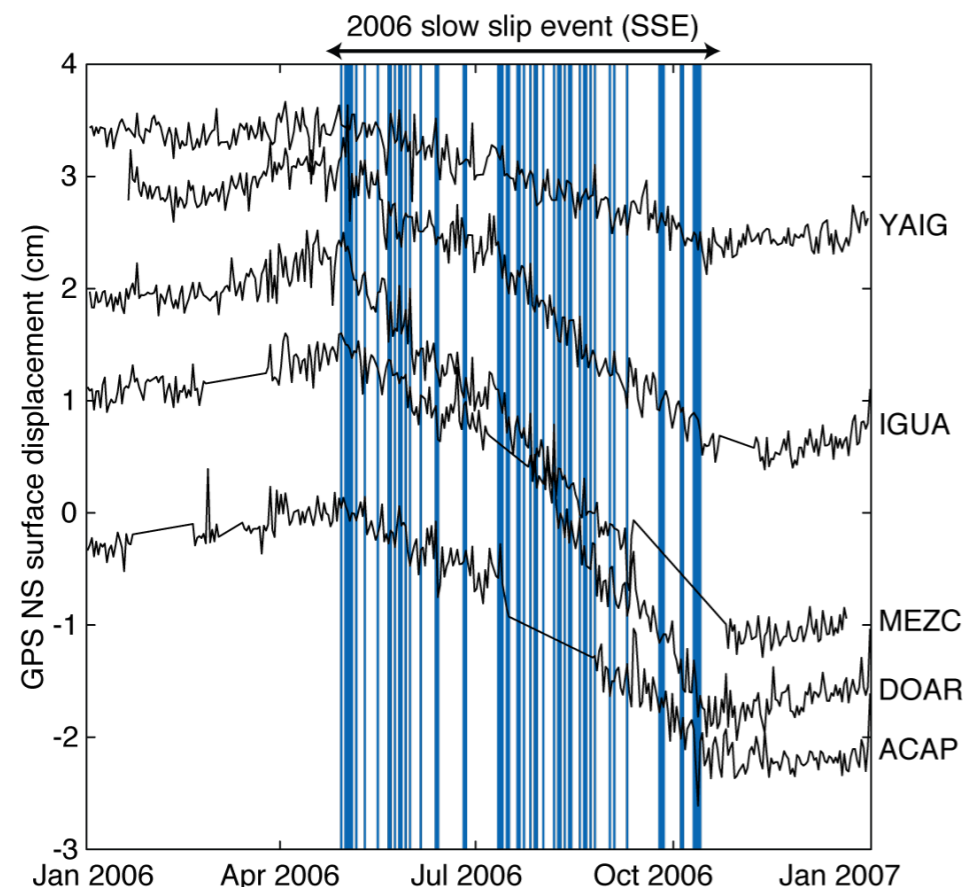


Modified from Frank et al., Sci. Adv., 2018

Displacement during intense LFE activity

Tectonic release (>threshold):

- ▶ 5x greater displacement rate
- ▶ Displacement happens during <60 days (three times faster!)

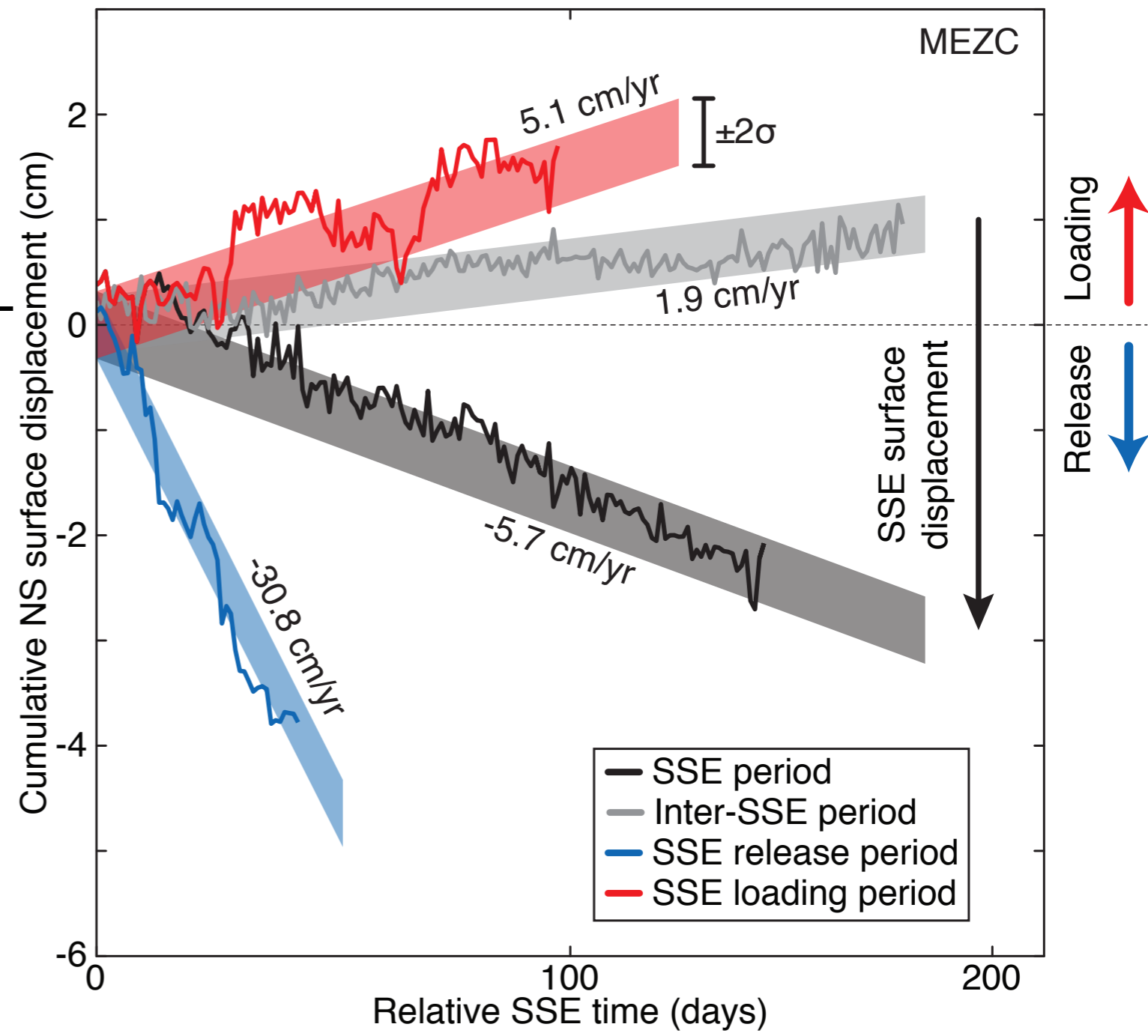
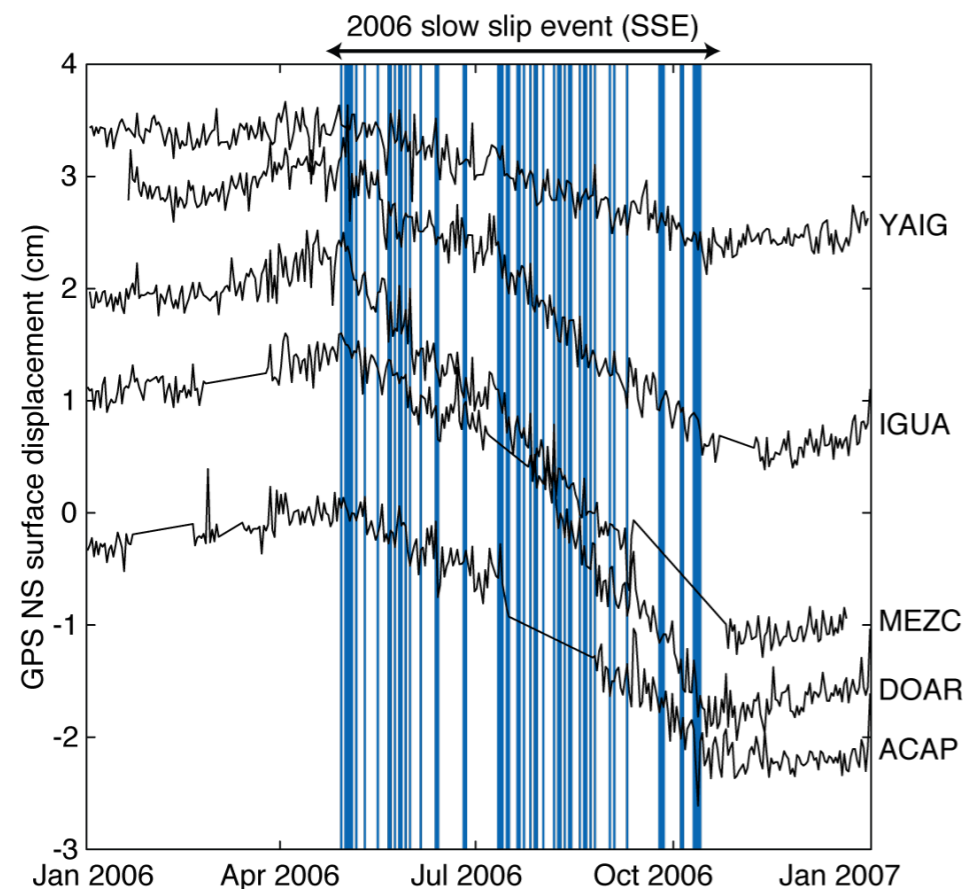


Modified from Frank et al., *Sci. Adv.*, 2018

Displacement the rest of the time

Tectonic loading (<threshold):

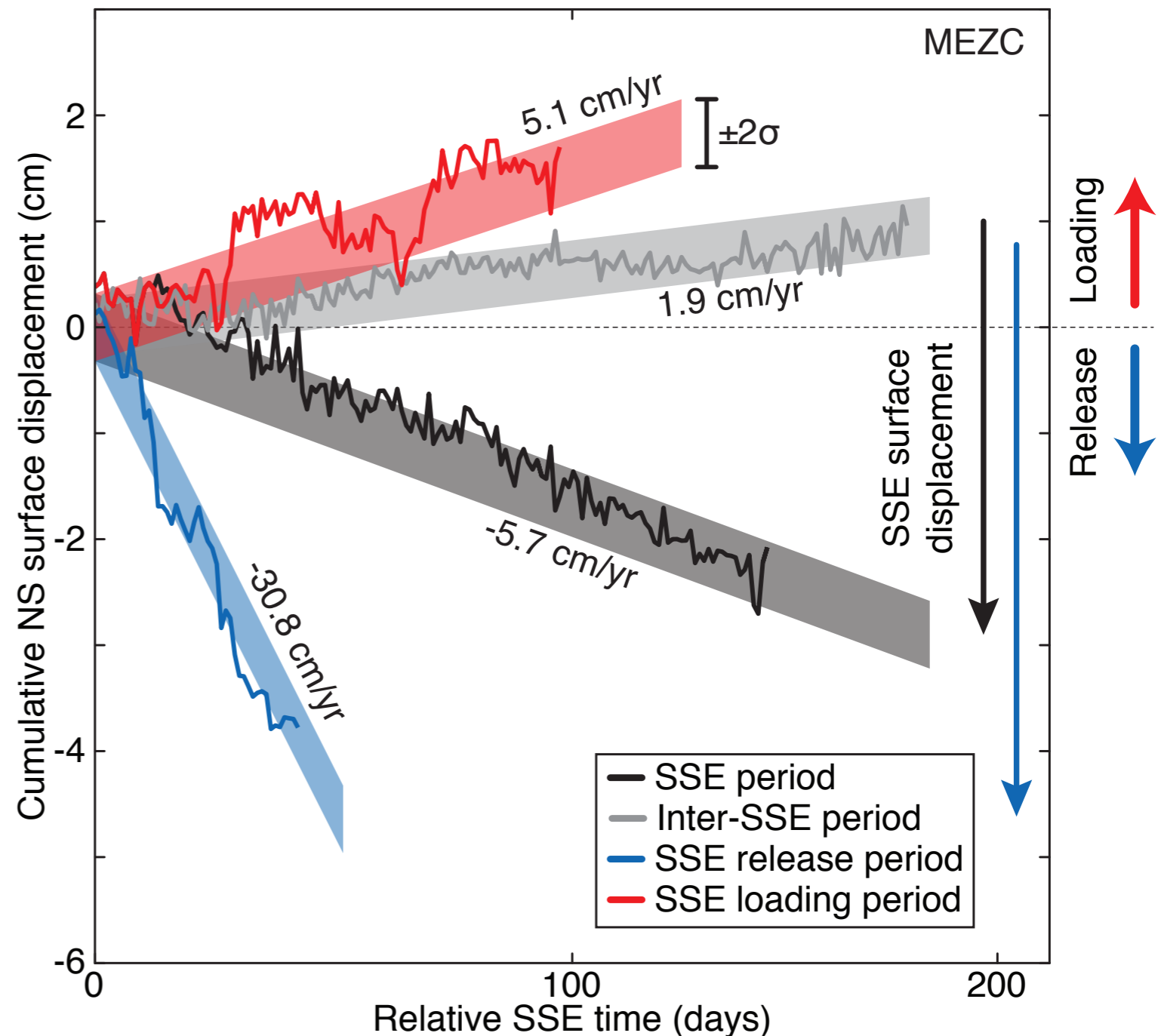
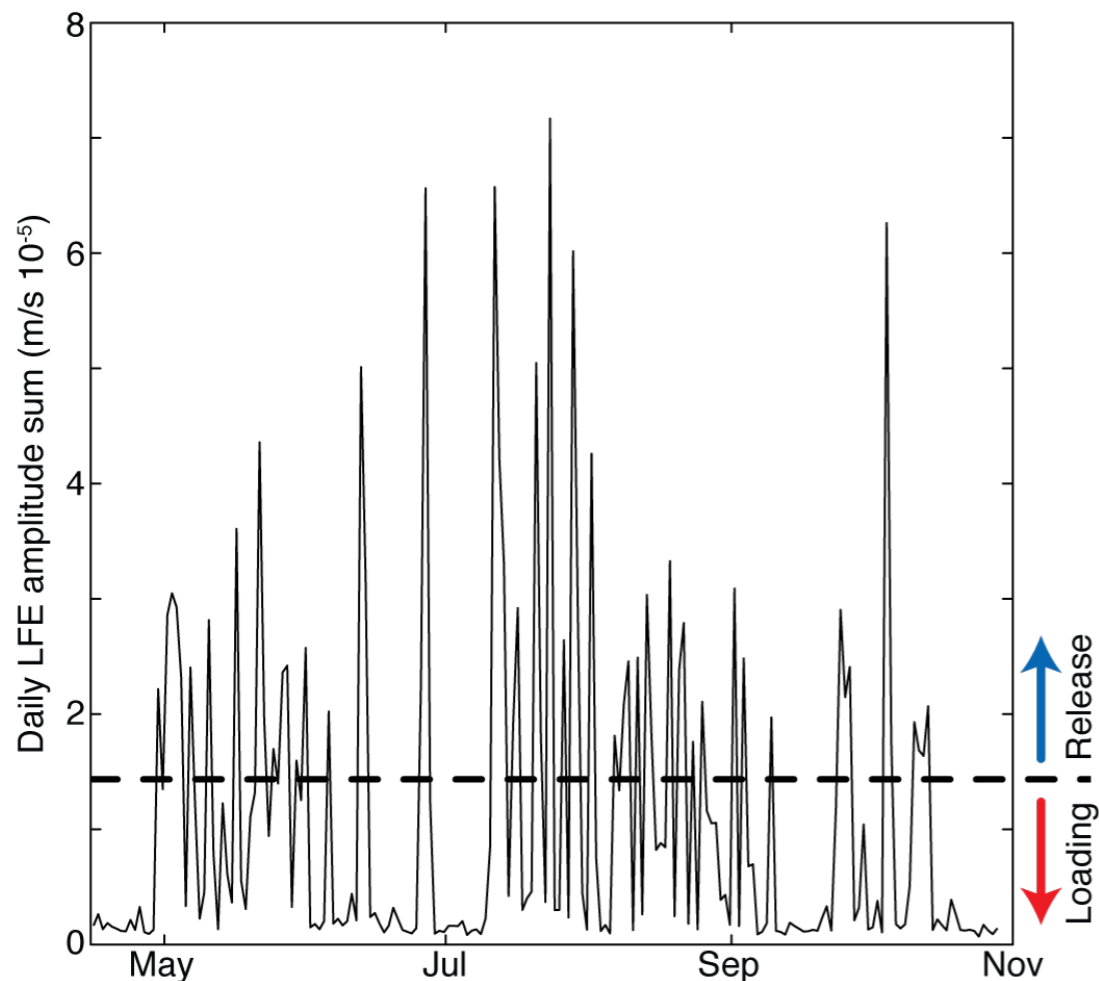
- ▶ Northward loading motion during slow slip!
- ▶ Loading rate greater than inter-SSE loading



Modified from Frank et al., Sci. Adv., 2018

Slow slip is an intermittent slip process

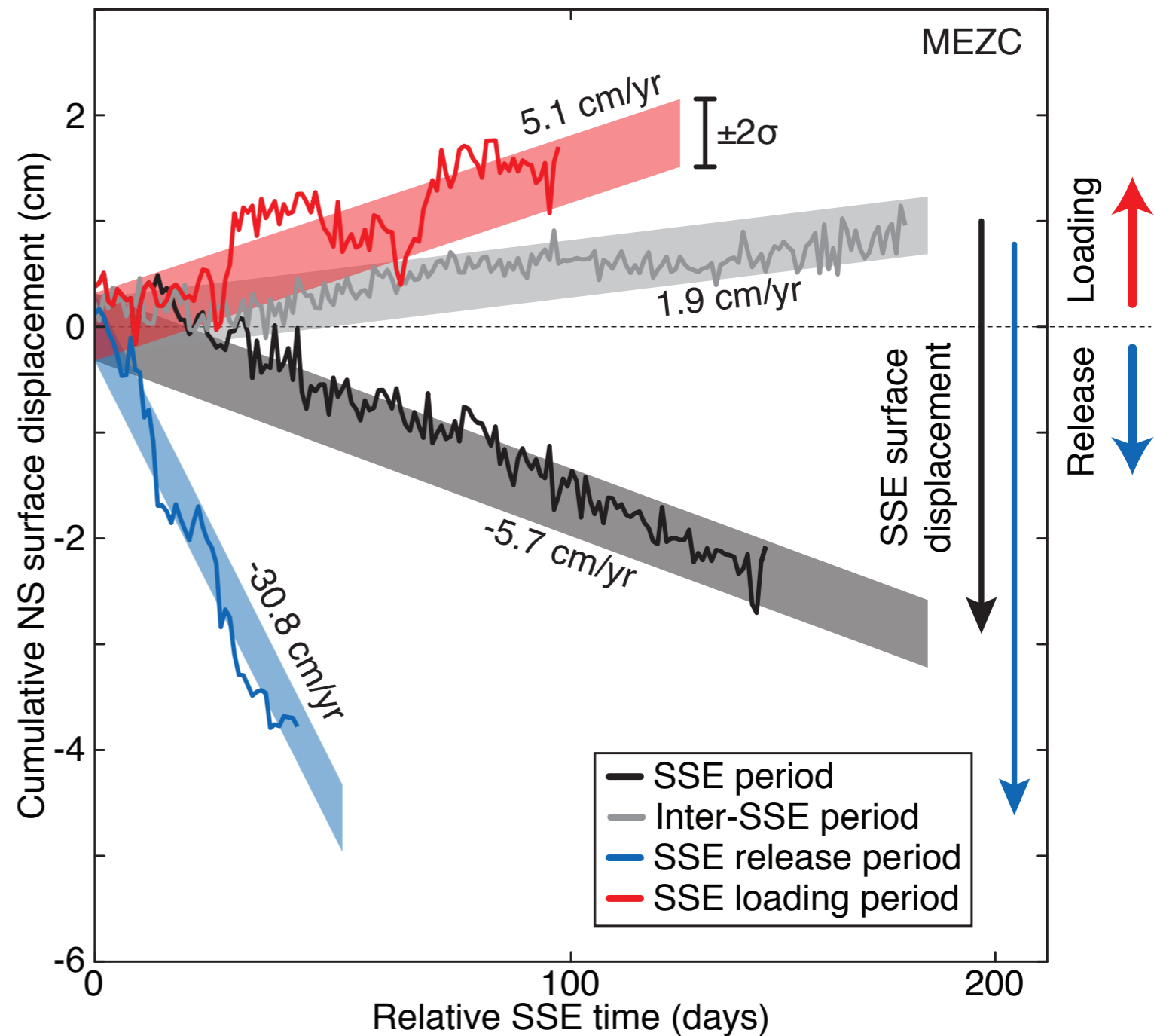
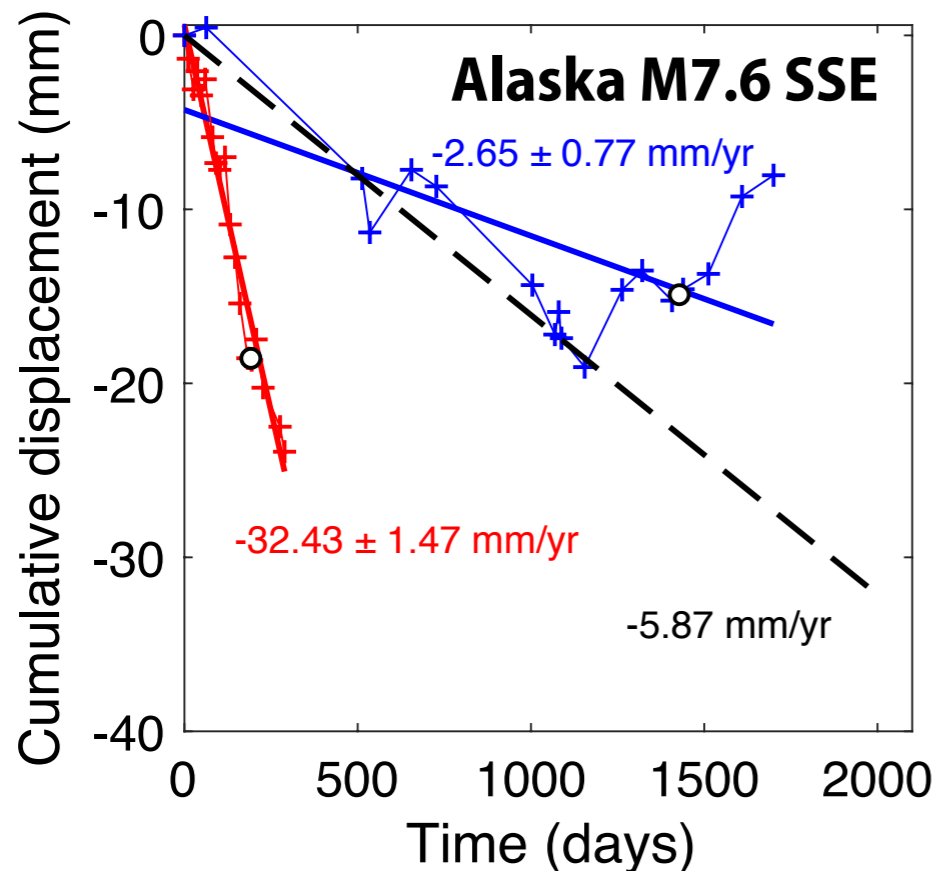
- ▶ 40% greater displacement *in a third of the time*
- ▶ Just as intermittent as LFE activity!
- ▶ Slow slip is faster and bigger than geodesy would suggest



Modified from Frank et al., *Sci. Adv.*, 2018

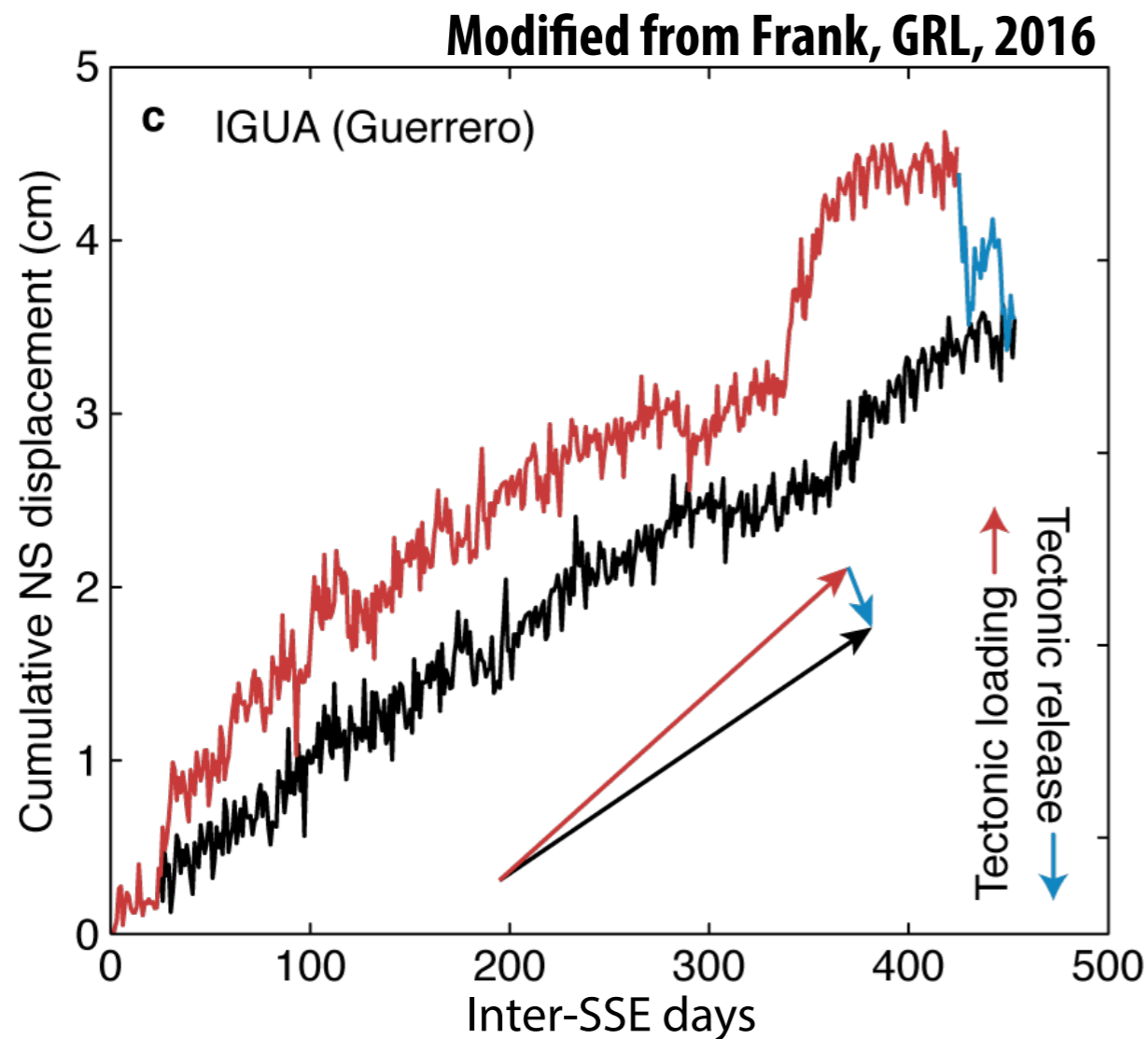
Slow slip is an intermittent slip process

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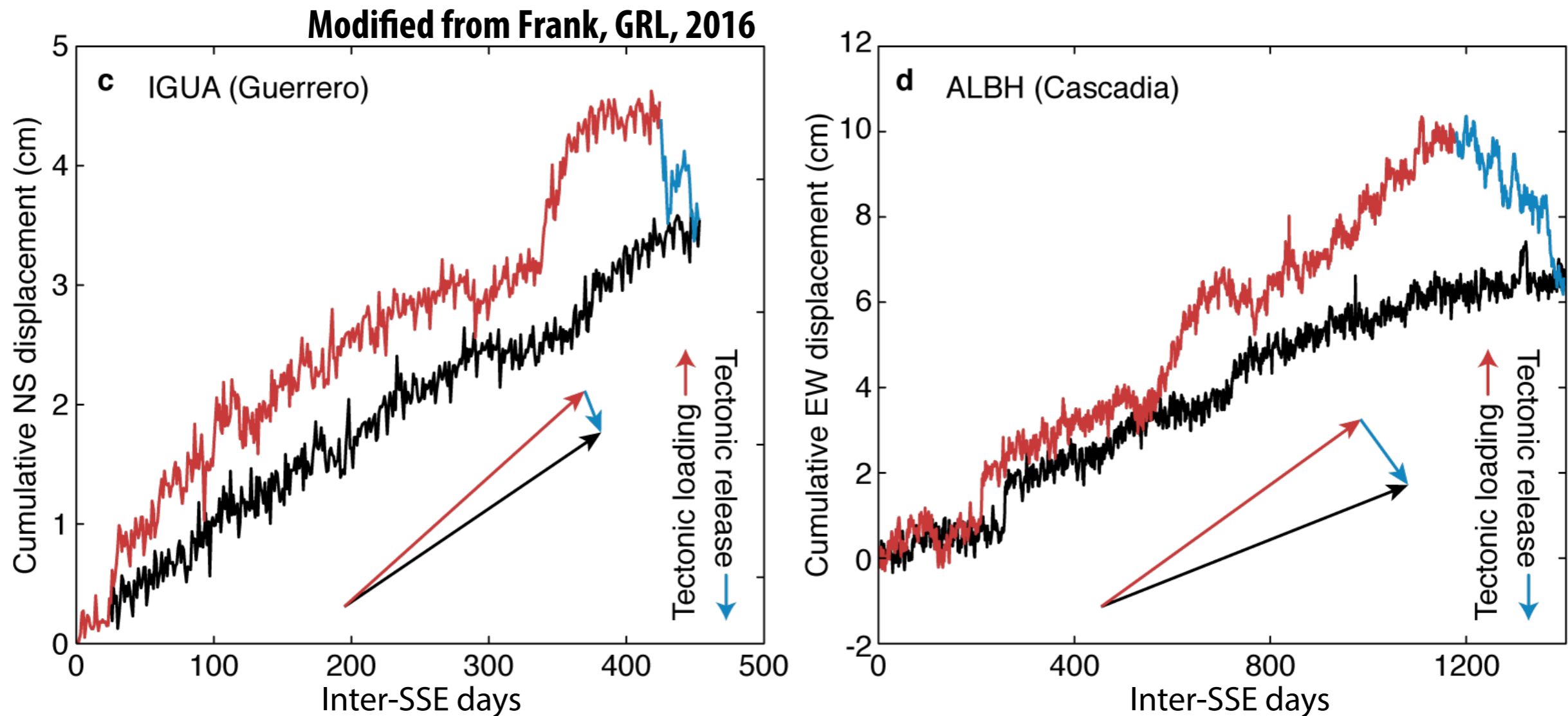
Modified from Frank et al., Sci. Adv., 2018

Slow slip is also intermittent outside of major slow slip events



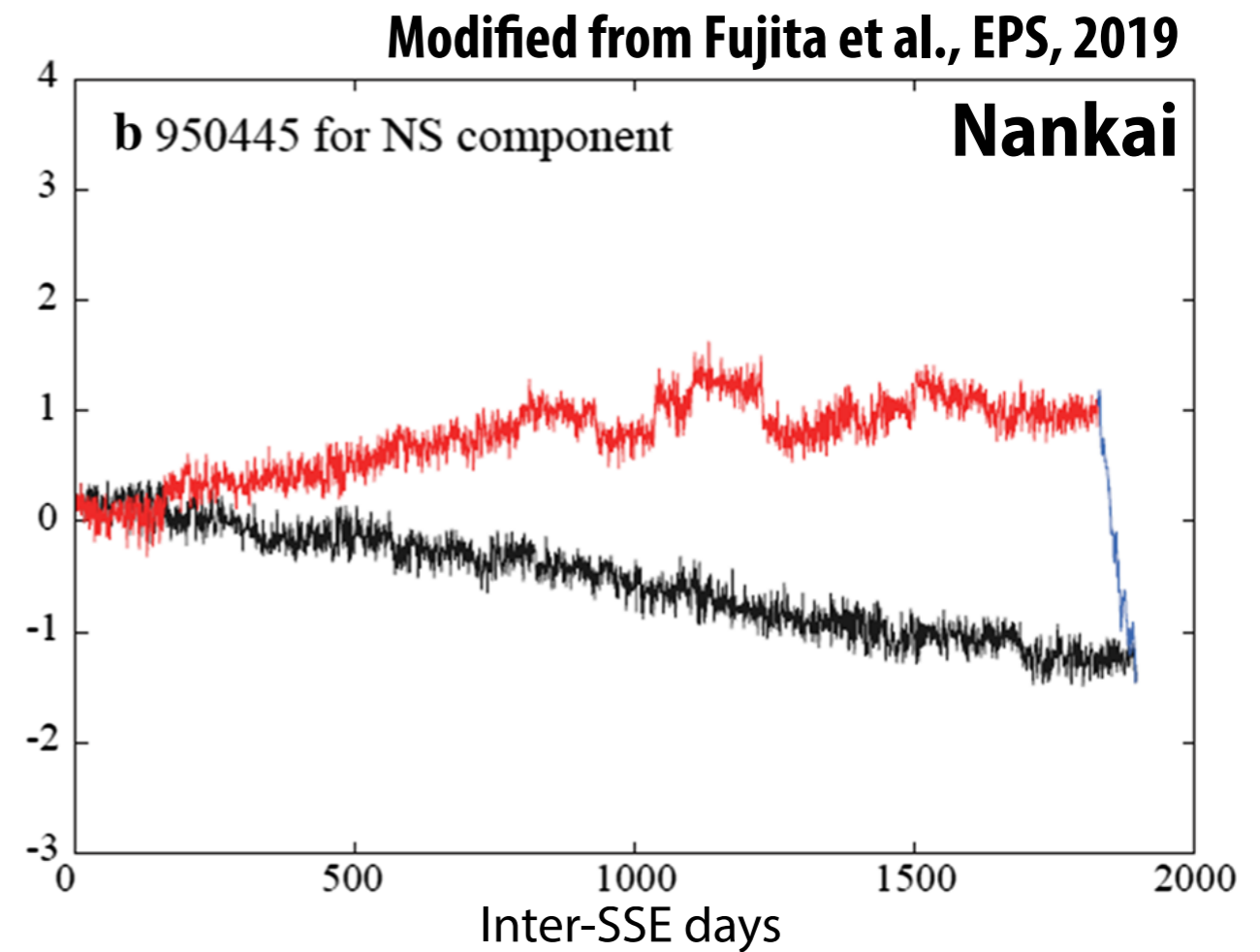
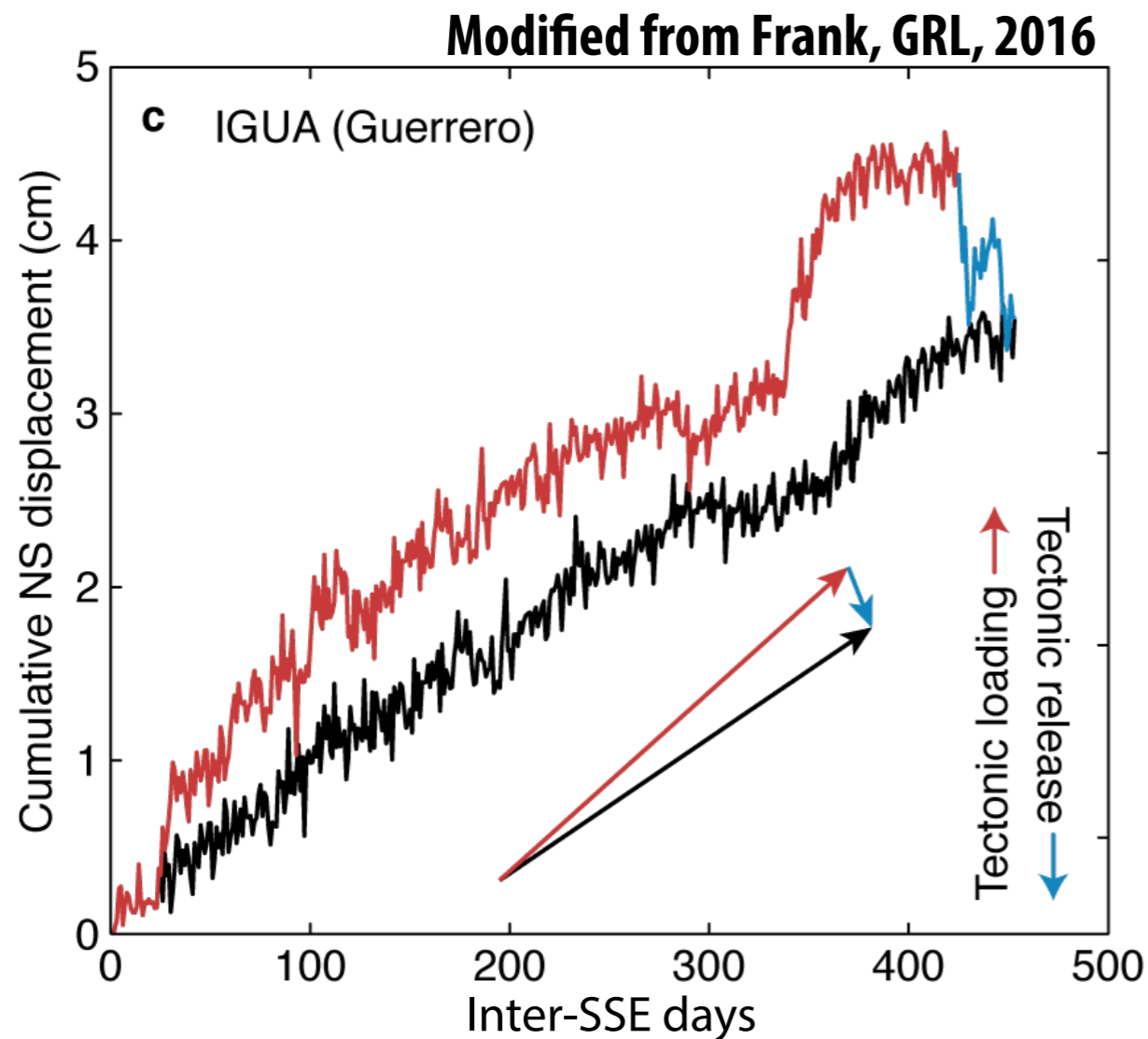
**Decomposed GPS displacements
between geodetically observed
slow slip events**

Slow slip is also intermittent outside of major slow slip events



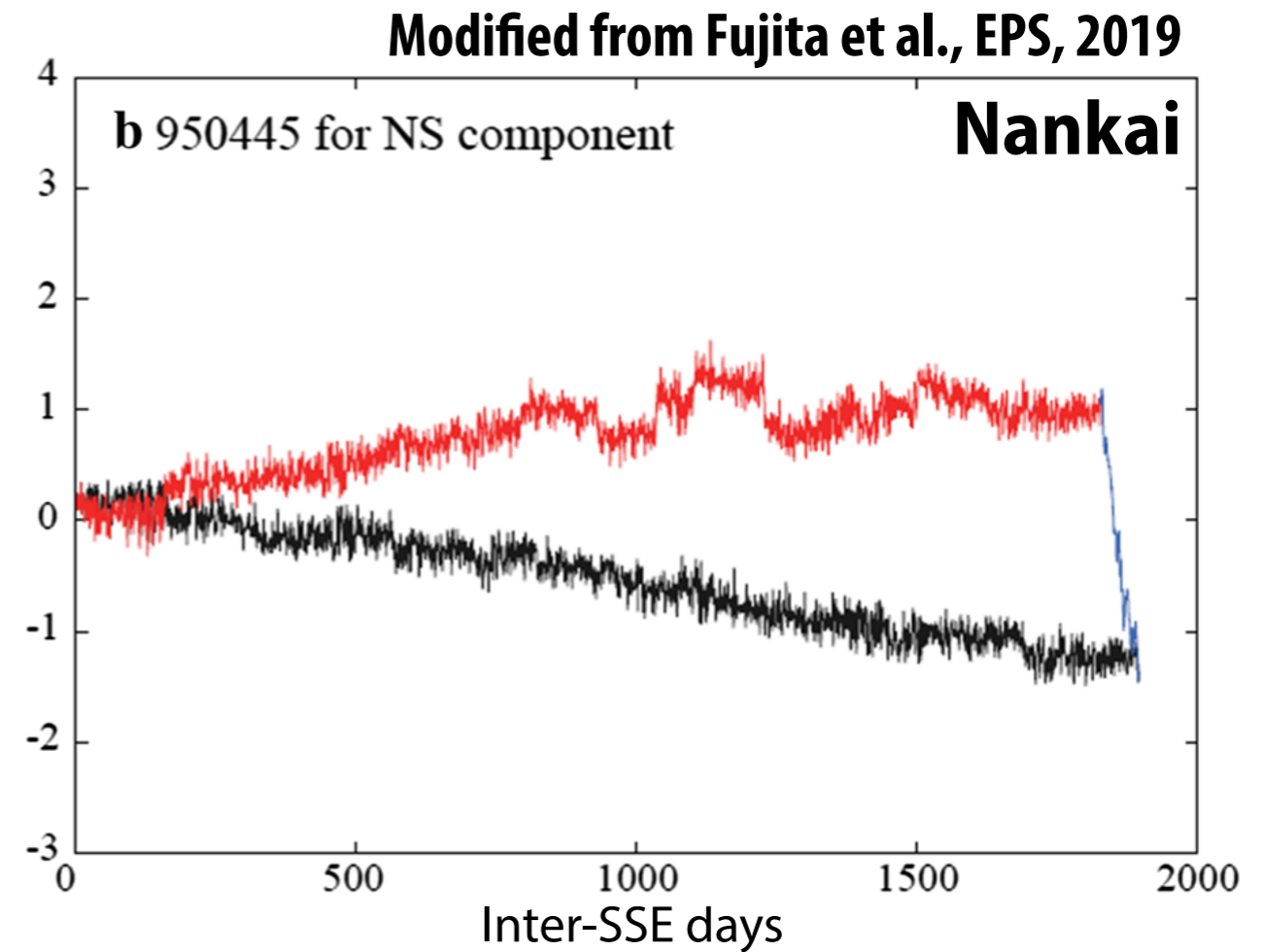
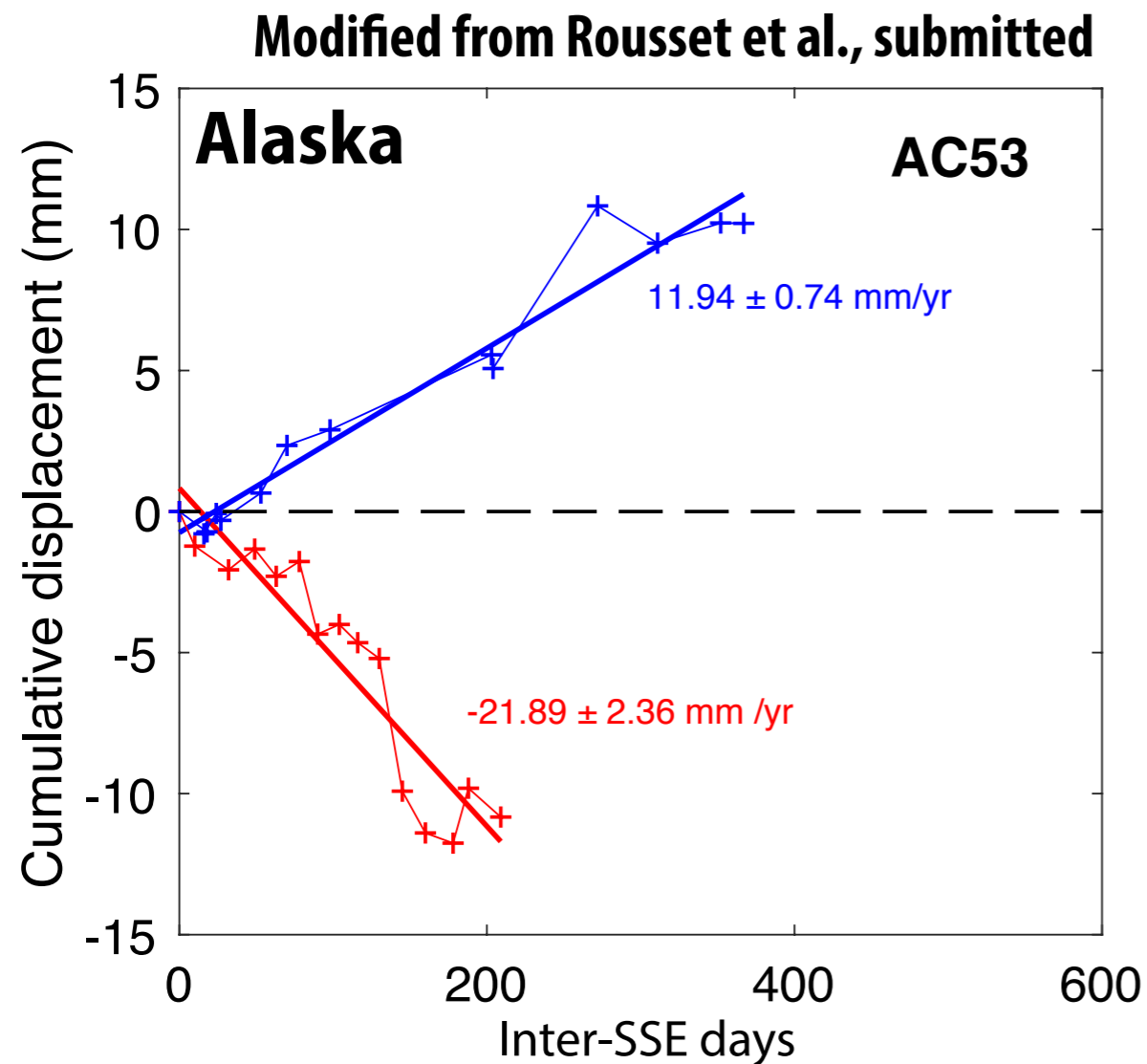
Intermittent slow slip is observed across many subduction zones

Slow slip is also intermittent outside of major slow slip events



Intermittent slow slip is observed across many subduction zones

Slow slip is also intermittent outside of major slow slip events



Intermittent slow slip is observed across many subduction zones

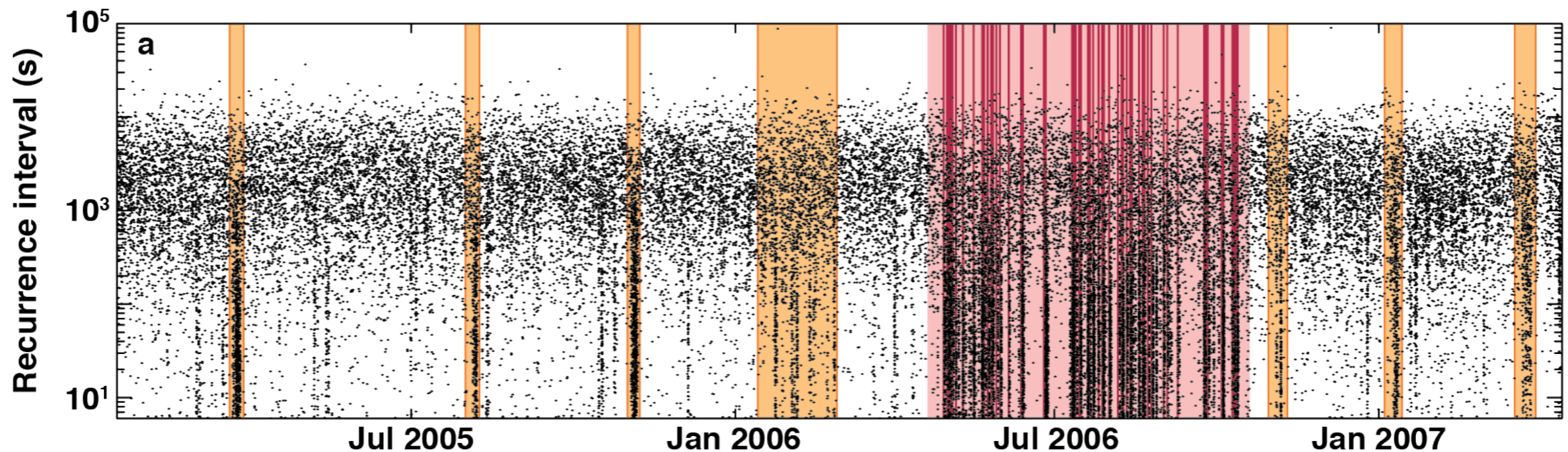
Is LFE moment rate diagnostic of slow slip?

$$\dot{M}_o^{\text{seis}} \propto \dot{M}_o^{\text{geo}} ?$$

Is LFE moment rate diagnostic of slow slip?

$$\dot{M}_0^{\text{seis}} \propto \dot{M}_0^{\text{geo}} ?$$

- ▶ If the LFE moment rate was diagnostic of the geodetic moment rate...

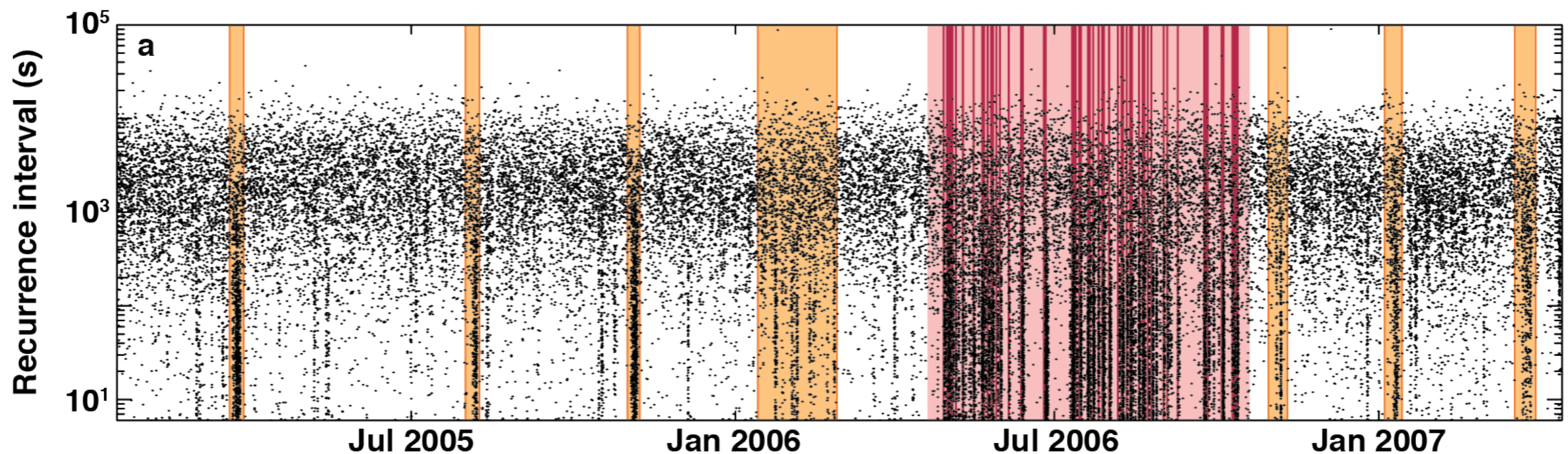


Is LFE moment rate diagnostic of slow slip?

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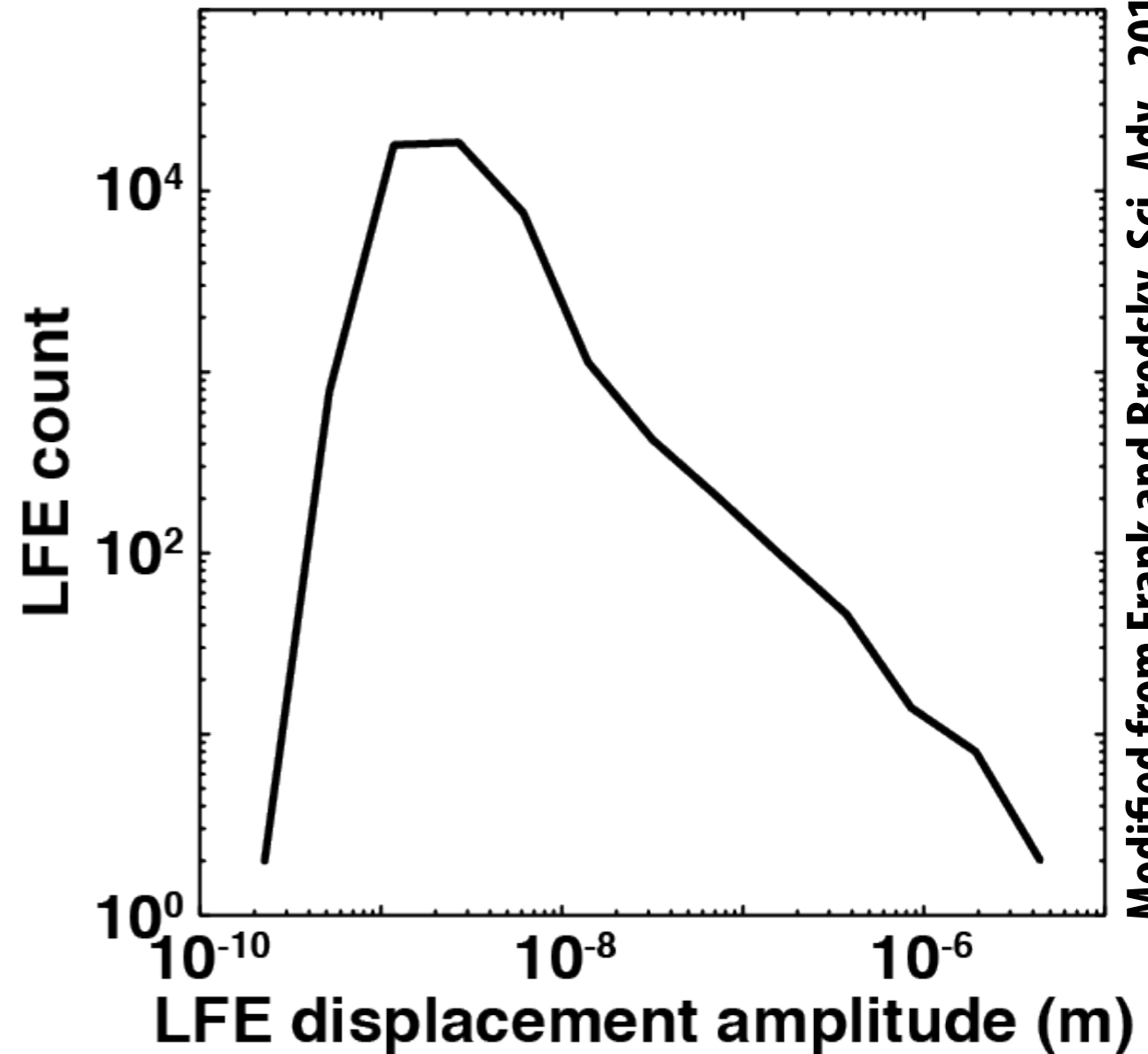
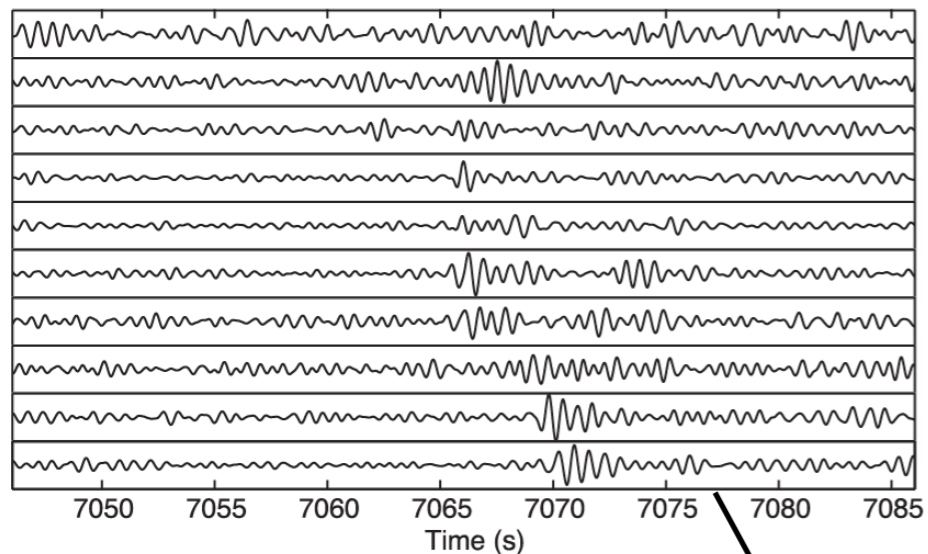
- ▶ If the LFE moment rate was diagnostic of the geodetic moment rate...

We could turn this catalog of LFEs into a catalog of slow slip!



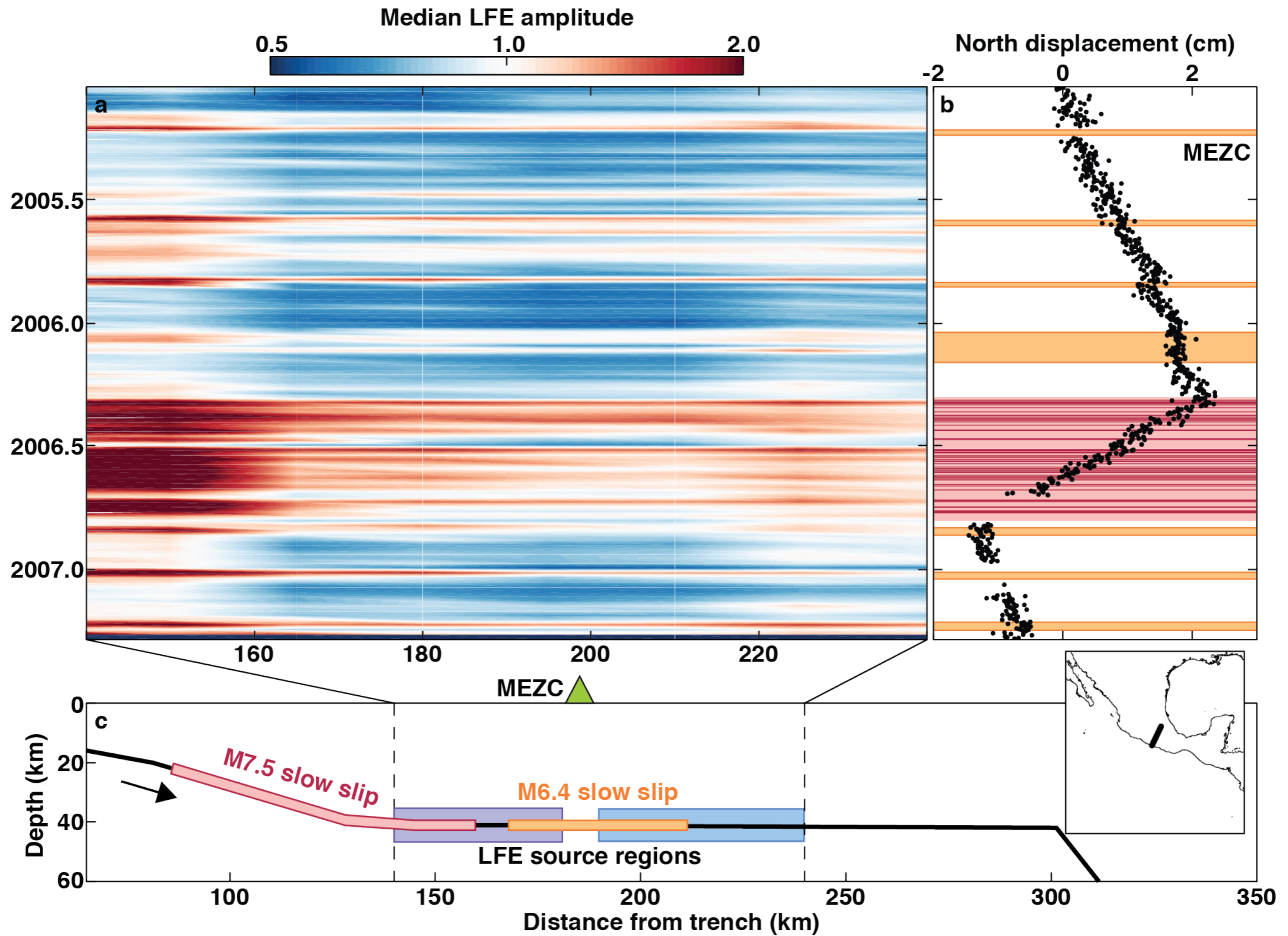
Measuring LFE (seismic) moment rate

- ▶ Seismic displacement amplitude is directly proportional to moment rate (Aki and Richards, 2002)
- ▶ Measure RMS displacement amplitude during every LFE S-wave



Modified from Frank and Brodsky, Sci. Adv., 2019

Spatiotemporal evolution of LFE moment rate

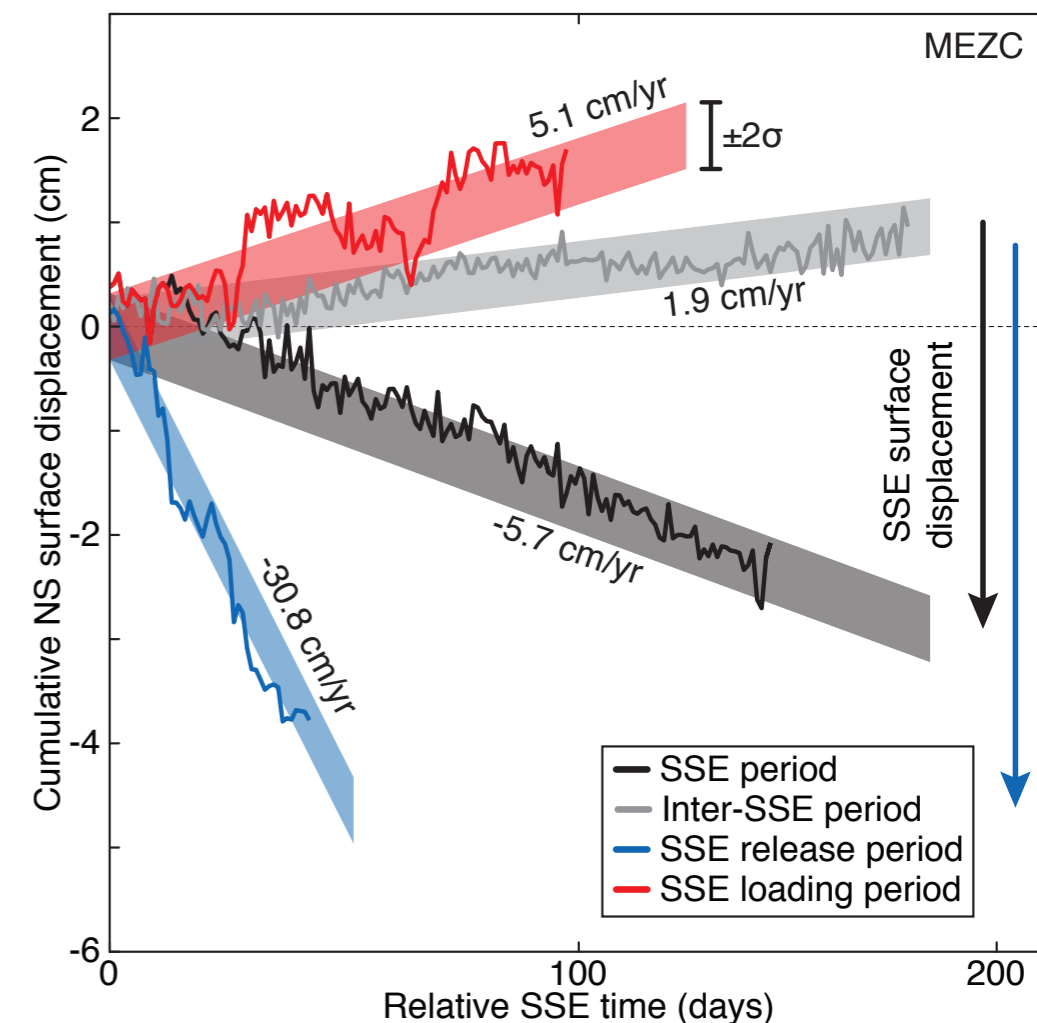
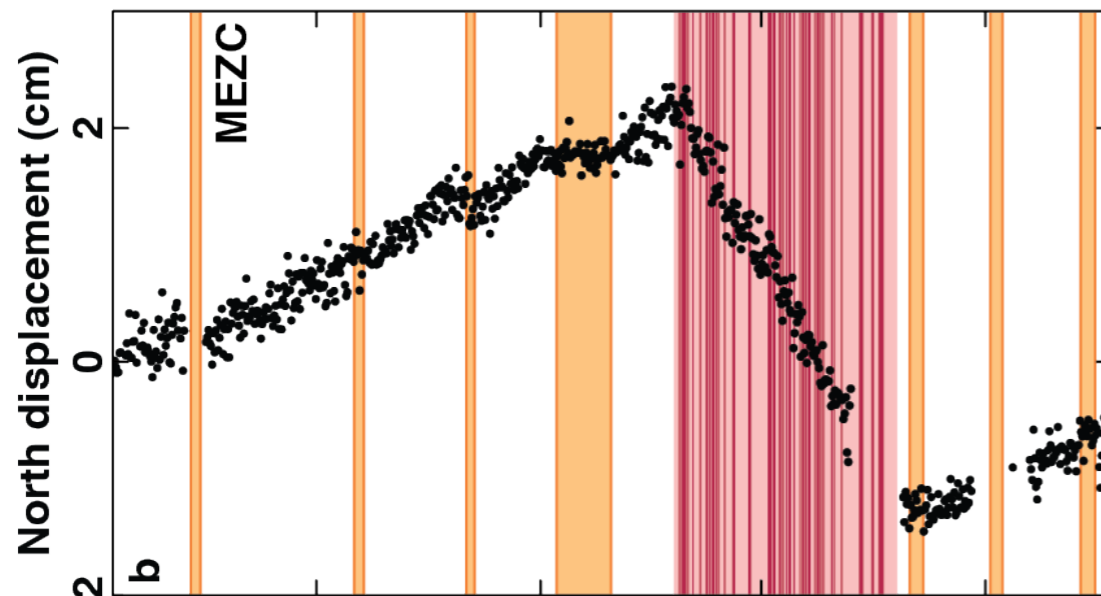


Modified from Frank and Brodsky, *Sci. Adv.*, 2019

Measuring moment rates of slow slip events

Geodetic moment rate of a slow slip event

- ▶ Geodetic moment \div duration
- ▶ NB: intermittent slip = larger moment and shorter duration!



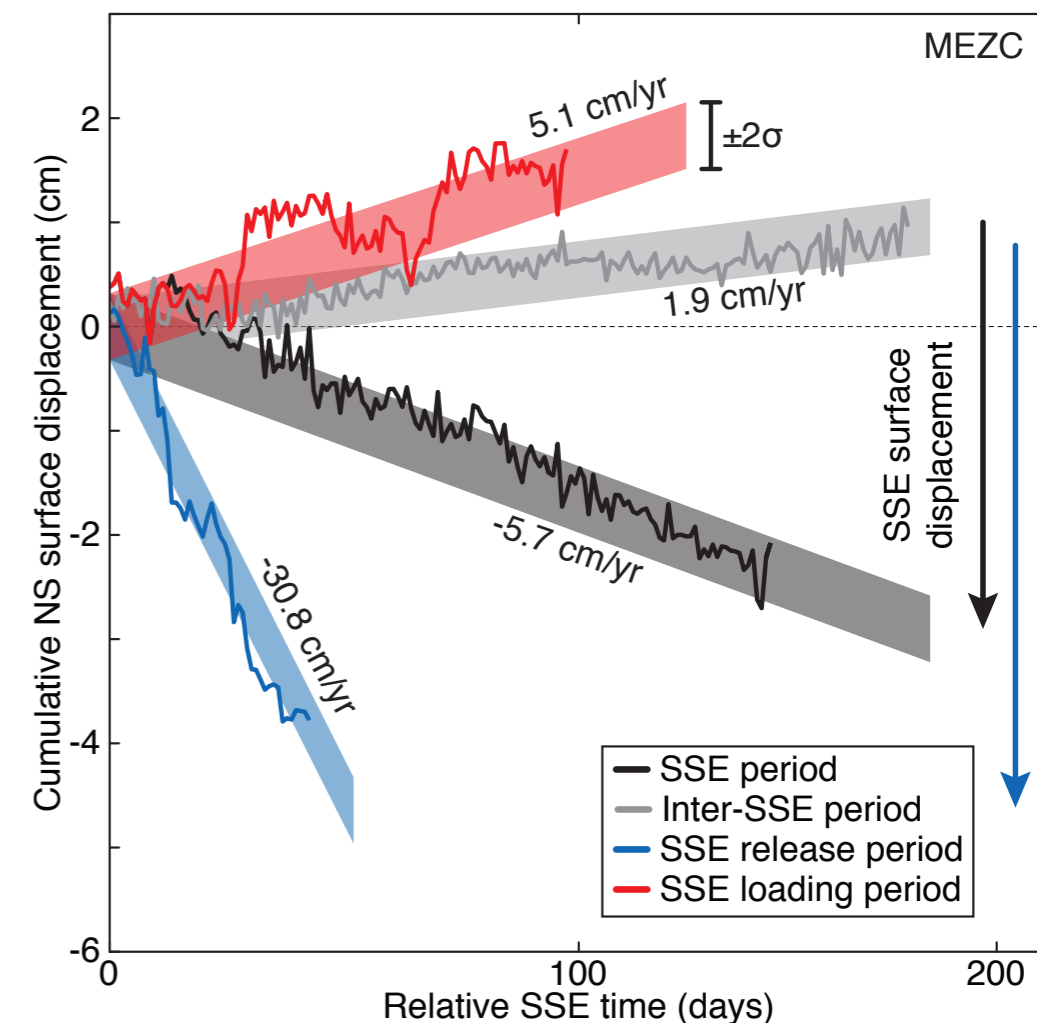
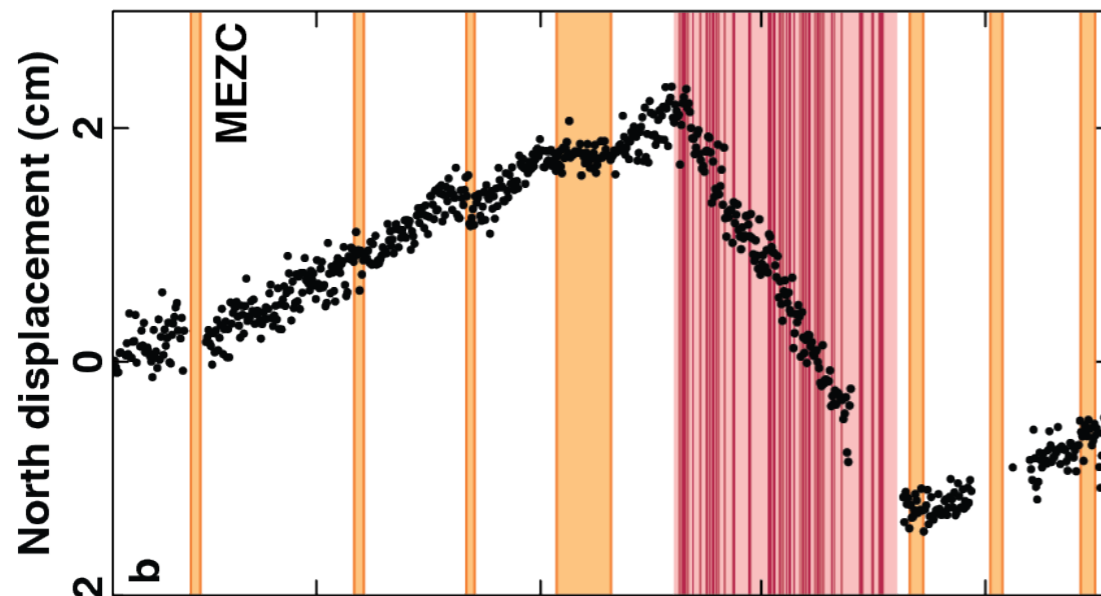
Modified from Frank et al., *Sci. Adv.*, 2018

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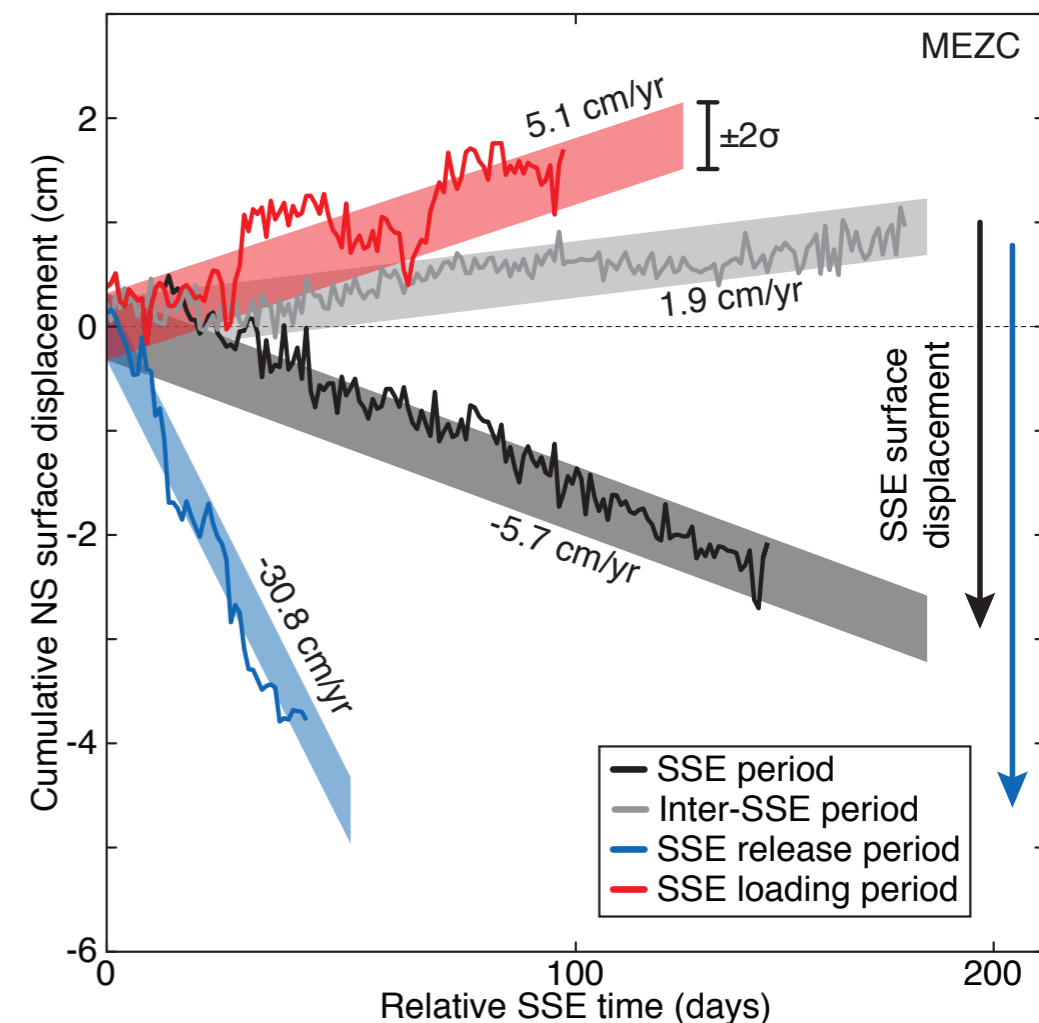
So what is the duration of a slow slip event?



Modified from Frank et al., *Sci. Adv.*, 2018

Slip duration of intermittent slow slip events

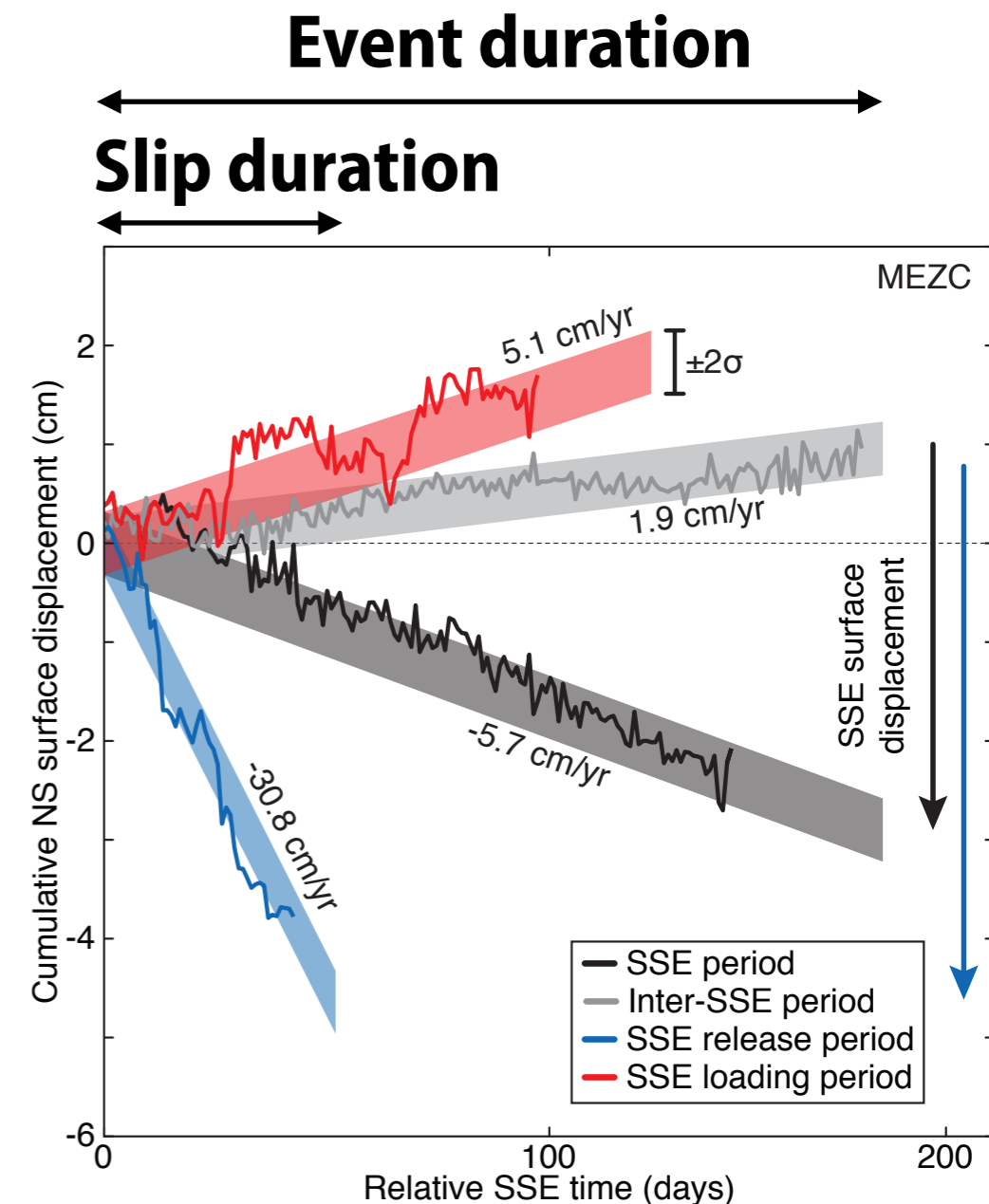
- ▶ **Observation:** Slow slip *mostly* happens during LFE activity...
- ▶ **Assumption:** slow slip **ONLY** happens during LFEs
 - ▶ Every LFE is driven by aseismic slip



Modified from Frank et al., *Sci. Adv.*, 2018

Slip duration of intermittent slow slip events

- ▶ **Observation:** Slow slip *mostly* happens during LFE activity...
- ▶ **Assumption:** slow slip **ONLY** happens during LFEs
 - ▶ Every LFE is driven by aseismic slip
- ▶ Duration should reflect slip duration, not total event duration
- ▶ Slow slip duration is proportional to N_{LFE}
- ▶ Average aseismic slip pulse duration of Δt

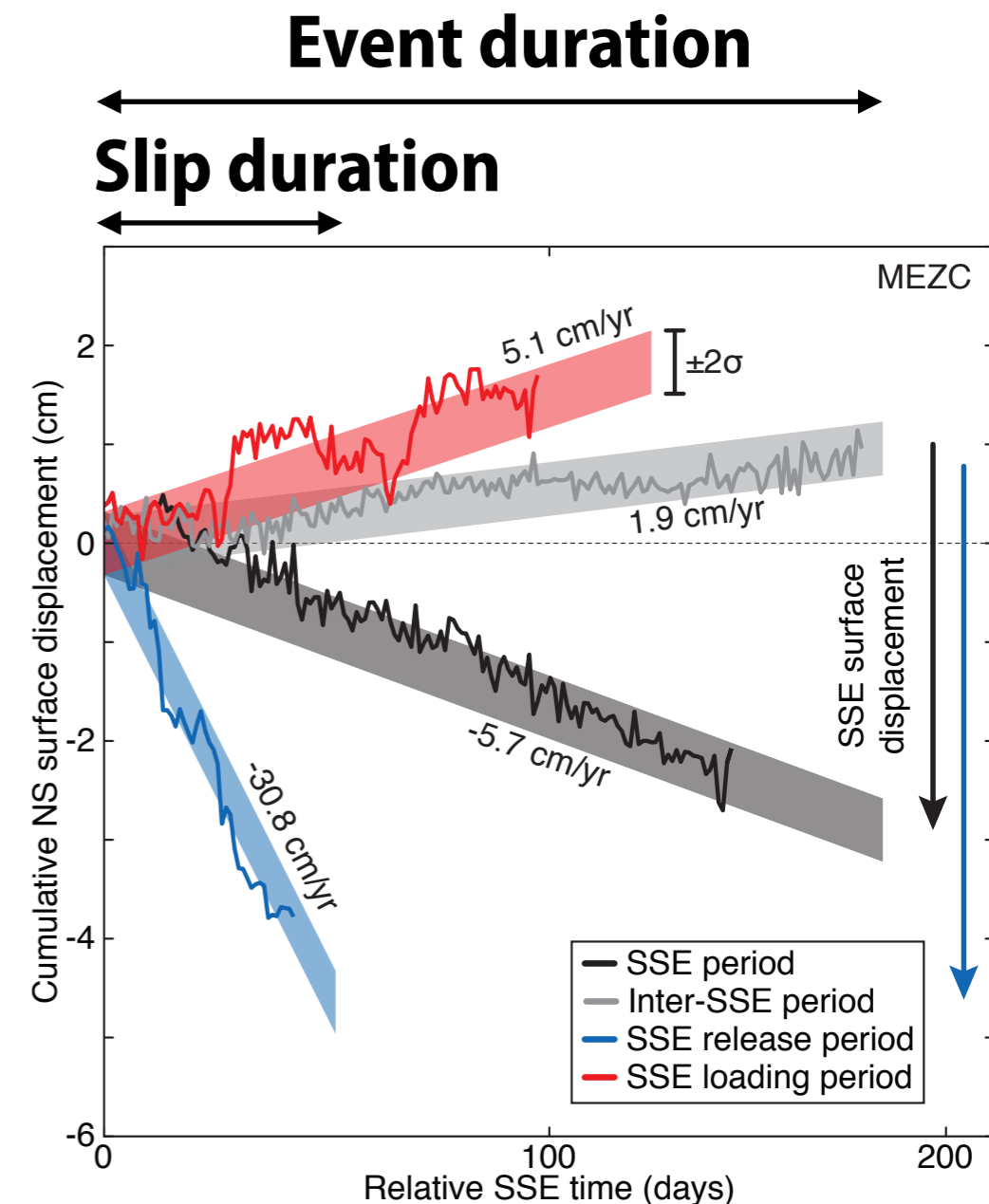


Modified from Frank et al., Sci. Adv., 2018

Slip duration of intermittent slow slip events

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$$\text{Slip duration} = N_{LFE} \times \Delta t$$



Modified from Frank et al., Sci. Adv., 2018

Measuring moment rate of slow slip events

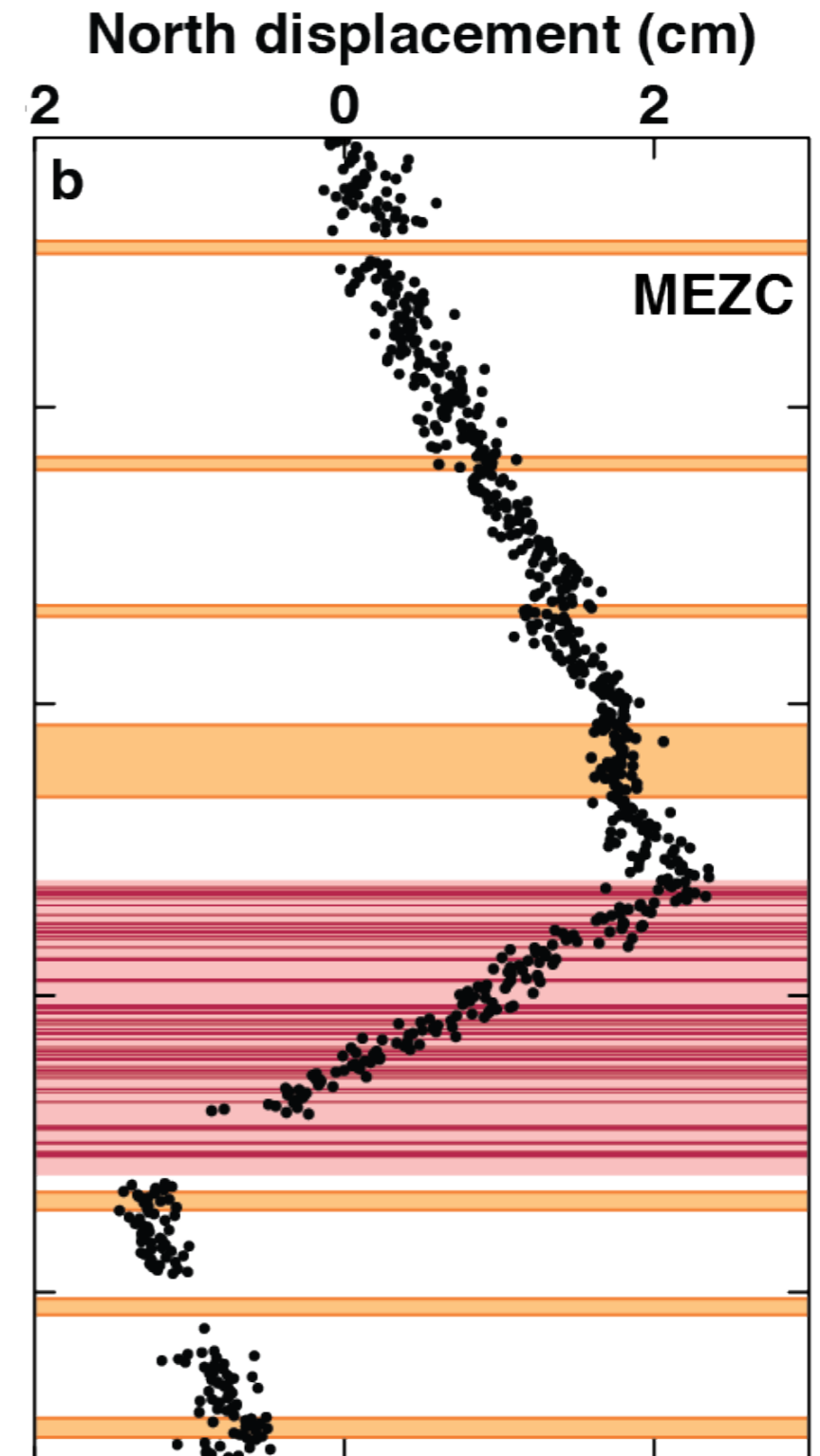
- ▶ Eight geodetically observed slow slip events
 - ▶ **2006 M7.5 slow slip**
 - ▶ Seven **M6.4 slow slips** every 75 days (Frank et al., GRL, 2015)

Geodetic moment rate of a slow slip event

- ▶ Geodetic moment \div duration
 - ▶ Slip duration = $N_{\text{LFE}} \times \Delta t$

Seismic moment rate of LFEs during slow slip

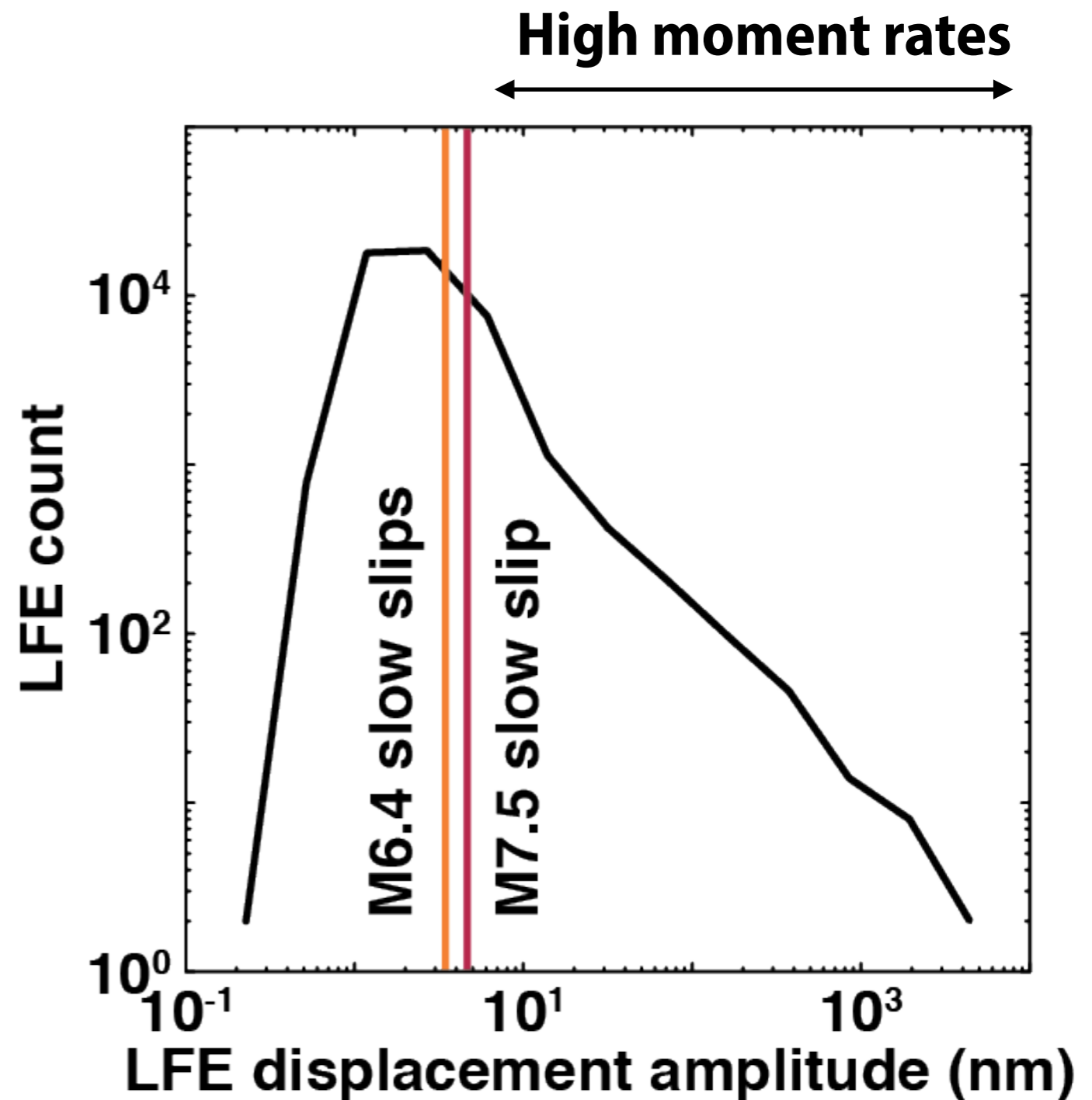
- ▶ Median amplitude of all LFEs within event



Modified from Frank and Brodsky, Sci. Adv., 2019

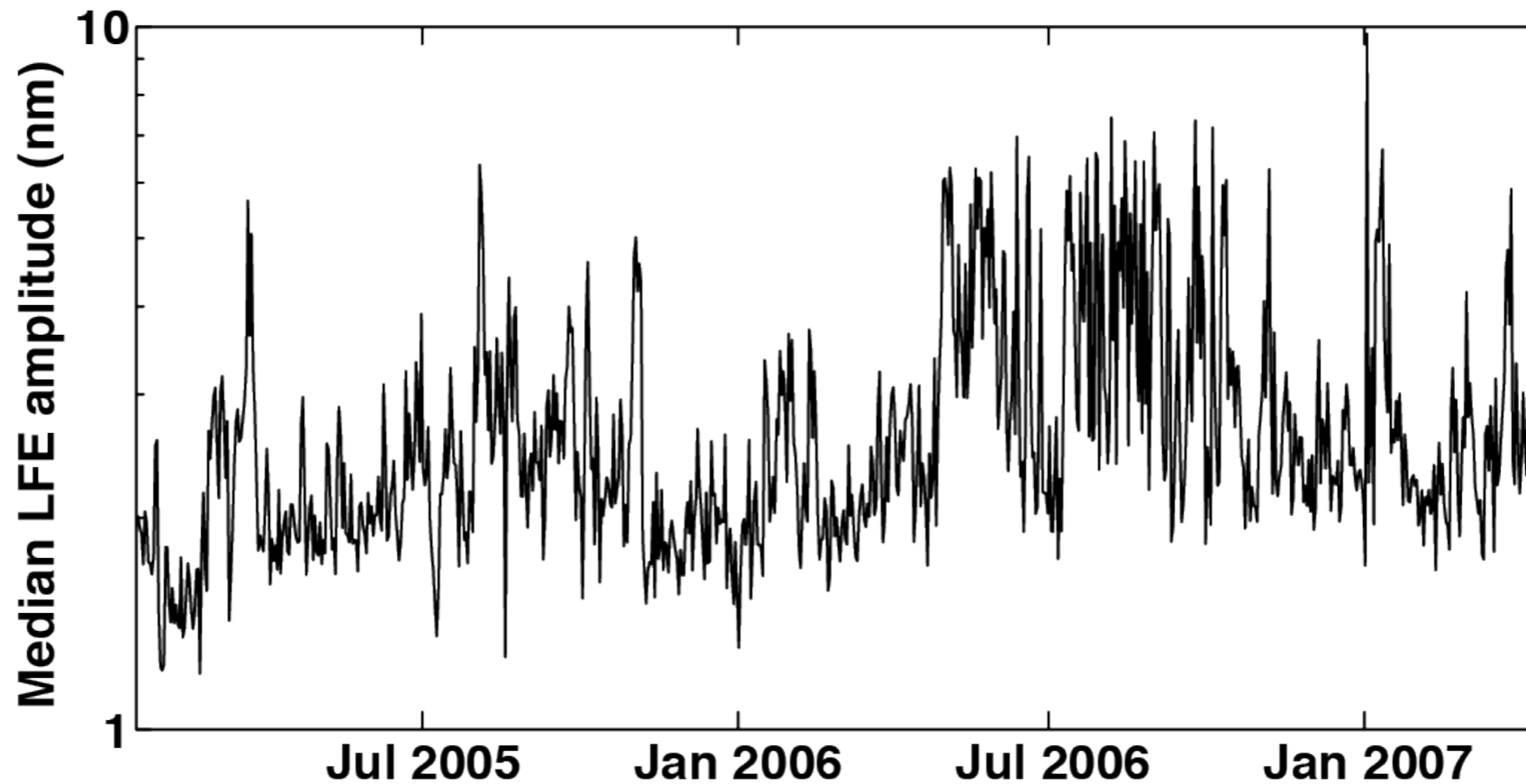
Average slow slip moment rate does not reflect highest moment rates

- ▶ Moment rates averaged over long time periods (weeks to months)
- ▶ Missing dynamics at high moment rates!



Sampling high moment rates

- ▶ Sample LFE amplitude on same time scale as GPS (daily)

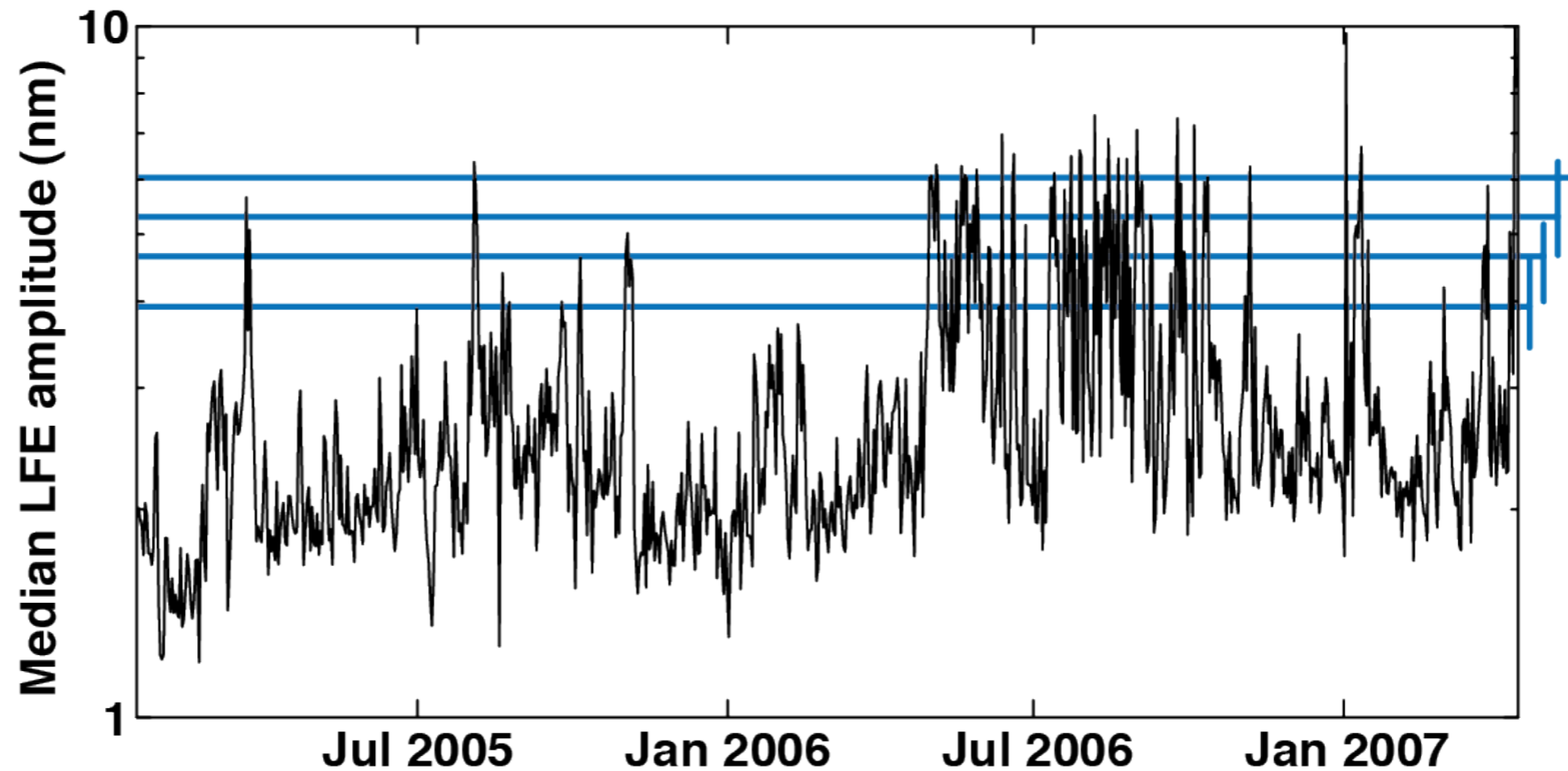


- ▶ Bin GPS displacements by LFE amplitude

Modified from Frank and Brodsky, *Sci. Adv.*, 2019

Sampling high moment rates

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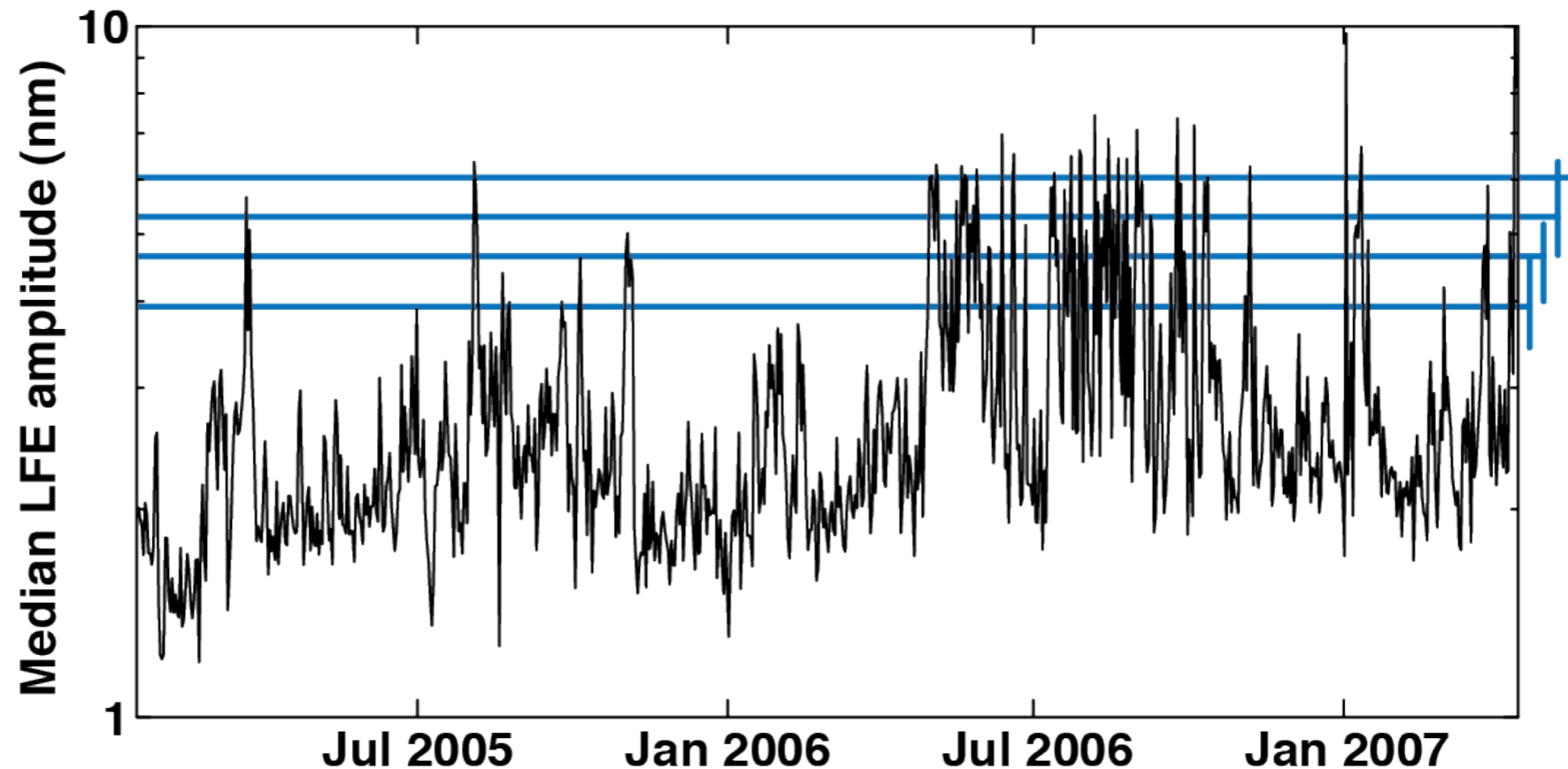


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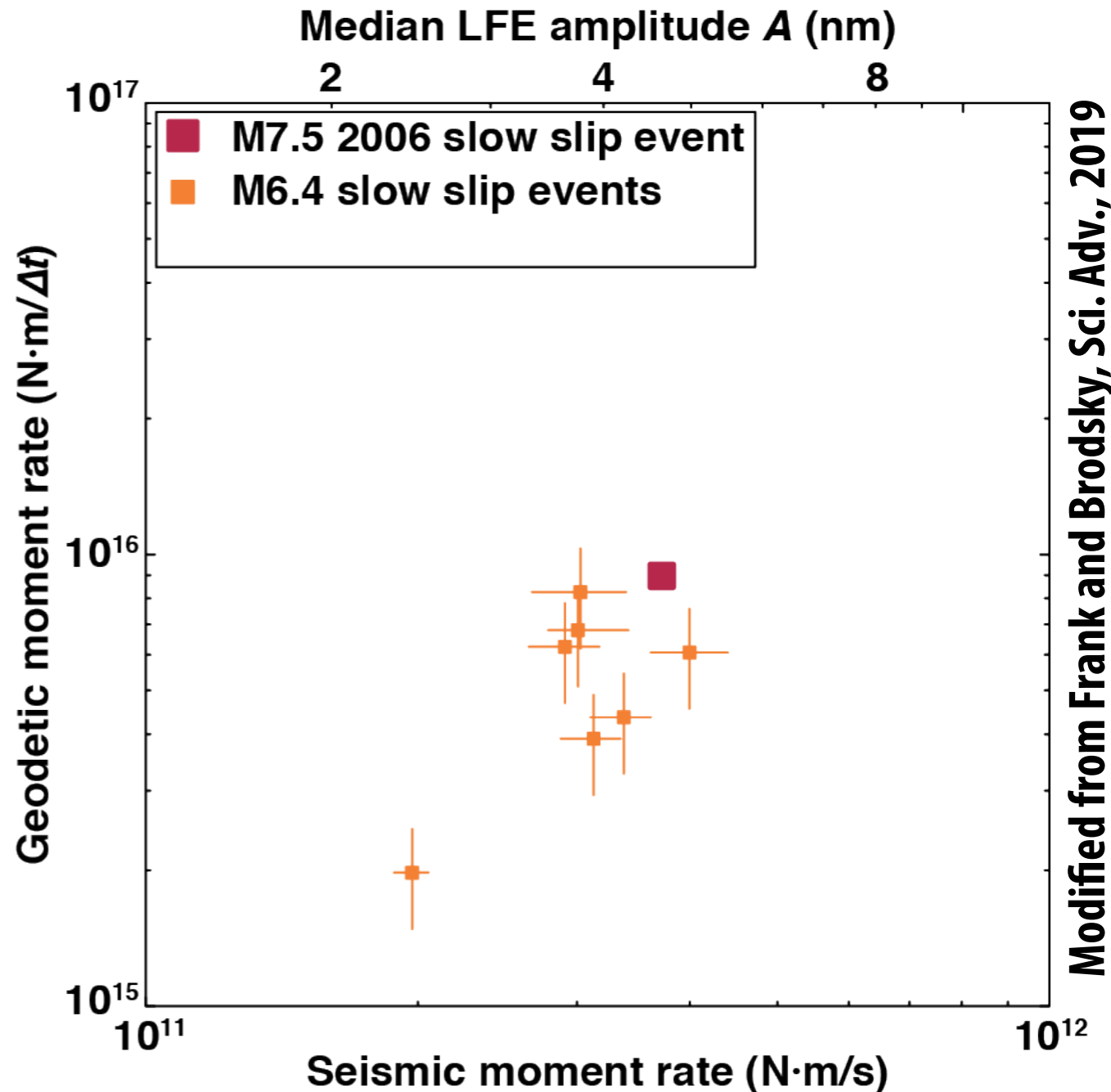
- ▶ Bin GPS displacements by LFE amplitude

Each bin represents slow transients that generate a given range of LFE amplitudes

Modified from Frank and Brodsky, Sci. Adv., 2019

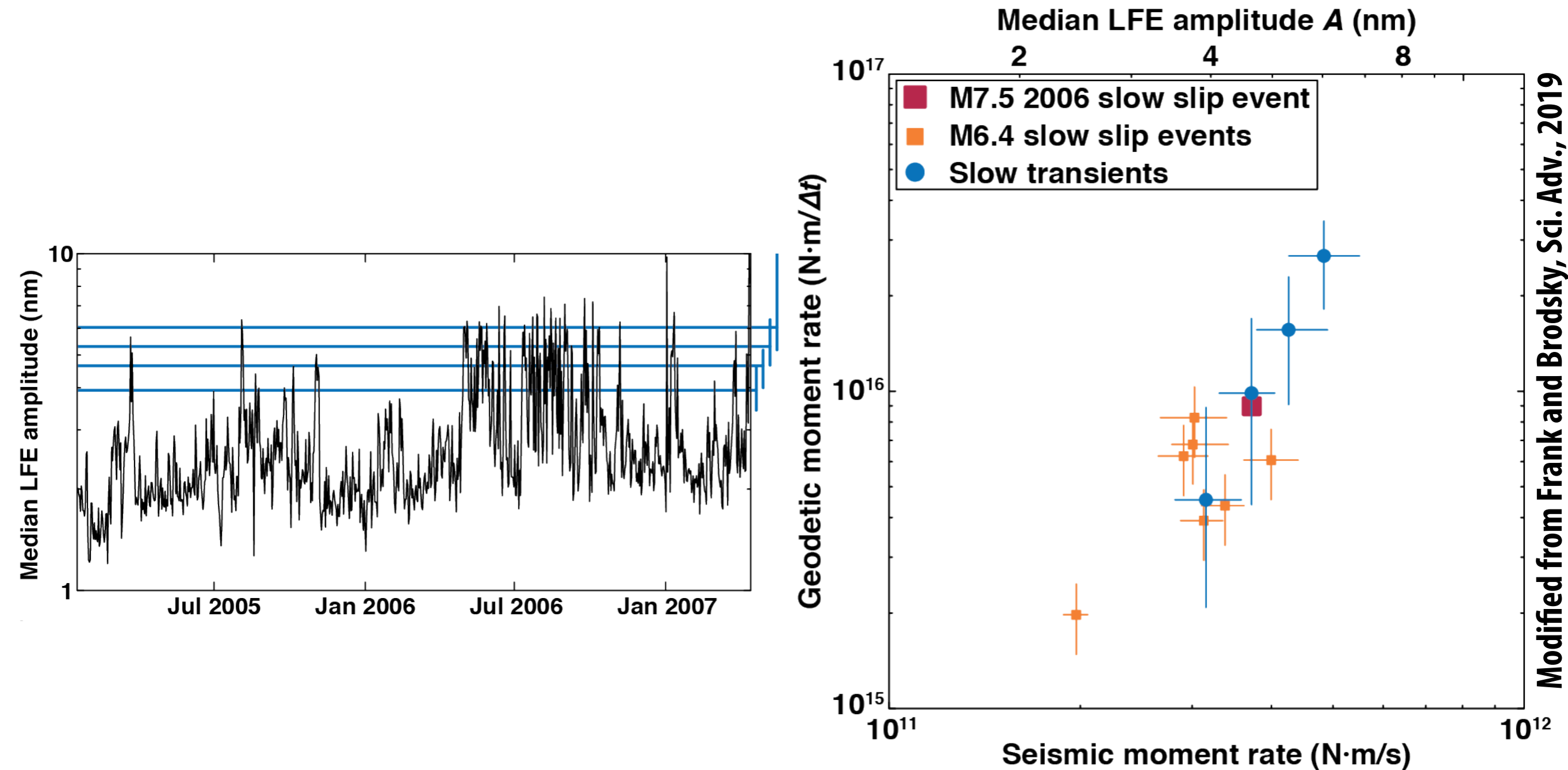
Avg. slow slip dynamics suggests a constant moment rate

- ▶ **Y-axis:** Average geodetic moment rate measured over weeks or months
- ▶ **X-axis:** Median seismic moment rate of all constituent LFEs



Modified from Frank and Brodsky, Sci. Adv., 2019

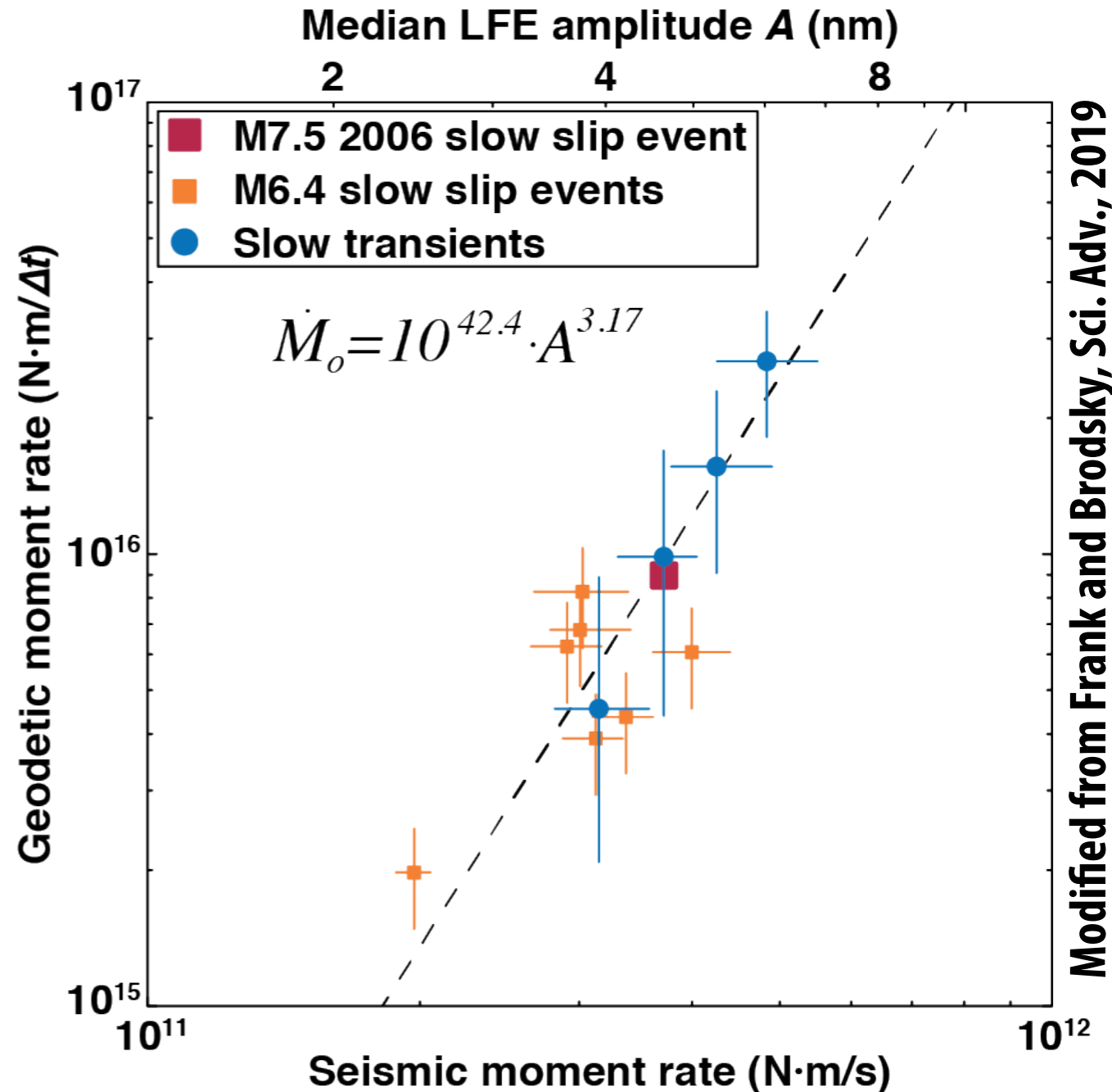
LFE-derived slow transients sample high moment rates



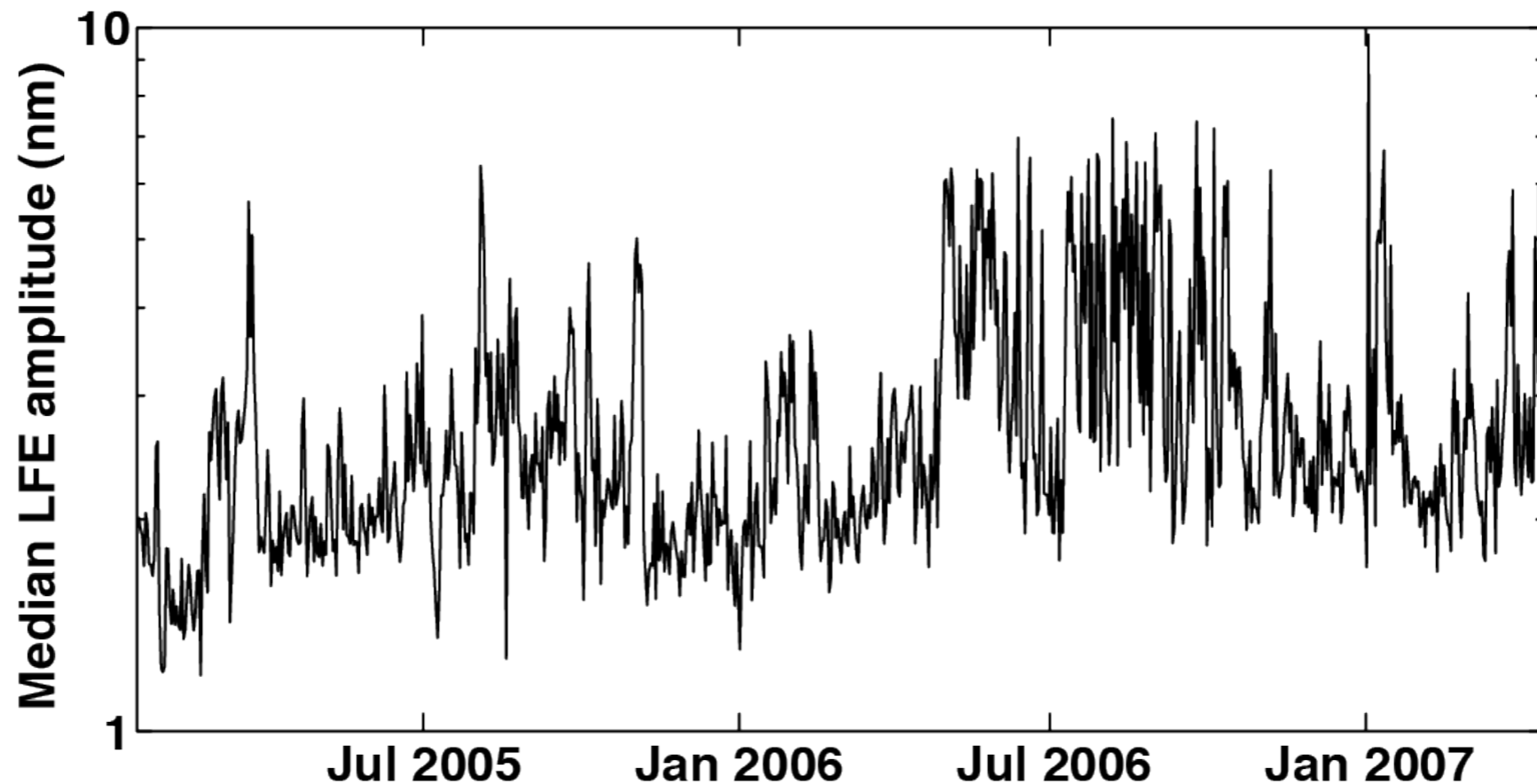
Modified from Frank and Brodsky, *Sci. Adv.*, 2019

LFEs are diagnostic of the driving slow slip

- ▶ Best-fit power law scaling
- ▶ Seismic to aseismic ratio during slow slip is at least 10^{-4}

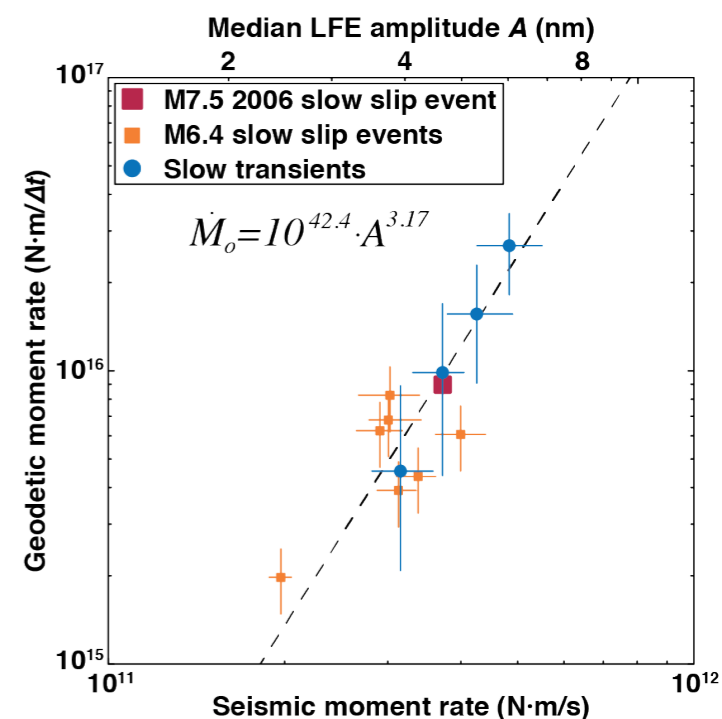


LFE amplitude to slow transient moment



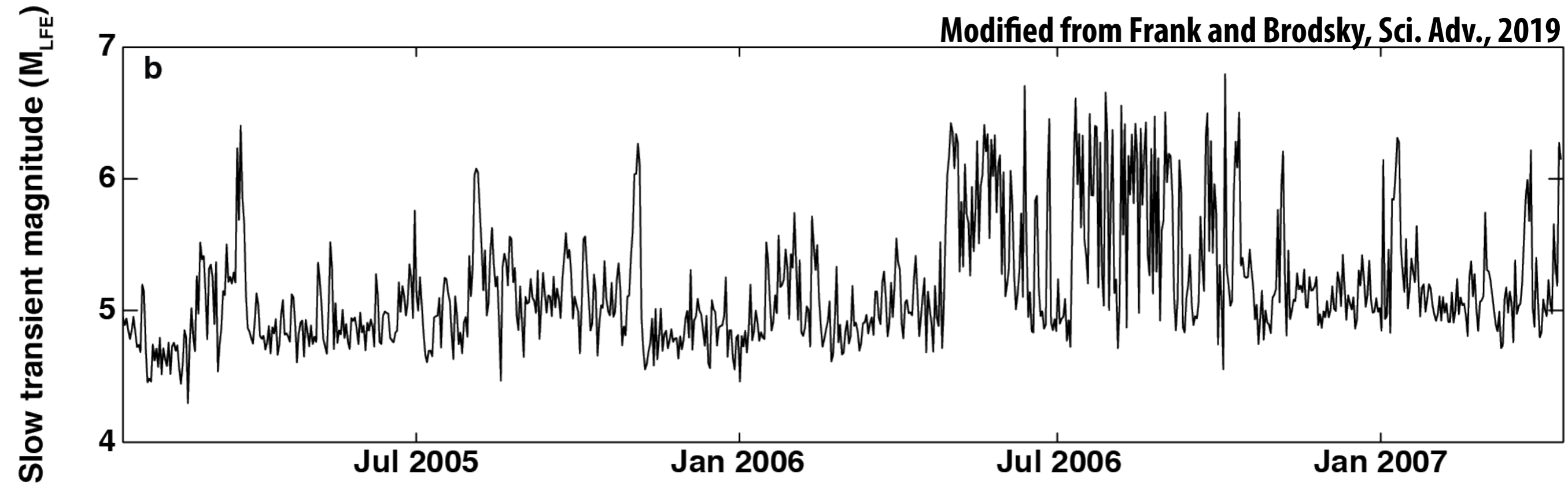
- ▶ LFE amplitude is converted to geodetic moment rate
- ▶ **Slow transient moment** = moment rate multiplied by slip duration (N_{LFE})

From an LFE catalog to...



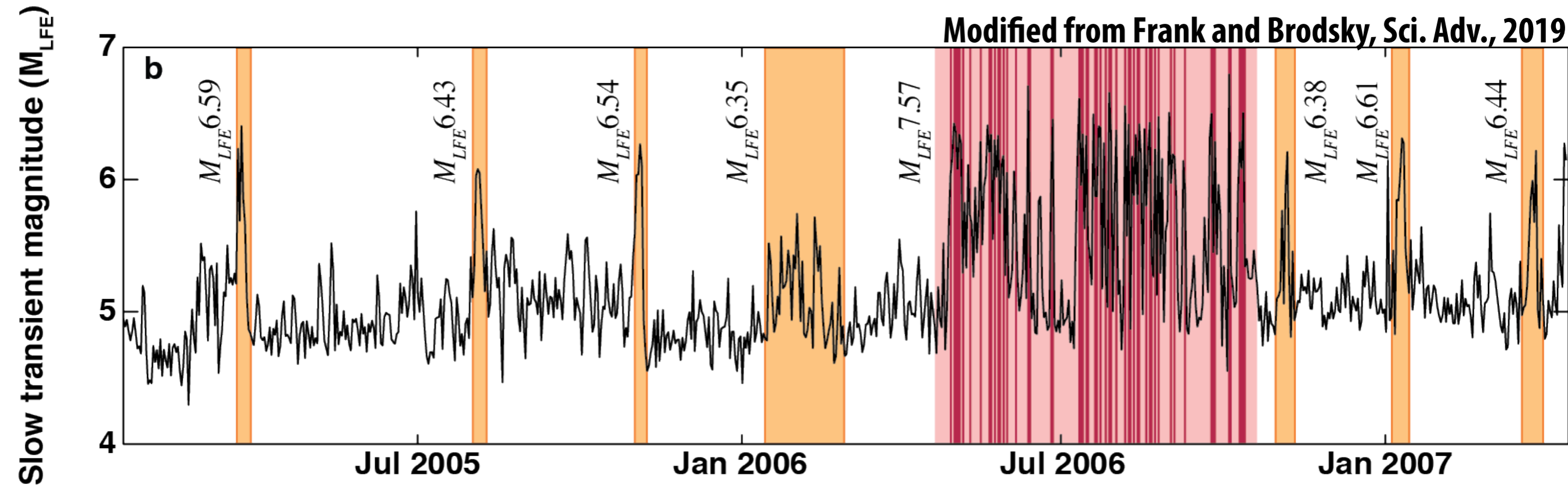
A catalog of slow transients

Modified from Frank and Brodsky, *Sci. Adv.*, 2019



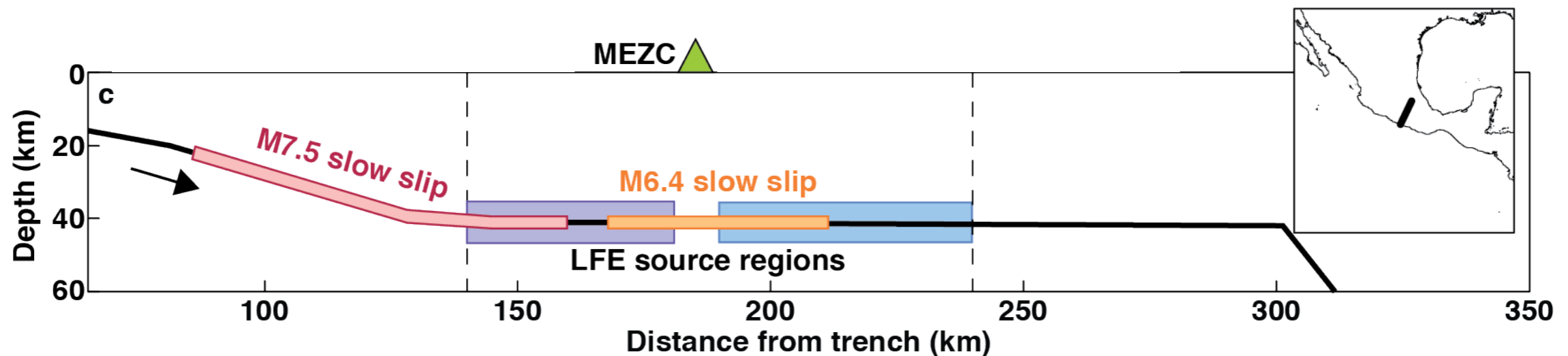
A catalog of slow transients

Modified from Frank and Brodsky, *Sci. Adv.*, 2019



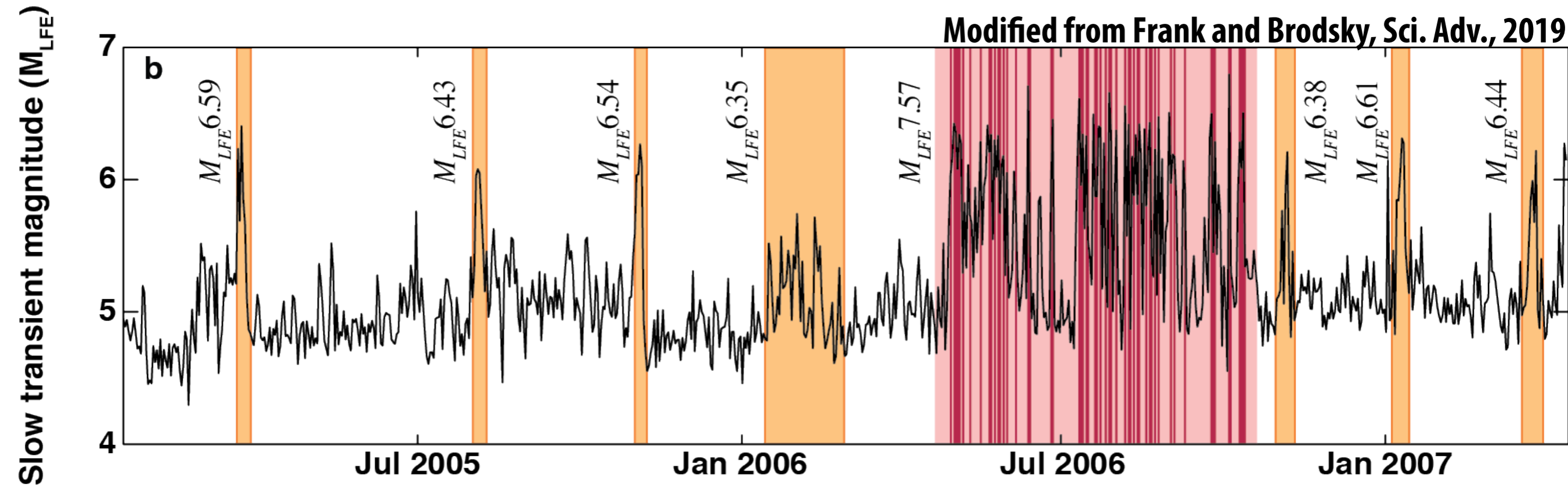
M7.5 slow slip every 4 years

M6.4 slow slip every 75 days



A catalog of slow transients

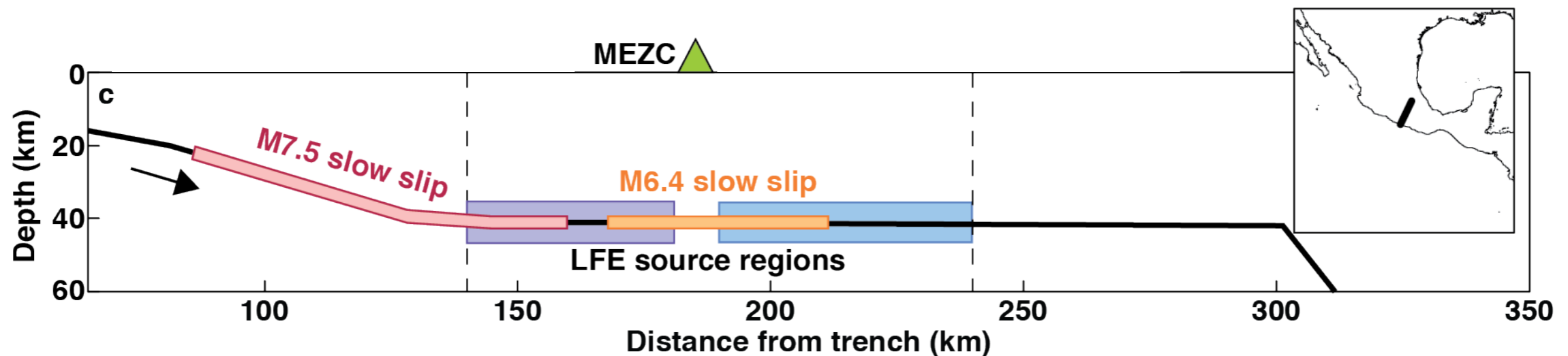
Modified from Frank and Brodsky, *Sci. Adv.*, 2019



M7.5 slow slip every 4 years

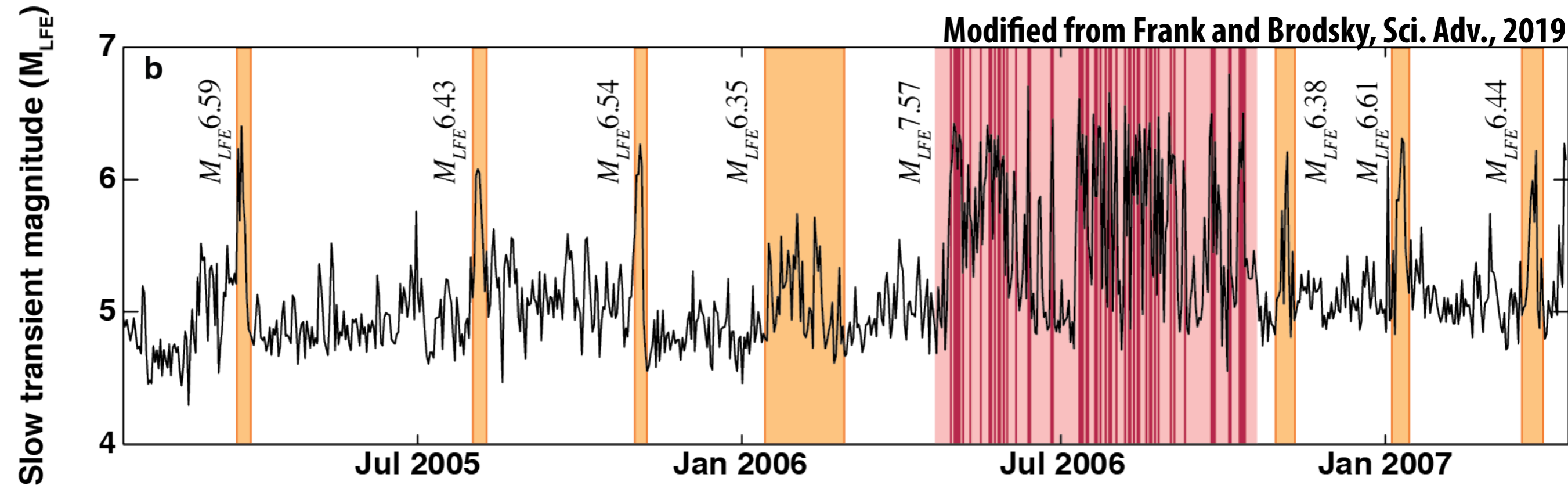
M6.4 slow slip every 75 days

Just a cluster of M6 transients



A catalog of slow transients

Modified from Frank and Brodsky, *Sci. Adv.*, 2019

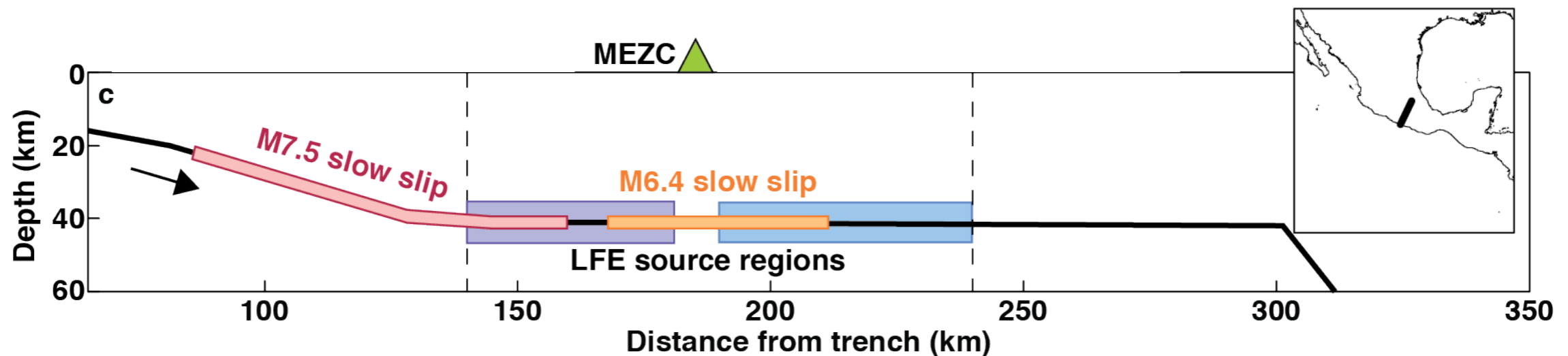


M7.5 slow slip every 4 years

M6.4 slow slip every 75 days

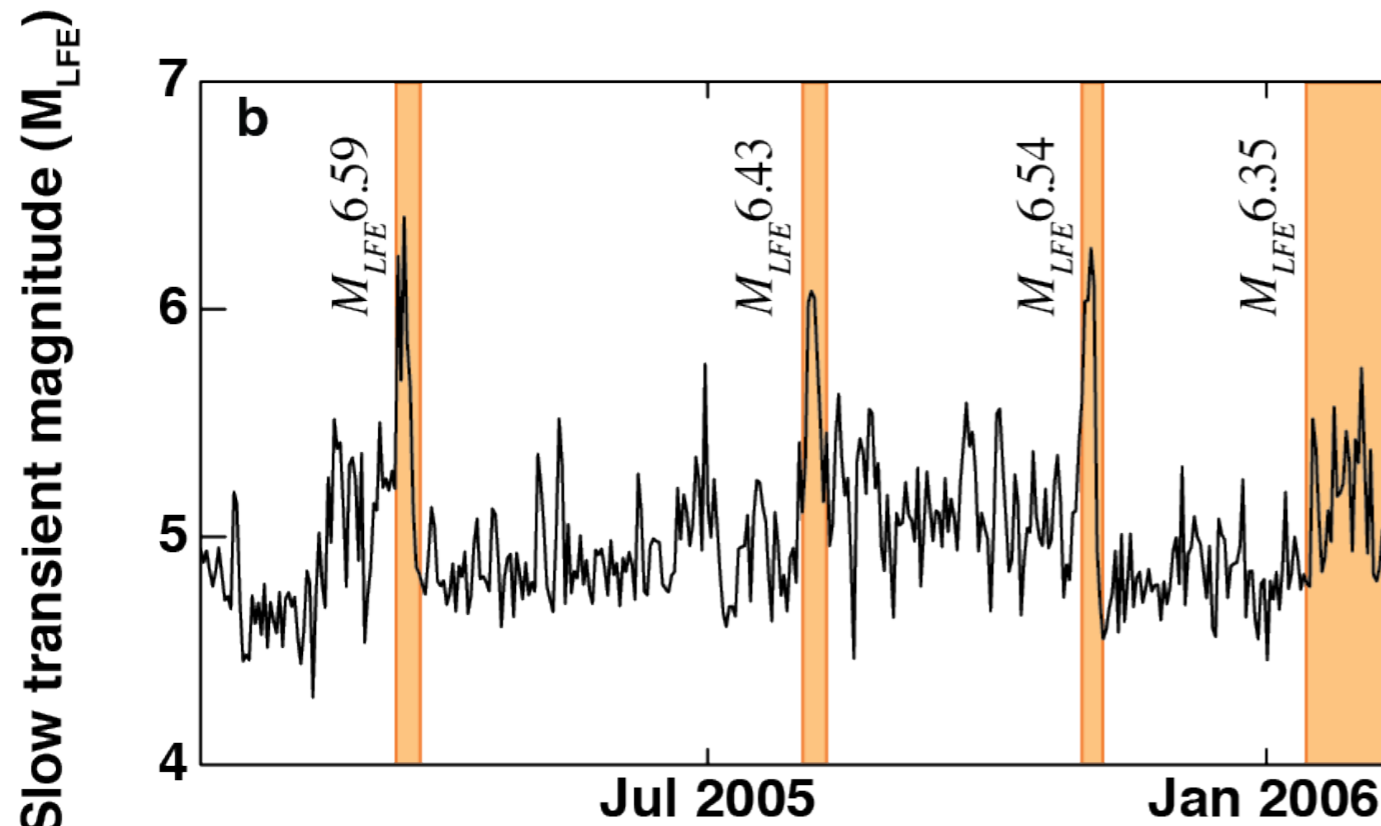
Just a cluster of M6 transients

Slow slip also happens every day!



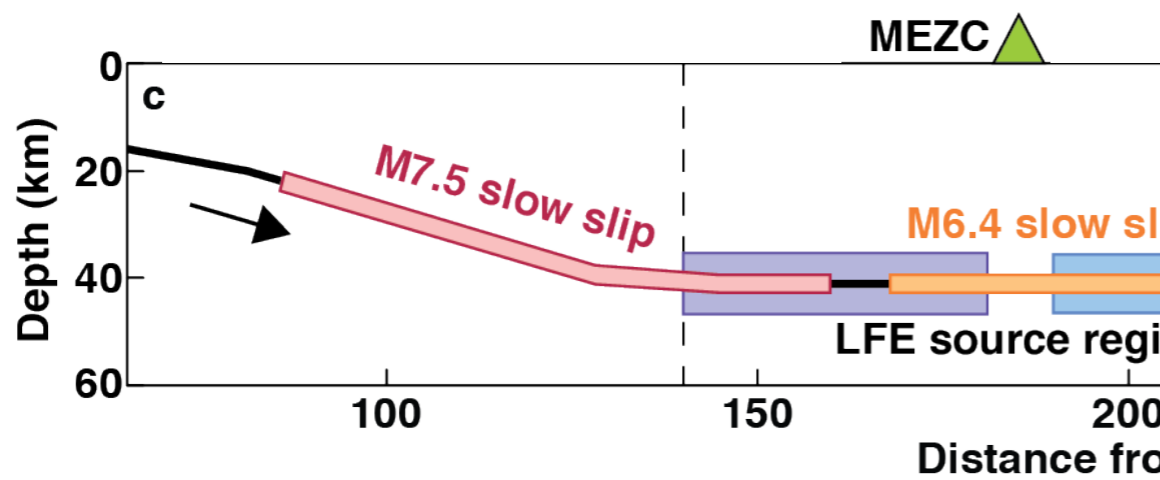
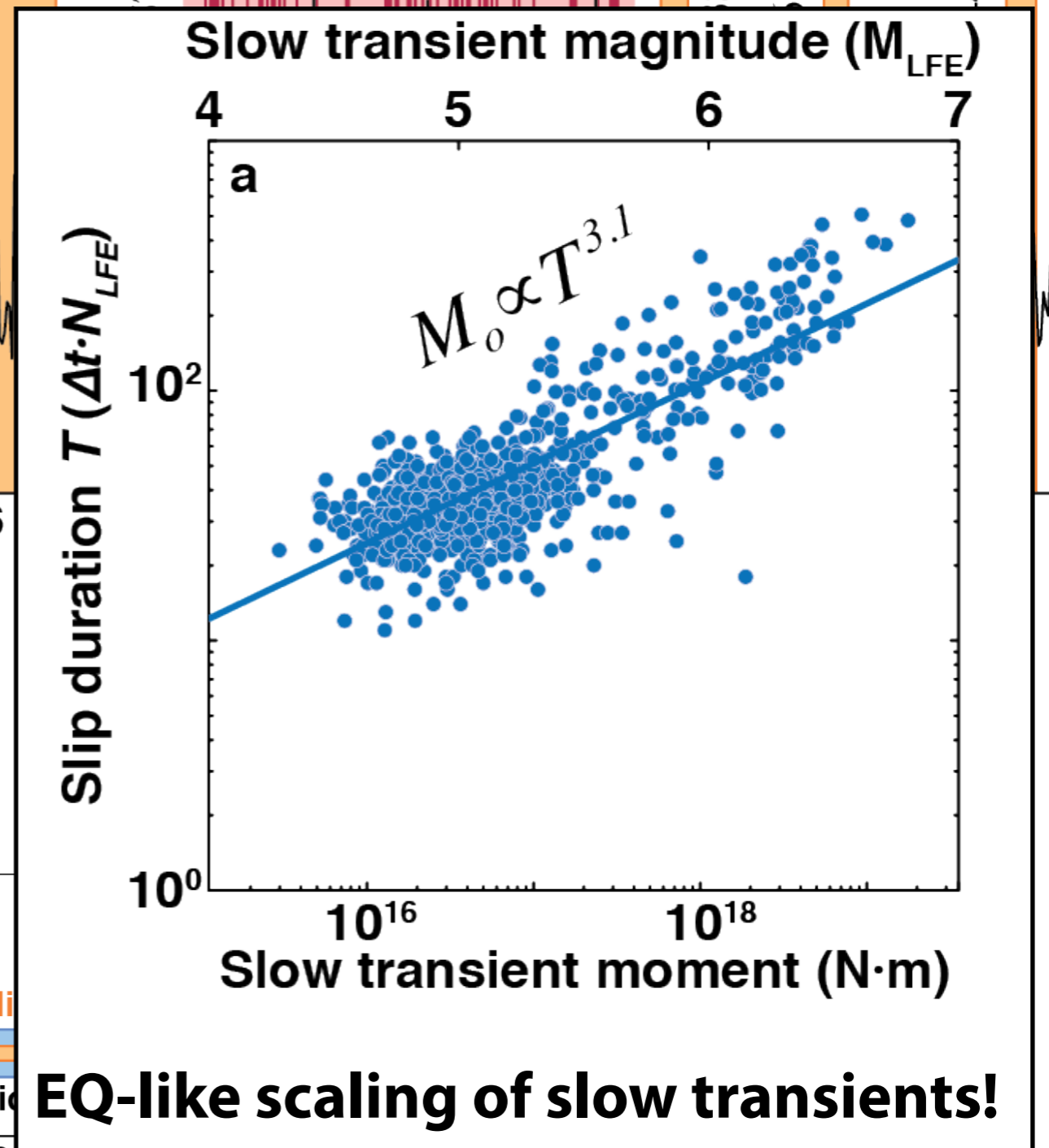
A catalog of slow transients

Modified from Frank and Brodsky, *Sci. Adv.*, 2019

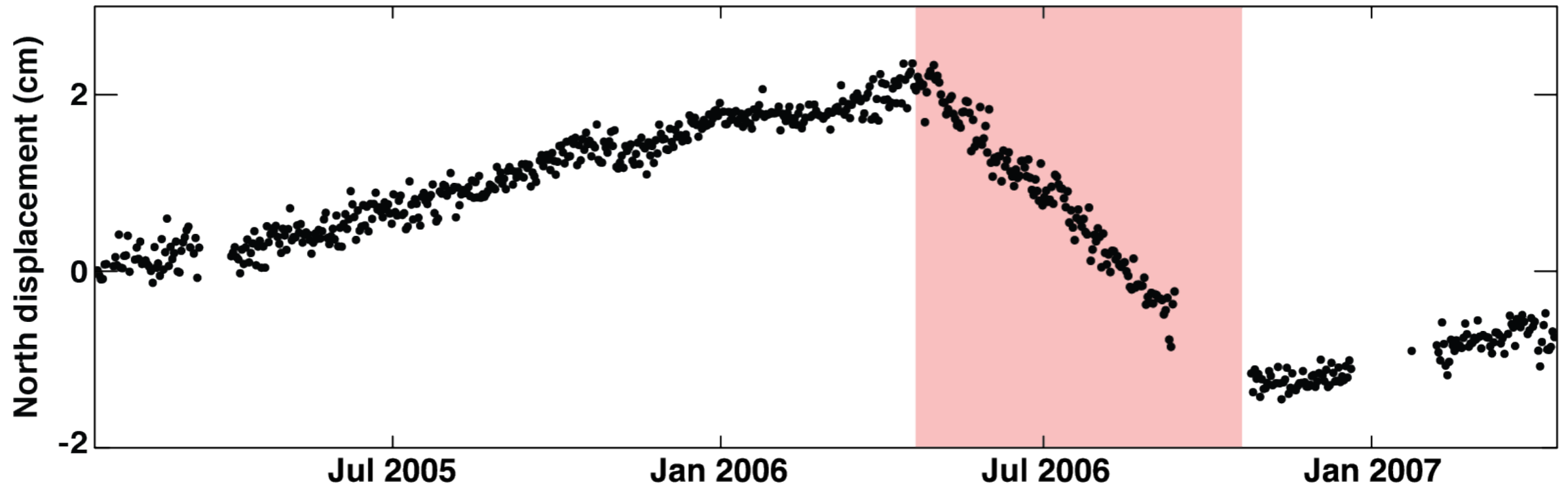


M7.5 slow slip every 4 years

Just a cluster of M6 transients

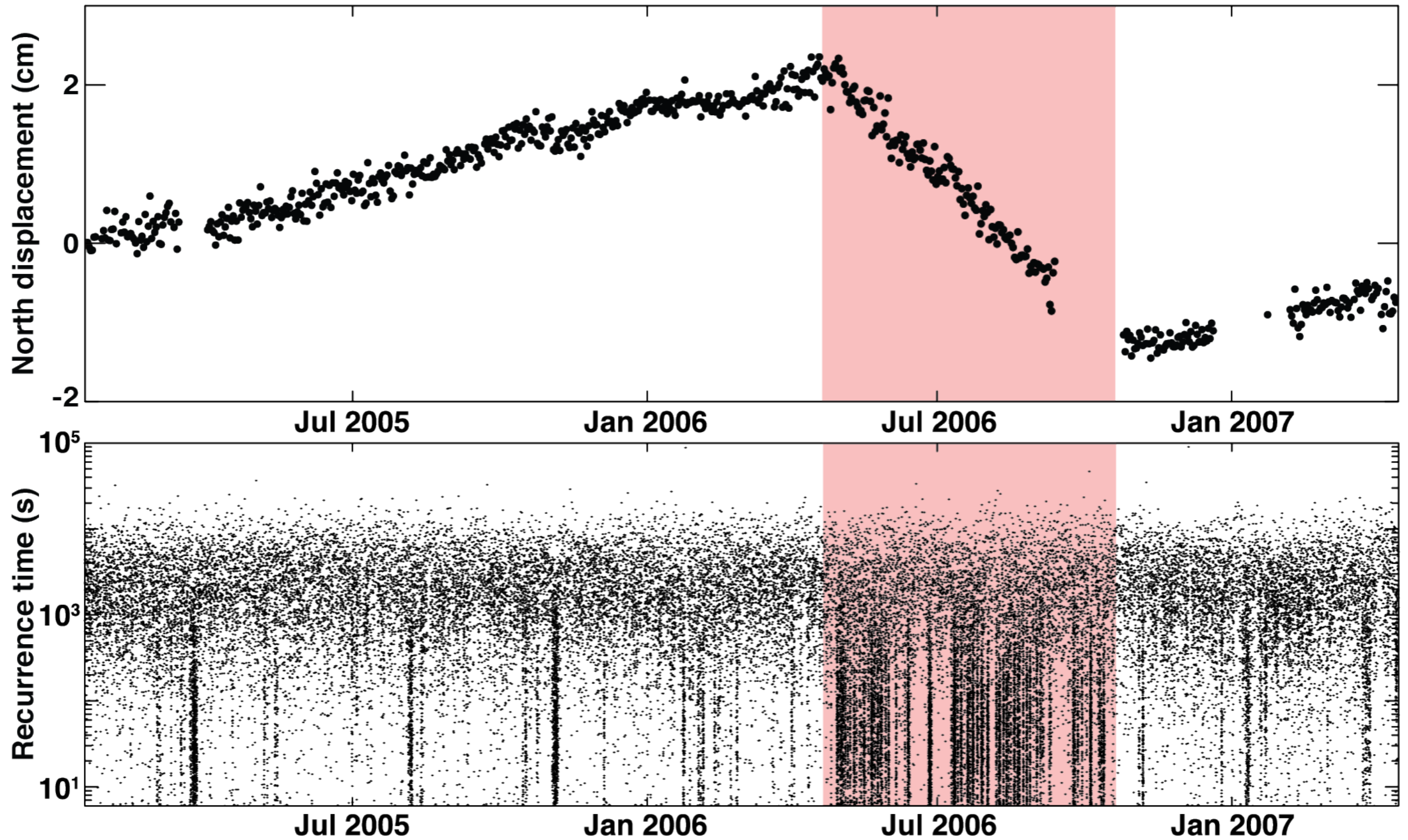


Our evolving grasp on slow slip dynamics



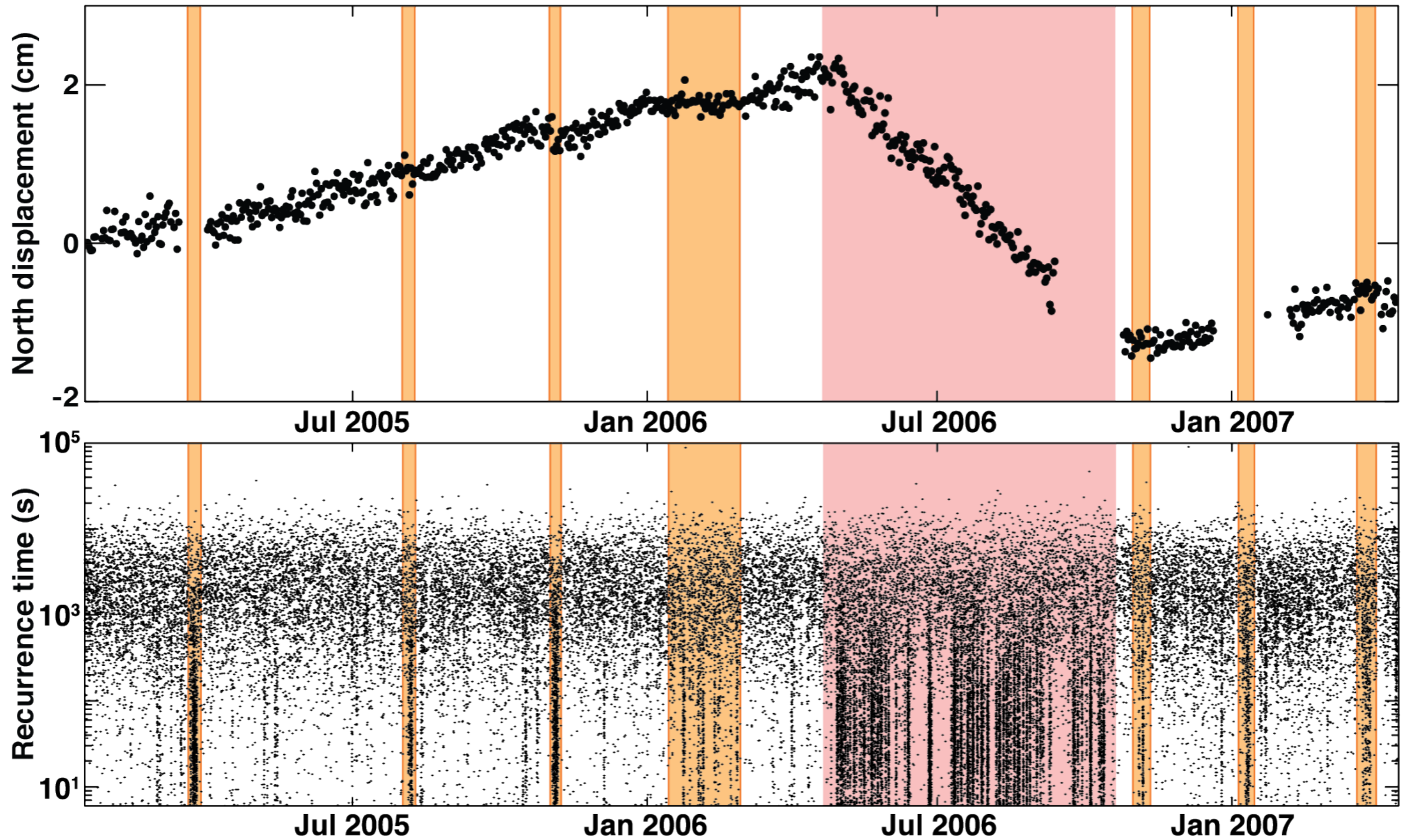
Slow slip is a smooth and continuous rupture

Our evolving grasp on slow slip dynamics



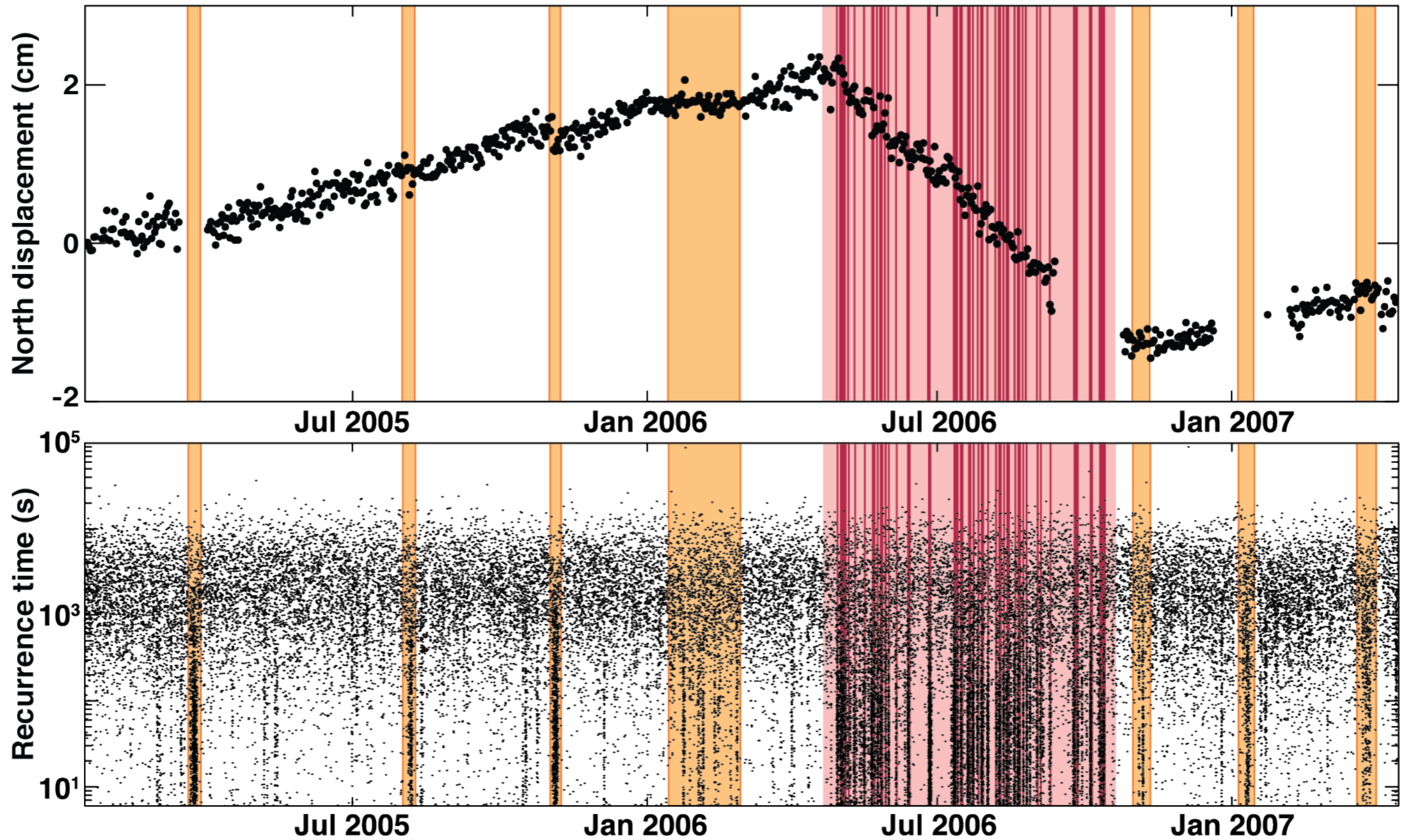
LFEs are driven by surrounding slow slip

Our evolving grasp on slow slip dynamics



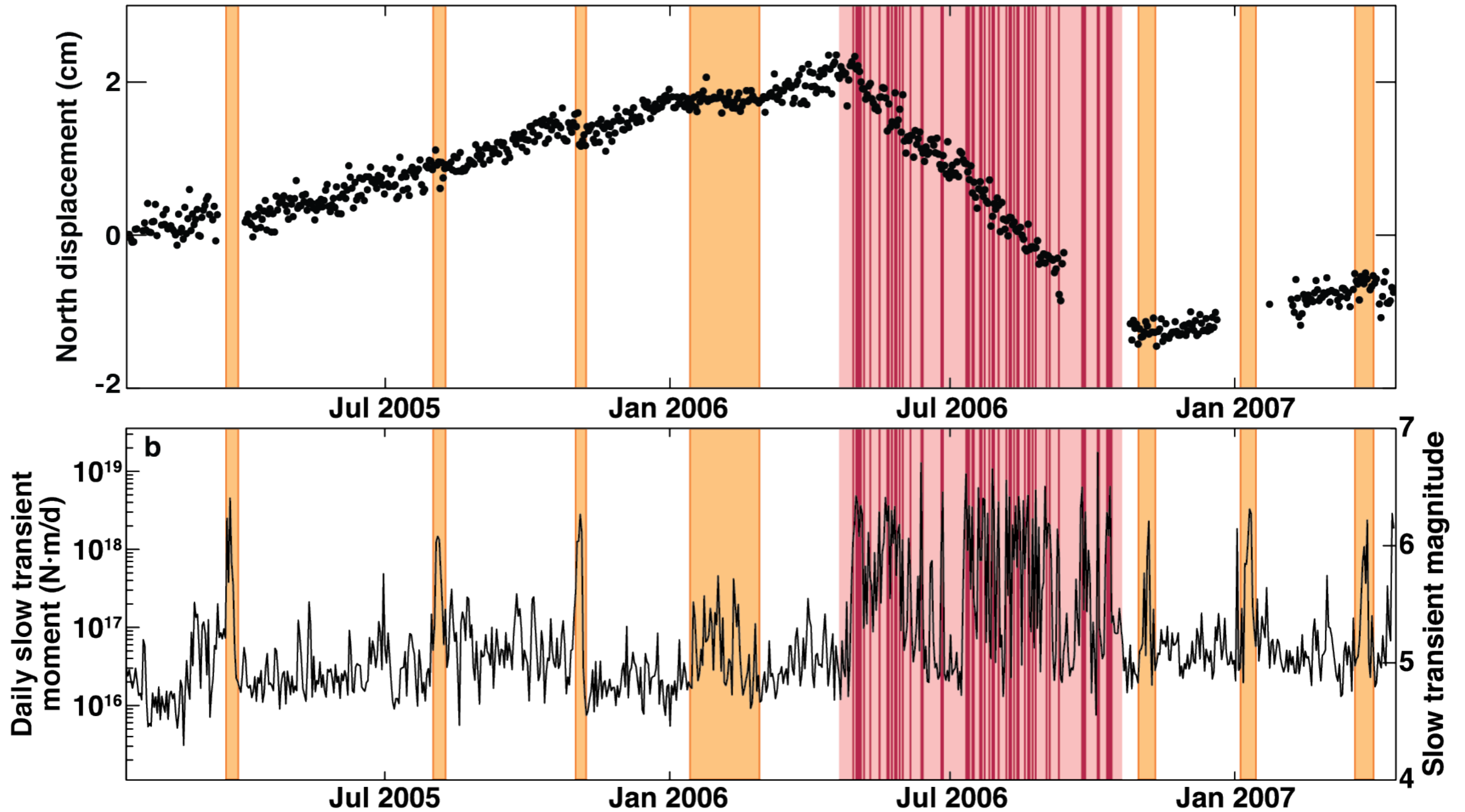
Smaller slow slip events occur more often than is obvious in the geodetic record

Our evolving grasp on slow slip dynamics



Major slow slip events are an intermittent cluster of small slow slips

Our evolving grasp on slow slip dynamics



Slow slip happens every day

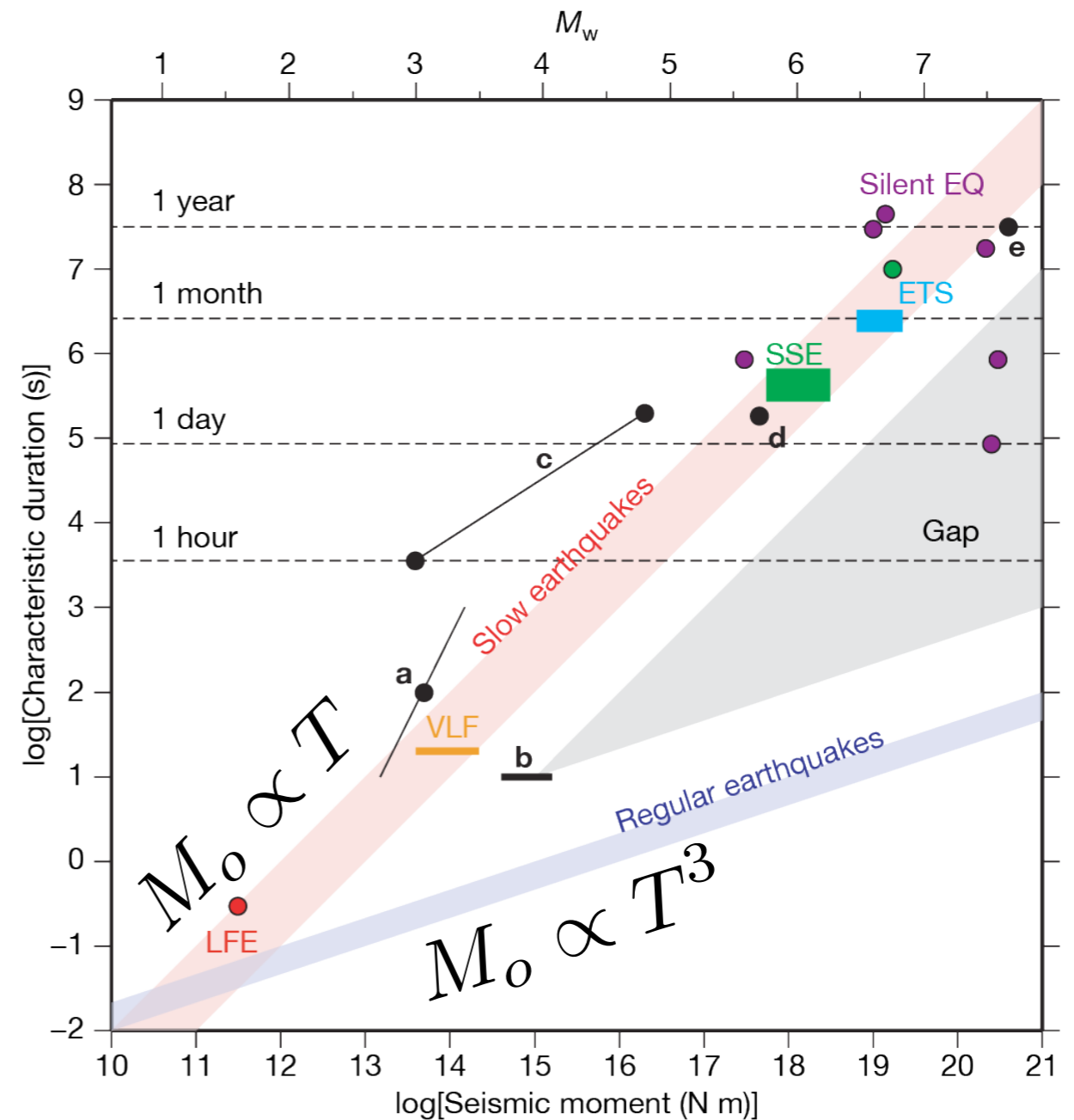
Take away messages (and questions)

- ▶ As observational resolution increases, we **observe smaller and smaller** slow slip events
- ▶ Major slow slip events are **made up of smaller events**
 - ▶ No reason to not expect the same for the small slow slips themselves...
 - ▶ Is a single LFE symptomatic of a **unit slow slip**?
- ▶ Slow slip is an **intermittent rupture process**, made up of a cluster of **earthquake-like slip transients**
 - ▶ Slow slip is **faster and bigger** than we thought
 - ▶ Does a **faster slip rate** have implications for triggering EQs?
- ▶ **Blending seismology and geodesy** together is essential to constrain a phenomenon that spans the bandwidth of multiple geophysical instruments

Moment-duration scaling of slow earthquakes

Scaling of fundamental parameters reflects underlying physics

- ▶ Moment M_0 of a simple fault dislocation scales with T^3
- ▶ Proposed slow earthquake scaling suggests fundamentally different physics

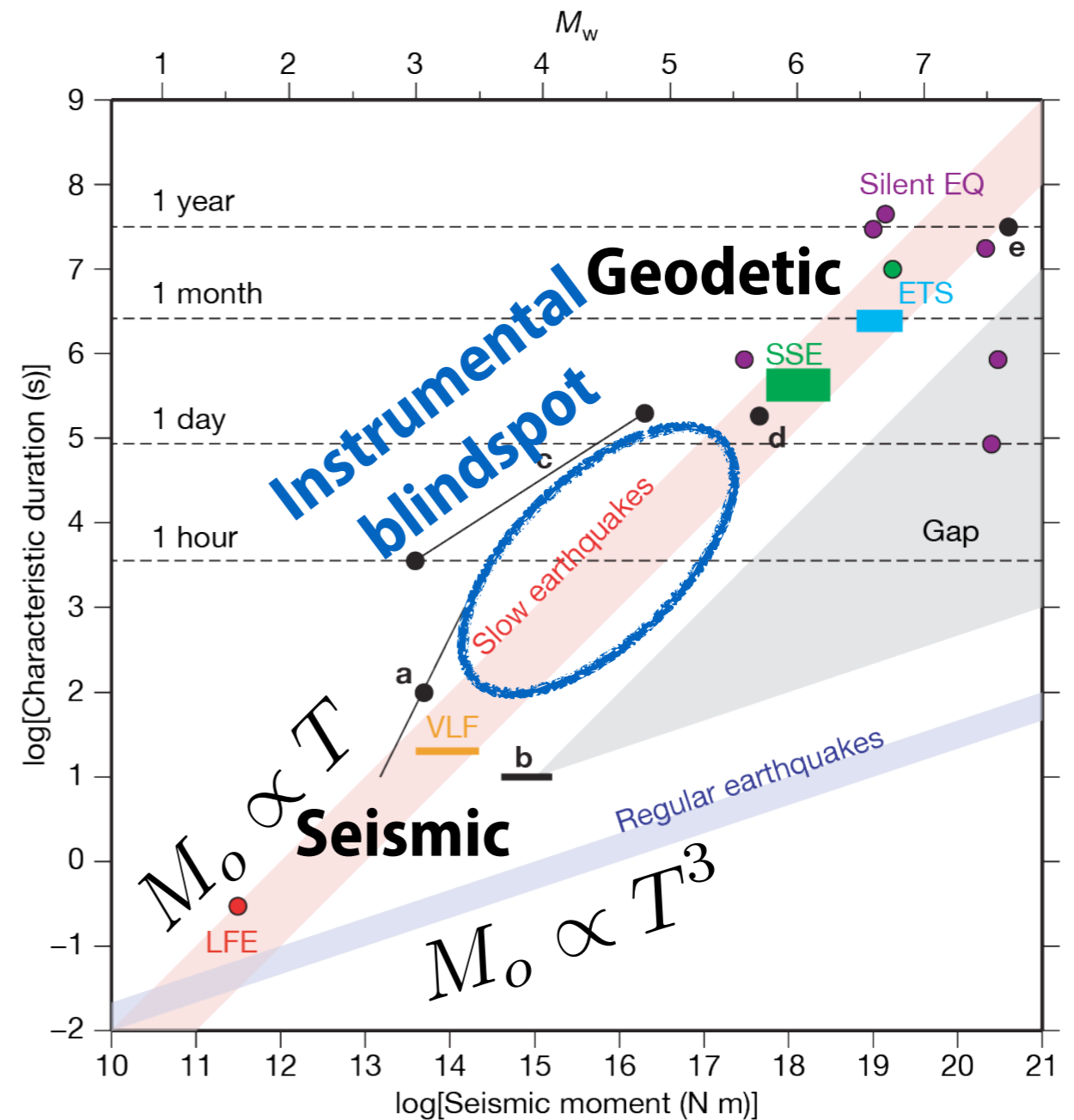


Modified from Ide et al., Nature, 2007

Moment-duration scaling of slow earthquakes

Scaling of fundamental parameters reflects underlying physics

- ▶ Moment M_0 of a simple fault dislocation scales with T^3
- ▶ Proposed slow earthquake scaling suggests fundamentally different physics
 - ▶ Constrained by observations on extreme ends of spectrum

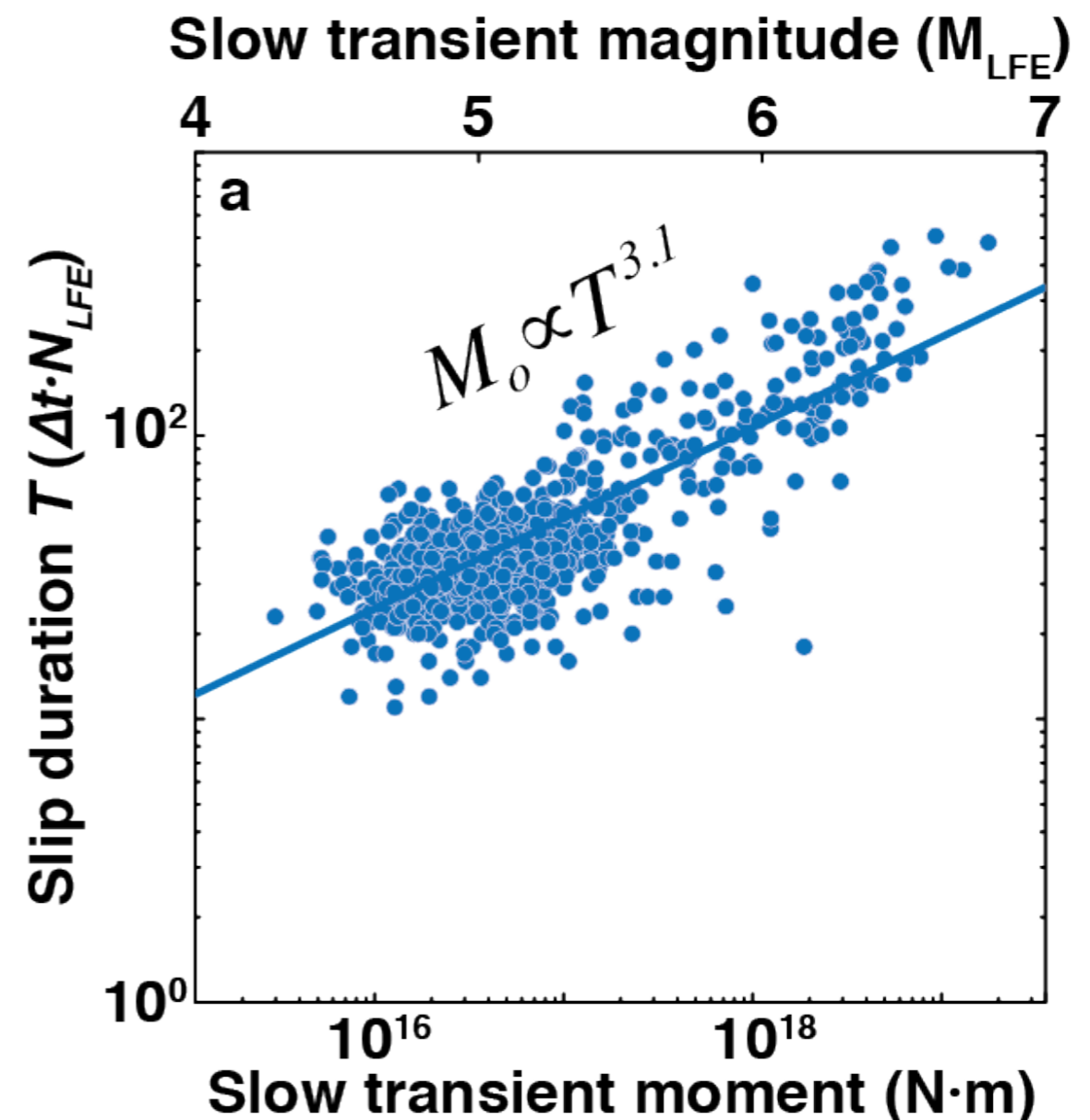
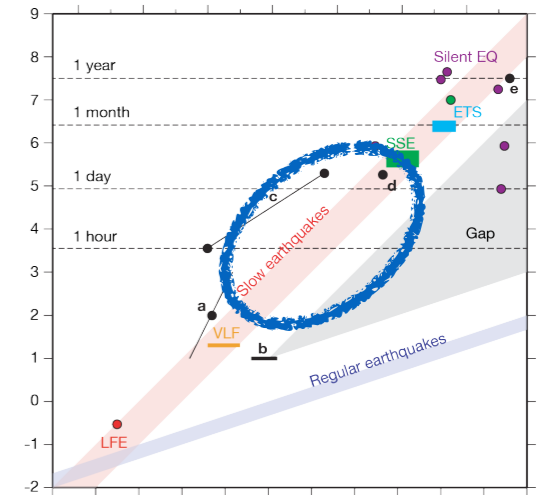


Modified from Ide et al., Nature, 2007

Earthquake-like moment-duration scaling

Slow transient moment scales with the cube of its duration

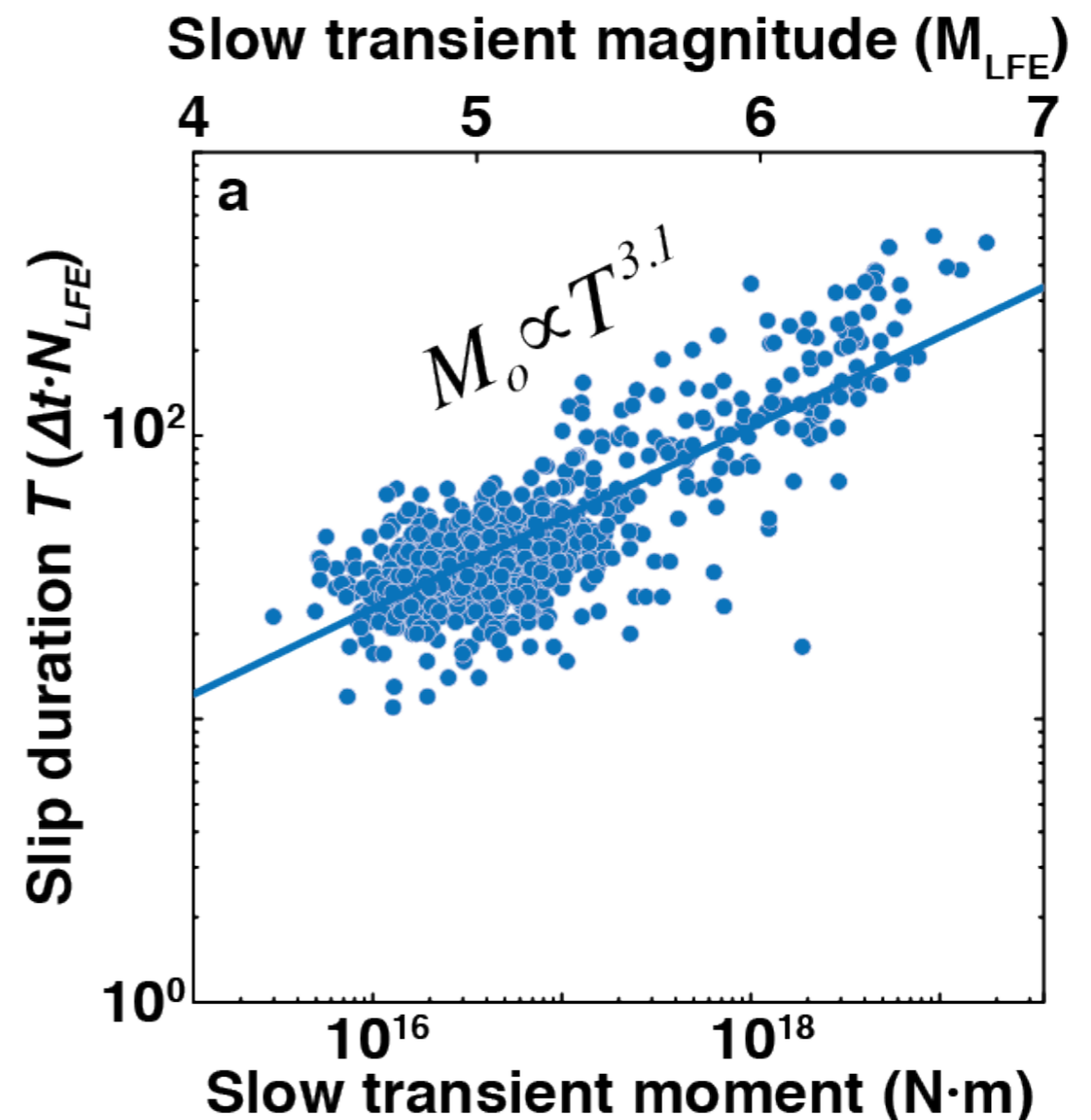
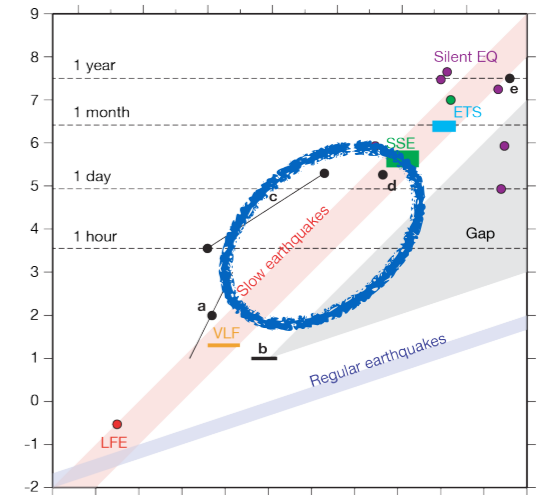
- ▶ Low-resolution GPS captures sum of the intermittent slow slip process
 - ▶ Slip during slow transients
 - ▶ Interrupted by relocking



Earthquake-like moment-duration scaling

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- ▶ Strip away the intermittent loading to focus on slip...



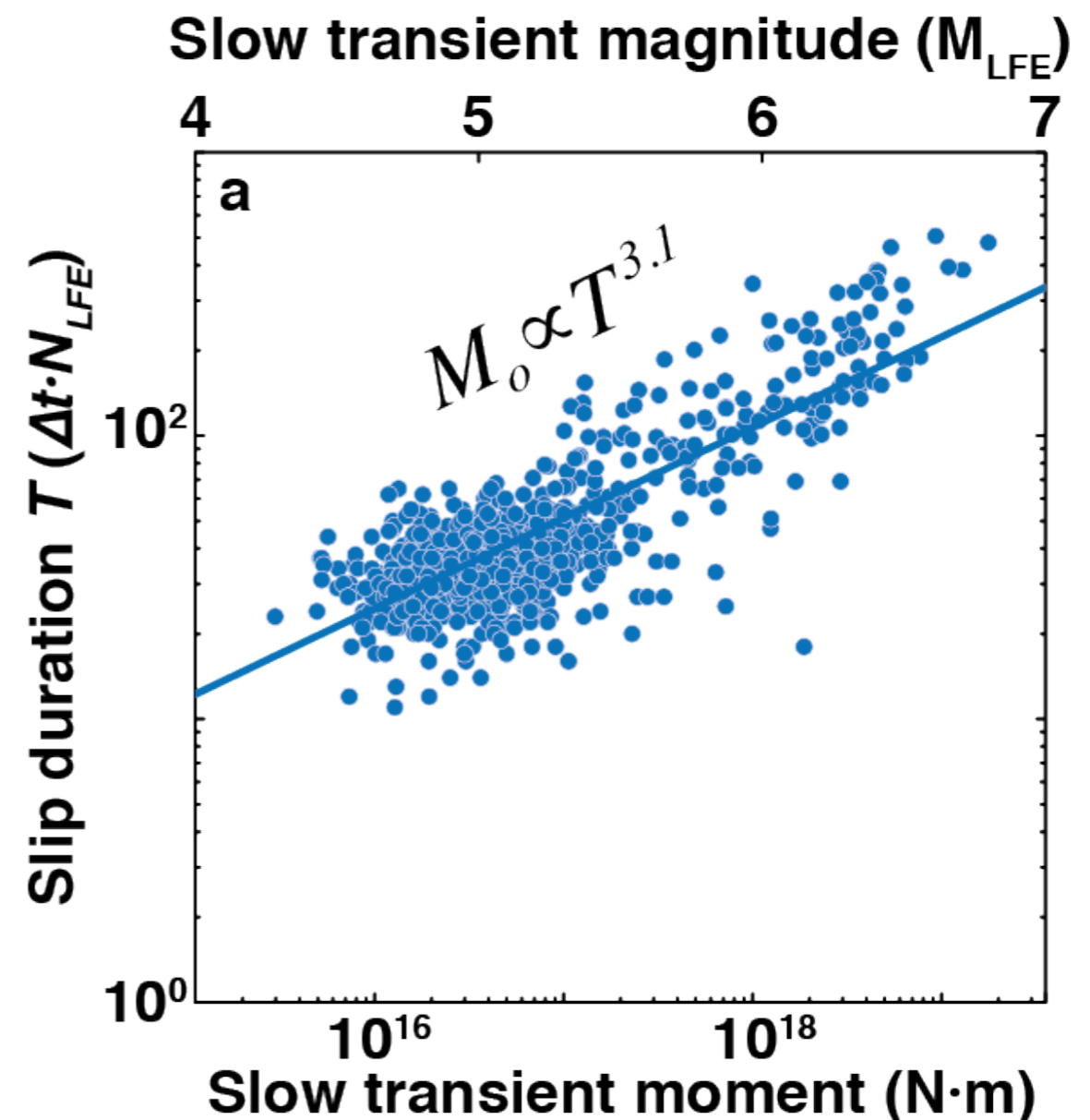
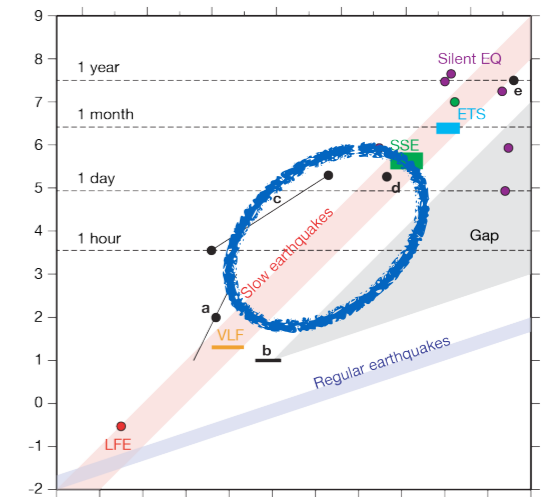
Modified from Frank and Brodsky, Sci. Adv., 2019

Earthquake-like moment-duration scaling

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- ▶ Low-resolution GPS captures sum of the intermittent slow slip process
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Slow slip scales like fast slip



Modified from Frank and Brodsky, Sci. Adv., 2019