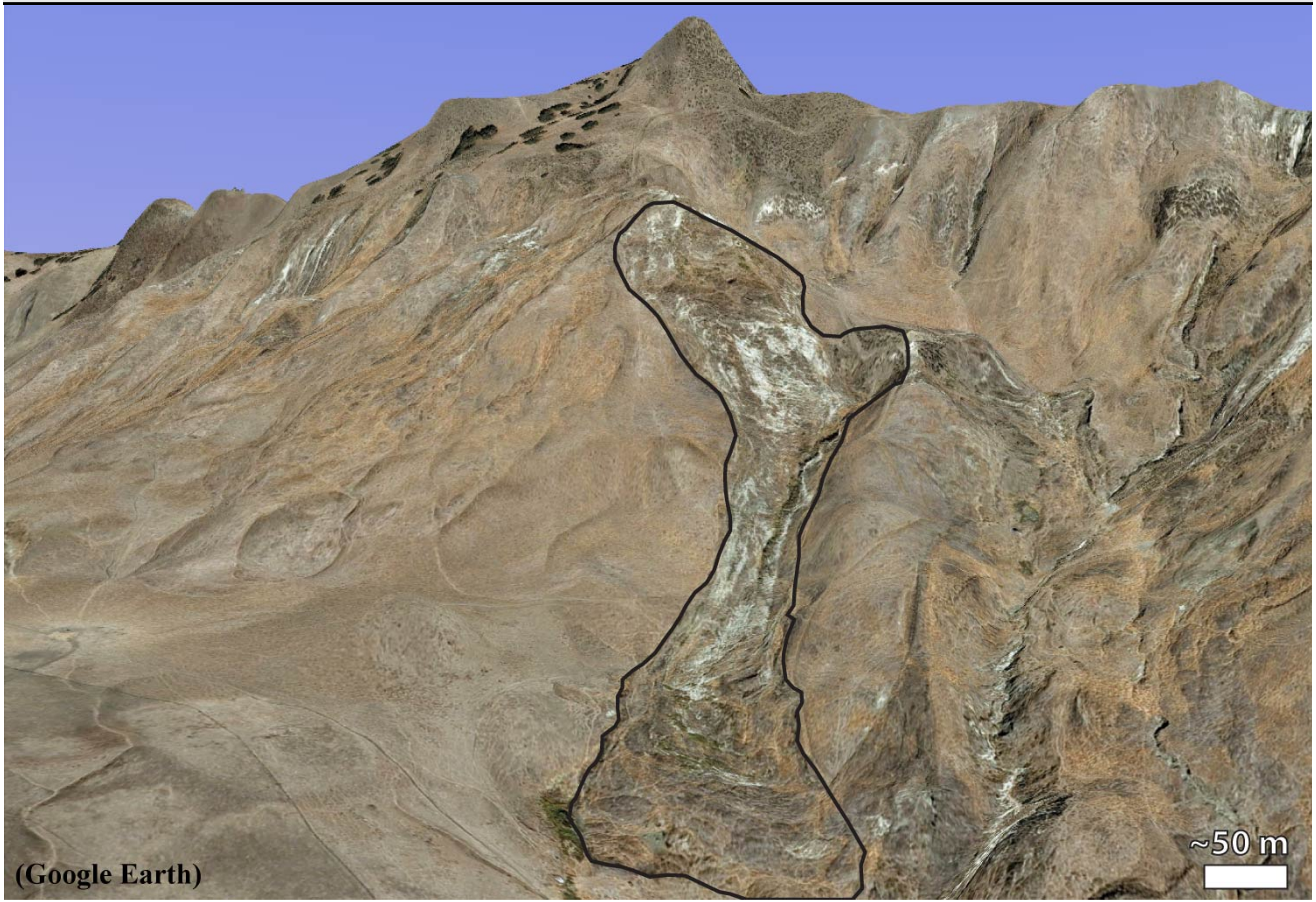
The influence of large-magnitude earthquakes and fault zone damage on the spatial distribution of slow-moving landslides

Joel Scheingross, Brent Minchew, Benjamin Mackey,
Mark Simons, Michael Lamb, Scott Hensley

Slow-moving landslides (“earthflows”)



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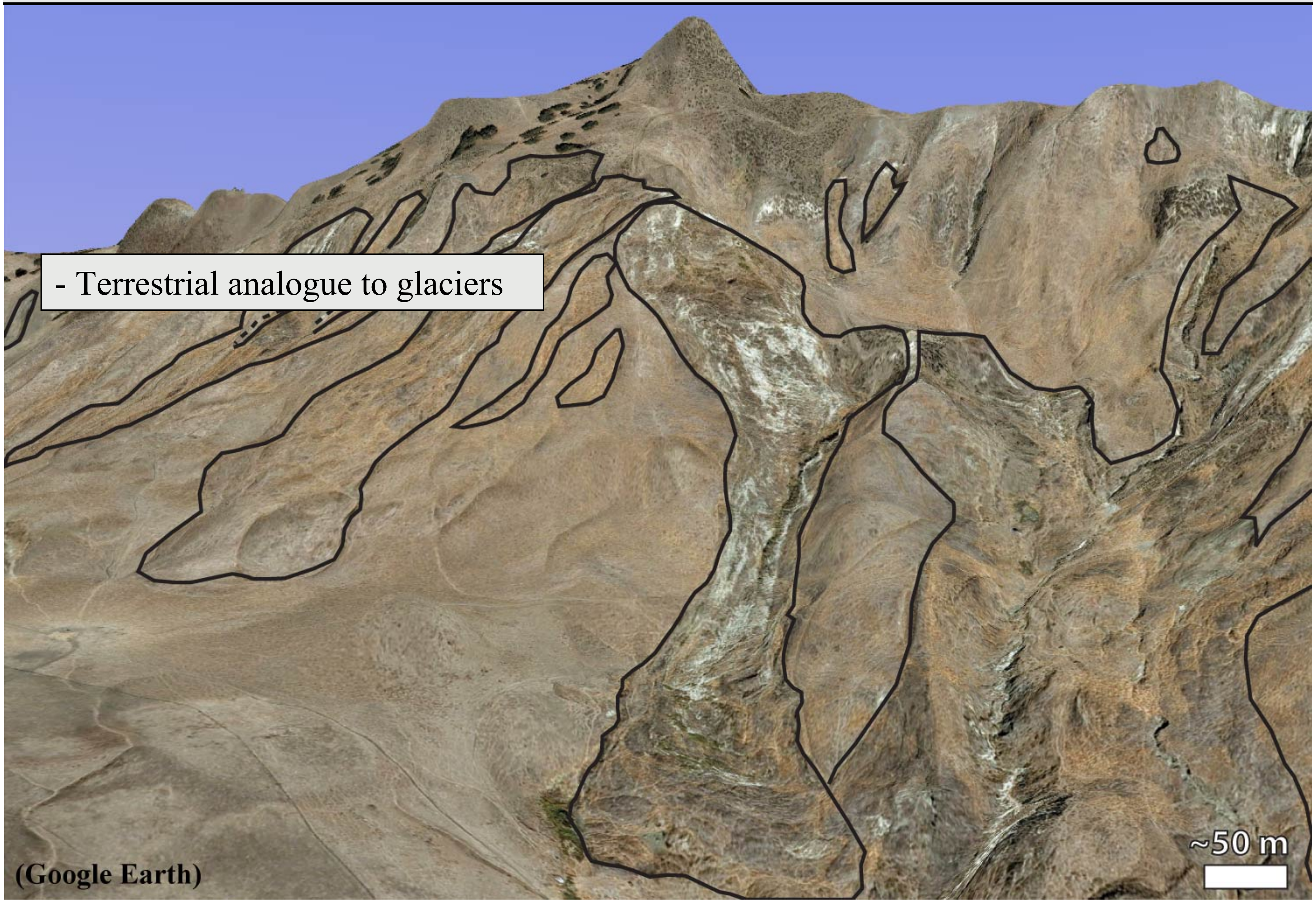

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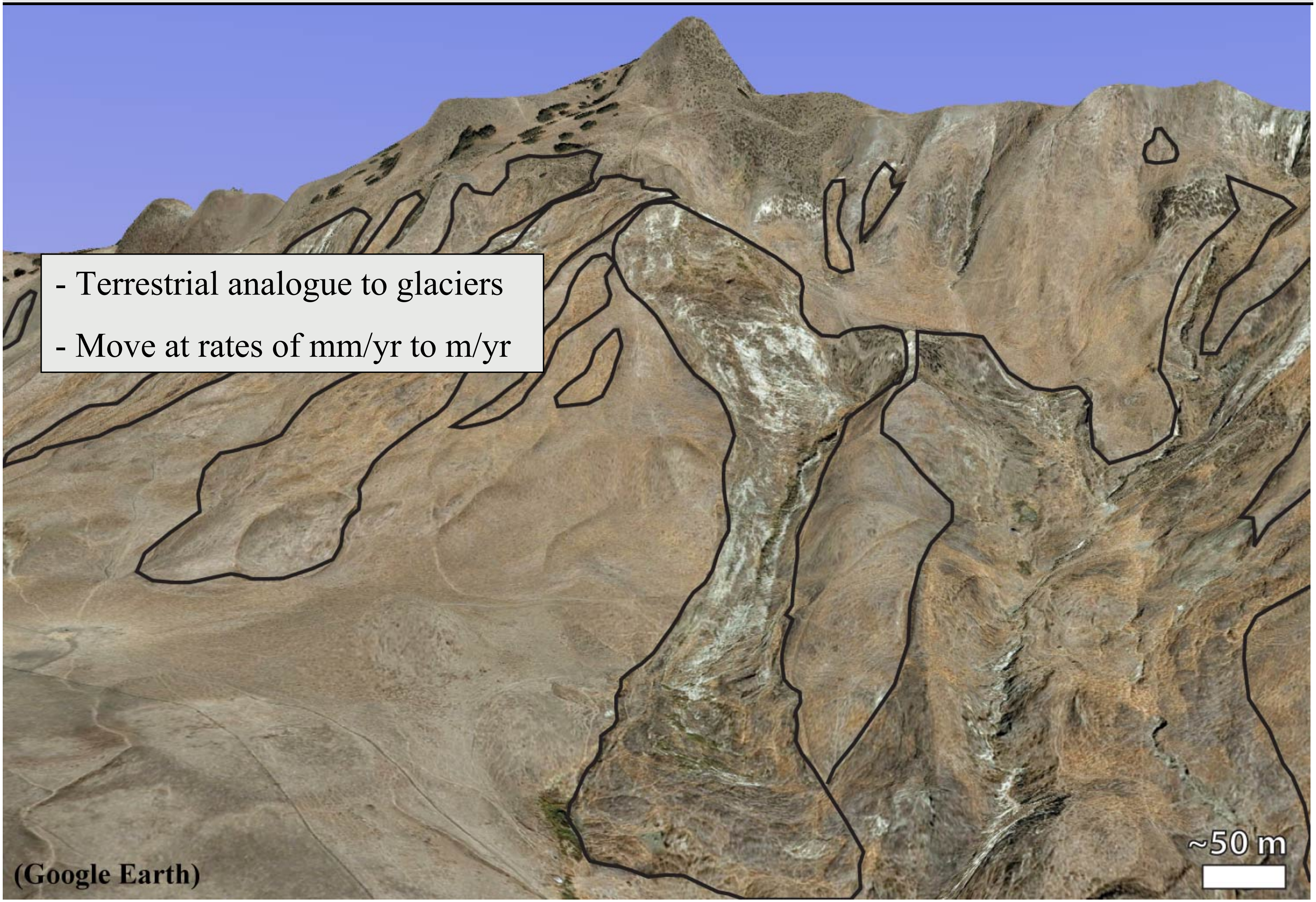

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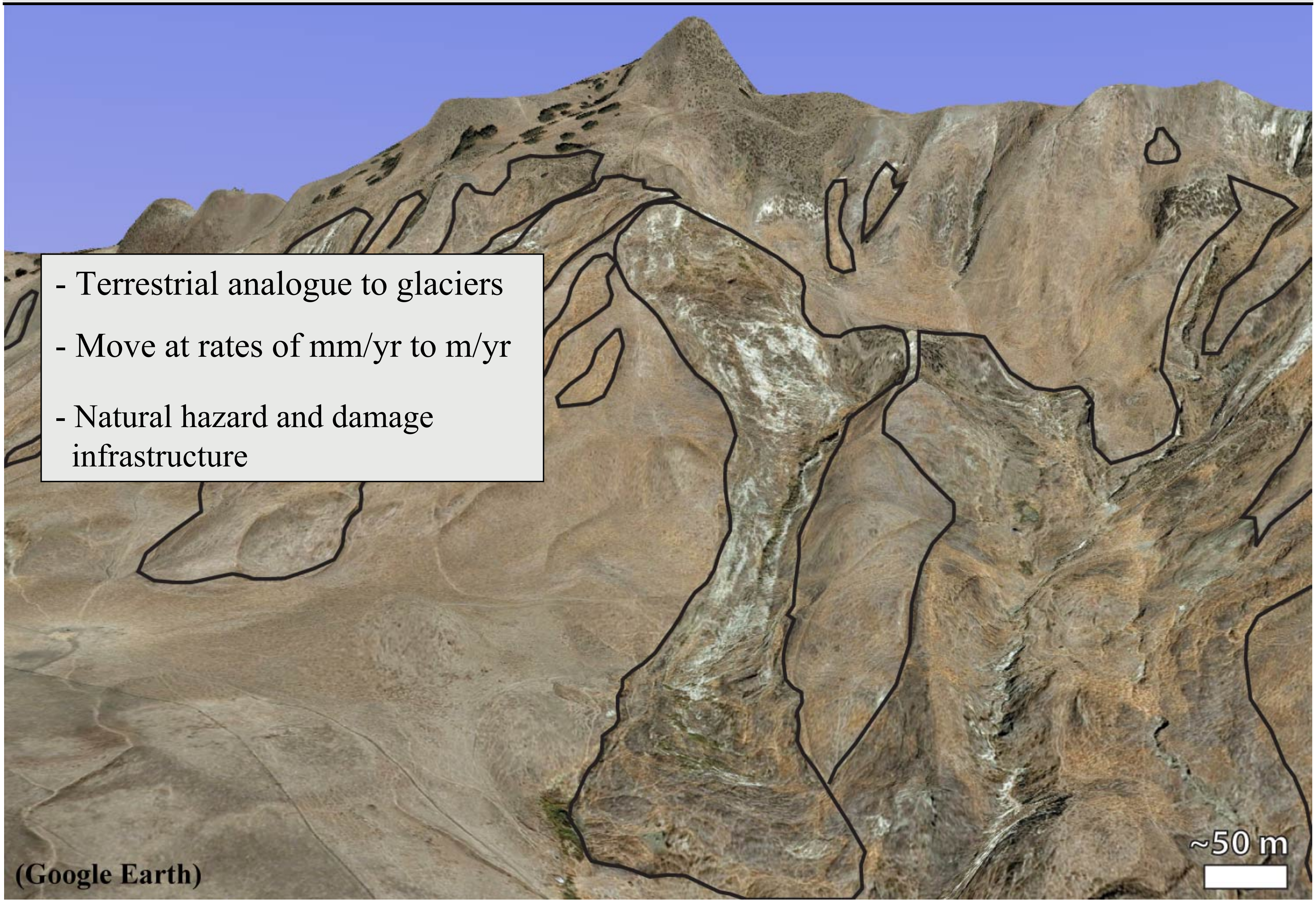
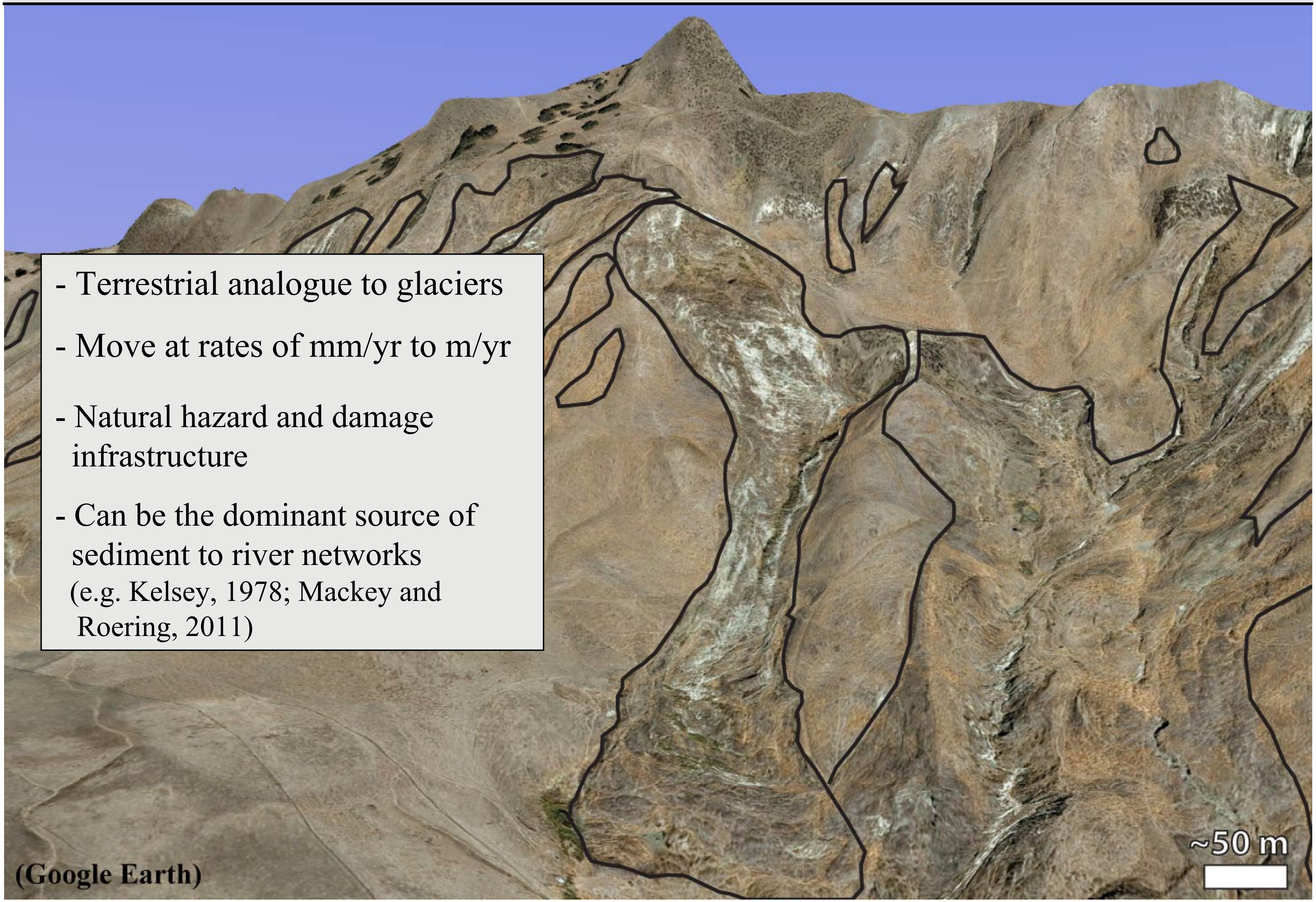


Slow-moving landslides ("earthflows")

- Terrestrial analogue to glaciers
- Move at rates of mm/yr to m/yr
- Natural hazard and damage infrastructure
- Can be the dominant source of sediment to river networks (e.g. Kelsey, 1978; Mackey and Roering, 2011)



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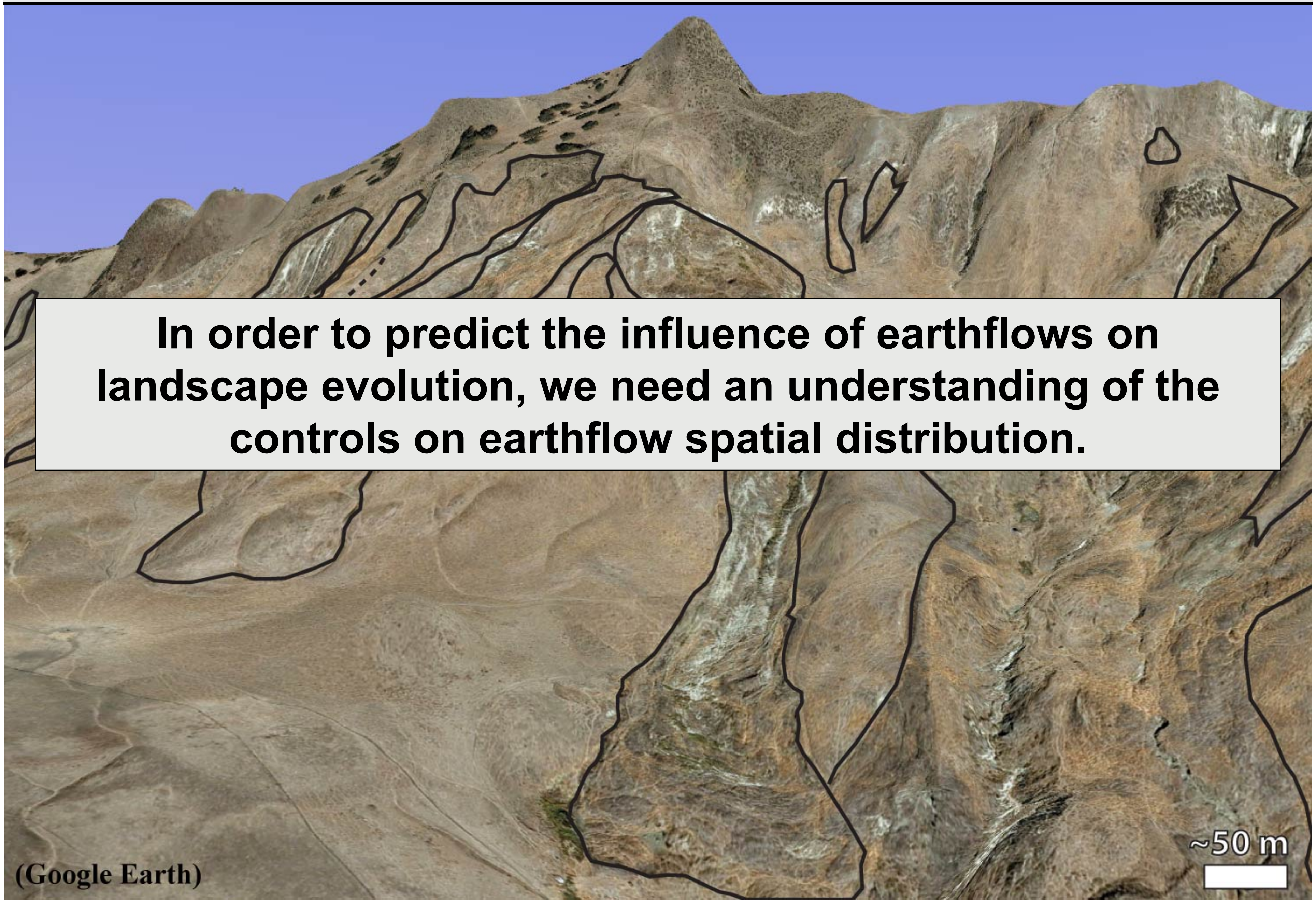
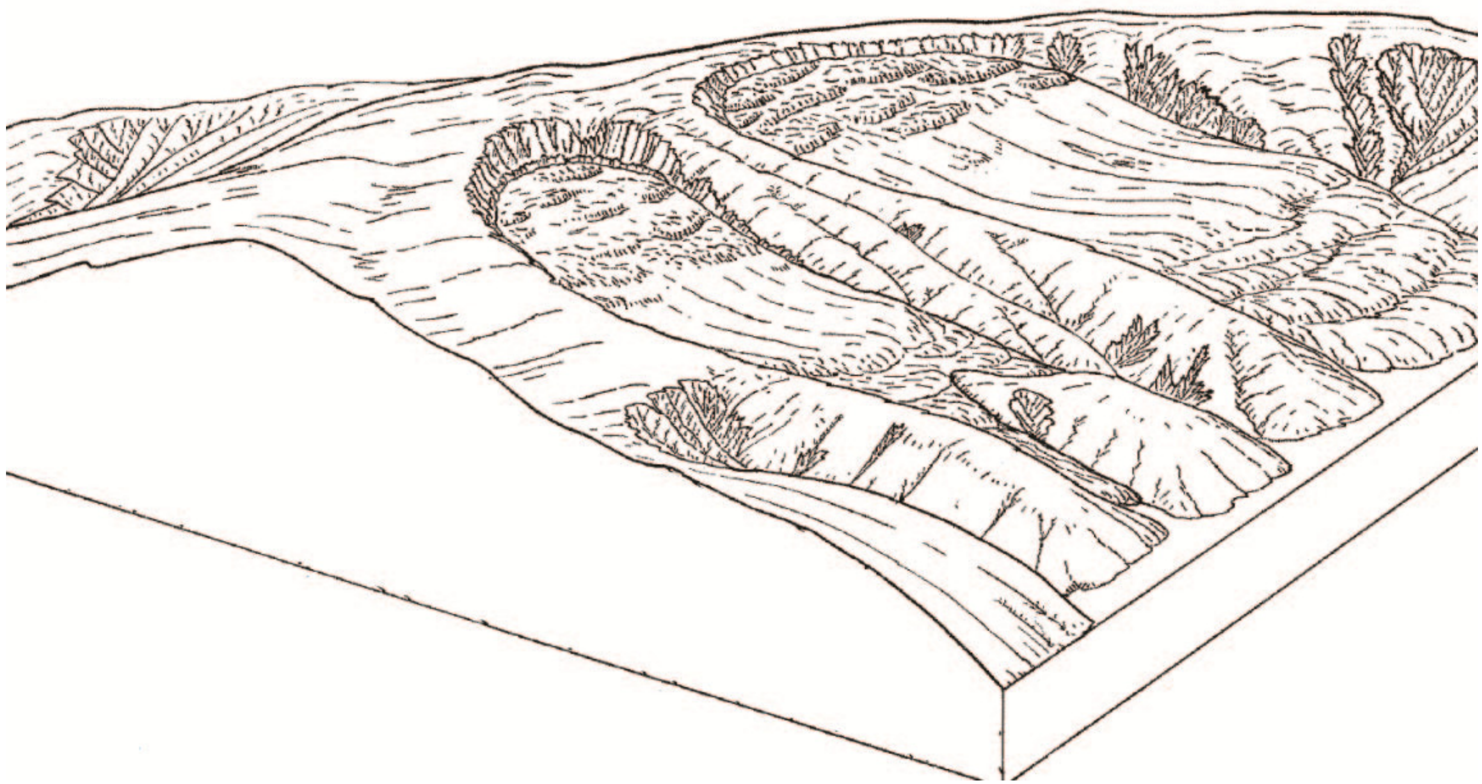


(Google Earth)

In order to predict the influence of earthflows on landscape evolution, we need an understanding of the controls on earthflow spatial distribution.

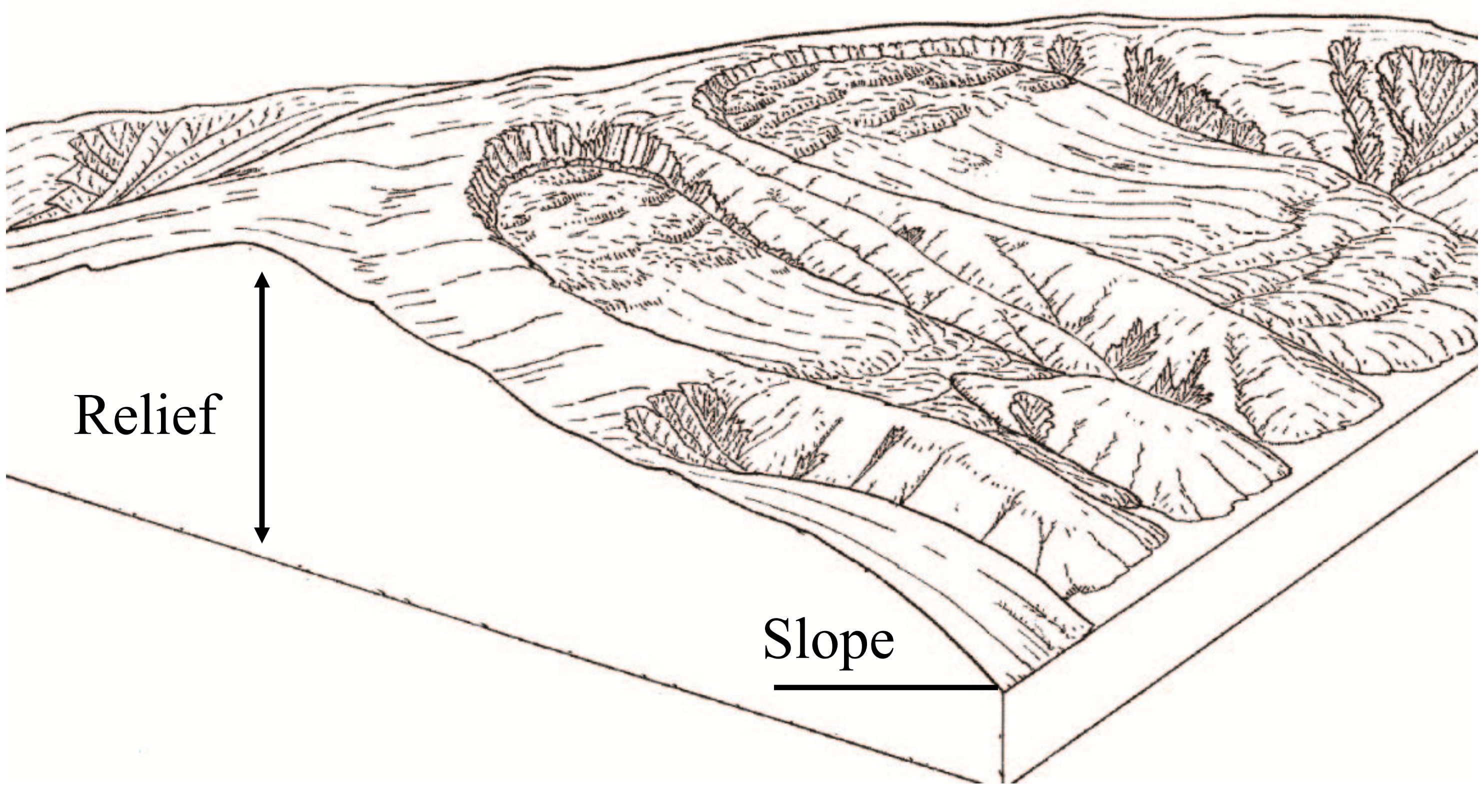
What controls earthflow spatial distribution?



Modified from Putnam and Sharp (1940)

What controls earthflow spatial distribution?

- Topography: hillslope gradient, relief, aspect, uplift (e.g, Keefer and Johnson, 1983; Booth and Roering, 2011; Mackey and Roering, 2011)



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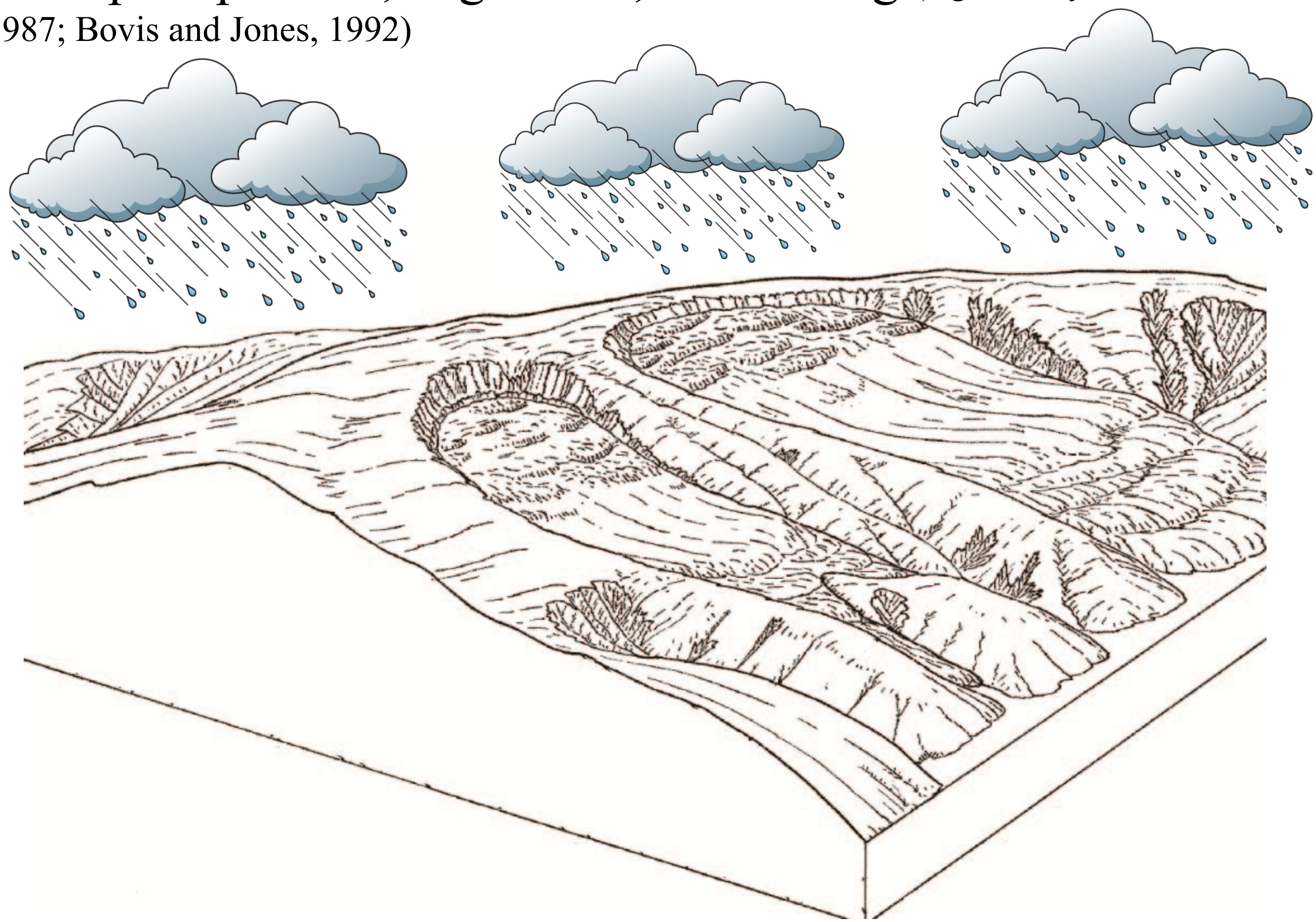
What controls earthflow spatial distribution?

- Climate: precipitation, vegetation, weathering (e.g. Kelsey, 1978; Iverson and Major, 1987; Bovis and Jones, 1992)



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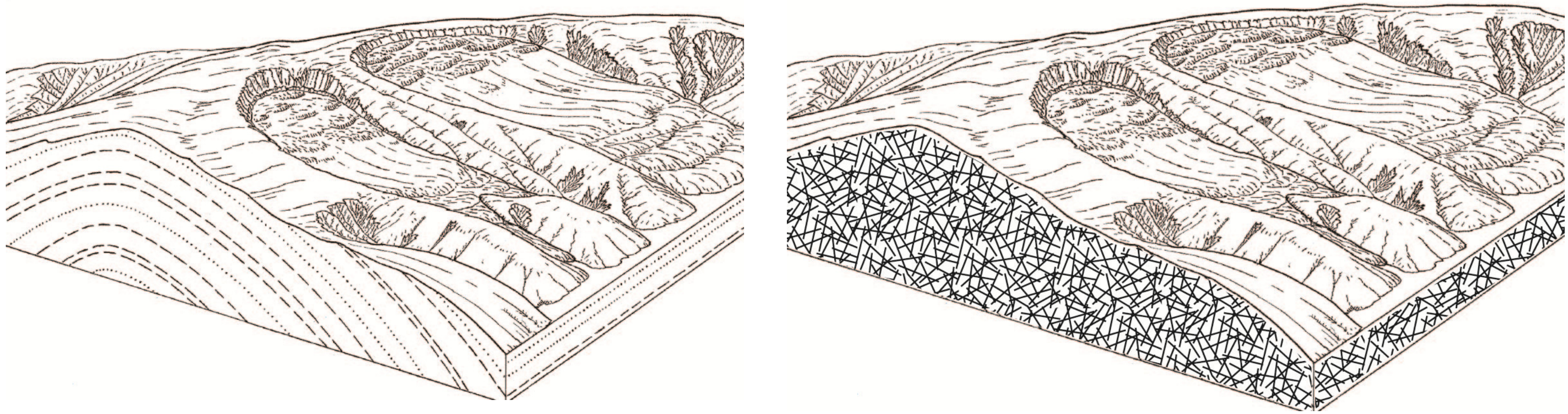
- Lithology: rock strength, structure, clay content, soil thickness (e.g., Putnam and Sharp, 1940; Kelsey, 1978; Keefer and Johnson, 1983)



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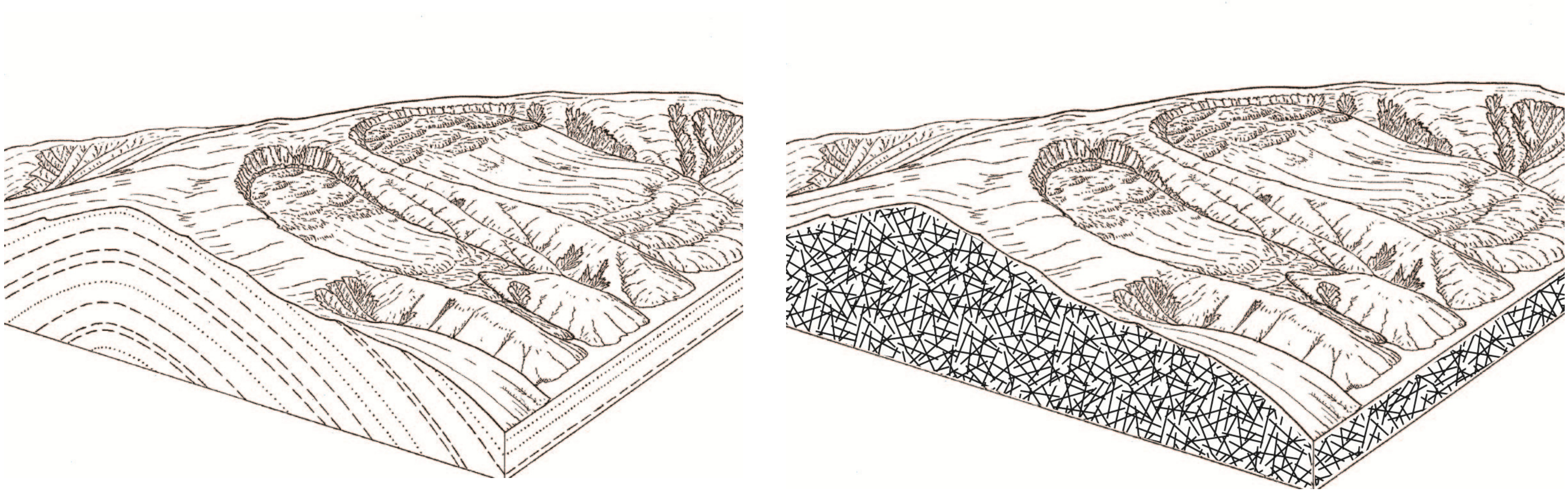

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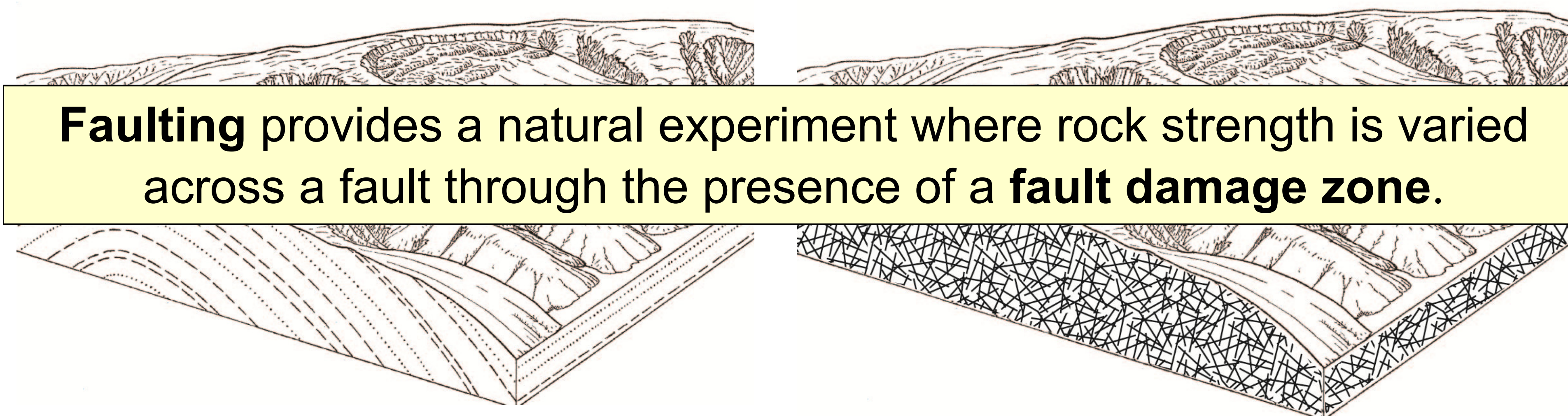

Faulting provides a natural experiment where rock strength is varied across a fault through the presence of a **fault damage zone**.

Modified from Putnam and Sharp (1940)

Fault damage zone (proxy for rock strength)

Fault damage zone: An area of increased bedrock fracturing and reduced rock strength extending meters to kilometers from the fault trace (e.g., Chester and Logan, 1986; Fialko et al., 2002, Ben-Zion and Sammis, 2003; Dor et al., 2006; Savage and Brodsky, 2011).

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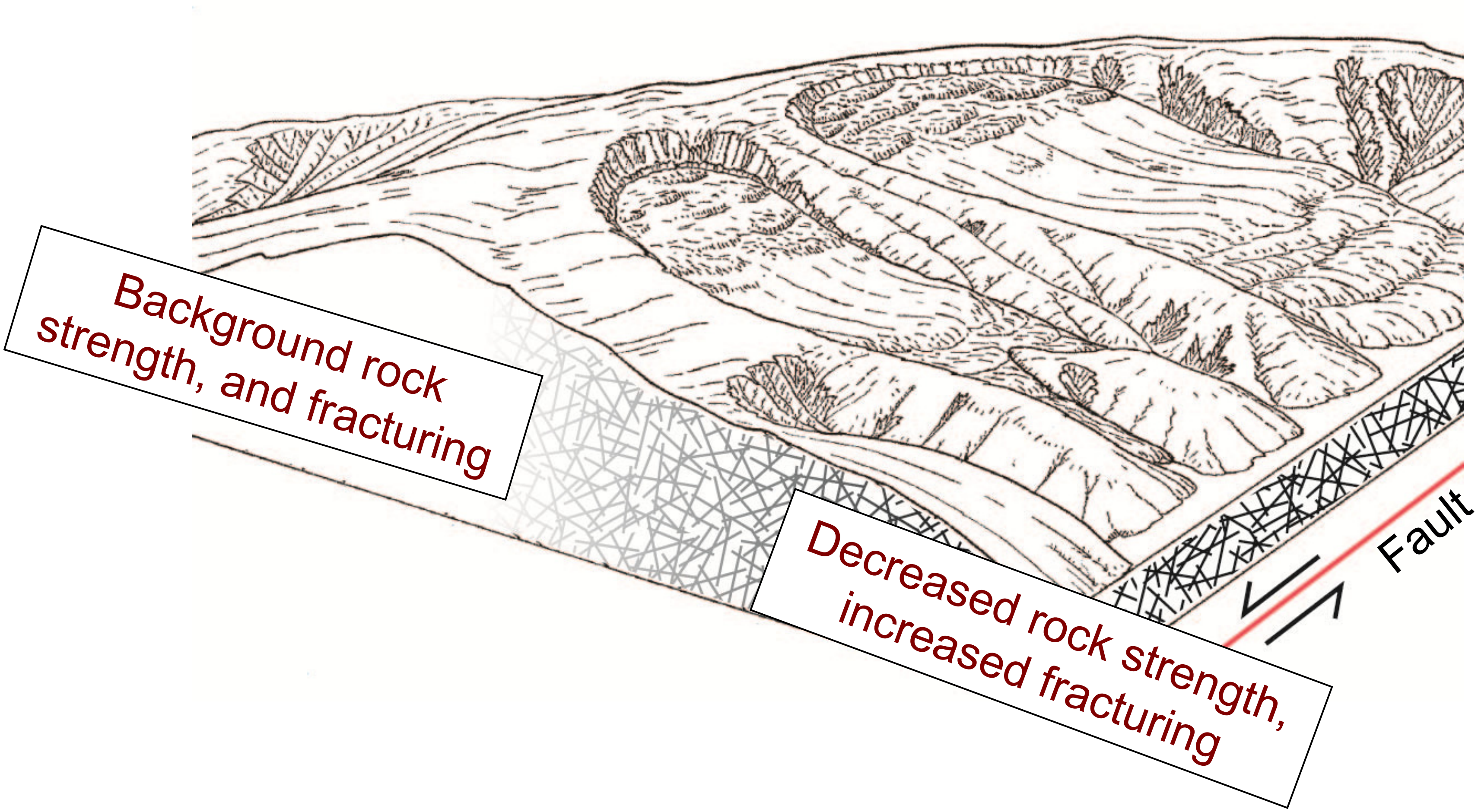

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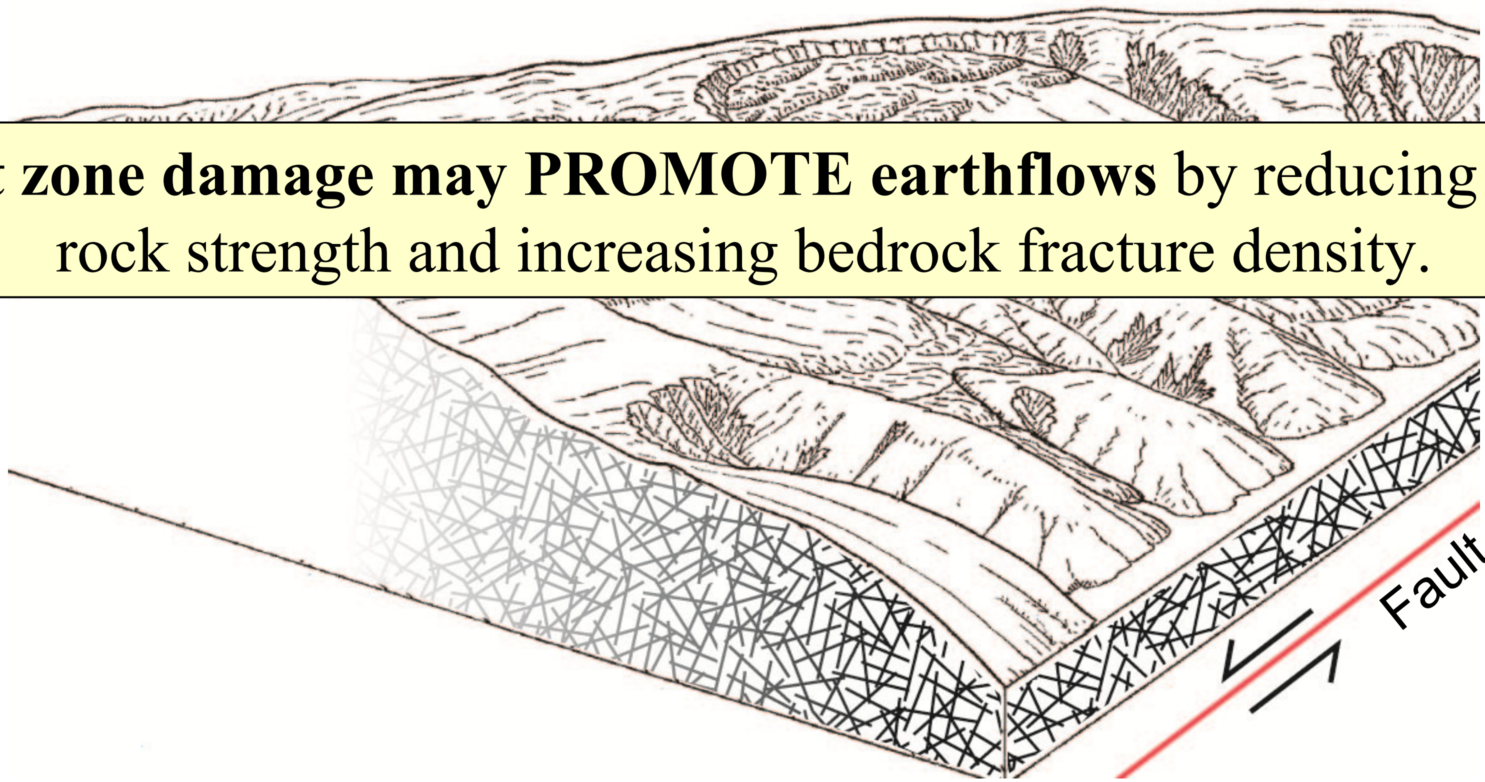

Fault zone damage may PROMOTE earthflows by reducing bulk-rock strength and increasing bedrock fracture density.

Modified from Putnam and Sharp (1940)

Earthquakes induce co-seismic landslides

Sumatra, 2009, M_w = 7.9

AP Photo / Dita Alangkara

Adek Berry / AFP / Getty Image

Earthquakes induce co-seismic landslides

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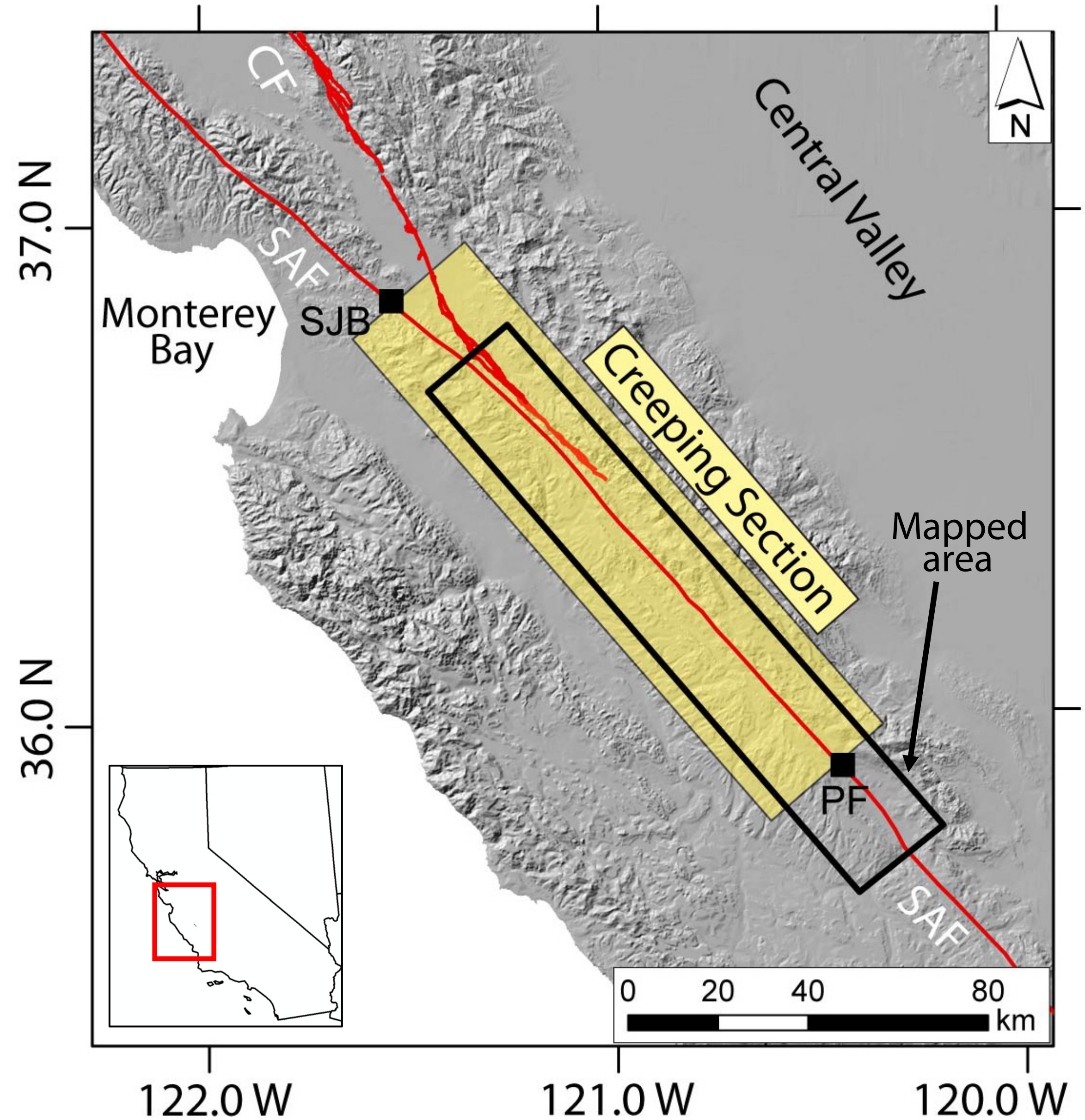
Large-magnitude earthquakes may SUPPRESS earthflows by inducing co-seismic landslides (e.g., Keefer 1984) which preferentially remove fractured and weathered rock from the fault damage zone (i.e., the system may become **supply limited**).

Outline

- **Study Site**: San Andreas Fault (SAF), California
- **Earthflow identification**: UAVSAR and aerial photos
- **Earthflow spatial distribution:** Central SAF
- **Central questions:**
    - Does reduced rock strength within fault damage zones promote earthflows?
    - Do large-magnitude earthquakes suppress earthflow development?

Central San Andreas Fault

Creeping section:
- Creep ~ 3 cm/yr
- Absence of large-magnitude earthquakes



Central San Andreas Fault

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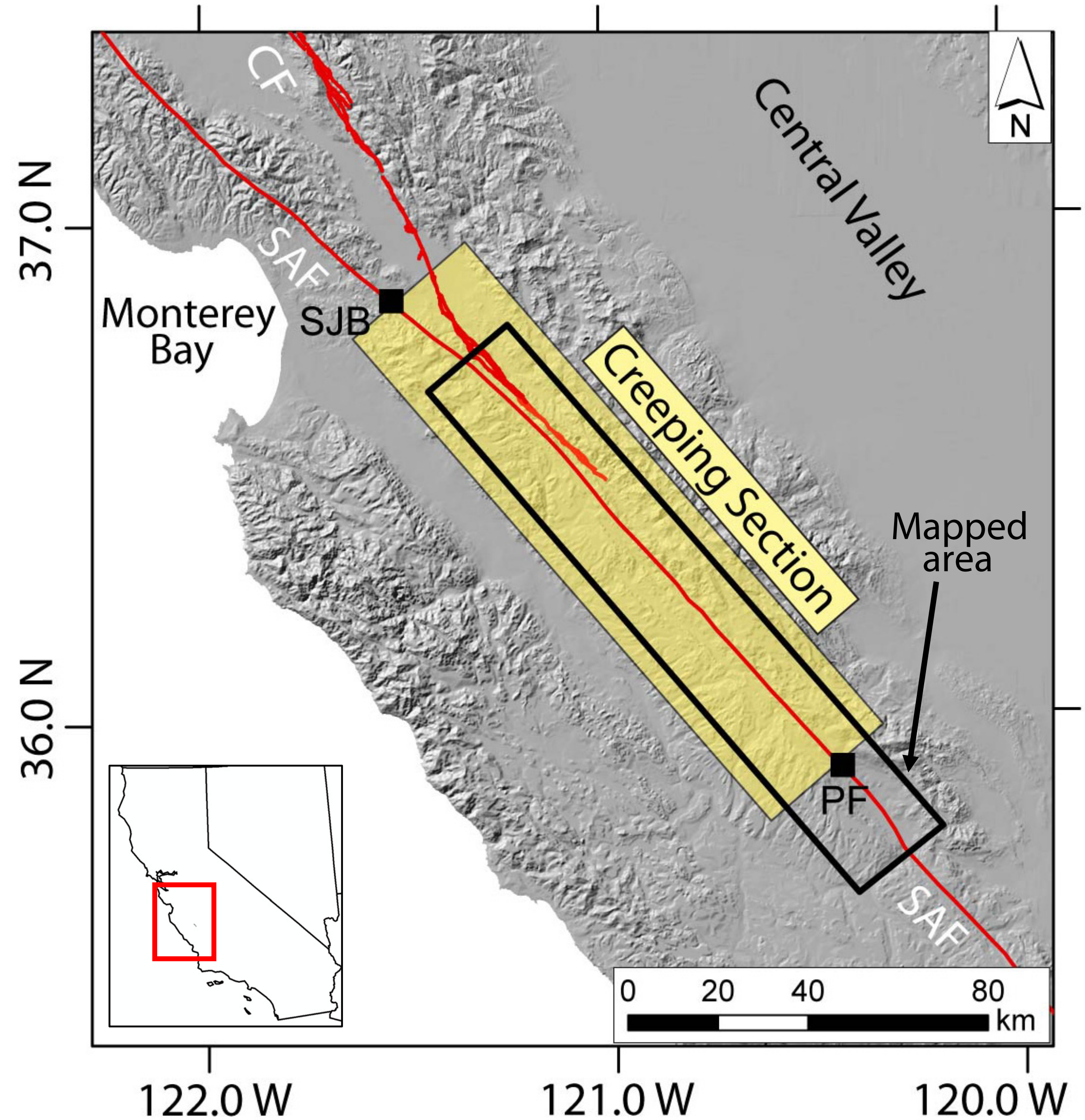
Locked section:

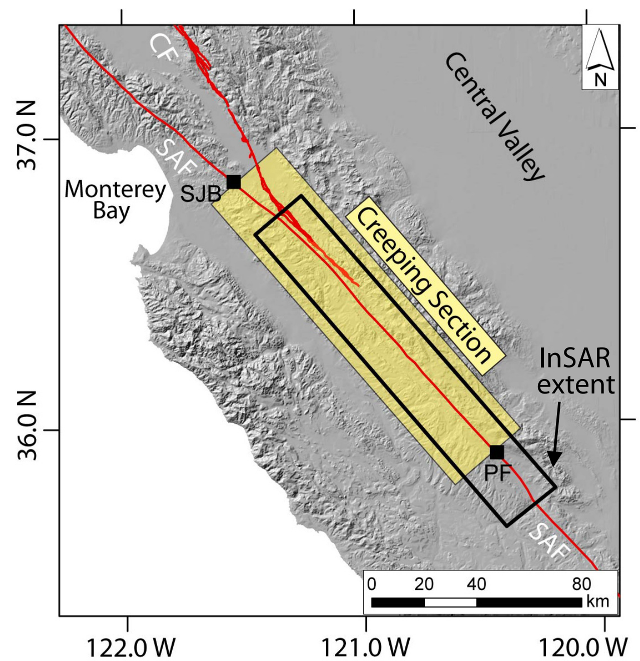
- Presence of large-magnitude earthquakes



Earthflow identification

1. Motion revealed by UAVSAR

- 4 fault parallel interferograms
- 30 fault perpendicular interferograms
- Custom SNAPHU unwrapping



Scheingross et al, 2013, *GSA Bulletin*

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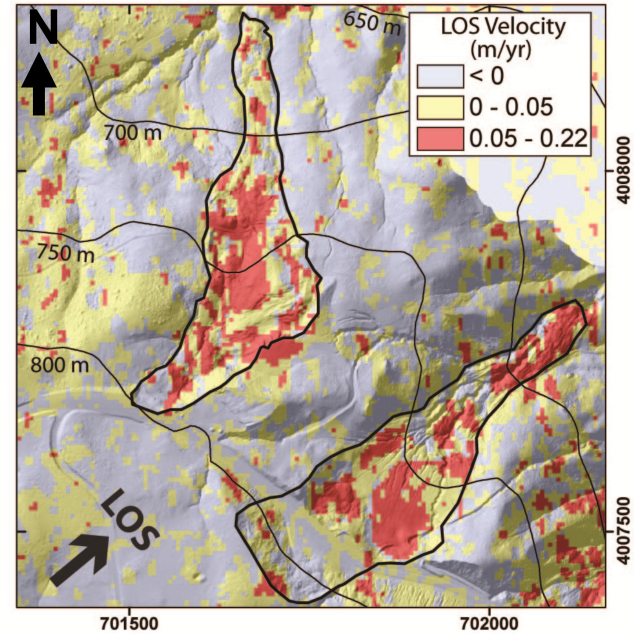

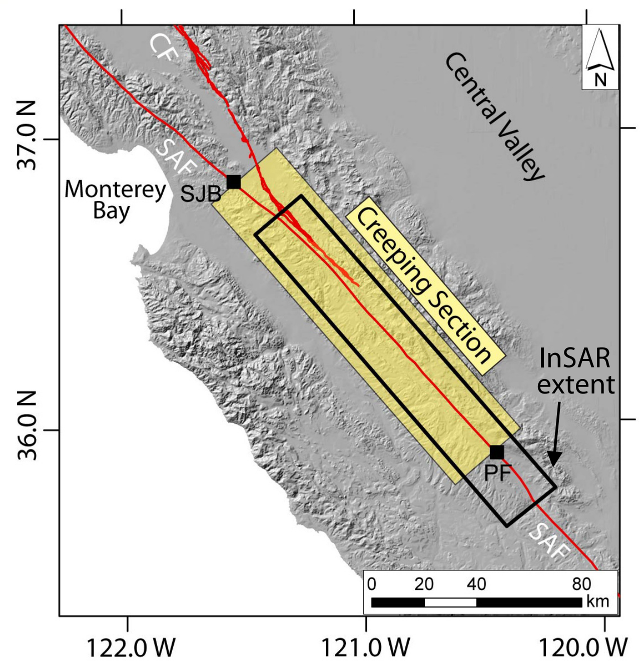

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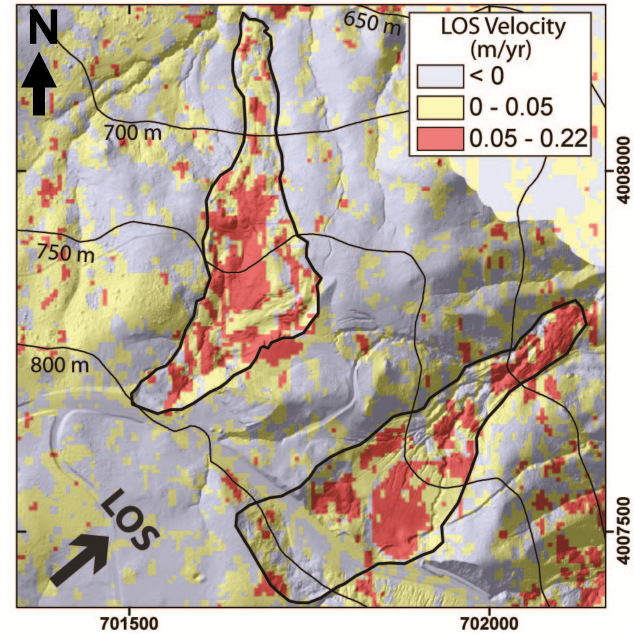
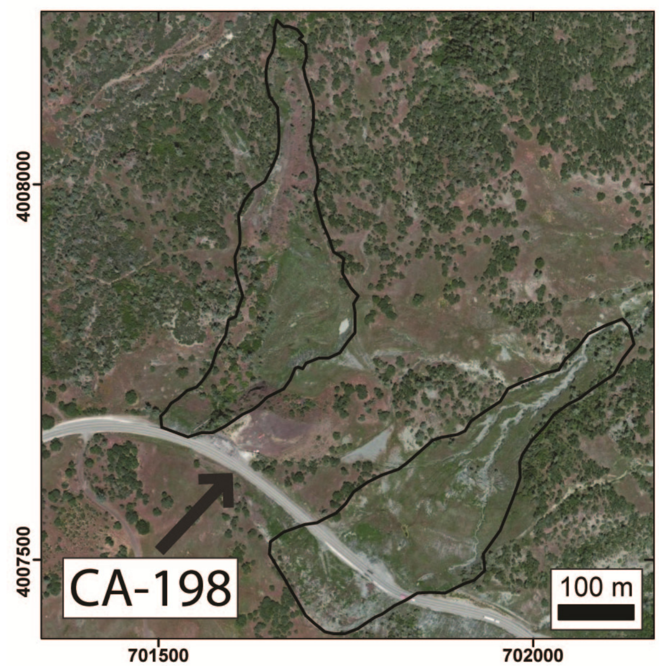


2. Morphometric features in aerial photographs

- Lateral margins, pressure ridges, and hummocky terrain (McKean and Roering, 2004)
- ~1 m^2 resolution aerial photographs (BING Maps)
- Accurately ortho-rectified within ESRI ArcMap



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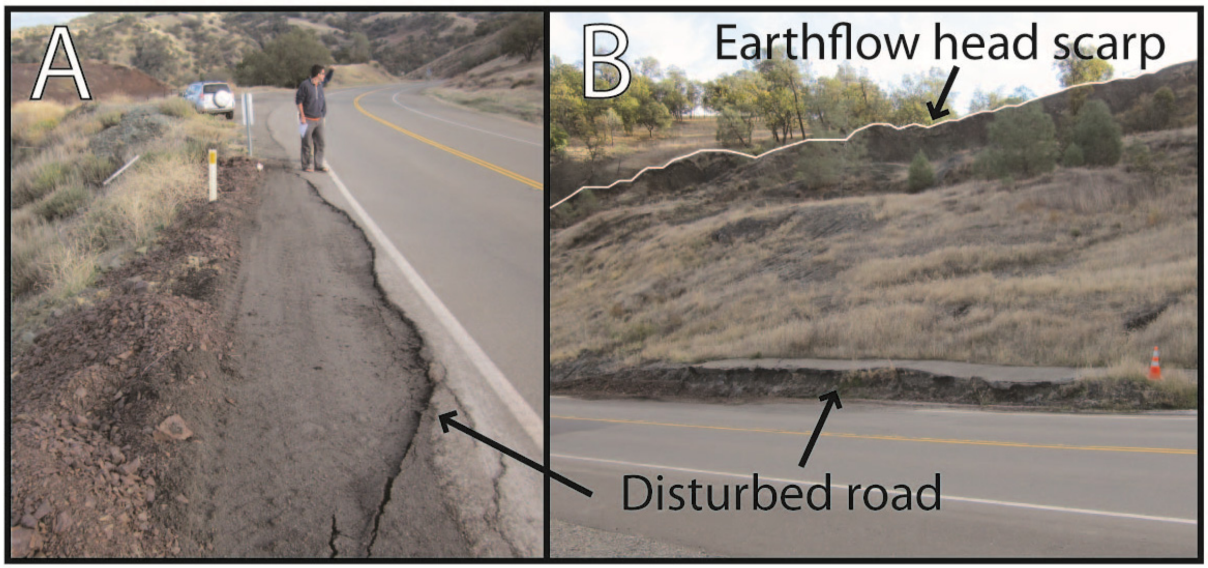
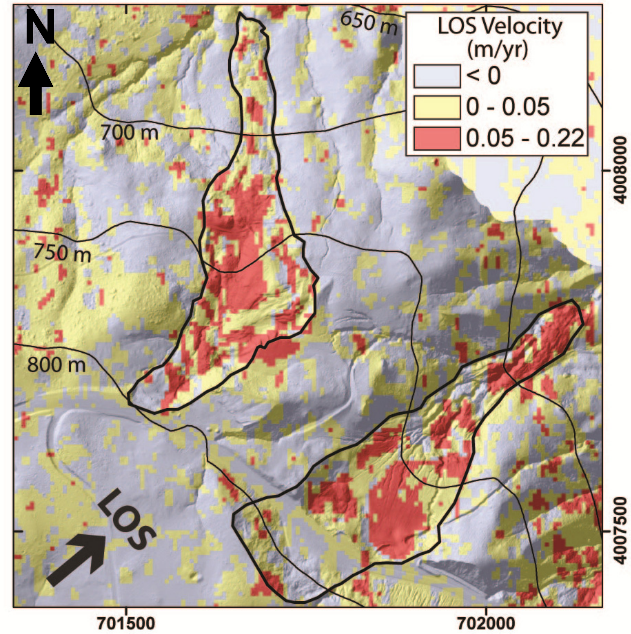
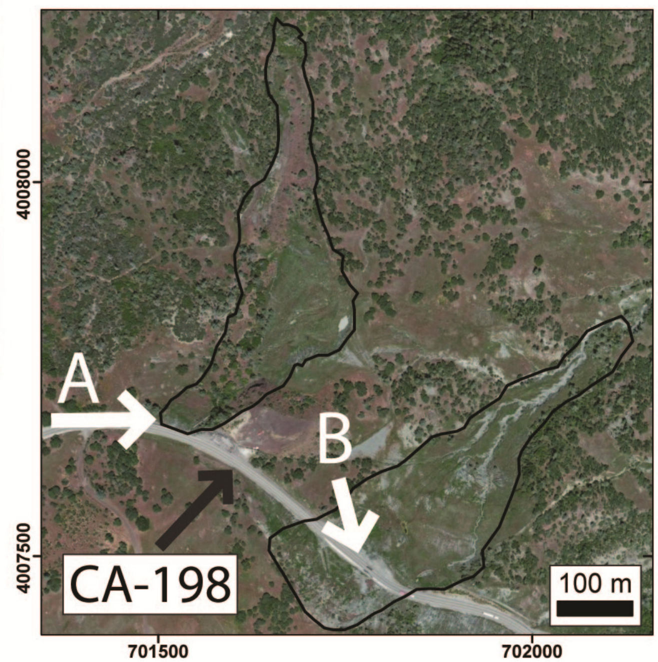
Earthflow identification

3. Field Visits

- Observations of deformed roads and active highway maintenance







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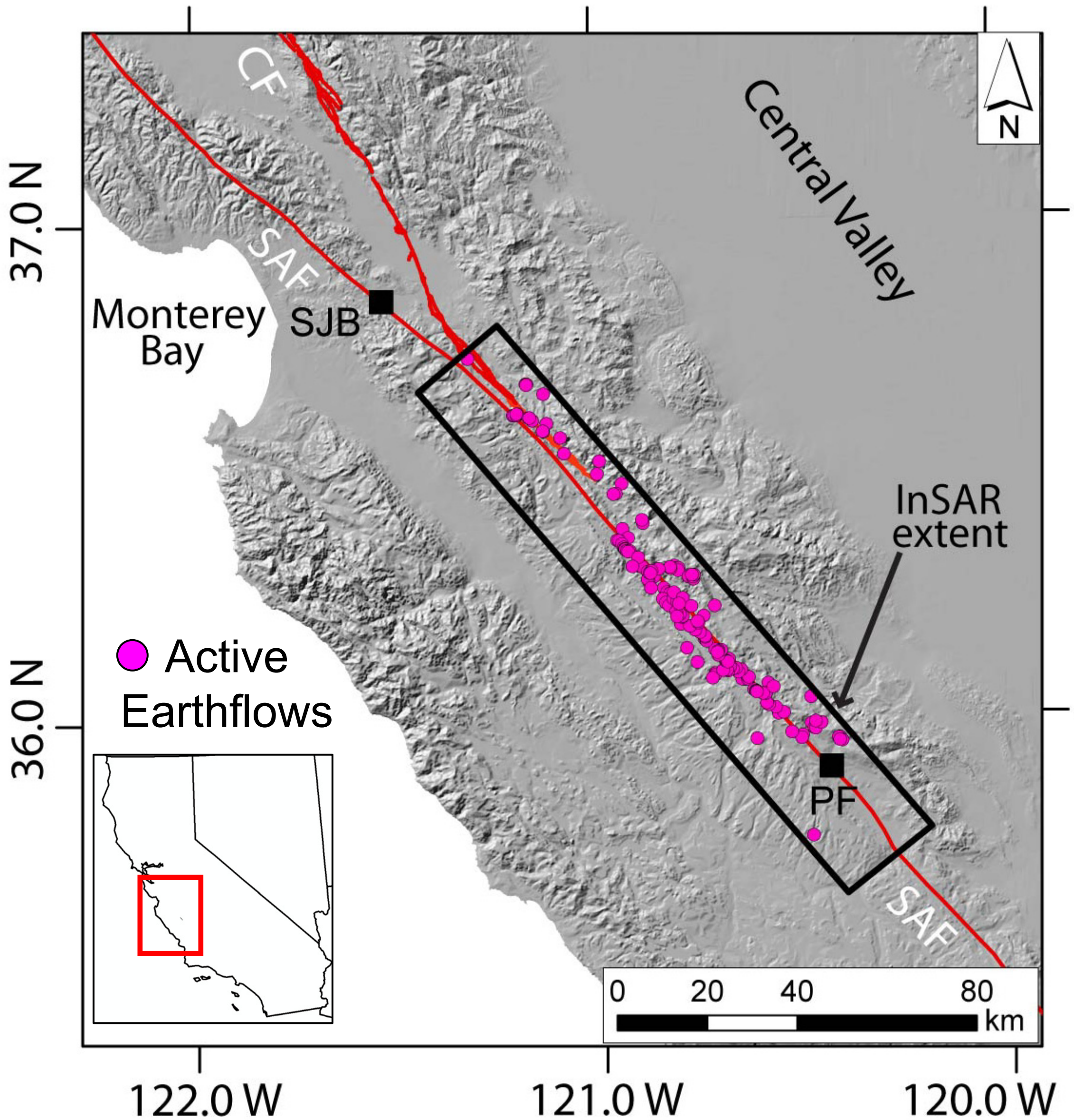
Earthflow spatial distribution

150 active earthflows identified May 2010 to July 2011



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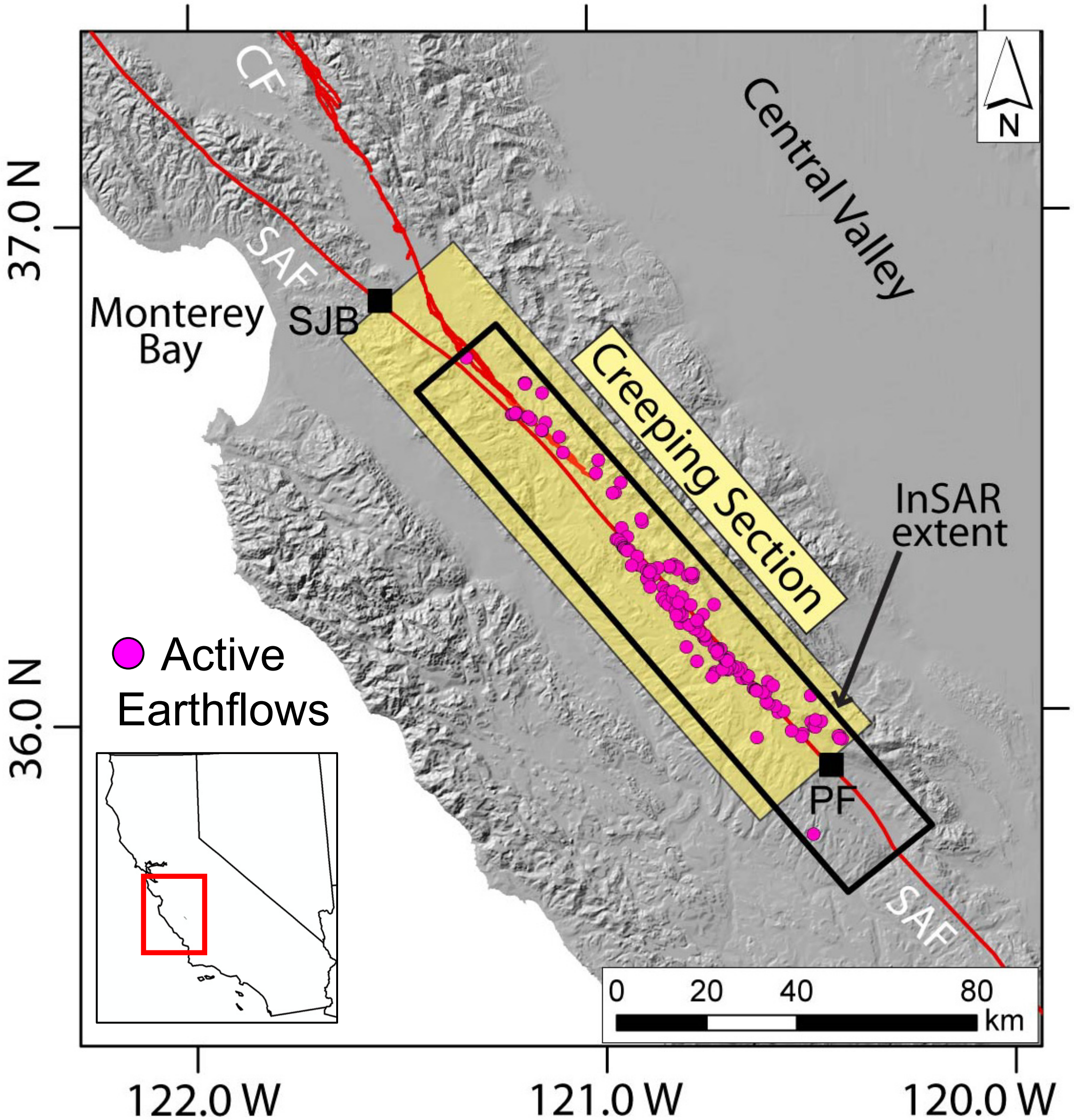

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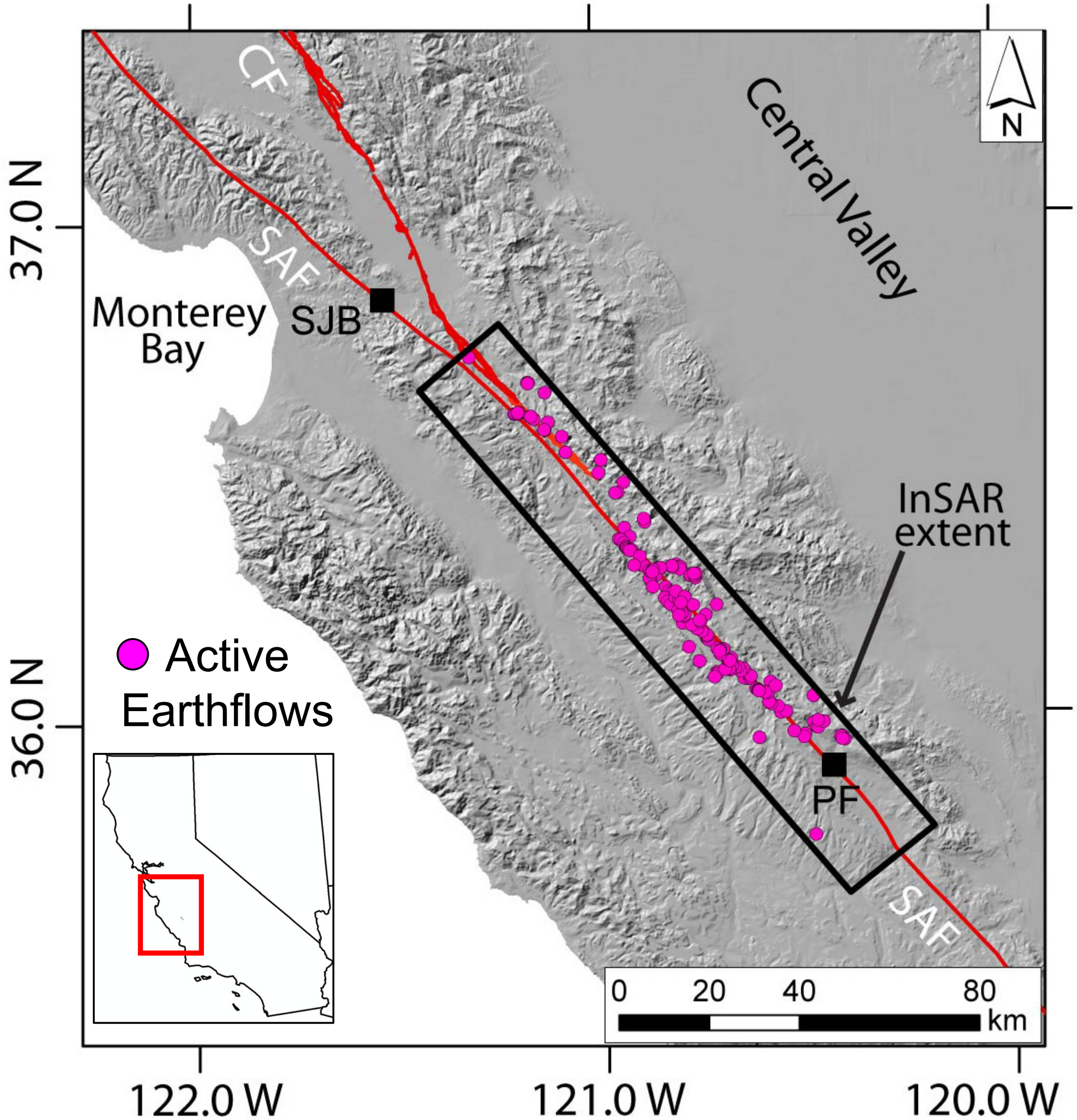

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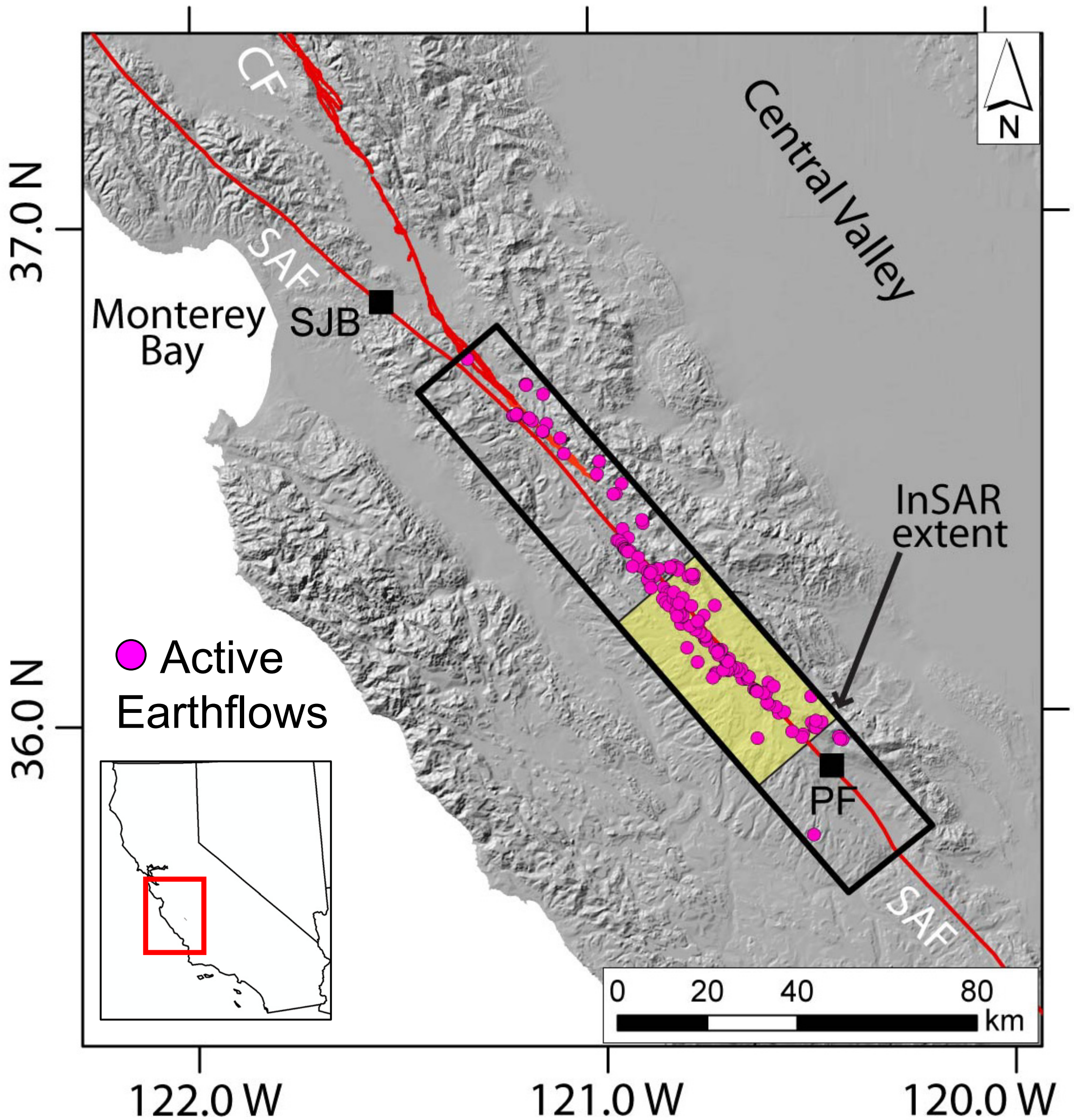

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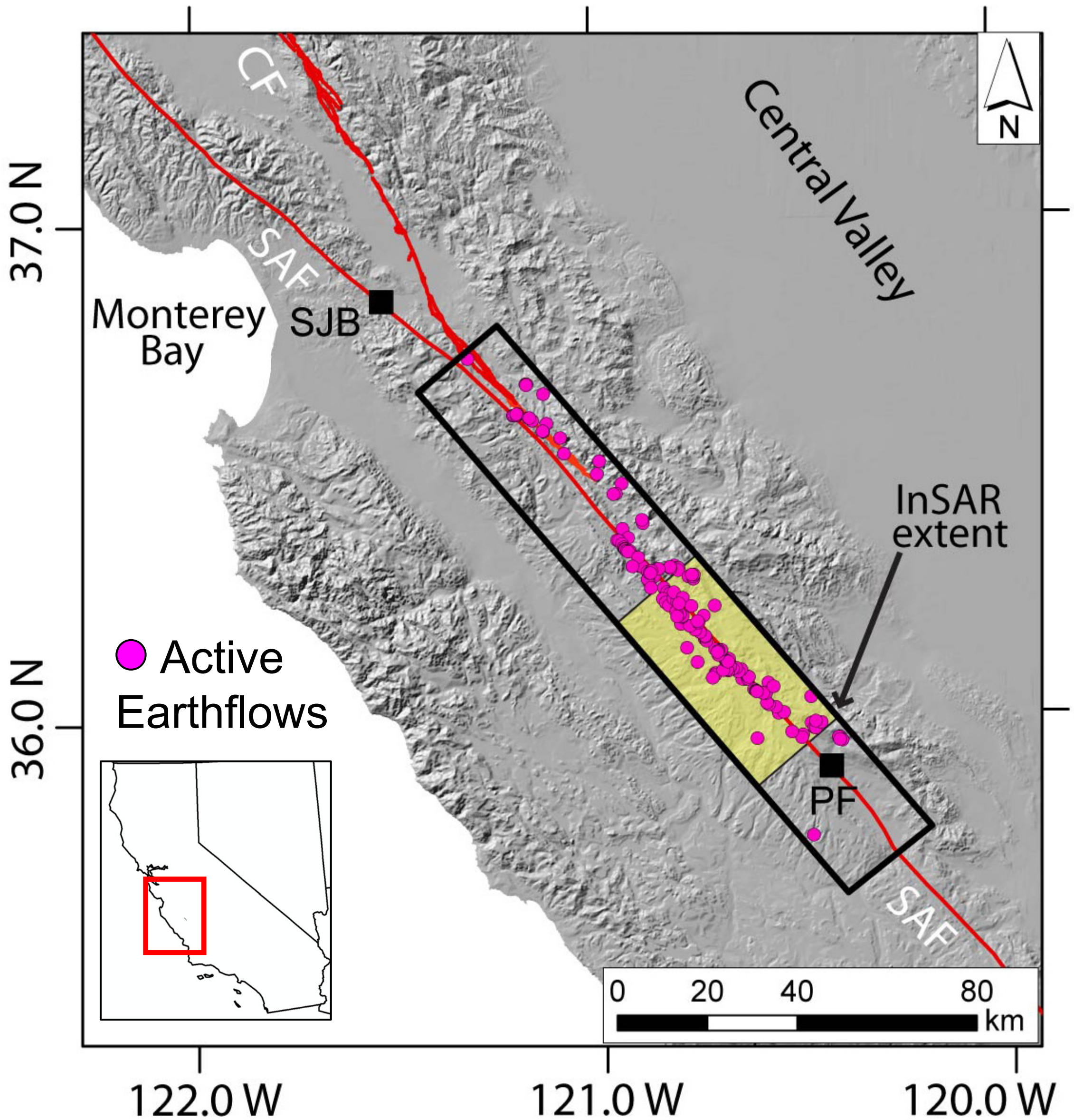

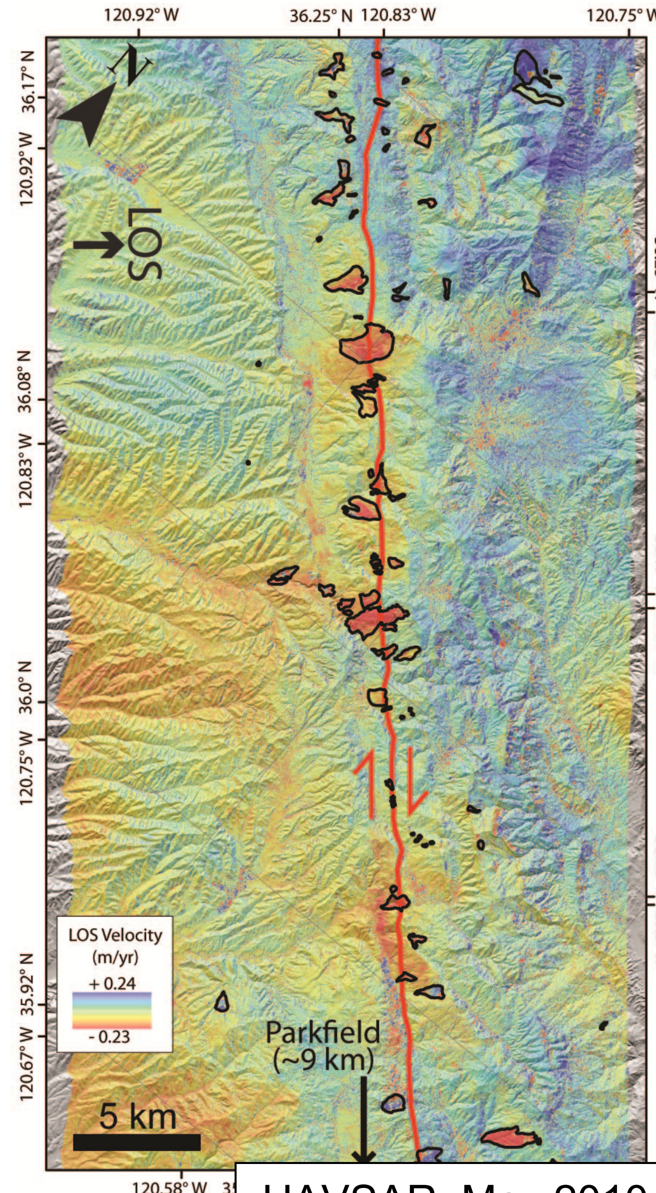

UAVSAR: May 2010 to July 2011 (427 days)

Scheingross et al, 2013, *GSA Bulletin*

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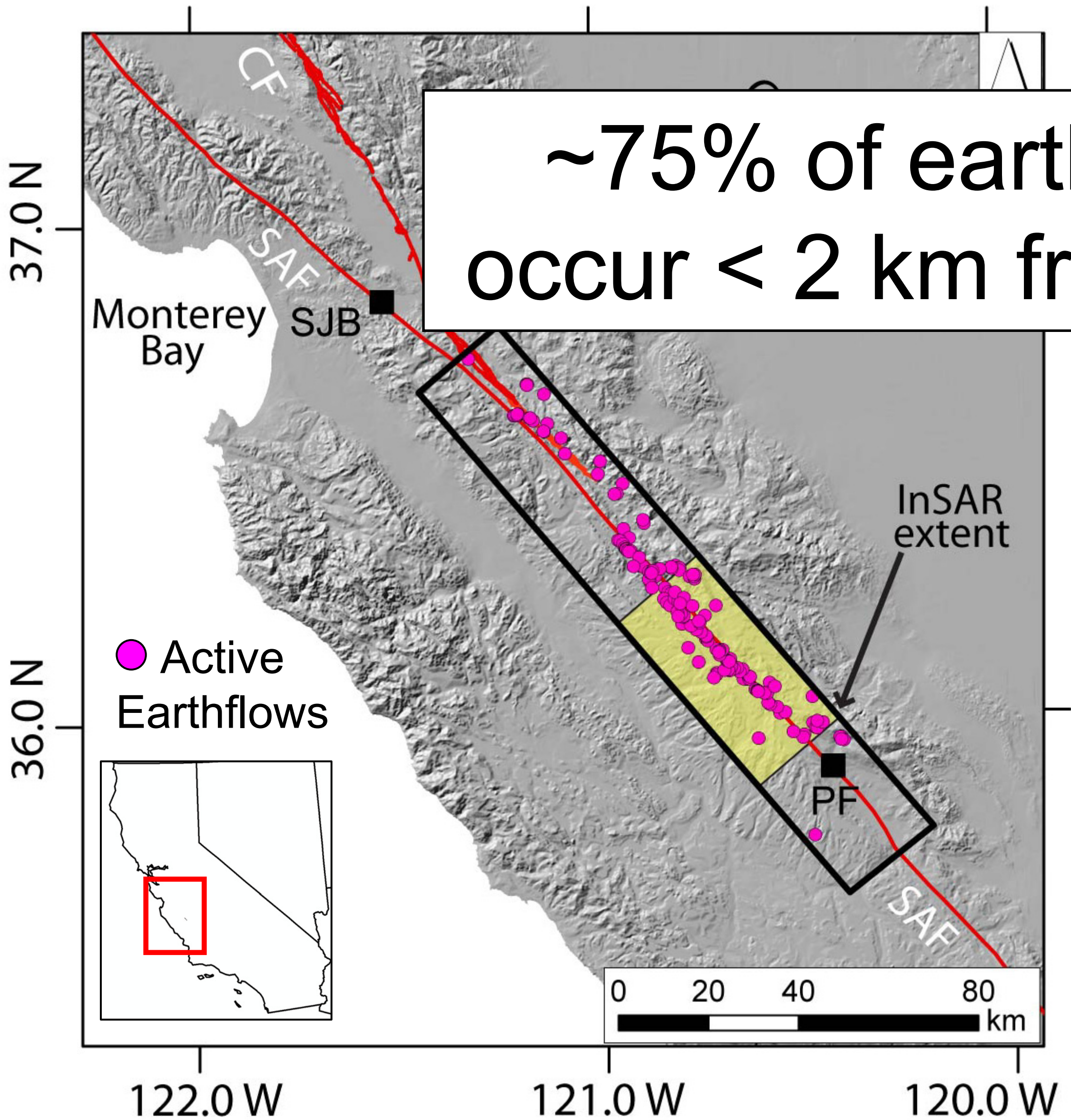

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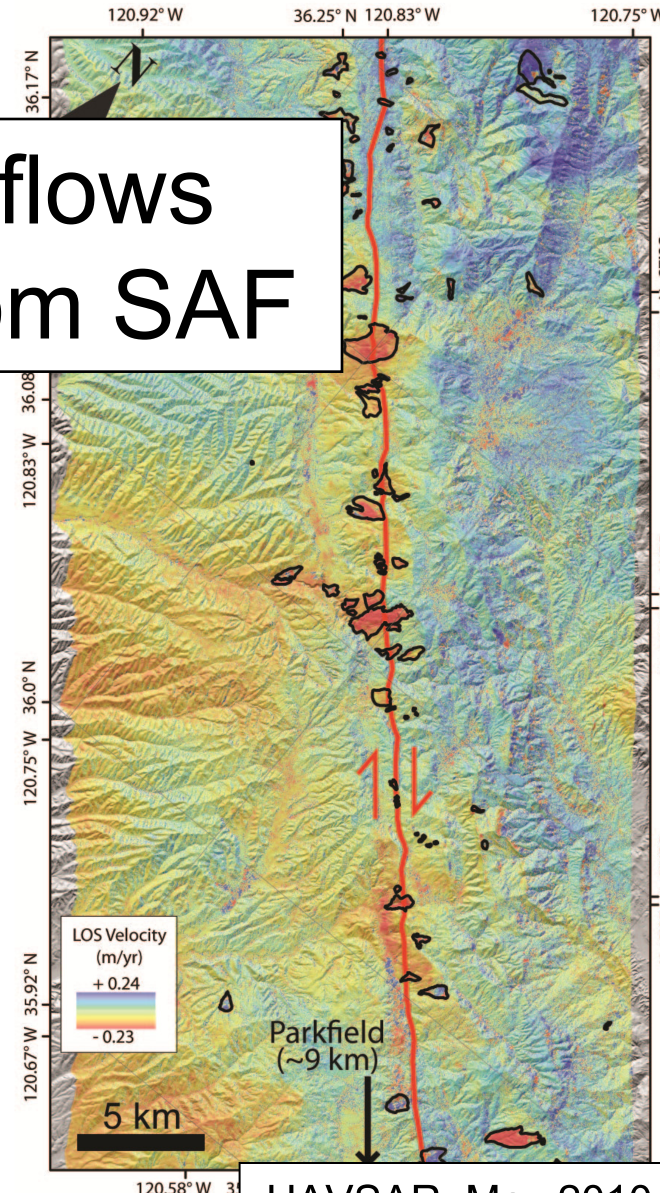
~75% of earthflows occur < 2 km from SAF



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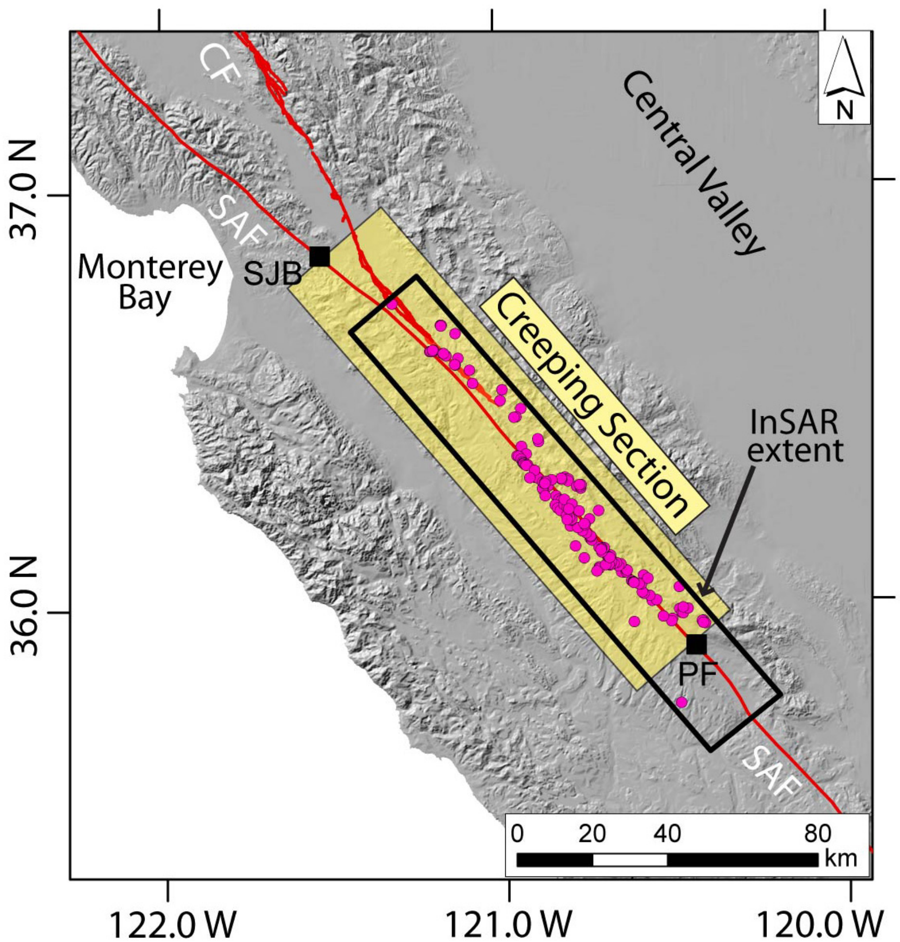
Central questions

- Does **reduced rock strength** within the fault damage zone influence earthflow spatial distribution?



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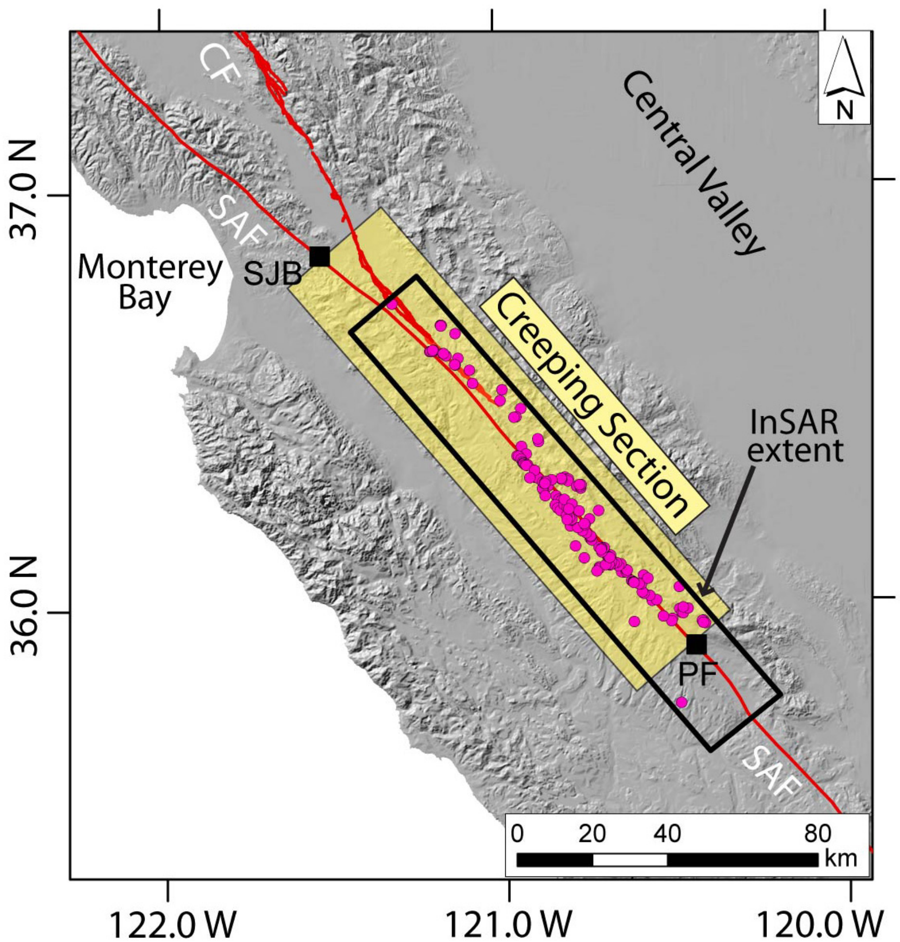


What about confounding variables?

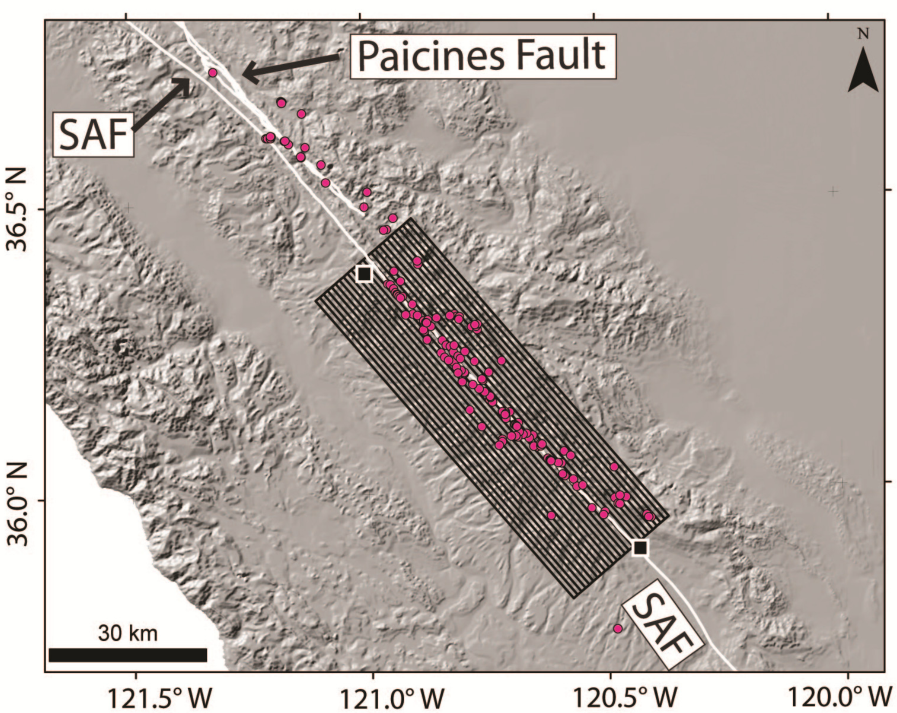
- Topography
- Climate
- Lithology

Scheingross et al, 2013, *GSA Bulletin*

Swath Profile Analysis

SAF parallel swaths

(1 km x 75 km)



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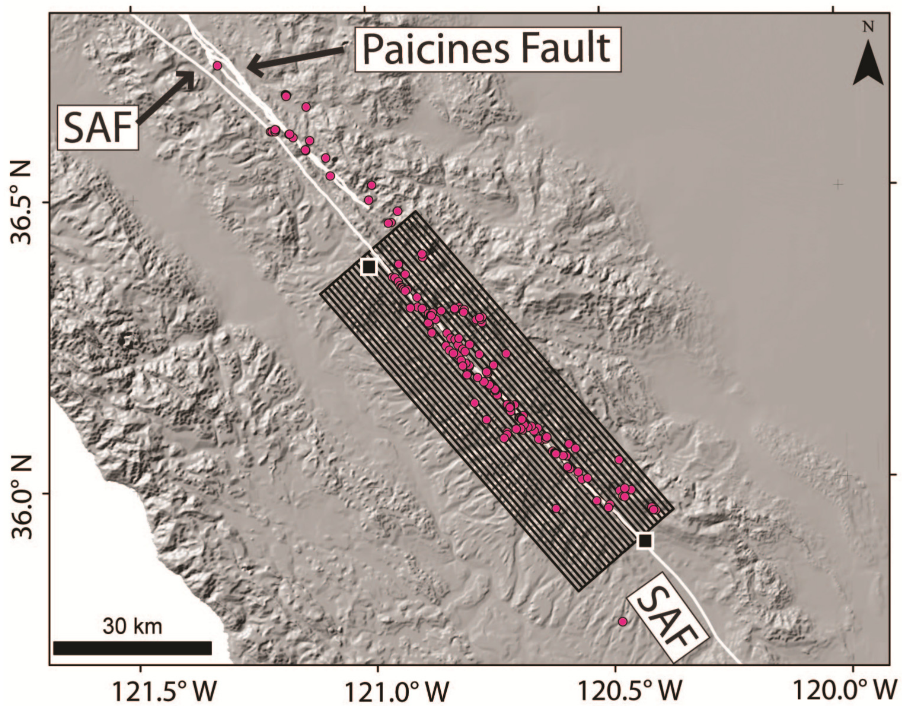

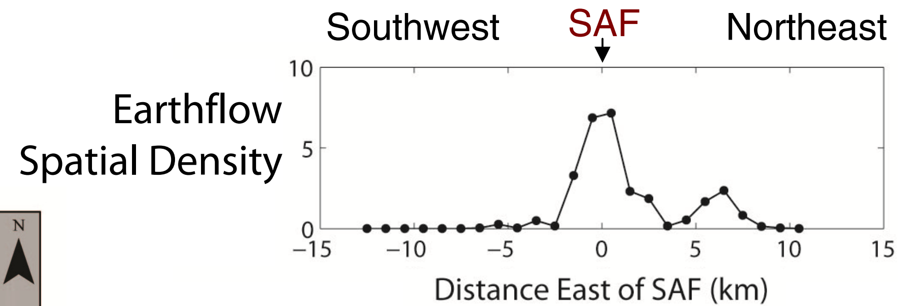

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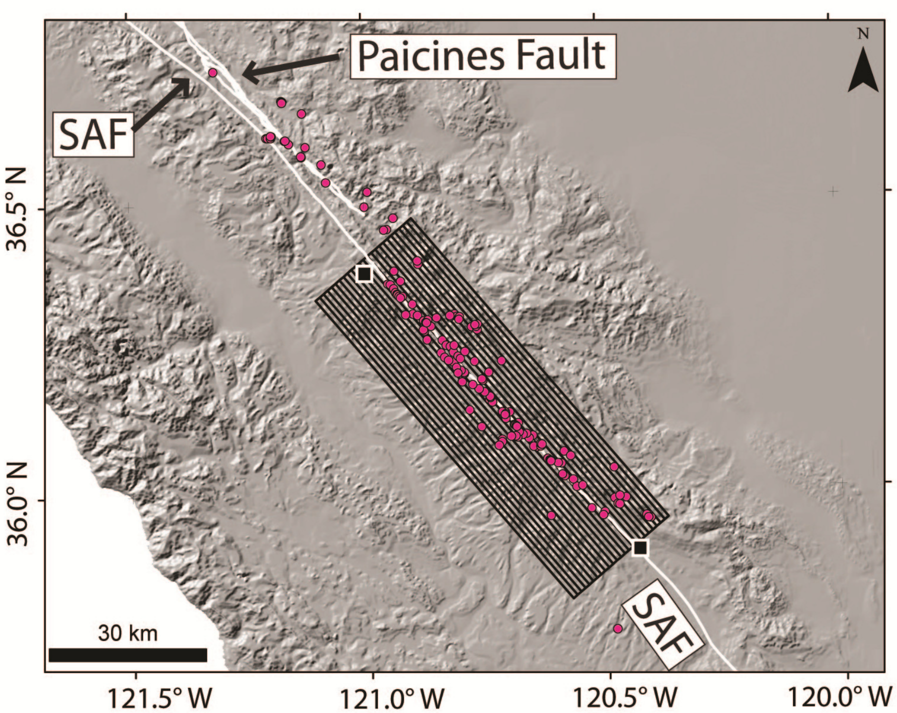

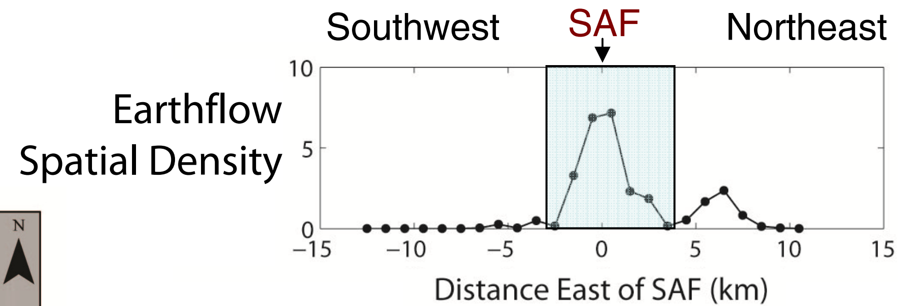

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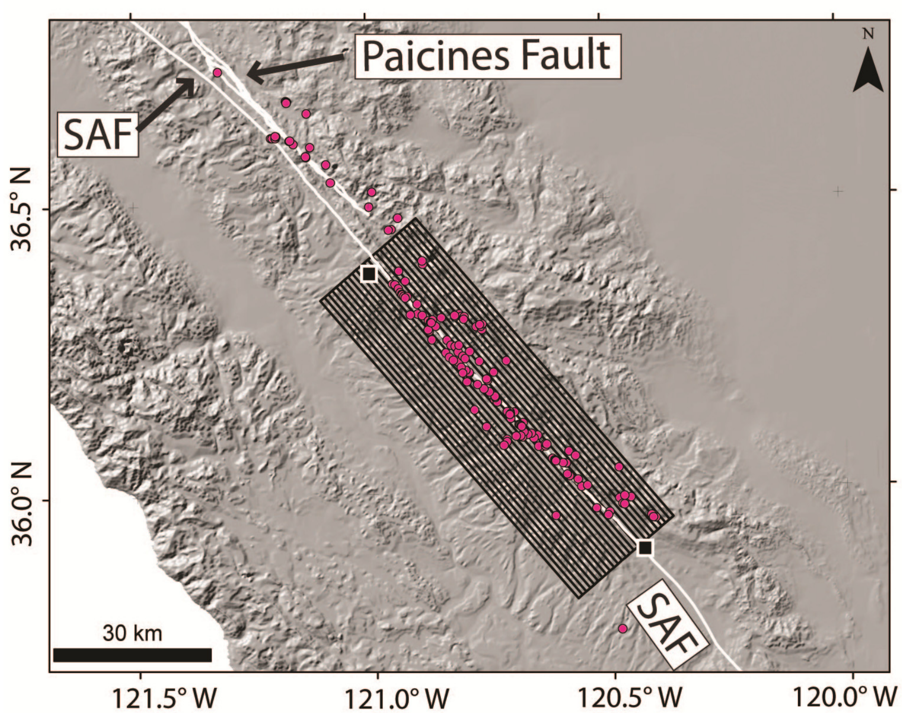

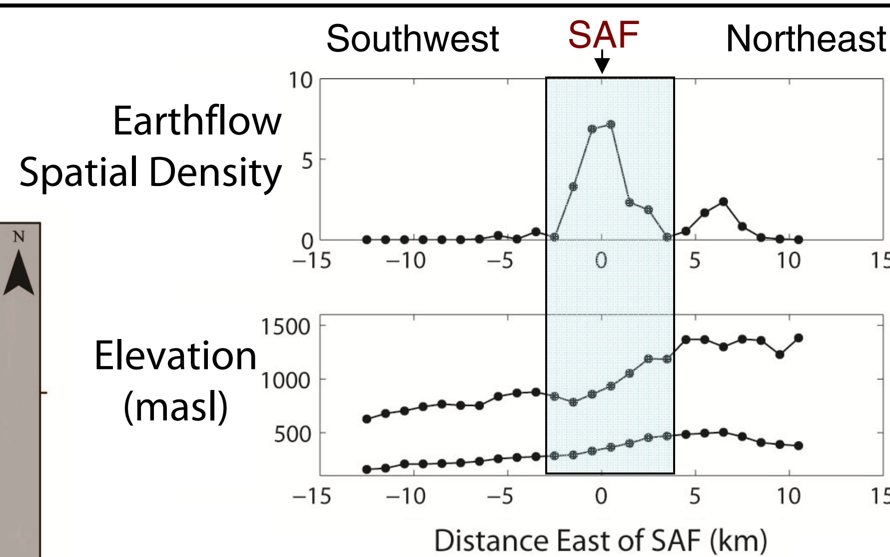

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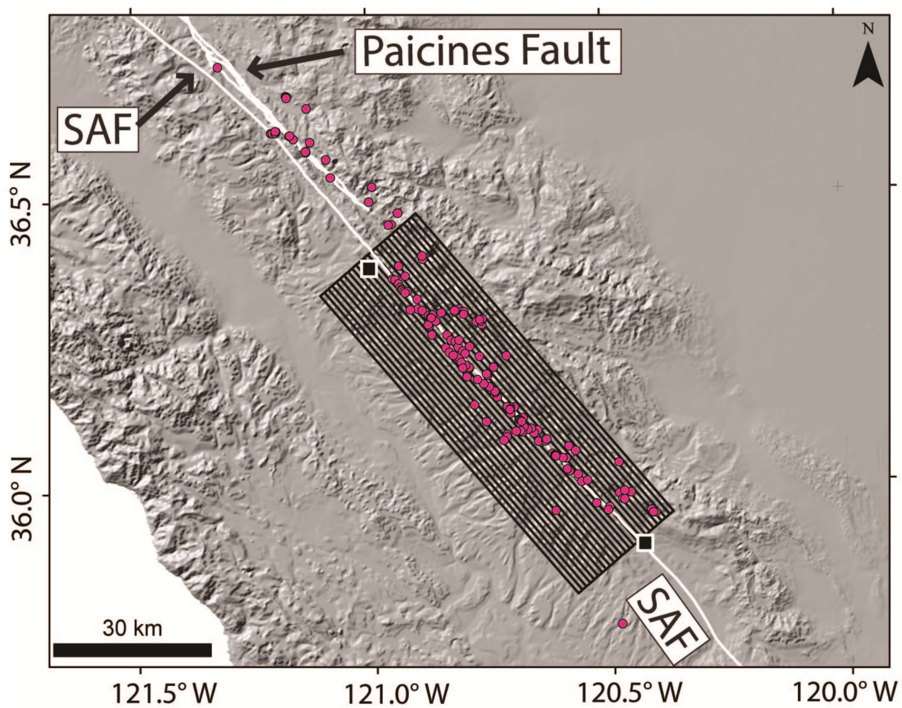

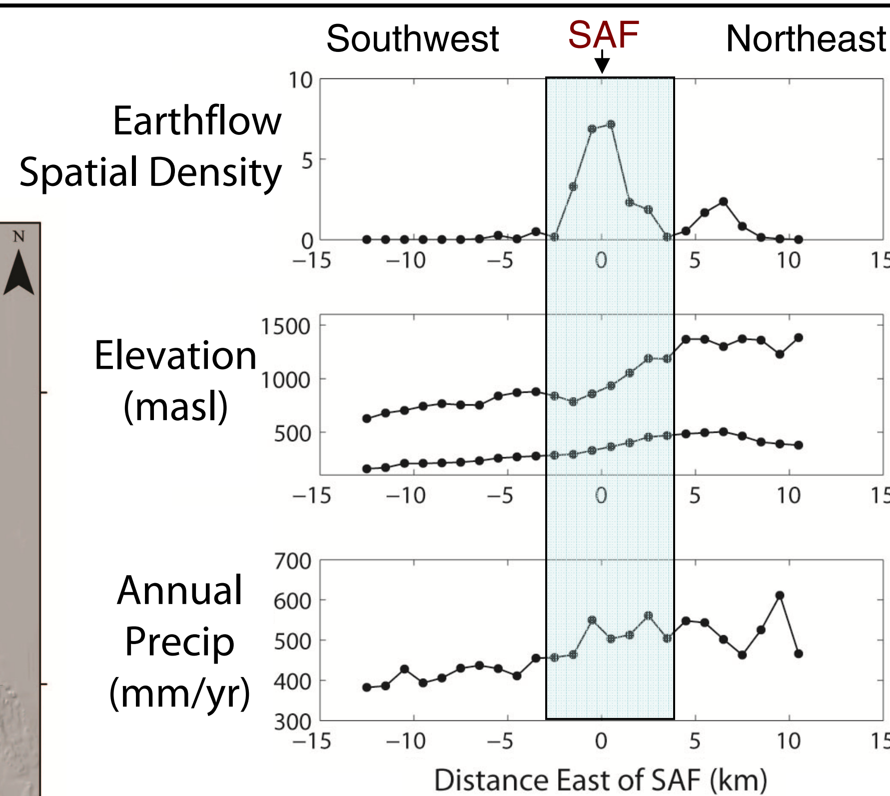

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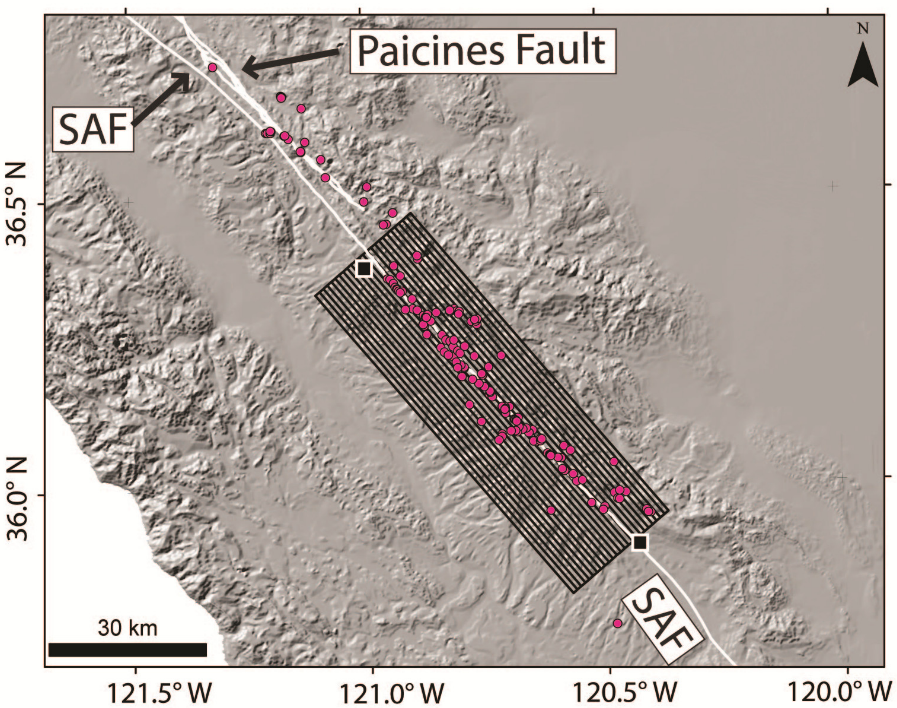

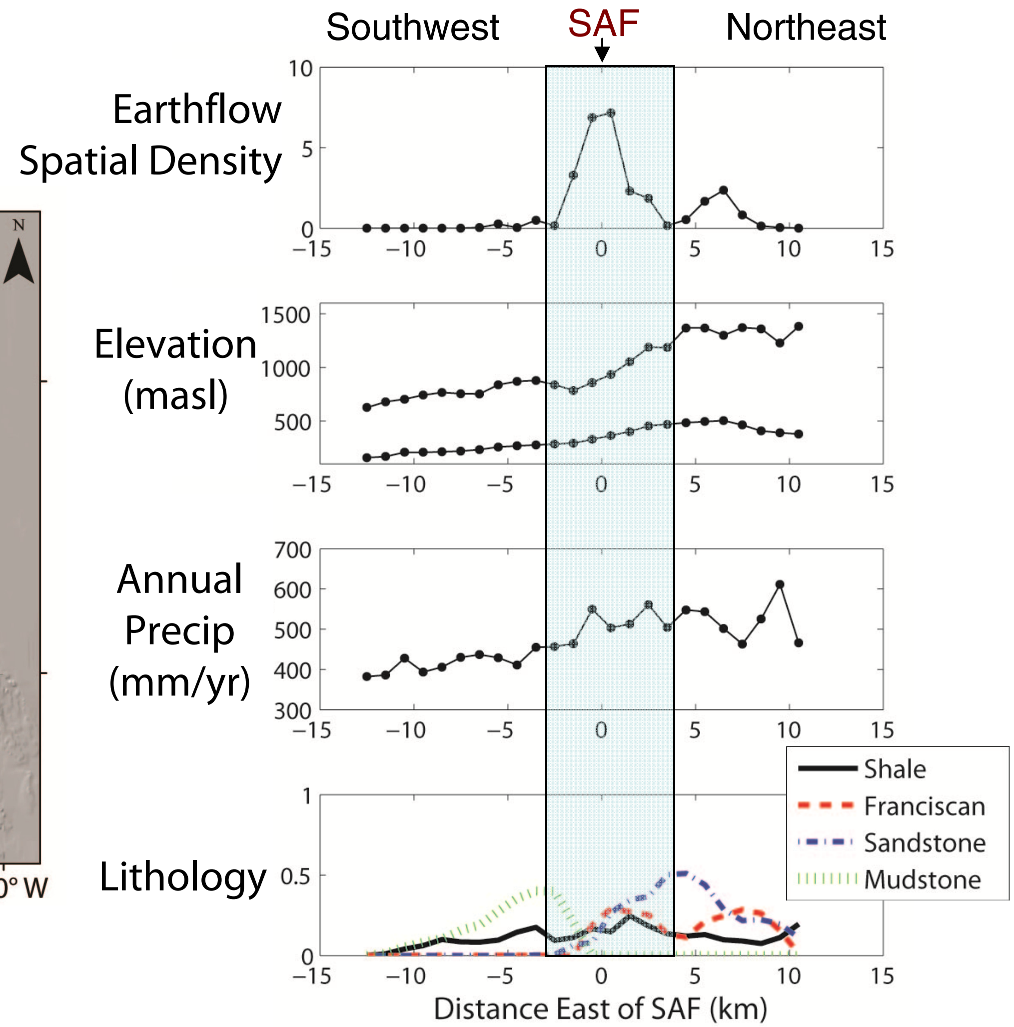

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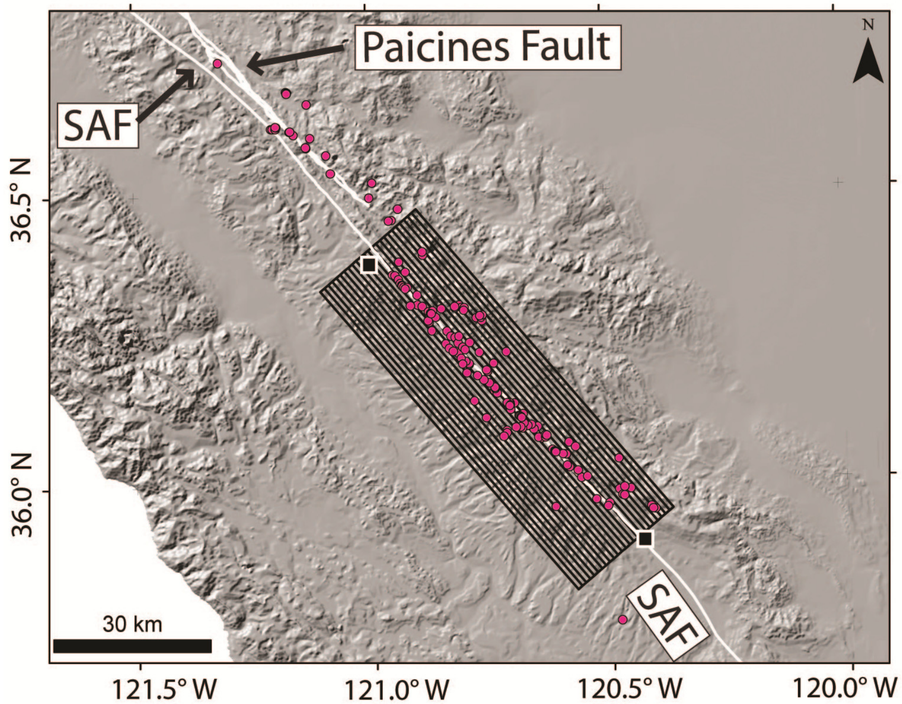

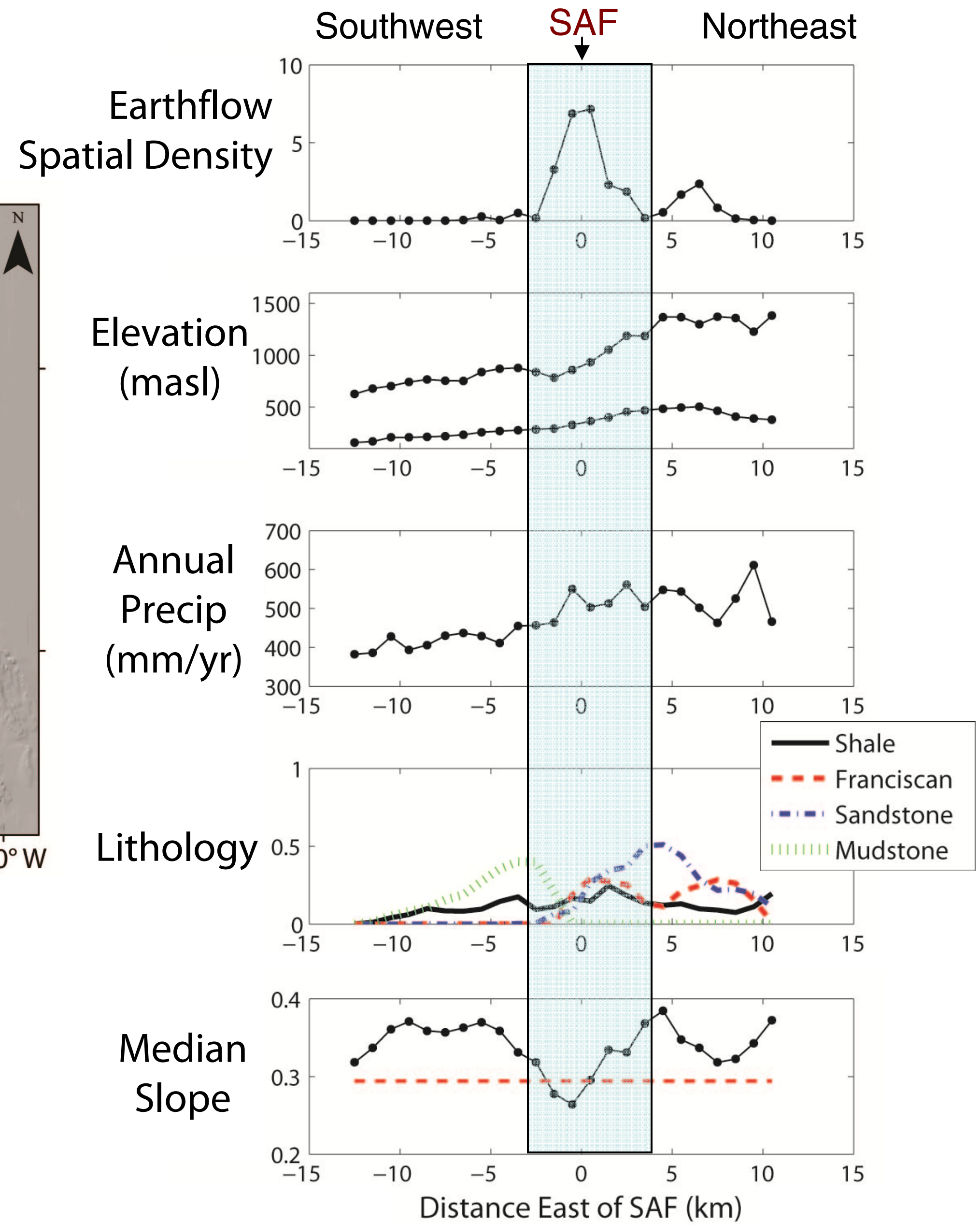

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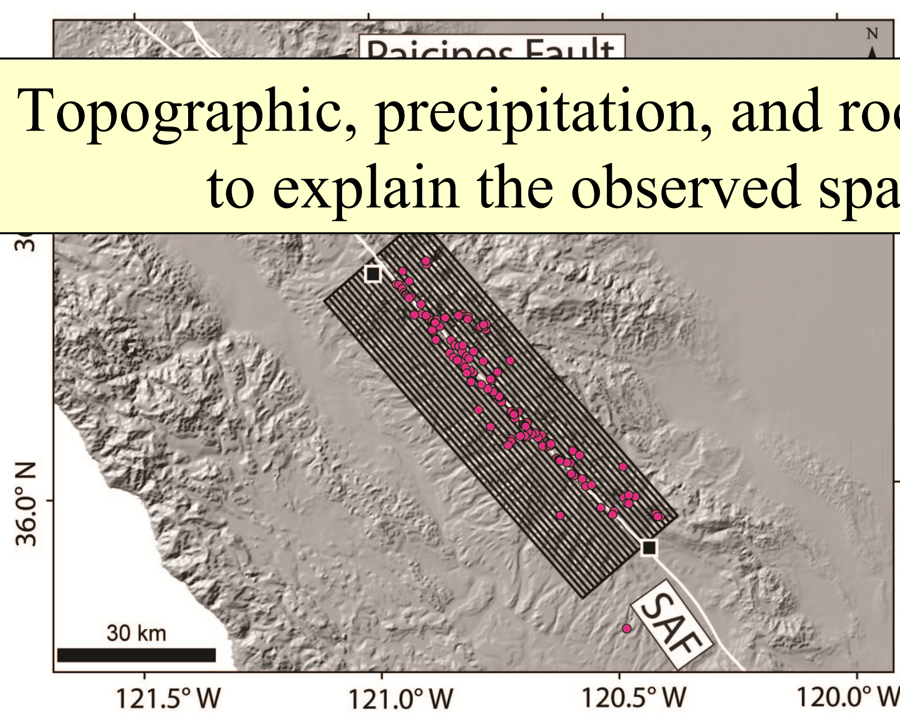

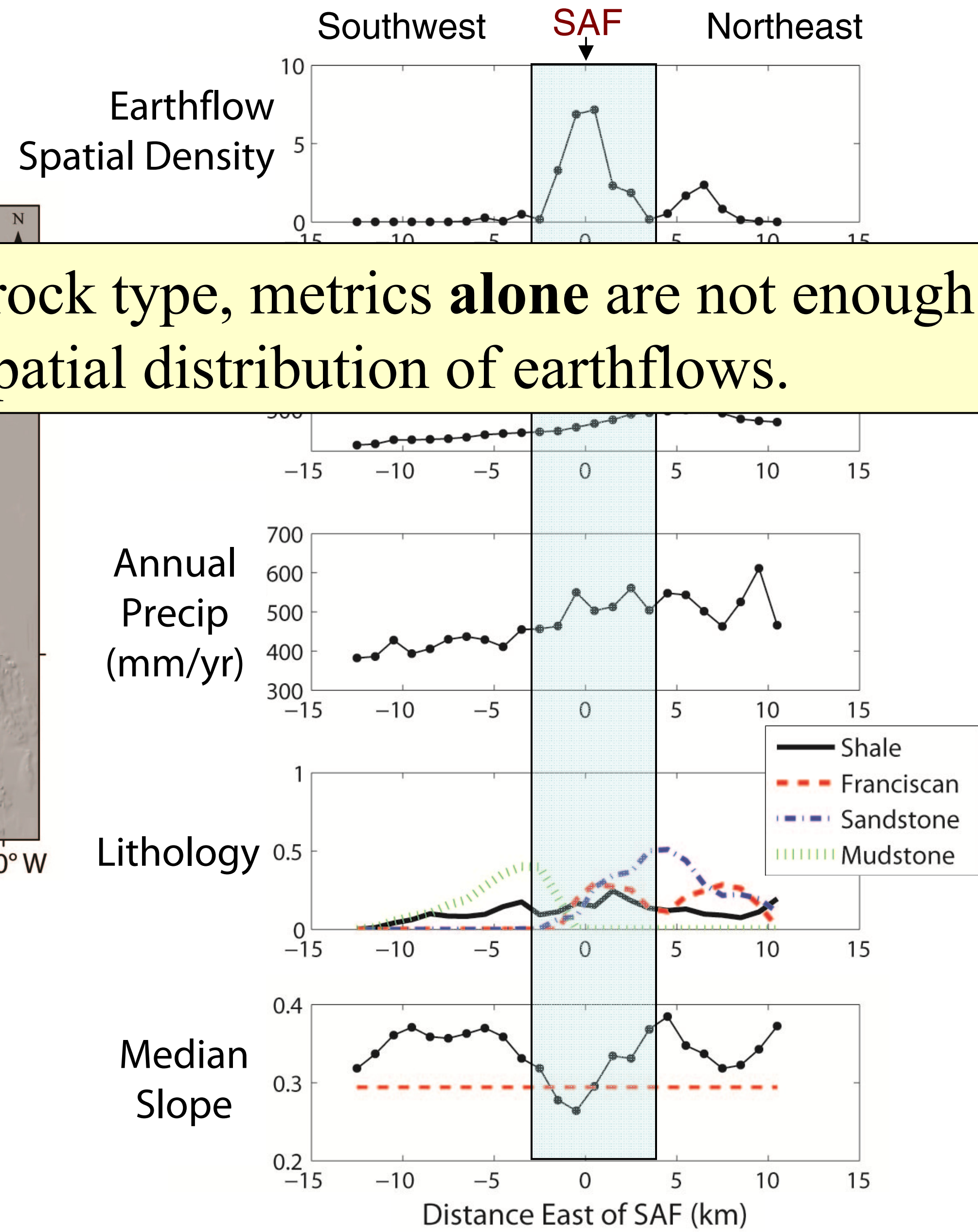

Topographic, precipitation, and rock type, metrics **alone** are not enough to explain the observed spatial distribution of earthflows.

Scheingross et al, 2013, *GSA Bulletin*

Fault damage zones

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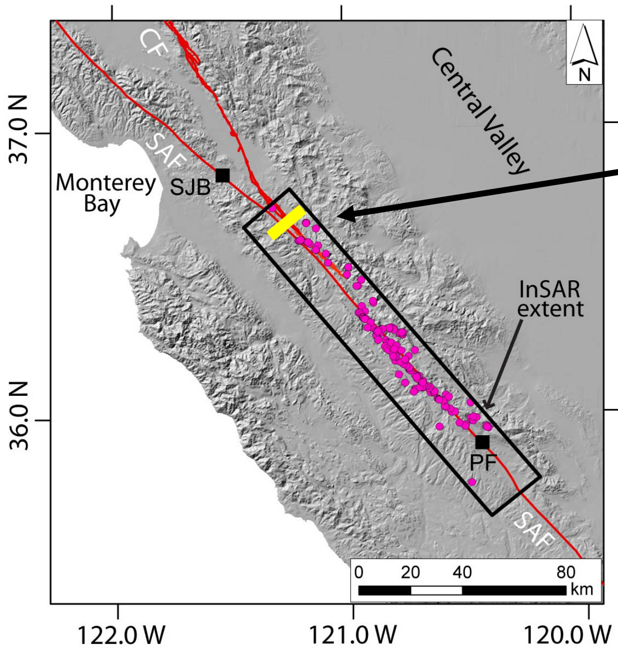

Seismic velocity profile
(Thurber et al, 1997)

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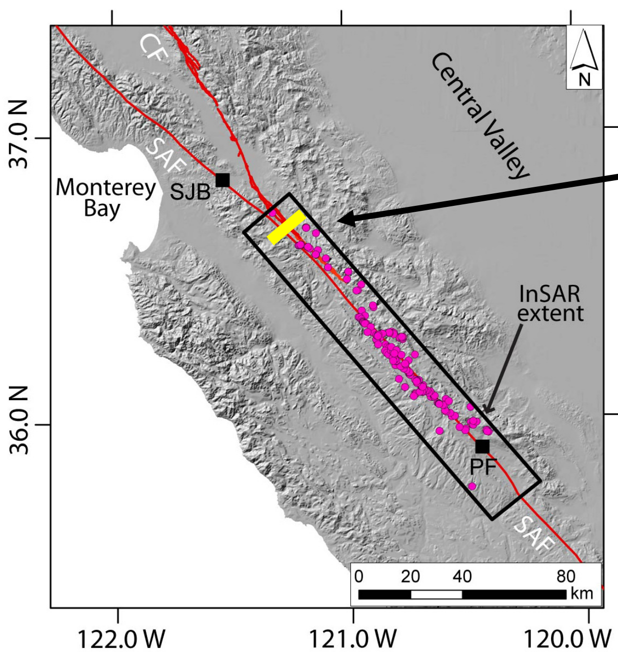

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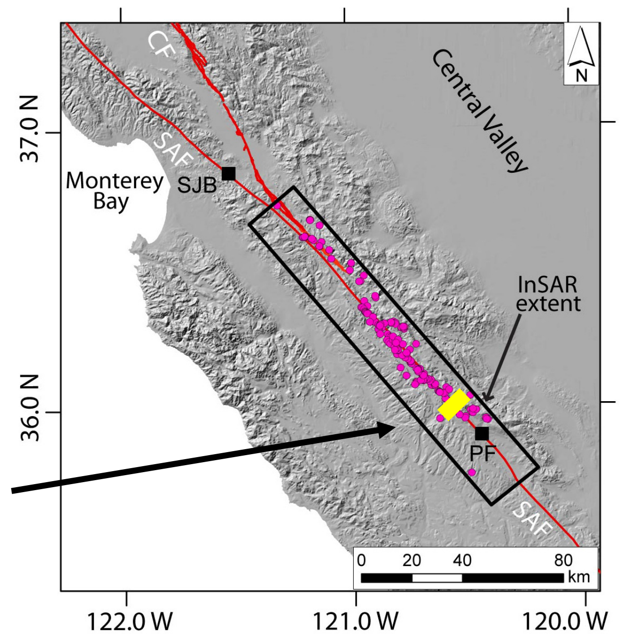

Electrical resistivity profile
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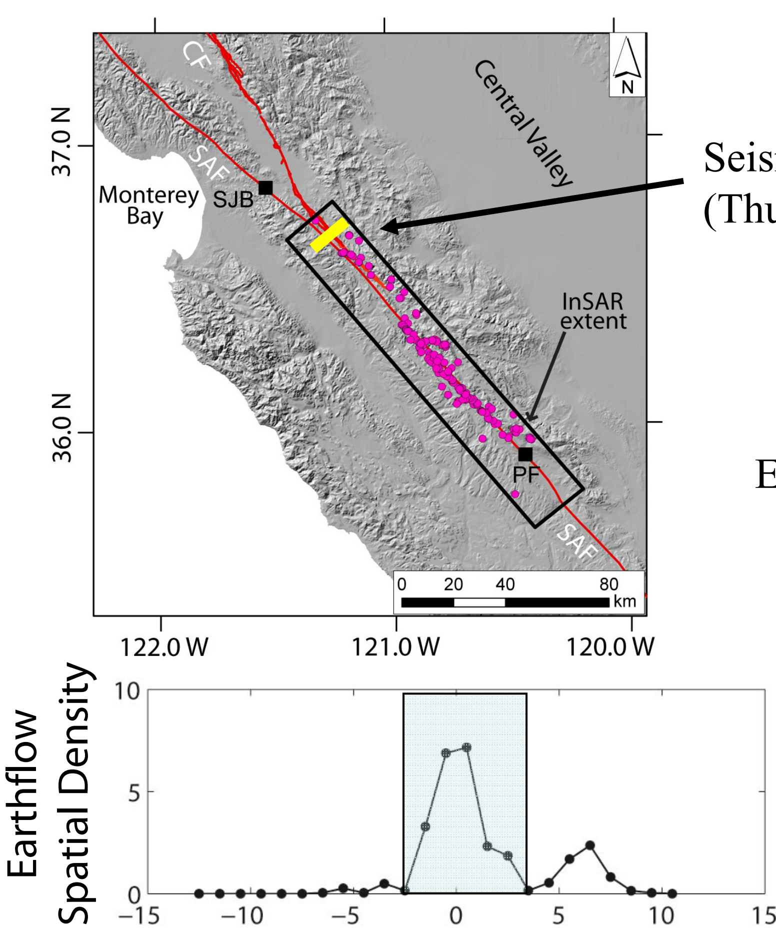

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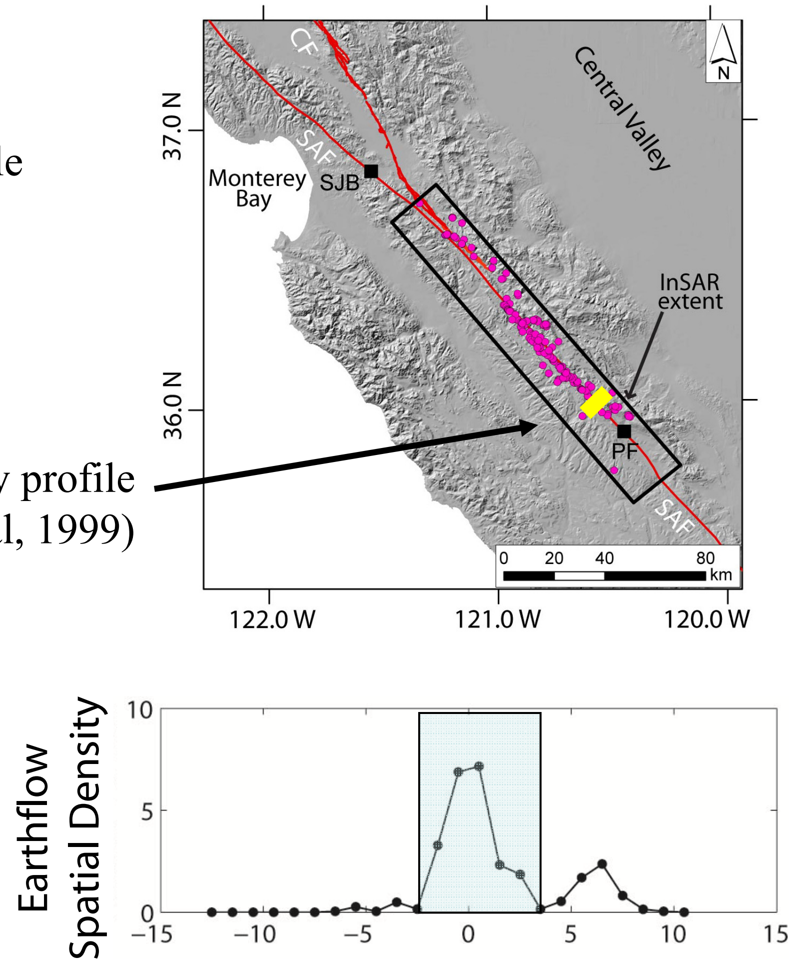

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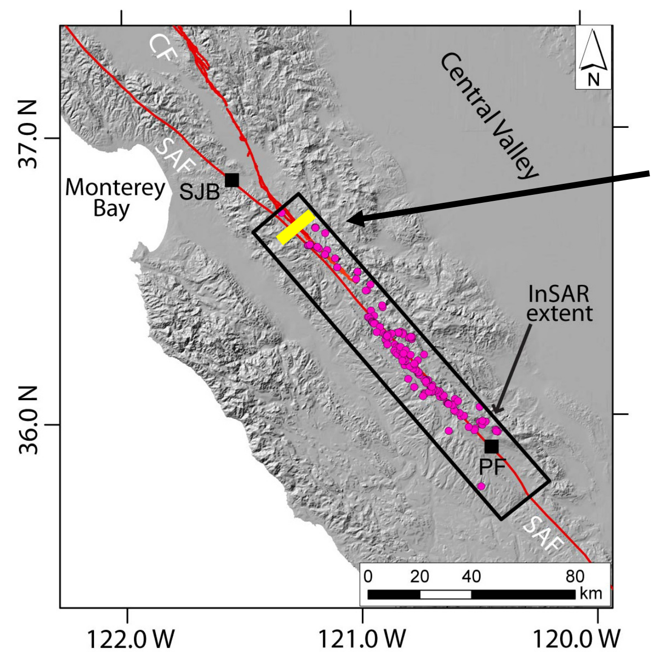

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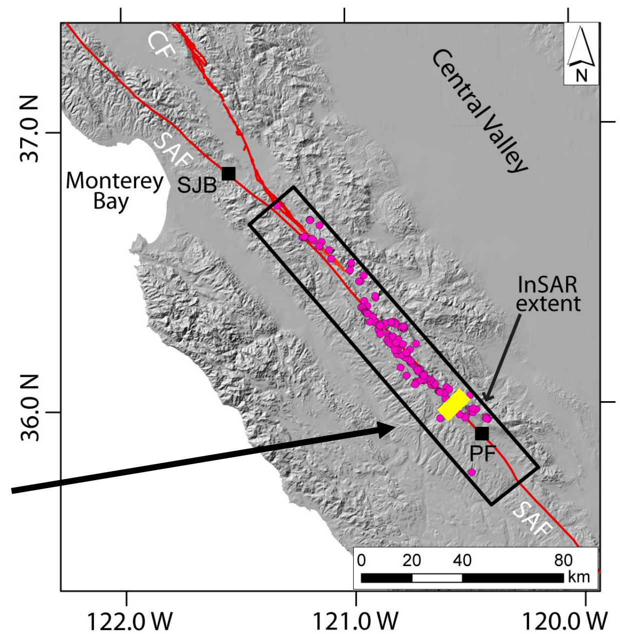
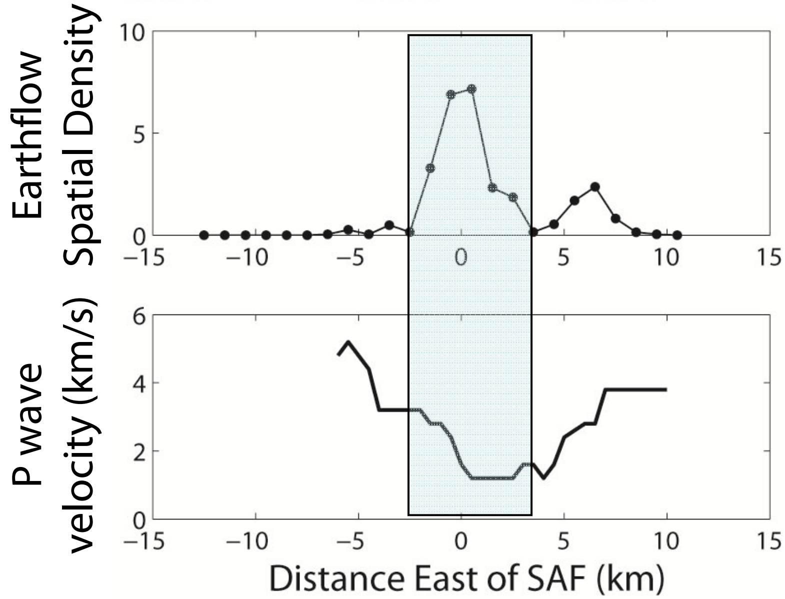
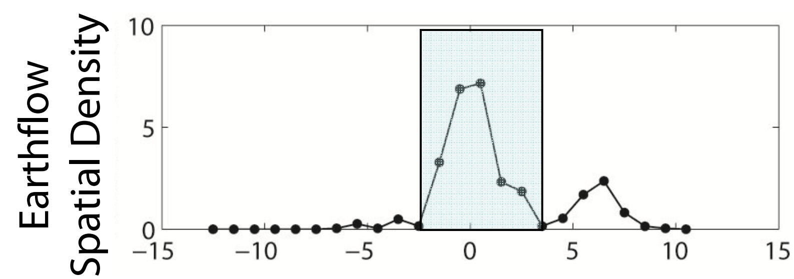


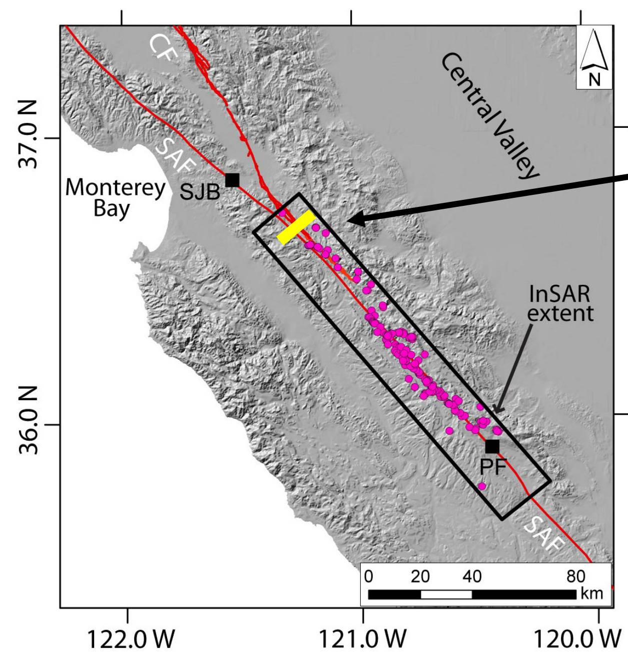
Electrical resistivity profile (Unsworth et al, 1999)





Decreasing rock strength

Fault damage zones



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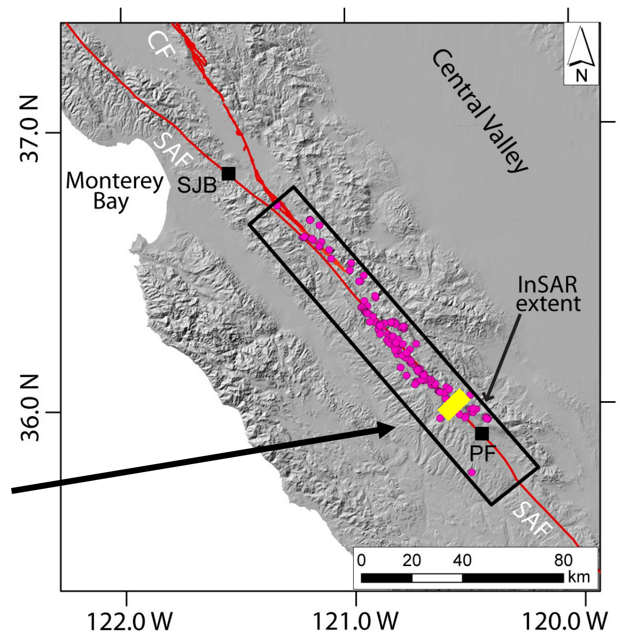

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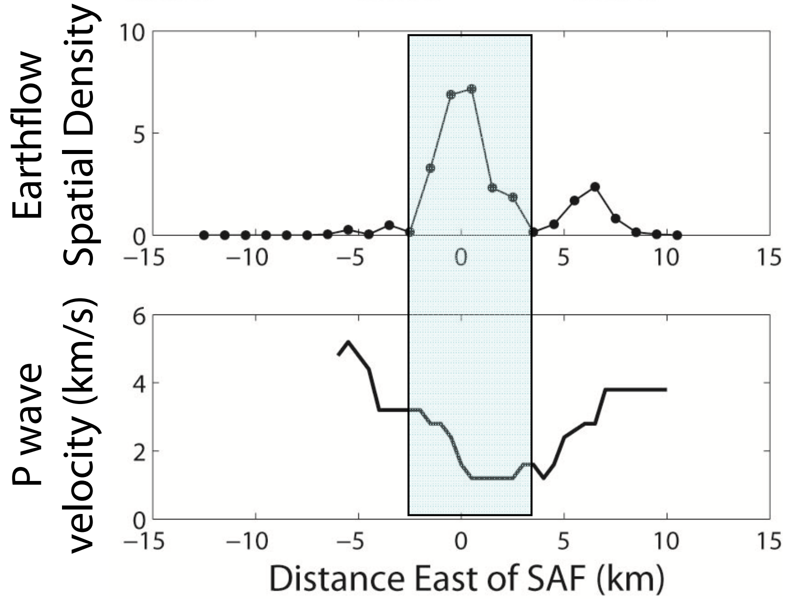

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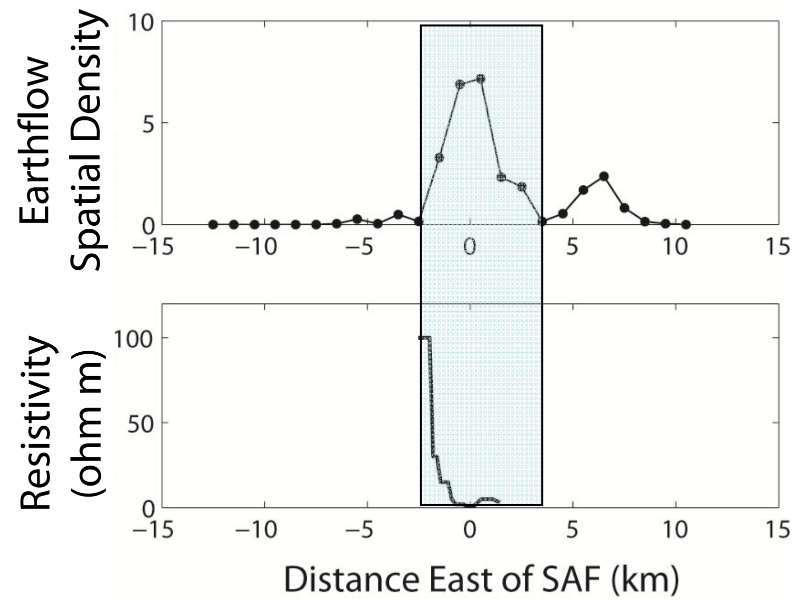
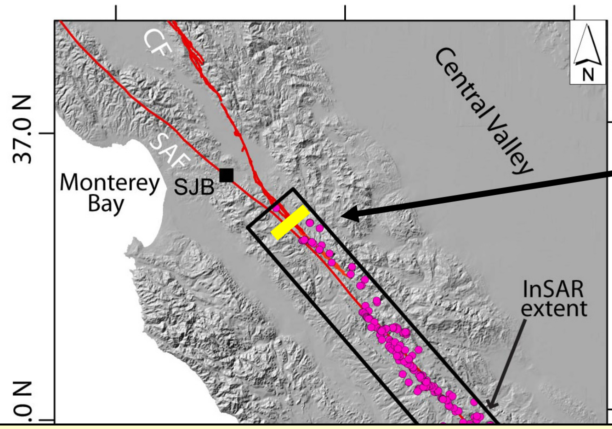
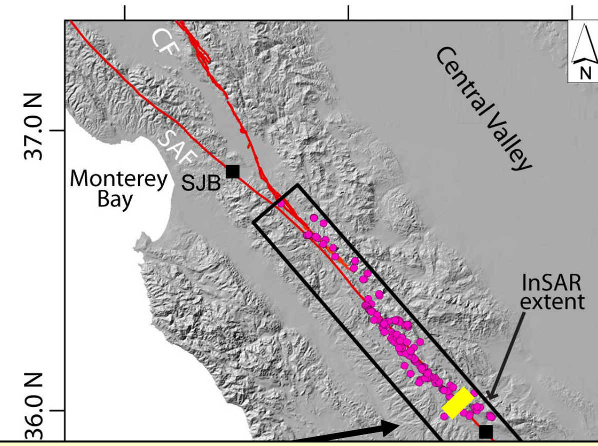


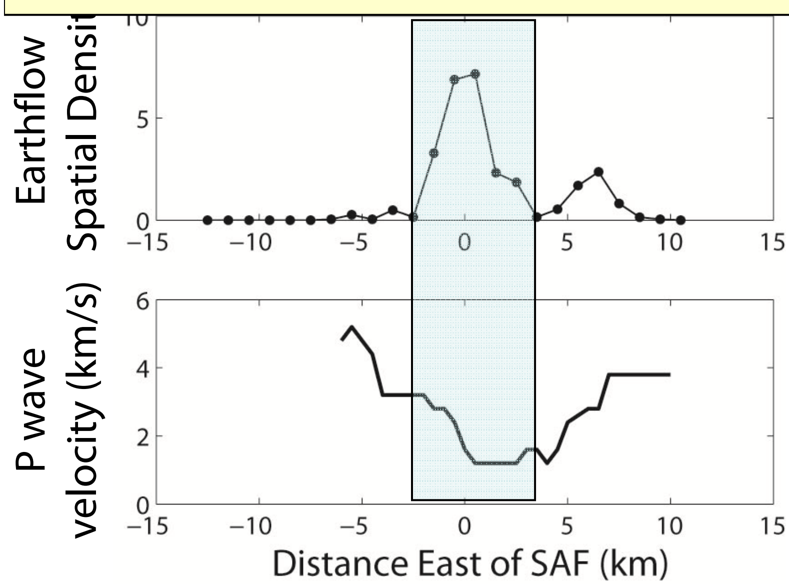
Fault damage zones



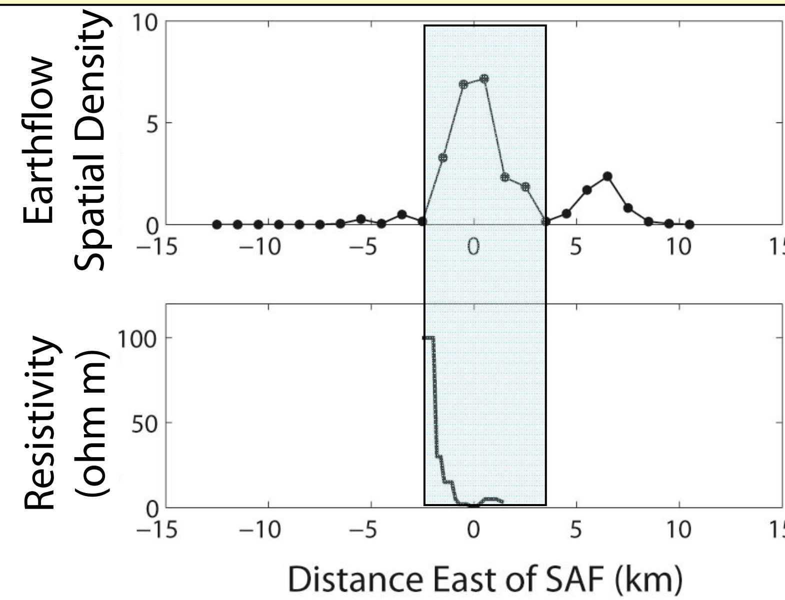
Seismic velocity profile
(Thurber et al, 1997)



Fault zone damage is observed to correlate with areas of high earthflow spatial density, and is **likely the first order control** on the cross-fault distribution of earthflows near the creeping SAF.

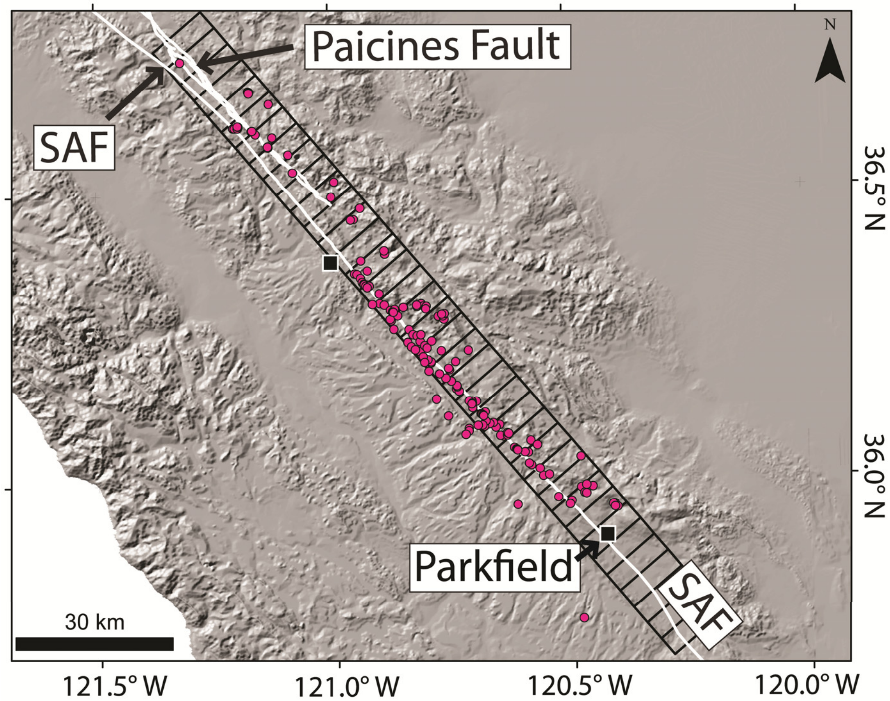


Decreasing rock strength



Swath Profile Analysis

SAF perpendicular swaths
(4 km x 12 km)



Scheingross et al, 2013, *GSA Bulletin*

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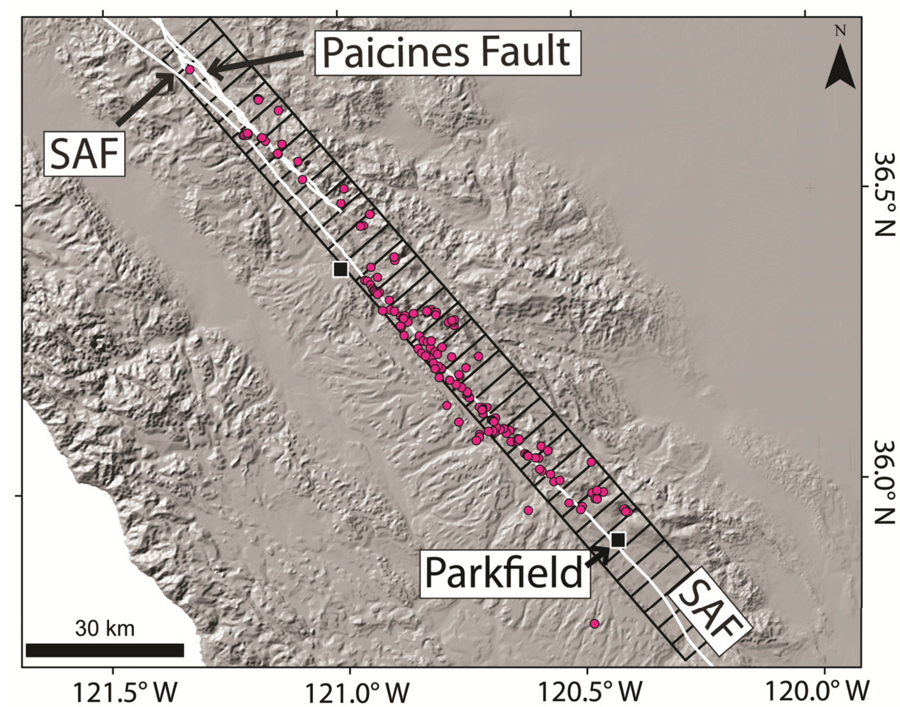

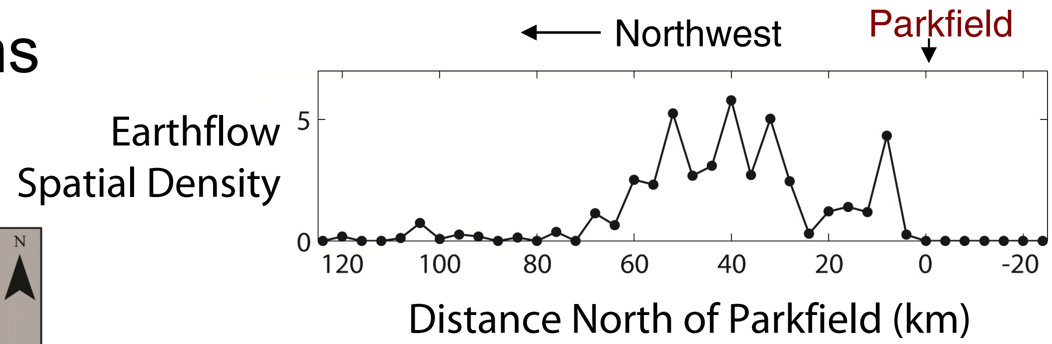

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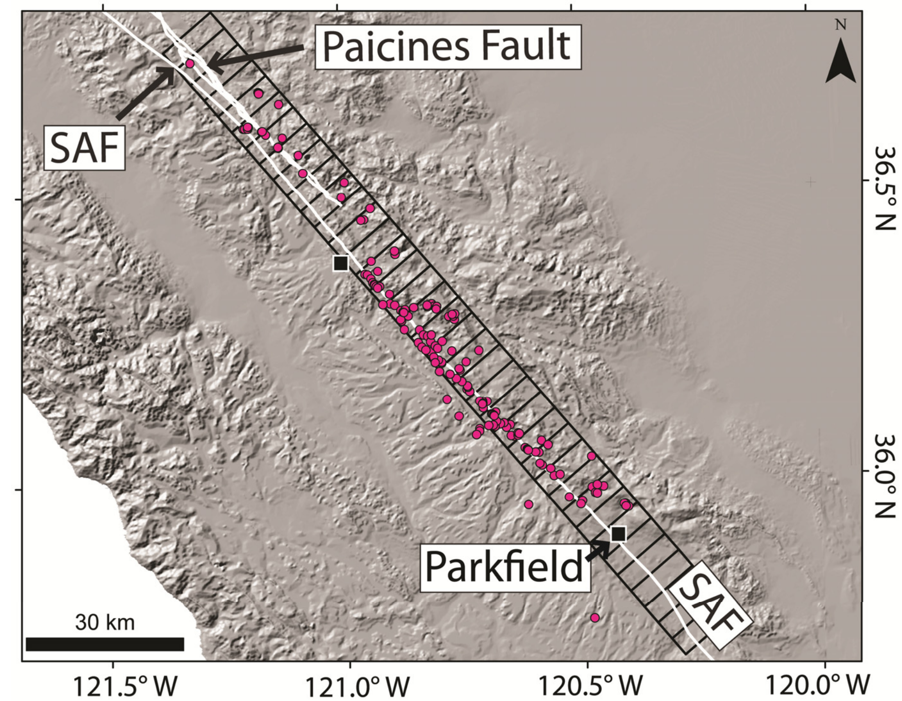

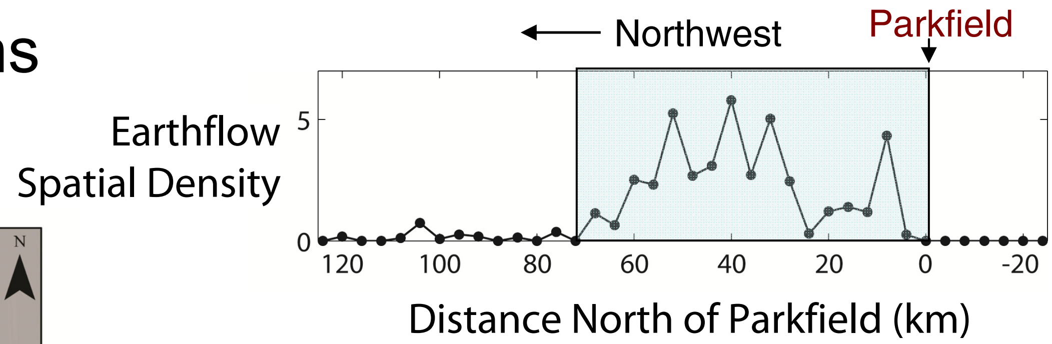

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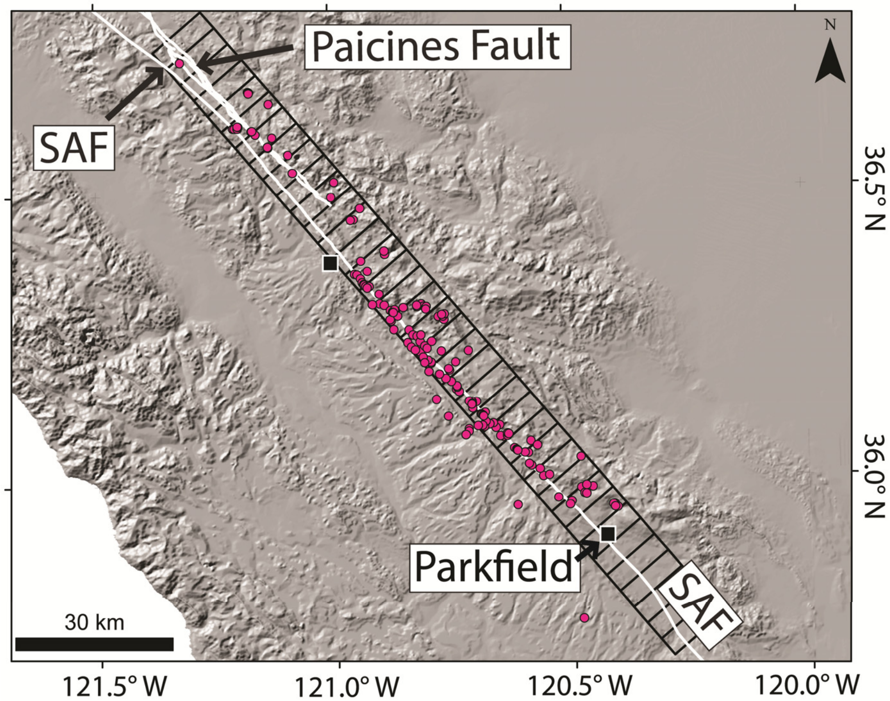

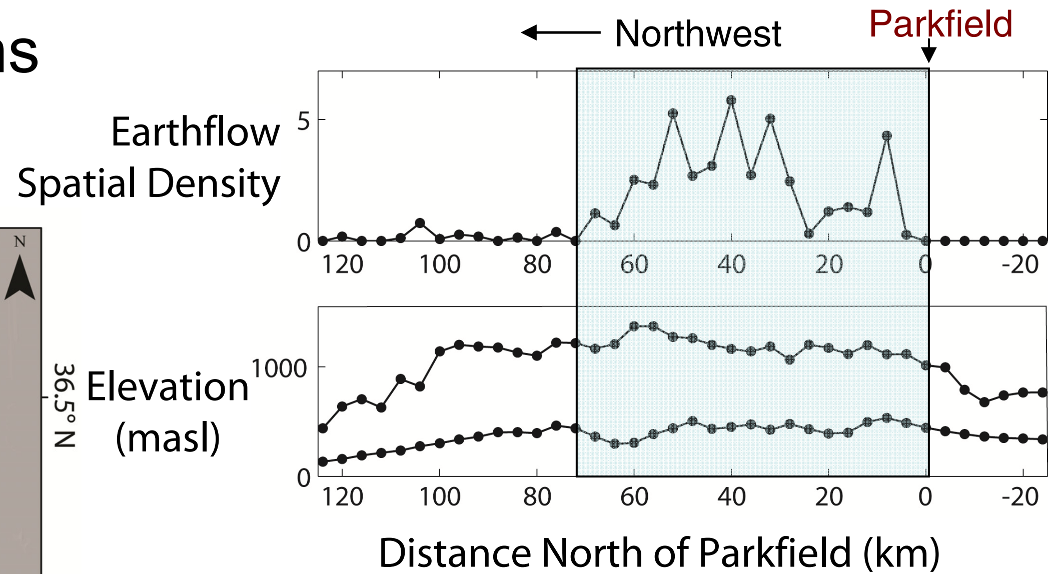

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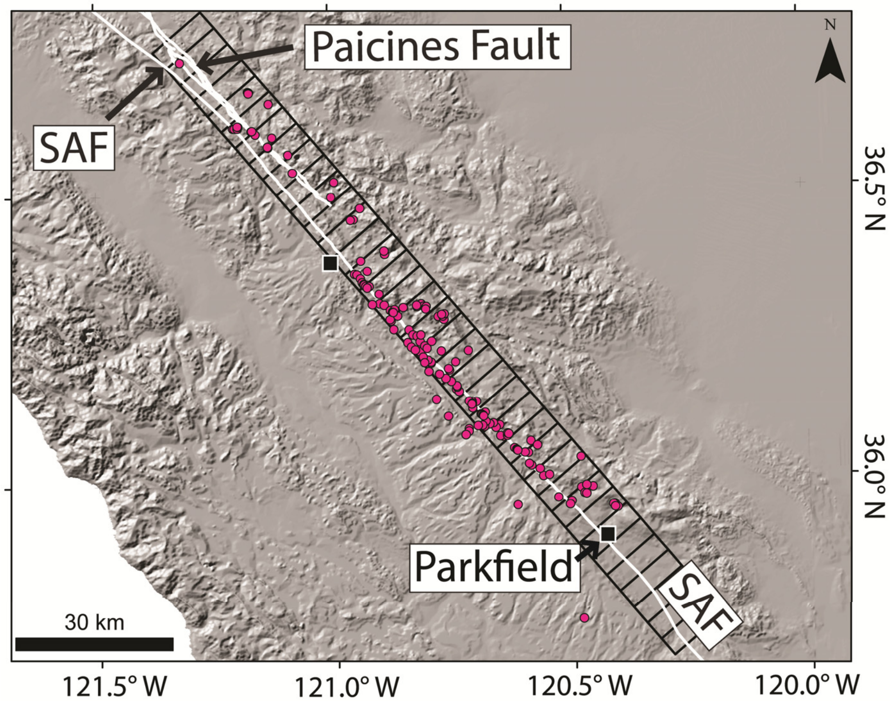

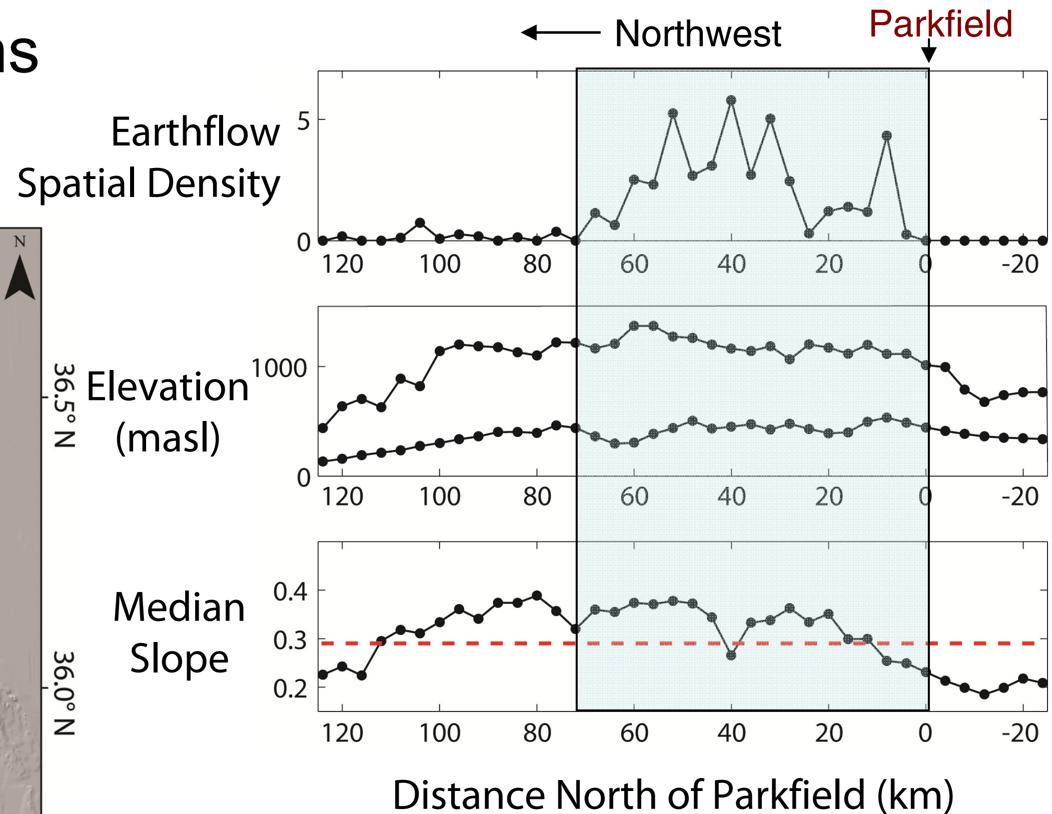

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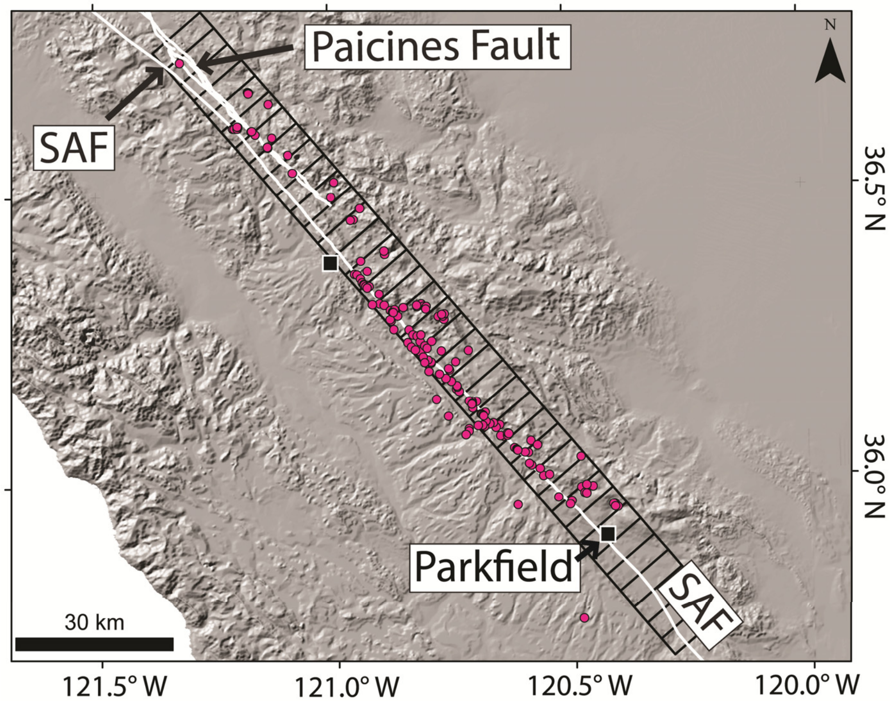

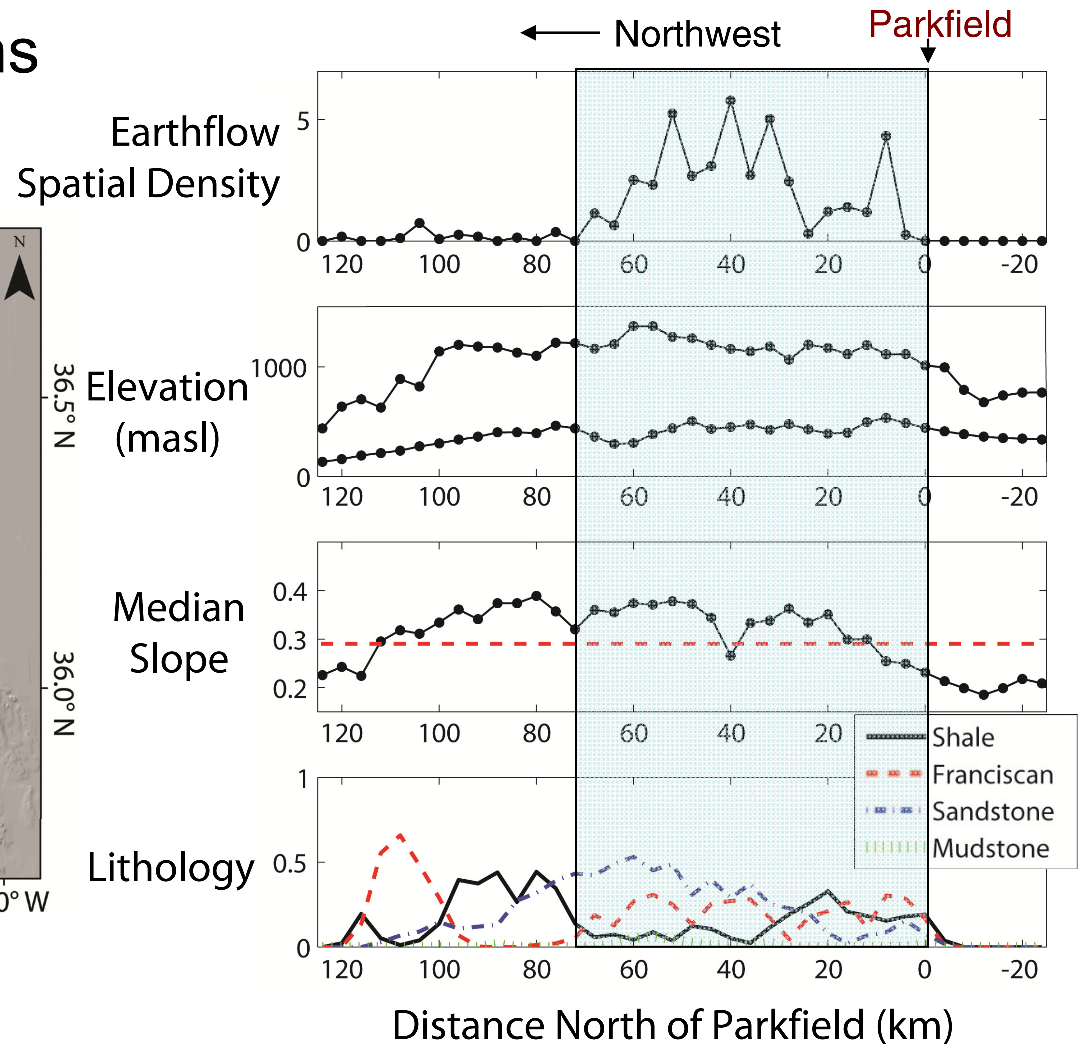

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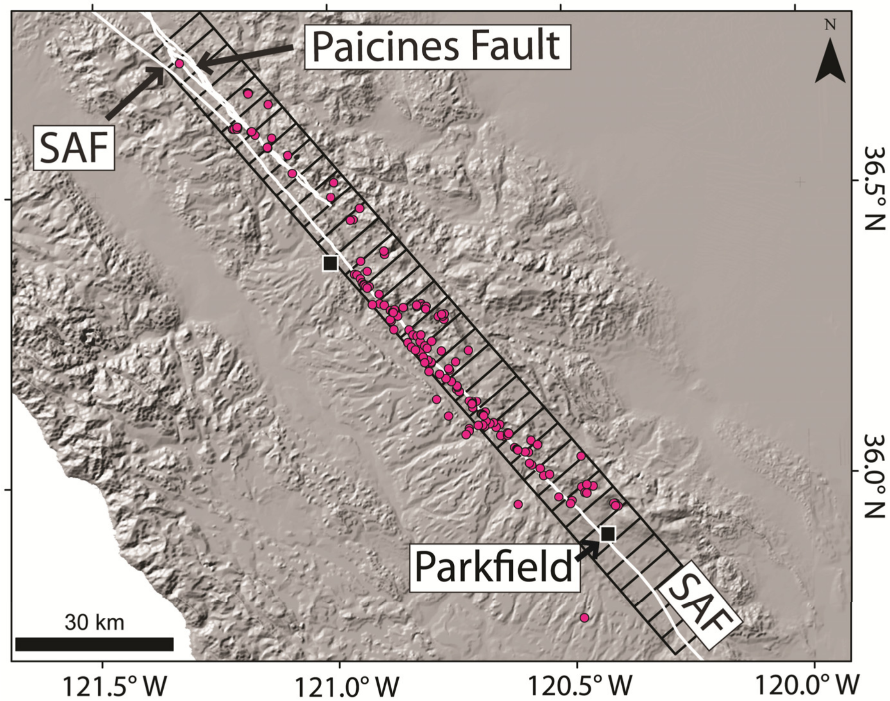

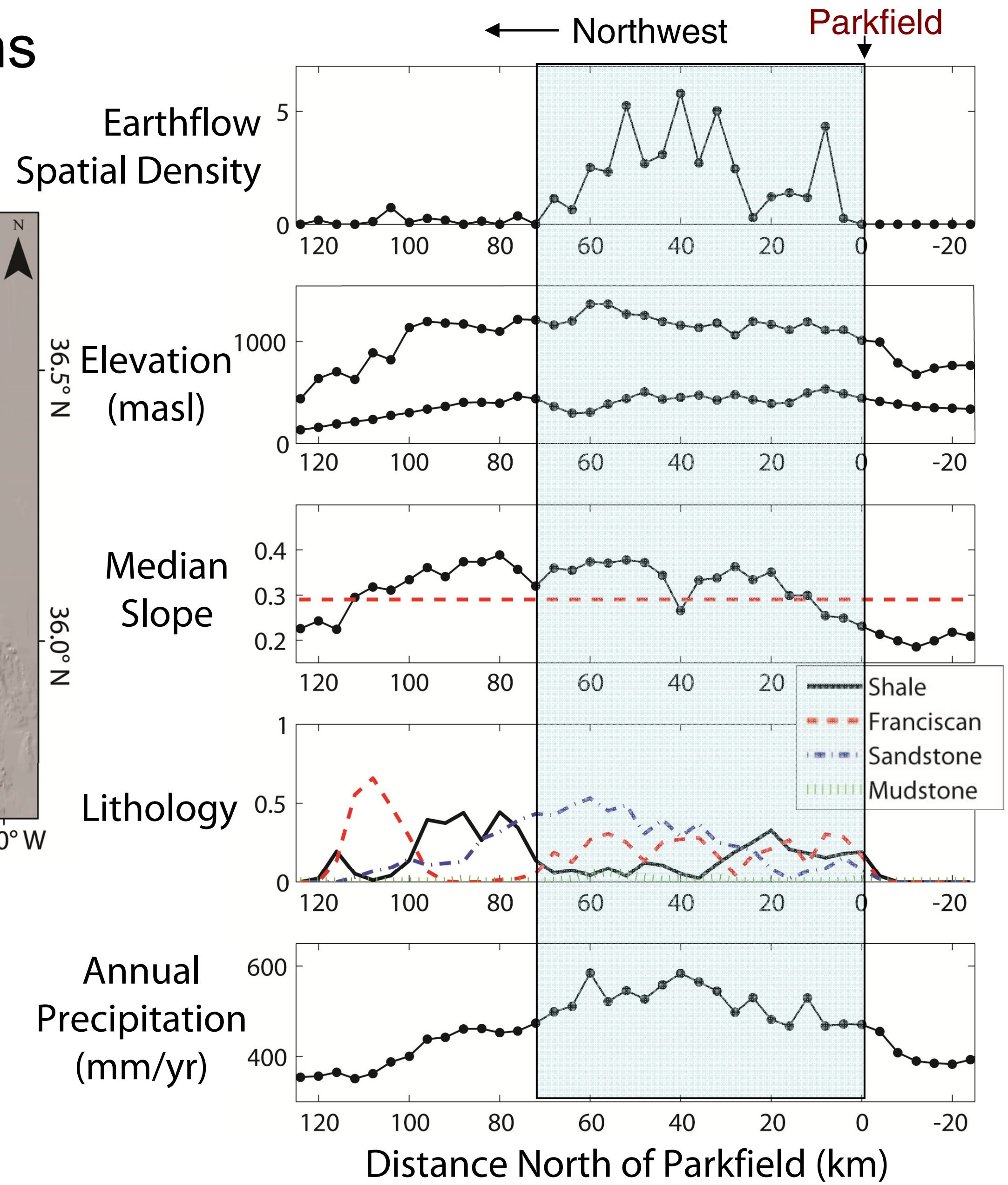

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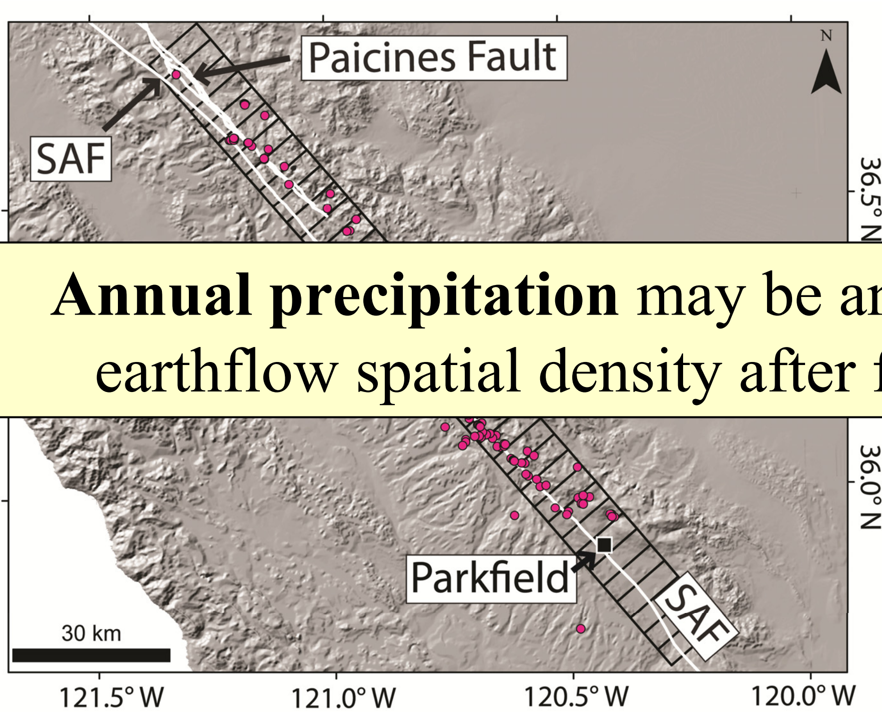
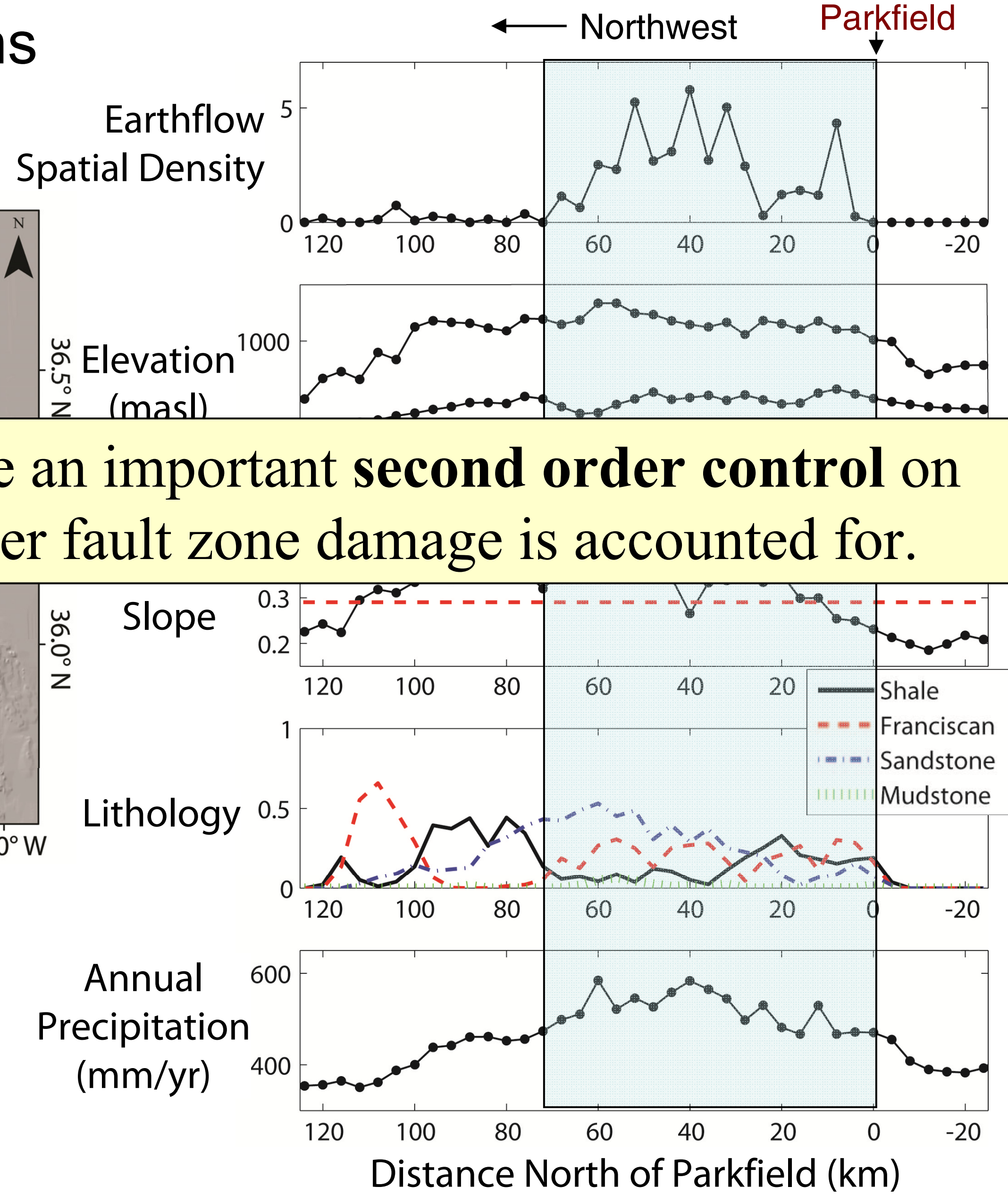
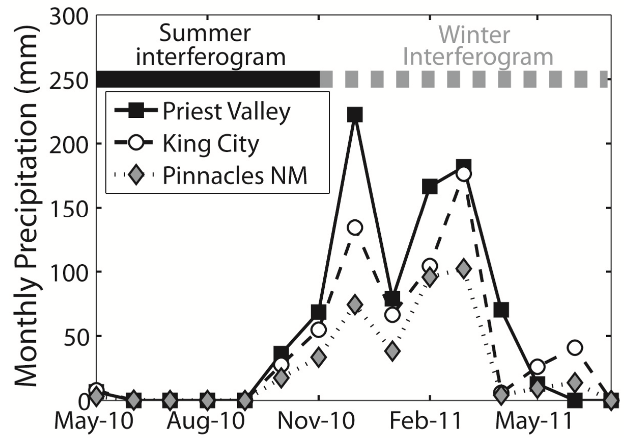




Annual precipitation may be an important **second order control** on earthflow spatial density after fault zone damage is accounted for.

Scheingross et al, 2013, *GSA Bulletin*

Movement in response to rainfall



Scheingross et al, 2013, *GSA Bulletin*

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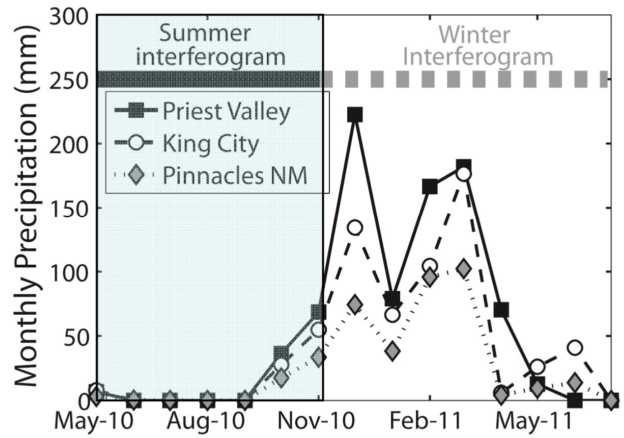

Scheingross et al, 2013, *GSA Bulletin*

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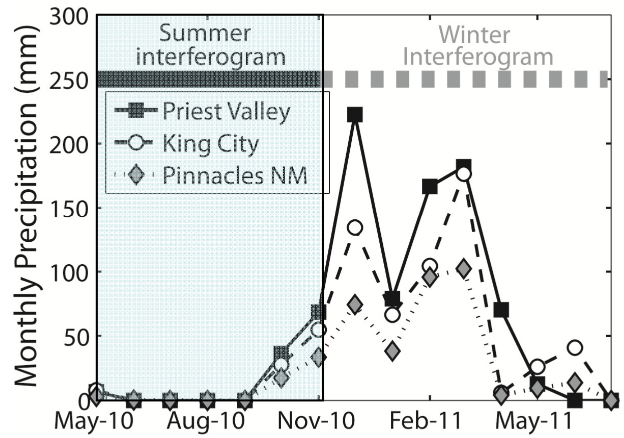

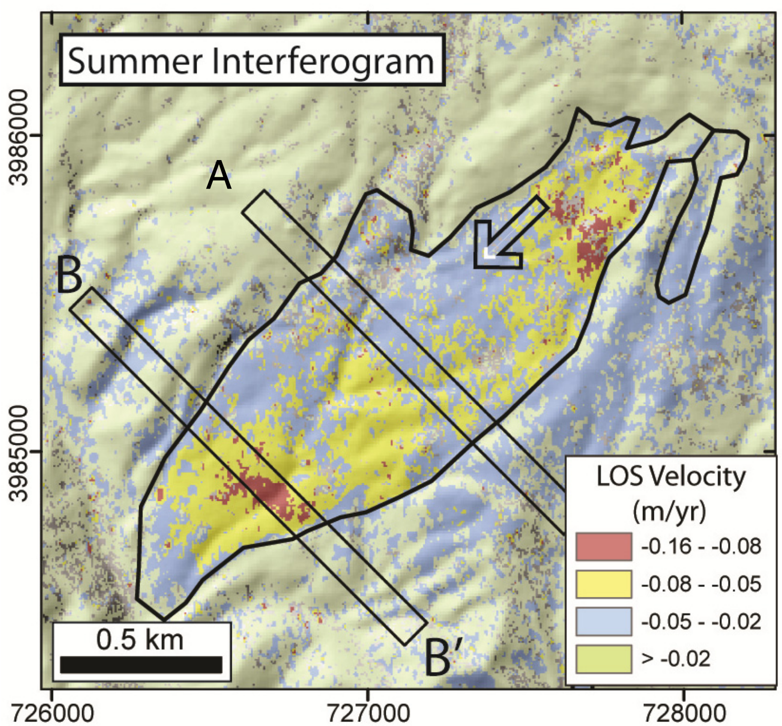

Scheingross et al, 2013, *GSA Bulletin*

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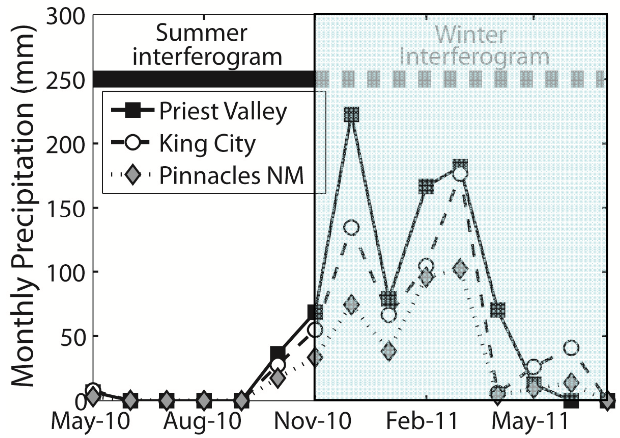

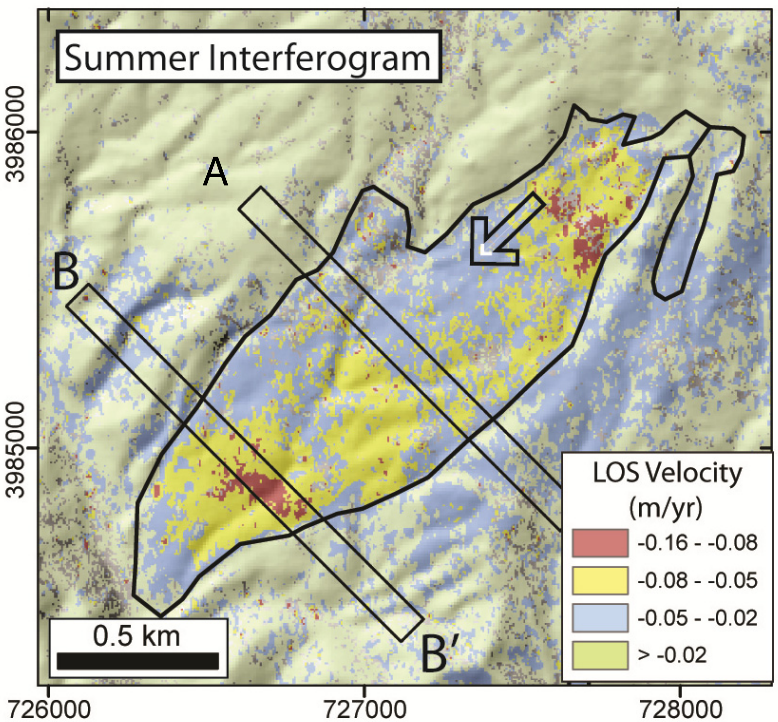

Scheingross et al, 2013, *GSA Bulletin*

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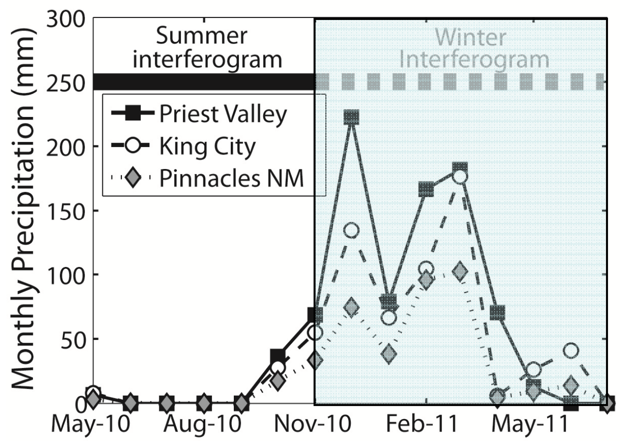
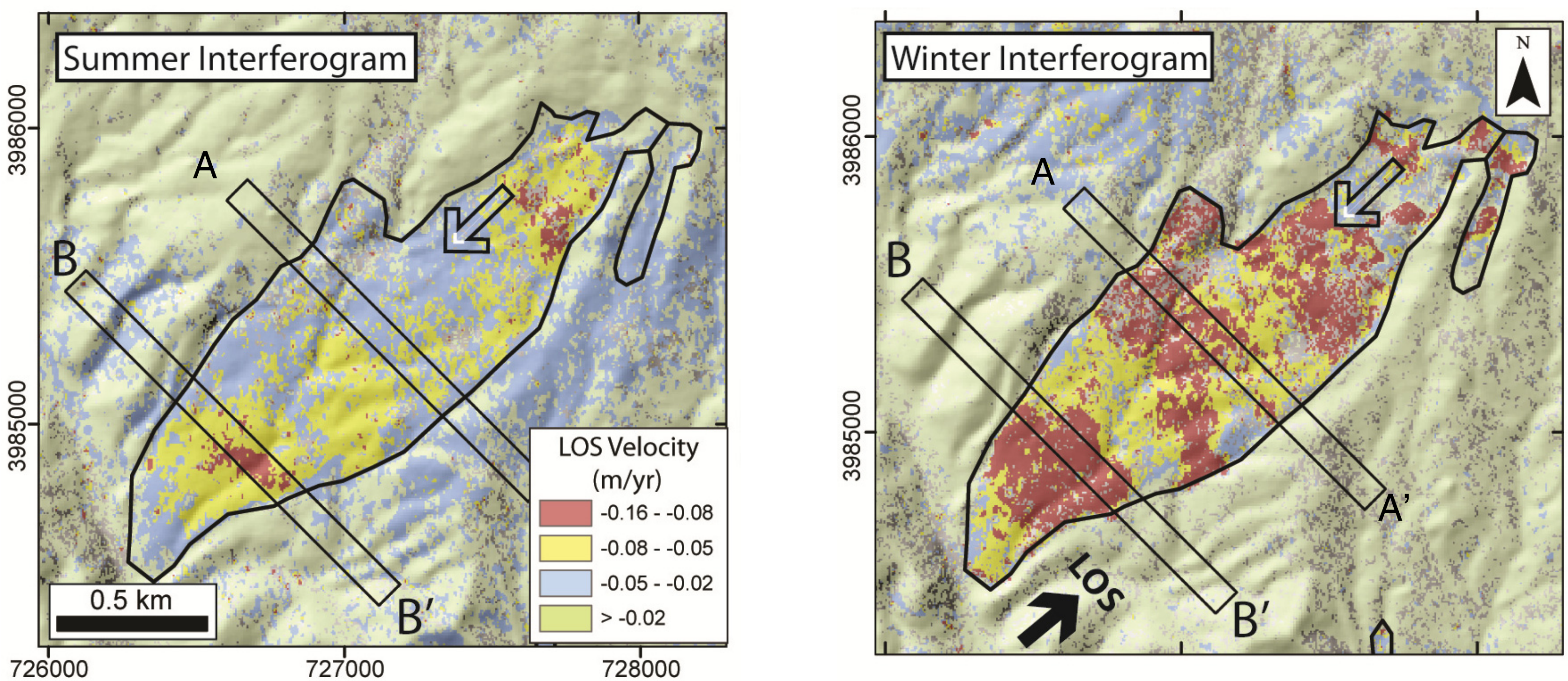
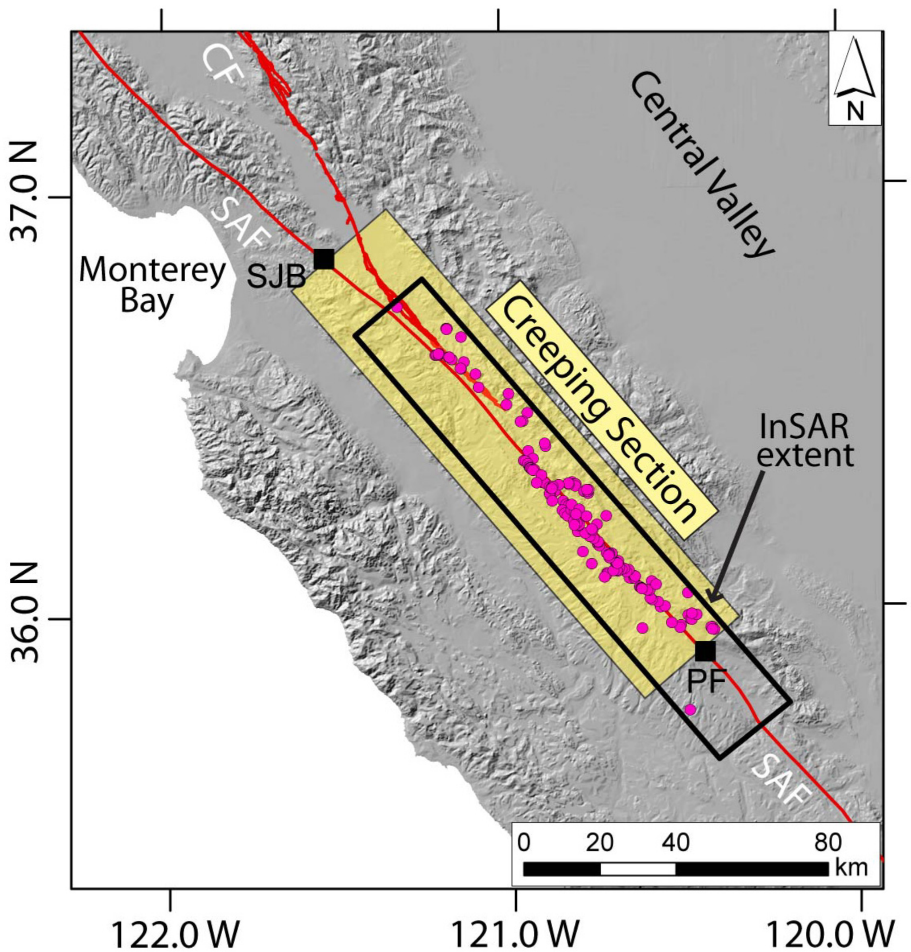




Scheingross et al, 2013, *GSA Bulletin*

Do earthflows occur along the locked SAF?



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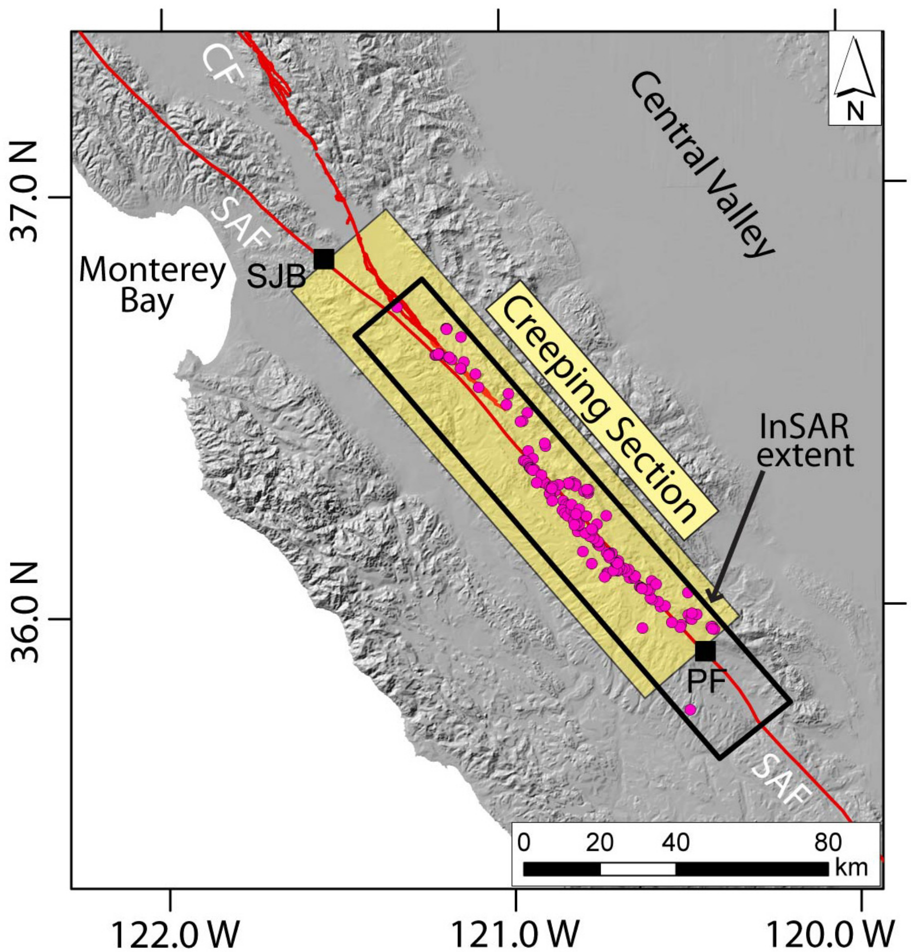

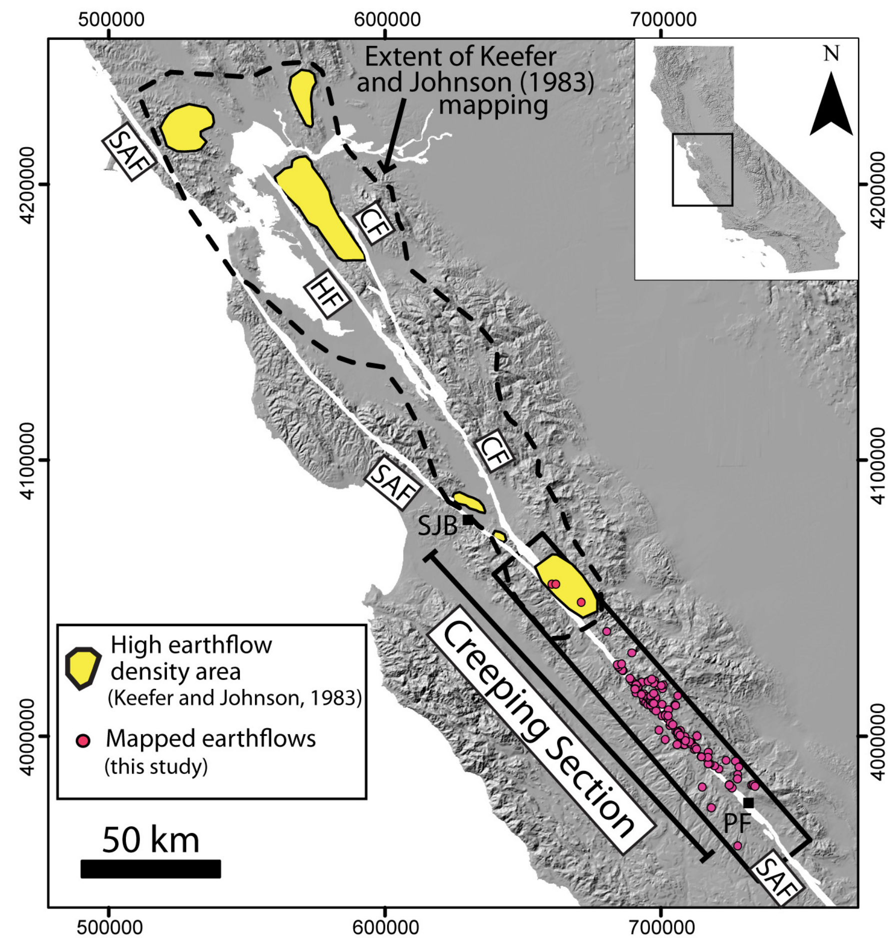

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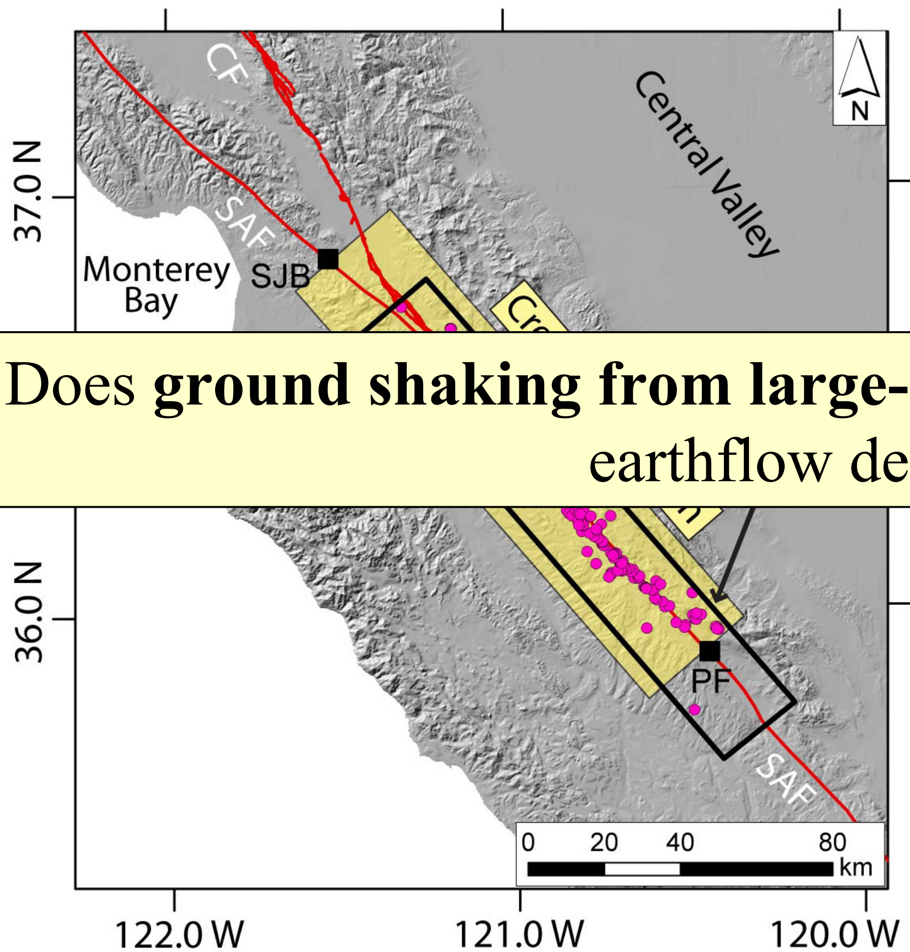
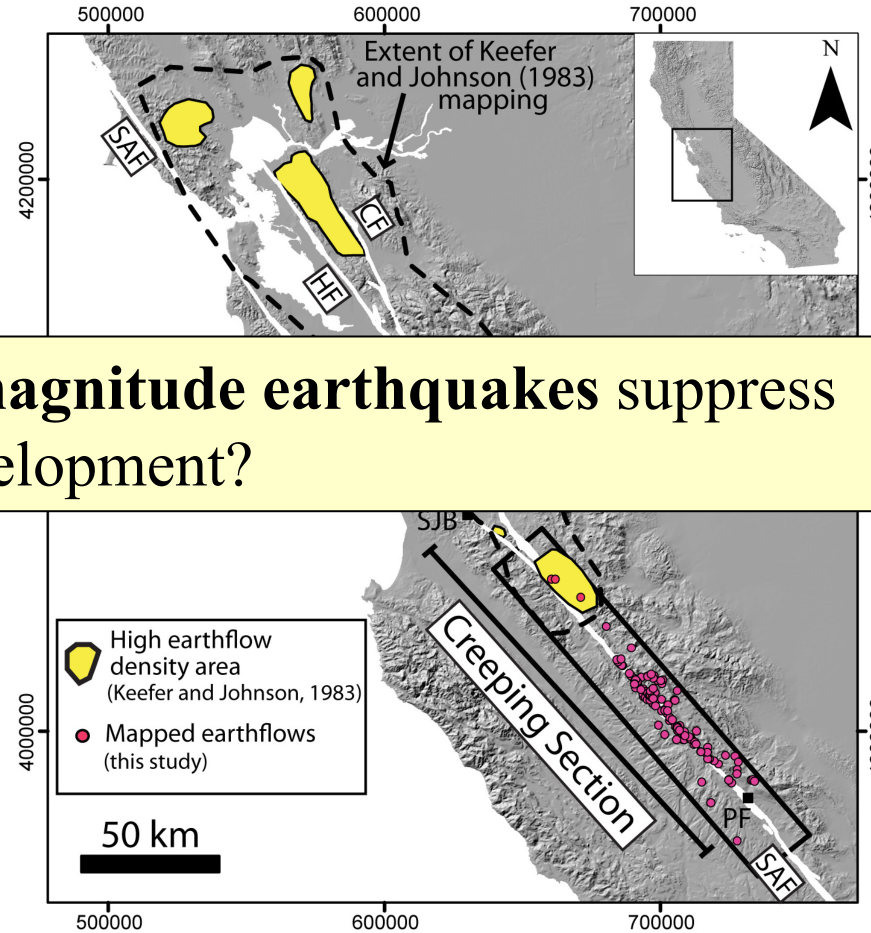




Does **ground shaking from large-magnitude earthquakes** suppress earthflow development?

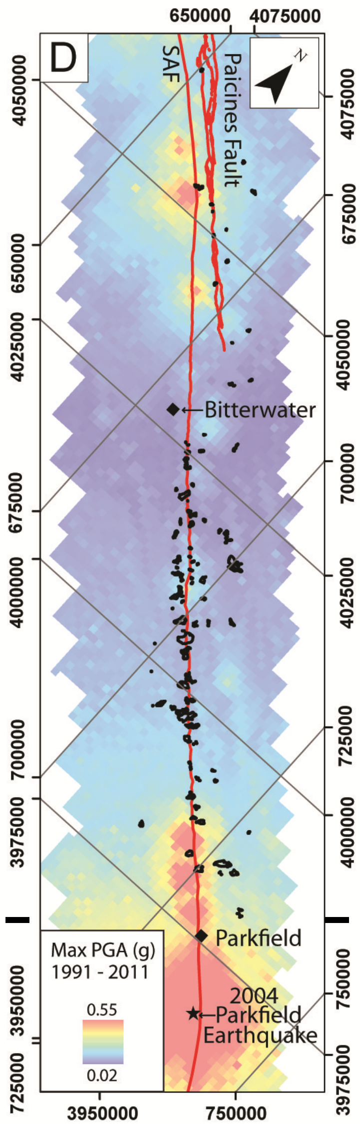
Do large-magnitude earthquakes suppress earthflows?

Peak ground acceleration (PGA) is a proxy for co-seismic landslide density (Meunier et al., 2007; Meunier et al., 2008).

Do large-magnitude earthquakes suppress earthflows?

Creeping

Locked



Predicted maximum **peak ground acceleration**
42,731 earthquakes between 1991-2011 (NCEDC)
(Boore and Atkinson, 2007)

Peak ground acceleration (PGA) is a proxy for co-seismic landslide density (Meunier et al., 2007; Meunier et al., 2008).

Frequent, small-magnitude earthquakes

Infrequent, large-magnitude earthquakes

Scheingross et al, 2013, *GSA Bulletin*

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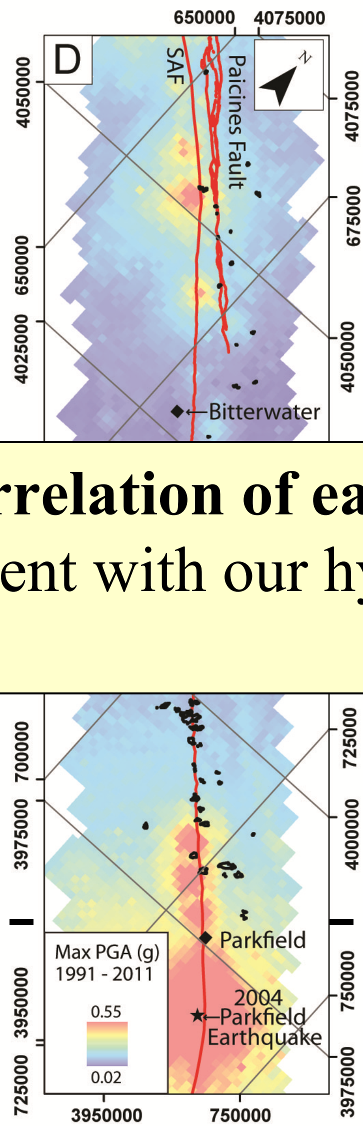

Anti-correlation of earthflows and peak ground acceleration is consistent with our hypothesis of co-seismic landslides limiting earthflow extent.

Locked

Infrequent, large-magnitude earthquakes

Predicted maximum **peak ground acceleration**
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Do large-magnitude earthquakes suppress earthflows?

Creeping

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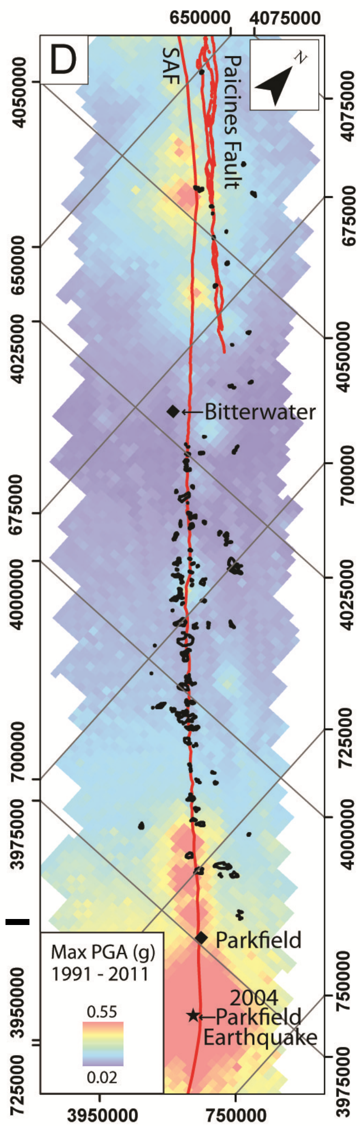

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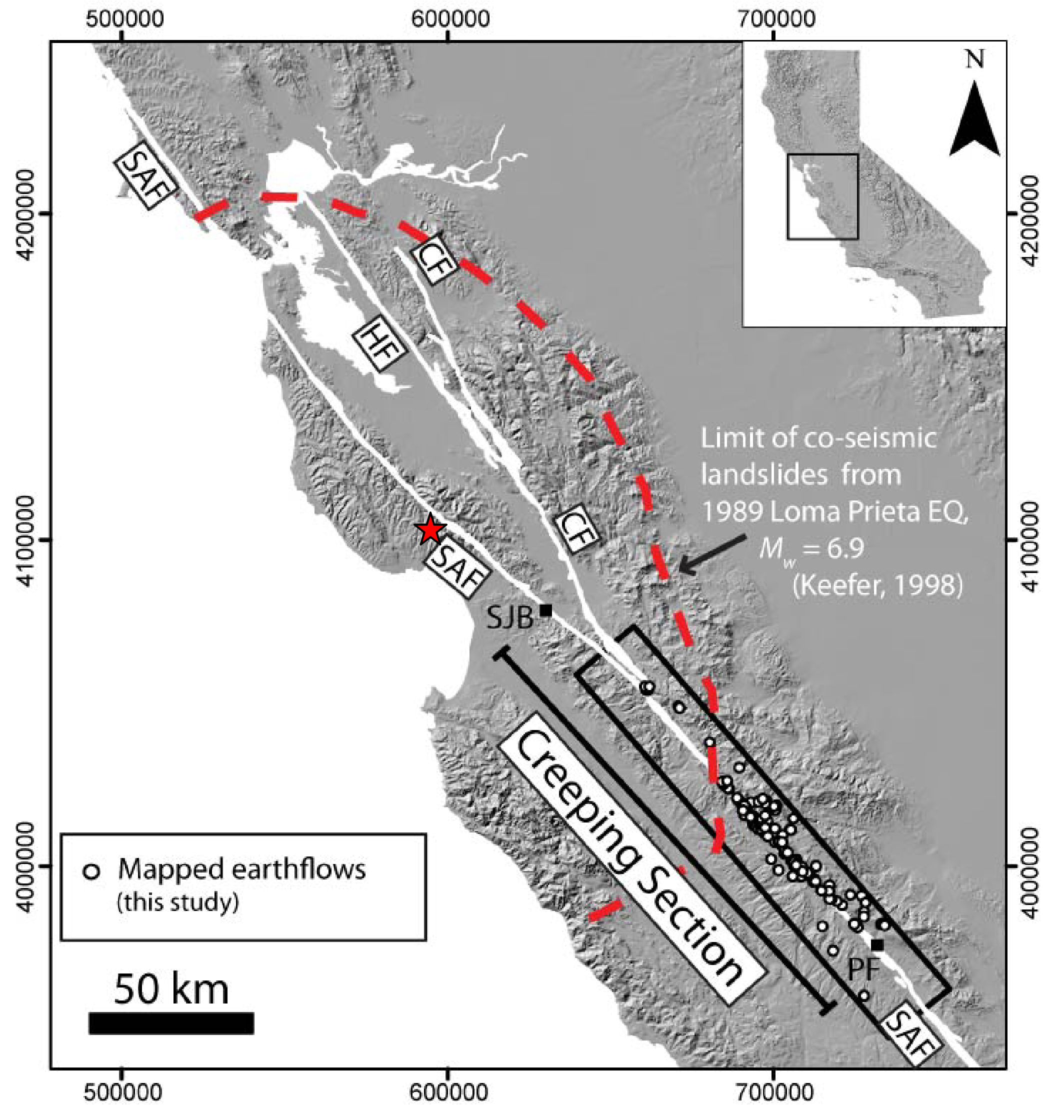
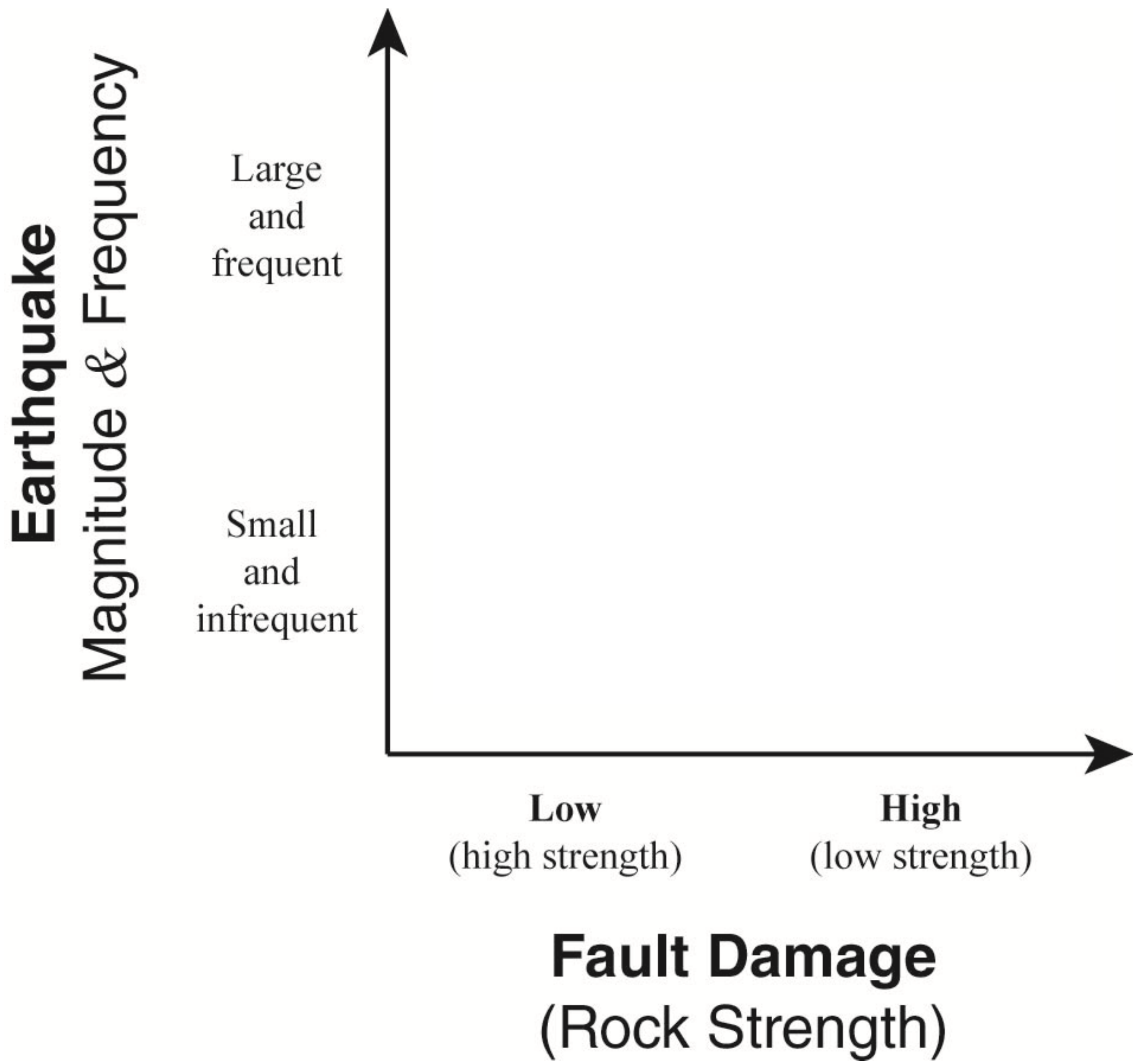


Scheingross et al, 2013, *GSA Bulletin*

Fault damage versus earthquakes



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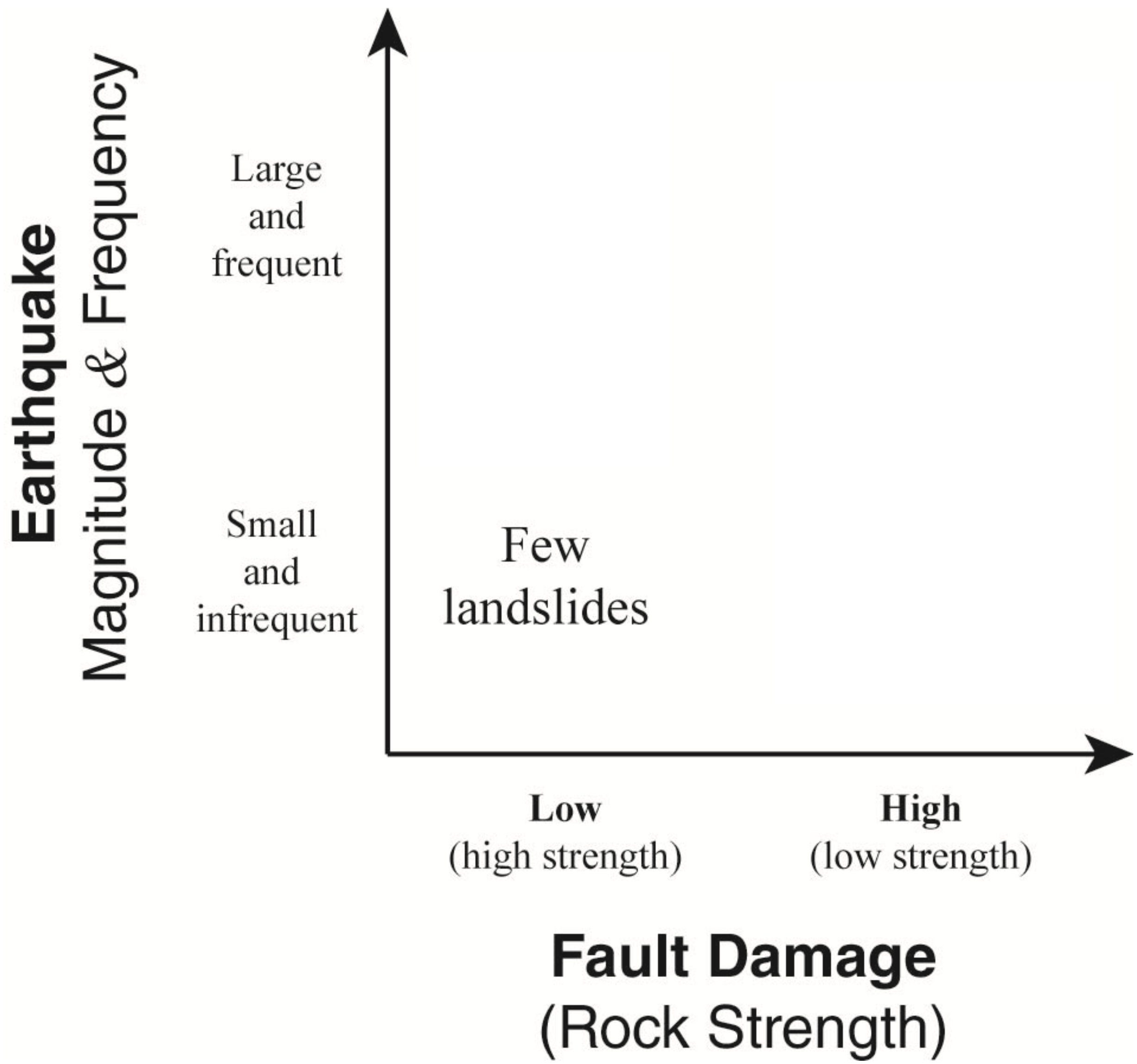

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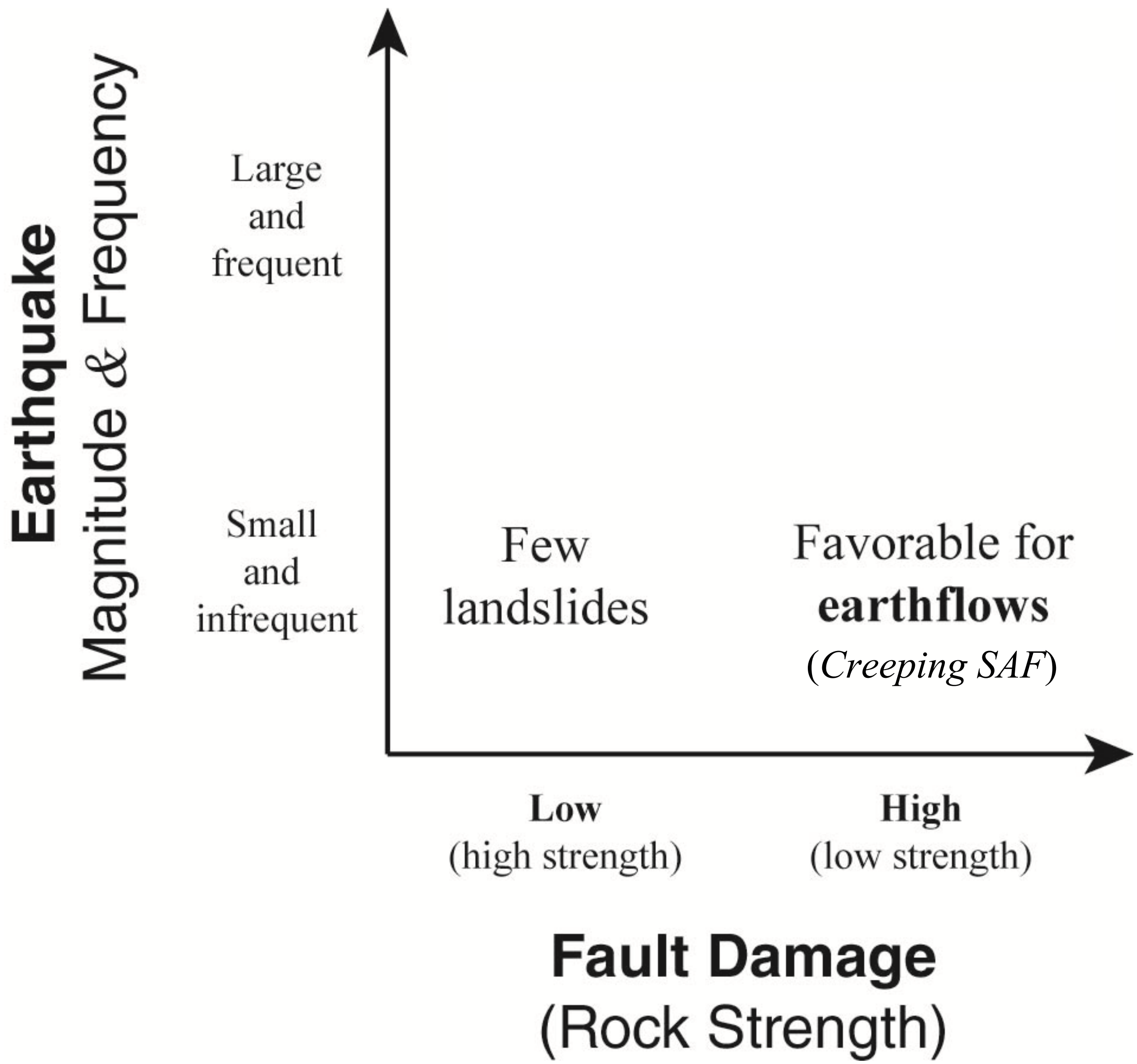

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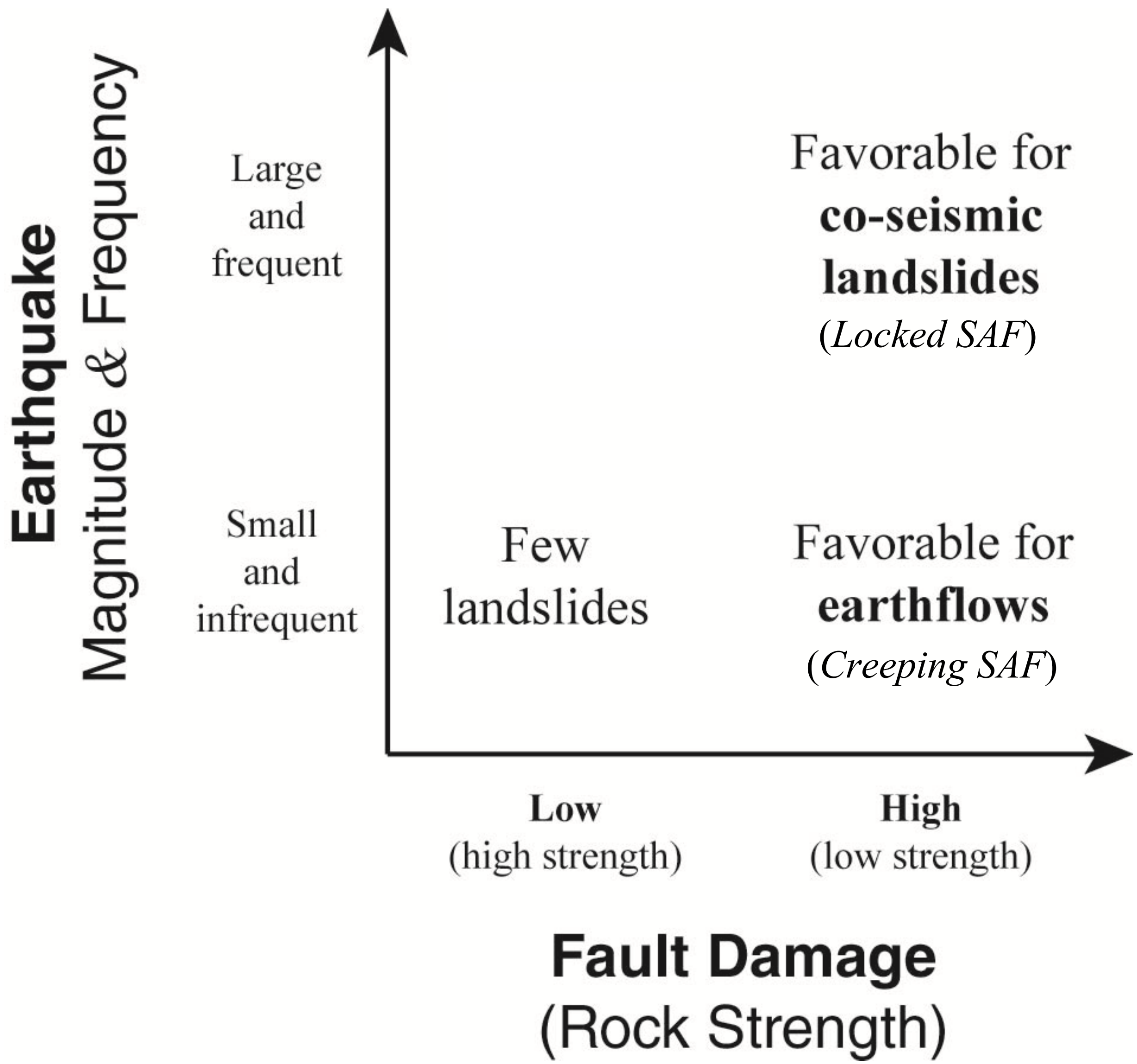

Conclusions

- Faulting introduces competing influences that can both **PROMOTE (via fault damage zones)** and **SUPPRESS (via large-magnitude earthquakes)** the occurrence of slow-moving landslides.

- Along the central SAF, fault zone damage and large-magnitude earthquakes appear to be the primary controls on the occurrence of slow-moving landslides.

    - Predictions of earthflow spatial distribution in other tectonically active landscapes should account for these variables.

    - Total annual precipitation and seasonal variation in precipitation may be important secondary controls on earthflow movement.