Finding Earthquakes in the Rock Record

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an NSF+USGS center

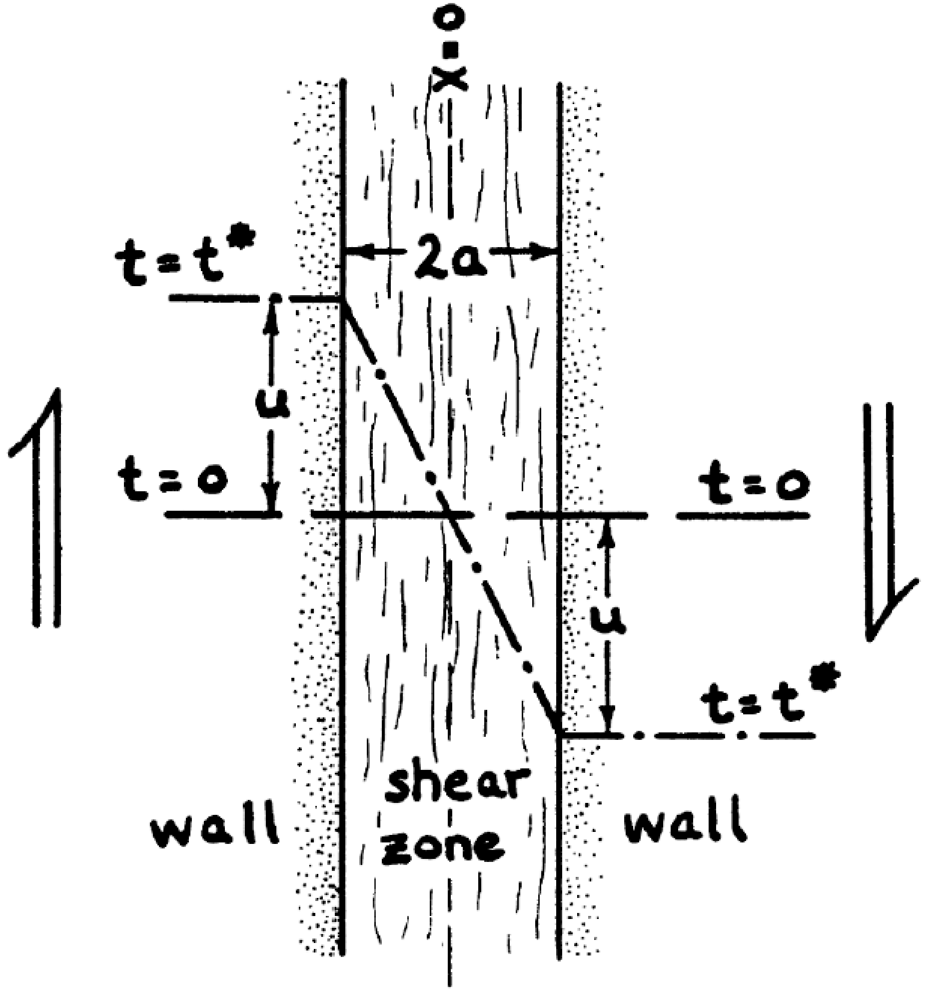
Why Do We Want to Find Earthquake Slip in the Rock Record?

1) Quantifying earthquake temperatures/earthquake energy budgets
2) Understanding spatial context of earthquake slip
3) Timing of earthquakes over longer timescales

Temperature Rise During an Earthquake

$$\Delta T = \frac{\tau V t}{\rho c_p a}\left(1 - 4i^2 \operatorname{erfc}\left(\frac{a}{\sqrt{4\alpha t}}\right)\right)$$

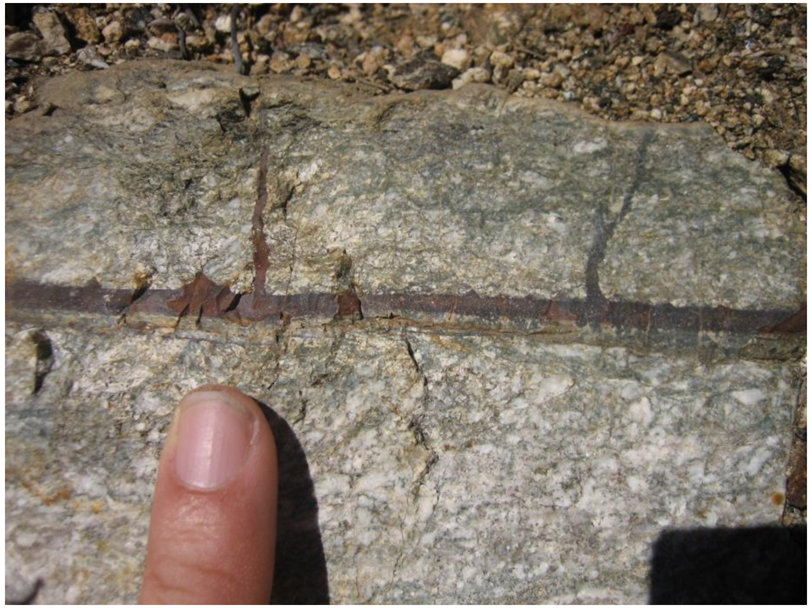
- τ = **shear stress**
- **V = slip velocity**
- **t = time**
- ρ = **density**
- **c_p = heat capacity**
- **a = ½ slip zone thickness**
- α = **thermal diffusivity**



Carslaw and Jaeger, 1959; Cardwell, 1978; Lachenbruch, 1986

Earthquake Temperature Proxies

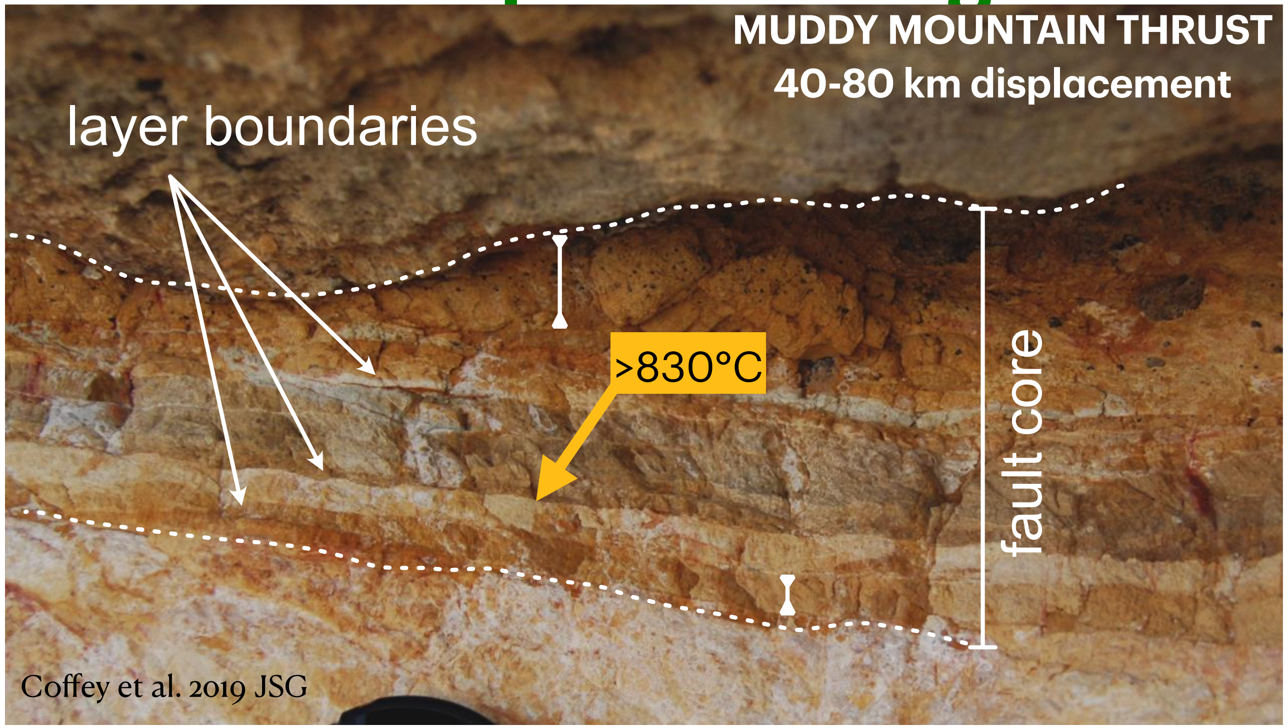
- **Pseudotachylyte** (*e.g. Sibson 1975*)
- **Clay Alteration** (*e.g. Schleicher et al., 2015*)
- **Decarbonation** (*e.g. Han et al. 2007*)
- **Low Temperature Thermochronometry** (e.g. *Ault et al. 2015*)
- **Thermal Maturity of Organic Matter** (*Bustin 1983; Polissar et al., 2011; Sakaguchi et al., 2011*)



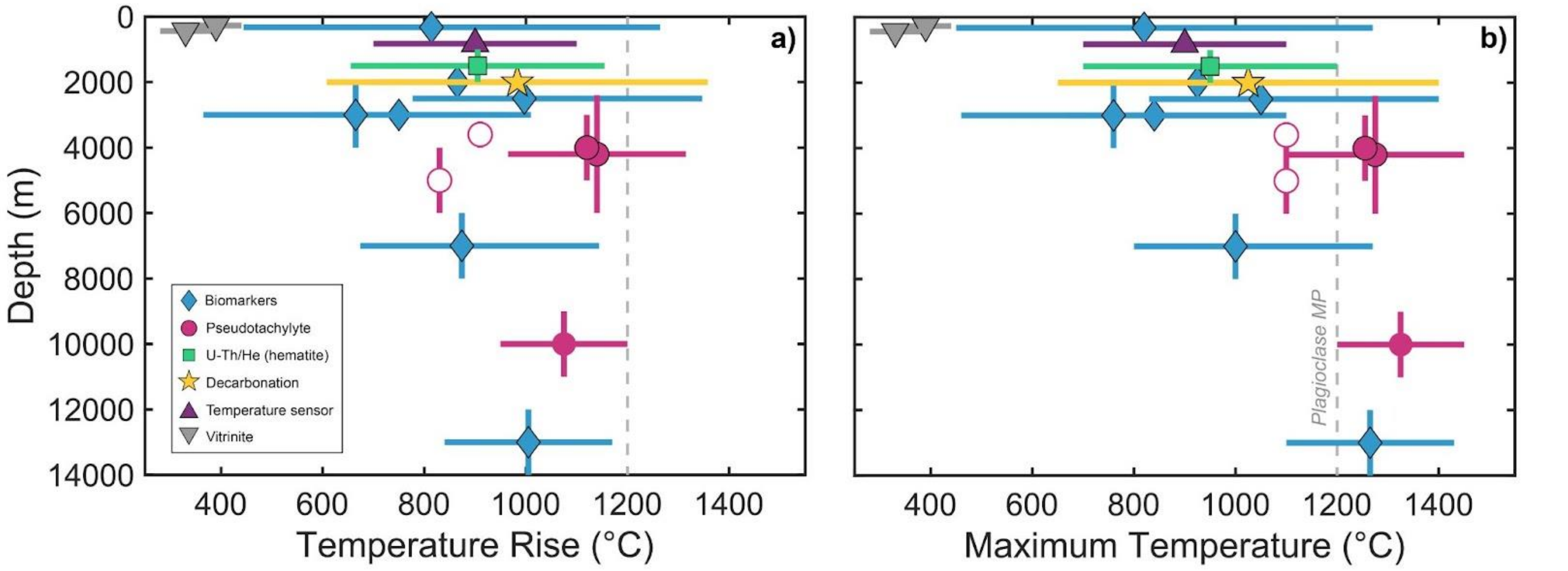
Santa Rosa Mylonite (courtesy of Christie Rowe)

1. Creating a Dataset of Faults with Temperature Signals

- **Depth range: 0.27- ~14km**
- **Temperature rise from a range of proxies**
- **Rock types: mud, granite, gneiss, dolostone, limestone, slate, schist, sandstone, and peridotite**



1. Maximum Earthquake Temperature

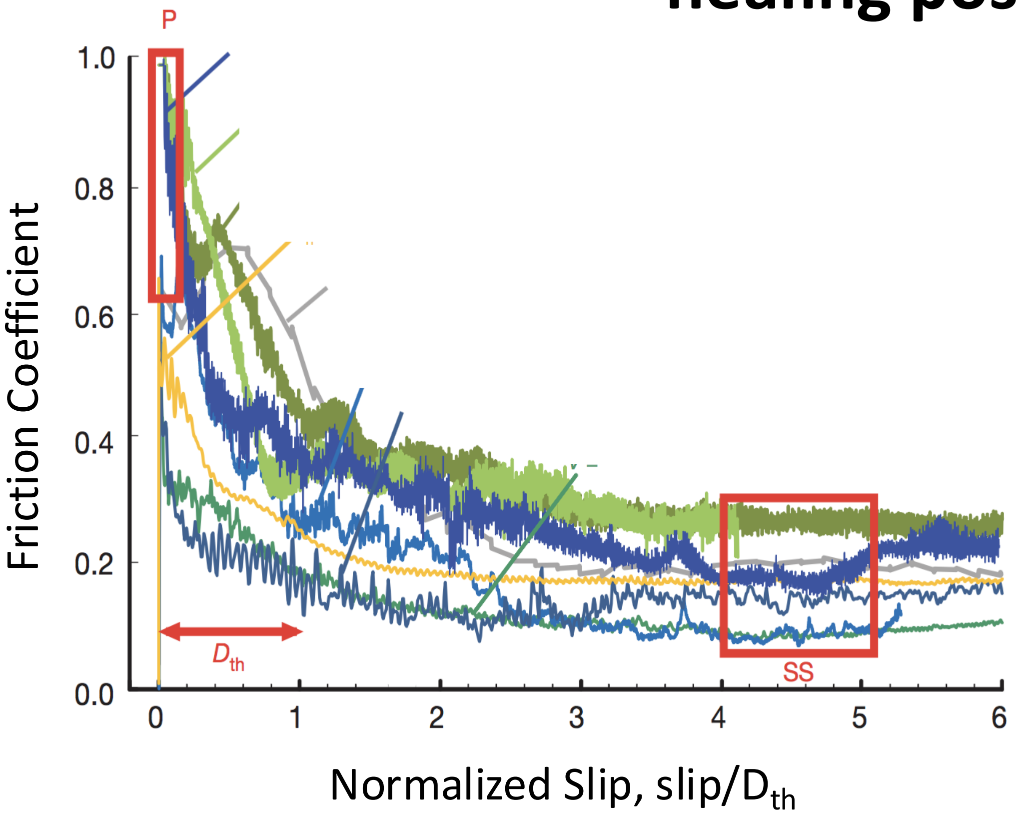


Coffey et al., 2023

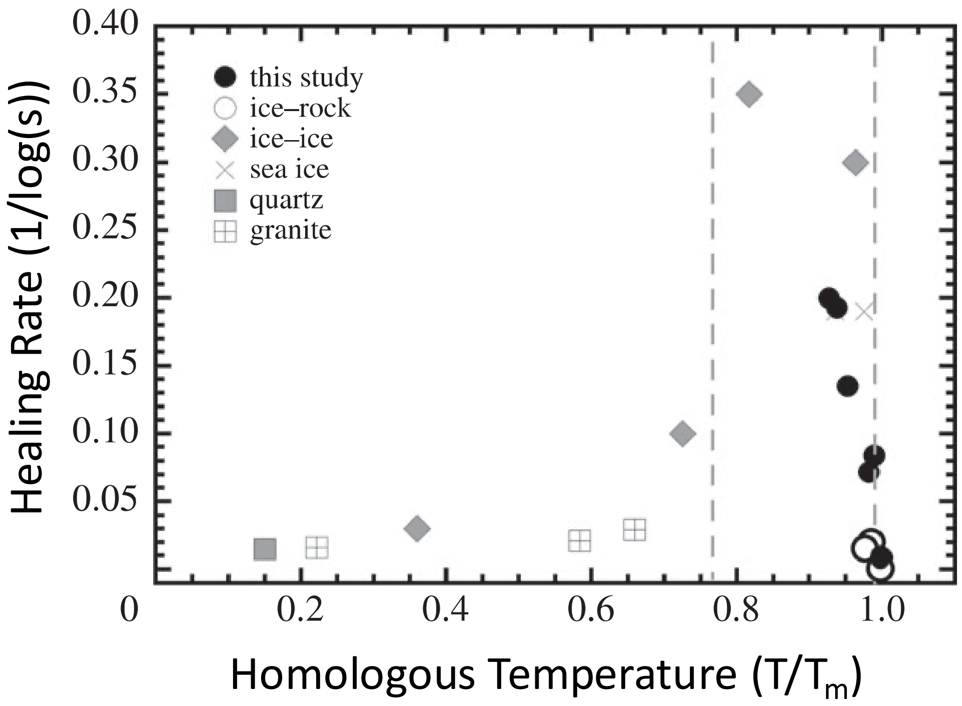
Muddy Mountain fault, Coffey et al. (2019); Central SAF, Coffey et al., 2022; Papaku Fault, Coffey et al., 2021; Hundalee, Coffey et al., 2023; Punchbowl, Savage & Polissar (2019); Marin thrust, Coffey et al., 2023; Pasagshak, Savage et al. (2014); Japan Trench, Rabinowitz et al. (2020), Brodsky et al. (2019); Spoleto, Collettini et al. (2013), Gole Larghe fault, Di Toro (2005), Pittarello (2008); Monte Maggio fault, Collettini et al. (2014); Skeeter fault, Kirkpatrick et al. (2009), Kirkpatrick et al. (2012); Nojima fault, Itsuki et al. (2003), Boullier (2011); Wasatch DZ, Ault et al. (2015), Mcdermott et al. (2017); Nankai splay & frontal thrust, Sakaguchi et al. (2011)

1. Impacts Coseismic and Postseismic Rheology

- **Temperature dependent rheologies for the earthquake cycle**
- **Both rapid weakening during seismic slip and rapid healing post-seismically**

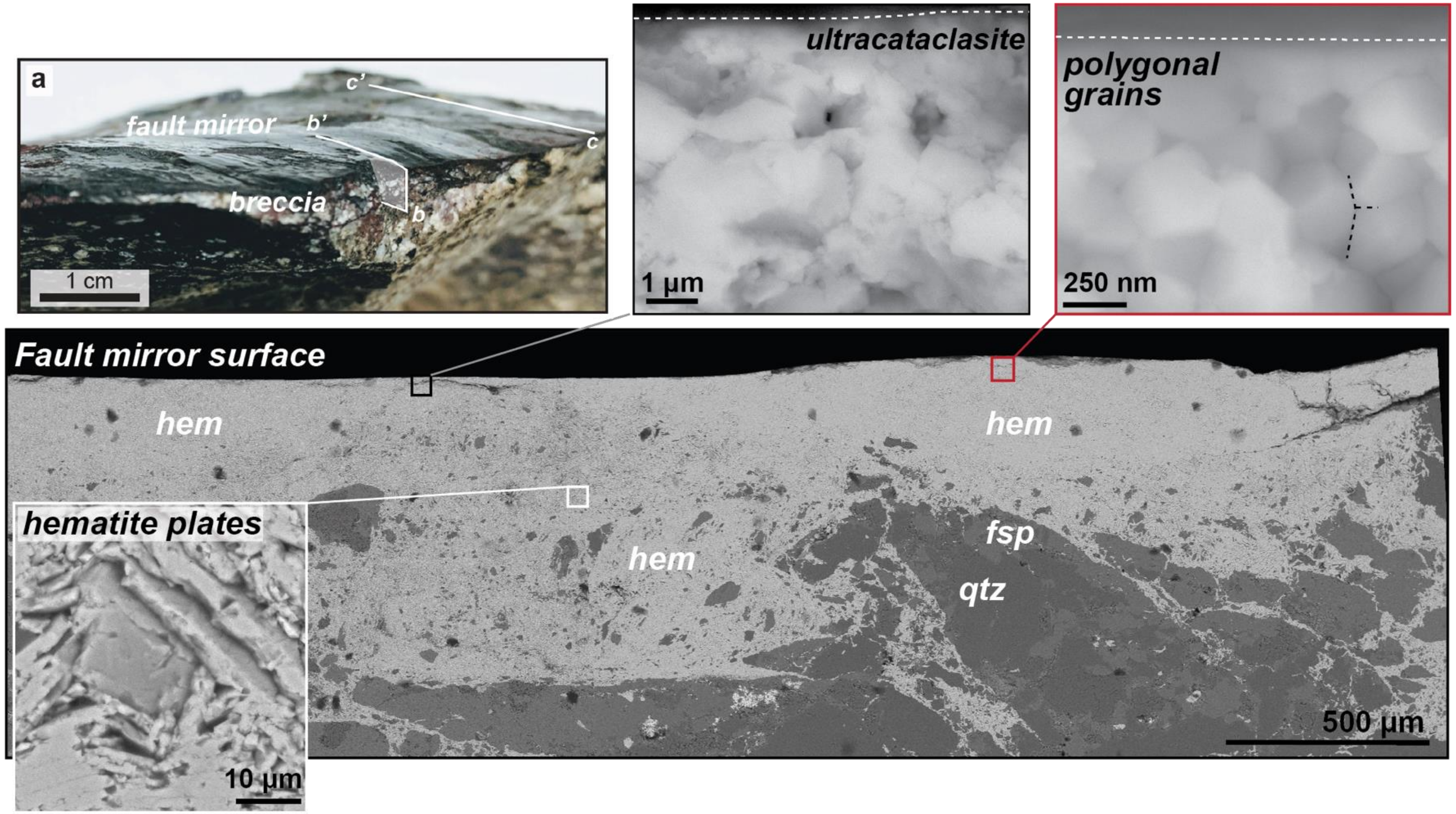


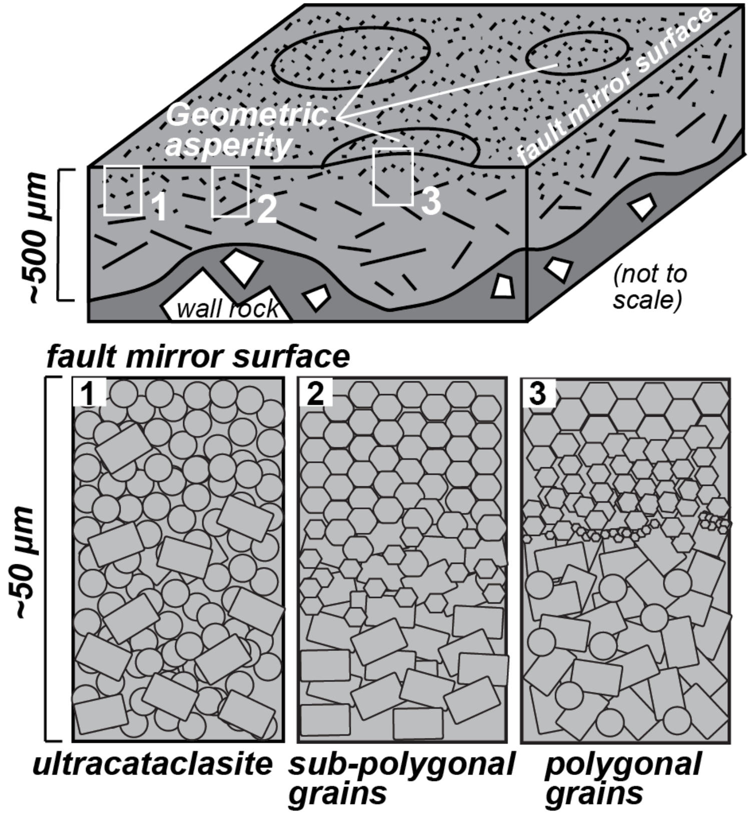
Di Toro et al. (2011)



McCarthy et al. 2017)

1. But Temperature Rise is Heterogeneous…





400 ºC   600-1000 ºC   >1200 ºC

- **coseismic temperature rise varies by 100s of ºC over sub-mm scales on a single slip surface**
- **textures reflect different coeval dynamic weakening mechanisms**

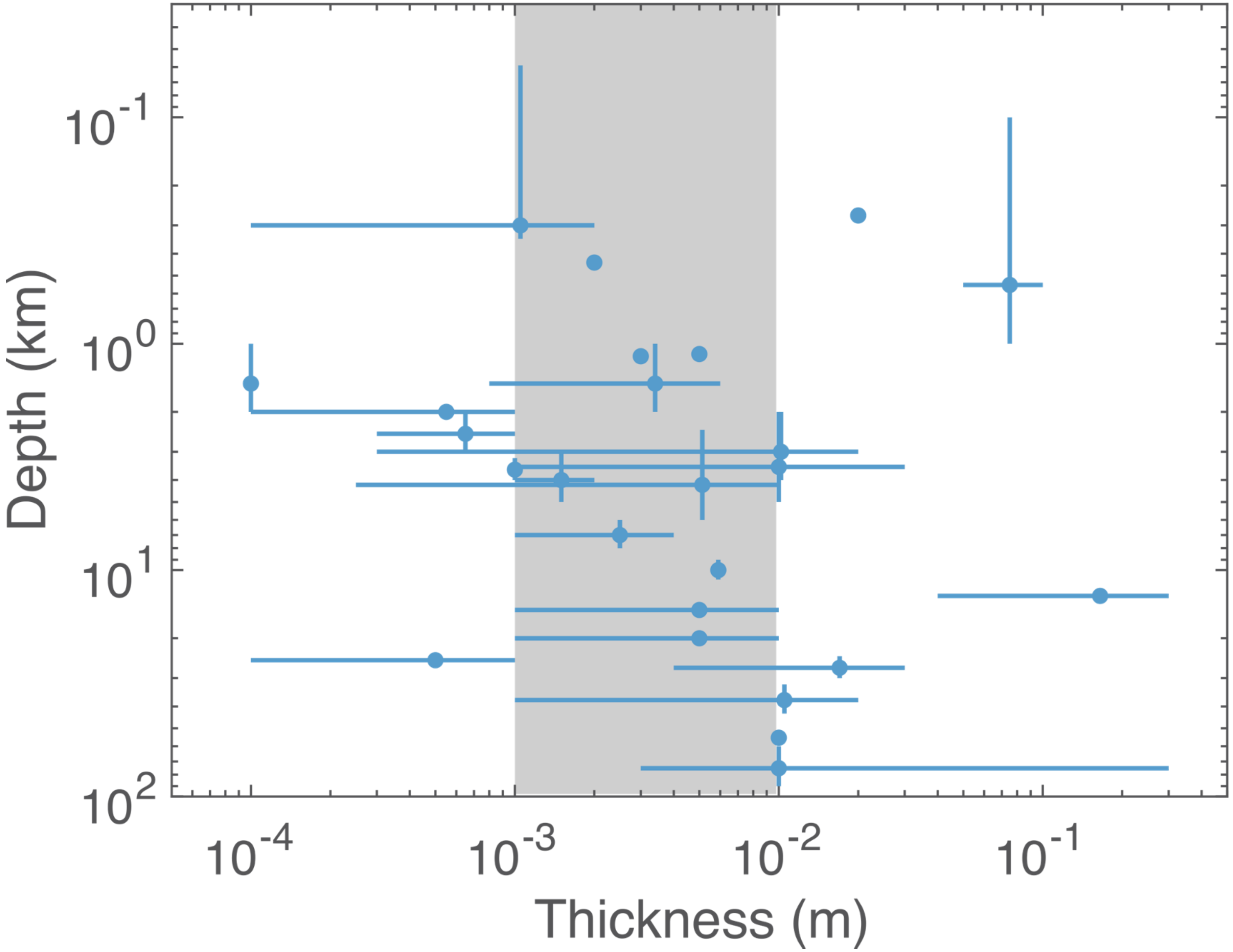
McDermott et al., 2023, JGRSE

2) Understanding Spatial Context of Earthquake Slip

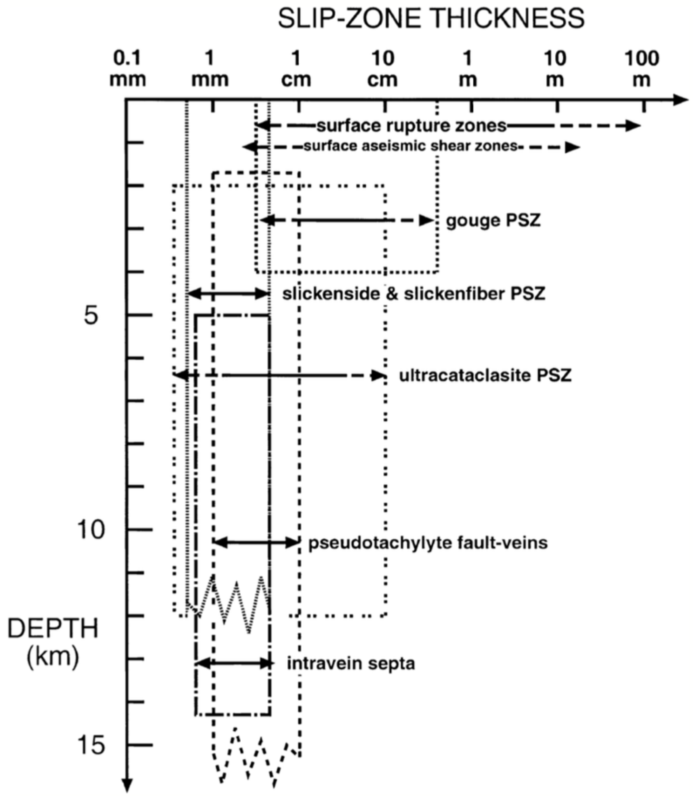
- **Fault zones are complex and earthquakes are localized**
- **Where earthquakes propagate through fault zones?**

Nester (2008)

2) Thickness is mm-cm in Scale, Independent of Depth

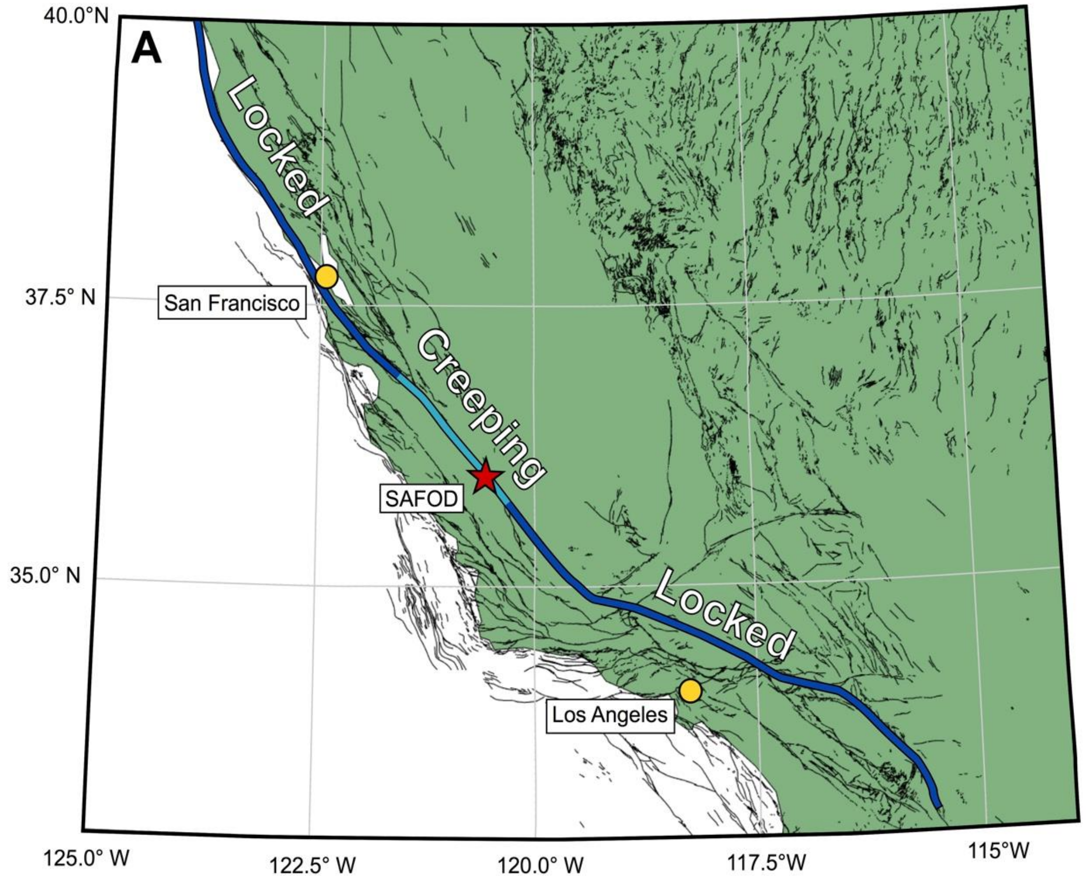


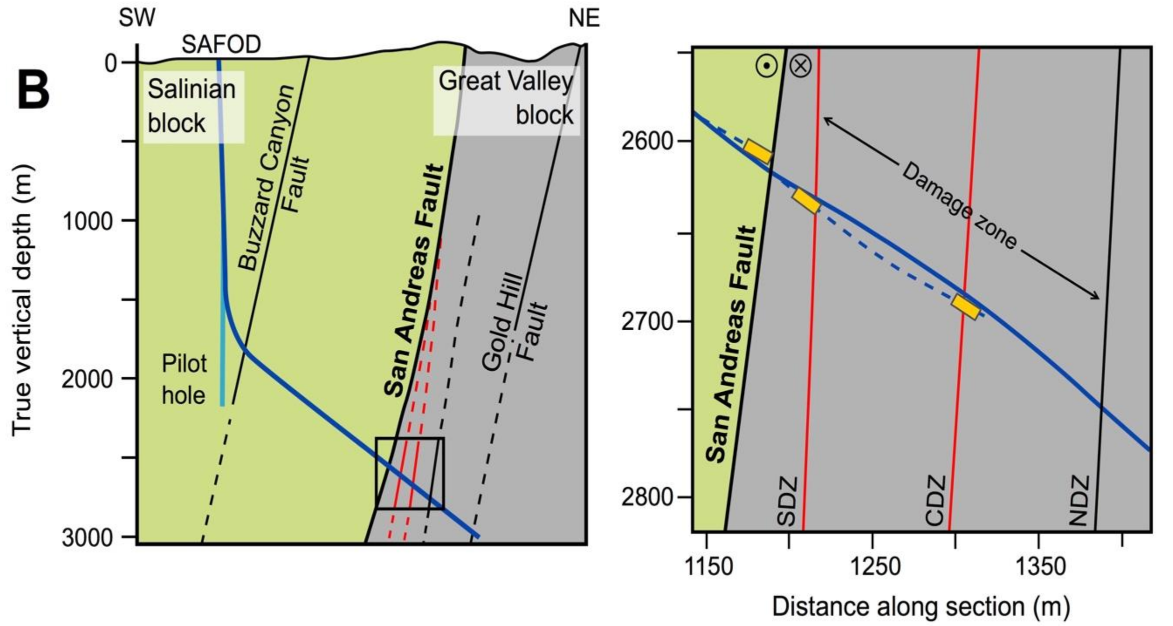
Savage and Rowe, in revision



Sibson, 2003

2. Finding Earthquakes in Creeping Faults

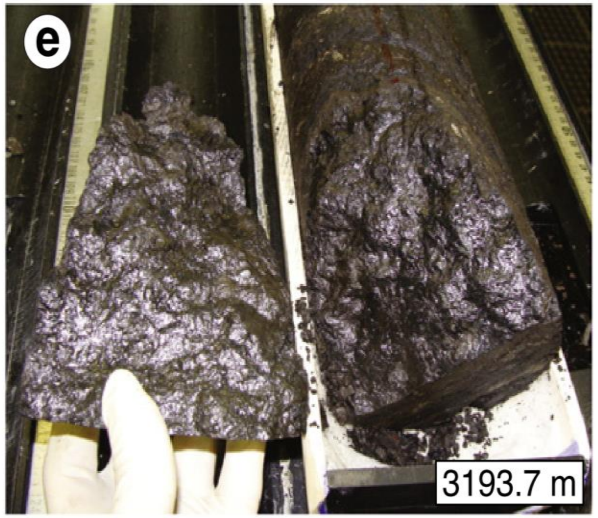


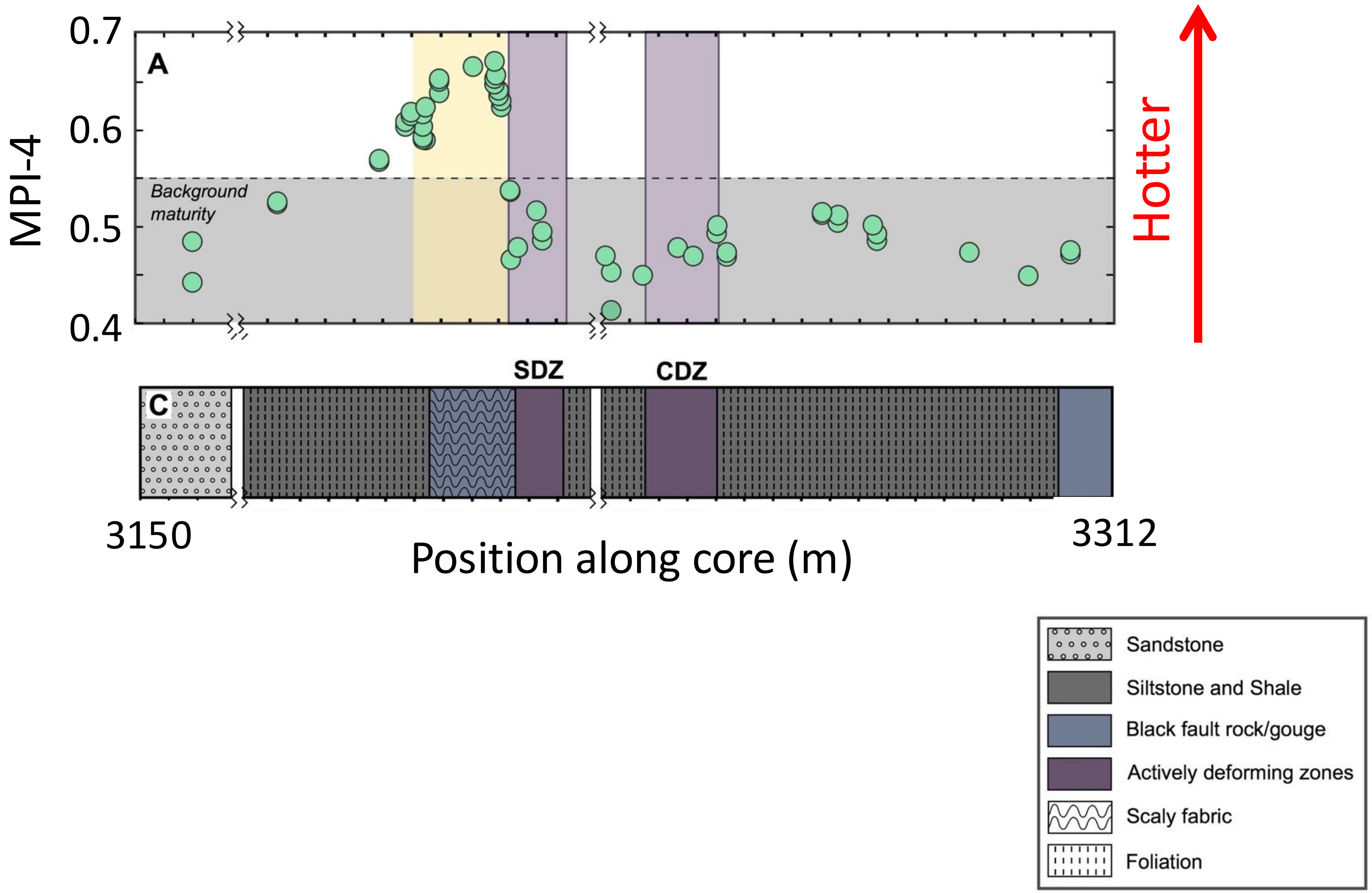


Coffey et al., 2022

Modified from Holdsworth (2011)

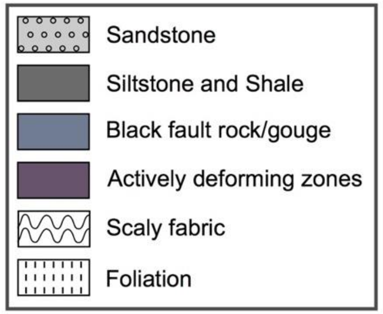
2. Earthquake Evidence at SAFOD

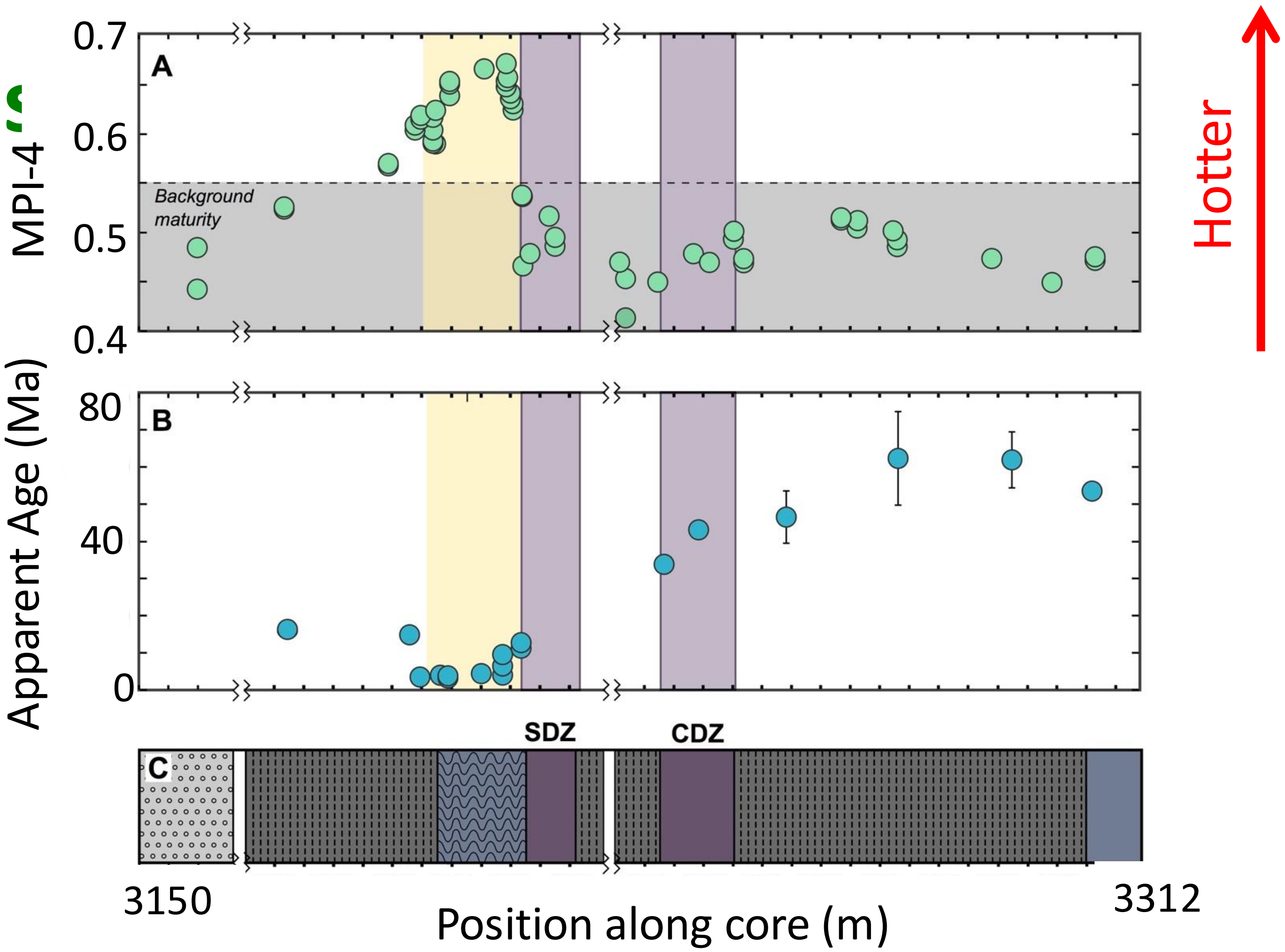




Coffey et al., 2022

Timing of Earthquakes

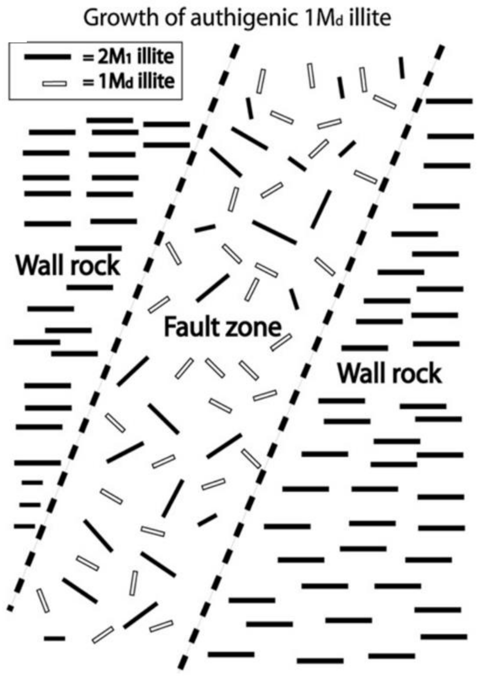




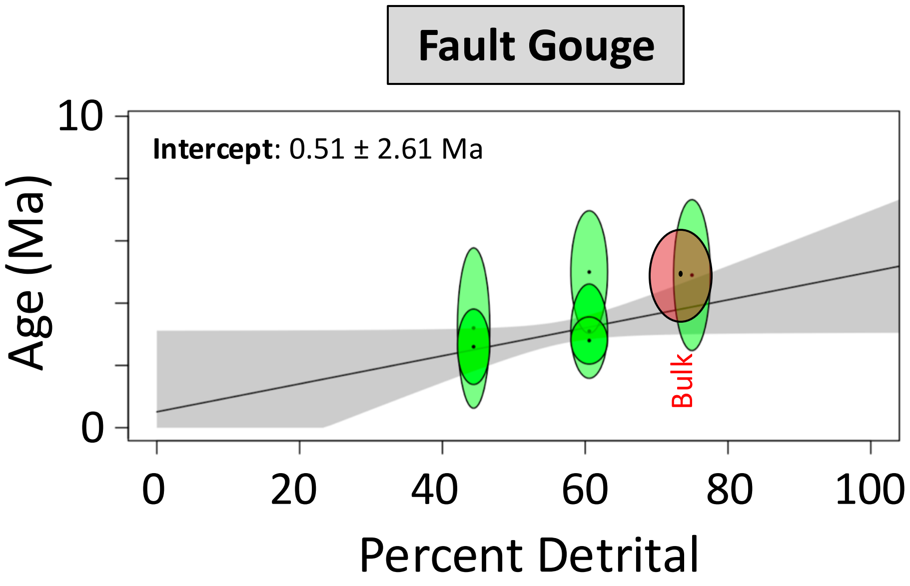
Coffey et al., 2022

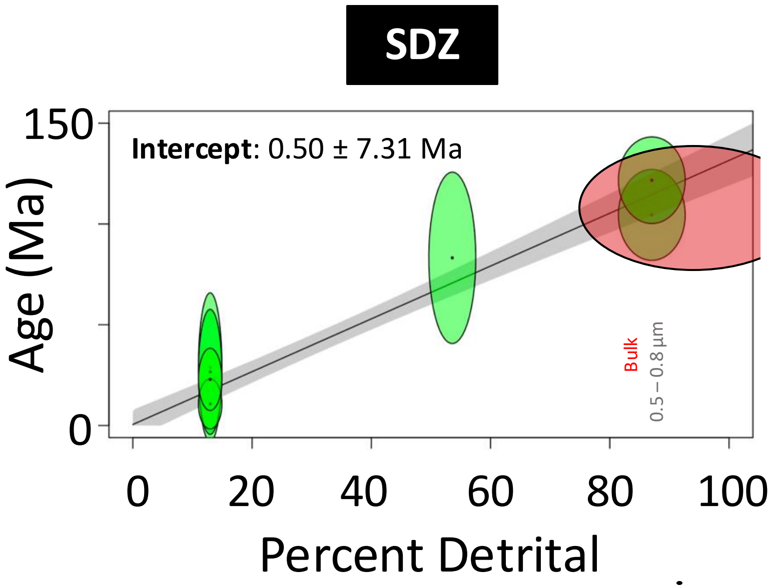
3. Timing of Earthquakes

- **WORK IN PROGRESS**
- **Separating authigenic clay fraction shows that authigenic ages are younger than the bulk ages**



Haines et al. (2008)

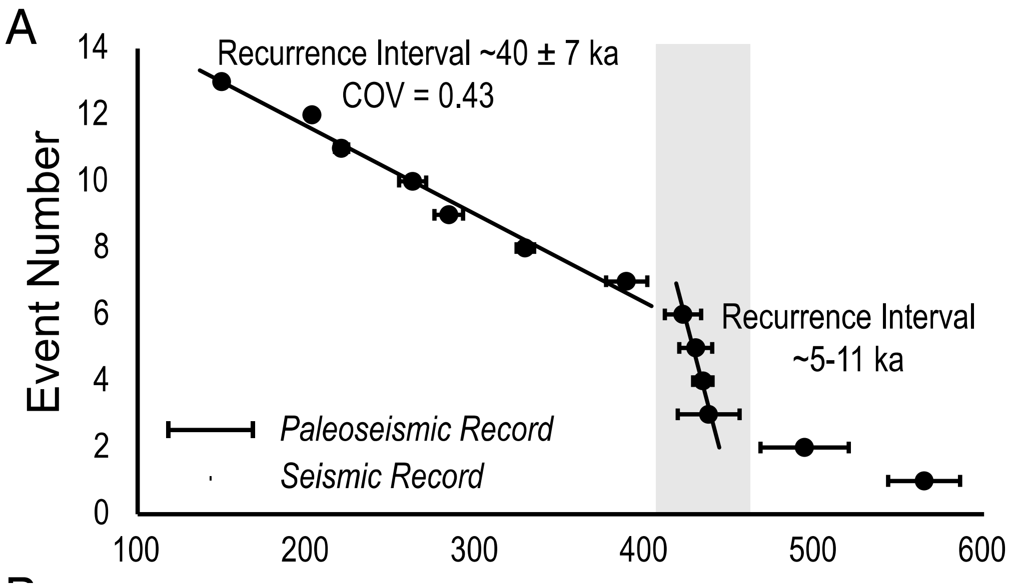




Everd et al., in prep

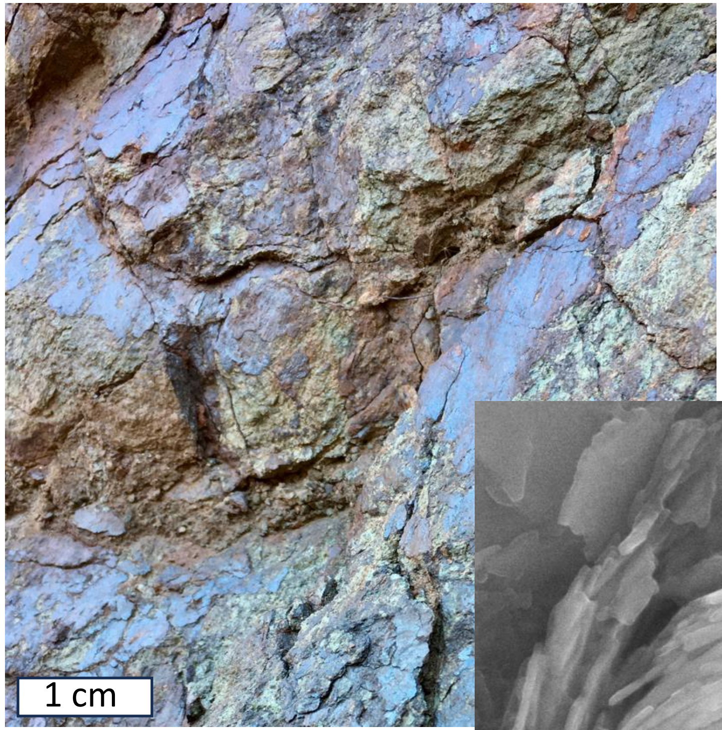
3. Timing of Earthquakes – dating fluid flow

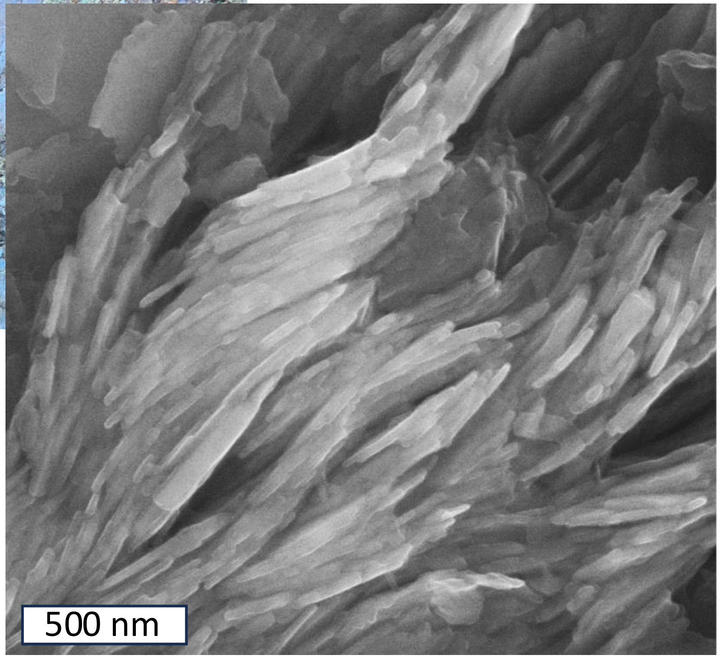
- **Calcite vein dating from the Rio Grande Rift**
- **Evidence of earthquake clustering over ~10,000 yr timescale**
- **Transient behavior not measurable over shorter timescales**

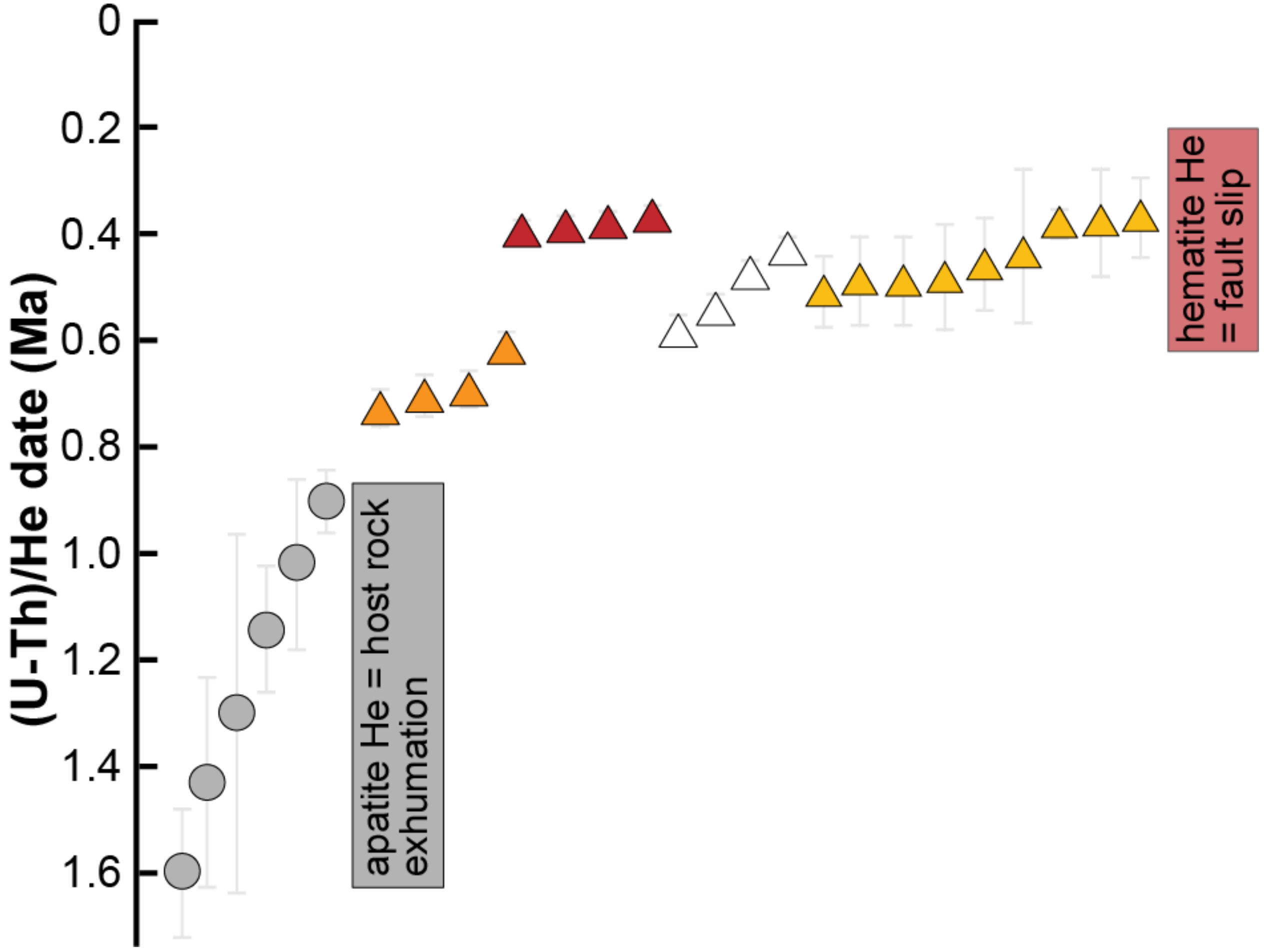


Williams et al. 2017

3. Timing of Transient Slow Slip







Moser et al., 2017, *EPSL*; DiMonte et al., 2022, *Geology*

Conclusions/Applications for SCEC

- **Temperature proxies are useful for finding earthquakes, contextualizing slip processes, developing long term records**
- **Considering longer timescales will mean considering more complex fault behavior, e.g. partitioning patterns among sub-parallel faults over time?**
- **More data are needed in the subsurface, more drilling?**

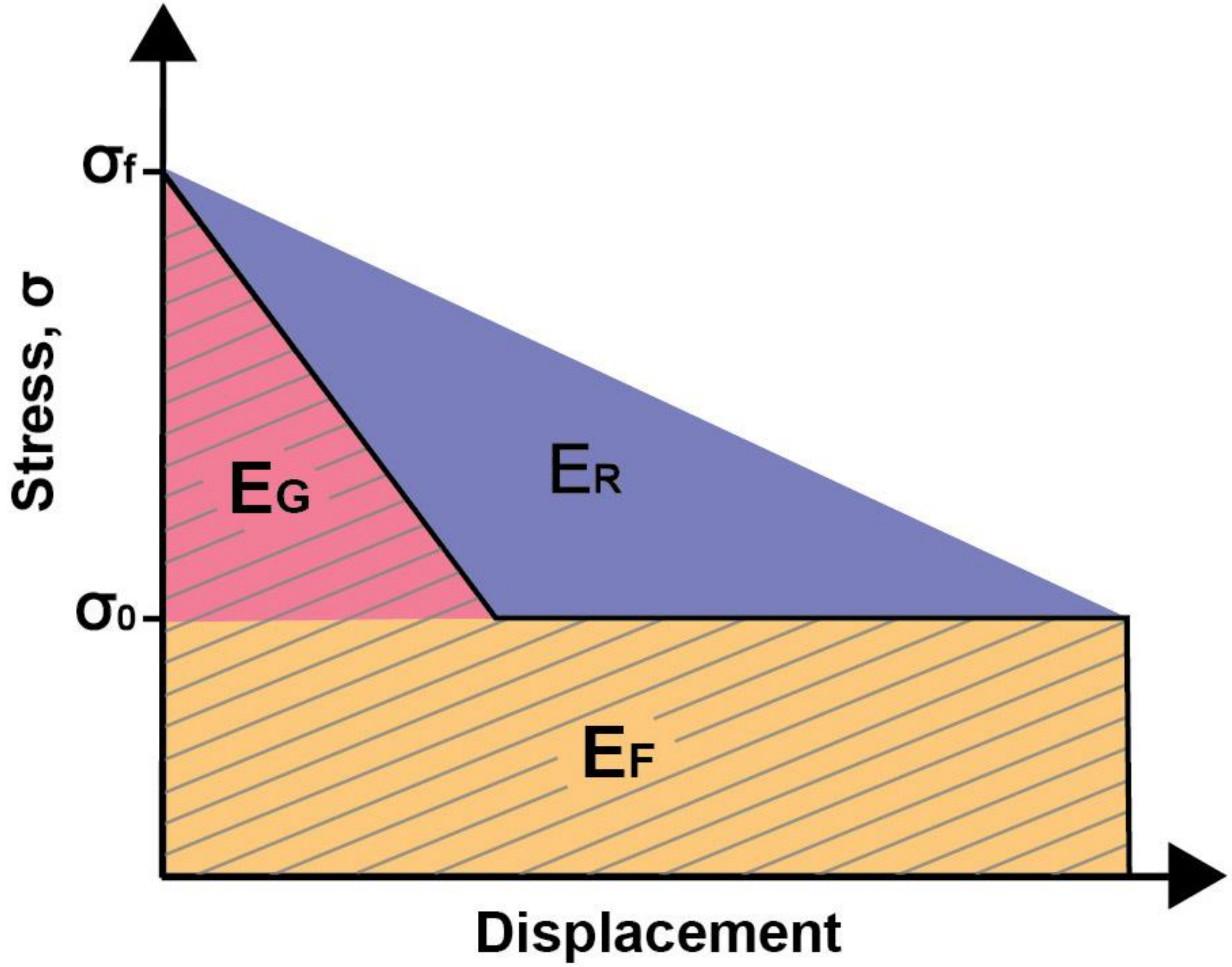
Extra Slides

Applications for SCEC

- **Focusing on energy balance rather might be way to move the needle on fault rupture modeling**

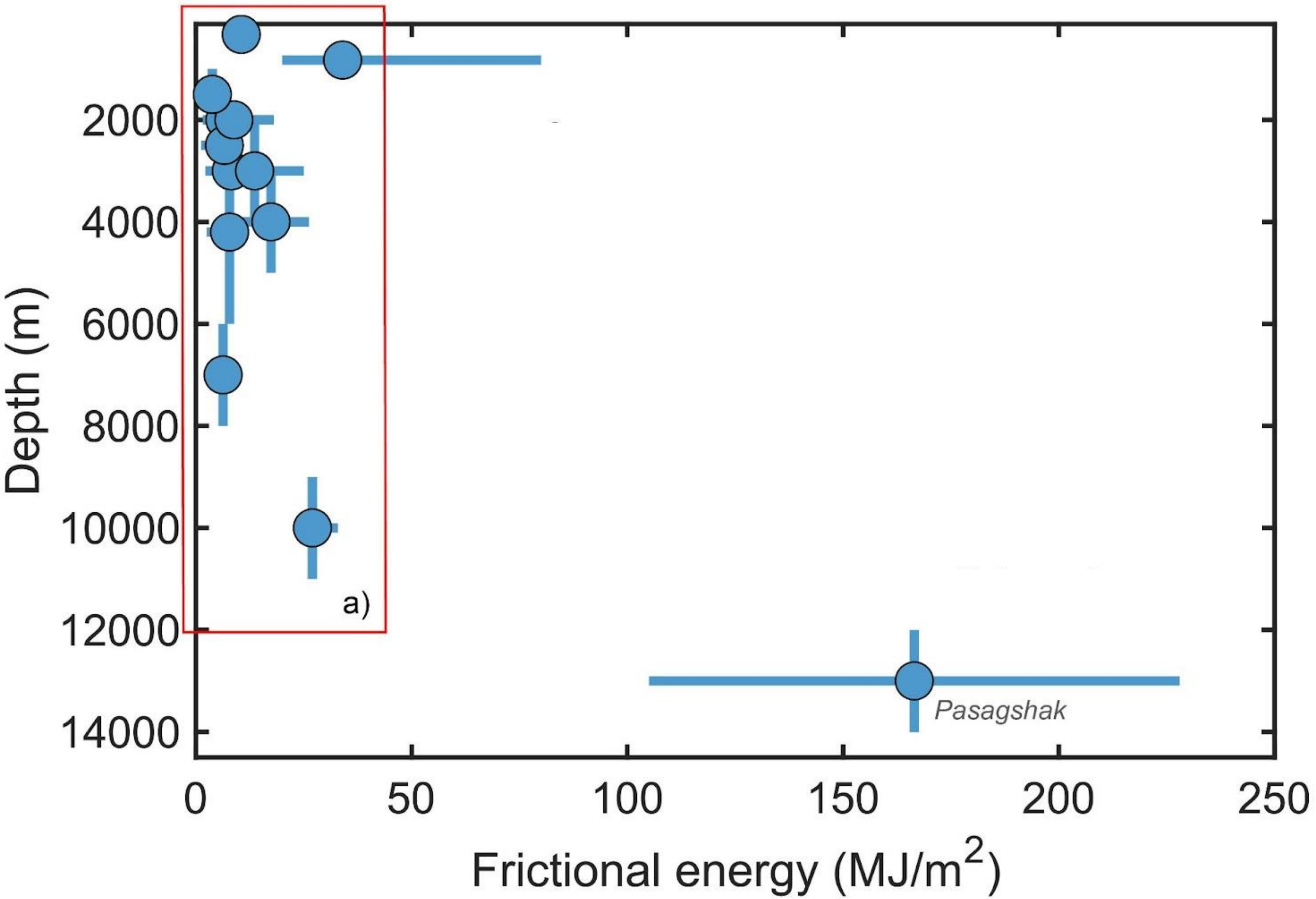
The Earthquake Energy Budget

$$\Delta T = \frac{\tau V t}{\rho c 2a}$$



Kanamori and Rivera, 2006

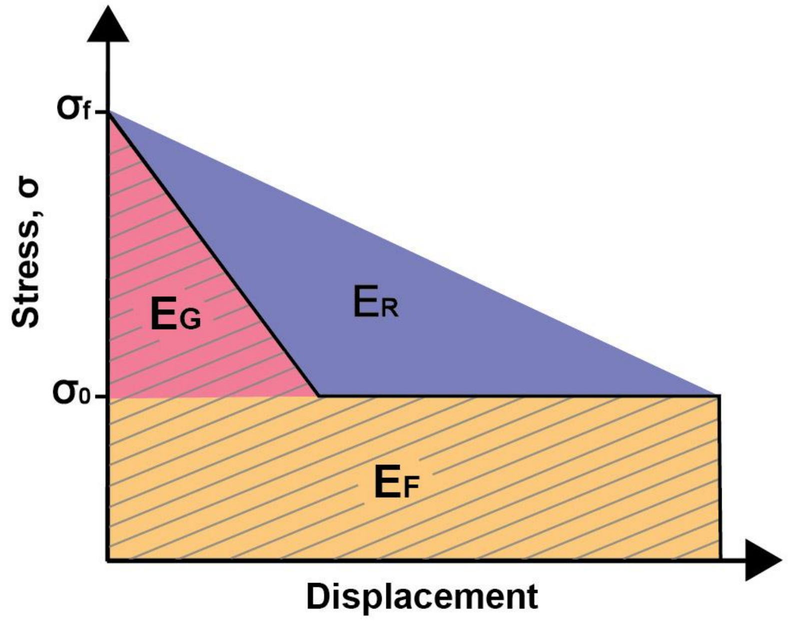
Frictional Energy



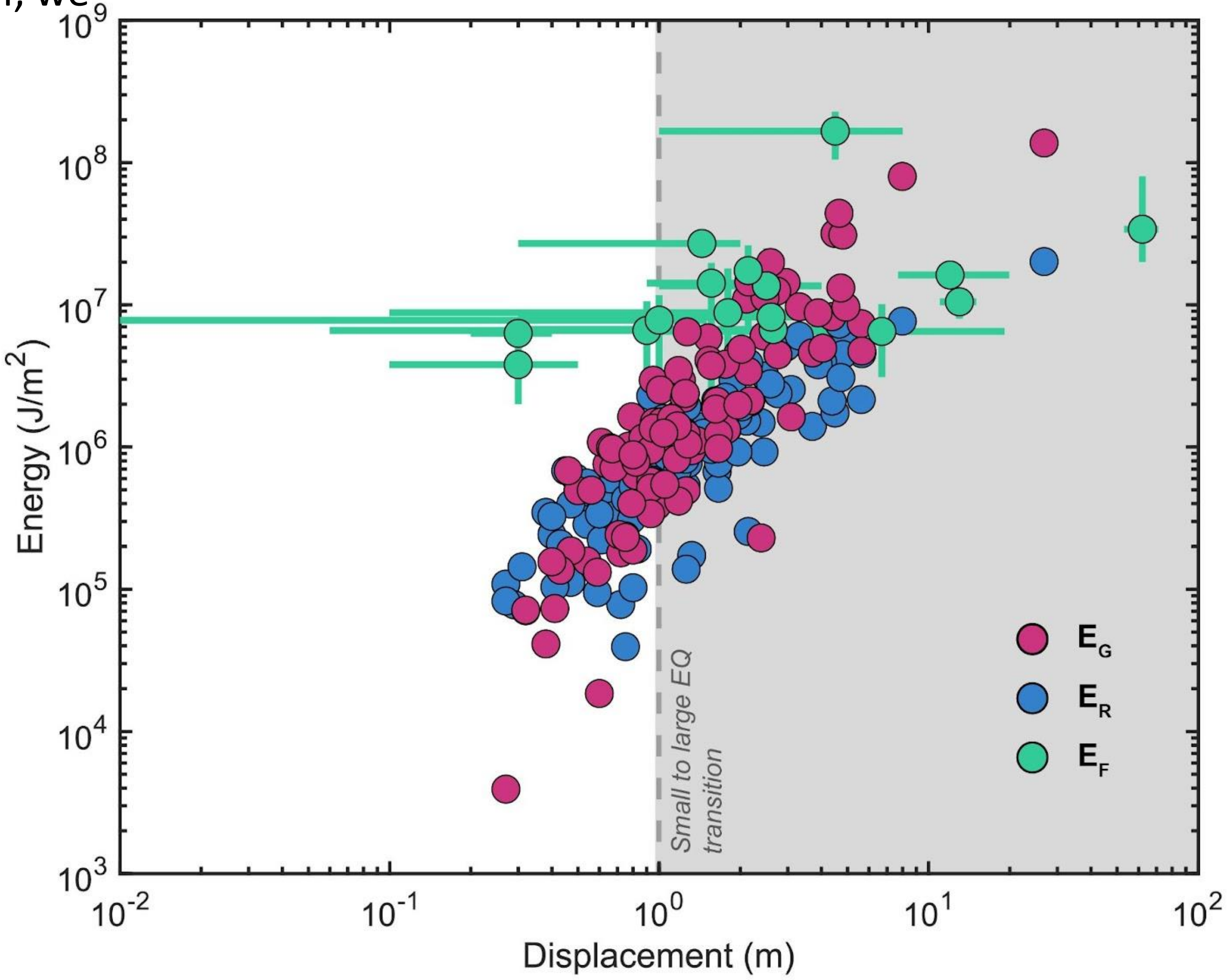
fey et al., 2023

Balancing the Budget

If we assume a normal stress based on depth and friction, we can estimate a displacement

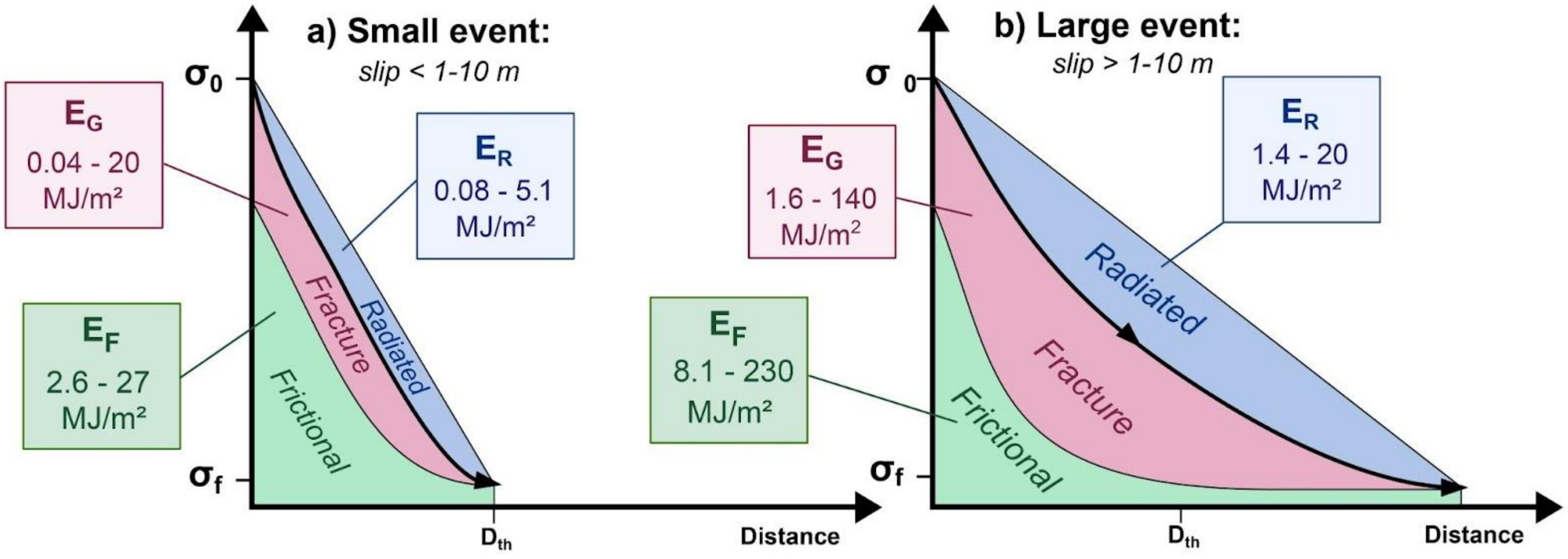


Fracture and Radiated Energy from Ye et al., 2016



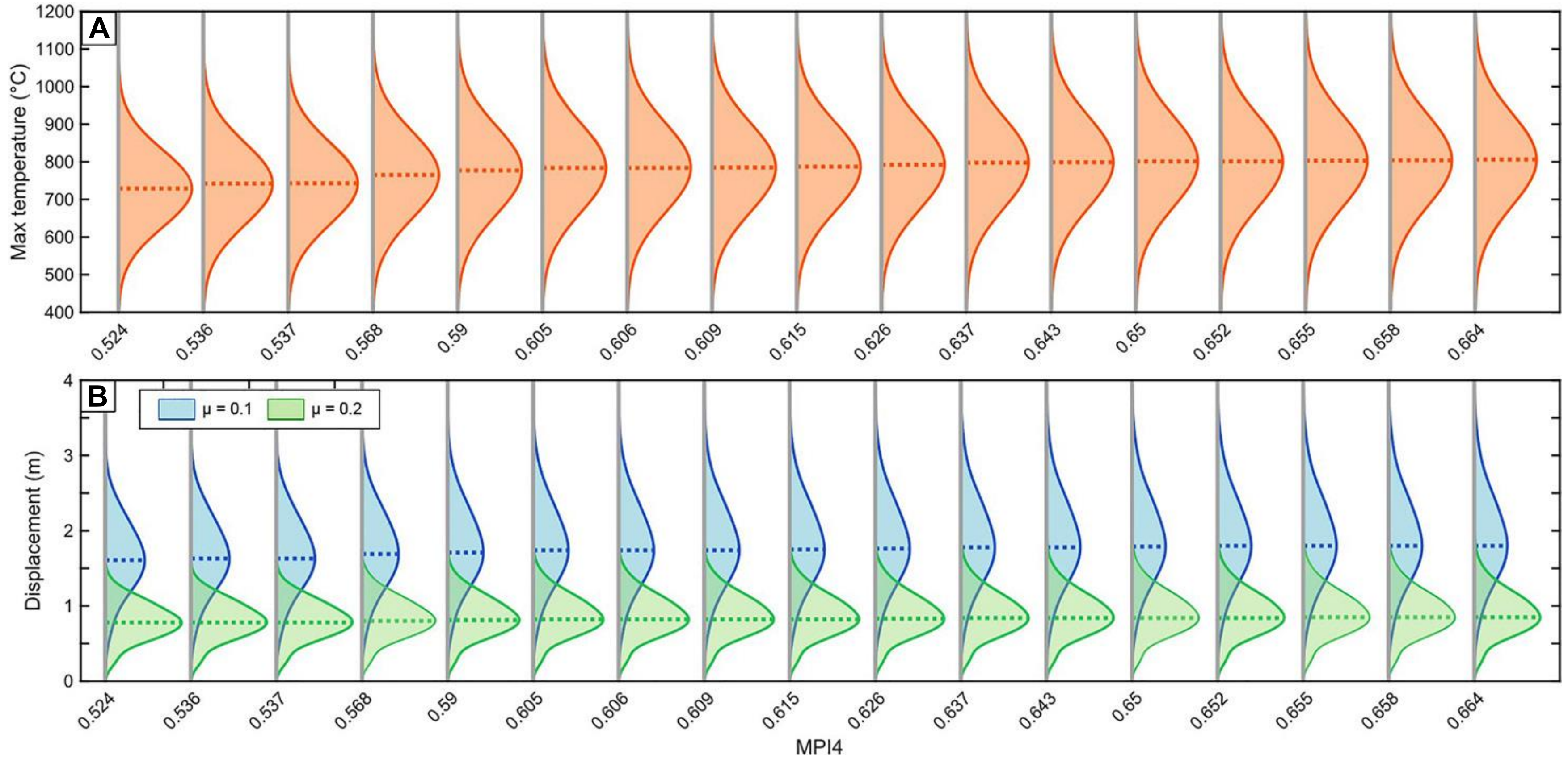
Coffey et al., 2023

Are Big Earthquakes Different than Small Earthquakes?



Coffey et al., 2023

How Big Are These Earthquakes?



Frictional Energy

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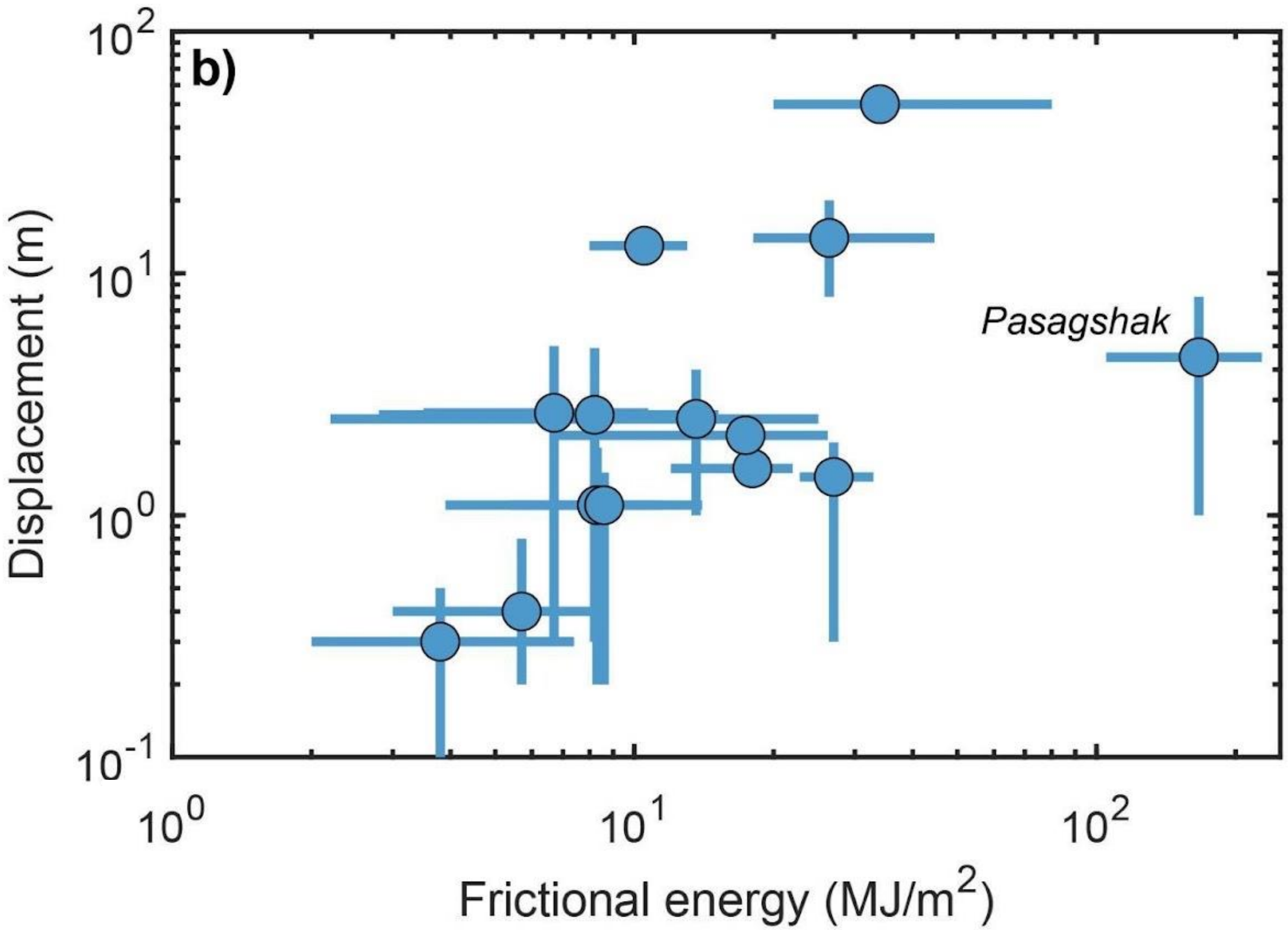
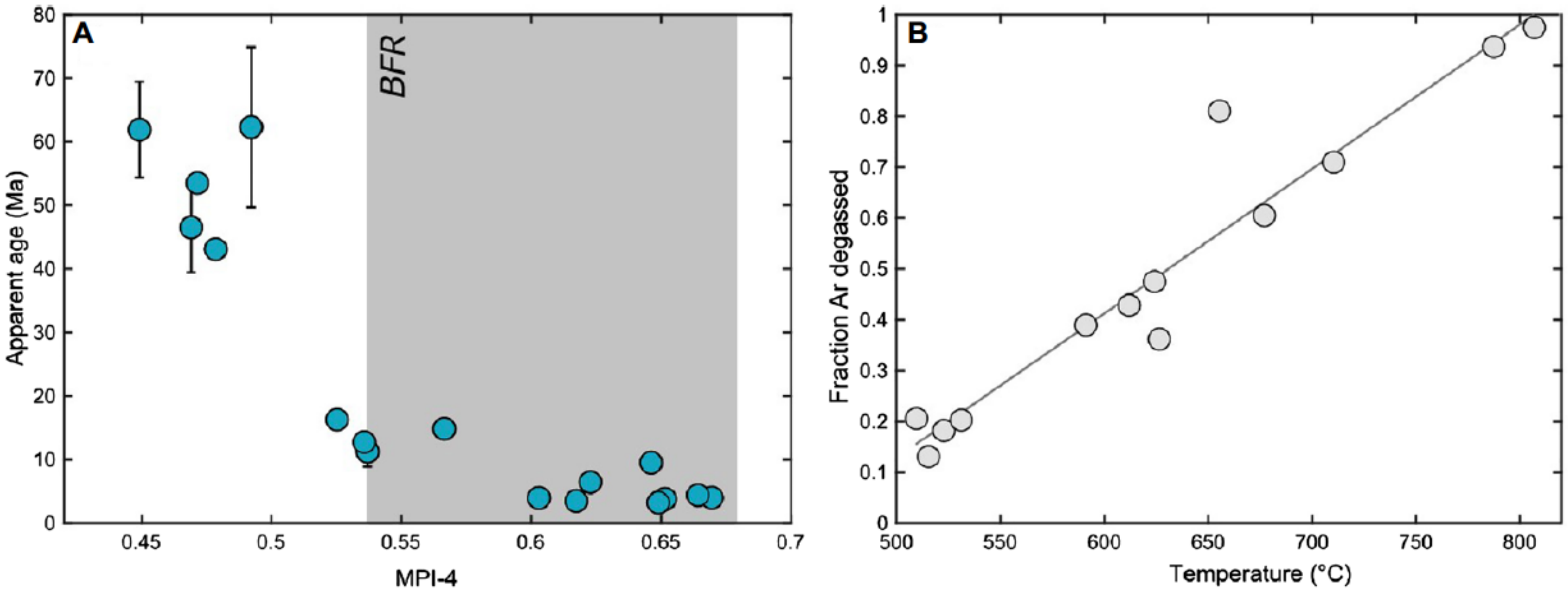


Coffey et al., 2023

How Old Are These Earthquakes?

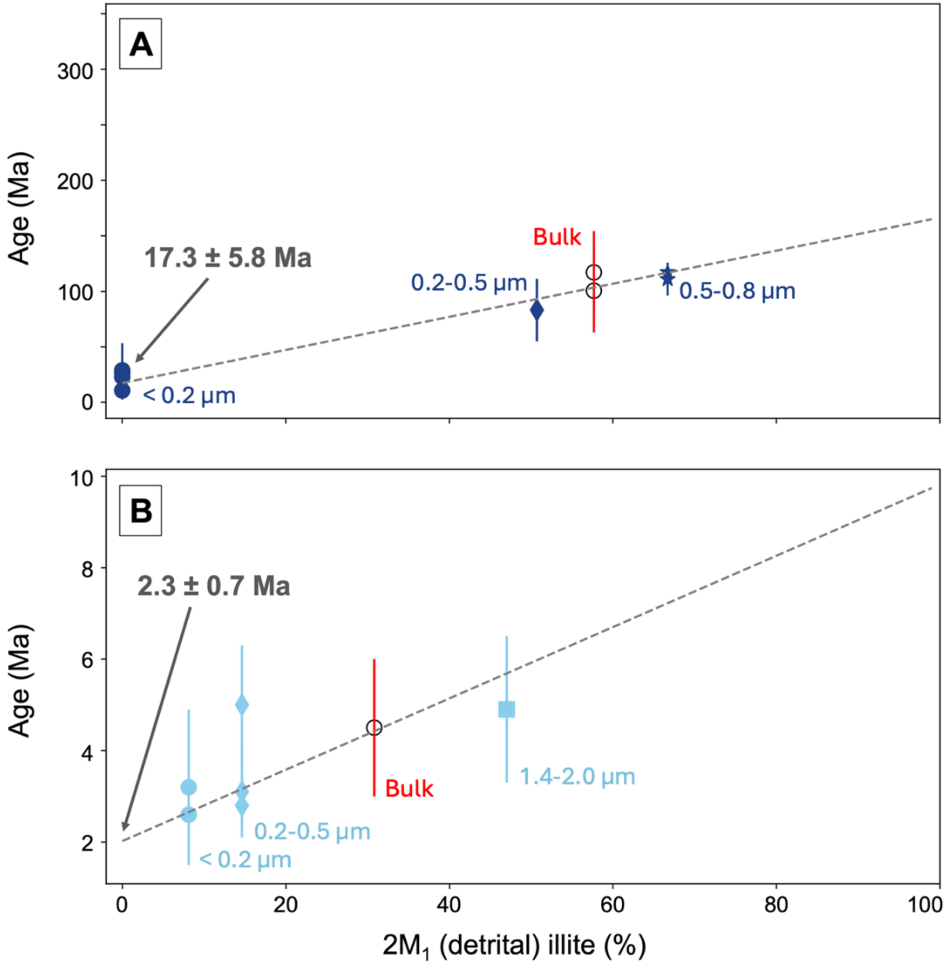


Coffey et al., 2022

How Old Are These Earthquakes?

Next Steps:

- **Size separation**
- **XRD to identify authigenic illite**



Evard et al., in prep

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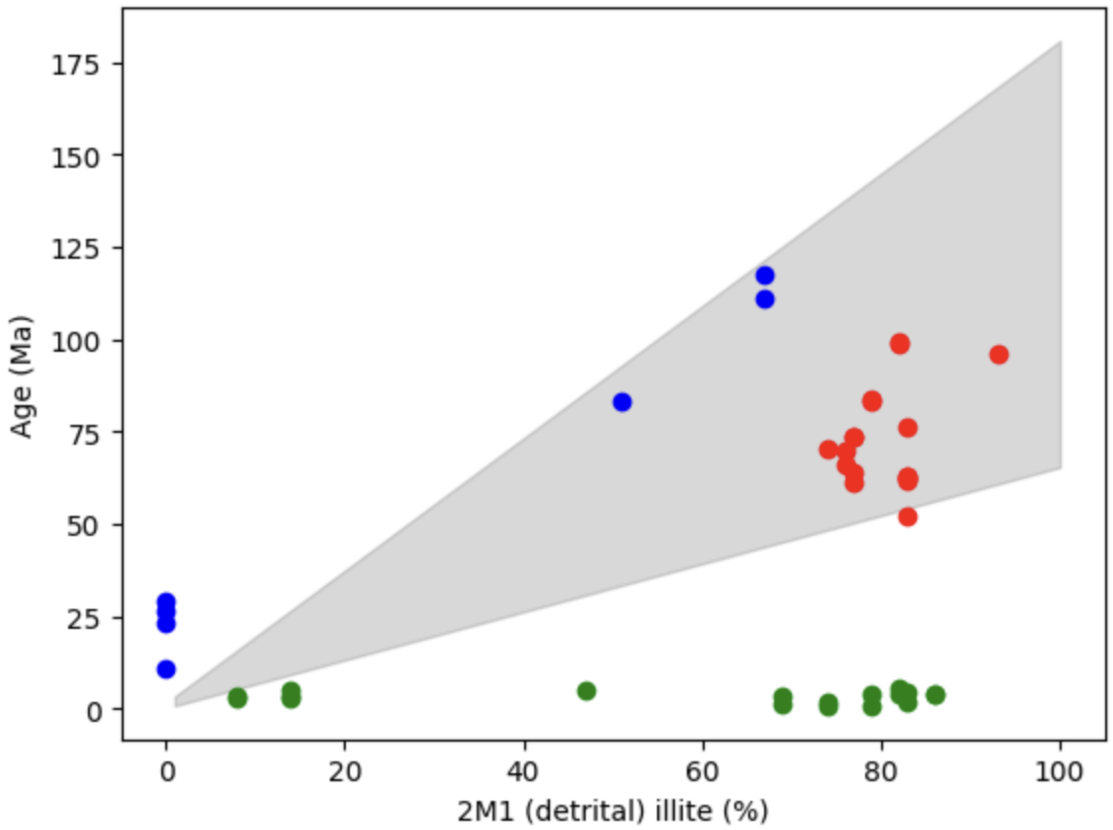
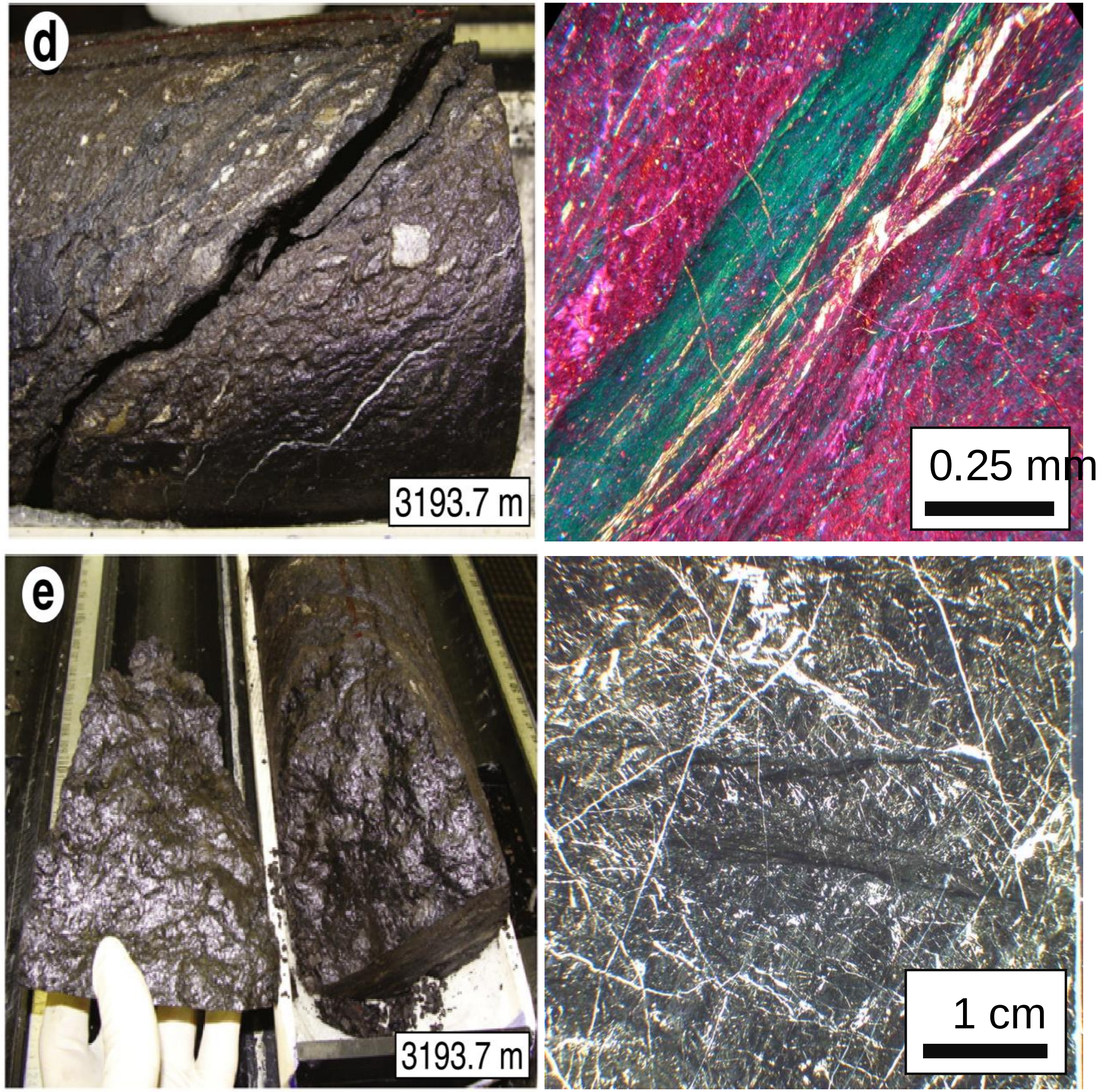


Evard et al., in prep

Deformed ultracataclasite

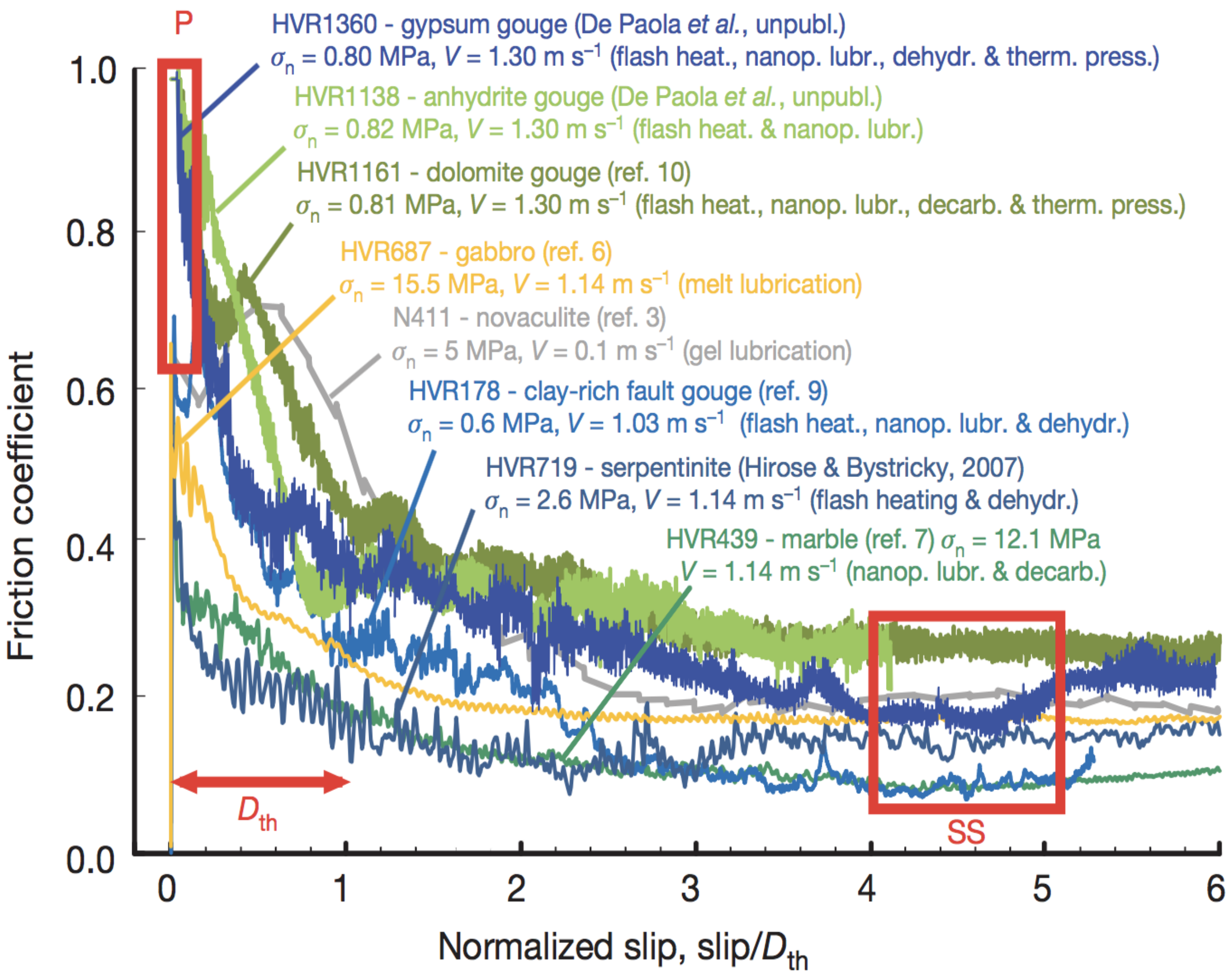
- Highly sheared cataclasite
- Scaly fabric
- Many discrete millimeter-centimeter thick slip surfaces
- Black staining
- Slickenlines
- Pervasive veining



Bradbury et al. (2011)

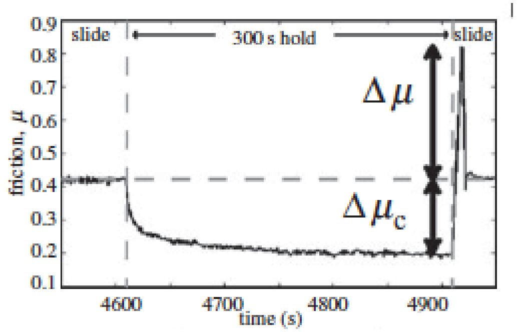
Other Reasons to Care About Coseismic Temperature Rise:

What dynamic weakening mechanisms might be activated?

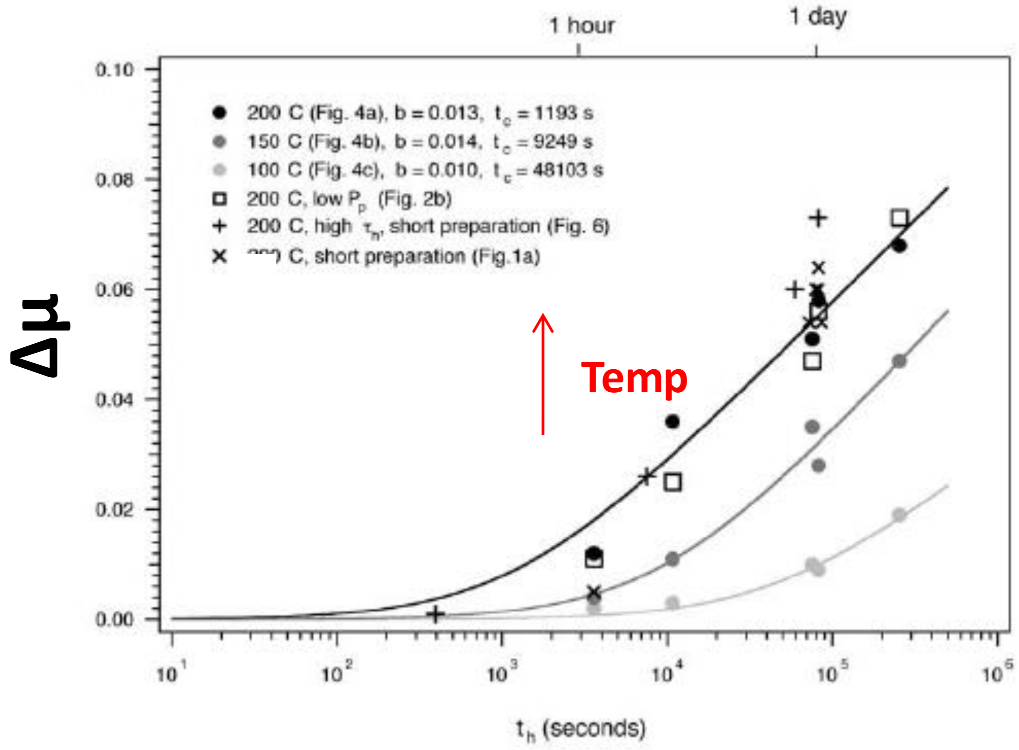


Di Toro et al. (2011)

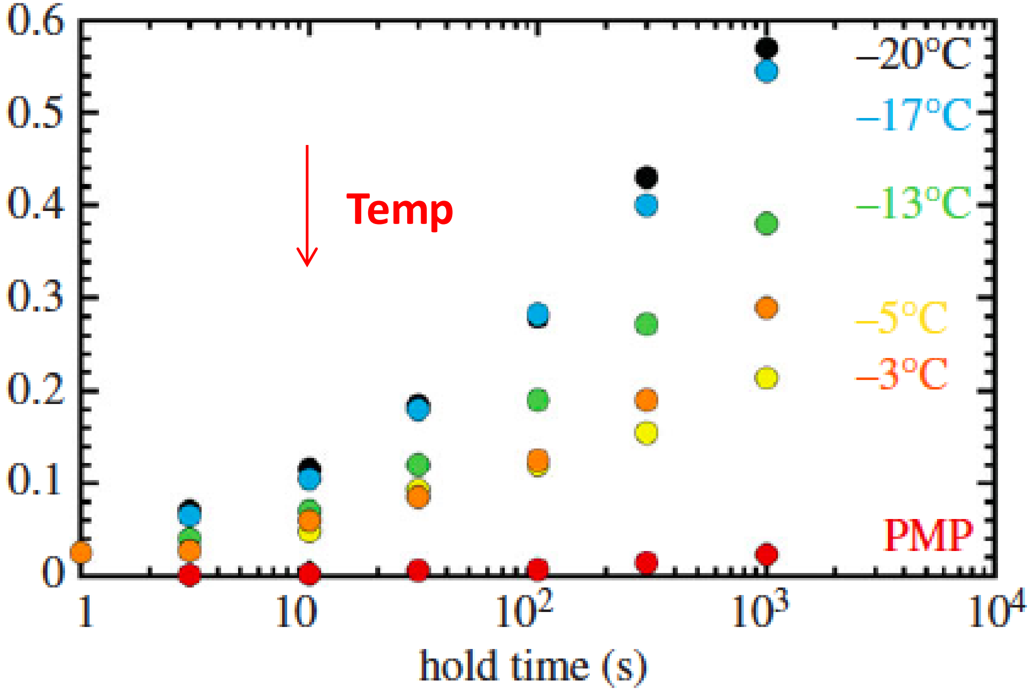
Temperature Affects Frictional Healing Rates



Quartz



Ice



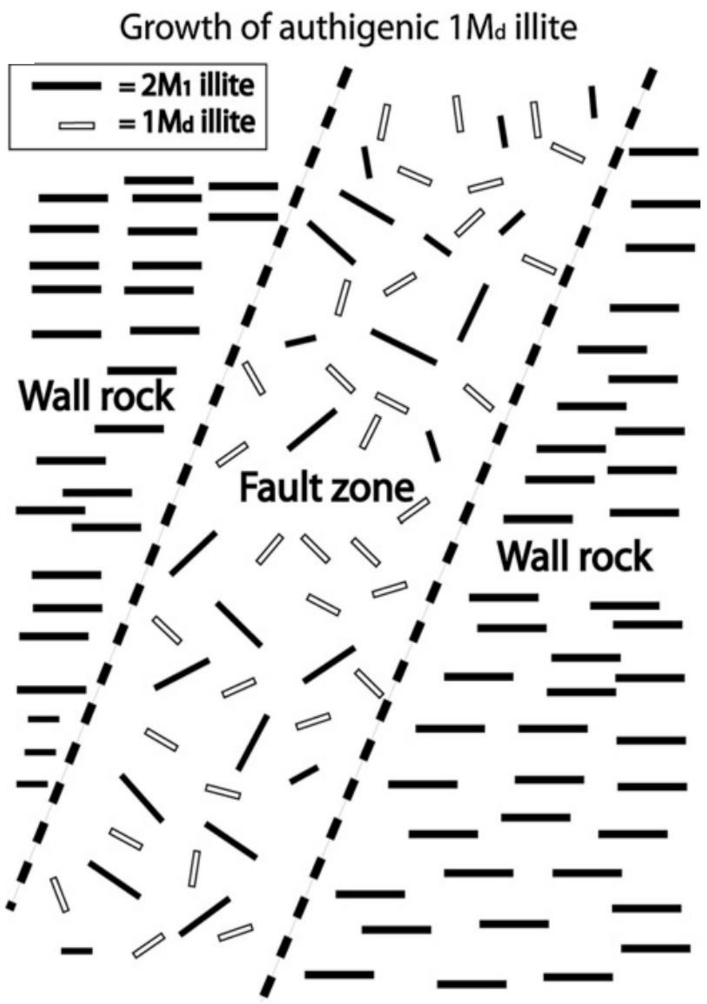
Nakatani and Scholz, 2004

McCarthy et al., 2017

How Old Are These Earthquakes?

K/Ar Ages may represent:

- **Age of clay formation**
- **Thermal resetting**



Haines et al. (2008)

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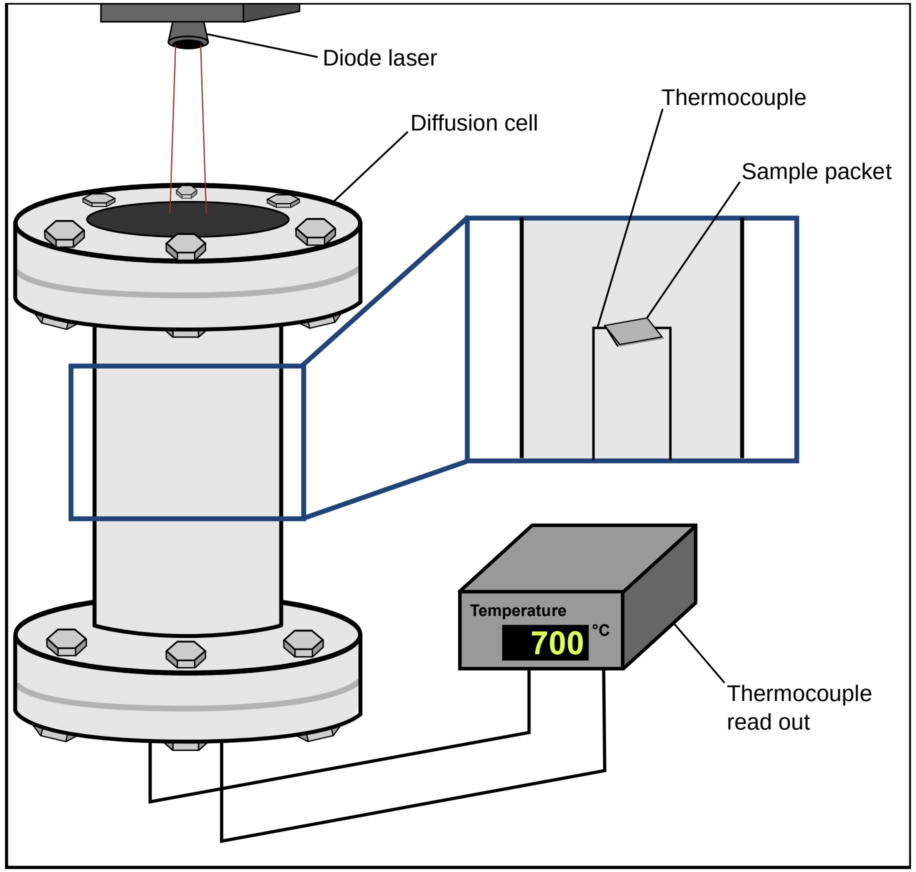

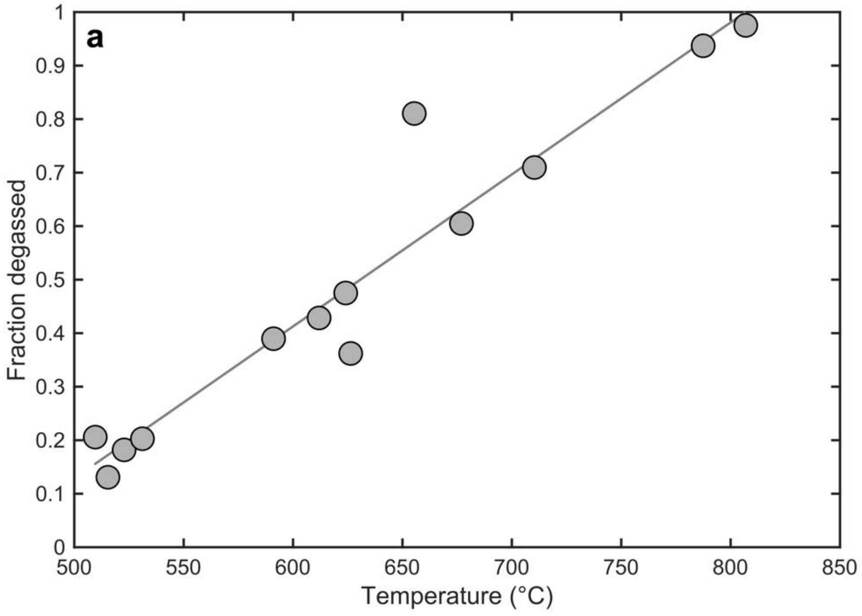

Coffey et al., 2022

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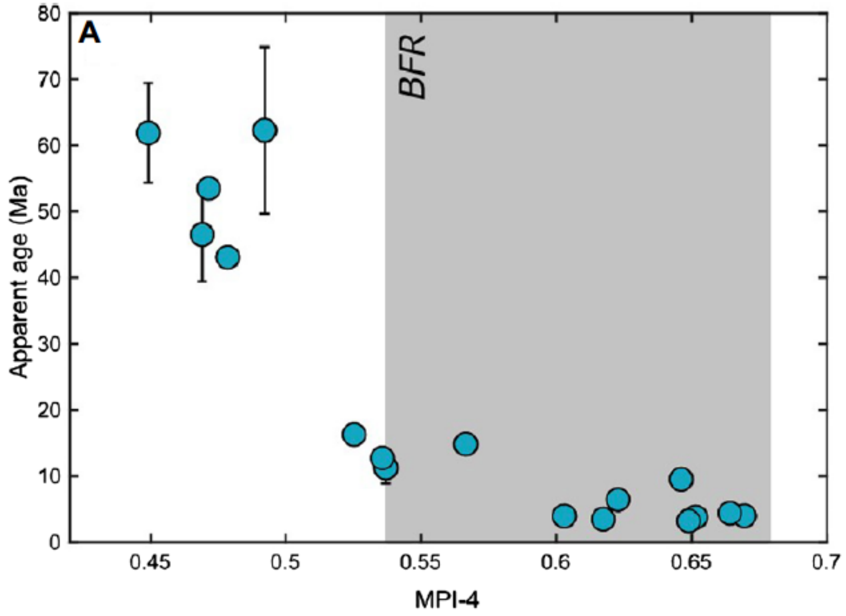
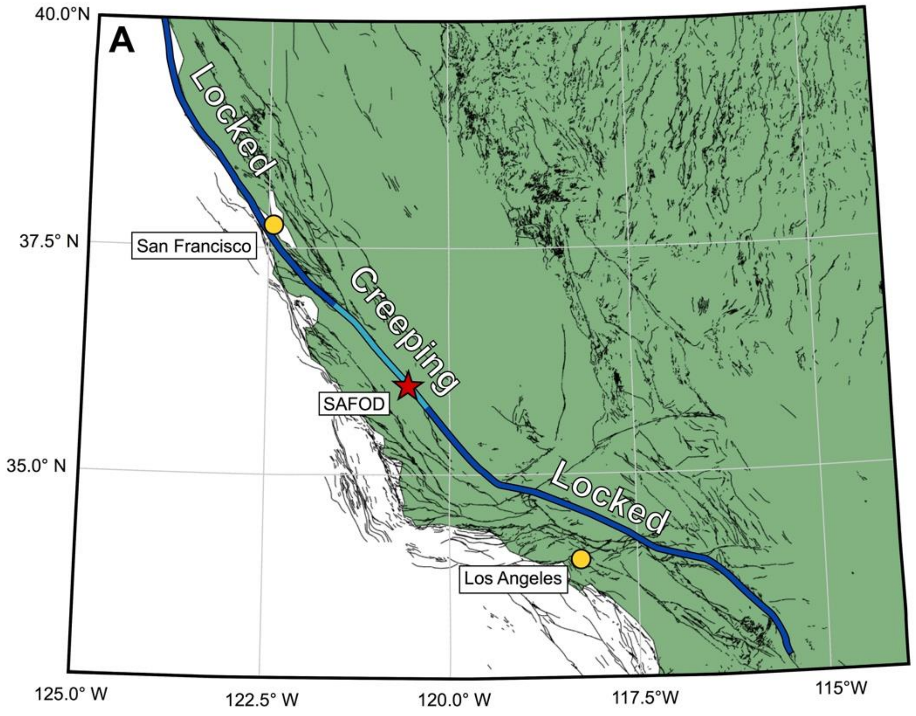
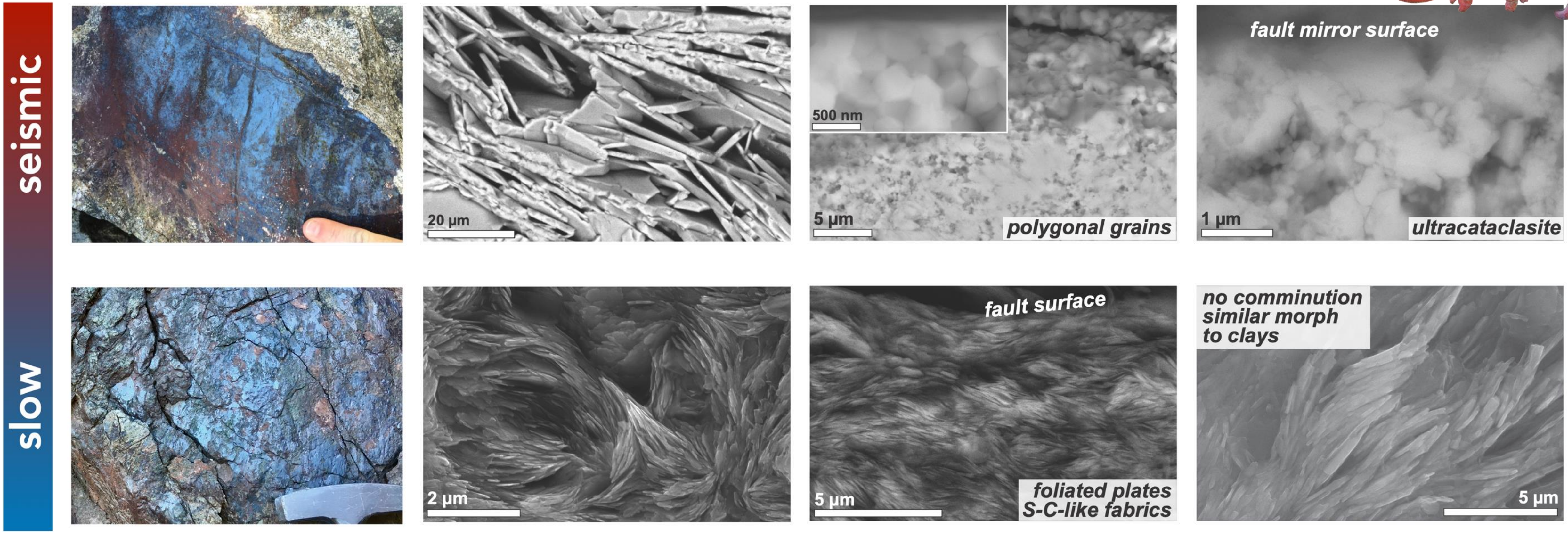




Coffey et al., 2022

hematite is common in fault rocks

its textures are diagnostic of slip rate and temperature



Ault et al., 2015, *Geology*; McDermott et al., 2017, *EPSL*; Moser et al., 2017, *EPSL*; Ault et al., 2019, *Geology*; McDermott et al., 2021, *EPSL*; DiMonte et al., 2022, *Geology*; Odlum et al., 2022, *Geosphere*

SCEC 17164, 21068