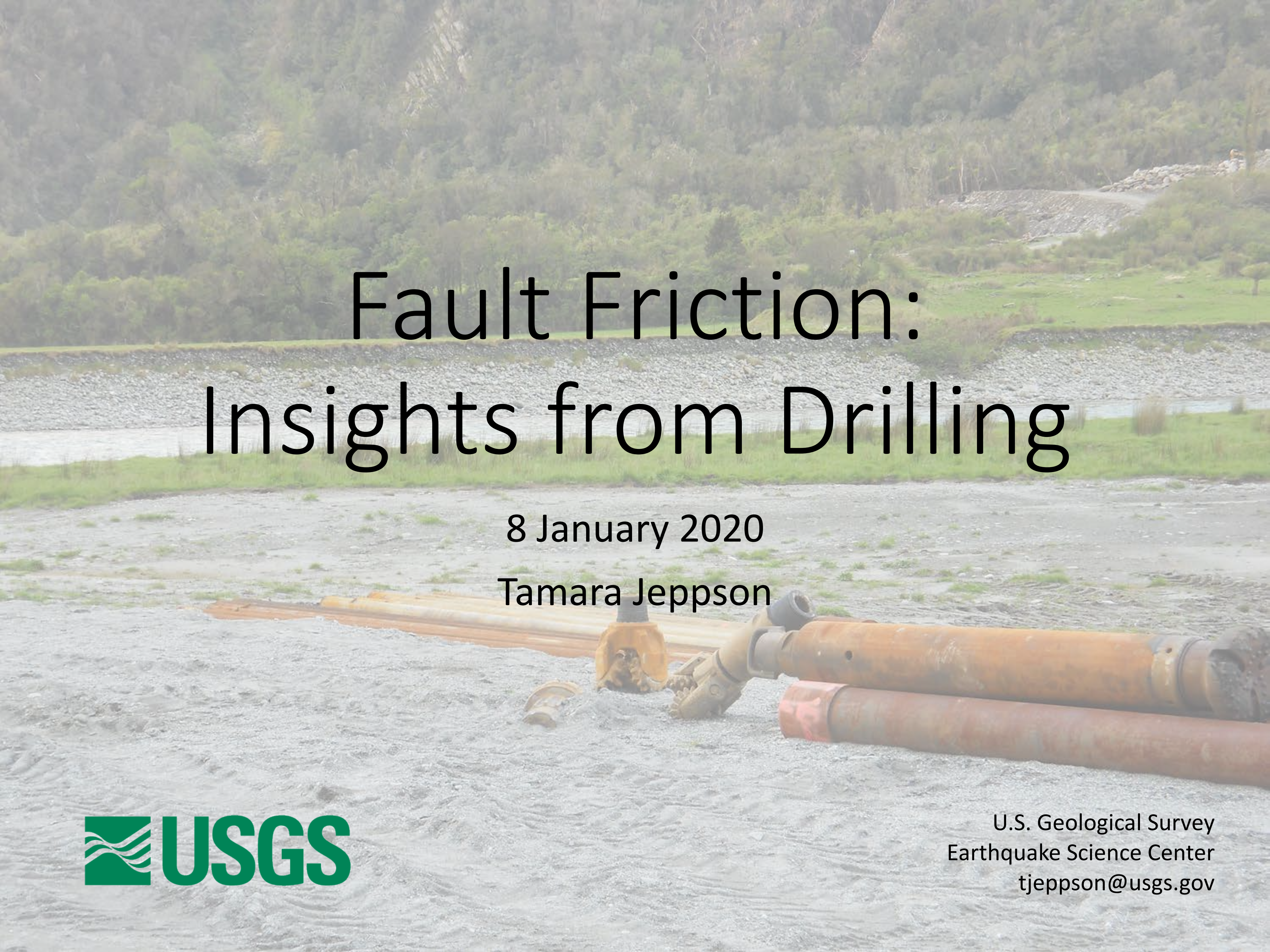

Fault Friction: Insights from Drilling

8 January 2020

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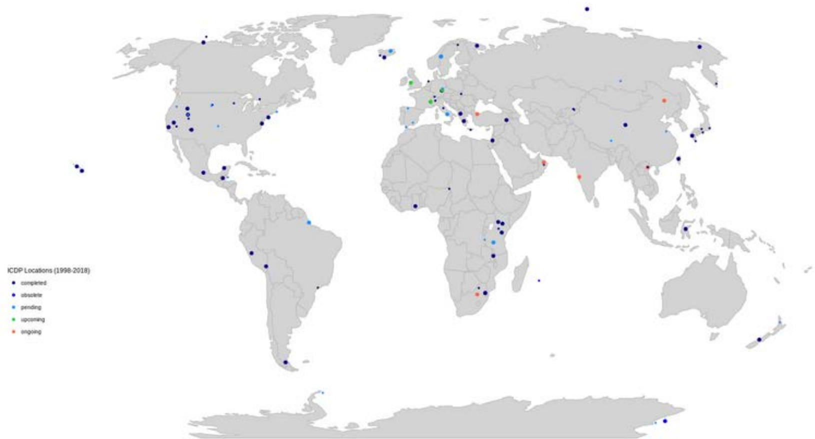
Why drill?

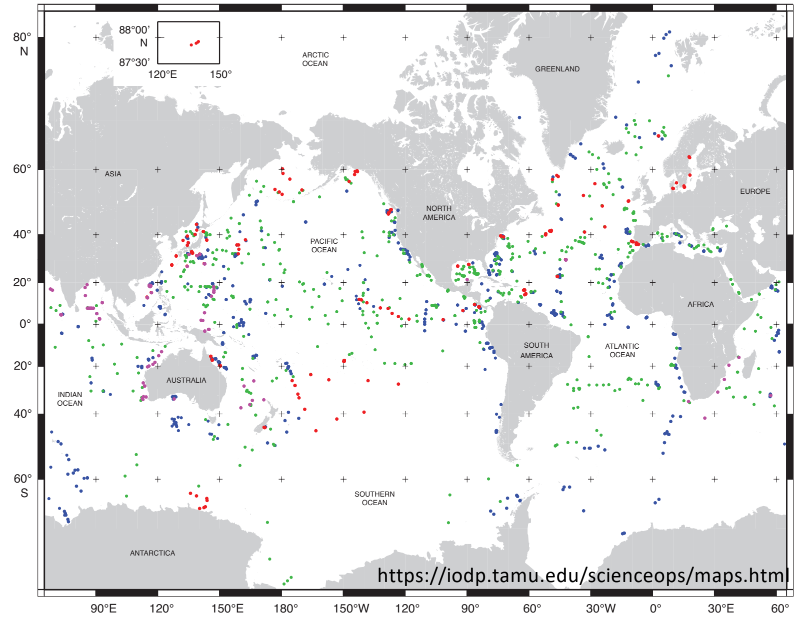
- In situ measurement
  - Temperature profiles
  - Stress measurements
  - Material and chemical properties
- In situ sampling
  - Structures
  - Mineralogy
  - Laboratory measurements

International Continental Drilling Program (ICDP)

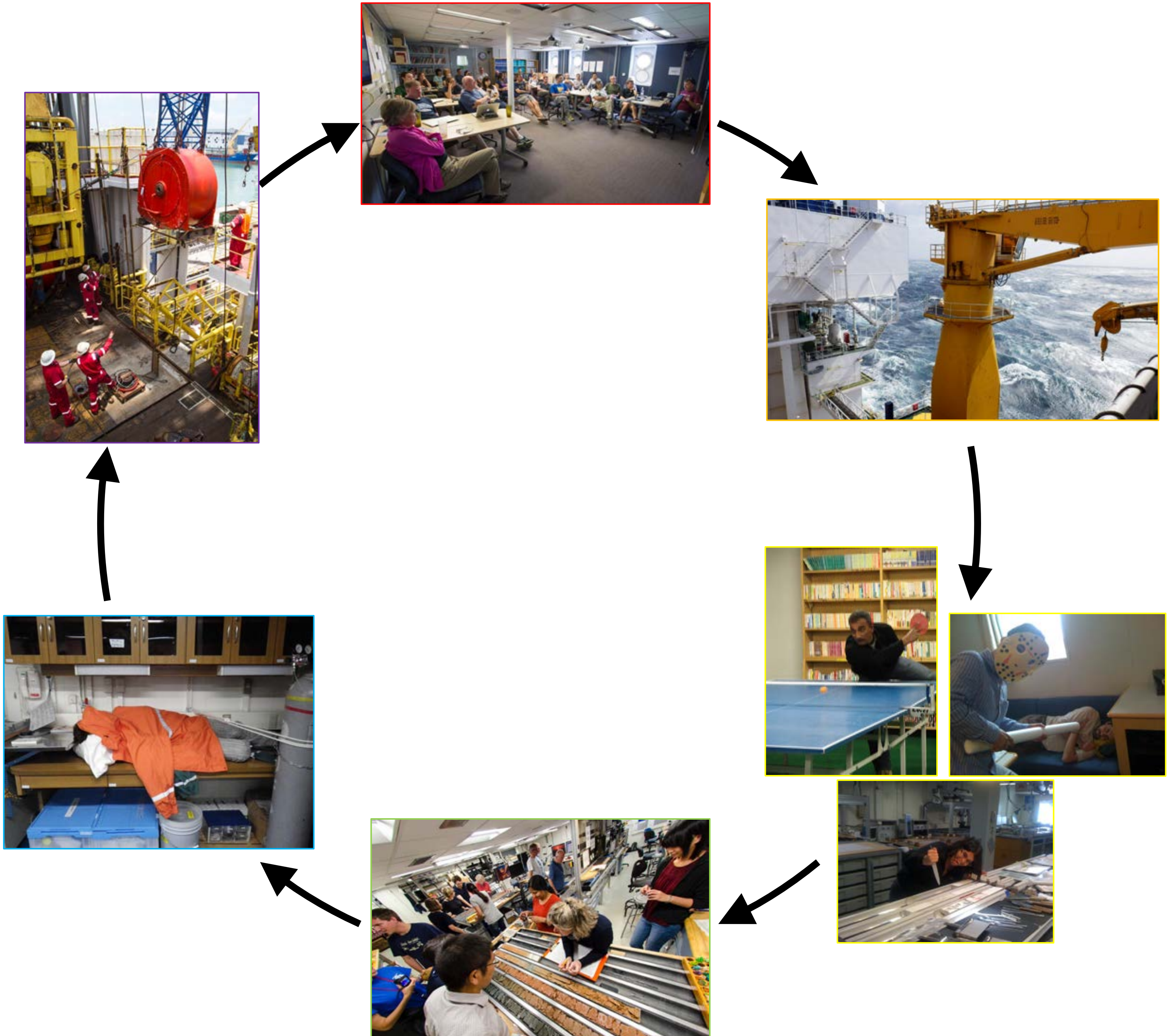


https://www.icdp-online.org/facts/project-facts/maps/icdp-world-maps-static/

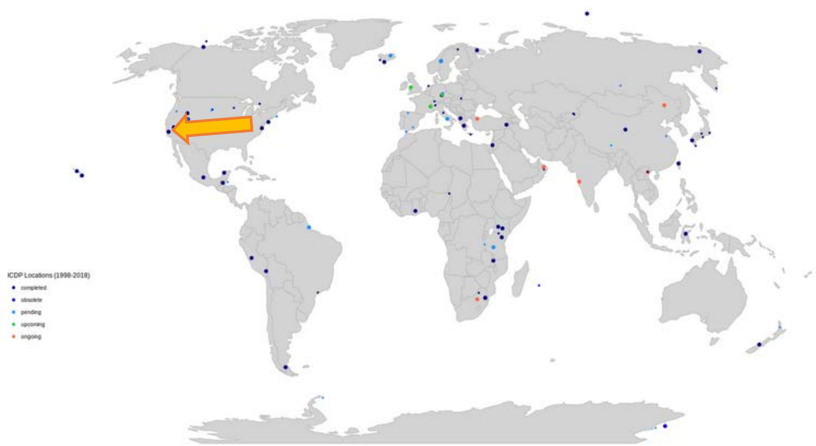
International Ocean Discovery Program (IODP)



DSDP Legs 1–96 (•), ODP Legs 100–210 (•), IODP Expeditions 301–348 (•), IODP Expeditions 349–371 (•)



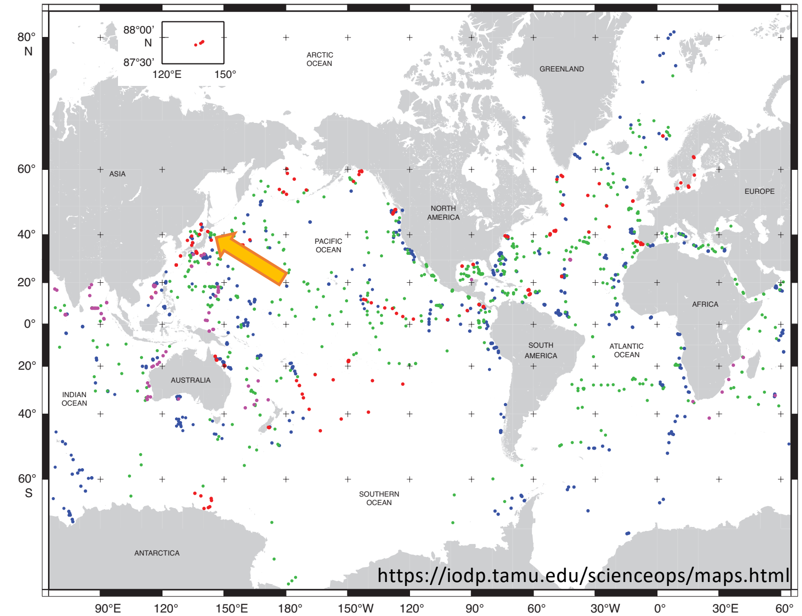
International Continental Drilling Program (ICDP)



https://www.icdp-online.org/facts/project-facts/maps/icdp-world-maps-static/

- San Andreas Fault, USA, SAFOD
- North Anatolian Fault, Turkey, GONAF
- Chelungpu, Taiwan, TCDP
- Alpine Fault, New Zealand, DFDP

International Ocean Discovery Program (IODP)

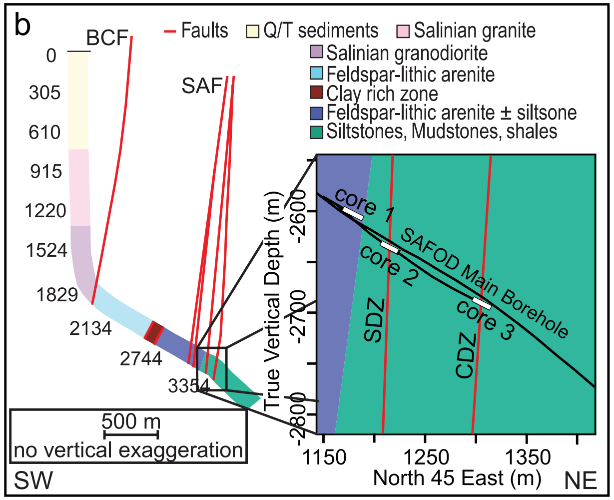


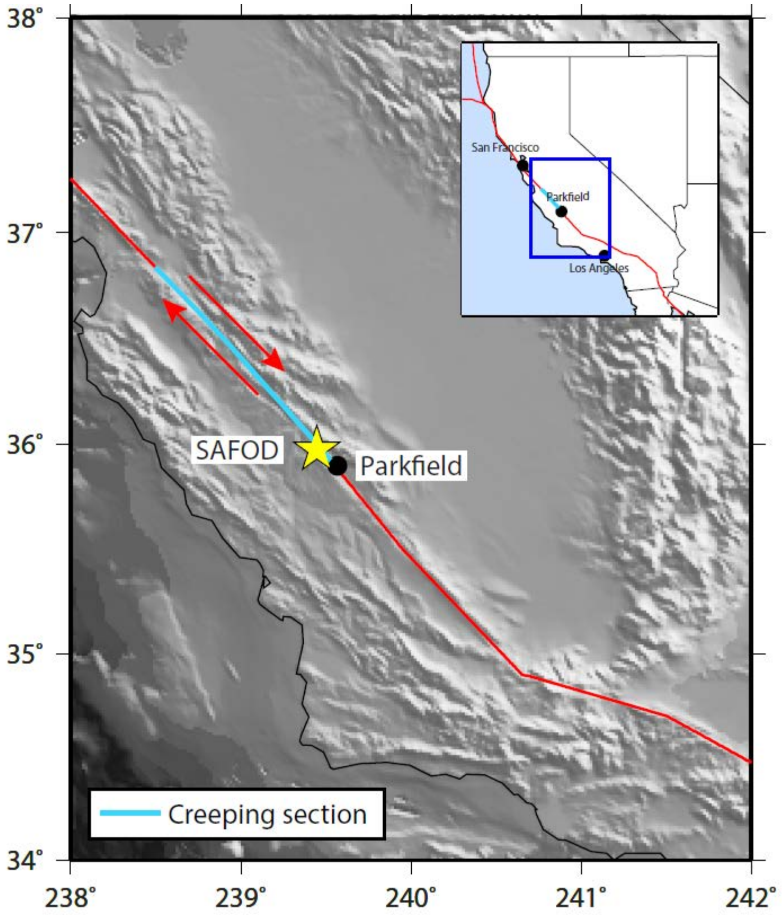
DSDP Legs 1–96 (•), ODP Legs 100–210 (•), IODP Expeditions 301–348 (•), IODP Expeditions 349–371 (•)

- Nankai Trough, Japan, NanTroSEIZE
- Japan Trench, Japan, JFAST
- Hikurangi, New Zealand, Exp. 372/375
- Middle America Trench, Costa Rica, CRISP

San Andreas Fault Obseratory at Depth (SAFOD)

- Multi-phase project
- Intersected actively deforming zones at 2620 and 2675 m TVD





Jeppson & Tobin, 2015

Outcrop Cuttings Synthetic mixtures

San Andreas Fault Obseratory at Depth (SAFOD)

- Multi-phase project
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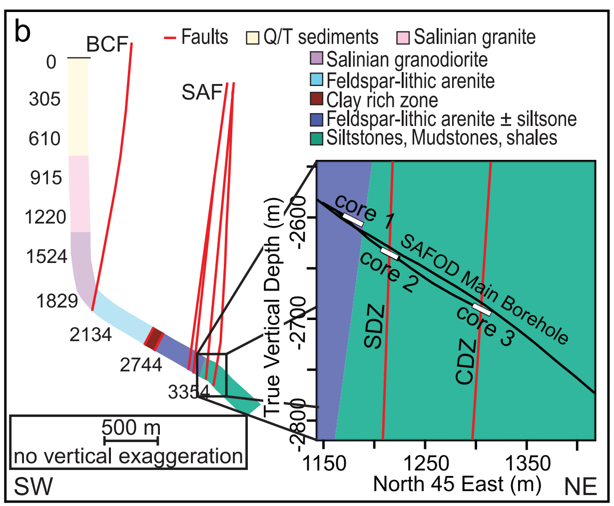
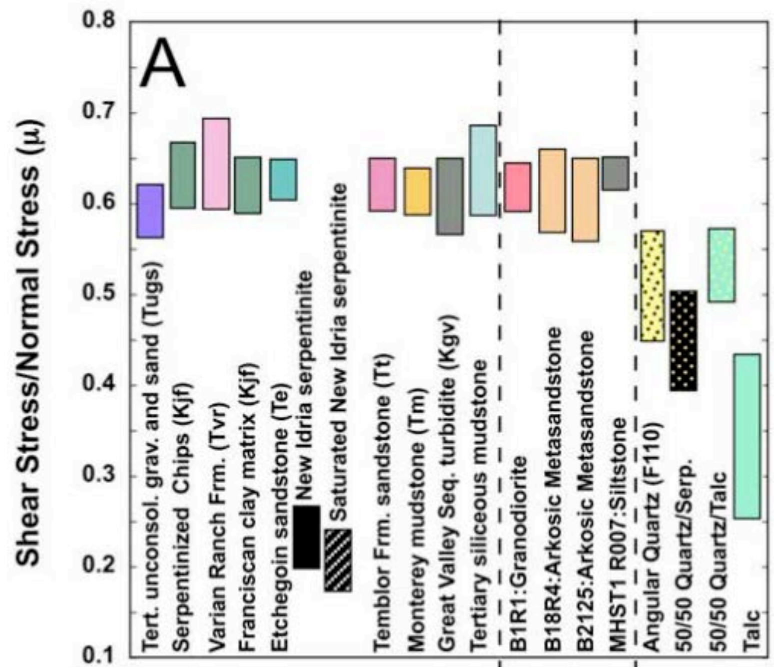
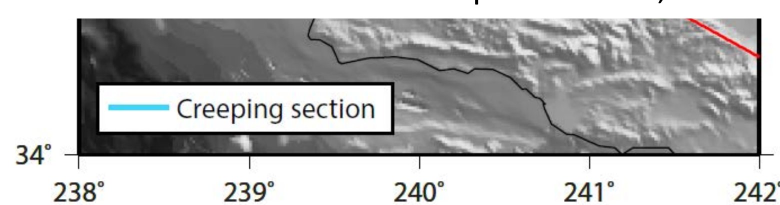




Carpenter et al., 2009



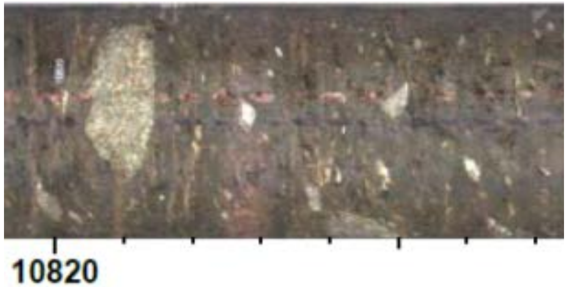
Jeppson & Tobin, 2015

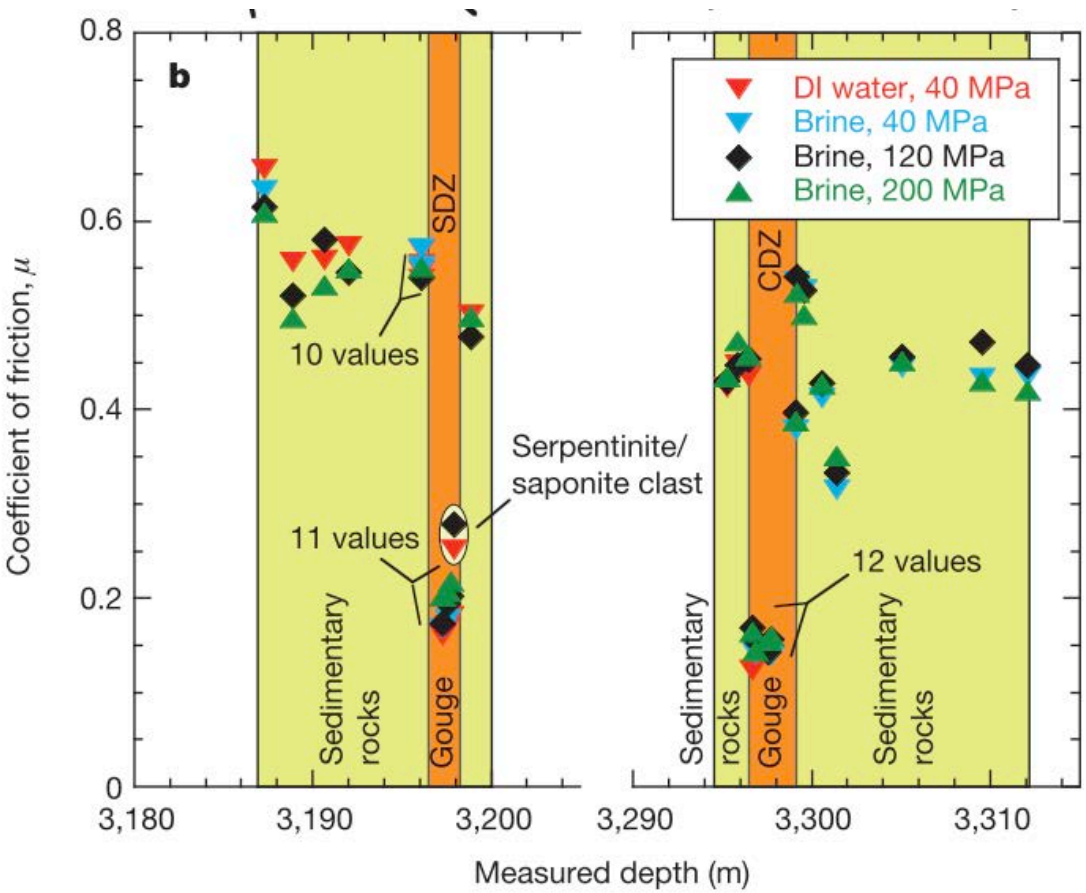
SAF Gouge

- Mg-rich Smectite (Saponite)
  - Schleicher et al, 2012;Moore et al., 2014

SAFOD Core Photo Atlas

SAF Gouge



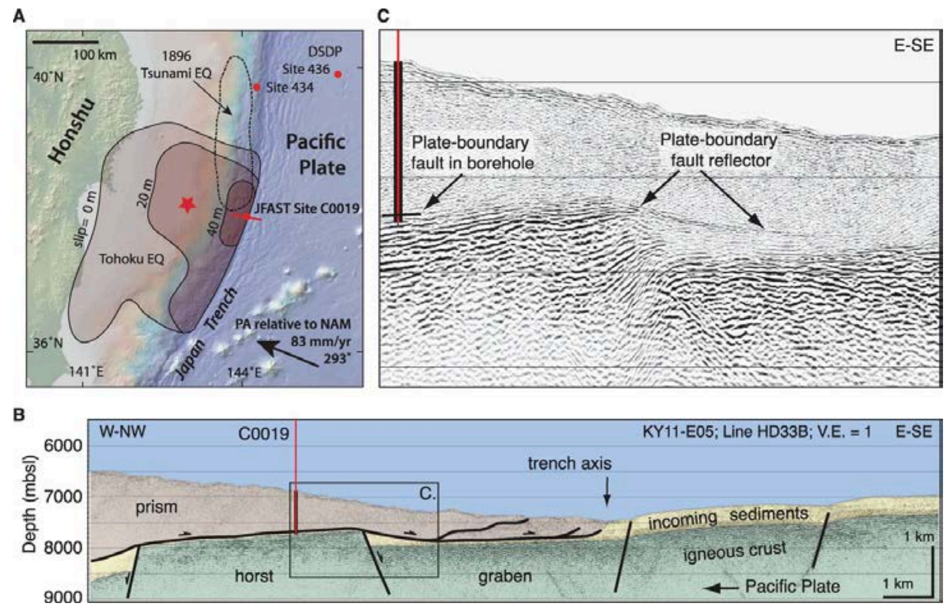


Lockner et al., 2011

SAFOD Core Photo Atlas

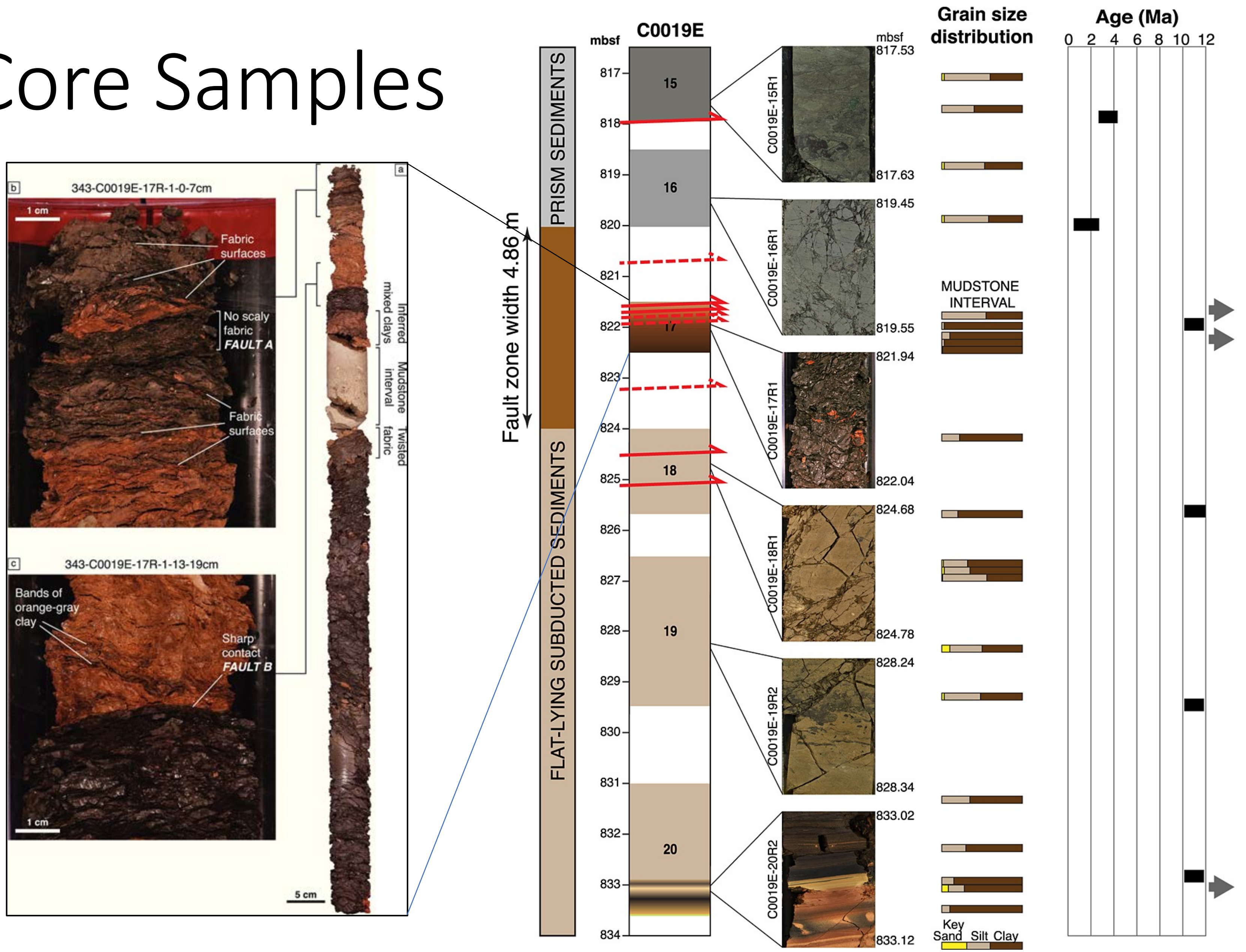
IODP Exp. 343 – Japan Trench Fast Drilling Project (JFAST)

- Rapid response to 2011 M_w 9.1 Tōhoku-oki earthquake
- Drilling began in April 2012
  - 2 boreholes, 850.5 and 844.5 mbsf
  - LWD logs and core
    - Recovered ~ 1 m of highly sheared clay from the décollement
  - Installed 55 temperature sensors and data loggers (July 2012)
    - Retrieved April 2013



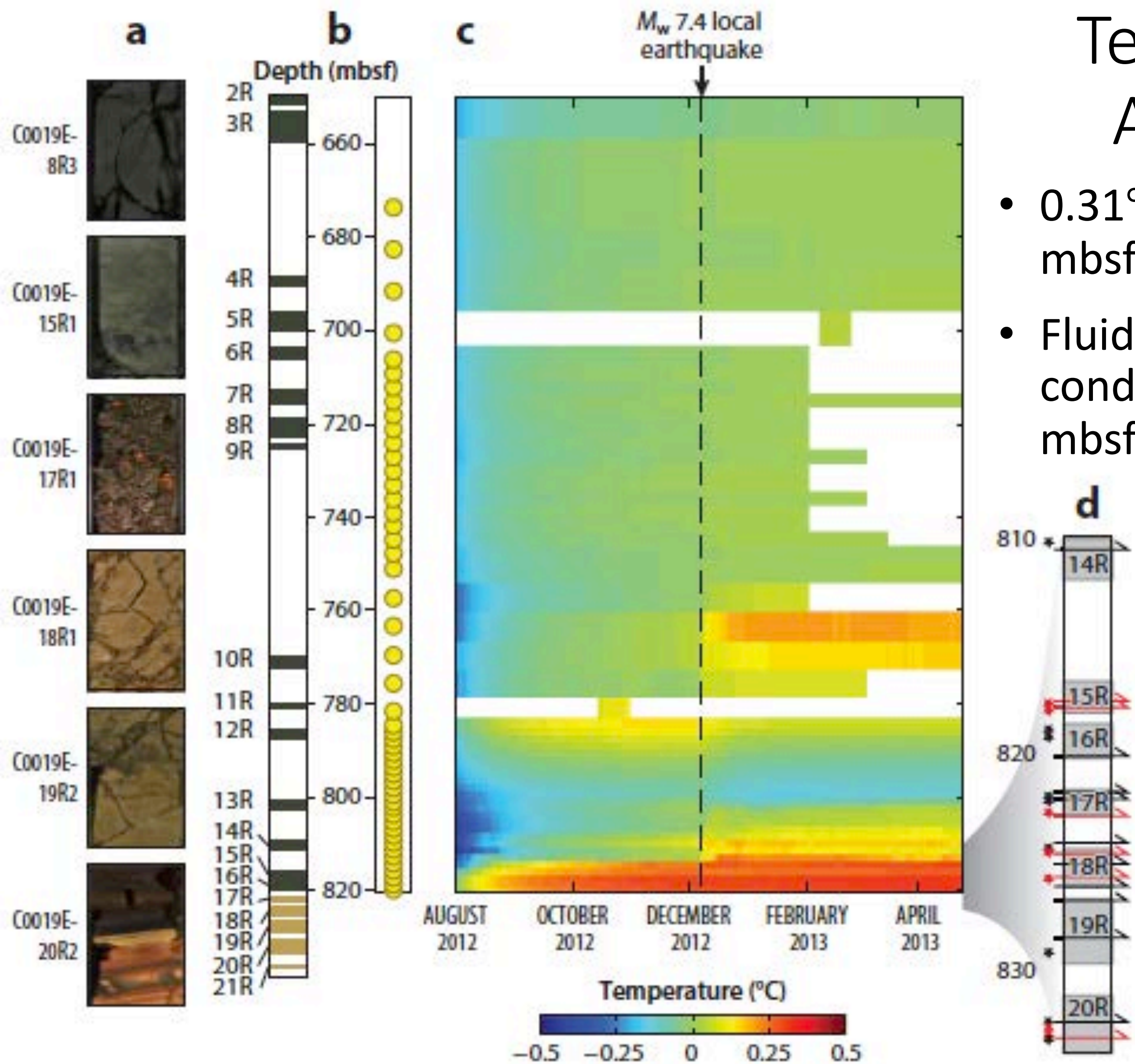
Chester et al., 2013

Core Samples



Kirkpatrick et al., 2015

Temperature Anomalies



- 0.31°C anomaly at 819 mbsf
- Fluid flow along fracture conduits at 784 & 763 mbsf

Brodsky et al., 2019

Coseismic Stress & Friction

$$\Delta T_{EQ}(z,t) = \frac{S}{2\sqrt{\pi\alpha t}} e^{-z^2/4\alpha t}$$

$$S = \frac{\tau D}{c\rho}$$

$$\tau = \mu(\sigma_n - p_p)$$

z = distance from fault
t = time since earthquake
α = thermal diffusivity
τ = shear stress
D = displacement on fault
c = specific heat
ρ = density
μ = coefficient of friction
$\boldsymbol{\sigma_n}$ = normal stress
$\boldsymbol{p_p}$ = pore pressure

Coseismic Stress & Friction

$$\Delta T_{EQ}(z,t) = \frac{S}{2\sqrt{\ldots}} e^{-z^2/4\alpha t}$$

$\tau \ldots$

z = distance from fault

t = time since earthquake

…ult

ρ = density

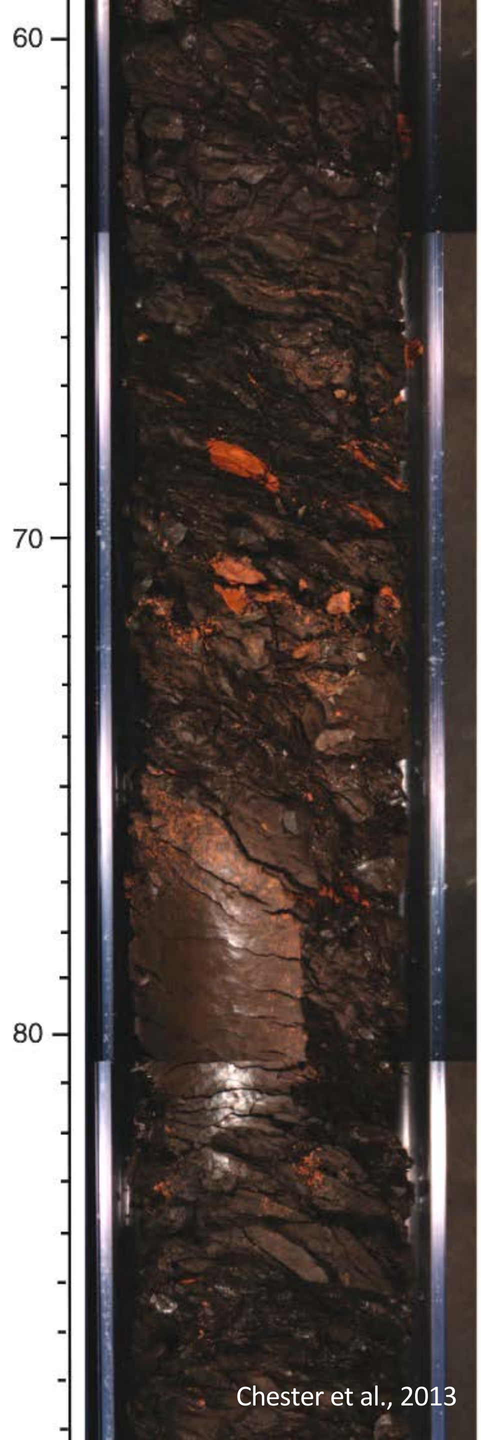
μ = coefficient of friction

$\boldsymbol{\sigma_n}$ = normal stress

$\boldsymbol{p_p}$ = pore pressure

JFAST Temperature anomaly:

- Shear stress = 0.30 – 1.3 MPa
- Apparent coseismic coefficient of friction = 0.05 – 0.19

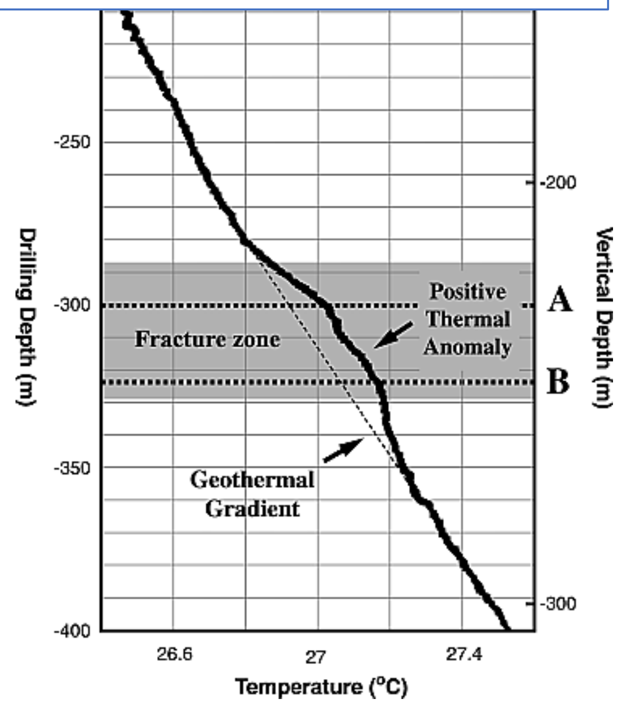


Other Estimates of Friction

- Drilling data (Ujiie et al., 2016)
  - Shear stress estimated from surface torque
    - Rotation rates of 0.8 -1.3 m/s
  - **μ** = 0.08 – 0.19 at plate boundary fault zone
- Laboratory studies
  - High velocity (Ujiie et al., 2013; Remitti et al., 2015)
    - *v* = 1.3 – 3.5 m/s; **μ** = 0.03 – 0.19
    - Velocity neutral to velocity weakening
  - Low velocity (Ikari et al., 2015)
    - *v* < 1 mm/s; **μ** = 0.2 – 0.26
    - Velocity strengthening to velocity weakening

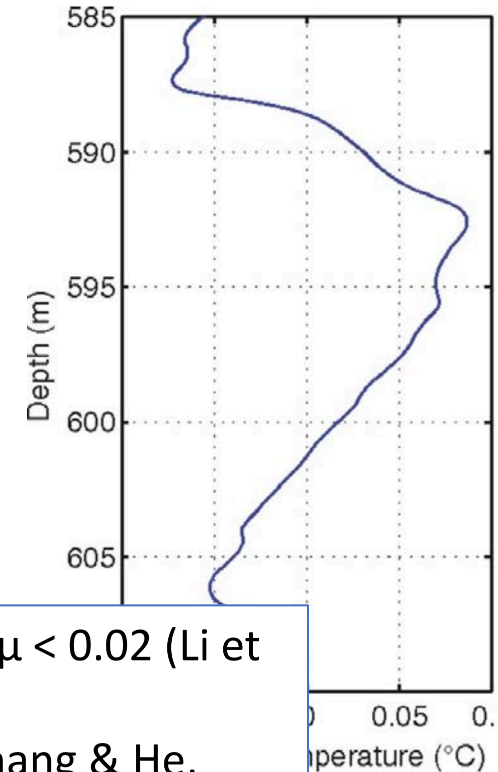
1999 (M_w 7.6) Chi-Chi earthquake, Taiwan

- Temperature: μ = 0.1– 0.2 (Tanaka et al., 2006)
- Laboratory (Tanikawa & Shimamoto, 2009)
    - High velocity: μ = 0.2 – 0.3
    - Low velocity: μ = 0.7



Tanaka et al., 2006

2008 (M_w 7.9) Wenchuan earthquake, China

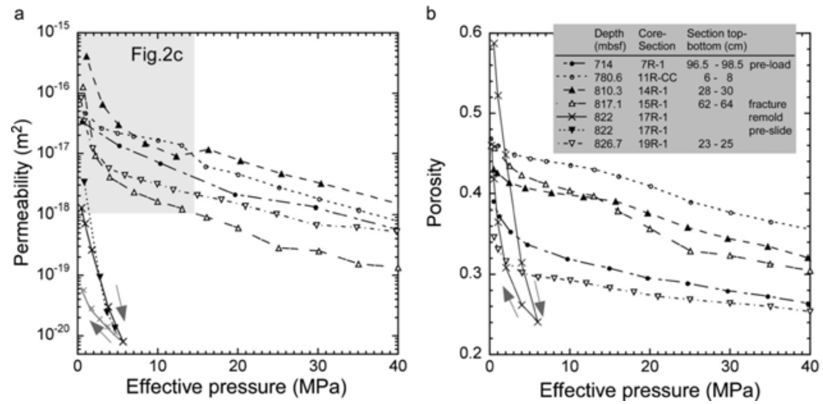


- Temperature: μ < 0.02 (Li et al., 2015)
- Laboratory (Zhang & He, 2013; Togo et al., 2016)
    - High velocity: μ = 0.02 – 0.15 (outcrop)
    - Low velocity: μ = 0.2 – 0.6 (outcrop)

Li et al., 2015

Mechanism of Weakening?

- Thermal pressurization
- Thermal decomposition
- Amorphization
- Dynamic reduction of $\boldsymbol{\sigma}_n$
- Local melting

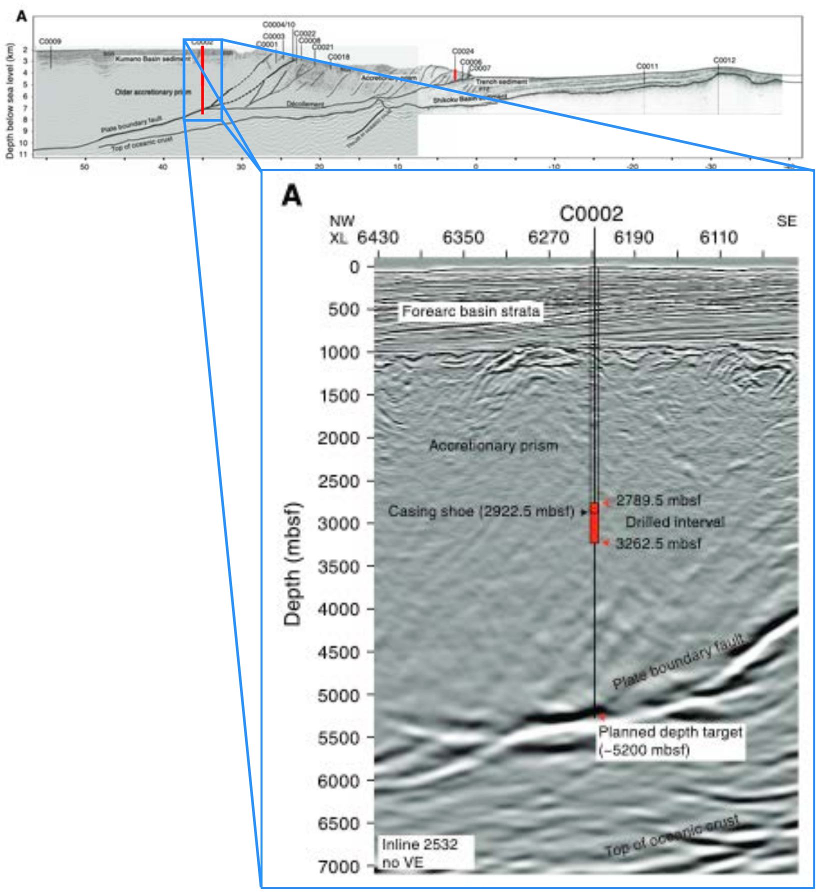


<u>Need more data!</u>

Tanikawa et al., 2013

Looking Forward: Drilling Deeper

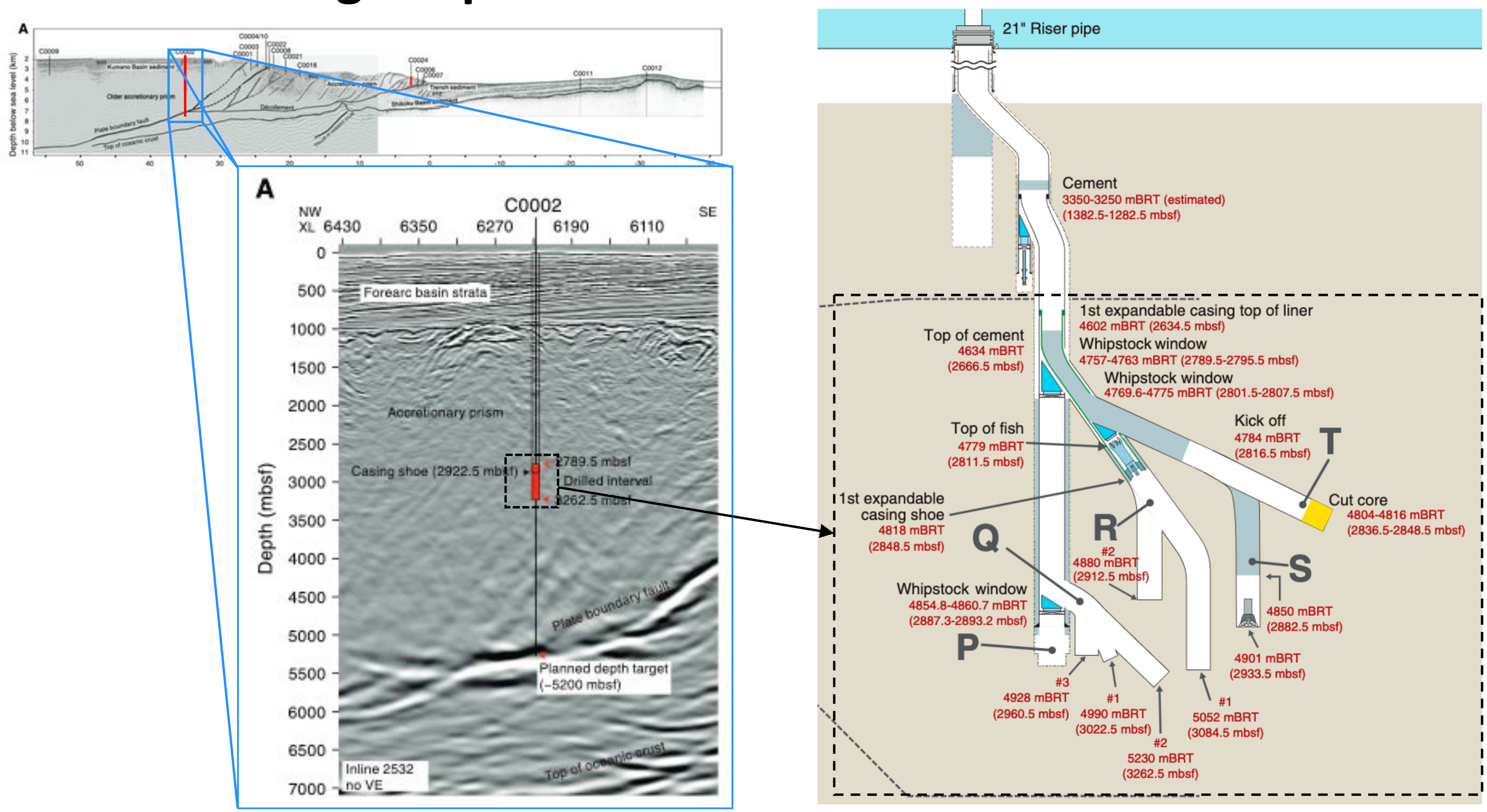
Nankai Trough Exp. 358



Tobin et al., 2019

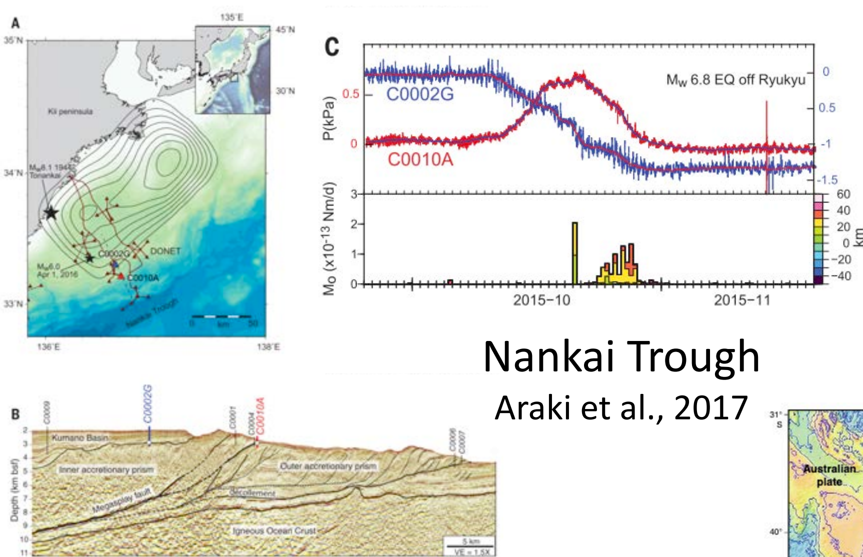
Looking Forward: Drilling Deeper

Nankai Trough Exp. 358

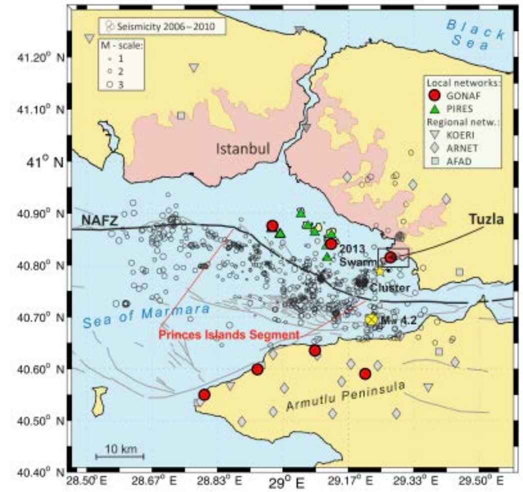


Tobin et al., 2019

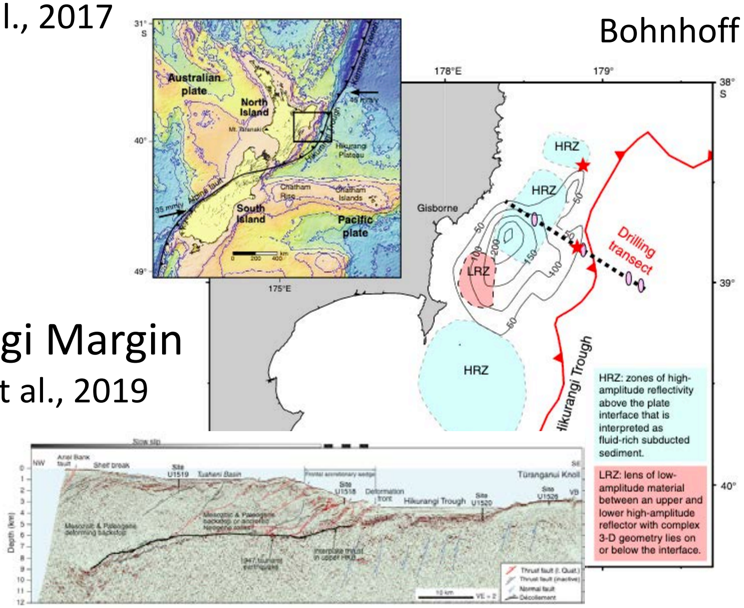
Looking Forward: Long Term Monitoring



Nankai Trough
Araki et al., 2017



North Anatolian Fault
Bohnhoff et al., 2017



Hikurangi Margin
Saffer et al., 2019

Thank you

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