Fault Friction: Insights from Drilling

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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)

https://iodp.tamu.edu/scienceops/maps.html

DSDP Legs 1–96 ( ), ODP Legs 100–210 ( ), IODP Expeditions 301–348 ( ), IODP Expeditions 349–371 ( )
International Continental Drilling Program (ICDP)

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

International Ocean Discovery Program (IODP)

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

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

https://iodp.tamu.edu/scienceops/maps.html
San Andreas Fault Observatory at Depth (SAFOD)

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

Jeppson & Tobin, 2015
San Andreas Fault Observatory at Depth (SAFOD)

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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
SAF Gouge

SAFOD Core Photo Atlas

Mg-rich Smectite (Saponite)

Schleicher et al., 2012; Moore et al., 2014

Lockner et al., 2011

Coefficient of friction, $\mu$

Measured depth (m)

DI water, 40 MPa
Brine, 40 MPa
Brine, 120 MPa
Brine, 200 MPa

10 values
11 values
12 values
Serpentineite/saponite clast
Sedimentary rocks
Gouge
SDZ
CDZ

10820

Lockner et al., 2011
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

Fault zone width 4.86 m

Grain size distribution

Age (Ma)

0 2 4 6 8 10 12

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
- \( \alpha \) = thermal diffusivity
- \( \tau \) = shear stress
- \( D \) = displacement on fault
- \( c \) = specific heat
- \( \rho \) = density
- \( \mu \) = coefficient of friction
- \( \sigma_n \) = normal stress
- \( p_p \) = pore pressure
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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
    - $\mu = 0.08 - 0.19$ at plate boundary fault zone

- Laboratory studies
  - High velocity (Ujiie et al., 2013; Remitti et al., 2015)
    - $v = 1.3 - 3.5$ m/s; $\mu = 0.03 - 0.19$
    - Velocity neutral to velocity weakening
  - Low velocity (Ikari et al., 2015)
    - $v < 1$ mm/s; $\mu = 0.2 - 0.26$
    - Velocity strengthening to velocity weakening
1999 ($M_w$ 7.6) Chi-Chi earthquake, Taiwan

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

2008 ($M_w$ 7.9) Wenchuan earthquake, China

- Temperature: $\mu < 0.02$ (Li et al., 2015)
- Laboratory (Zhang & He, 2013; Togo et al., 2016)
  - High velocity: $\mu = 0.02 – 0.15$ (outcrop)
  - Low velocity: $\mu = 0.2 – 0.6$ (outcrop)
Mechanism of Weakening?

- Thermal pressurization
- Thermal decomposition
- Amorphization
- Dynamic reduction of $\sigma_n$
- Local melting

need more data!
Looking Forward: Drilling Deeper

Nankai Trough Exp. 358
Looking Forward: Drilling Deeper

Nankai Trough Exp. 358

Tobin et al., 2019
Looking Forward: Long Term Monitoring

Nankai Trough
Araki et al., 2017

Hikurangi Margin
Saffer et al., 2019

North Anatolian Fault
Bohnhoff et al., 2017
Thank you