# The shallow reaches of earthquake rupture

## peculiar aspects and energy dissipation


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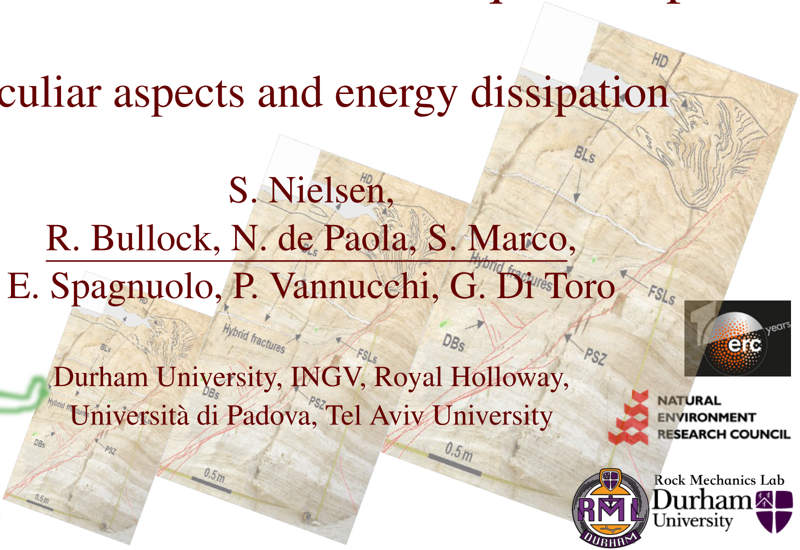


Rock Mechanics Lab
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# How frequent and how large are shallow slip and surface breaching ?

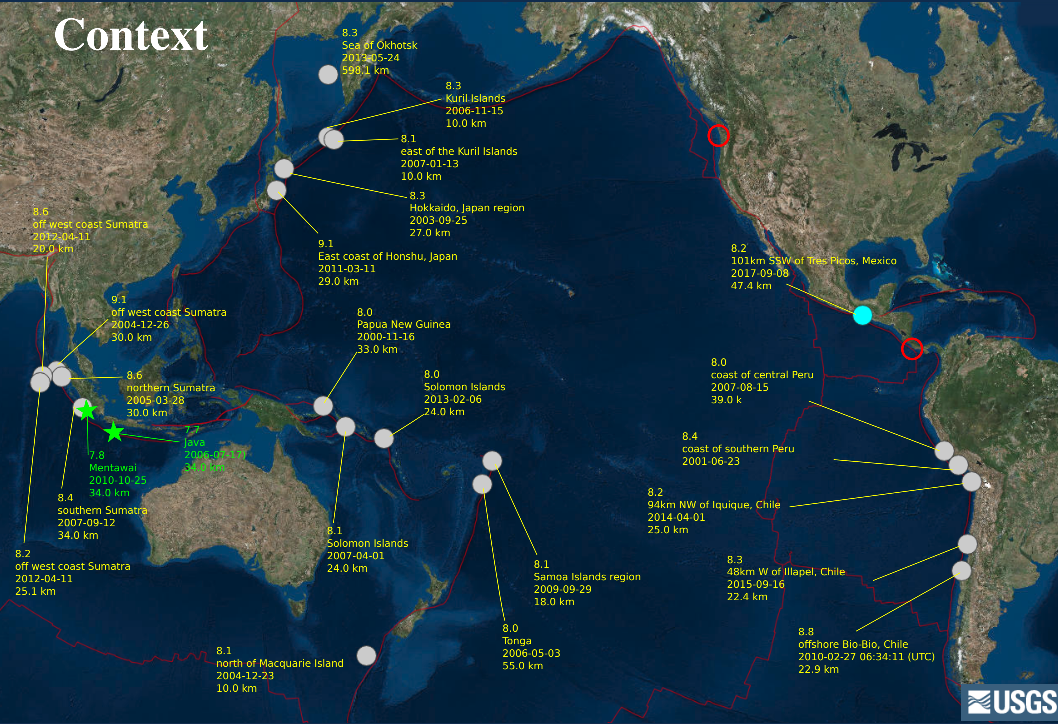
This question has important hazard implications but is surprisingly difficult to answer:

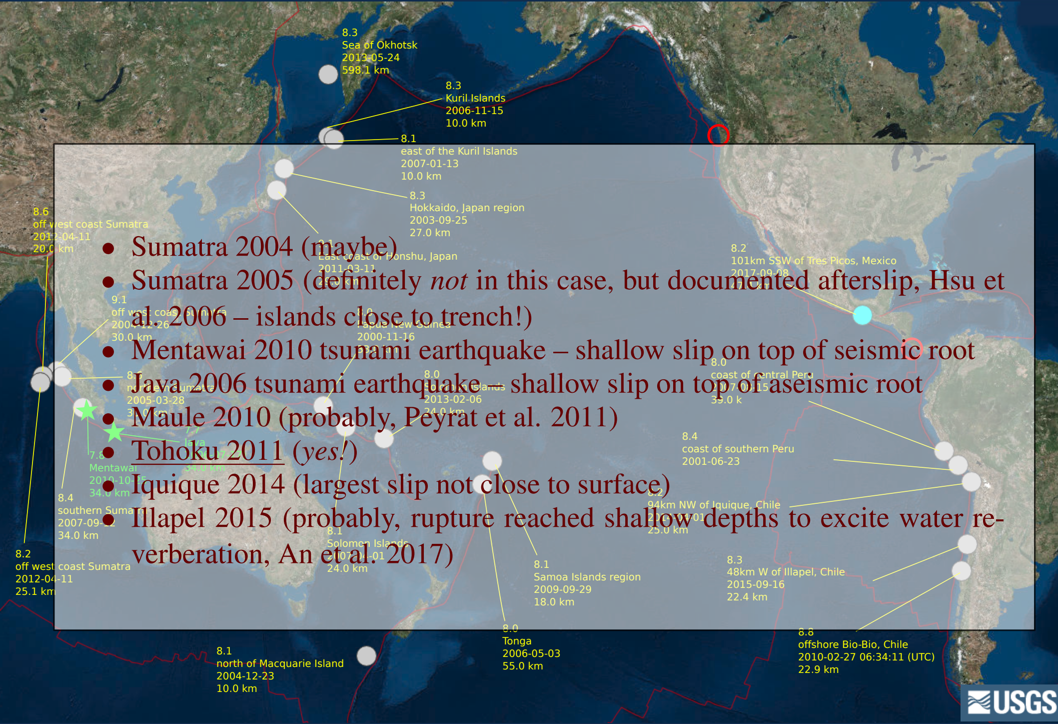
→ Many large earthquakes are underwater:
  - Not easy for inspection
  - Often far from traditional, on-land geodetic and seismic implementation

→ Difficult to in separate co- and post-seismic slip

Megathrust and tsunami earthquakes can (seismically) breach the seafloor. Clear examples are few. But since the 2011 Tohoku (Japan) earthquake we know for sure that rupture em can breach the sea-floor.

# Context


8.3
Sea of Okhotsk
2013-05-24
598.1 km
8.3
Kuril Islands
2006-11-15
10.0 km
8.1
east of the Kuril Islands
2007-01-13
10.0 km
8.3
Hokkaido, Japan region
2003-09-25
27.0 km
9.1
East coast of Honshu, Japan
2011-03-11
29.0 km
8.6
off west coast Sumatra
2012-04-11
20.0 km
9.1
off west coast Sumatra
2004-12-26
30.0 km
8.0
Papua New Guinea
2000-11-16
33.0 km
8.6
northern Sumatra
2005-03-28
30.0 km
8.0
Solomon Islands
2013-02-06
24.0 km
7.7
Java
2006-07-17)
34.0 km
7.8
Mentawai
2010-10-25
34.0 km
8.4
southern Sumatra
2007-09-12
34.0 km
8.2
off west coast Sumatra
2012-04-11
25.1 km
8.1
Solomon Islands
2007-04-01
24.0 km
8.1
Samoa Islands region
2009-09-29
18.0 km
8.0
Tonga
2006-05-03
55.0 km
8.1
north of Macquarie Island
2004-12-23
10.0 km
8.2
101km SSW of Tres Picos, Mexico
2017-09-08
47.4 km
8.0
coast of central Peru
2007-08-15
39.0 k
8.4
coast of southern Peru
2001-06-23
8.2
94km NW of Iquique, Chile
2014-04-01
25.0 km
8.3
48km W of Illapel, Chile
2015-09-16
22.4 km
8.8
offshore Bio-Bio, Chile
2010-02-27 06:34:11 (UTC)
22.9 km
USGS




- Sumatra 2004 (maybe)
- Sumatra 2005 (definitely *not* in this case, but documented afterslip, Hsu et al. 2006 – islands close to trench!)
- Mentawai 2010 tsunami earthquake – shallow slip on top of seismic root
- Java 2006 tsunami earthquake – shallow slip on top of aseismic root
- Maule 2010 (probably, Peyrat et al. 2011)
- Tohoku 2011 (*yes!*)
- Iquique 2014 (largest slip not close to surface)
- Illapel 2015 (probably, rupture reached shallow depths to excite water reverberation, An et al. 2017)

# Aims

The mechanical behaviour of shallow faulting is poorly understood and poorly anticipated in current models (e.g. unexpected entity of superficial slip in Tohoku quake). Earthquakes like to ... surprise us! ow to better constrain our rupture models?

Here I will explore how:

- Results on laboratory experiments
- Theory on the rupture energy budget
- Some peculiar features of shallow faulting

can give us information to feed into modelling of shallow rupture.


I'll make the ground shake, BOOM!
After the shaking, a tsunami will come SPLOOSH!
Be Prepared for the Nankai Trough Earthquake (*Nankai Torafu Jishin*)!
OK!!
We also have a [Summary]!!
Earthquake Man (Jishin Man)
Tsunami Man (Tsunami Man)
Professor Trough (Torafu Hakase)
Miss Helper (Herupa-chan)
Mr. Be-Prepared (Taisaku Kun)
Mr. Guide (Yudo Kun)
Kochi Prefecture Disaster Prevention Characters ©やなせたかし

# Context

- Dynamic interaction with surface (or sea-bottom)
- More compliant, poorly consolidated materials, and different frictional behavior
- Low normal stress $\longrightarrow$ low elastic energy storage
- Generally considered as passive participant to sesmic slip, if at all
- Yet the contribution of shallow slip to hazard is massive (quake and Tsunami)
- *Tsunami earthquakes* are not deep-rooted, indicating that stress accumulation in the shallow reaches is possible

# Context

The shallow reaches of ruptures are hosted either in sediment-rich, accretionary prisms or in more crystalline rocks (erosive margins). In the case of accretionary prisms,

- Built of sediments which are offscraped from the subducting plate
- Large volumes of poorly consolidated to compacted sediments
- Rich in fluids (though not necessarily over-pressured)
- Silty clays, silicate and carbonate fossil content (nanofossils, planktonic and benthonic foraminifera, radiolarians, diatoms, sponge spicules...
- Relatively low seismic velocities but rapid increase with depth ($V_p \approx$ 7 km/s at 10 km bsb, Nankai trough, Kamei et al. 2012).

Faulting structure is that of a complex branching network around (or above) a mature fault zone (subduction channel or decollement)

- Many strands of in-sequence and out of sequence thrusts and splay faults
- A multi-scale branching under constant evolution
- Possibly co-seismic growth and episodic localisation on immature fault strands

# Open questions, prejudice and paradox

Shallow fault structures have often been considered as:

- Unlocked (stable sliding), therefore incapable of building-up stress
- Sometimes depicted as precluding high velocity (seismic) slip (velocity hardening)
- Many large thrusts are at sea, limiting the amount of GPS observation and the resolution on shallow slip (coseismic and interseismic)

However evidence points to opposite behaviour:

- Tsunami earthquakes seismically rupture *only* at shallow depth
- Both Tsunami and megathrust earthquakes can show large, shallow coseismic slip

# Observations

Shallow fault reaches are showing:

- Relatively slow rupture velocities
- Relatively reduced radiation
  - in Tsunami earthquakes the radiated energy versus moment is small
  - in great earthquakes (when radiation contributions can be de-aggregated) the shallow reaches radiate less high frequency than expected (eg. Tohoku, Ide et al. 2011).
- Low sliding friction
  - from laboratory experiments (Faulkner et al 2011, Bullock et al. 2015)
  - from and structural evidence (Keren and Kirkpatrick 2016)
- Low fracture energy (Faulkner et al 2011, Bullock et al. 2015)

# Factors affecting shallow rupture

- ◦ Prestress
- ◦ Coseismic impulse coming from neighbouring or deeper fault sections
- ◦ Wave velocity and density adjacent (and less adjacent) the fault
  $\rightarrow$ Lay & Bilek interpretation in terms of $\mu$
  $\rightarrow$ Tomography of seismic velocities in the prism
- ◦ Inhomogeneity
- * Geometry and boundary conditions (e.g. dip and surface proximity)
- ** Fault structure
- *** Dissipative factors (friction, fracture energy) influencing rupture propagation and slip

*... Can't study all but will focus on ** and ***

All models are wrong.
Some models are useful.

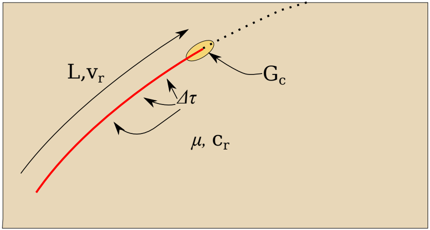
(George Box)

# Rupture propagation or arrest ?

## the energy budget

The energy balance controlling rupture propagation can be obtained in different ways, but always results in the same dimensionless parameter.

$$B = \frac{G_c\, \mu'}{\Delta\tau^2\, L}\; \frac{2\,\pi}{1-\nu} \qquad \begin{cases} B > 1 & \text{rupture arrest} \\ B \simeq 1 & \text{rupture nucleation} \\ 0 < B < 1 & \text{dynamic rupture} \end{cases}$$




$$\begin{aligned} G_c &= \text{ fracture energy} \\ \Delta\tau = \tau_0 - \tau_d &= \text{ dynamic stress drop} \\ L &= \text{ current rupture length} \\ \mu' &= \text{ shear stiffness} \end{aligned}$$

# Energy budget à la Rivera-Kanamori

$$E_r = E_{tot} - W_f - G_c = \frac{1}{2}\Delta\tau U - G_c$$

$$\text{replace } U = \frac{2\,\pi}{1-\nu}\,\frac{\Delta\tau}{\mu'}L$$

$$E_r = \frac{2\,\pi}{1-\nu}\frac{\Delta\tau^2}{2\mu'}L - G_c$$

$$\frac{2\,\pi}{1-\nu}\,\frac{G_c\,\mu'}{\Delta\tau^2\,L} = 1 \;\;(\text{ setting } E_r = 0)$$

# The Griffith crack (for shear fracture, Andrews 1976):

istic length is chosen to be the critical half-length of a Griffith crack in plane strain (derived in a later section of this paper),

$$L_c = \frac{8}{\pi} \frac{\mu(\lambda + \mu)}{(\lambda + 2\mu)} \frac{G_c}{(\tau_0 - \tau_f)^2}$$

# Energy budget from the energy flow:

$$\text{Stress intensity: } K_0 = \sqrt{\frac{1}{2\pi}}\,\Delta\tau\,\sqrt{L}$$

$$\text{Static strain energy flow: } G_0 = \frac{K_0^2}{2\mu'}(1-\nu)$$

$$\text{Dynamic strain energy flow: } G = G_0\, g(v_r) \quad \text{where} \quad g(v_r) \approx \sqrt{1-\frac{v_r^2}{c_r^2}}$$

Then the balance $G$ of *energy flow* to *fracture energy* $G_c$ is:

$$G_0\sqrt{1-\frac{v_r^2}{c_r^2}} = G_c \;\longrightarrow v_r = c_r\sqrt{1-\frac{G_c\,\mu'}{\Delta\tau^2\,L}\;\frac{2\,\pi}{1-\nu}}$$

We can also implement a simple solution for inhomogeneous stress drop (Fossum and Freund 1973):

$$K_0(x) = \sqrt{\frac{2}{\pi}} \int_0^L \frac{\Delta\tau(x)}{\sqrt{L(t) - x}} dx$$

$$\left( \text{for const. } \Delta\tau: \;\; K_0 = \sqrt{\frac{1}{2\pi}}\, \Delta\tau \sqrt{L} \right)$$

Using piecewise constant prestress ($\Delta\tau$ for the deep fault root, $\Delta\tau_1$ for the shallow part) we can write:

$$K_0(L) = \sqrt{\frac{1}{2\pi}} \Delta\tau \sqrt{L} \left( 1 - \left( 1 - \frac{\Delta\tau_1}{\Delta\tau} \right) \sqrt{1 - \frac{L_1}{L}} \right)$$

And again obtain the energy flow

$$G_0 = \frac{K_0^2}{2\mu'}(1-\nu)$$

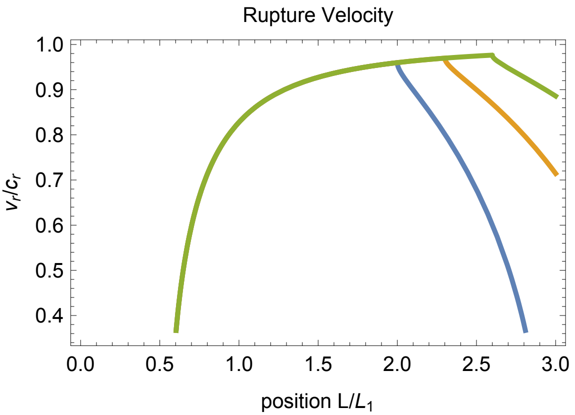
$$G = G_0\, g(v_r) \quad \text{where} \quad g(v_r) \approx \sqrt{1-\frac{v_r^2}{c_r^2}}$$

which is equated to the fracture *fracture energy* To retrieve $v_r$

$$G_0\sqrt{1-\frac{v_r^2}{c_r^2}} = G_c \longrightarrow v_r = c_r\sqrt{1-\frac{\Gamma^2}{G_0^2(L)}}$$

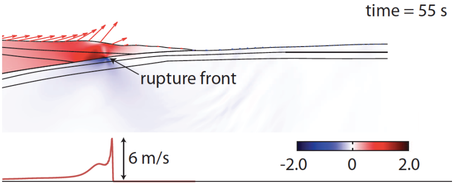
For the case of zero prestress in the shallow reaches of the fault, we obtain:

$$G_0 = \frac{4(1-\nu)}{\pi}\frac{\Delta\tau^2}{\mu'}\,L\,\left(1-\sqrt{1-\frac{L_r}{L}}\right)^2$$

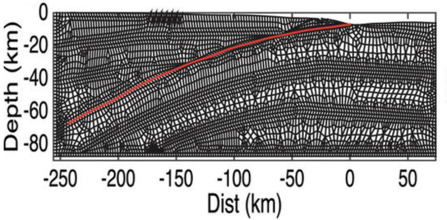



The rupture decelerates in the zero-stress, shallow region. However if the shallow region is small enough relative to the fault root, then rupture can reach the surface before stopping.

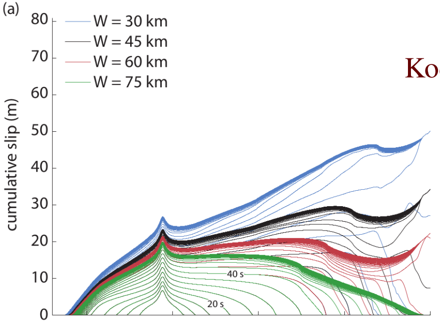
# More sophisticated models:



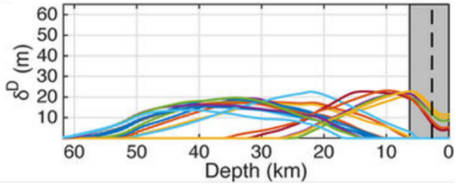

Kodzon & Dunham 2012




Murphy et al 2016




Kodzon & Dunham 2012




Murphy et al. 2016

$$G_0 = \frac{4(1-\nu)}{\pi}\frac{\Delta\tau^2}{\mu'} L \left(1-\sqrt{1-\frac{L_r}{L}}\right)^2$$

# What can we measure in laboratory experiments?

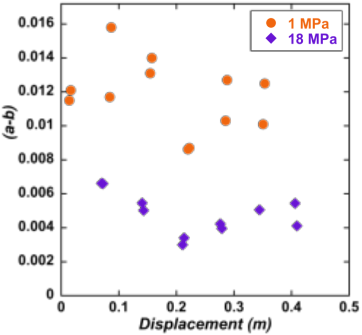
$$B = \frac{G_c \, \mu'}{\Delta\tau^2 \, L} \, \frac{2\,\pi}{1-\nu}$$

| | | |
|---|---|---|
| $G_c =$ | fracture energy | YES! but... |
| $\Delta\tau = \tau_0 - \tau_d =$ | dynamic stress drop | YES! but... |
| $L =$ | current rupture length | NO! |
| $\mu' =$ | shear stiffness | YES! |

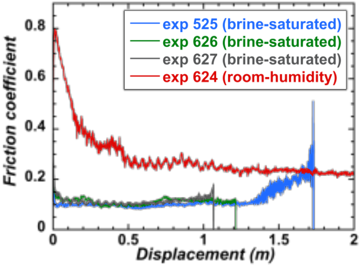
...and can we complete the laboratory measures with field observations?

# Frictional properties of experimental PSZs

Slow....



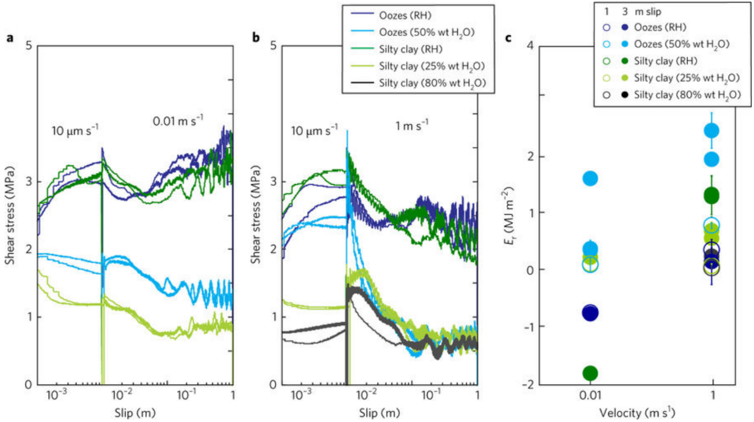

Fast!




(Bullock et al, submitted to Geology)

Water-saturated, clay-rich gouge shows vel. stre. at low V, vel. weak. at high V and very low fracture energy (defined as area below shear weakening and above min. sliding stress)in agreement with (Faulkner et al. 2011)

# Frictional properties of experimental PSZs




Vannucchi et al. 2017

However extremely low friction and fracture energy seems at odds with the very low radiation efficiency observed in the shallow reach of earthquake faults. How can we reconcile the two?

Laboratory experiments simulate one Principal Slip Zone – but:

- What about off-fault damage?
- How is it expressed in shallow faulting?
- How can it affect the dissipation?

# Structural features of shallow fault reaches

- General features of shallow fault segments
- accretionary (cotinental margin) and erosionary (ocean margin) differences
- Observations (IODP, fossil, ...)
- Cases of PCS (poorly consolidated sediments)
- Distributed network – doubts on where the earthquake slip has happened (which fault strand?)

How important is the contribution of SFR in overall Moment, slip and damage?

How important is the contribute of SFR in the energy balance? (low normal stress, low friction, passive role?)

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ARTICLES

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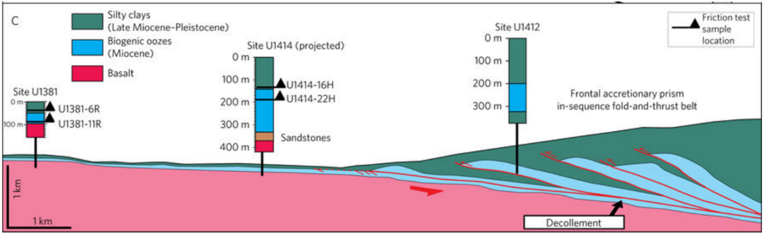
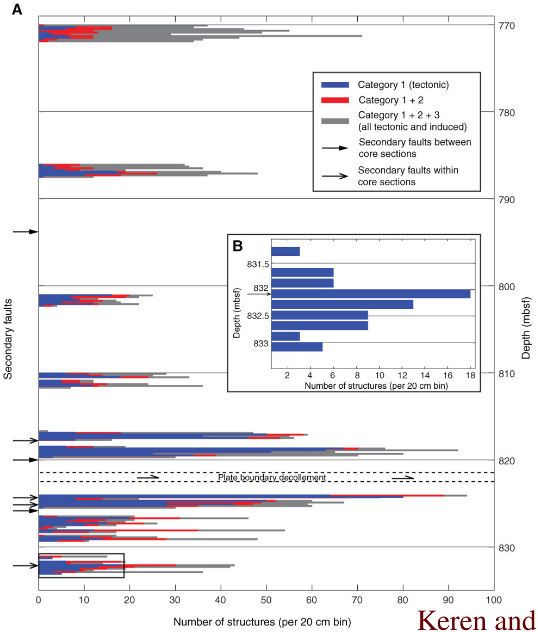
# Past seismic slip-to-the-trench recorded in Central America megathrust

Paola Vannucchi[1,2*], Elena Spagnuolo[3], Stefano Aretusini[4], Giulio Di Toro[4,5], Kohtaro Ujiie[6], Akito Tsutsumi[7] and Stefan Nielsen[8]

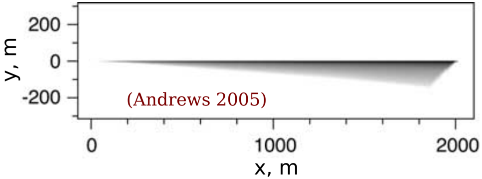


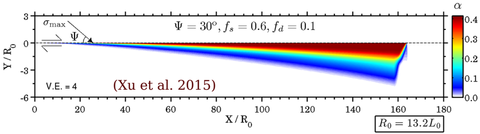



Keren and Kirkpatrick 2012

# Off-fault damage: Numerical models

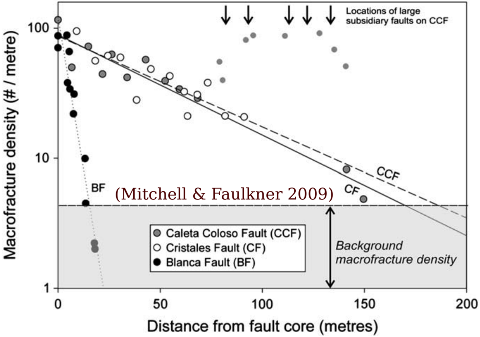
**Andrews, 2005**; Ben-zion and Shi, 2005; Rice et al. 2007; Bhat et al. 2007; Duan and day, 2008; Templeton and Rice, 2008; Hok et al. 2010; Ma and Andrews, 2010; Dunham et al., 2011; Kaneko and Fialko, 2011; Xu and Ben-zion, 2013; Gabriel et al., 52013; Xu et al. 2015. (Brittle material model of response developed by Lyakhovsky et al. 2011) **BUT NO LOCALISATION**



# Off-fault damage: field observations

Fractures and microfractures: Bhat et al, 2007; Mitchell nd Faulkner, 2009; Faulkner et al. 2011. Pulverisation: Dor et al, 2006; Mitchell et al. 2011; (numerous Experimental studies (Doan et al, 2009; Barber & Griffith 2017). Focus on fracture density and/or surface energy.



# Damage (fracture creation) and dissipation

Damage (creation of fracture) is not the dominant energy sink, because the net amount of surface enrgy is negligible –except for extreme cases of pulverisation (Barber & Griffith 2017).

The dominant energy sink is anelastic mechanical work:

$$W_T = \int_{\varepsilon_{ij}^0}^{\varepsilon_{ij}^1} \tau_{ij}\, d\varepsilon_{ij} = \int_{\theta_{ij}^0}^{\theta_{ij}^1} \tau_{ij}\, d\theta_{ij} \rightarrow (= W_e = \text{elastic}, \text{recoverable}) + \int_{\gamma_{ij}^0}^{\gamma_{ij}^1} \tau_{ij}\, d\gamma_{ij} \rightarrow (= W_f = \text{anelastic}, \text{sink})$$

$W_T$ is the total mechanical work p.u. volume,
total strain $\varepsilon_{ij} = \theta_{ij} + \gamma_{ij}$ = elastic + anelastic

# Strain is localised slip (most of it) in shallow (seismic) environnement

- Even apparently ductile or “diffuse”strain, is accommodated along many tiny slip surfaces
- Plastic, viscous or particulate flow is triggered marginally:
  - in the PSZ at high slip velocity (Ask G. Di Toro:)
  - in deep earthquakes (ask A. Schubnel:)

Per unit fault zone area, the anelastic work can be written:

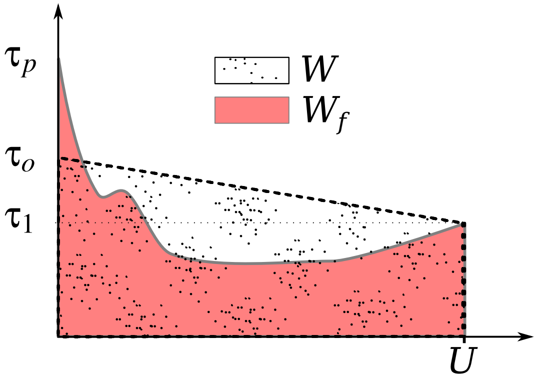
$$W_f = \int_H dz \int_{\gamma_0}^{\gamma_1} \tau_{ij}\, d\gamma_{ij}$$

but if the deformation is accomodated through slip $u_1$ on a localised surface, it can be shown that

$$W_f = \int_0^U \tau(u) du$$

and for a series of sub-parallel faults $i$

$$W_f = \sum_{i=1}^{N} \int_0^{U(i)} \tau\, du(i)$$




$$E_R = \frac{1}{2}\overline{(\tau^0 + \tau^1)}\ \overline{\Delta u} - \int_0^{\Delta u_{psz}} \overline{\tau}(u_{psz})\ du_{psz} - 2\Gamma$$

$$E_R = \frac{1}{2}\overline{(\tau^0 + \tau^1)}\ \overline{\Delta u} - \int_0^{\Delta u_{psz}} \overline{\tau}(u_{psz})\ du_{psz} - \sum_{i=2}^{N} \int_0^{\Delta u_i} \overline{\tau}(u_i)\ du_i$$

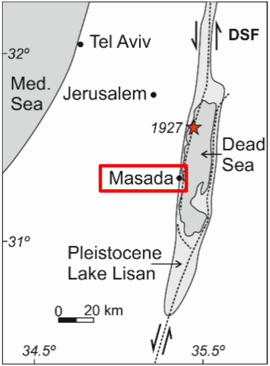
$$W_f = \sum_{i=1}^{N} \int_0^{U(i)} \tau \, du(i)$$

If we measure $W_f$ on the Principal Slip Zone alone, we may under-estimate it. But producing slip on an array of faults in the lab is problematic.

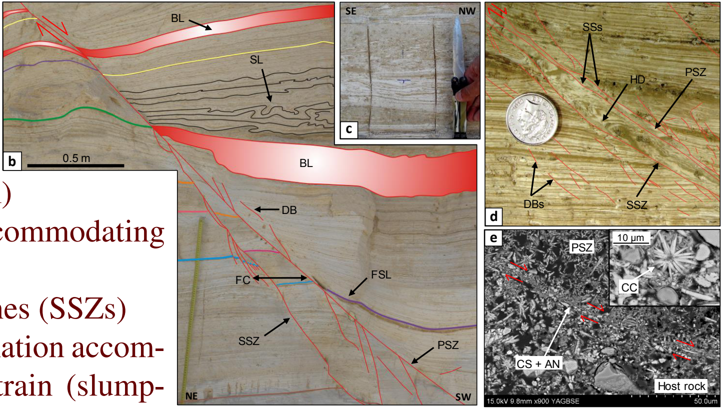
**Can field evidence be used in conjunction with laboratory measurements to investigate slip distribution on a fault array?**

A small-scale analog for what takes place at the subduction scale:

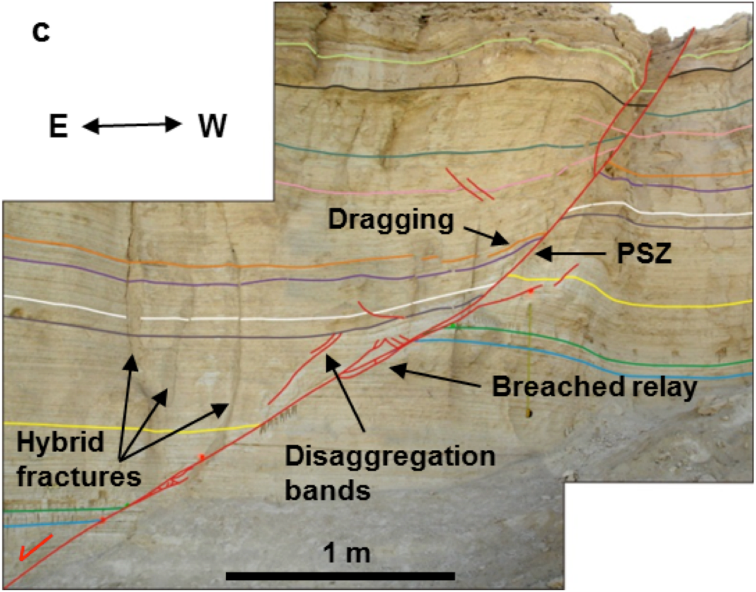
# The Masada fault system
## (not a thrust!)




- Dead Sea fault system in Israel
- Poorly lithified sediments (generally underwater and not well preserved, here preserved by desert)
- Evidence of seismicity (three $M_w \approx 6$). Seismites (not Marmite!), breccia and slumps in the sedimentary sequences
- Seismites as marker of seismicity have been supported by a striking correspondence in dates between geological record and historical earthquakes recorded by archeologic ancient structures, e.g.
  - Ateret fortress built on a fault trace (Marco et al. 1997)
  - Kasr-e-Tilah roman reservoir (Klinger et al., 2000)
- Aragonite and clay-rich detrital sediments (Pleistocene, Lisan formation) plus small amounts of gypsum, quartz and calcite




- Fault core (few dm)
- Several PSZs (accommodating most strain)
- Subsidiary slip zones (SSZs)
- Distributed deformation accommodating minor strain (slumping, folding, dragging)
- PSZs are 2-3 mm thick and bounded by very sharp surfaces, with:
  - Minimal evidence for fracturing and/or comminution within PSZs
  - Intense shear strain localization (e.g. clay smear)
  - Structural evidence for rolling, rotation and particulate flow (Fossen 2007)
- SSZs are adjacent and sometimes branching from the PSZs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Dragging
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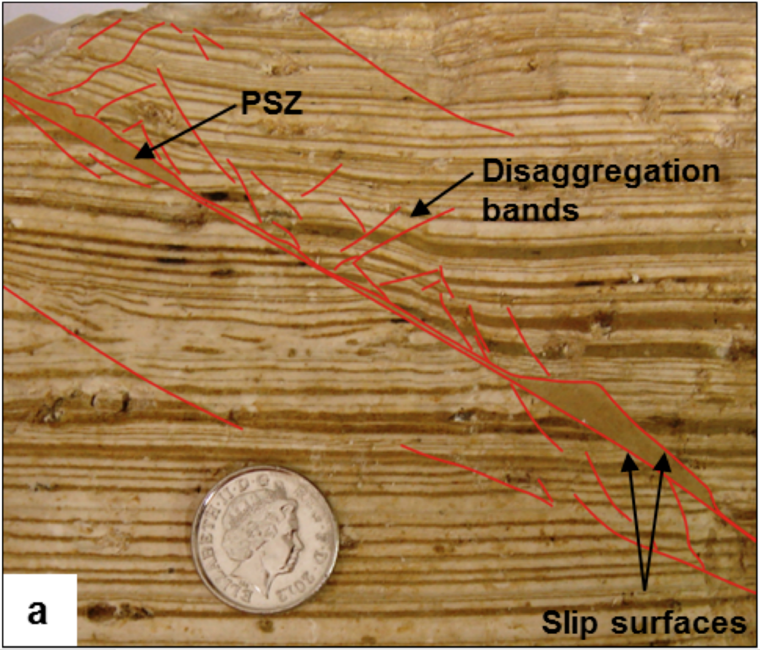
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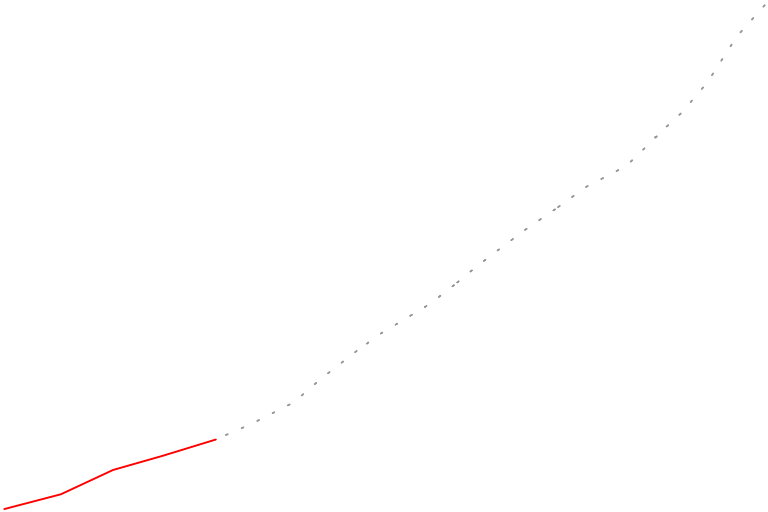
# Propagation and localisation



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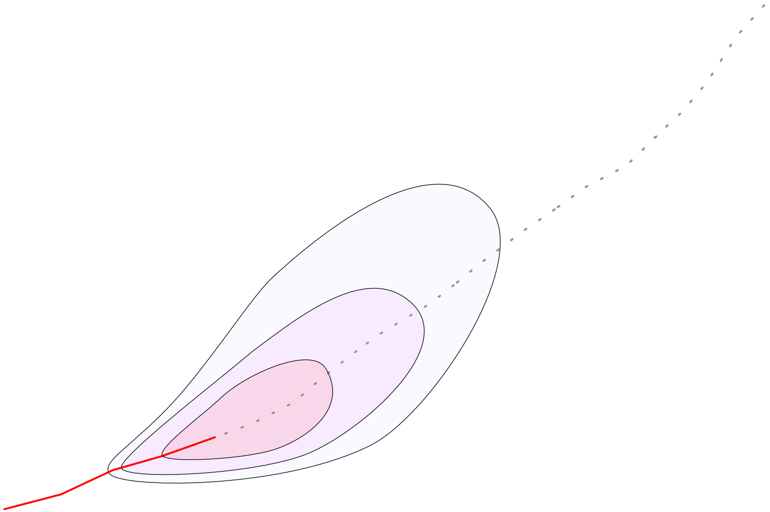

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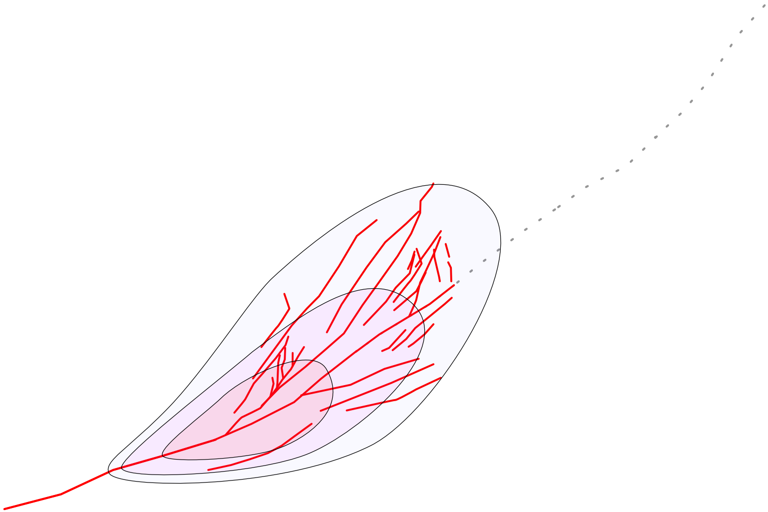

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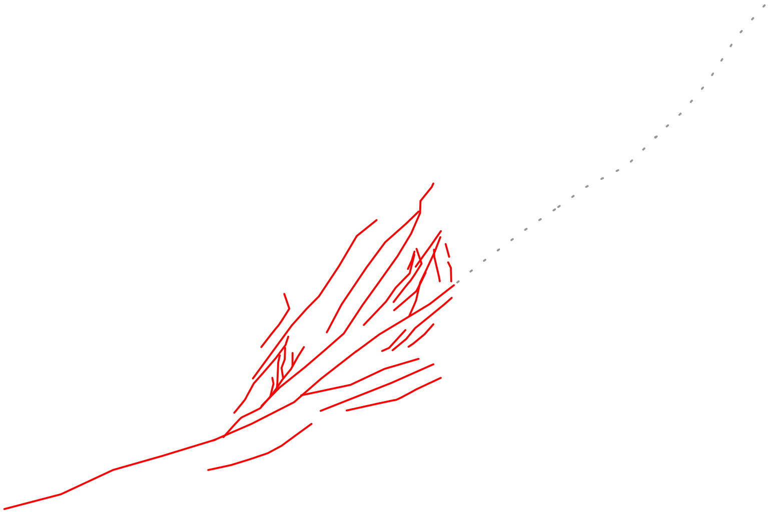

# Propagation and localisation

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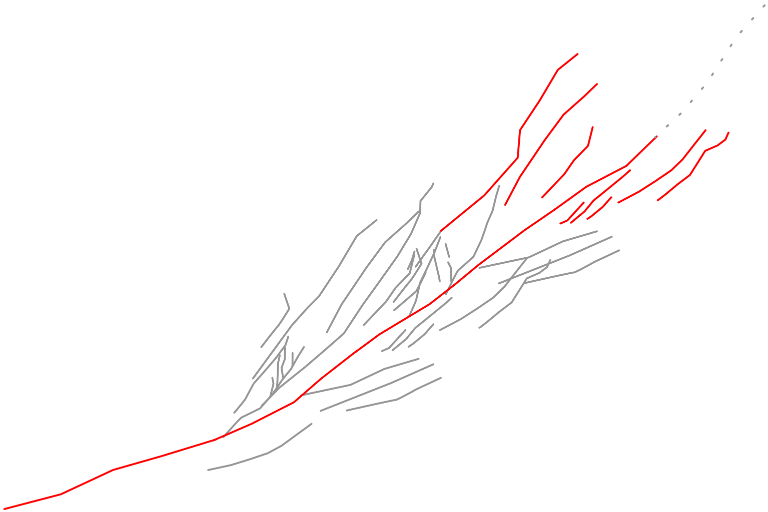
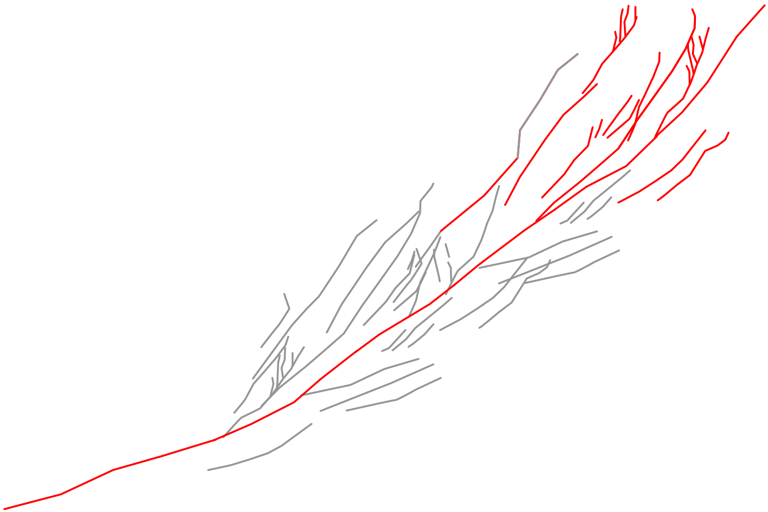
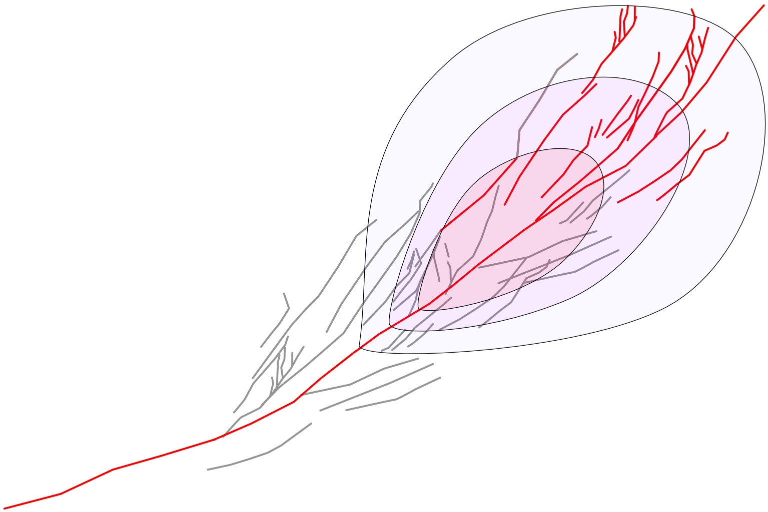


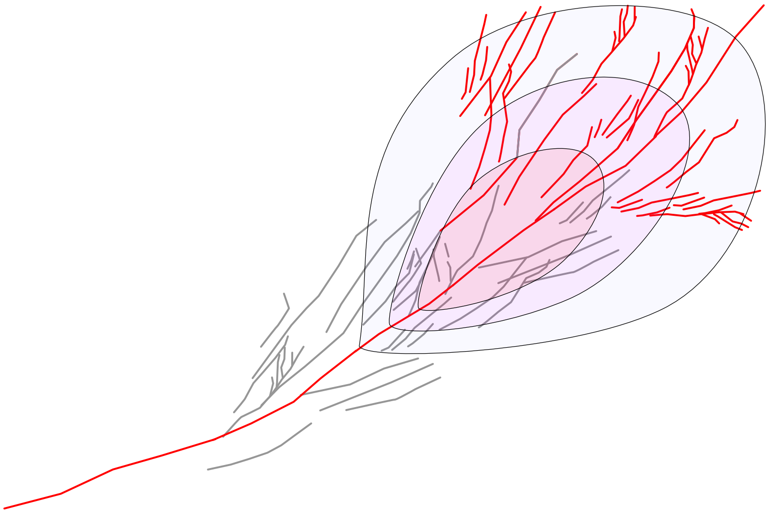
# Propagation and localisation



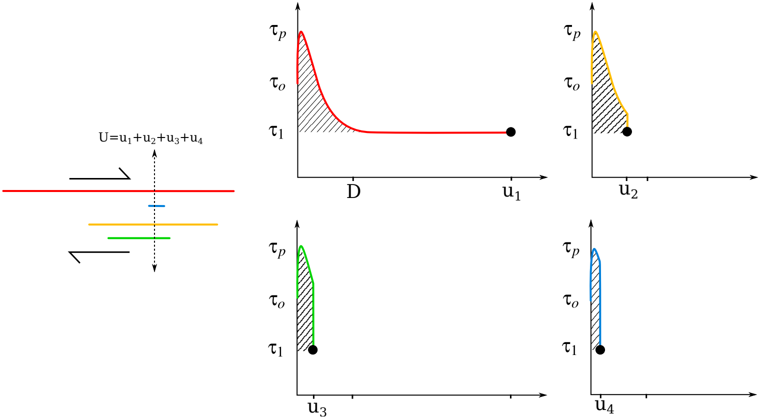
# Propagation and localisation



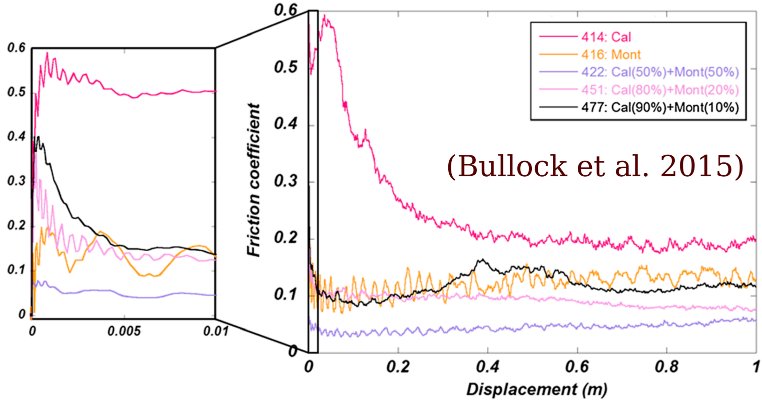
# Propagation and localisation



# Slip and dissipation on a fault array

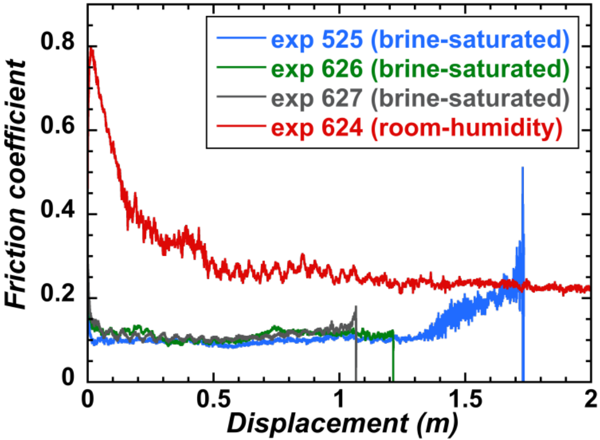


# Experimental weakening curves



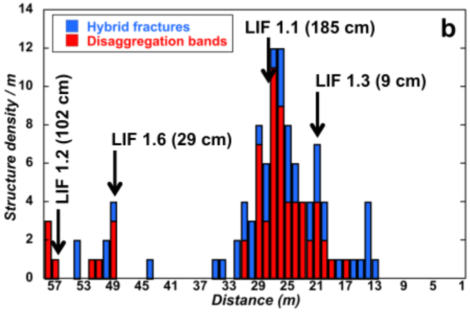

(Bullock et al. 2015)

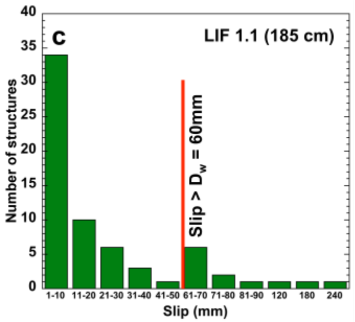
# Experimental weakening curves

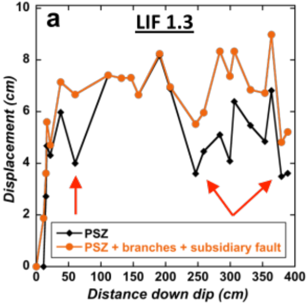



(from Bullock et al. submitted to Geology)

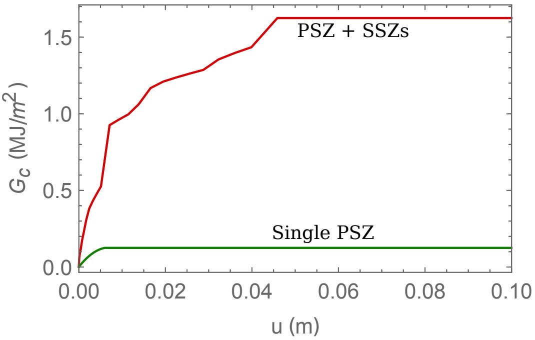
# Fault statistics and...



# Effective fracture energy




Single PSZ: $G_c \approx 0.12\text{MJ m}^{-2}$, $u \approx 0.2\text{m}$
PSZ + SSZs: $G_c \approx 1.65\text{MJ m}^{-2}$, $u \approx 0.6\text{m}$
The tenfold increase in fracture energyis due to the many more faults sliding under high, initial stress, thus magnifying the frictional work.

# Localised vs. diffuse strain in earthquake slip:
## an energy minimisation prospect

$$\text{Posit that} \begin{cases} \text{Velocity-hardening favours distributed slip} \\ \text{Velocity-weakening favours localised slip} \end{cases}$$

$N$ sub-parallel faults $i$ slide at velocity $\simeq v_i$. Across the width of the fault zone, traction is continuous but slip is cumulative, therefore

$$V = \sum_{i=1}^{N} v_i; \quad U = \sum_{i=1}^{N} u_i$$

$$v_i \approx \frac{V}{N}; \quad u_i \approx \frac{U}{N};$$

$$\text{however: } \tau = \tau_i.$$

Letting $f(v,\dots)$ be the frictional stress with velocity dependence,

$$\tau = f(v_i,\dots) \approx f\left(\frac{V}{N},\dots\right)$$

and the work of friction becomes:

$$W_f = \sum_{i=1}^{N} \tau\, u_i \approx \tau \times N \times \frac{U}{N} = f\left(\frac{V}{N},\dots\right) \times U$$

# Conclusions

- On natural fault zones, multiple subsidiary strands (SSZ) are expected to be active in the initial part of the slip
- Here an example of a very superficial, immature fault in unconsolidated solid
- The SSZs cumulate small slip individually, but they are many more and under but a high stress in the initial part of the weakening curve
- The effective frictional dissipation is much higher than that measured on a sinlg PSZ
- Knowledge of typical co-seismic slip distribution on a fault array may allow to re-calibrate laboratory findings in terms of seismic fracture enrgy

Open questions: Lack of generality of this field evidence.
Similar outcrops on mature faults? THANK-YOU!!!