Advanced Workshop on Earthquake Fault Mechanics: Theory, Simulation and Observations

ICTP, Trieste, Sept 2-14 2019

Lecture 6: macroscopic source properties

Jean Paul Ampuero (IRD/UCA Geoazur)

Overview

Macroscopic source properties constrained by seismology:

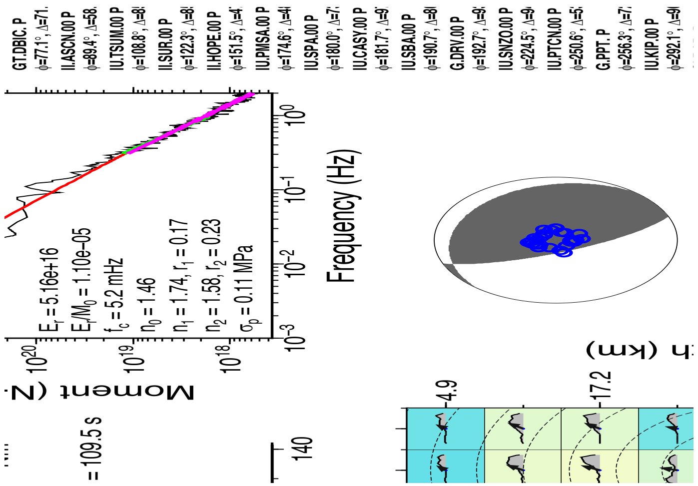
- seismic moment
- source time function
- corner frequency
- radiated energy

→ stress drop, rupture speed, rupture size

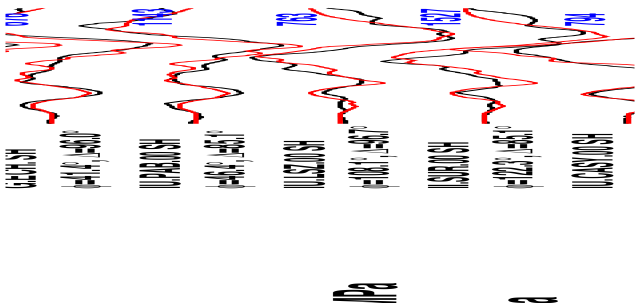
Detailed source parameters

Outputs of dynamic rupture models:

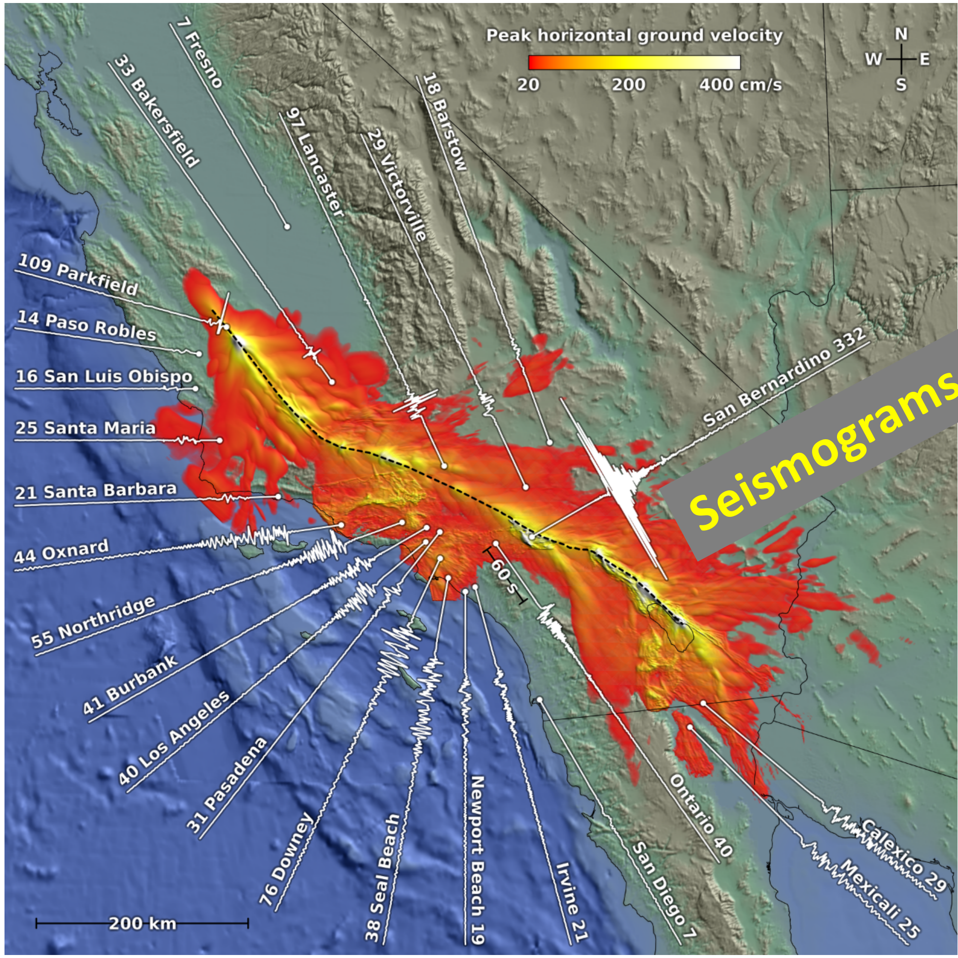
Detailed space-time distribution of slip on the fault



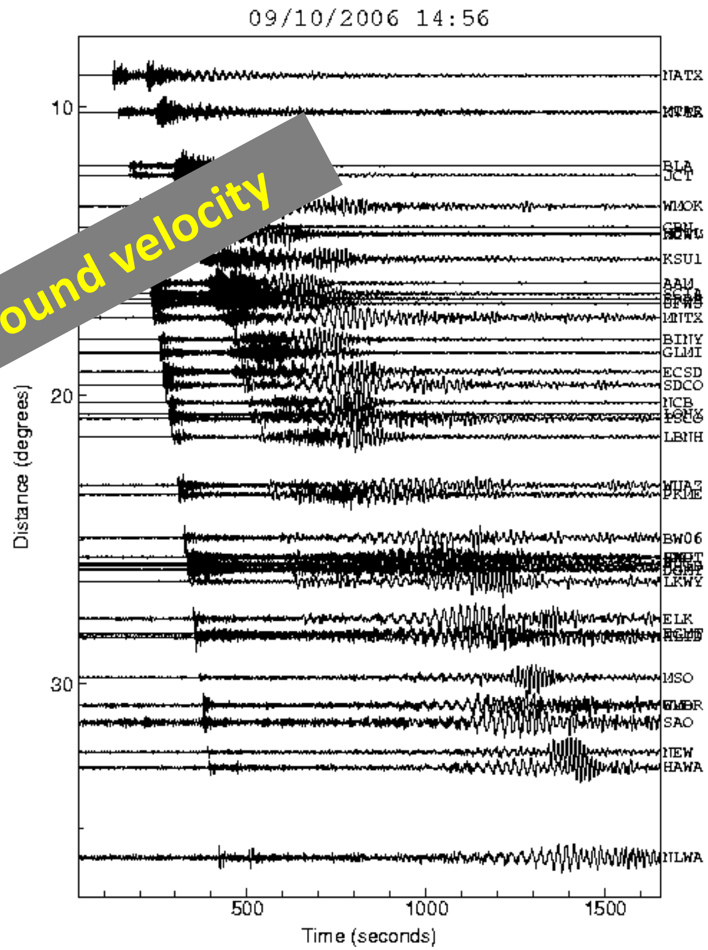
+ seismograms & ground displacements



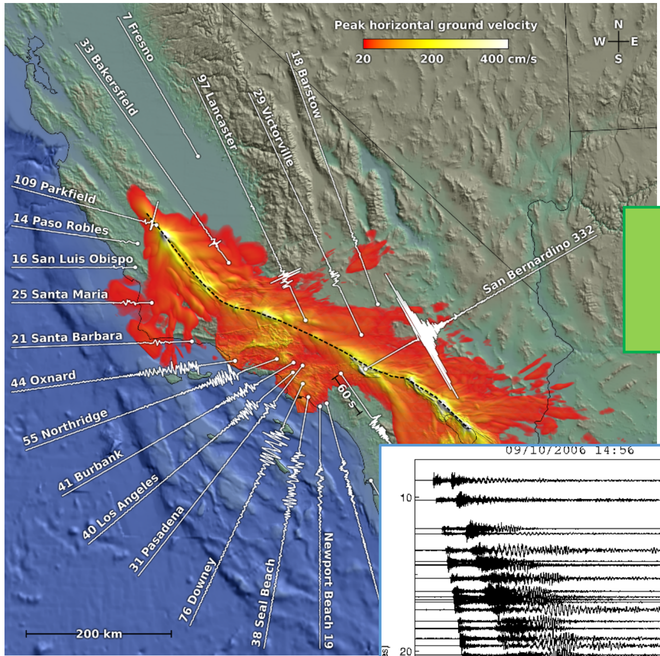
From ground motion recordings …

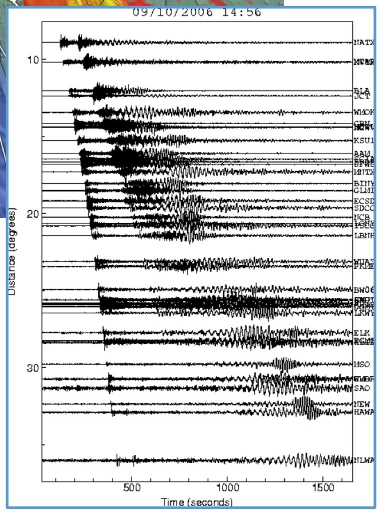


Seismograms = ground velocity

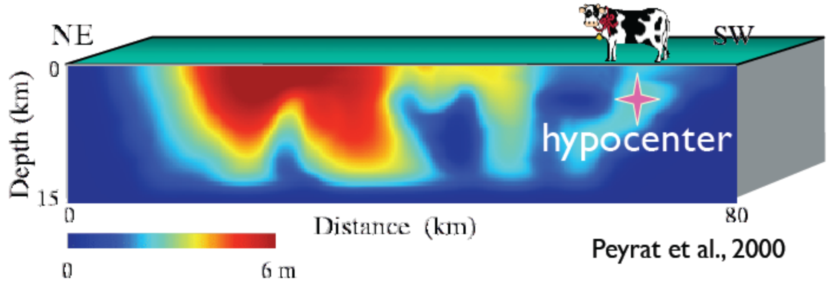


From ground motion recordings to the rupture process

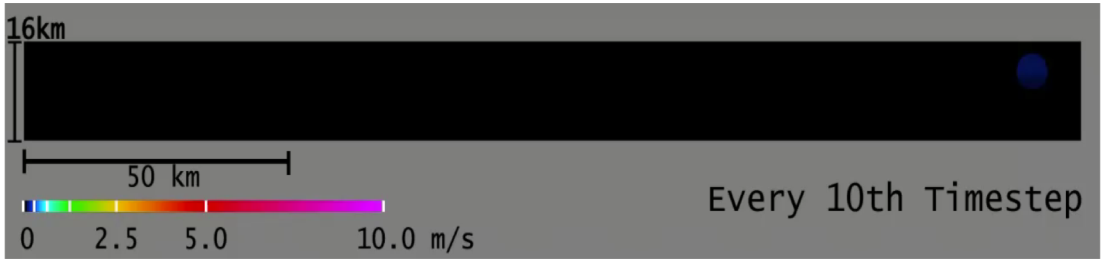




How much did the **fault** slip?



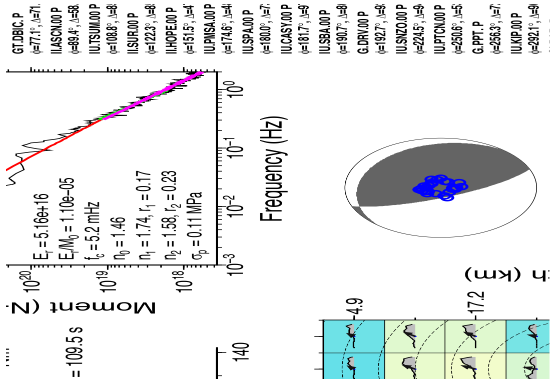
How did it slip?
Fast/slow? Smooth/tortuous? Loud/silent?



Fine vs. coarse source parameters

Outputs of dynamic rupture models:

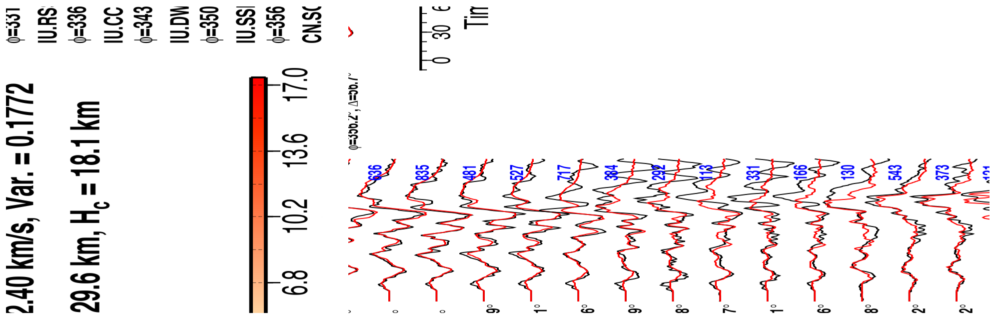
Detailed space-time distribution of slip on the fault



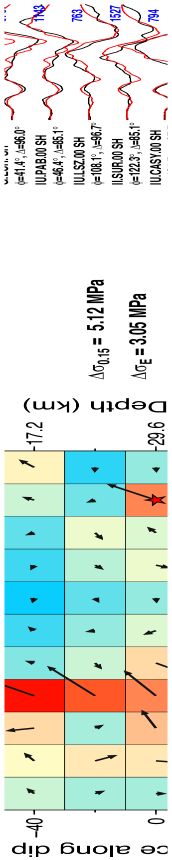
+ seismograms & ground displacements

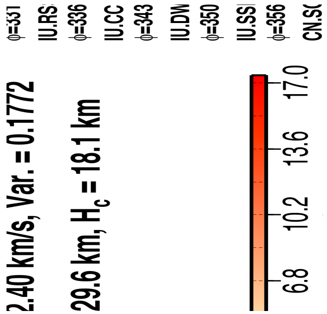
Macroscopic source parameters:

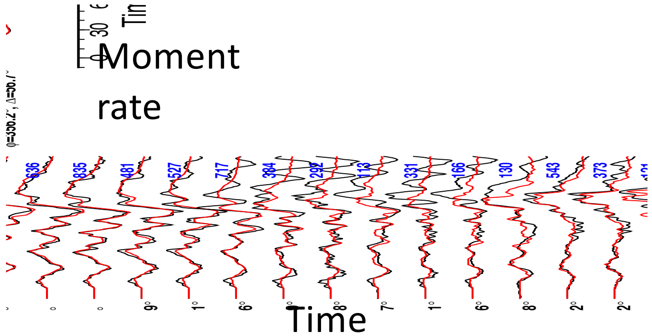
- Seismic moment
- Seismic moment rate (source time function)
- Rupture size
- Rupture duration
- Average rupture speed

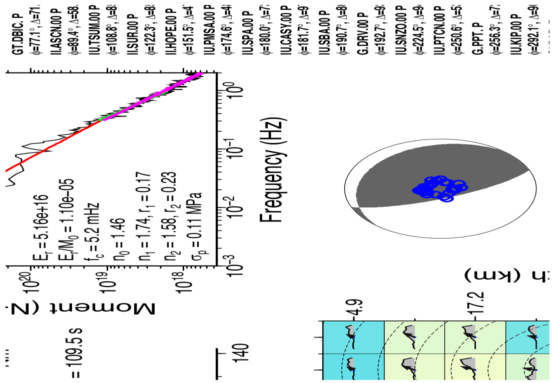


Trade-offs in earthquake source studies









High fidelity

Less uncertainty

High definition

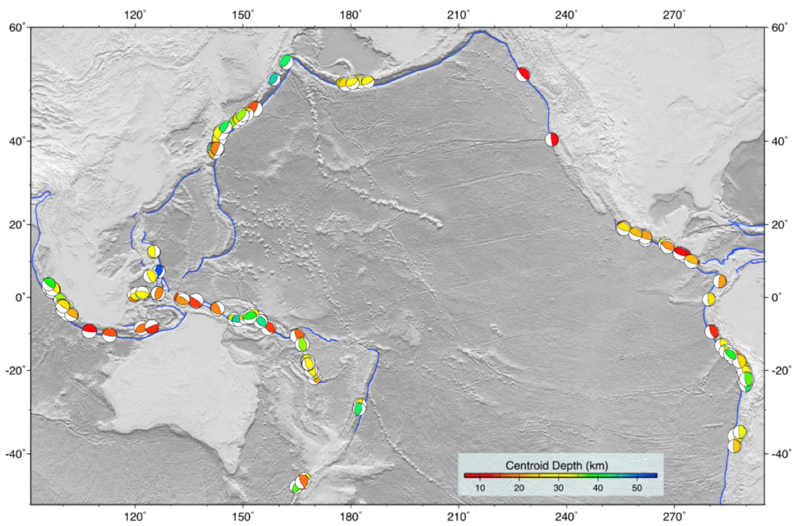
More detail

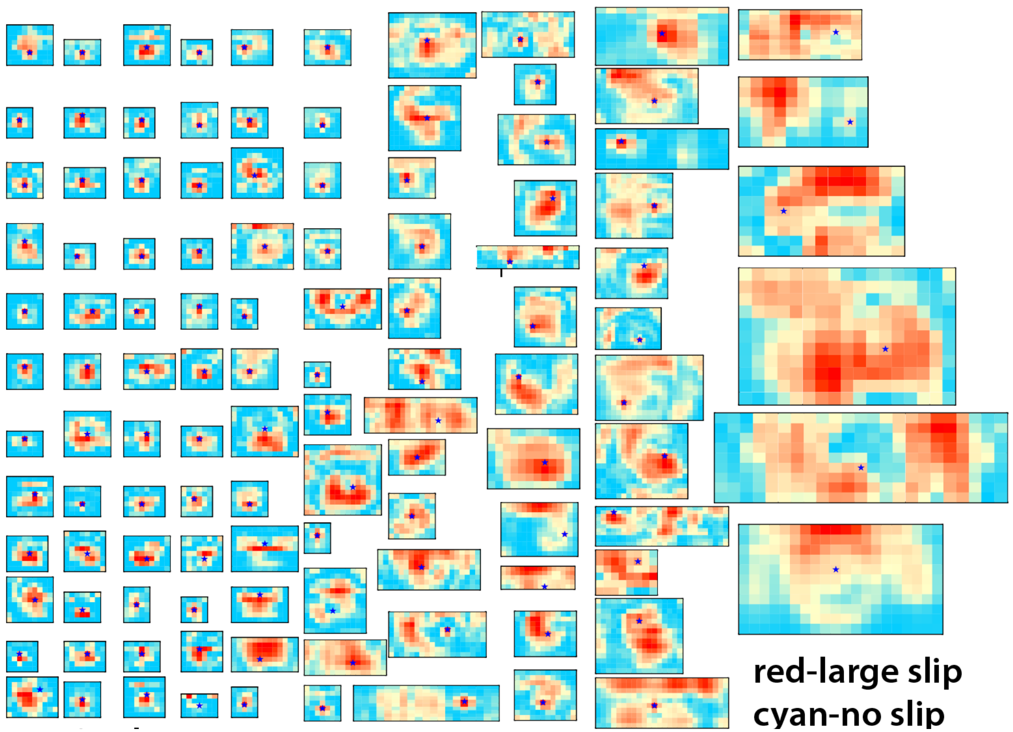
Source time functions

Global source studies

Ye et al (JGR 2016)

- 116 **M7+** shallow **subduction zone** thrust earthquakes
- finite source **inversions with teleseismic data**, 0.005-0.9 Hz
- Robust source time functions (STF, m**oment rate)**
- Uniform method and careful manual analysis





red-large slip
cyan-no slip

Global source studies

Ye et al (JGR 2016)

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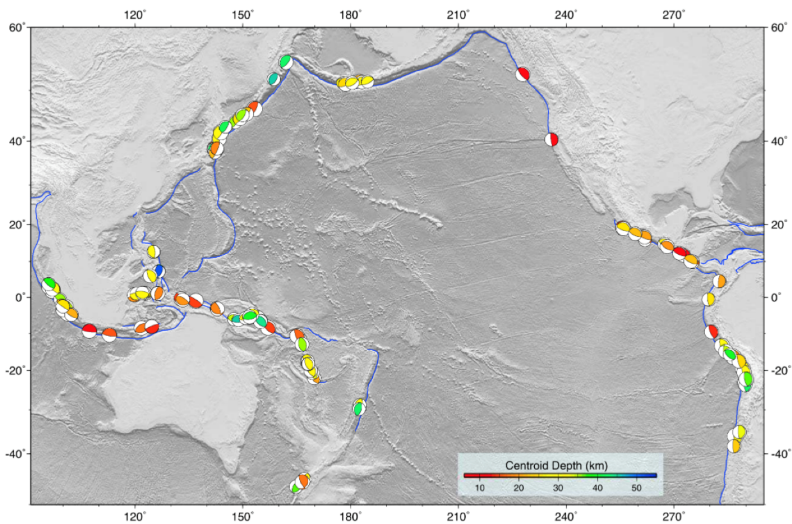
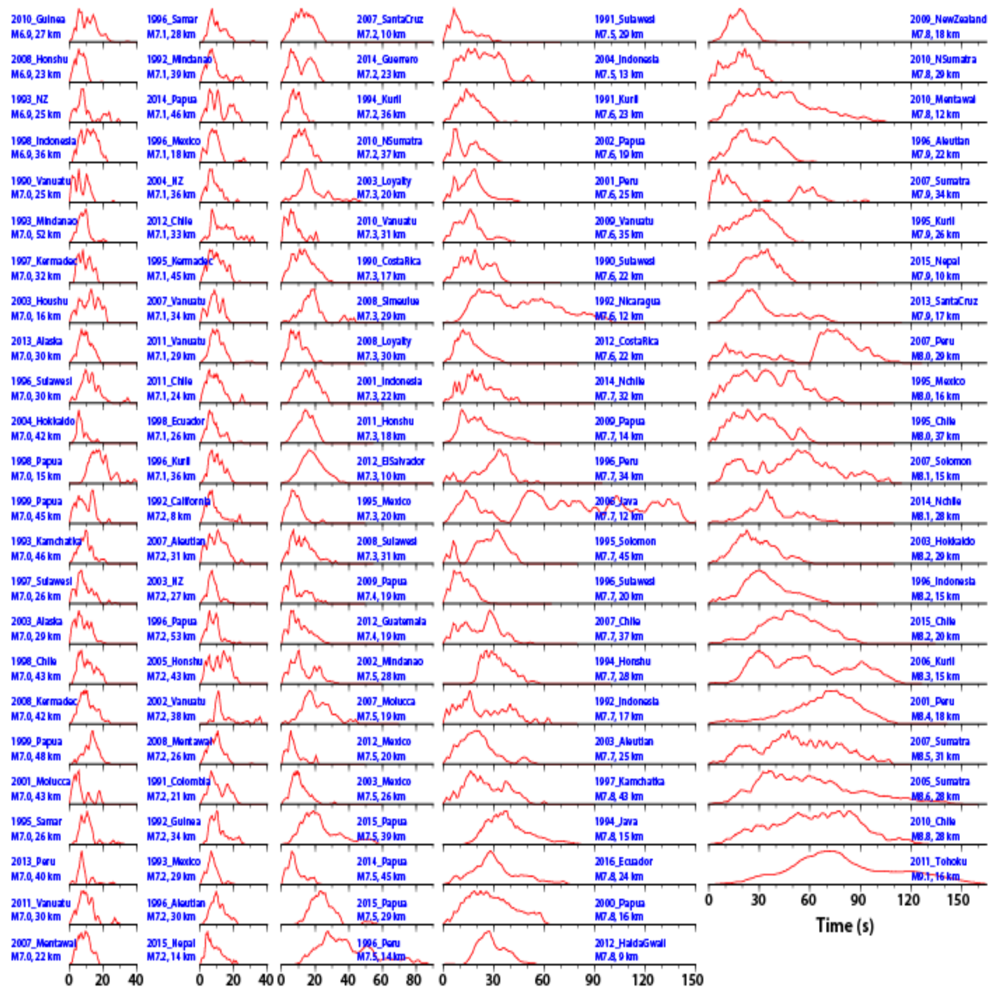
- Robust source time functions (STF, m**oment rate)**
- Uniform method and careful manual analysis





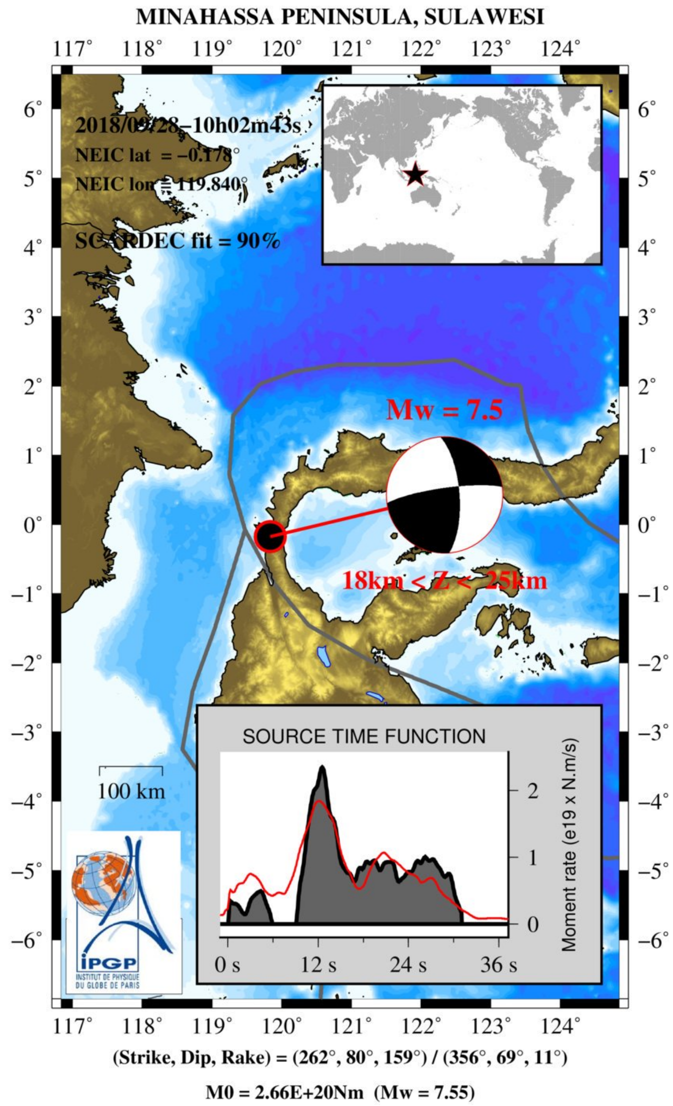
STF from deconvolution

seismogram = (Green's function)*(Source Time Function)

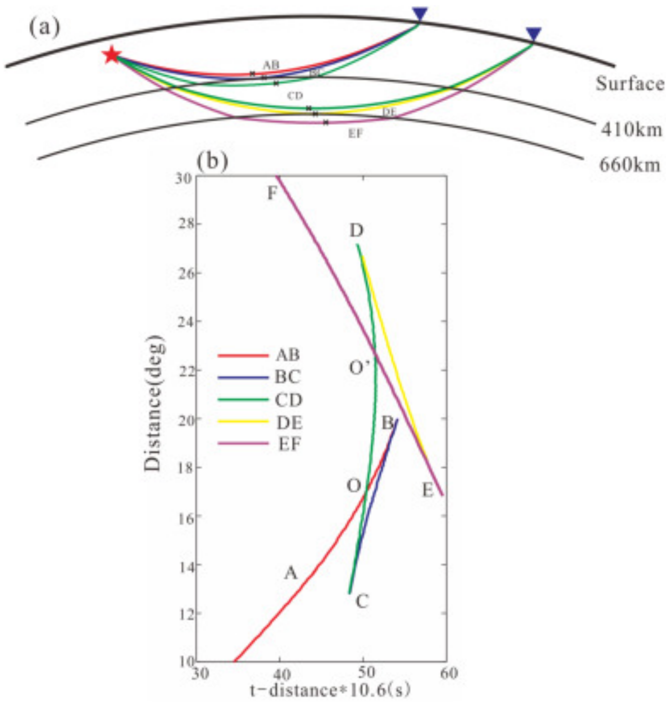
$$d_i(t) = G_i(t) * \dot{M}_0(t)$$

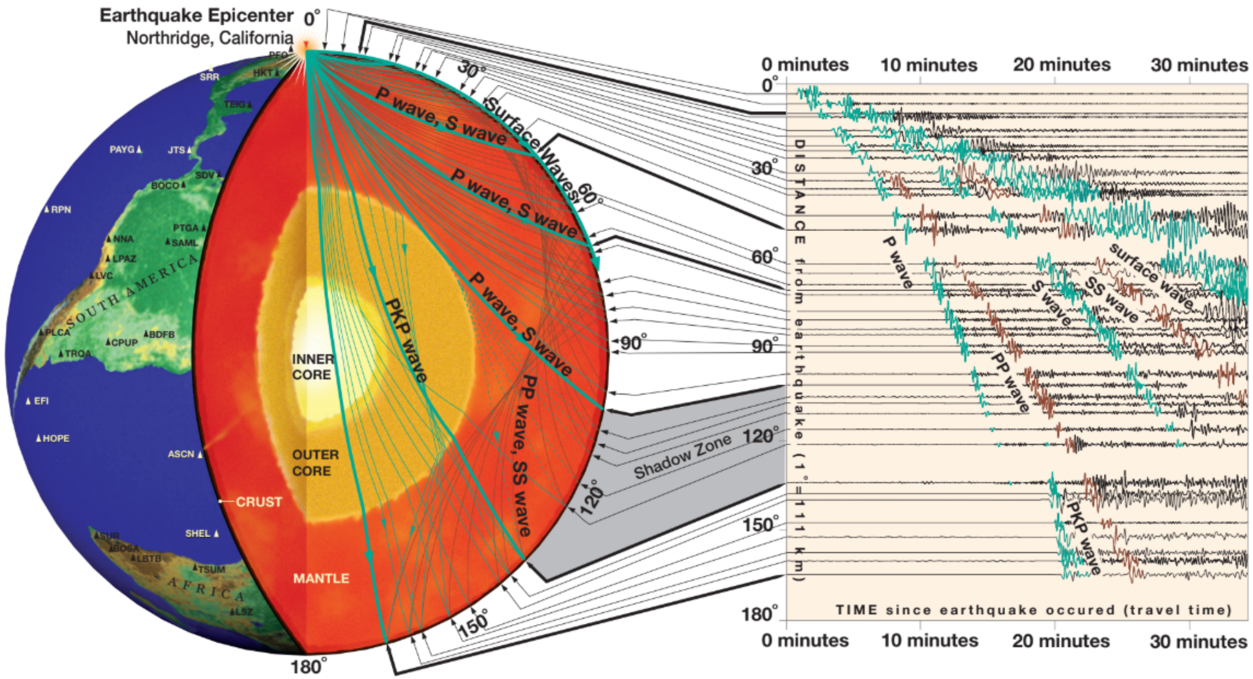
* means convolution
G can be synthetic or empirical
Deconvolution: infer $\dot{M}_0(t)$ from $d_i(t)$

SCARDEC (by Martin Vallée, IPGP):
real-time STF from teleseismic data
large catalog of past events
new events posted rapidly on Twitter by @geoscope_ipgp

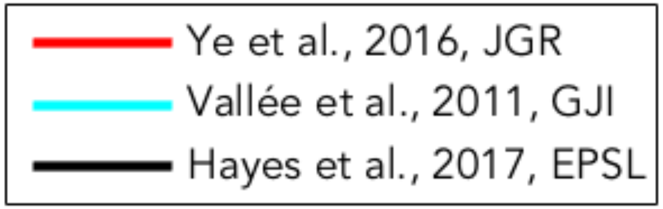


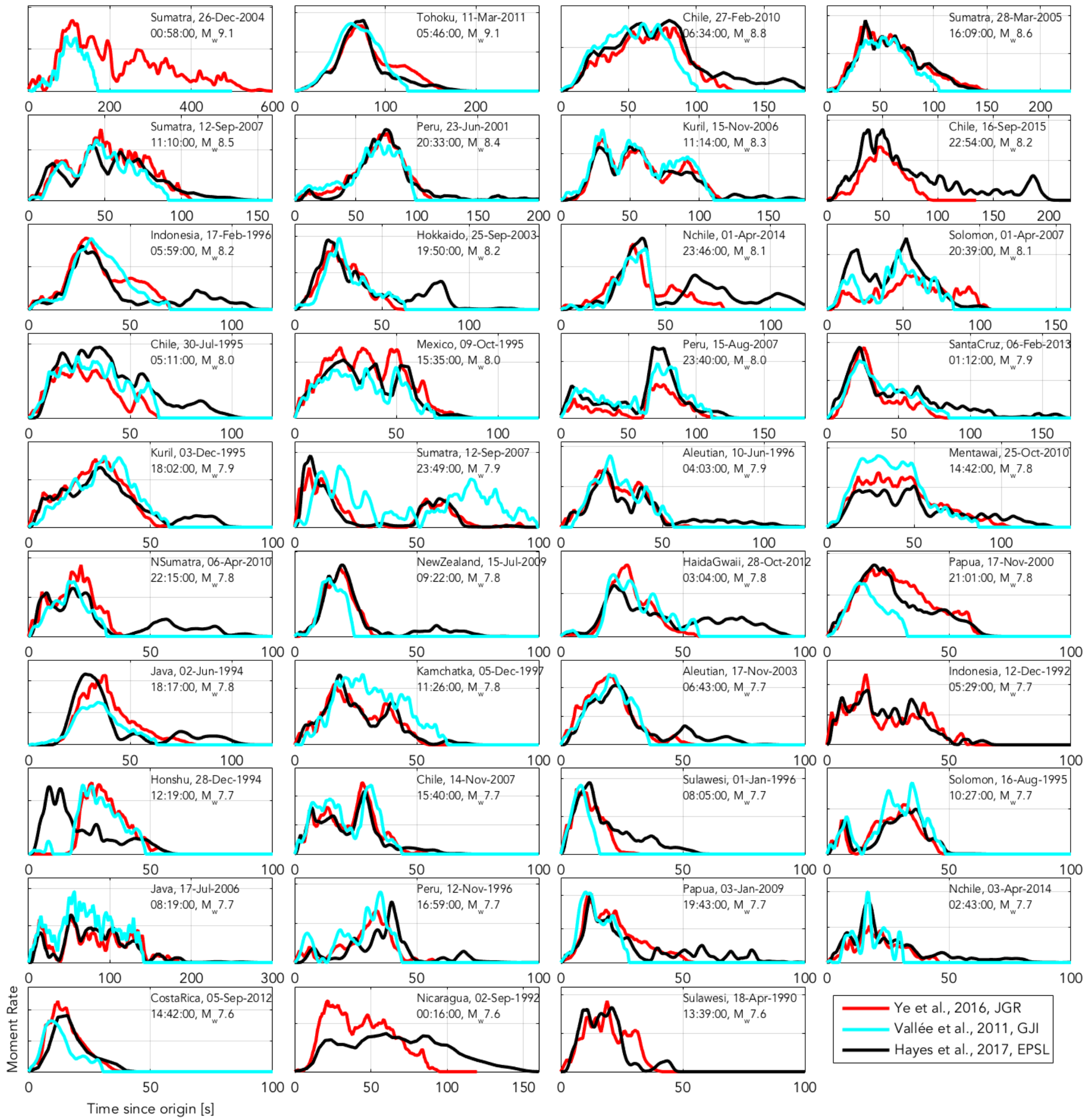
Teleseismic waves





https://www.iris.edu/hq/inclass/fact-sheet/


Ye et al., 2016, JGR
Vallée et al., 2011, GJI
Hayes et al., 2017, EPSL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Tohoku, 11-Mar-2011 05:46:00, Mw 9.1
Chile, 27-Feb-2010 06:34:00, Mw 8.8
Sumatra, 28-Mar-2005 16:09:00, Mw 8.6
Sumatra, 12-Sep-2007 11:10:00, Mw 8.5
Peru, 23-Jun-2001 20:33:00, Mw 8.4
Kuril, 15-Nov-2006 11:14:00, Mw 8.3
Chile, 16-Sep-2015 22:54:00, Mw 8.2
Indonesia, 17-Feb-1996 05:59:00, Mw 8.2
Hokkaido, 25-Sep-2003 19:50:00, Mw 8.2
Nchile, 01-Apr-2014 23:46:00, Mw 8.1
Solomon, 01-Apr-2007 20:39:00, Mw 8.1
Chile, 30-Jul-1995 05:11:00, Mw 8.0
Mexico, 09-Oct-1995 15:35:00, Mw 8.0
Peru, 15-Aug-2007 23:40:00, Mw 8.0
SantaCruz, 06-Feb-2013 01:12:00, Mw 7.9
Kuril, 03-Dec-1995 18:02:00, Mw 7.9
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Aleutian, 10-Jun-1996 04:03:00, Mw 7.9
Mentawai, 25-Oct-2010 14:42:00, Mw 7.8
NSumatra, 06-Apr-2010 22:15:00, Mw 7.8
NewZealand, 15-Jul-2009 09:22:00, Mw 7.8
HaidaGwaii, 28-Oct-2012 03:04:00, Mw 7.8
Papua, 17-Nov-2000 21:01:00, Mw 7.8
Java, 02-Jun-1994 18:17:00, Mw 7.8
Kamchatka, 05-Dec-1997 11:26:00, Mw 7.8
Aleutian, 17-Nov-2003 06:43:00, Mw 7.7
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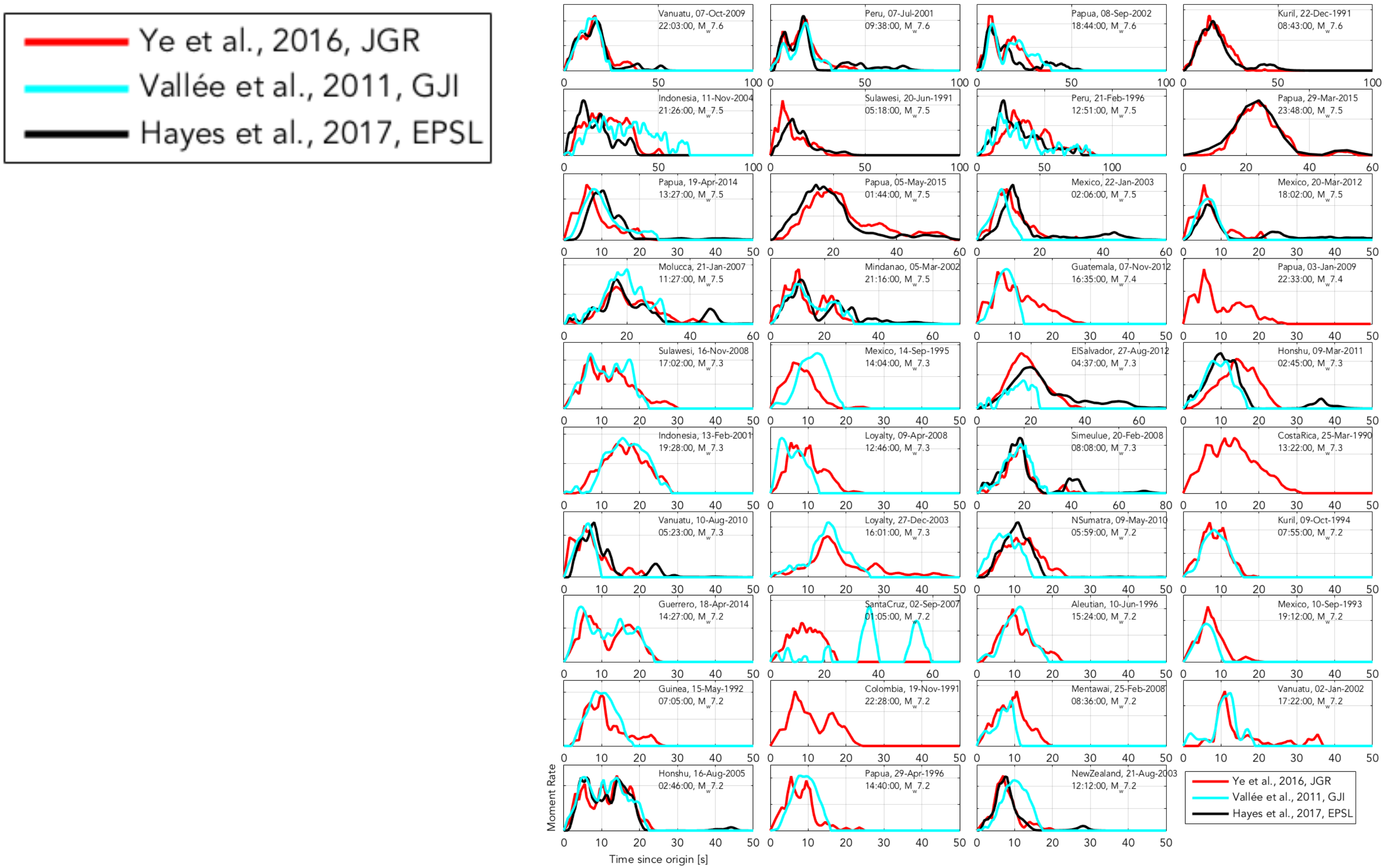
Sulawesi, 18-Apr-1990 13:39:00, Mw 7.6
Ye et al., 2016, JGR
Vallée et al., 2011, GJI
Hayes et al., 2017, EPSL
Moment Rate
Time since origin [s]



Ye et al., 2016, JGR
Vallée et al., 2011, GJI
Hayes et al., 2017, EPSL
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Sulawesi, 20-Jun-1991 05:18:00, Mw 7.5
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Vanuatu, 10-Aug-2010 05:23:00, Mw 7.3
Loyalty, 27-Dec-2003 16:01:00, Mw 7.3
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Colombia, 19-Nov-1991 22:28:00, Mw 7.2
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Vanuatu, 02-Jan-2002 17:22:00, Mw 7.2
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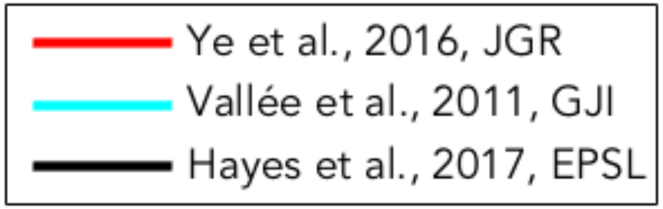
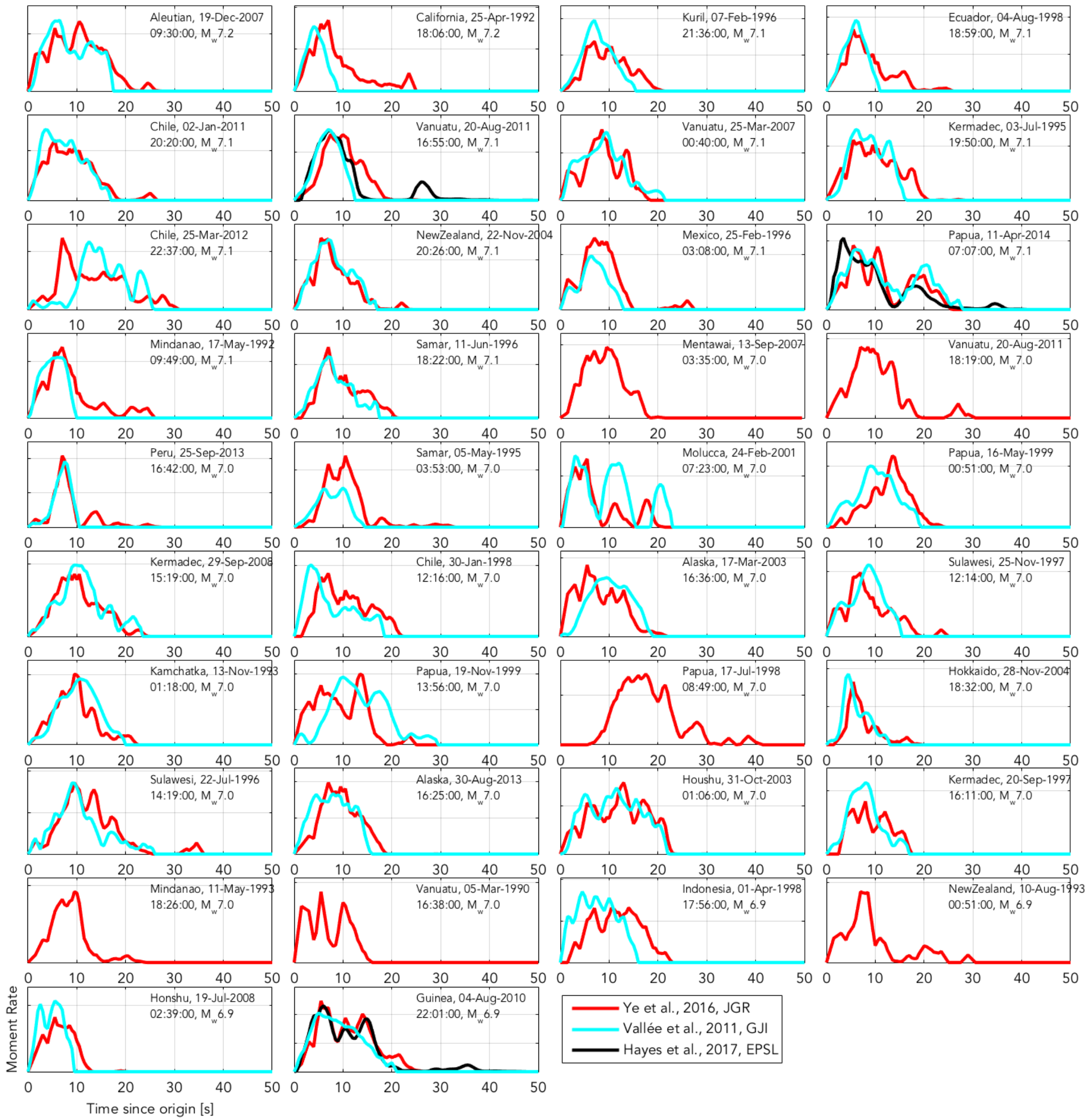
NewZealand, 21-Aug-2003 12:12:00, Mw 7.2
Moment Rate
Time since origin [s]



Ye et al., 2016, JGR
Vallée et al., 2011, GJI
Hayes et al., 2017, EPSL



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California, 25-Apr-1992 18:06:00, M_w 7.2
Kuril, 07-Feb-1996 21:36:00, M_w 7.1
Ecuador, 04-Aug-1998 18:59:00, M_w 7.1
Chile, 02-Jan-2011 20:20:00, M_w 7.1
Vanuatu, 20-Aug-2011 16:55:00, M_w 7.1
Vanuatu, 25-Mar-2007 00:40:00, M_w 7.1
Kermadec, 03-Jul-1995 19:50:00, M_w 7.1
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NewZealand, 22-Nov-2004 20:26:00, M_w 7.1
Mexico, 25-Feb-1996 03:08:00, M_w 7.1
Papua, 11-Apr-2014 07:07:00, M_w 7.1
Mindanao, 17-May-1992 09:49:00, M_w 7.1
Samar, 11-Jun-1996 18:22:00, M_w 7.1
Mentawai, 13-Sep-2007 03:35:00, M_w 7.0
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Peru, 25-Sep-2013 16:42:00, M_w 7.0
Samar, 05-May-1995 03:53:00, M_w 7.0
Molucca, 24-Feb-2001 07:23:00, M_w 7.0
Papua, 16-May-1999 00:51:00, M_w 7.0
Kermadec, 29-Sep-2008 15:19:00, M_w 7.0
Chile, 30-Jan-1998 12:16:00, M_w 7.0
Alaska, 17-Mar-2003 16:36:00, M_w 7.0
Sulawesi, 25-Nov-1997 12:14:00, M_w 7.0
Kamchatka, 13-Nov-1993 01:18:00, M_w 7.0
Papua, 19-Nov-1999 13:56:00, M_w 7.0
Papua, 17-Jul-1998 08:49:00, M_w 7.0
Hokkaido, 28-Nov-2004 18:32:00, M_w 7.0
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Kermadec, 20-Sep-1997 16:11:00, M_w 7.0
Mindanao, 11-May-1993 18:26:00, M_w 7.0
Vanuatu, 05-Mar-1990 16:38:00, M_w 7.0
Indonesia, 01-Apr-1998 17:56:00, M_w 6.9
NewZealand, 10-Aug-1993 00:51:00, M_w 6.9
Honshu, 19-Jul-2008 02:39:00, M_w 6.9
Guinea, 04-Aug-2010 22:01:00, M_w 6.9
Ye et al., 2016, JGR
Vallée et al., 2011, GJI
Hayes et al., 2017, EPSL
Moment Rate
Time since origin [s]
0 10 20 30 40 50

Questions to address:

- What are the common features of earthquakes?
  - Do small and large earthquakes start equal?
  - Are earthquakes self-similar at all magnitudes?
- How are earthquakes different from each other?
  - Is there such a thing as a freak event?
- What do those similarities and differences tell us about earthquake dynamics?

Meier *et al.*, *Science* **357**, 1277–1281 (2017) 22 September 2017

The hidden simplicity of subduction megathrust earthquakes

M.-A. Meier,* J. P. Ampuero, T. H. Heaton

Enabled by global earthquake source products by
Lingling Ye (Caltech), Martin Vallée (IPGP) and Gavin Hayes 5USGS)

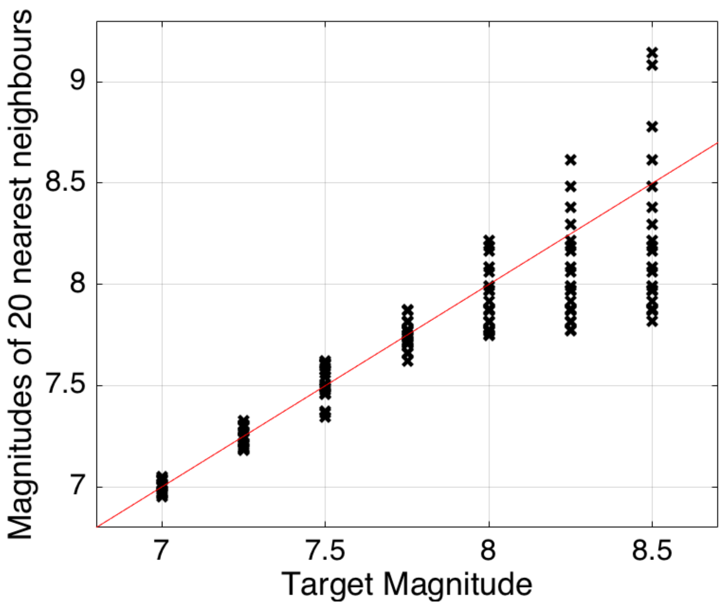
Caltech

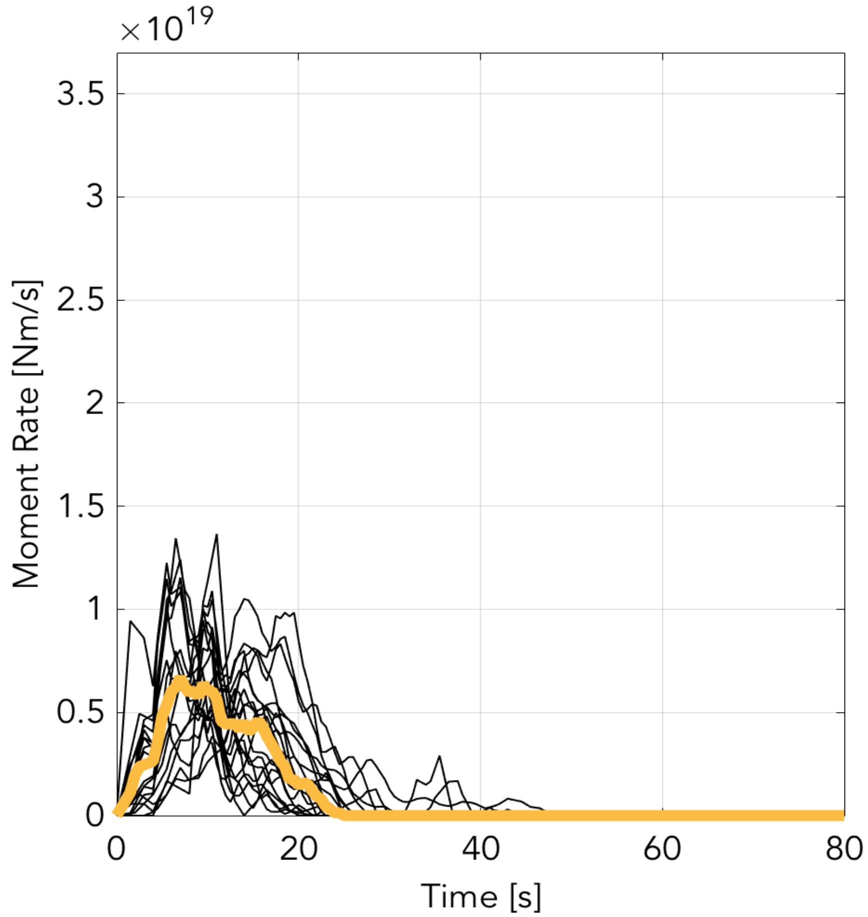
SEISMOLOGICAL LABORATORY
California Institute of Technology

NSF

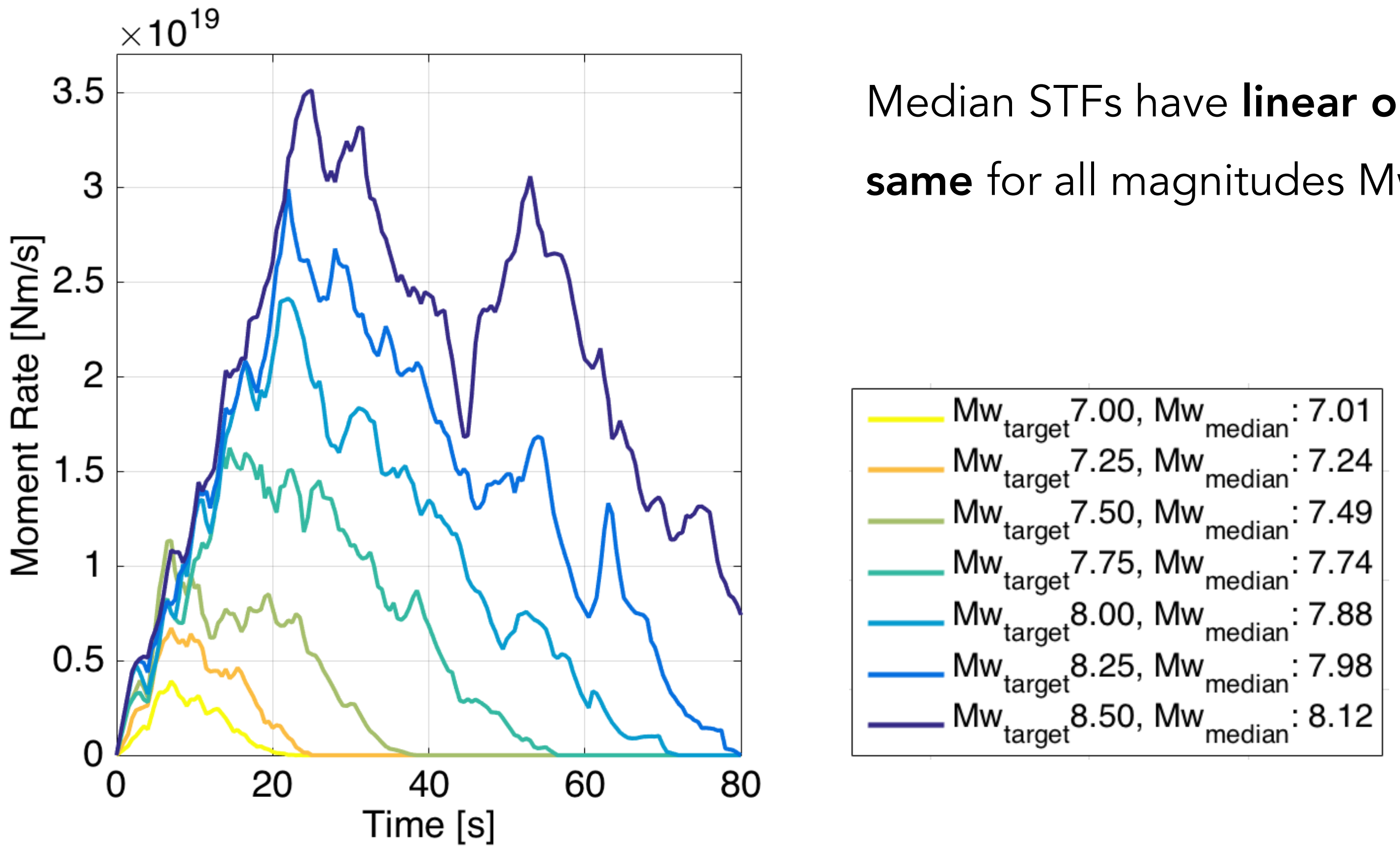
General patterns of Source Time Functions

- Bin STFs by magnitude, 20 **nearest neighbours**
- In each bin, at each point in time, compute **median STF**





General patterns of Source Time Functions



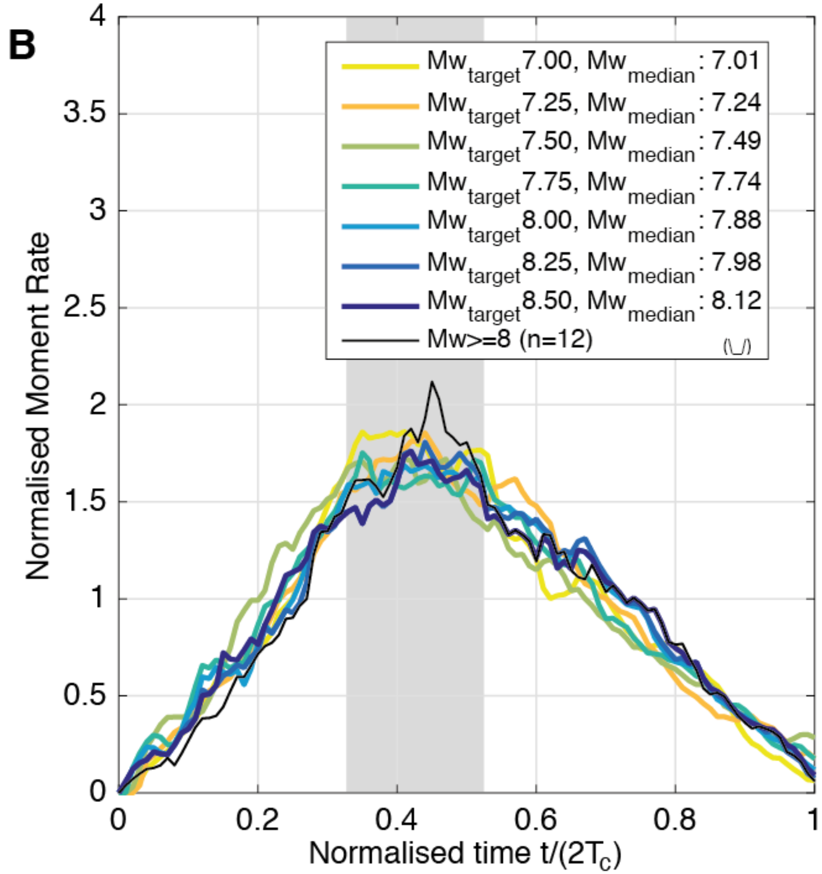
Median STFs have **linear onset,**

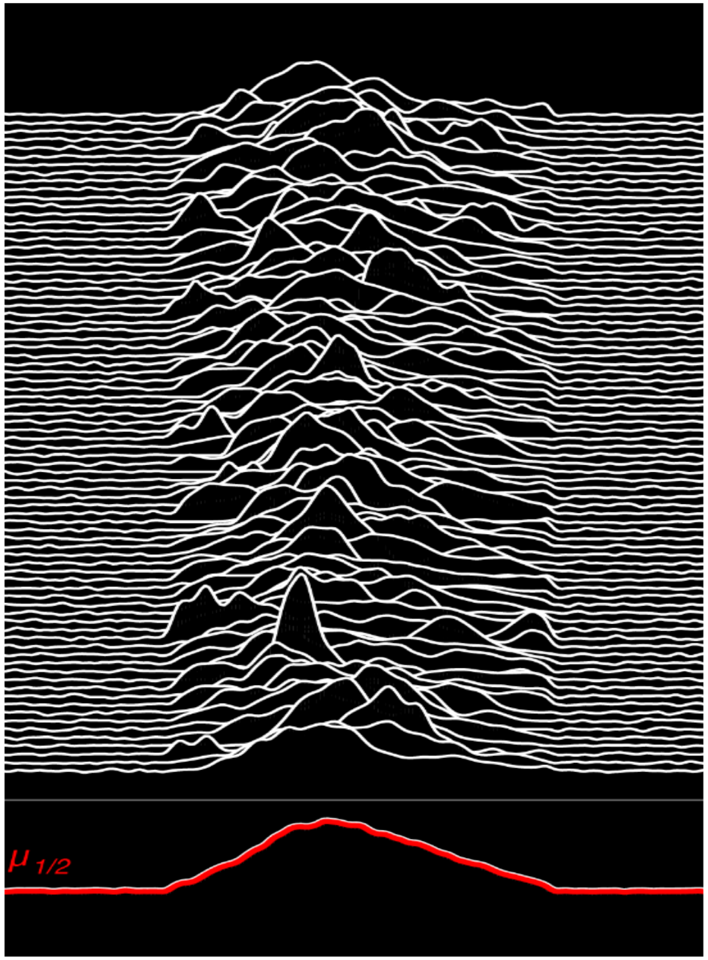
same for all magnitudes Mw>7.2

General patterns of STFs

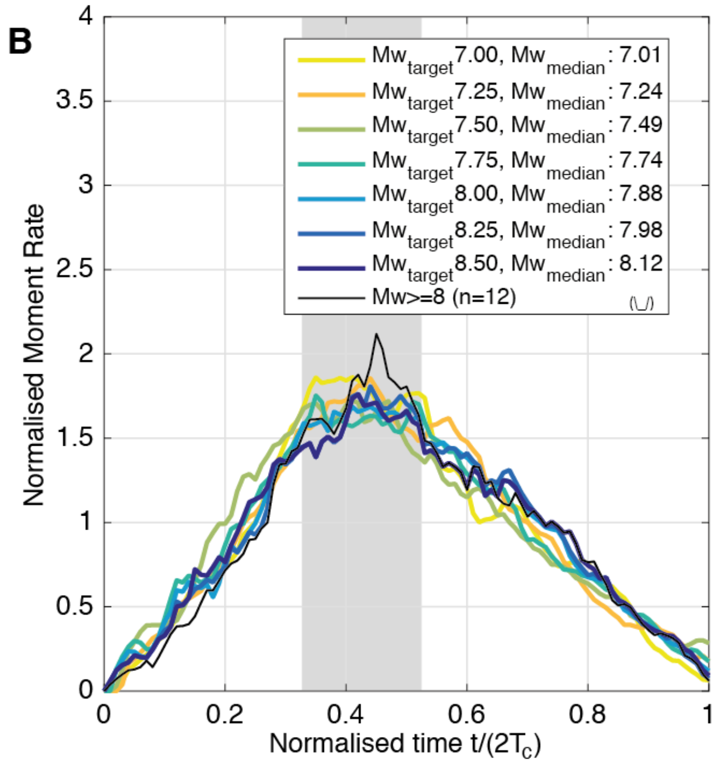
- **Normalize each STF by its duration**
- Scale them such that they integrate to 1
- Compute median of normalized STF

On average, all STFs
can be scaled to a very simple,
quasi-triangular shape

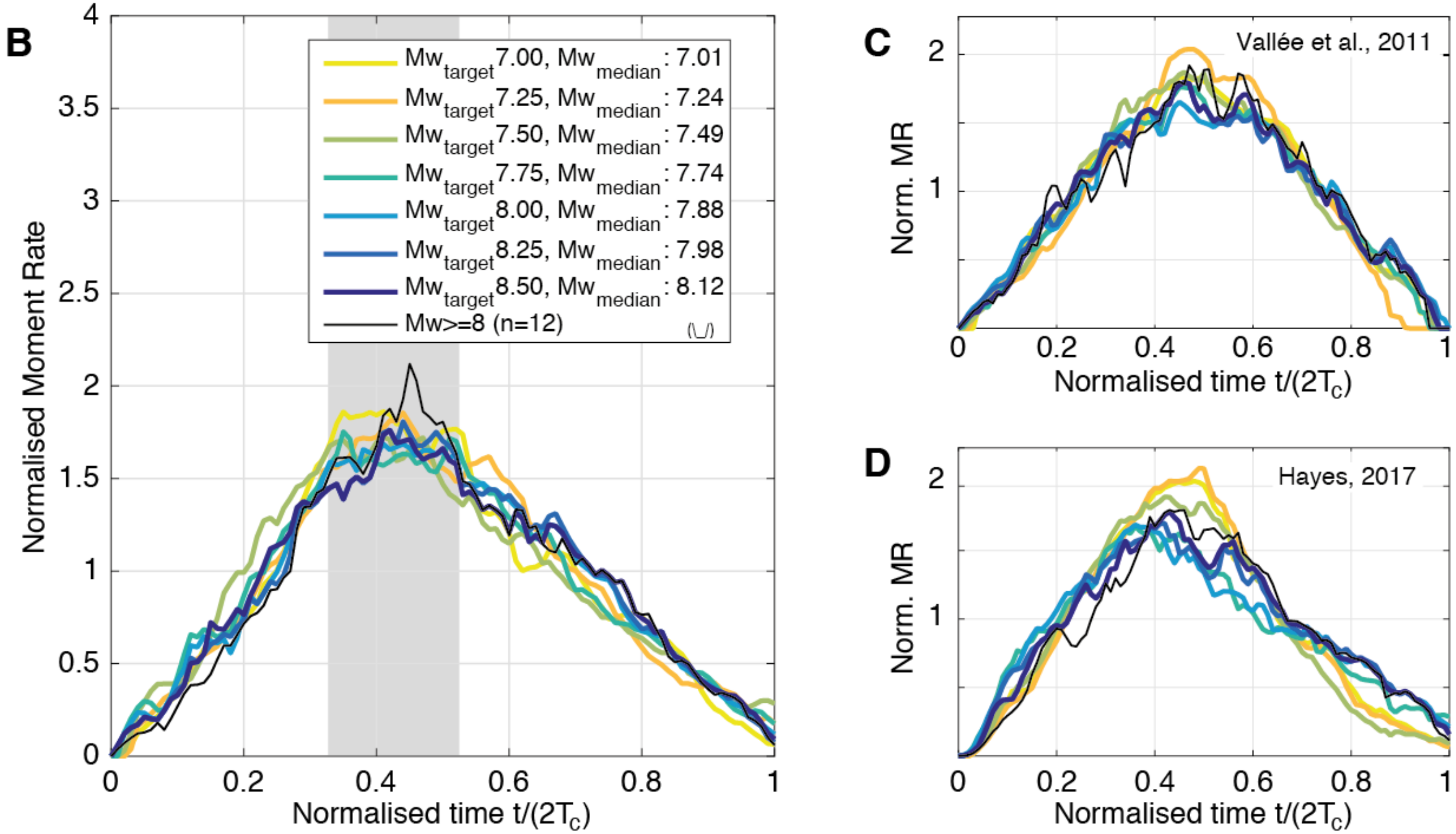




On average (median), all STFs can be scaled to a very simple, quasi-triangular shape

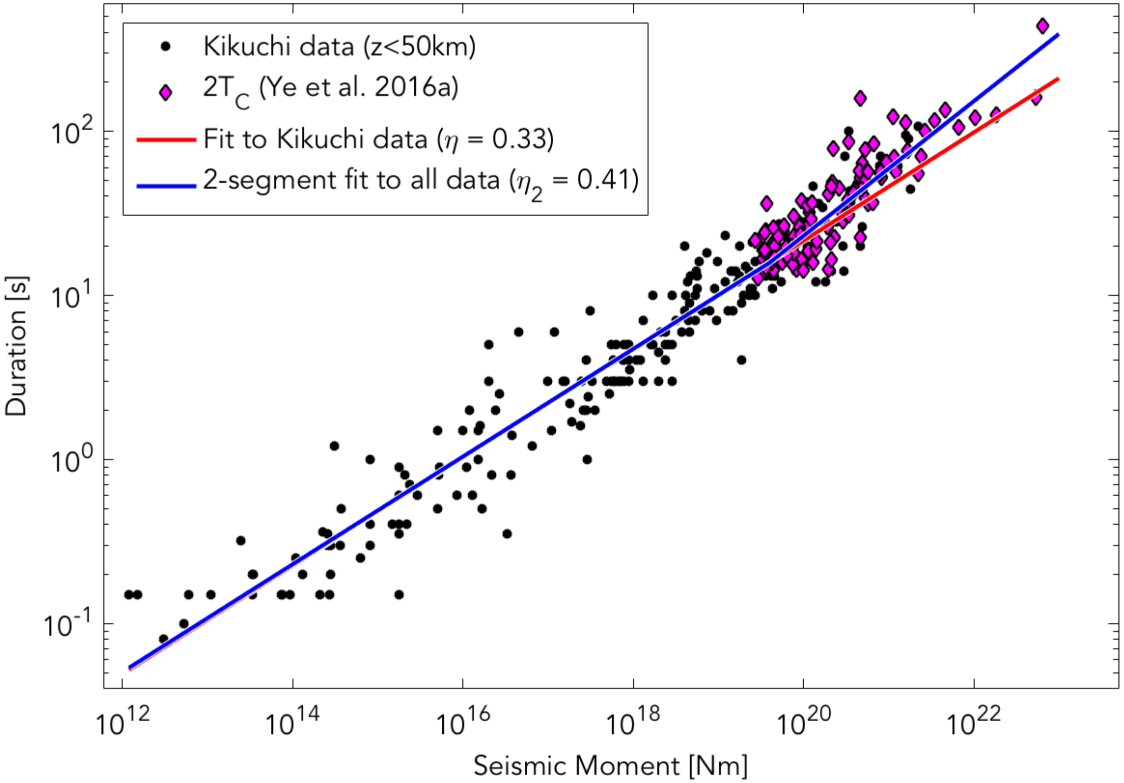


Meier, Ampuero and Heaton (2017)



B
Mwtarget7.00, Mwmedian: 7.01
Mwtarget7.25, Mwmedian: 7.24
Mwtarget7.50, Mwmedian: 7.49
Mwtarget7.75, Mwmedian: 7.74
Mwtarget8.00, Mwmedian: 7.88
Mwtarget8.25, Mwmedian: 7.98
Mwtarget8.50, Mwmedian: 8.12
Mw>=8 (n=12)
Normalised Moment Rate
Normalised time t/(2Tc)
C
Vallée et al., 2011
Norm. MR
Normalised time t/(2Tc)
D
Hayes, 2017
Norm. MR
Normalised time t/(2Tc)

Implications for moment / duration scaling



Linear growth suggests $M_0 \sim T^2$ scaling

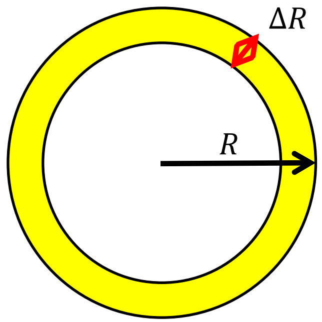
In contrast to the widely reported $M_0 \sim T^3$ scaling

→ scaling break !

Why is linear moment rate growth surprising?

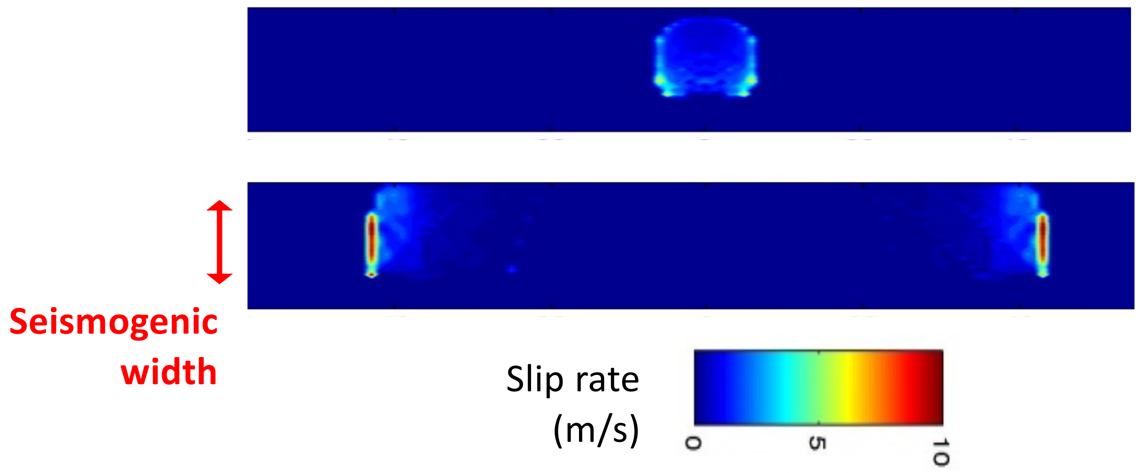
Self-similar model for small earthquakes:
Circular rupture with constant stress drop and constant rupture speed

$$\dot{M}_0 \propto t^2$$



Ruptures become **elongated** after they break the whole **seismogenic width:**
moment grows slower than quadratic

But the linear trend ($M_0 \sim t$) is observed after ~5 s,
before rupture saturates the seismogenic width



Implications for Rupture Growth Scaling

- Observed **STF growth is linear** $STF \propto t^1$
- If rupturing **area** grows as $A(t) \propto t^\alpha$
- … and **average slip** grows as $D(t) \propto t^\beta$
- Seismic **moment** $M_0(t) \propto A(t)D(t) \propto t^{\alpha+\beta}$
- Moment rate **exponent** $\eta = \alpha + \beta - 1$
- Since we observe linear growth $\eta^{obs} \sim 1 \rightarrow \alpha + \beta \sim \mathbf{2}$

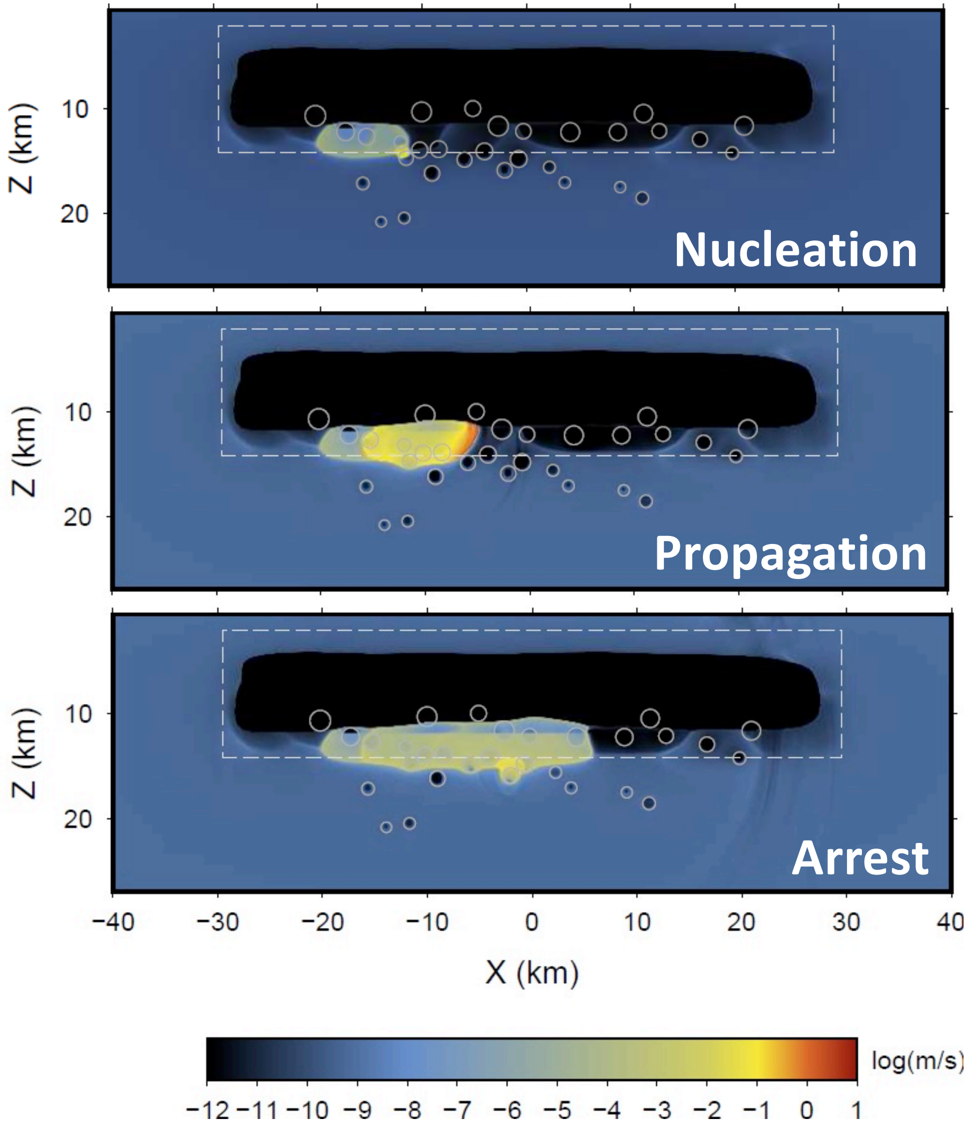
- Self-similar pulse or crack $\eta^{ss} = 2 + 1 = 3$

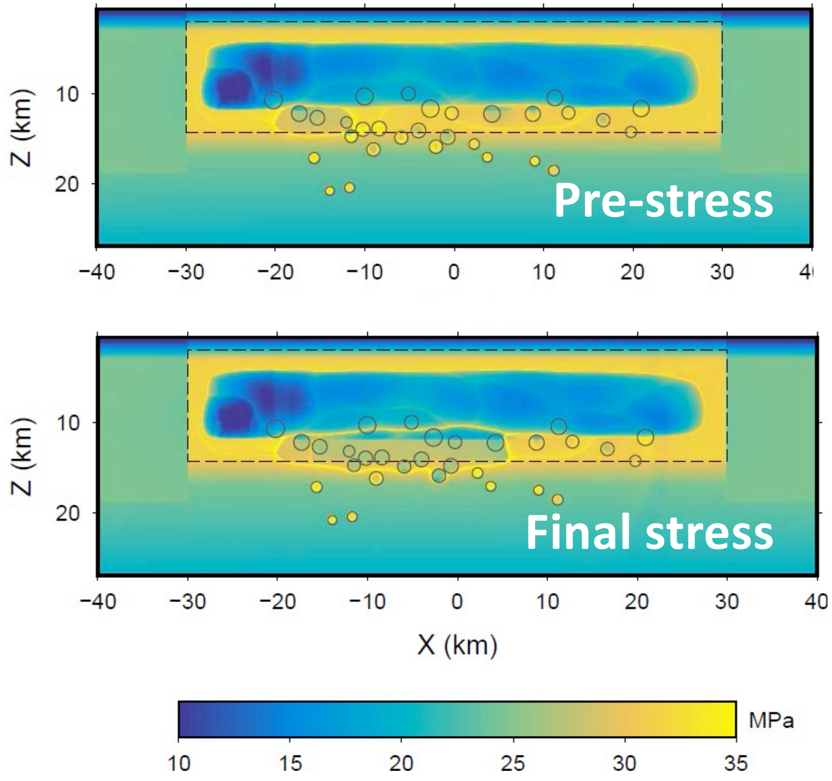
→ How can we lower the moment rate growth?

- Lower alpha, lower beta, or combination of both?
- Pulse-like rupture with areas of systematic slip deficits?

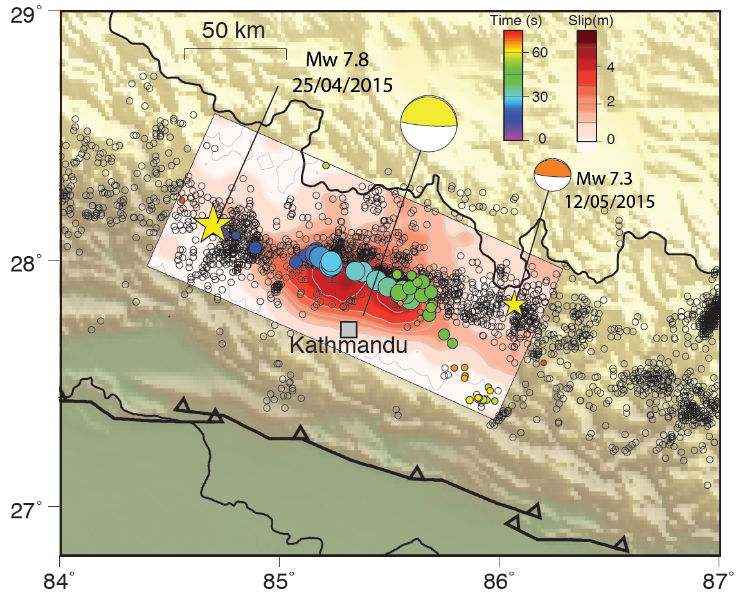
Intermediate-size event unzipping part of the lower edge of the coupled zone

(Junle Jiang, Caltech)



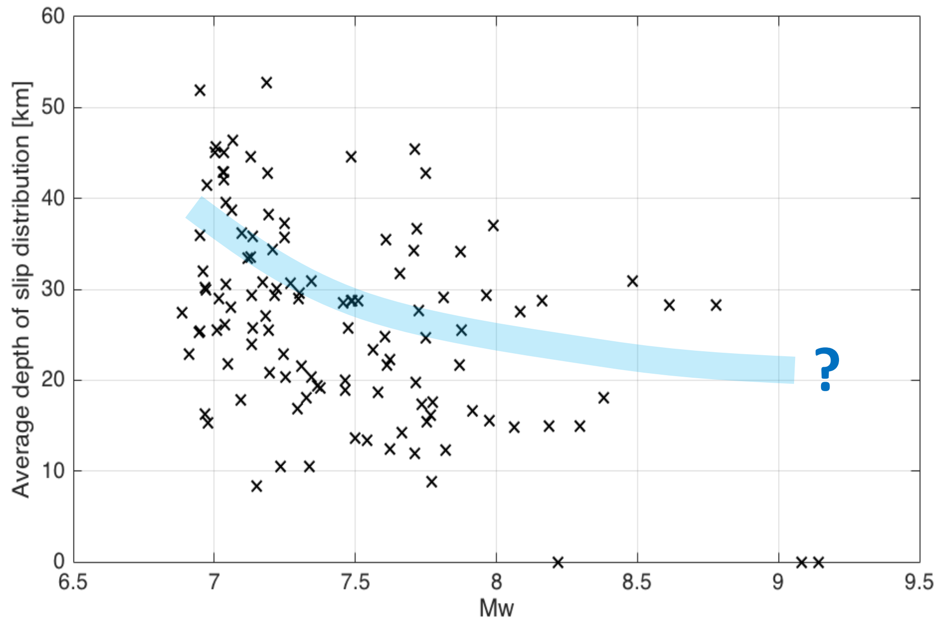


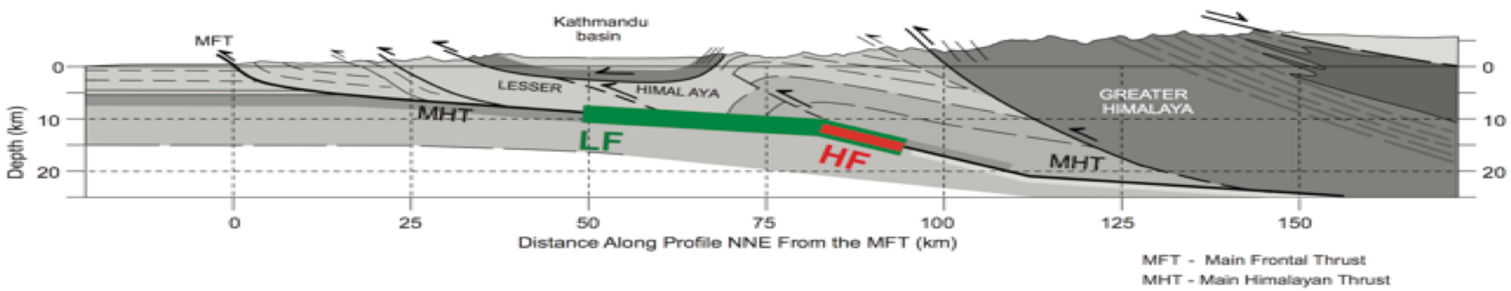
2015 Mw 7.8 Gorkha, Nepal earthquake



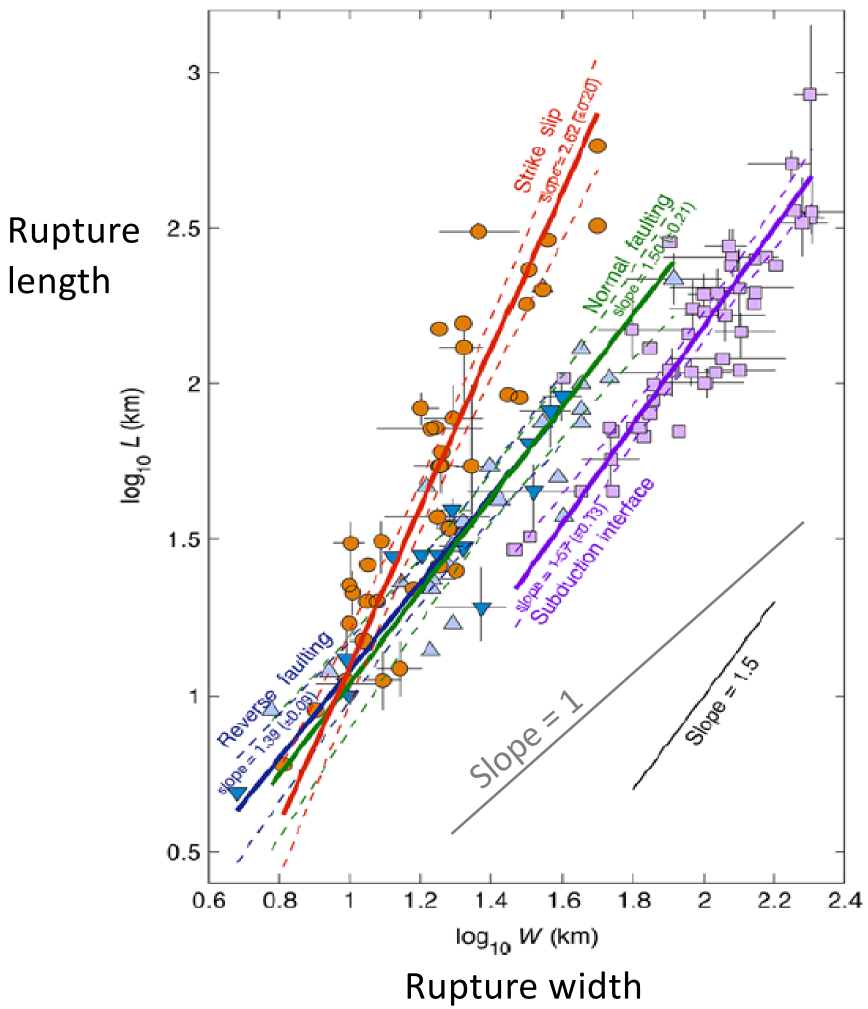
Avouac et al (Nat Geo, 2015)

All M>7 subduction earthquakes





Thingbaijam et al (2017)



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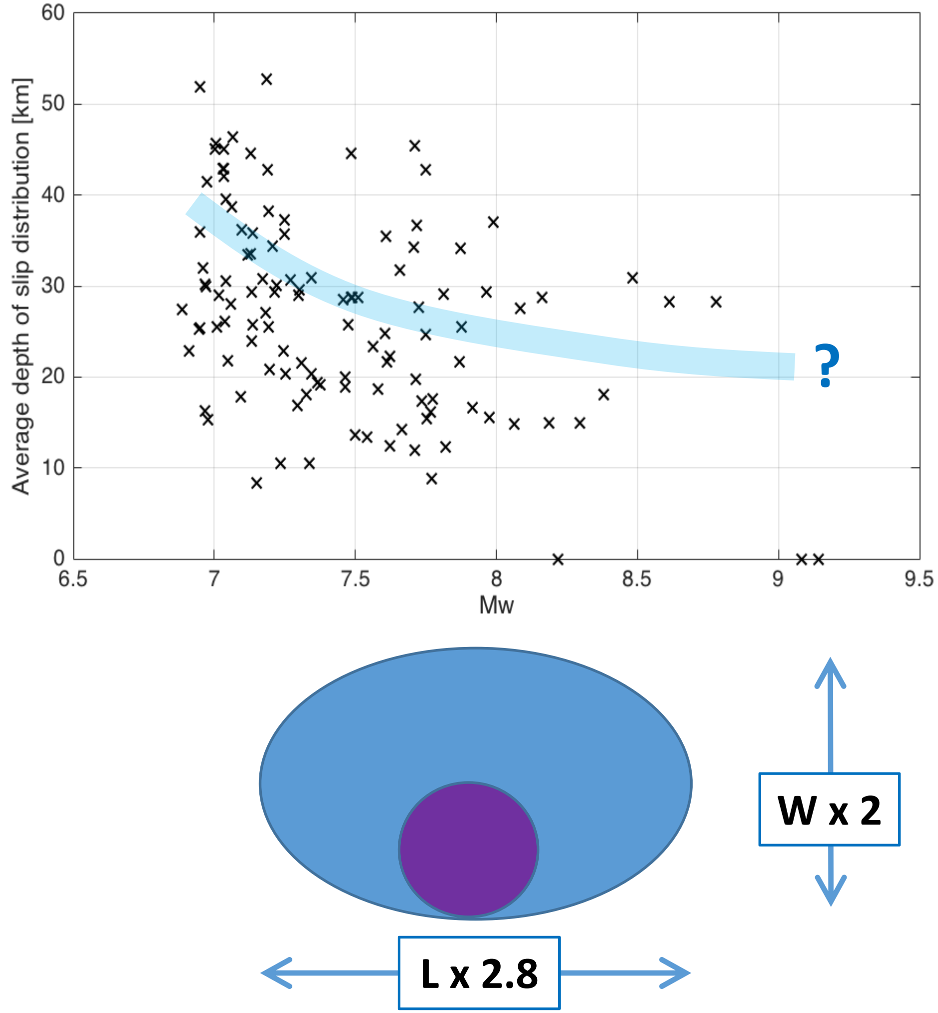
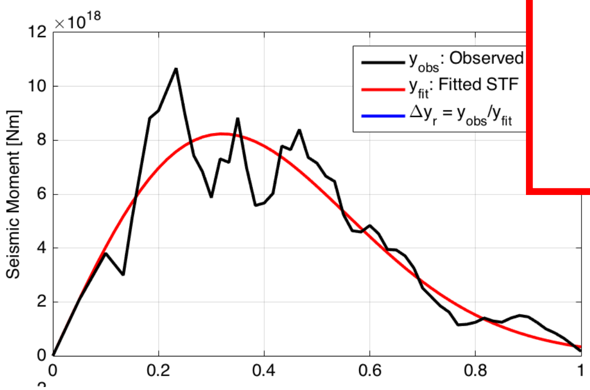


Fluctuations around the median STF

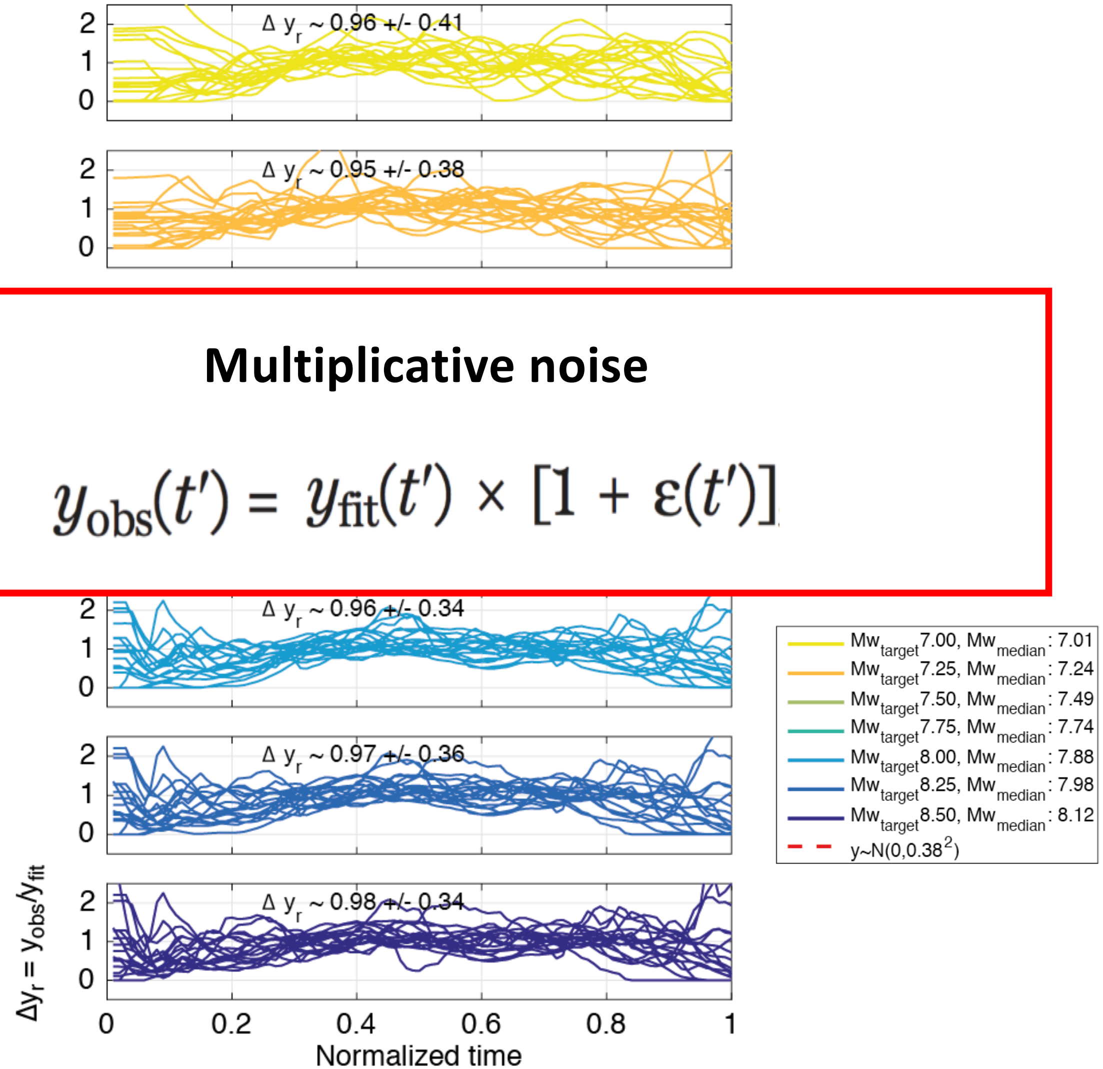
Fit a function to STFs:

$$y = \mu \ t \ \exp[-1/2*(\lambda * t)^{\eta}]$$



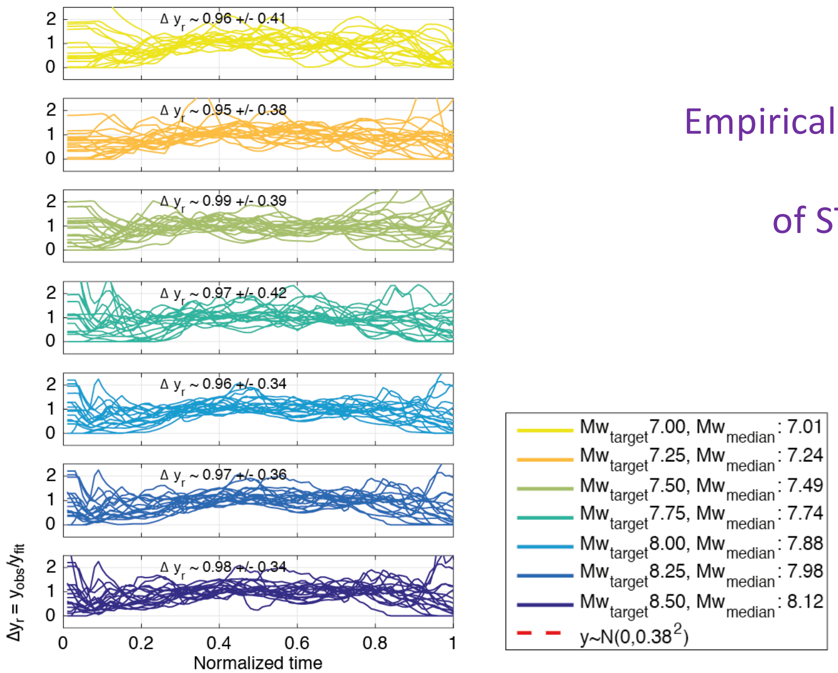
Multiplicative noise

$$y_{\text{obs}}(t') = y_{\text{fit}}(t') \times [1 + \varepsilon(t')]$$

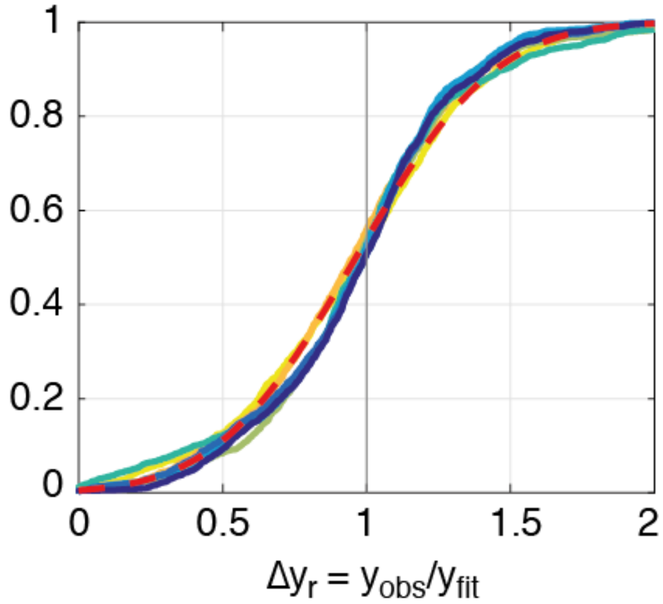


STF residuals

STF fluctuations are multiplicative **and Gaussian**

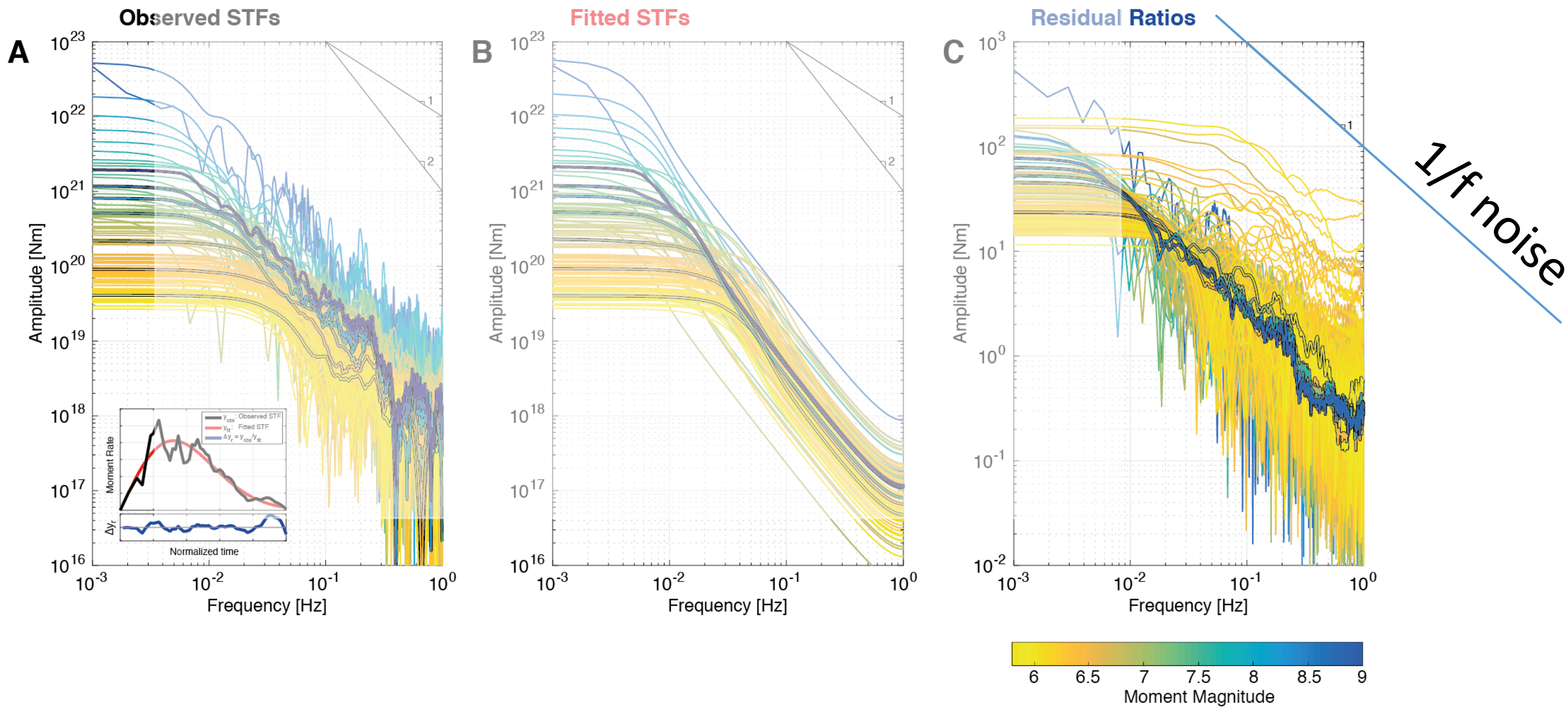


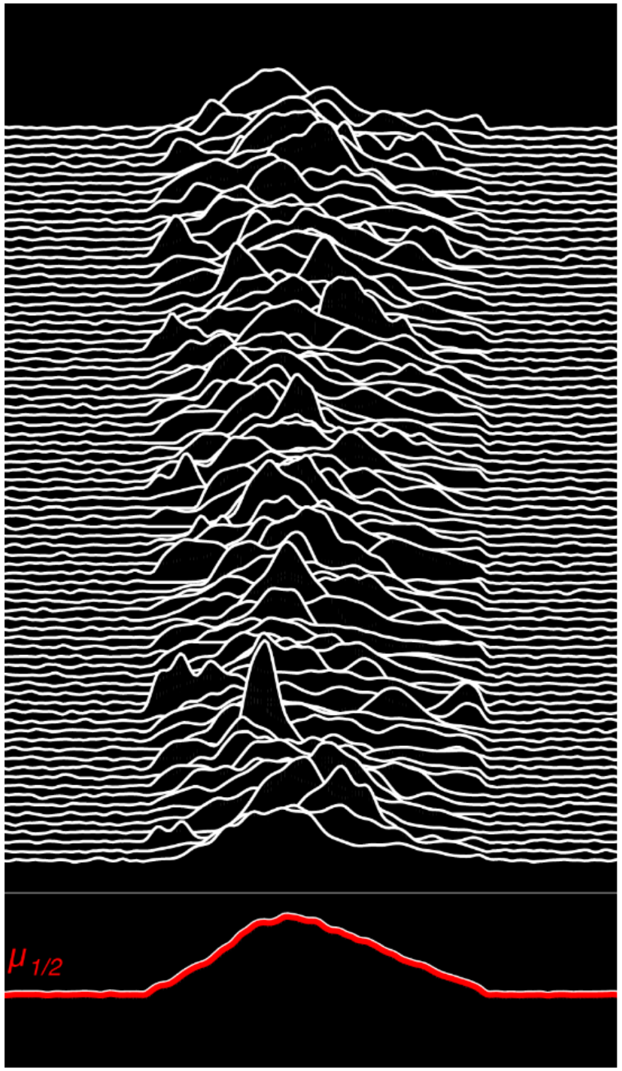
Empirical cumulative distribution of STF residuals



$$y_{obs}(t') = y_{fit}(t') \times [1 + \varepsilon(t')], \text{ where } \varepsilon \sim N(0,0.38^2)$$

STF fluctuations are multiplicative, Gaussian and Brownian



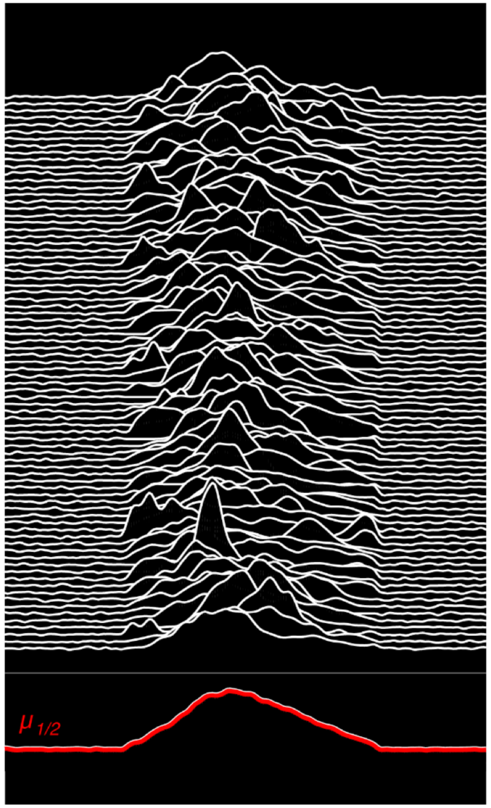


Summary of observed STF characteristics, Mw>7

- All STFs can be scaled to a common, quasi-triangular shape
- Onsets are linear and the same for all
- Fluctuations are multiplicative, Gaussian and Brownian

Conclusions

Today we have **enough data** to uncover **general patterns of earthquake rupture**
Focusing on ***temporal* evolution** facilitates testing conceptual rupture models



A few things are certain

- Large earthquakes are small earthquakes that did not stop **(all earthquakes start the same)**
- Earthquakes have large variability, but on average they follow a **simple pattern**
- The pattern **deviates from standard models after few seconds**
- Rupture evolution is **weakly predictable**

More questions than answers

- **Physical origin** of the pattern?
- What **dynamical models** can explain the linear STF growth?
- What causes **break of self-similarity** at ~1s?
- Transition to **elongated ruptures** at the bottom of seismogenic zone?

What to do next?

- Analysis of strike-slip ruptures
- Source studies with uncertainty quantification
- Develop methods for systematic analysis across the magnitude range of scaling transition from M6 to M8+

  → break of self-similarity, scaling of rupture aspect ratio
- Develop dynamic rupture models consistent with these observations

Corner frequency

Earthquake spectra

seismogram
= (Green's function)*(Source Time Function)

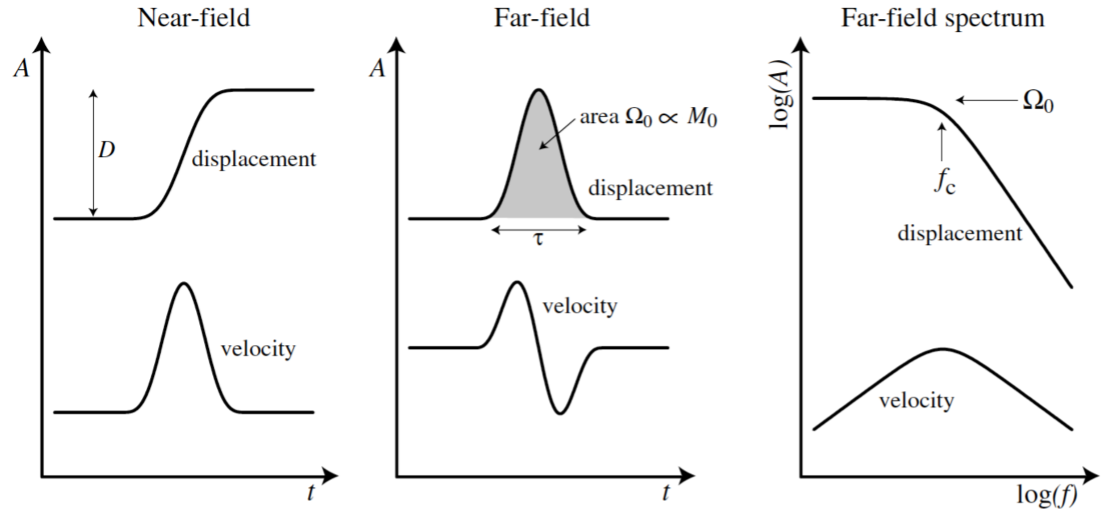
$$d(t) = G(t) * \dot{M}_0(t)$$

In the far-field, $G(t) \propto \delta(t - r/c)$

$$d(t) \propto \dot{M}_0(t - r/c)$$

→ Far-field displacements are proportional to Source Time Function

→ Far-field spectrum $d(f)$ proportional to moment rate spectrum $\dot{M}_0(f)$



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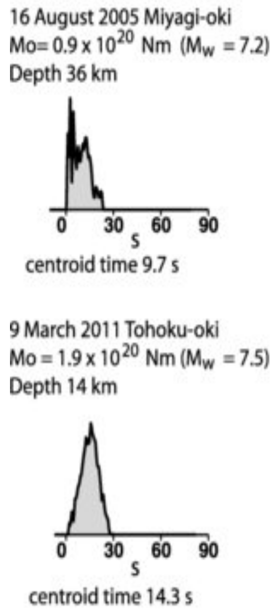
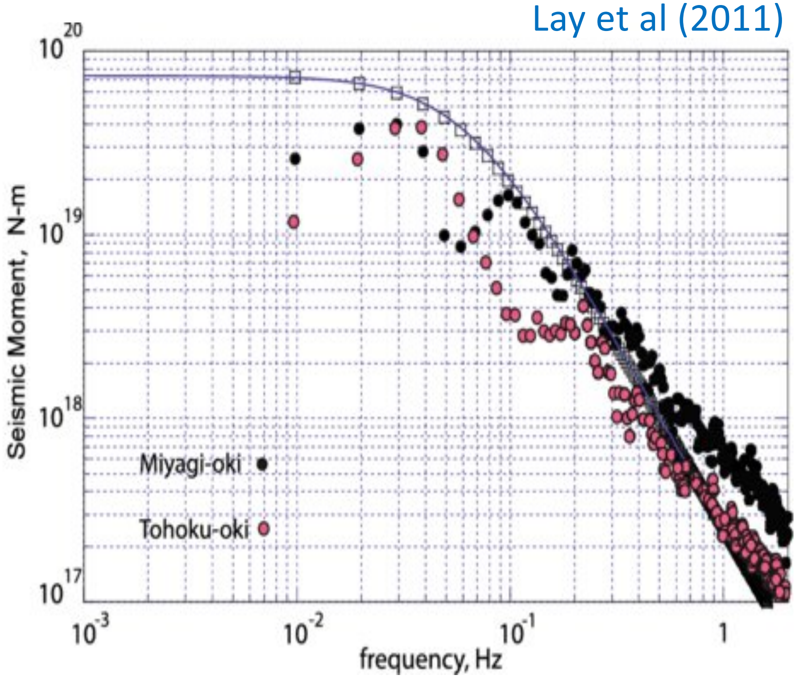
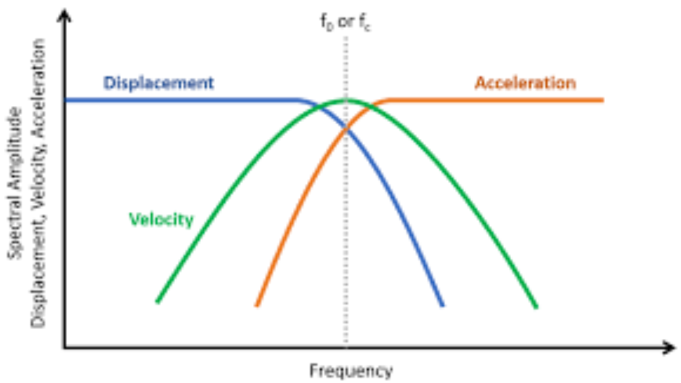


Lay et al (2011)



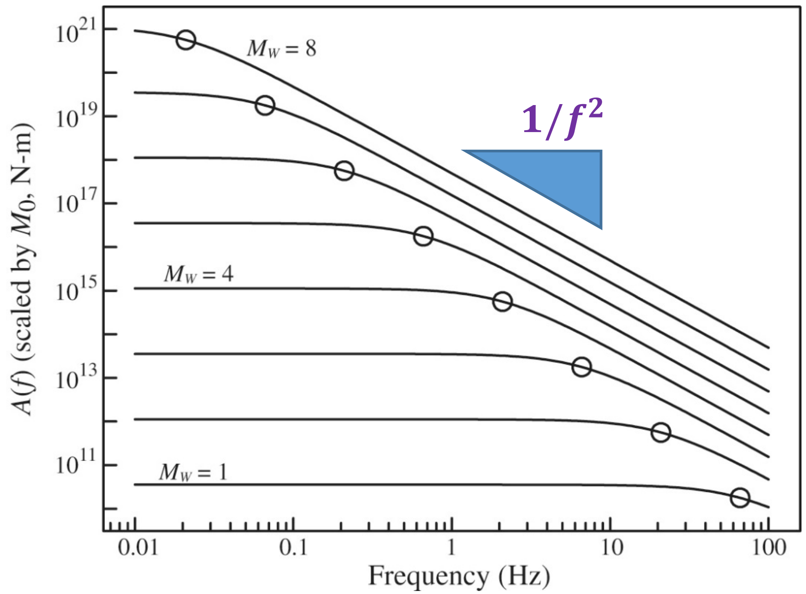
ω^2 model of earthquake spectrum

One corner frequency, f_c, that separates flat spectrum at low-f and $1/\omega^2$ at high-f:



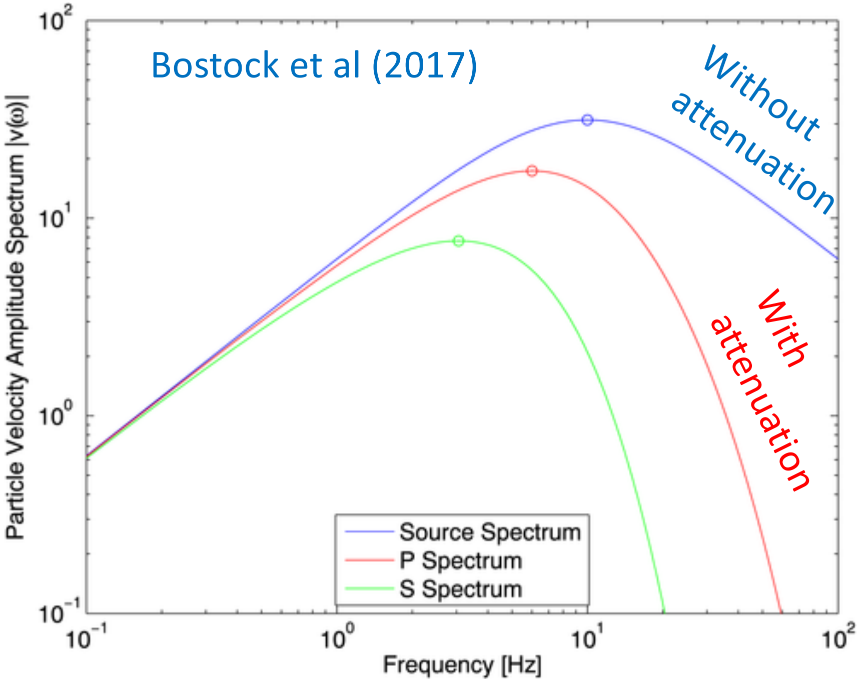
At high frequencies ($f \gg f_c$):

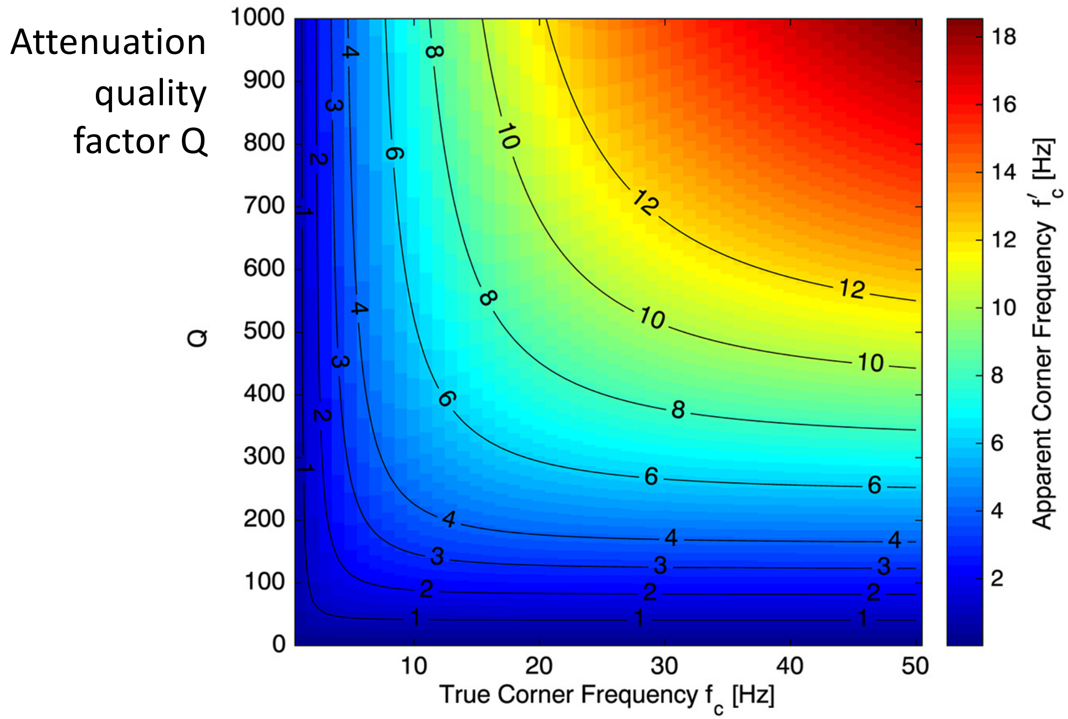
$$\dot{M}_0(f) \approx M_0 f_c^2 / f^2$$



$$d(f) \propto \dot{M}_0(f) \rightarrow \; a(f) \propto f^2 \dot{M}_0(f) \approx M_0 f_c^2$$

Attenuation vs corner frequency



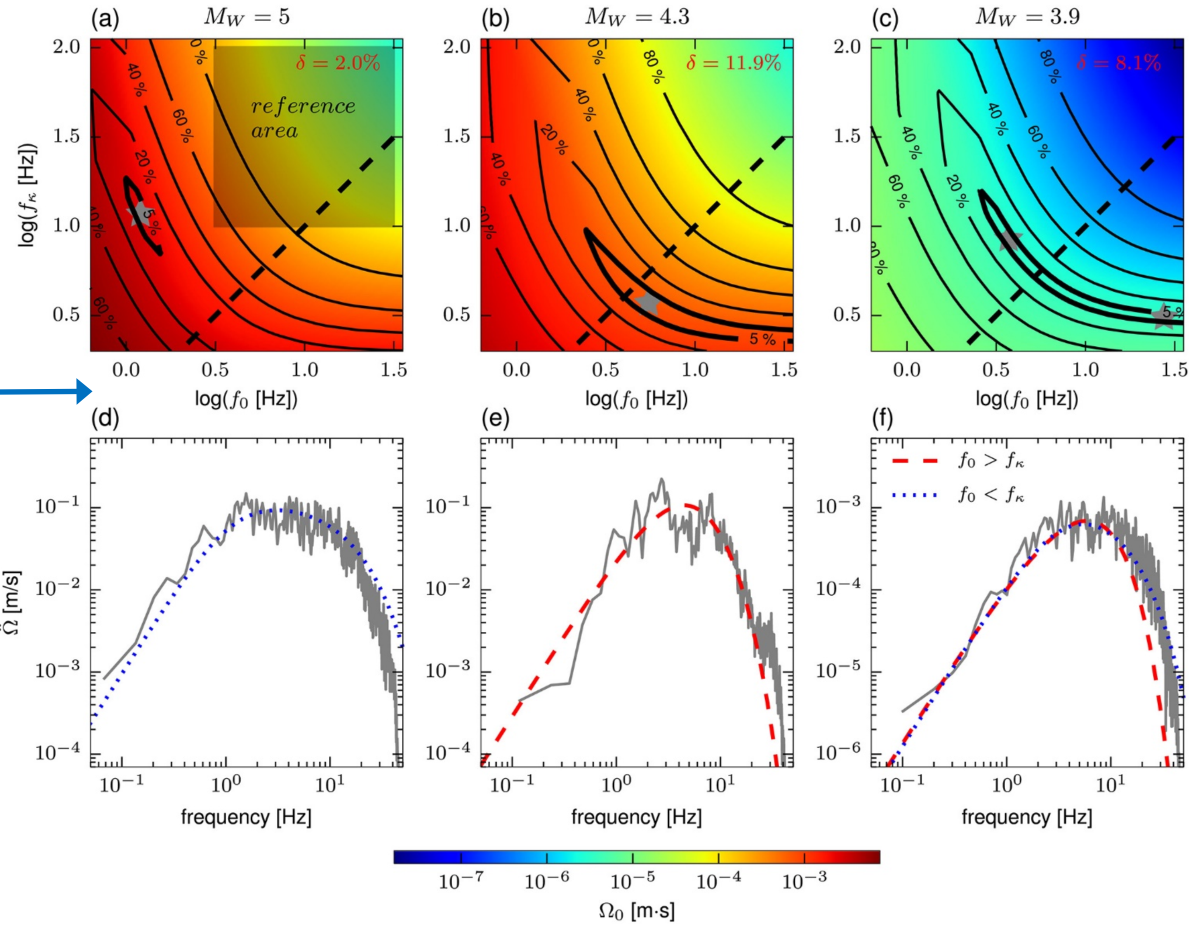


Attenuation (low Q) multiplies the spectrum by $\exp(-\pi f r/cQ)$
It reduces the apparent corner frequency

Trade-off between attenuation and corner frequency

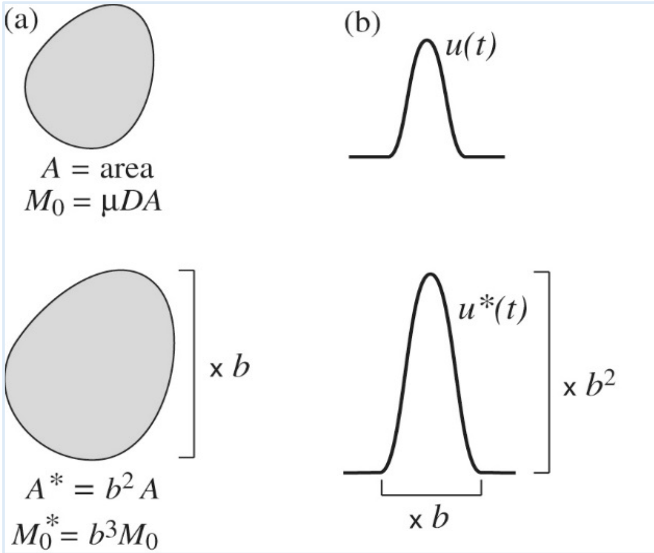
$$f_\kappa = \frac{1}{\pi\kappa} \sim \frac{1}{Q}$$

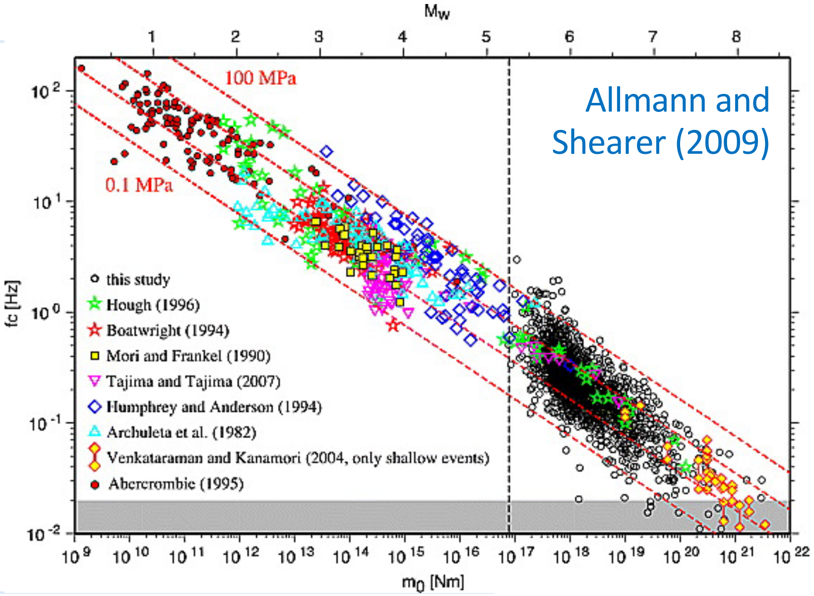
f_c



Lior and Ziv (2018)

Self-similar source model





Corner frequency $f_c \sim 1/(\text{source duration})$

$\rightarrow \quad f_c \sim M_0^{-1/3}$

Circular rupture model

Circular rupture, constant rupture speed, final radius R.
Only one characteristic time-scale: source duration

$$T \approx 2R/v_r$$

- corner frequency

$$f_c = \frac{kv_r}{R} \approx 1/T$$

where k is a factor of order 1 that depends mildly on rupture speed ($k = 0.44$ for $v_r = 0.9c_S$).

- relation between stress drop and slip from elasticity theory:

$$\Delta\sigma = \frac{7\pi}{16}\ \mu\frac{D}{R}$$

- definition of seismic moment $M_0 = \mu D\pi r^2$

→ Corner frequency scaling $\boxed{f_c = kv_r\left(\frac{16}{7}\frac{\Delta\sigma}{M_0}\right)^{1/3}}$ → estimate of stress drop: $\boxed{\Delta\sigma = \frac{7}{16}\left(\frac{f_c}{kv_r}\right)^3 M_0}$

Rectangular rupture model

Rupture length L $\gg$ width W.

- Rupture duration controlled by the longest rupture dimension: $f_c \sim 1/T$ with $T = L/v_r$.
- Elastic stiffness controlled by the shortest rupture dimension: $\Delta\tau \sim \frac{\mu}{W} D$
- Seismic moment: $M_0 = \mu D W L \sim \Delta\tau W^2 L$

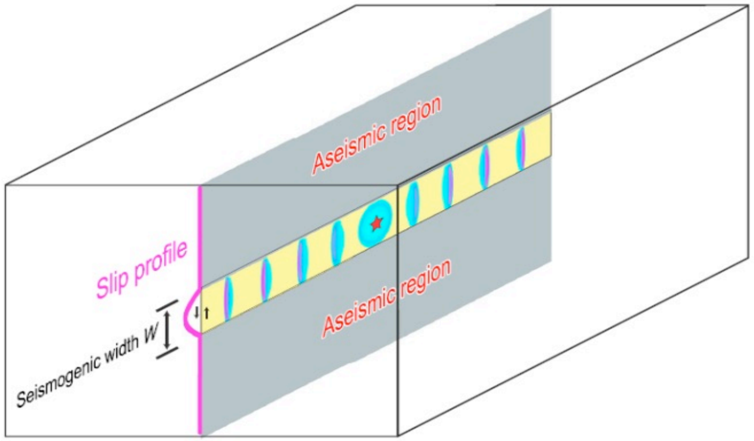
→ corner frequency scaling $\boxed{f_c \sim \Delta\tau W^2 v_r \times M_0^{-1}}$

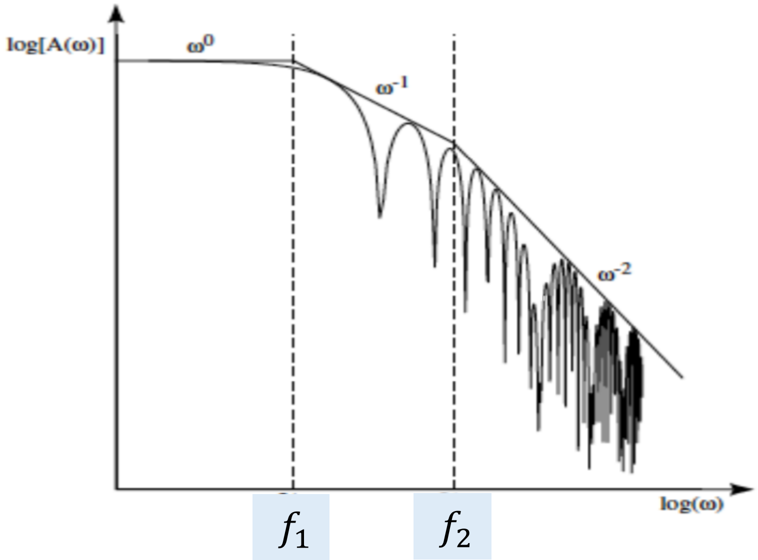
→ estimate of stress drop $\boxed{\Delta\tau \sim M_0 f_c / W^2 v_r}$

A dependence of rupture aspect ratio on magnitude can break self-similarity and affect estimates of stress drop.

Spectra with two corner frequencies

Haskell's model, unilateral pulse-like rupture



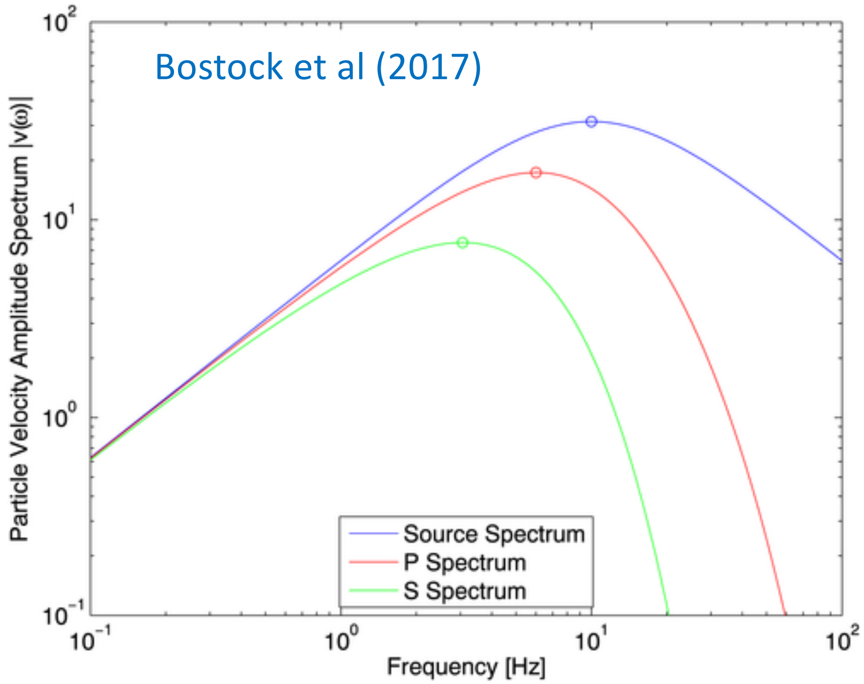


Two time scales:
Total rupture duration $T_{rup} = L/v_r$
Local slip duration, rise time T_{ris}

→ two corner frequencies:
$f_1 = 1/T_{rup}$
$f_2 = 1/T_{ris}$

Radiated energy

Radiated energy



Energy radiated to the far-field:

$$E \propto \int \dot{u}(t)^2 dt$$

$$E \propto \int \dot{u}(f)^2 df$$

… integrated over a far-field sphere

Observational challenges:

- attenuation
- incomplete coverage of take-off angles
- interference between depth phases

Radiated energy

Energy radiated to the far-field:

$$E \propto \int \dot{u}^2 dt \propto \dot{u}^2\, T$$

Self-similar model: $\Delta\sigma$ and v_r do not depend on earthquake size R

$$M_0 \propto R^3$$
$$T \propto R$$

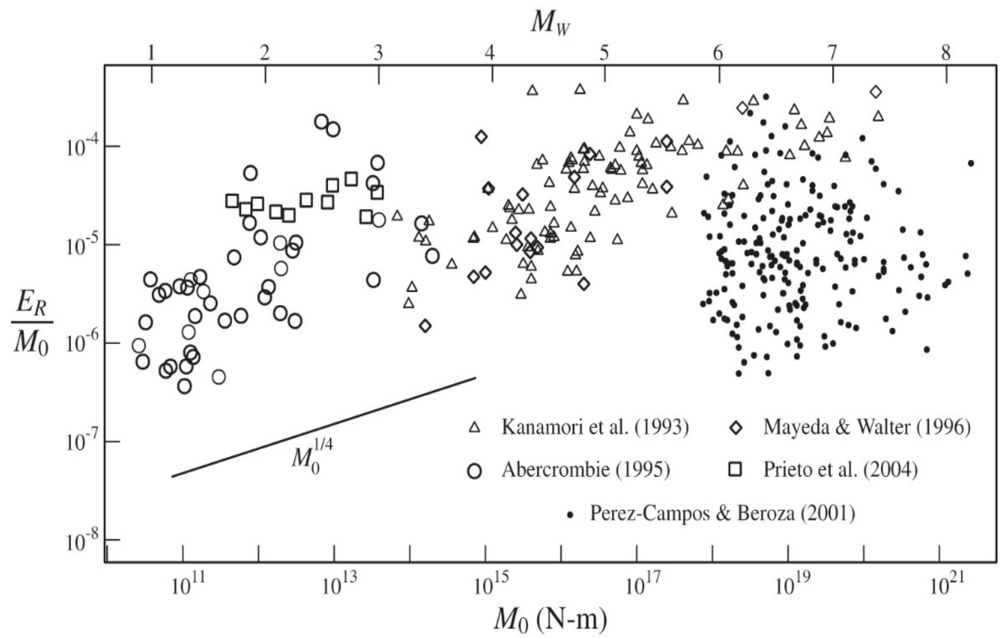
Far-field displacement and veocity:

$$u \propto \dot{M}_0 \sim M_0/T \propto R^2 \propto M_0^{2/3}$$
$$\dot{u} \propto \ddot{M}_0 \sim M_0/T^2 \propto R \propto M_0^{1/3}$$

→ Energy radiated to the far-field:

$$E \propto \dot{u}^2\, T \propto M_0$$

$$\log_{10} E = \log_{10} M_0 + f(\Delta\tau, v_r) + \cdots$$



Earthquake energy balance

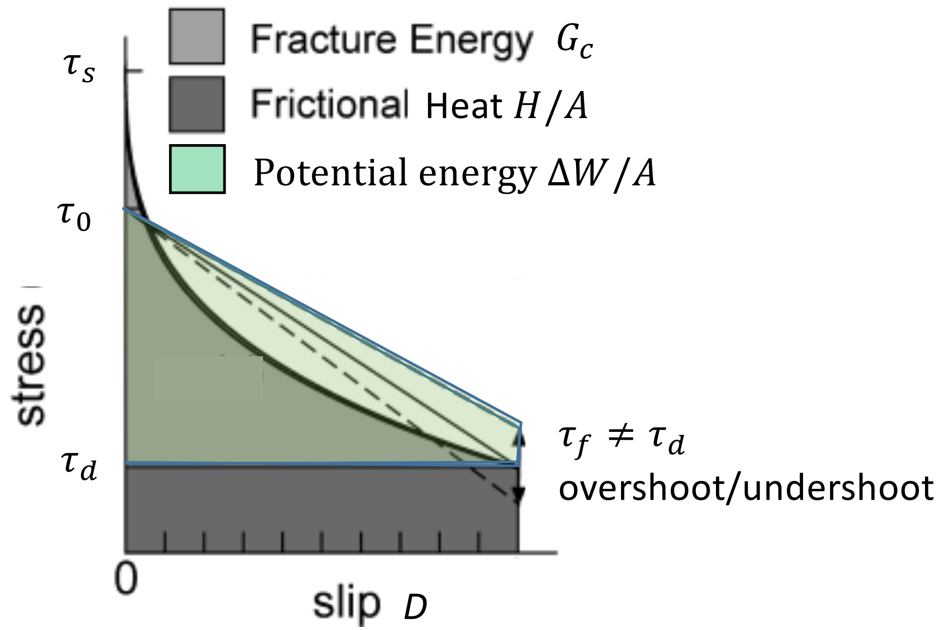
Potential energy change =
fracture energy + heat + radiated energy

$$\Delta W = G_c A + H + E_r$$

Per unit of fault surface:

$$\frac{1}{2}(\tau_0 + \tau_f)D = G_c + \tau_d D + E_r/A$$

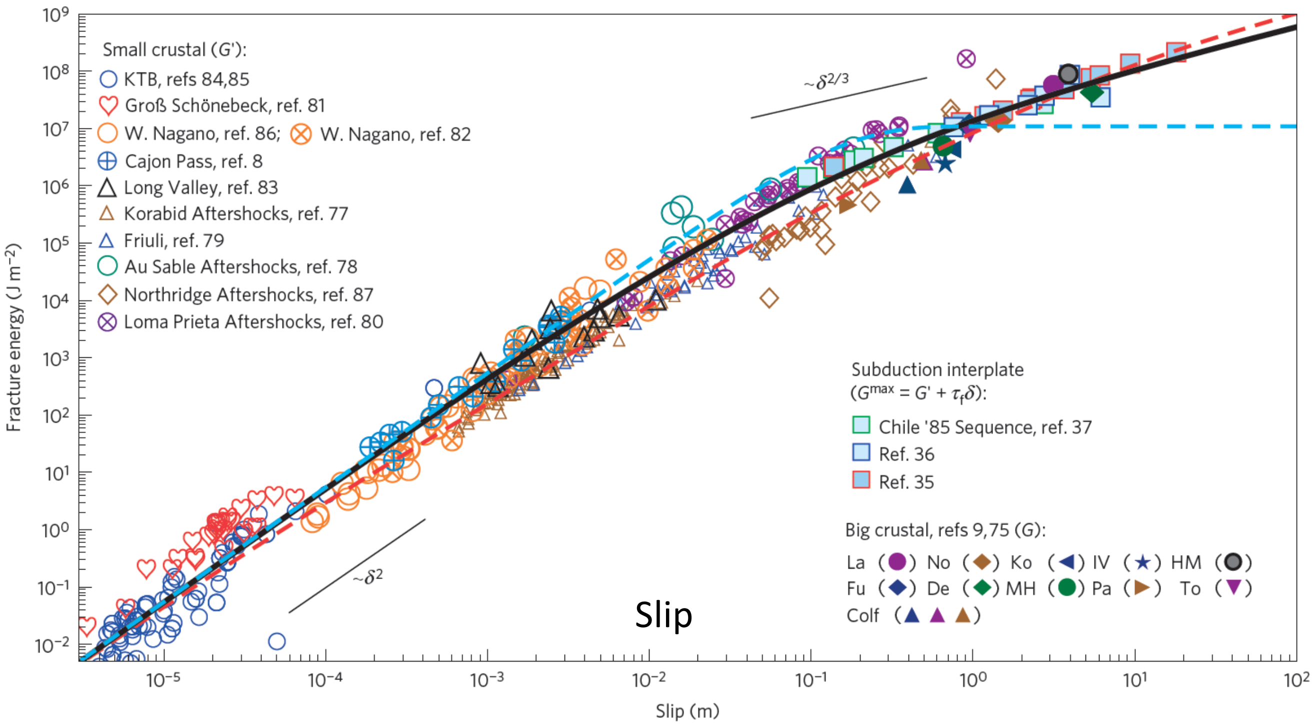
$$G_c = \frac{1}{2}(\tau_0 - \tau_f)D - \frac{E_r}{A} + (\tau_f - \tau_d)D$$



Seismological constraints

Gc inferred from radiated energy, seismic moment and corner frequency, or from finite source inversion

Fracture energy



Slip

Viesca and Garagash (2015)

Seismological constraints

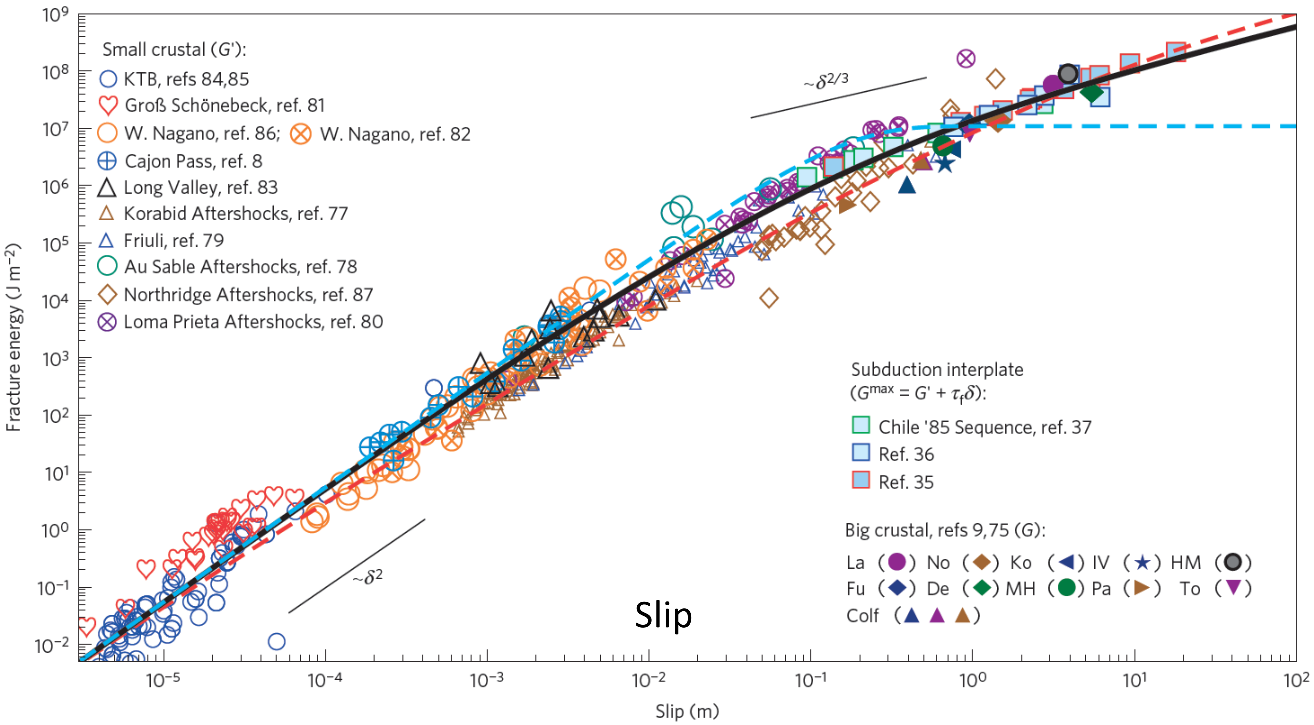
Gc inferred from radiated energy, seismic moment and corner frequency, or from finite source inversion

Consistent with **thermal pressurization weakening** $\tau = \mu(\sigma - P)$

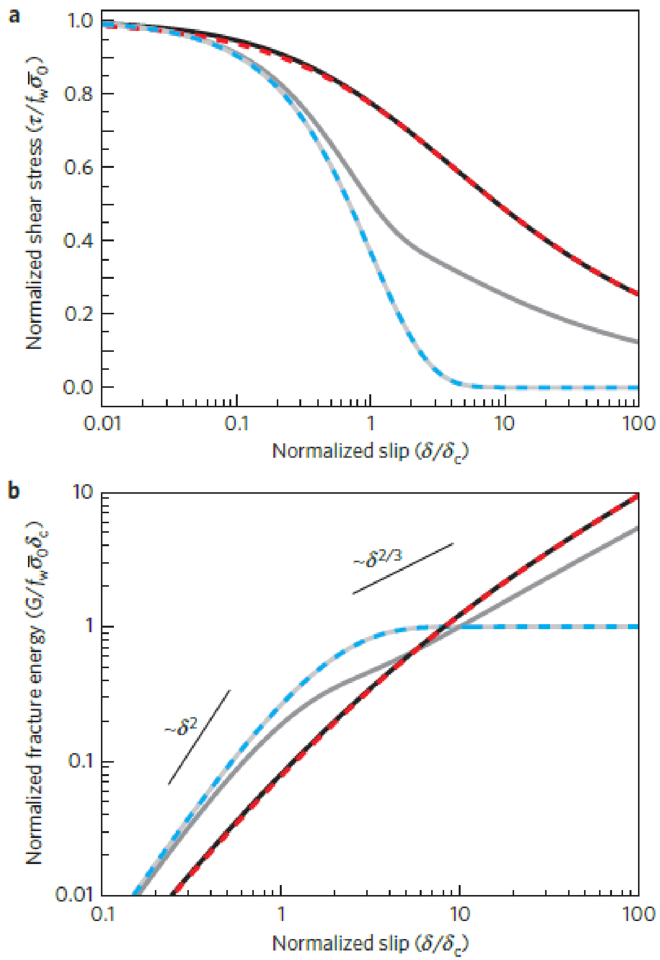
Hydrothermal diffusion

Undrained-adiabatic

Fracture energy



Viesca and Garagash (2015)



Velocity-and-slip-dependent friction law:

$$\mu(V,\delta) \sim \mu_{FH}\left(\frac{V}{V_c}\right) \mu_{UA}\left(\frac{\delta}{\delta_c}\right) \mu_{HD}\left(\frac{\delta}{\delta_d}\right)$$

Flash heating:

$$\mu_{FH}(x) = \mu_d + \frac{(\mu_s - \mu_d)}{1+x}$$

Undrained-adiabatic thermal pressurization:

$$\mu_{UA}(x) = \exp(-x)$$

Diffusion-dominated thermal pressurization:

$$\mu_{HD}(x) = 1/(1+x^{1/3})$$

Overview

Macroscopic source properties constrained by seismology:

- seismic moment
- source time function
- corner frequency
- radiated energy

→ stress drop, rupture speed, rupture size