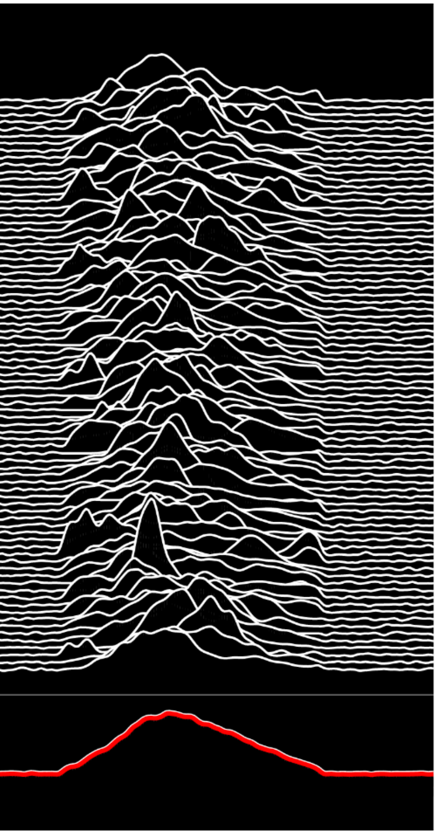


Under the ‘macroscope’: the dynamics of very large earthquakes

Pablo Ampuero

Caltech Seismolab / Université Côte d’Azur, IRD, Géoa

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

The hidden simplicity of subduct megathrust earthquakes

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

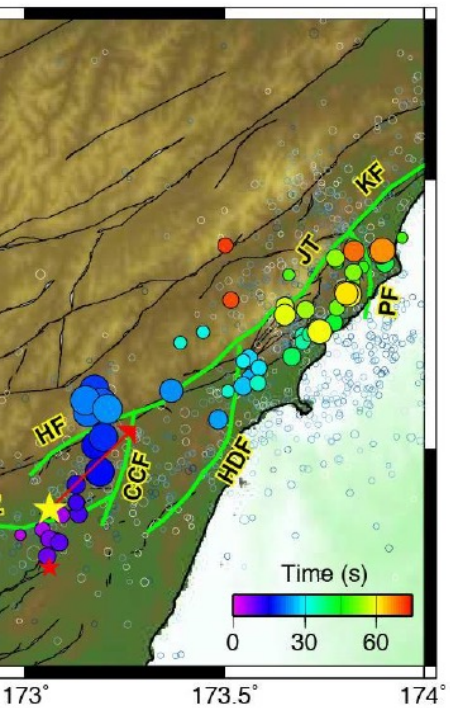
Enabled by global earthquake source product
Lingling Ye (Caltech), Martin Vallée (IPGP) and Gavin Hayes 5US

Caltech

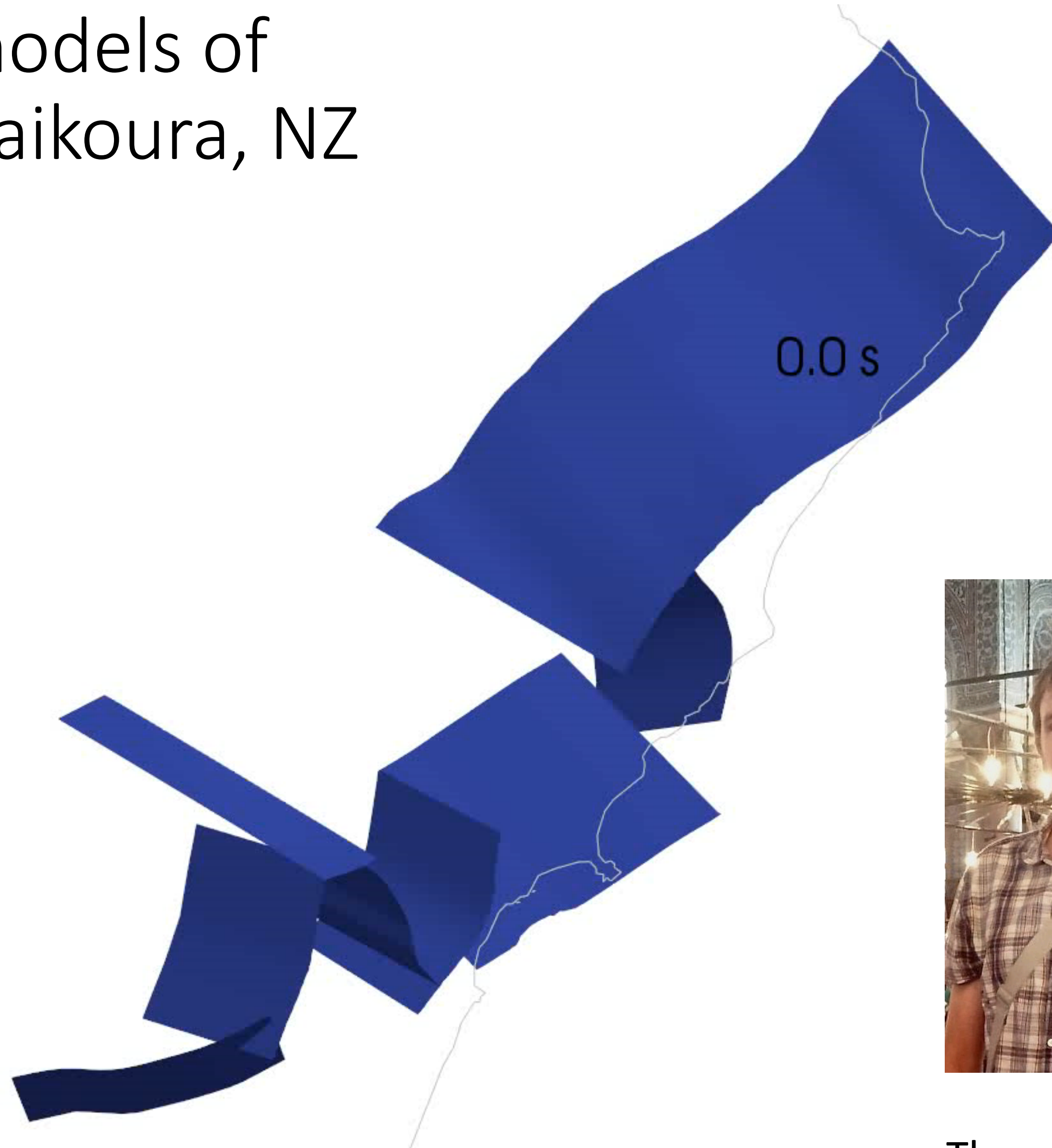
SEISMOLOGICAL LABORATORY
California Institute of Technology

NSF

ynamic rupture models of
e 2016 Mw 7.8 Kaikoura, NZ
arthquake

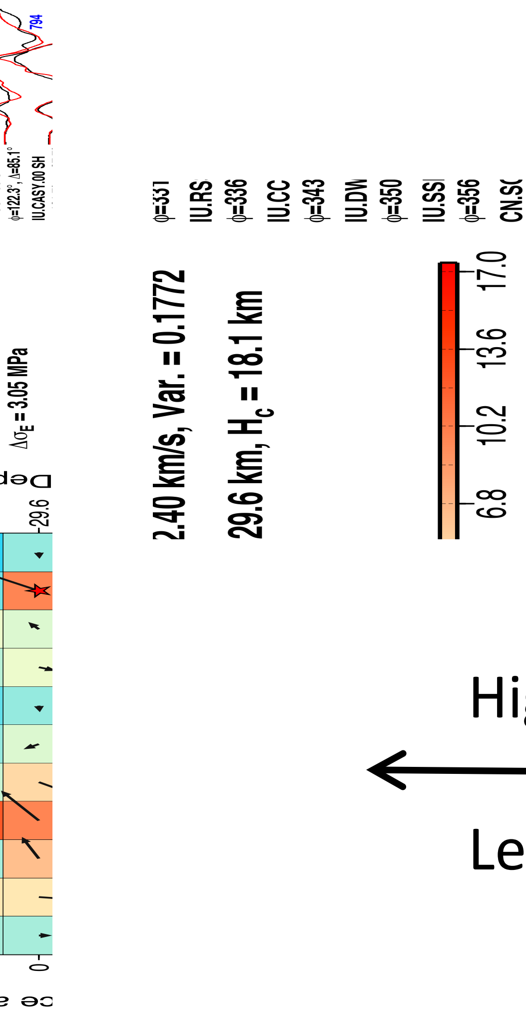


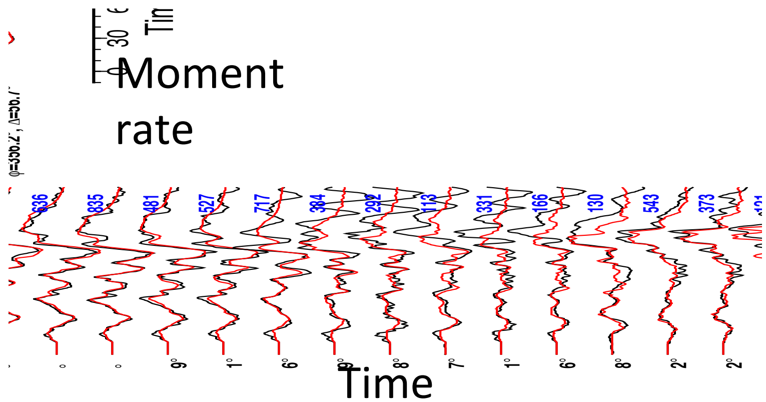
seismic back-projection
gsen Meng, UCLA)

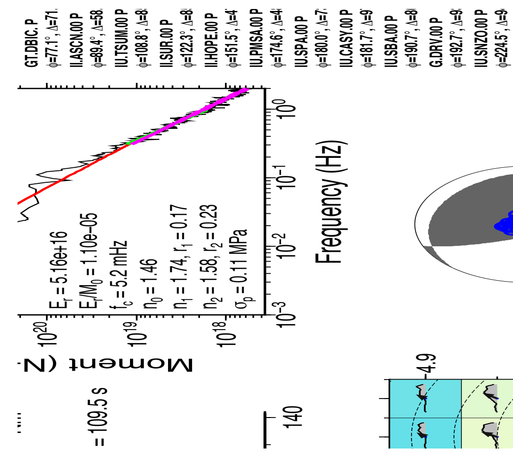



Thomas Ulrich and Alice Ga
SeisSol Team (LMU, Munich

Trade-offs in earthquake source studies







High fidelity

Less uncertainty

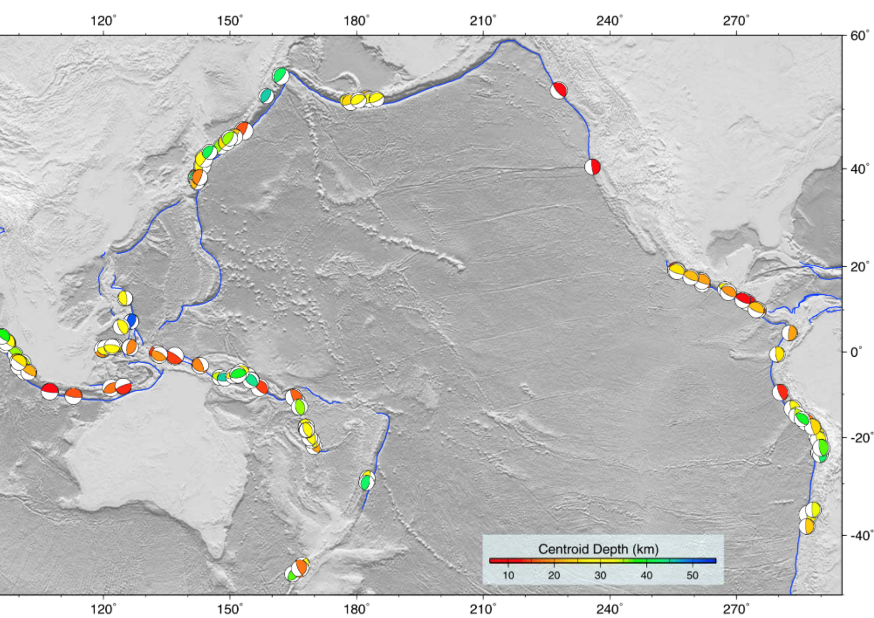
High definition

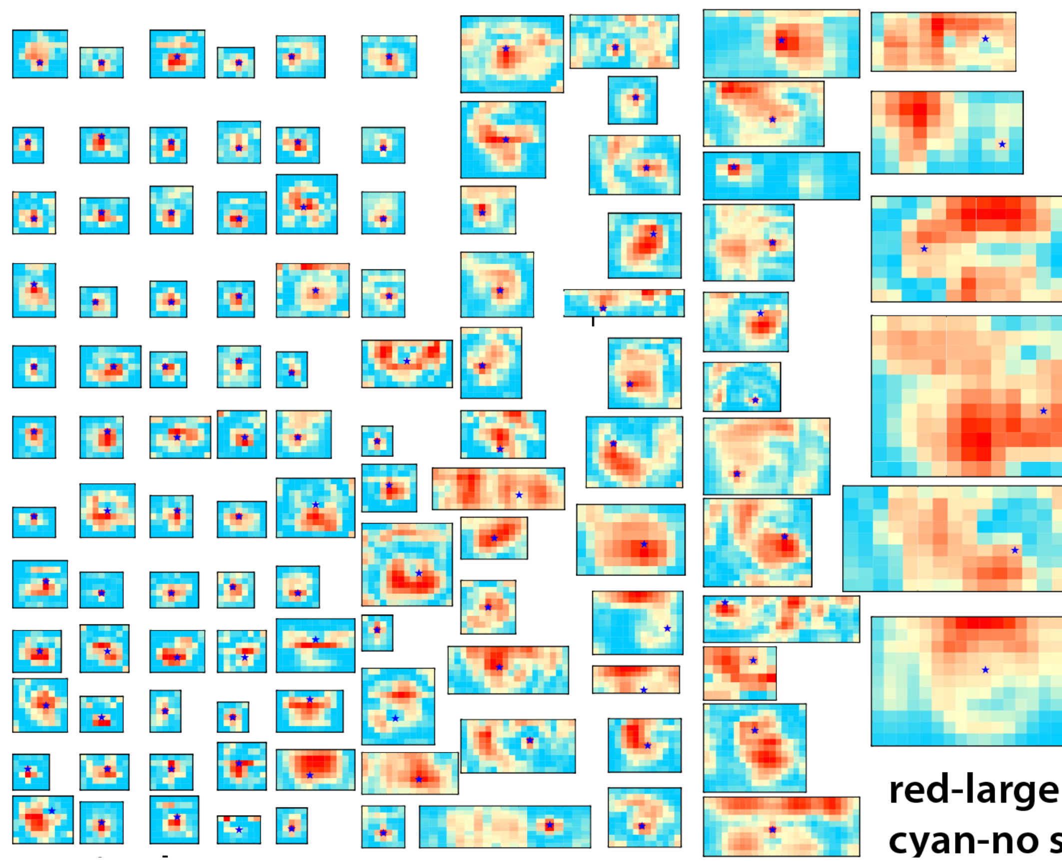
More detail

lobal source studies

et al (JGR 2016)

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





lobal source studies

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- 16 **M7+** shallow **subduction zone** thrust earthquakes
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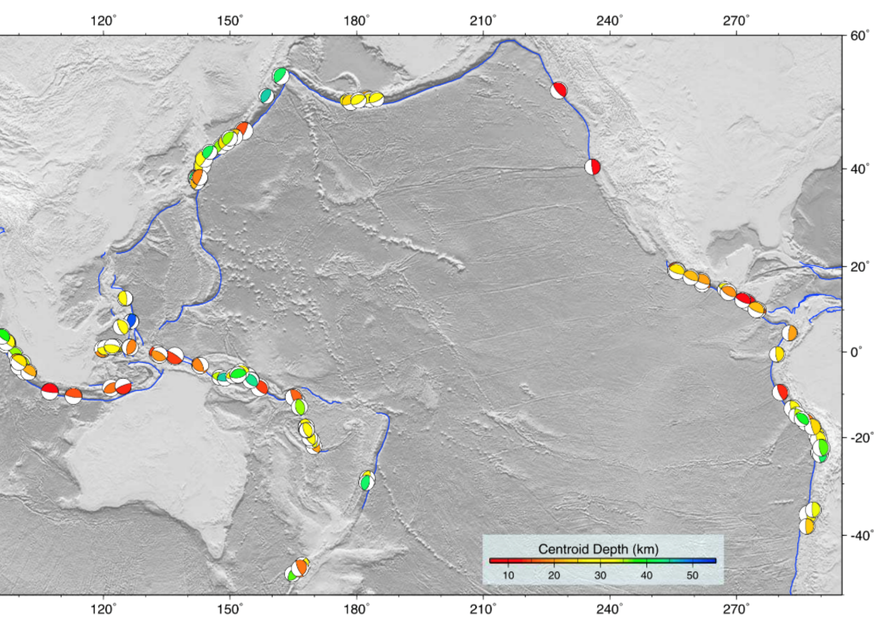
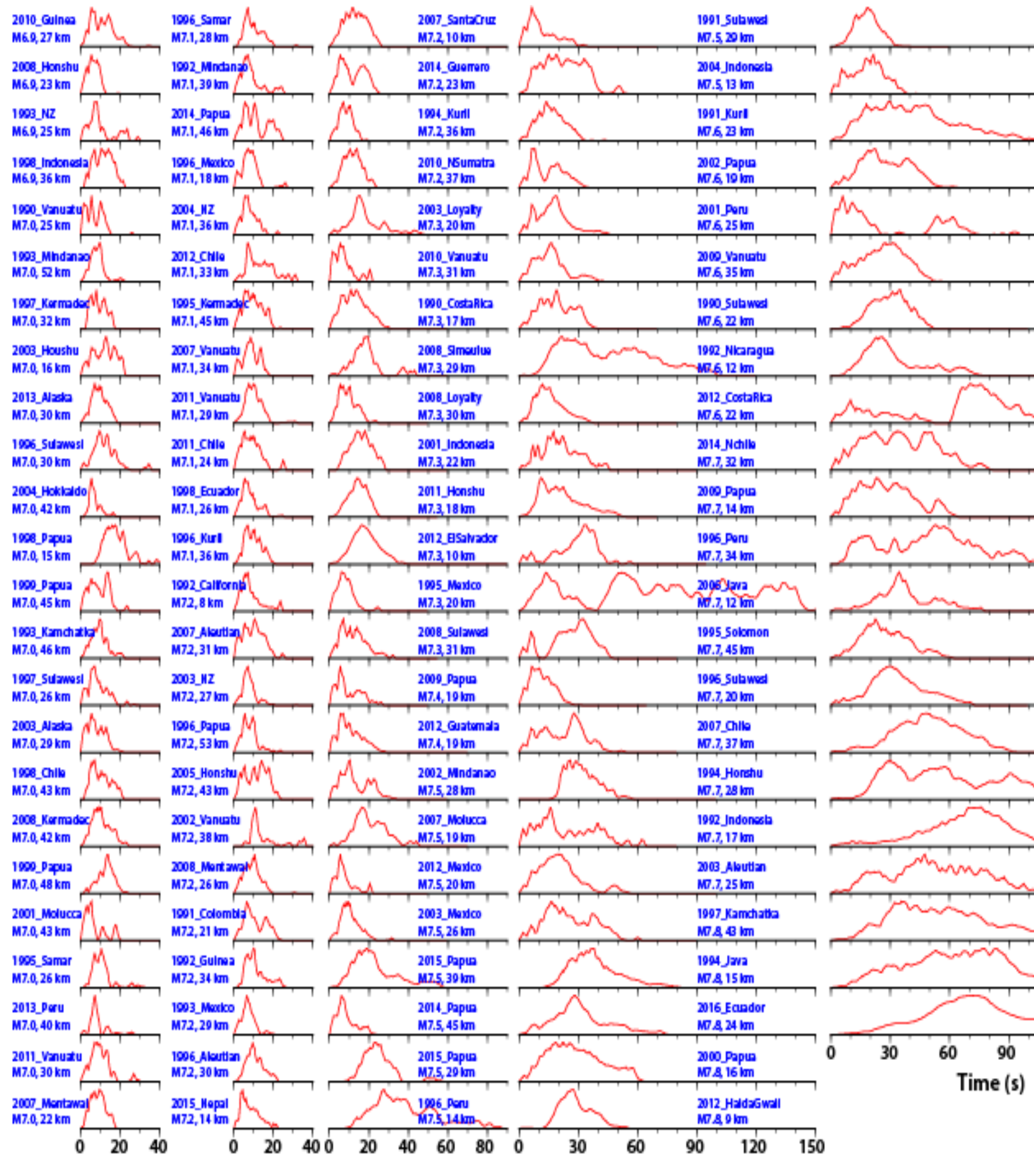


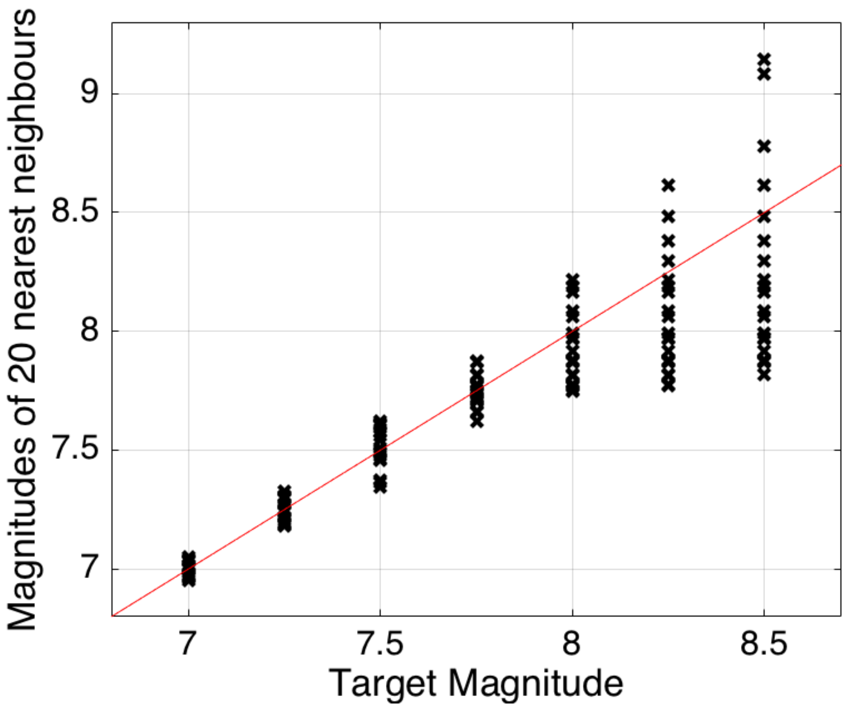


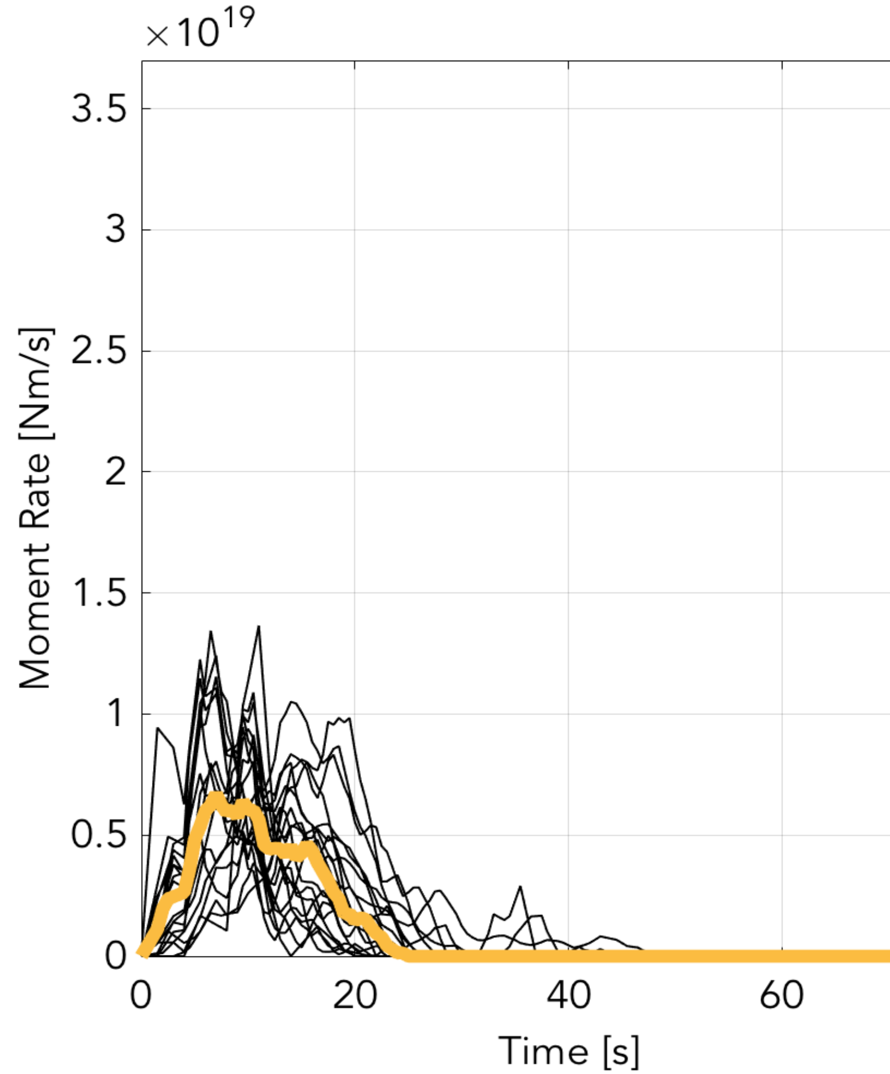
Questions to address under the macroscope

- 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?

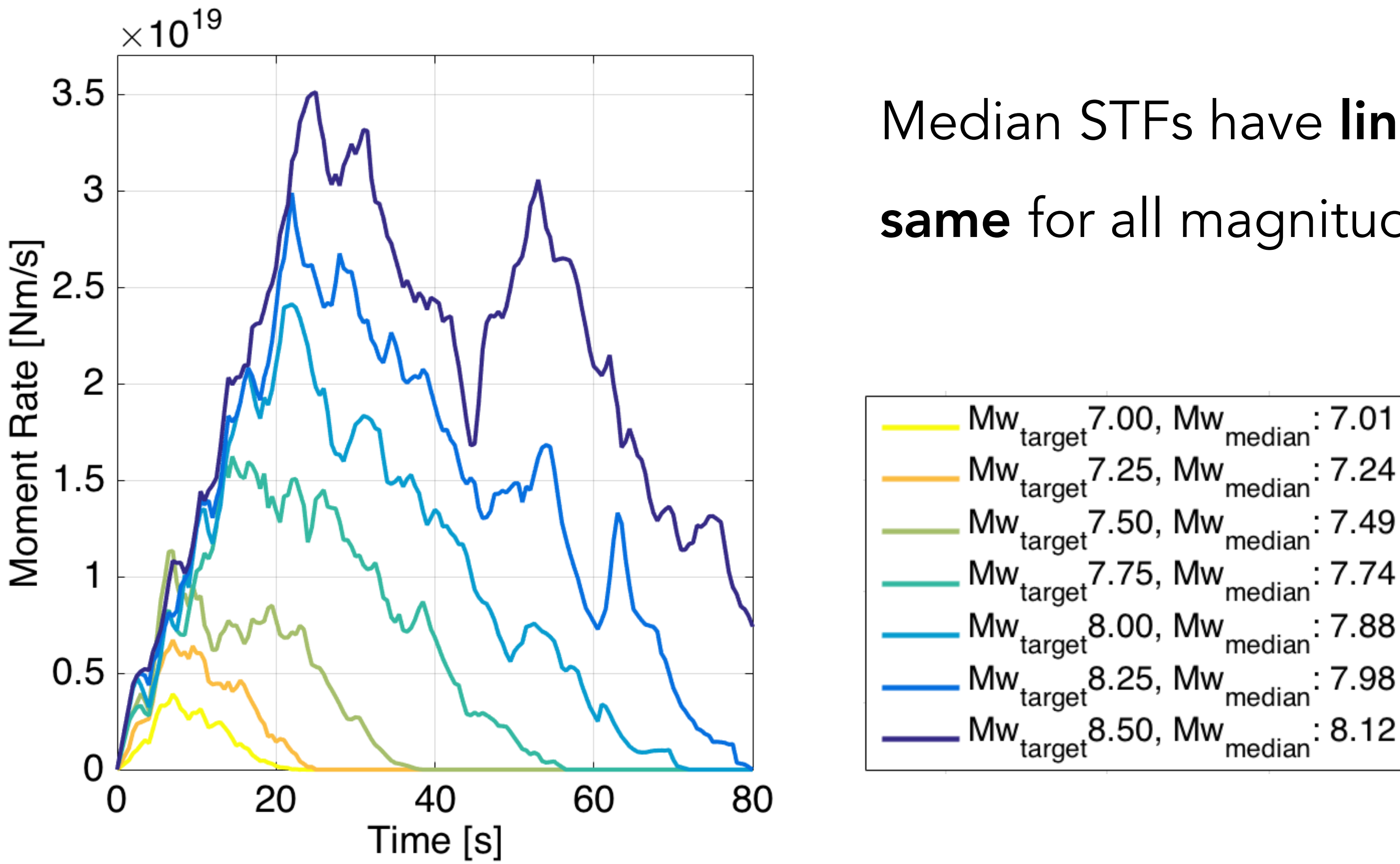
What **general patterns** do the STF follow?

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



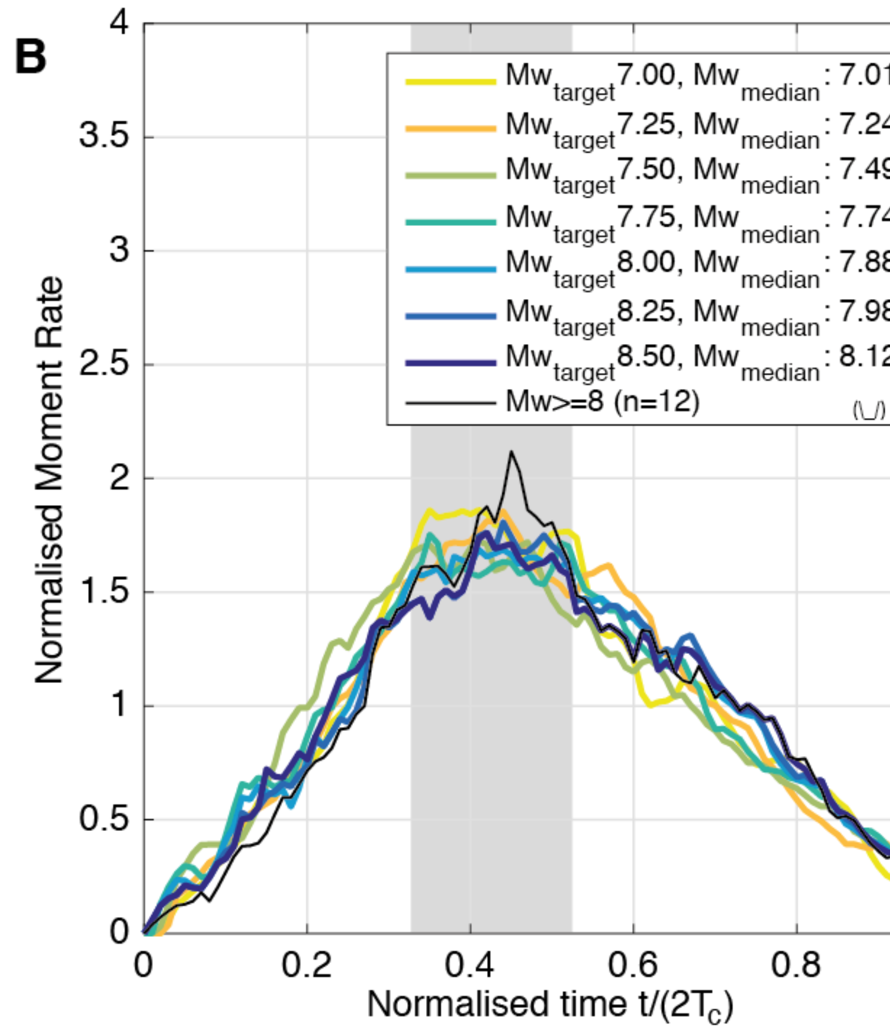


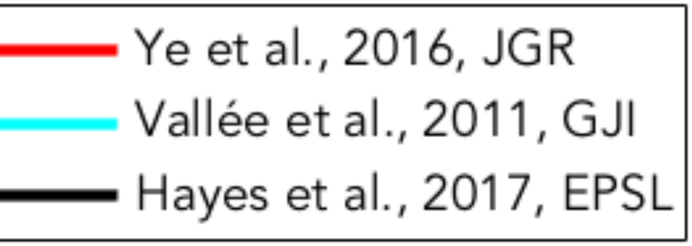
Median STFs have **linear onset**, **same** for all magnitudes Mw>7

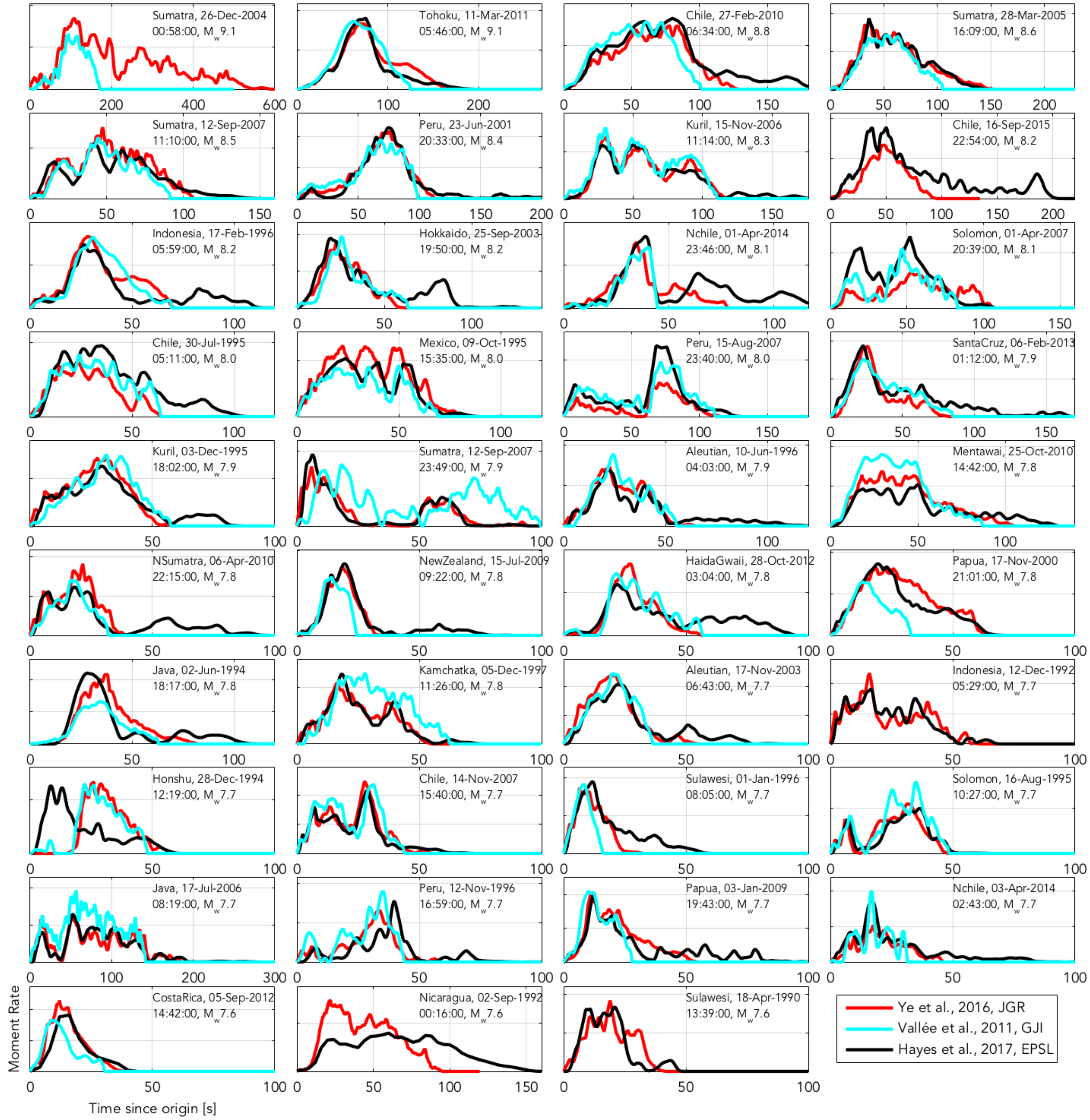


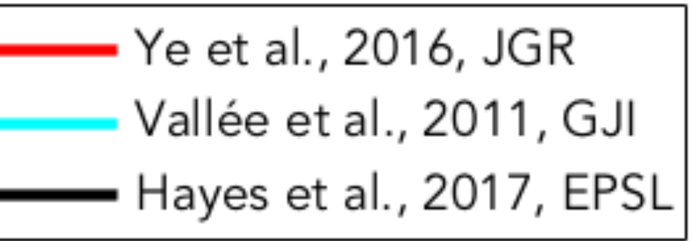
Normalize each STF by its duration
Scale them such that they integrate to 1
Compute median of normalized STF

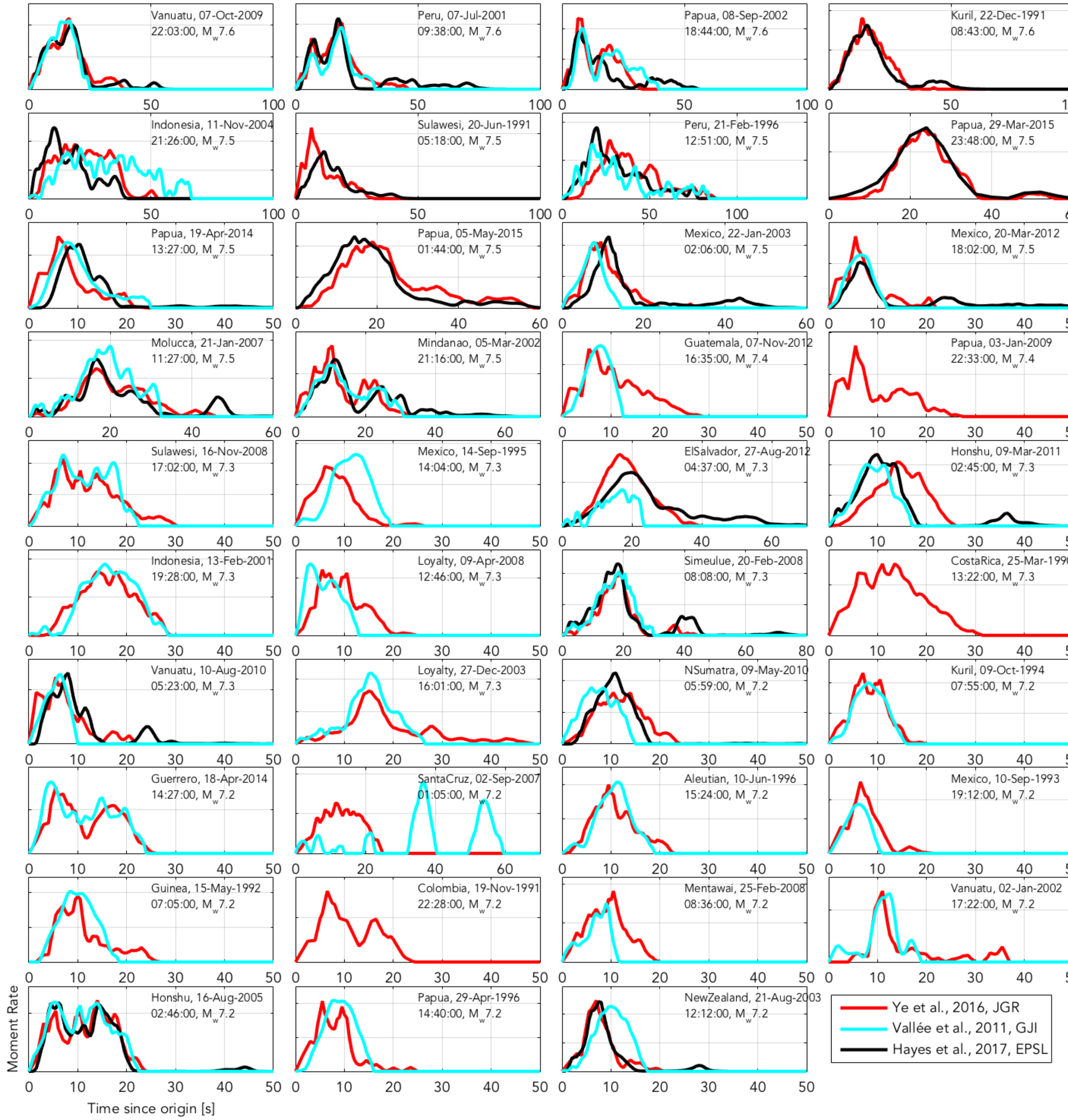
On average, all STFs
can be scaled to a very simple,
quasi-triangular shape




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


Sumatra, 26-Dec-2004 00:58:00, Mw 9.1
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
Sumatra, 12-Sep-2007 23:49:00, Mw 7.9
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
Indonesia, 12-Dec-1992 05:29:00, Mw 7.7
Honshu, 28-Dec-1994 12:19:00, Mw 7.7
Chile, 14-Nov-2007 15:40:00, Mw 7.7
Sulawesi, 01-Jan-1996 08:05:00, Mw 7.7
Solomon, 16-Aug-1995 10:27:00, Mw 7.7
Java, 17-Jul-2006 08:19:00, Mw 7.7
Peru, 12-Nov-1996 16:59:00, Mw 7.7
Papua, 03-Jan-2009 19:43:00, Mw 7.7
Nchile, 03-Apr-2014 02:43:00, Mw 7.7
CostaRica, 05-Sep-2012 14:42:00, Mw 7.6
Nicaragua, 02-Sep-1992 00:16:00, Mw 7.6
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


Vanuatu, 07-Oct-2009 22:03:00, M_w 7.6
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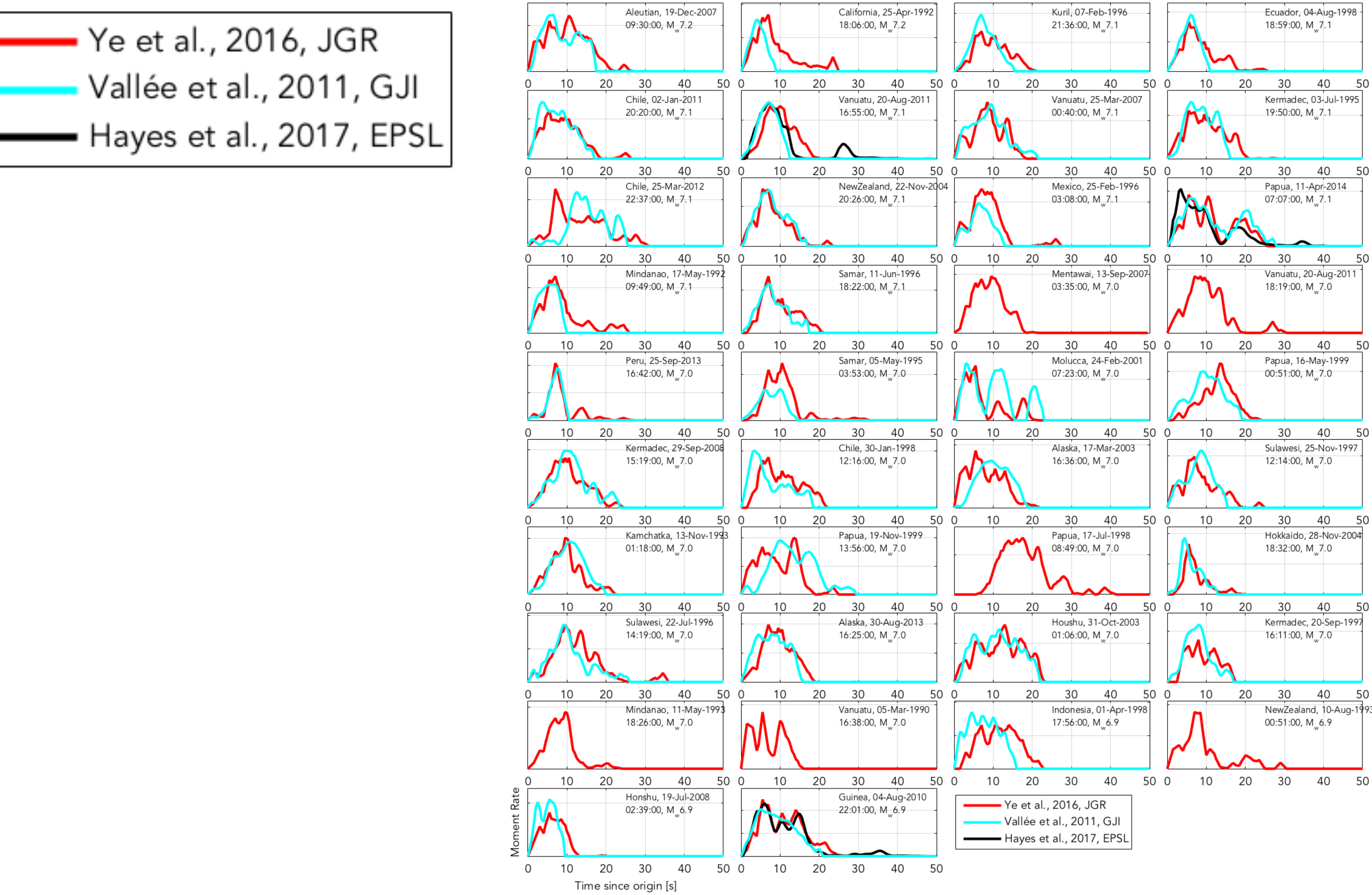
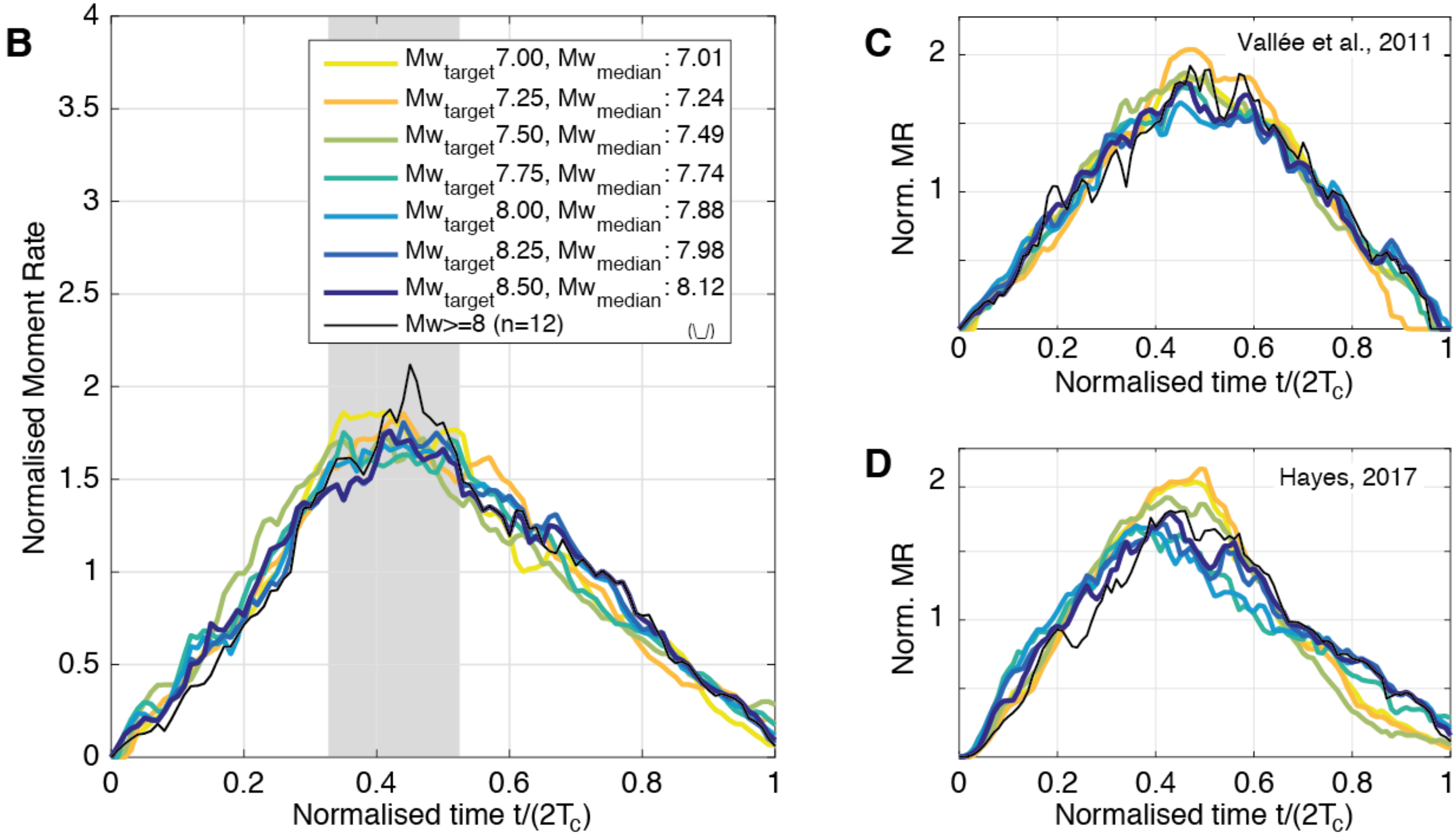
Papua, 08-Sep-2002 18:44:00, M_w 7.6
Kuril, 22-Dec-1991 08:43:00, M_w 7.6
Indonesia, 11-Nov-2004 21:26:00, M_w 7.5
Sulawesi, 20-Jun-1991 05:18:00, M_w 7.5
Peru, 21-Feb-1996 12:51:00, M_w 7.5
Papua, 29-Mar-2015 23:48:00, M_w 7.5
Papua, 19-Apr-2014 13:27:00, M_w 7.5
Papua, 05-May-2015 01:44:00, M_w 7.5
Mexico, 22-Jan-2003 02:06:00, M_w 7.5
Mexico, 20-Mar-2012 18:02:00, M_w 7.5
Molucca, 21-Jan-2007 11:27:00, M_w 7.5
Mindanao, 05-Mar-2002 21:16:00, M_w 7.5
Guatemala, 07-Nov-2012 16:35:00, M_w 7.4
Papua, 03-Jan-2009 22:33:00, M_w 7.4
Sulawesi, 16-Nov-2008 17:02:00, M_w 7.3
Mexico, 14-Sep-1995 14:04:00, M_w 7.3
ElSalvador, 27-Aug-2012 04:37:00, M_w 7.3
Honshu, 09-Mar-2011 02:45:00, M_w 7.3
Indonesia, 13-Feb-2001 19:28:00, M_w 7.3
Loyalty, 09-Apr-2008 12:46:00, M_w 7.3
Simeulue, 20-Feb-2008 08:08:00, M_w 7.3
CostaRica, 25-Mar-1990 13:22:00, M_w 7.3
Vanuatu, 10-Aug-2010 05:23:00, M_w 7.3
Loyalty, 27-Dec-2003 16:01:00, M_w 7.3
NSumatra, 09-May-2010 05:59:00, M_w 7.2
Kuril, 09-Oct-1994 07:55:00, M_w 7.2
Guerrero, 18-Apr-2014 14:27:00, M_w 7.2
SantaCruz, 02-Sep-2007 01:05:00, M_w 7.2
Aleutian, 10-Jun-1996 15:24:00, M_w 7.2
Mexico, 10-Sep-1993 19:12:00, M_w 7.2
Guinea, 15-May-1992 07:05:00, M_w 7.2
Colombia, 19-Nov-1991 22:28:00, M_w 7.2
Mentawai, 25-Feb-2008 08:36:00, M_w 7.2
Vanuatu, 02-Jan-2002 17:22:00, M_w 7.2
Honshu, 16-Aug-2005 02:46:00, M_w 7.2
Papua, 29-Apr-1996 14:40:00, M_w 7.2
NewZealand, 21-Aug-2003 12:12:00, M_w 7.2
Moment Rate
Time since origin [s]
Ye et al., 2016, JGR
Vallée et al., 2011, GJI
Hayes et al., 2017, EPSL


Ye et al., 2016, JGR
Vallée et al., 2011, GJI
Hayes et al., 2017, EPSL
Aleutian, 19-Dec-2007 09:30:00, M_w 7.2
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
Chile, 25-Mar-2012 22:37:00, M_w 7.1
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
Vanuatu, 20-Aug-2011 18:19:00, M_w 7.0
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
Sulawesi, 22-Jul-1996 14:19:00, M_w 7.0
Alaska, 30-Aug-2013 16:25:00, M_w 7.0
Houshu, 31-Oct-2003 01:06:00, M_w 7.0
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
Moment Rate
Time since origin [s]

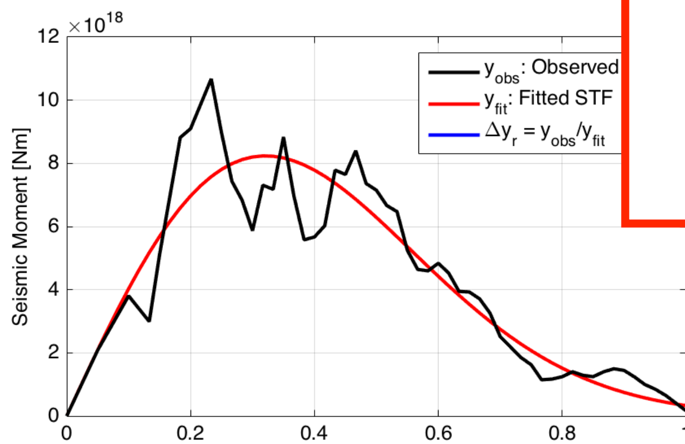


B
Normalised Moment Rate
Normalised time t/(2T$_c$)
Mw$_{target}$ 7.00, Mw$_{median}$: 7.01
Mw$_{target}$ 7.25, Mw$_{median}$: 7.24
Mw$_{target}$ 7.50, Mw$_{median}$: 7.49
Mw$_{target}$ 7.75, Mw$_{median}$: 7.74
Mw$_{target}$ 8.00, Mw$_{median}$: 7.88
Mw$_{target}$ 8.25, Mw$_{median}$: 7.98
Mw$_{target}$ 8.50, Mw$_{median}$: 8.12
Mw>=8 (n=12)
C
Vallée et al., 2011
Norm. MR
Normalised time t/(2T$_c$)
D
Hayes, 2017
Norm. MR
Normalised time t/(2T$_c$)

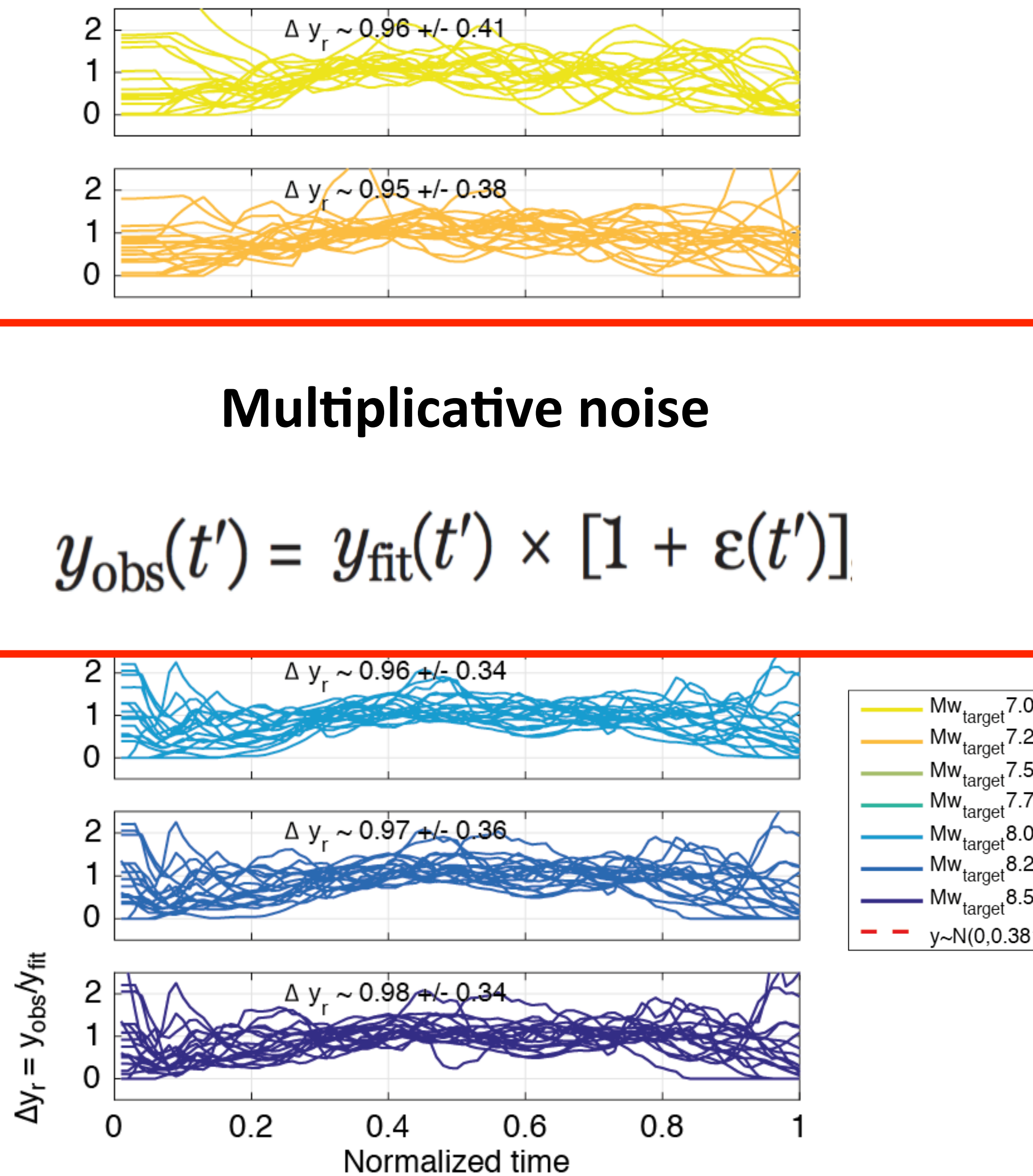
uctuations around
ne median STF

Fit a function to STFs:

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



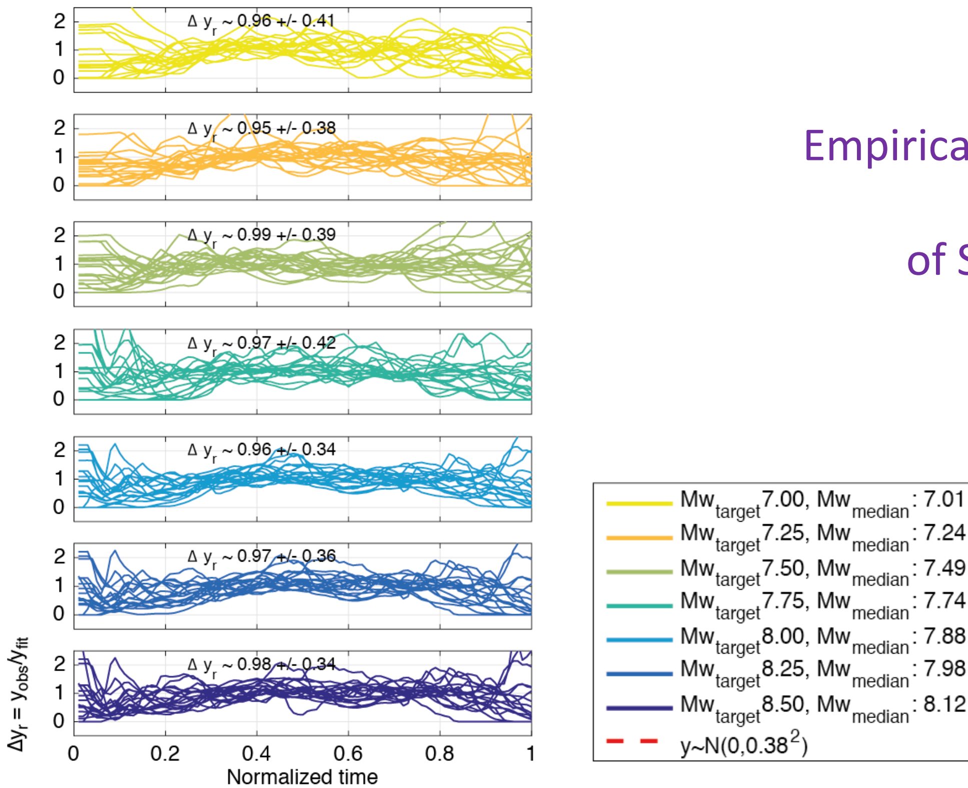
esiduals



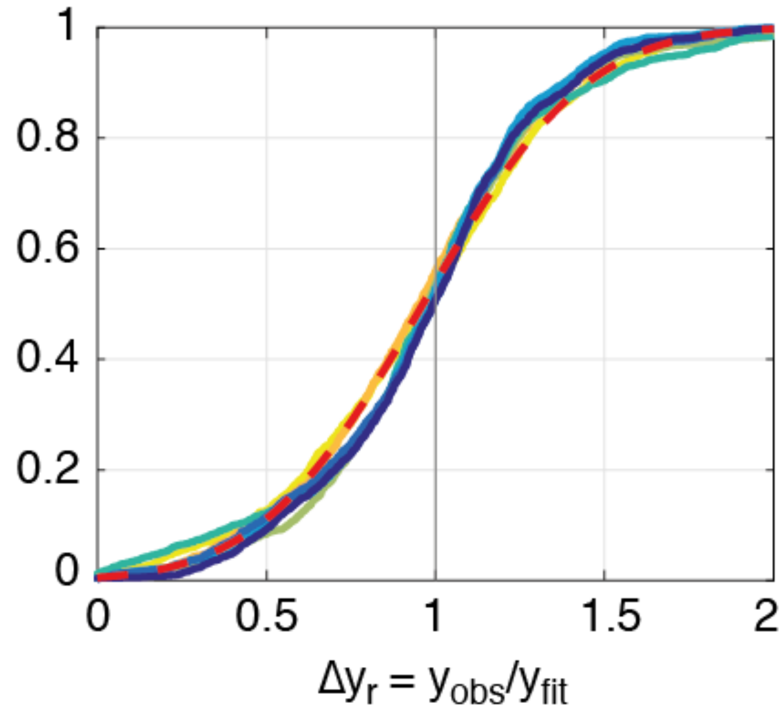
Multiplicative noise

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

STF fluctuations are multiplicative **and Gaussian**

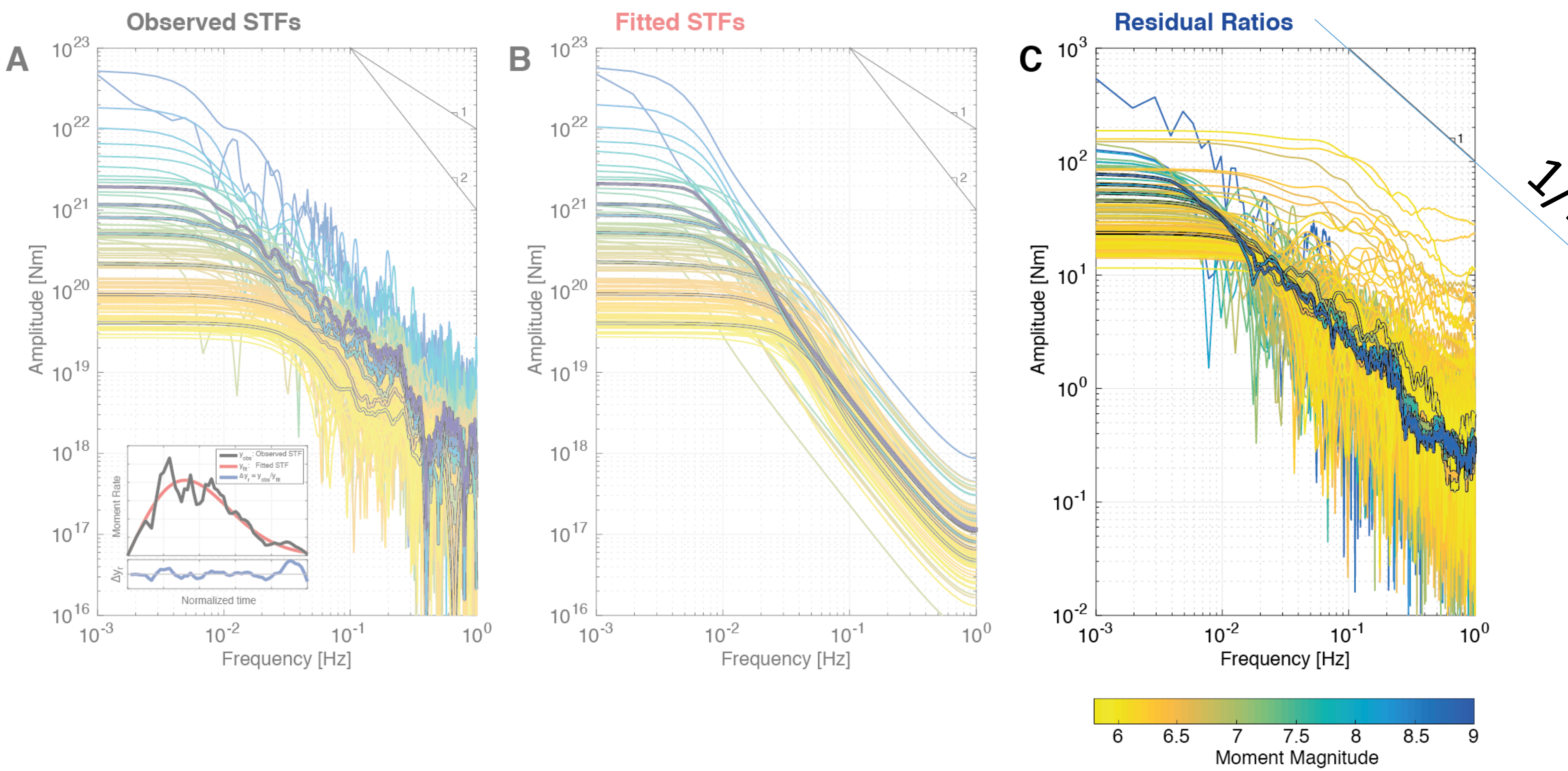


Empirical cumulative distribution of STF residuals



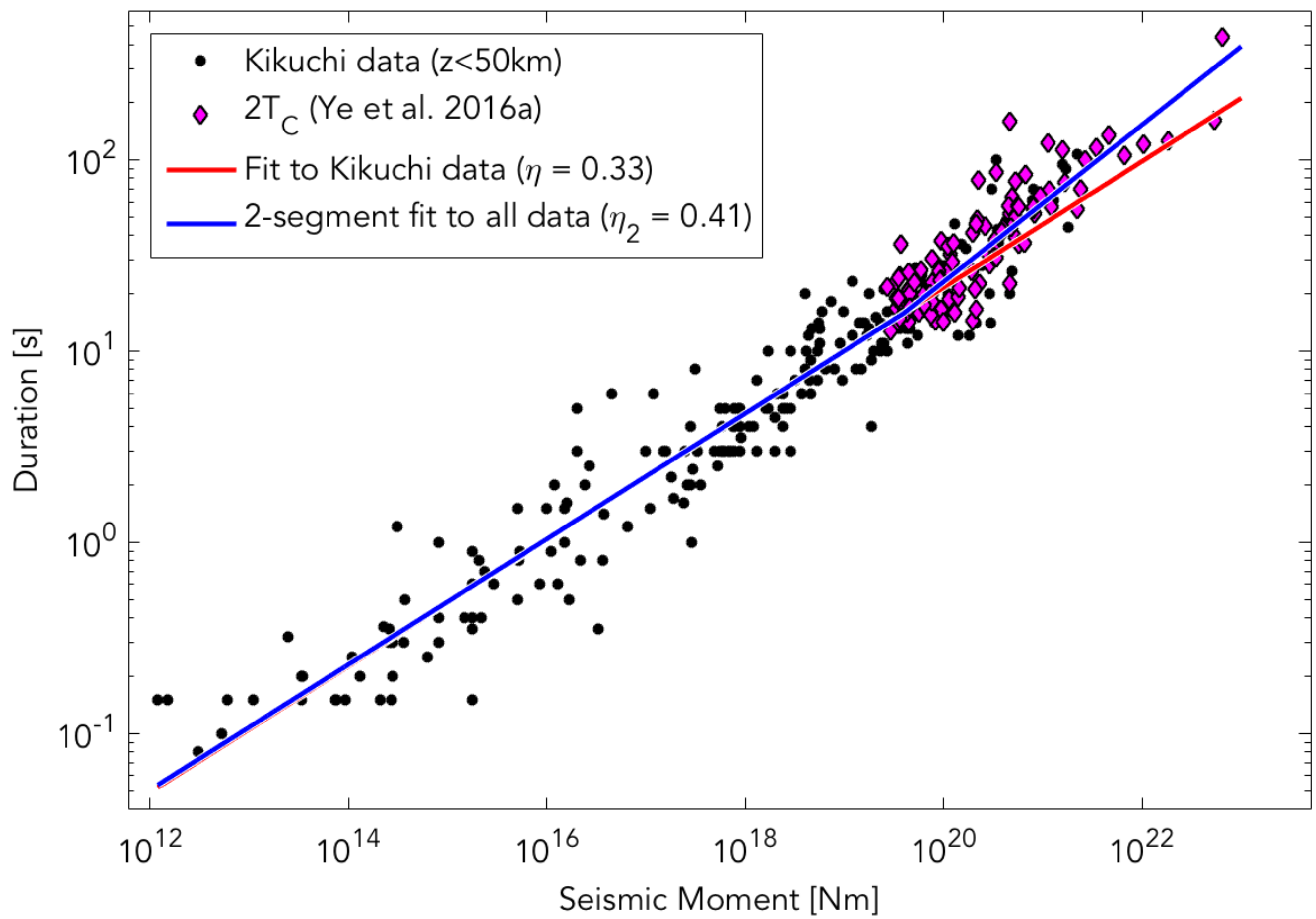
$$y_{\mathrm{obs}}(t') = y_{\mathrm{fit}}(t') \times [1 + \varepsilon(t')], \text{ where } \varepsilon \sim N(0, 0.38^2)$$

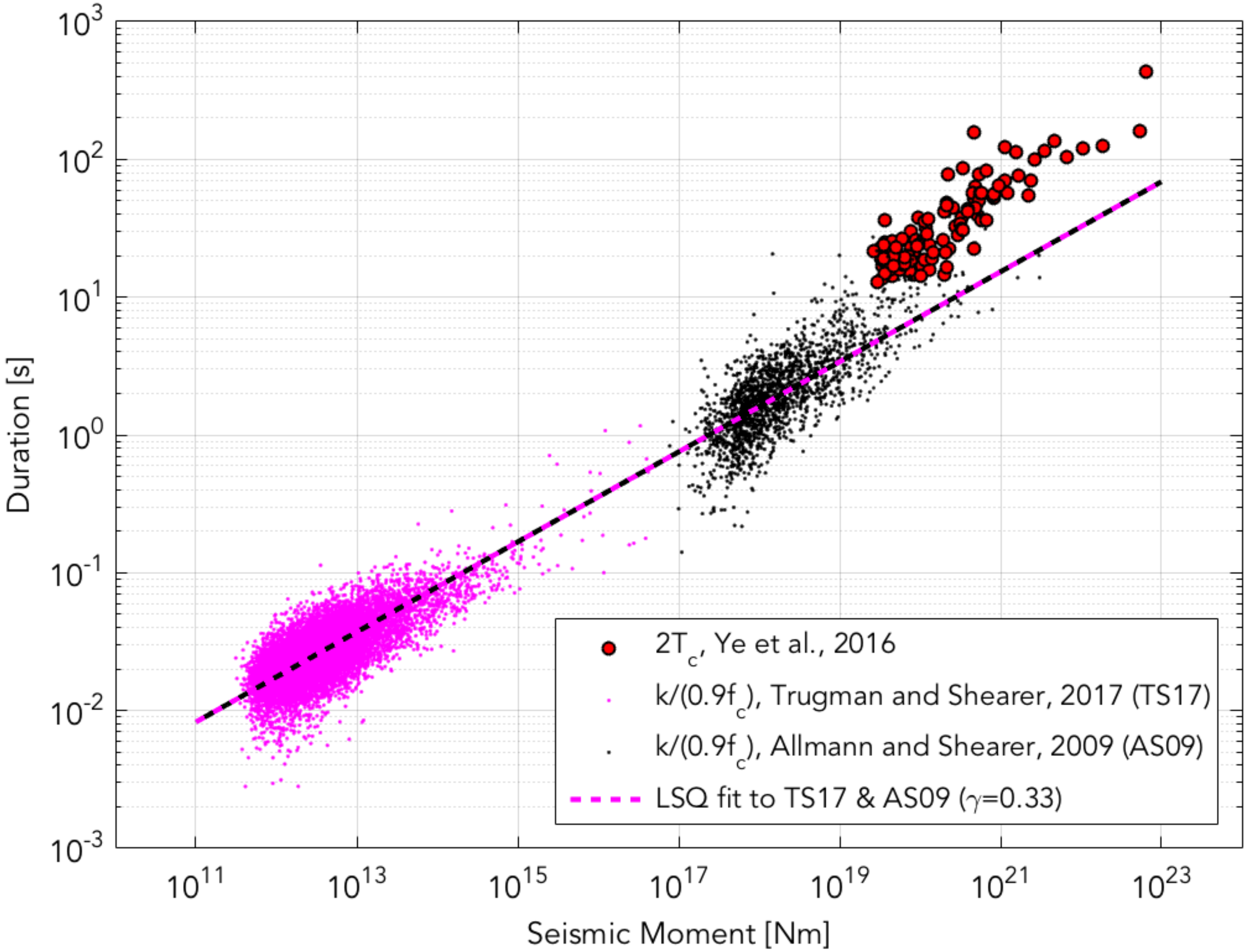
STF fluctuations are multiplicative, Gaussian **and Brownian**



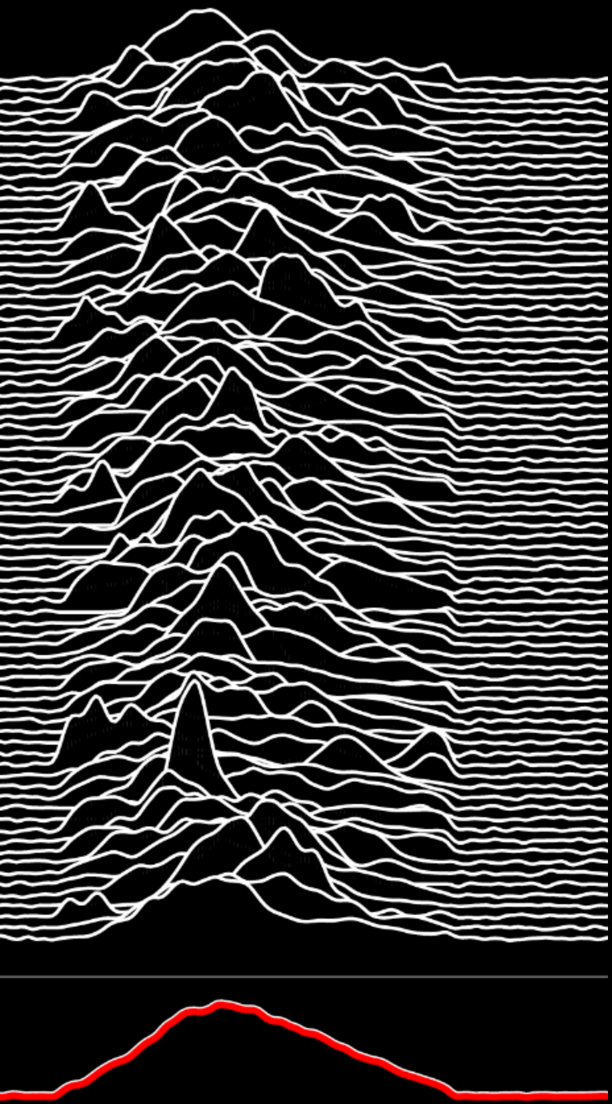
Implications for moment / duration scaling

- Linear growth suggests $M_0 \sim T^2$ scaling
- In contrast to the widely reported $M_0 \sim T^3$ scaling
  → scaling break?





Duration [s]
Seismic Moment [Nm]
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{11}
10^{13}
10^{15}
10^{17}
10^{19}
10^{21}
10^{23}
$2T_c$, Ye et al., 2016
$k/(0.9f_c)$, Trugman and Shearer, 2017 (TS17)
$k/(0.9f_c)$, Allmann and Shearer, 2009 (AS09)
LSQ fit to TS17 & AS09 (γ=0.33)



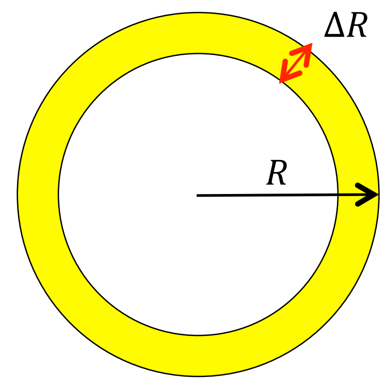
Summary of observed STF characteristics, Mw>7

- 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

Why is linear moment rate growth surprising?

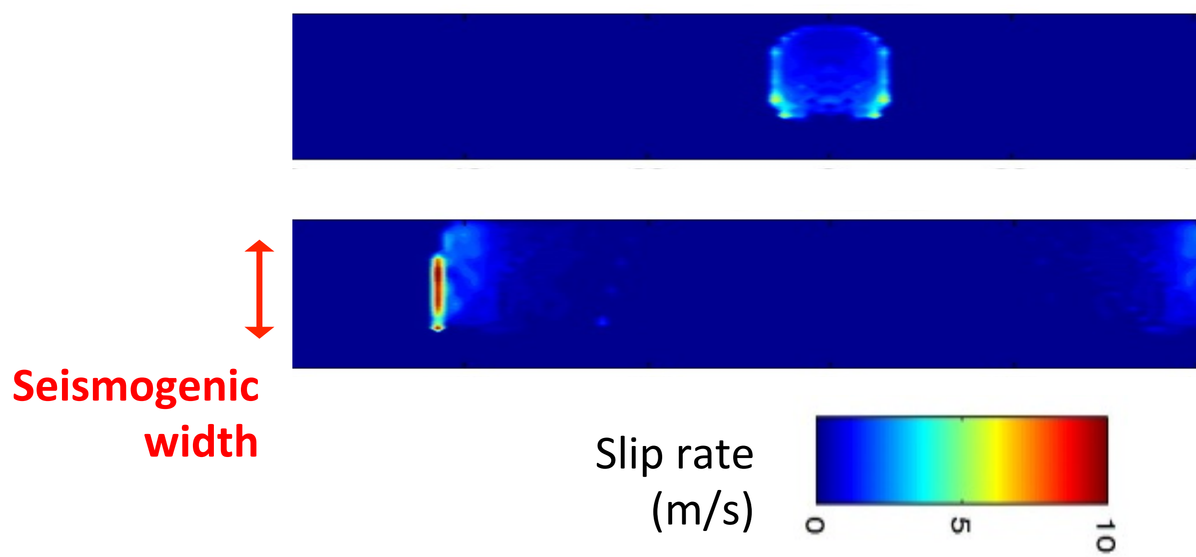
Self-similar model for small earthquakes:
Circular rupture with constant stress drop and constant rupture speed

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



ery large earthquakes: **elongated rupture**
nce **seismogenic width is saturated:**
noment grows slower than quadratic

But linear trend is observed
after 5-10 s,
oefore rupture saturates the
seismogenic width



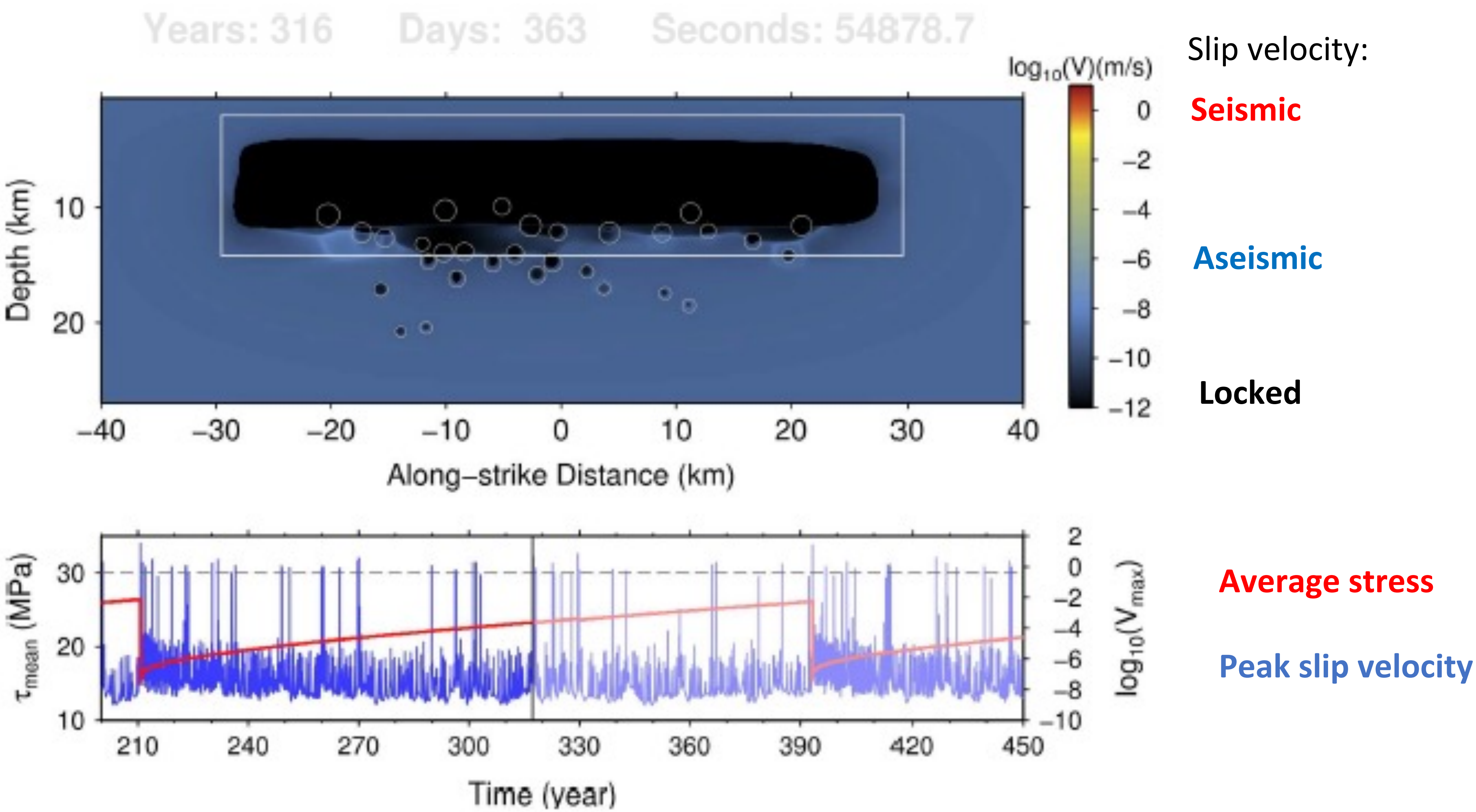
Implications for Rupture Growth Scaling

- 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 $\eta^{obs} \sim 1 \rightarrow \alpha + \beta \sim 2$

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

→ How can we lower the moment rate growth?

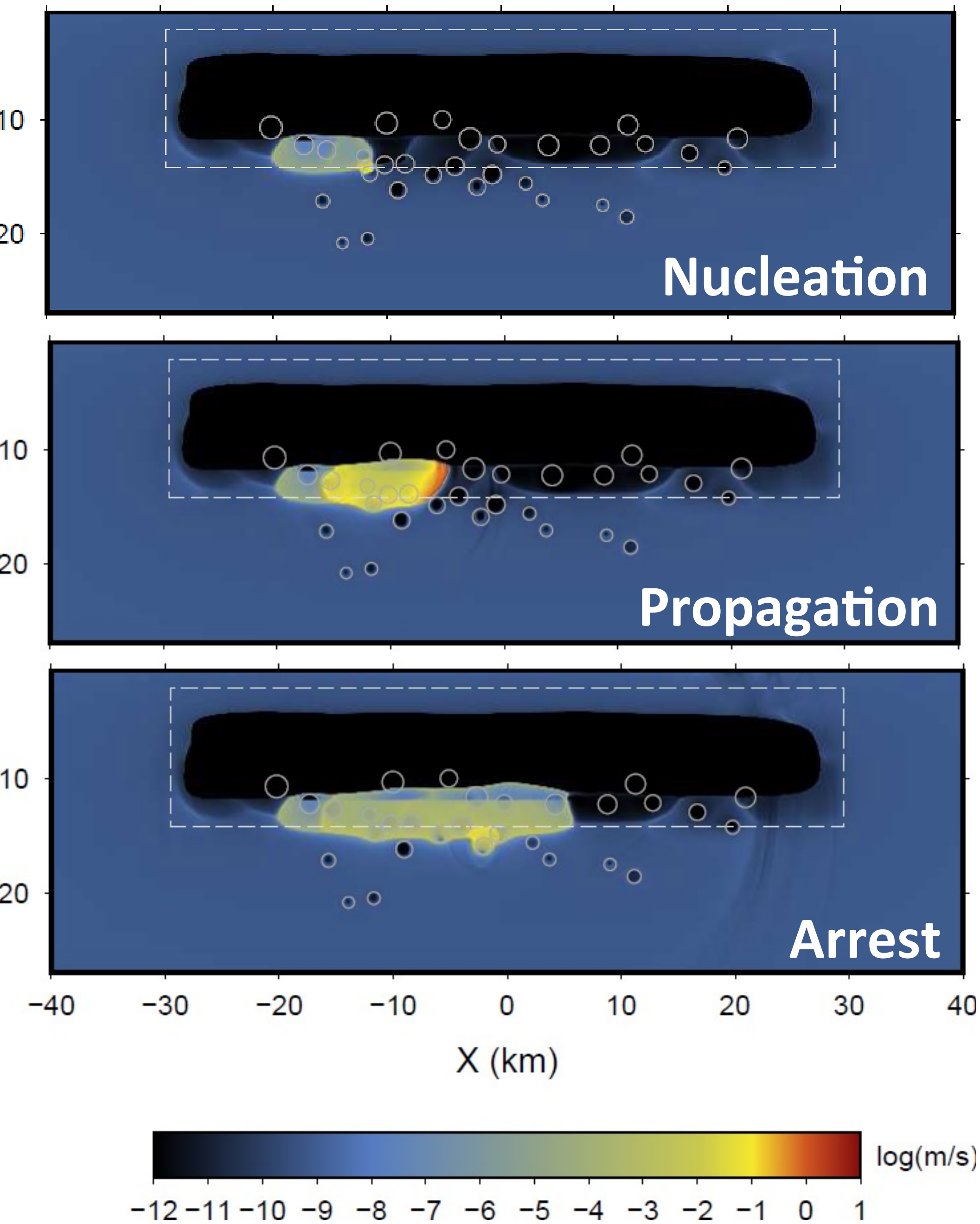
- Lower alpha, lower beta, or combination of both?
- Pulse-like rupture with areas of systematic slip deficits?

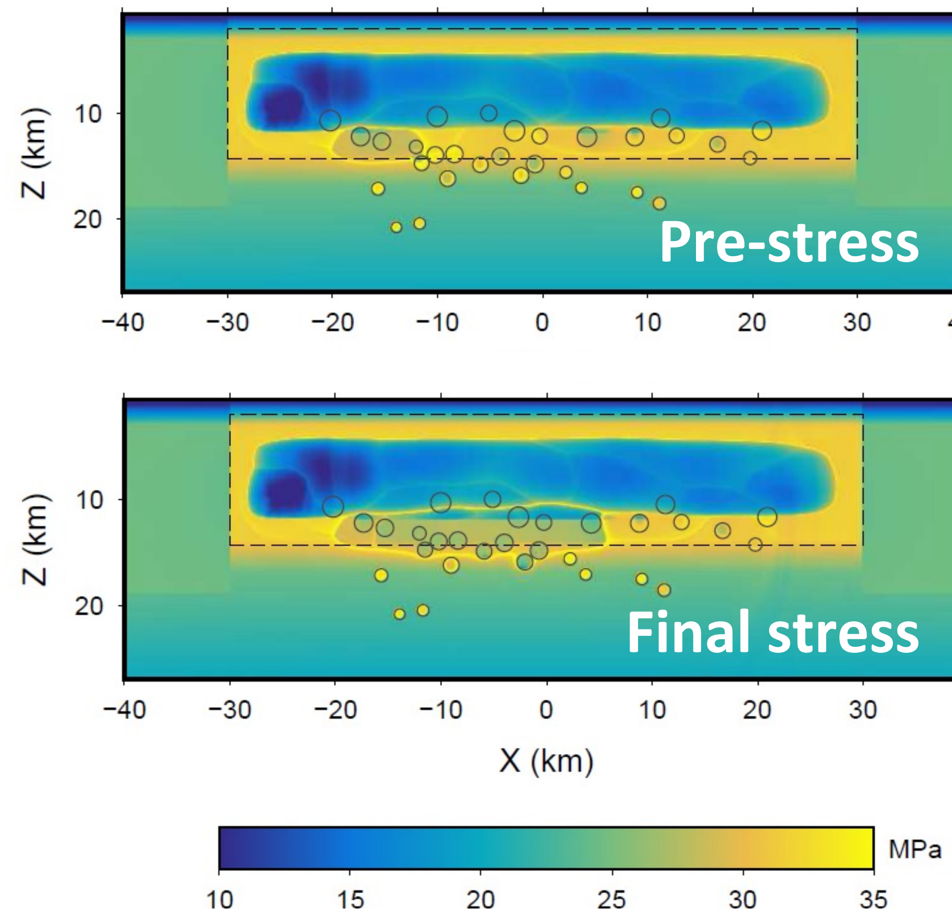


Extracted from Junle Jiang and Nadia Lapusta's dynamic earthquake cycle simulations.

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

(Junle Jiang, Calte





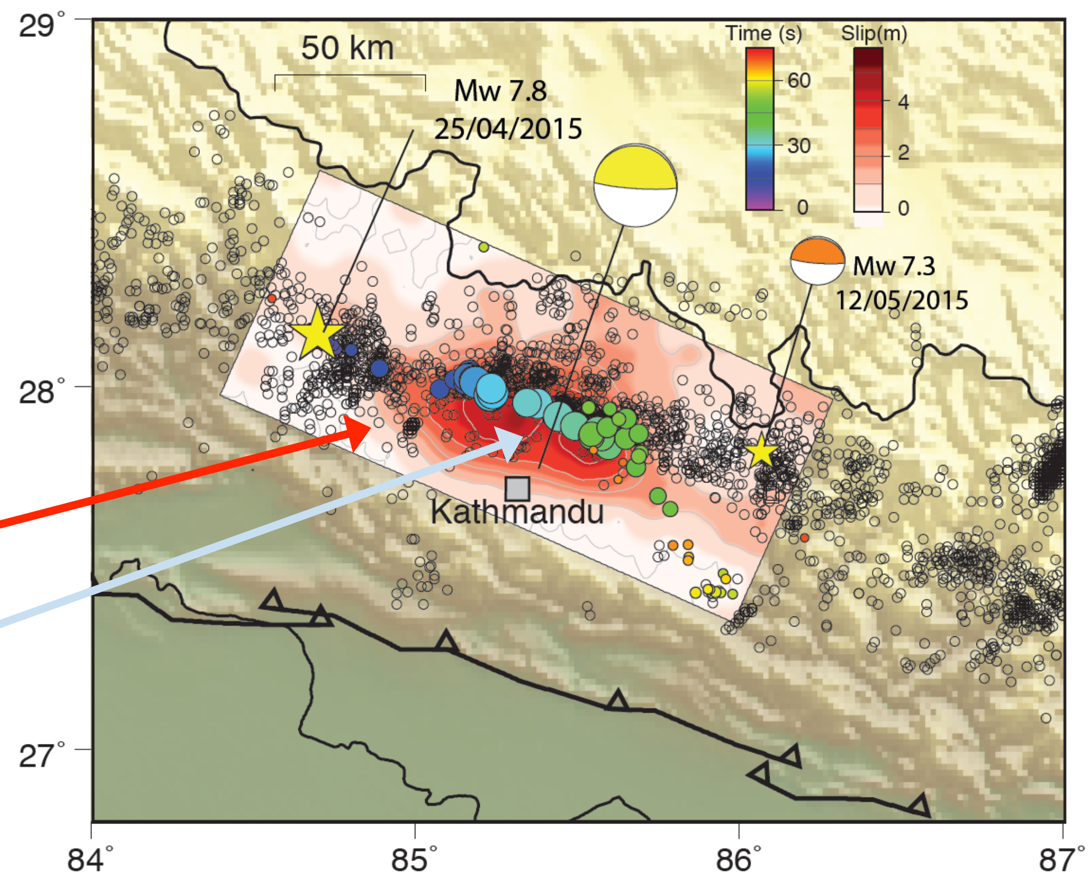
e April 25 2015, Mw 7.8 Gorkha,
pal earthquake

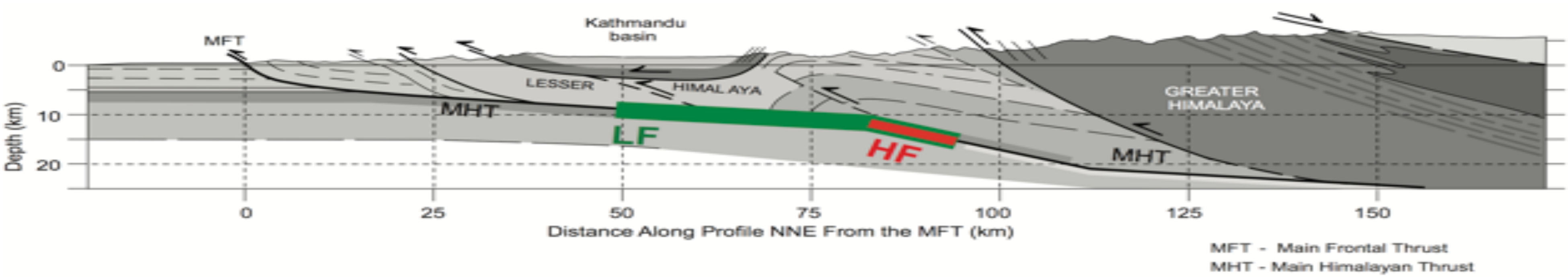
Rupture confined in depth
High-frequency deeper than low-
requency slip, concentrated along
he deep edge of the locked zone

dish contours: slip (frequencies < 0.1 Hz)

red circles: High-frequency radiation (1 Hz)

ac et al (Nature Geoscience, 2015)





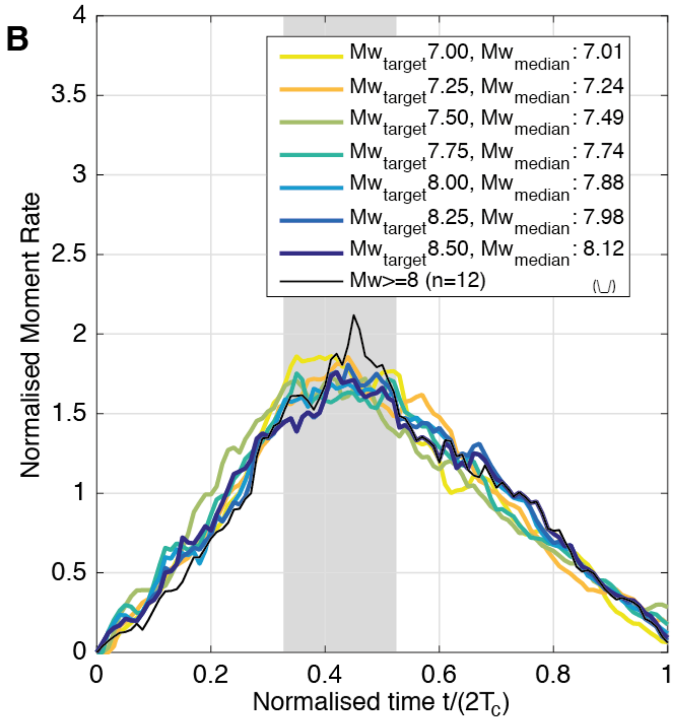
Conclusions

Today we have **enough data** to uncover **general patterns** of earthquake rupture

Focusing on ***temporal* evolution** facilitates testing of conceptual rupture models

A few things are certain …

- Large earthquakes are small earthquakes that did not stop
- Individual earthquakes have large variability, but on average they follow a **remarkably simple pattern**
- Observed pattern systematically **deviates from standard models after few seconds**
- Pattern makes rupture evolution **weakly predictable**



More questions than answers …

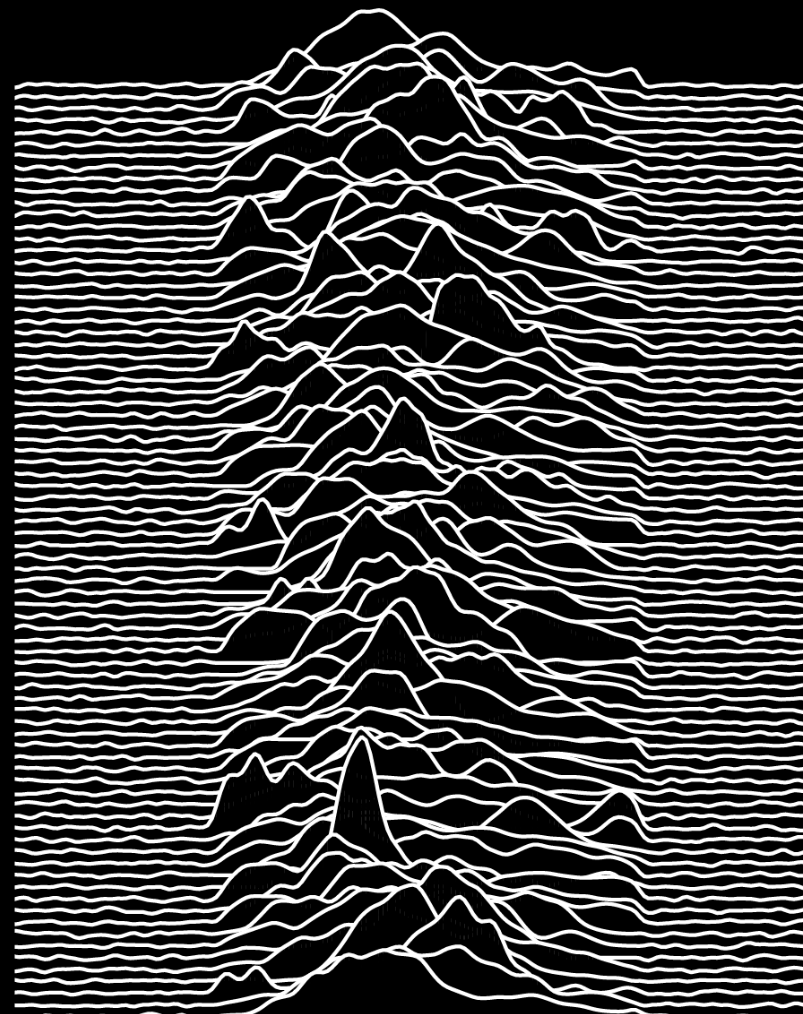
- **Physical origin** of the pattern?
- What **dynamical models** can explain the linear STF growth?
- What causes **break of self-similarity** at ~1s?

Food for thought!

What's 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

thank you



Pulses?