European Center for Geodynamics and Seismology
Centre Européen de Géodynamique et de Séismologie

Stress drop and scaling variations in Japan: what is the driving mechanism ?

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Earthquake source physics on various scales
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What are these 20 min all about?

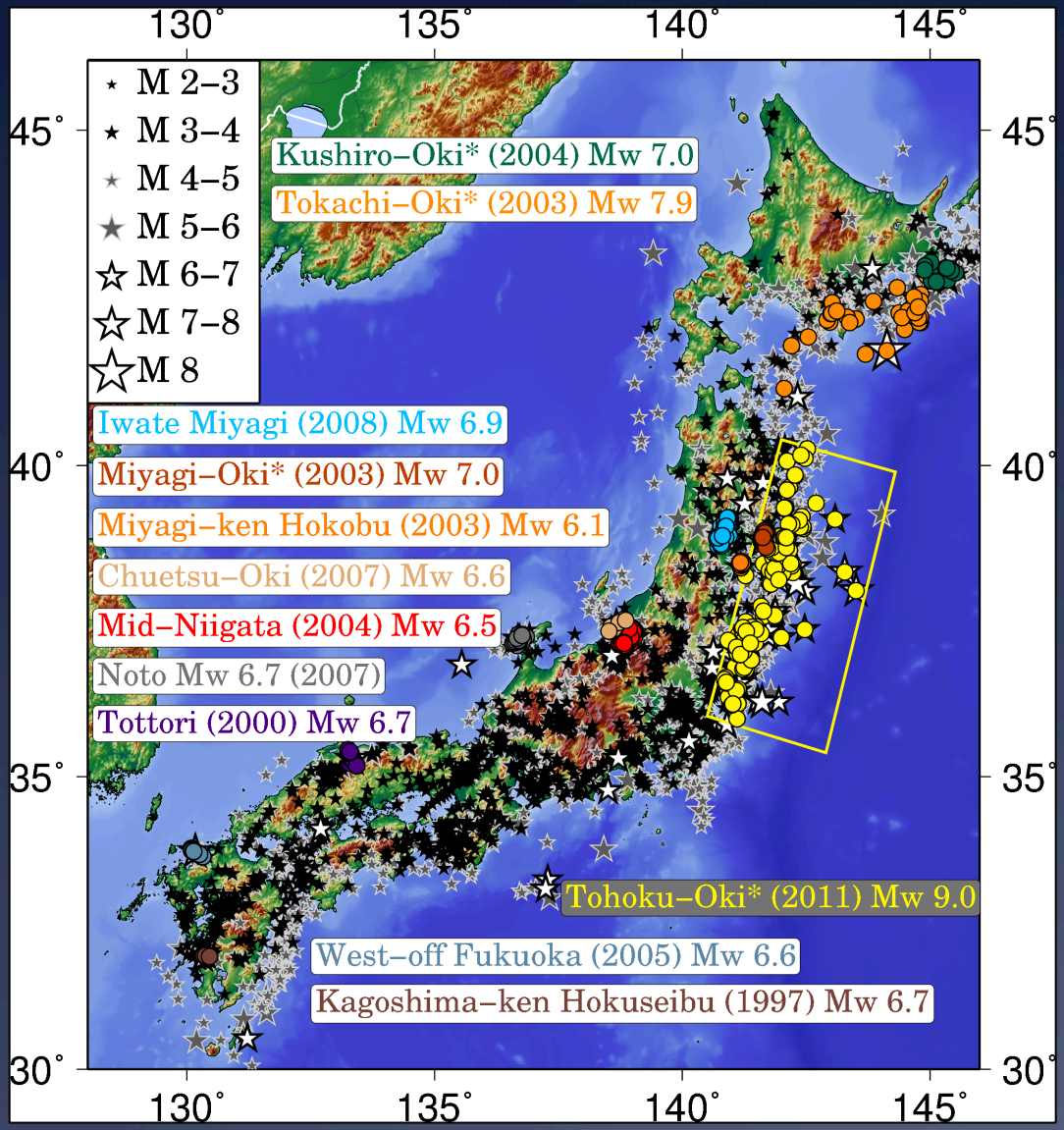
- Parameters under discussion: **stress drop & scaled energy**
  - Fundamental for understanding earthquake source physics and for ground motion modeling/prediction
  - Controversial results (in particular regarding their dependency on earthquake size) in literature
- Stress drop measurements carry large uncertainties, and even more difficult is the robust quantification of their variability
- Excellent datasets are required to gain insights into this subject – **region of choice: Japan**

What are these 20 min all about?

- **Questions addressed in this presentation:**
  - Stress drops, scaling (i.e. variation of stress drop/scaled energy with earthquake size) and their variability?
  - Do individual sequences behave differently compared to seismic activity of entire region?
  - Are there spatial variations of stress drop?
  - What are the controlling factors of these? I will discuss
    - ✓ Mechanism-dependence
    - ✓ Strain rates
    - ✓ Heat flow / volcanic arc

Dataset and Methodology

Dataset used in this study



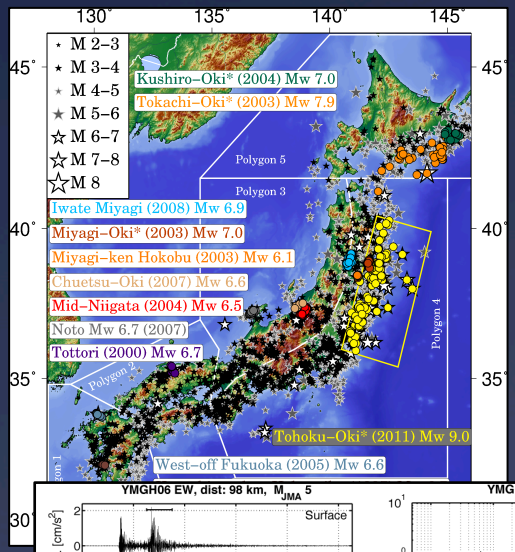
- **Records from earthquakes all over Japan**
  - **>53,000 records** from **3,964 earthquakes (M_{JMA} 2.7 – 8)**
  - M_W fixed to NIED value when $M_{JMA} > 5.0$
  - Small events: M_W from spectral fits consistency-checked with M_W from NIED (F-NET), adapted constants in spectral fits
- **12 individual sequences** extracted
- Separation of **crustal** (depth ≤ 30 km) and **subcrustal** (depth >30 km) events
- **Tohoku:** main shock not included, too complex for ω^{-2}-model !

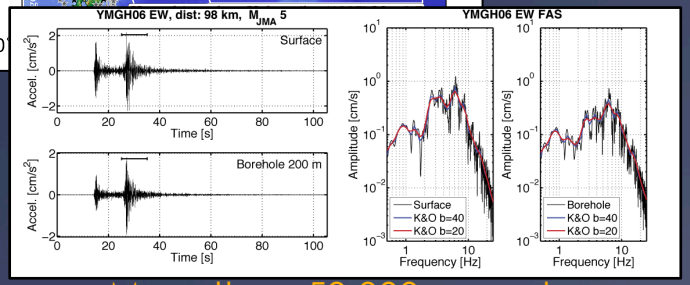
Methodology (following Oth et al., 2010, 2011)

$$U(t) = S(t) * A(t) * G(t) \Rightarrow U_{ij}(f,R) = S_i(f) \cdot A(f,R) \cdot G_j(f)$$

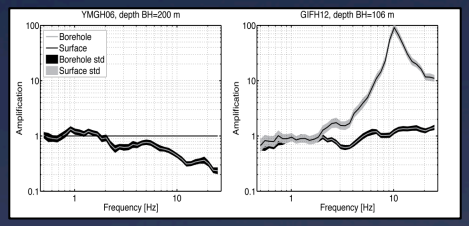
Source **Propagation** **Site** source i, site j, hypocentral distance R

Large dataset:
3,964 earthquakes

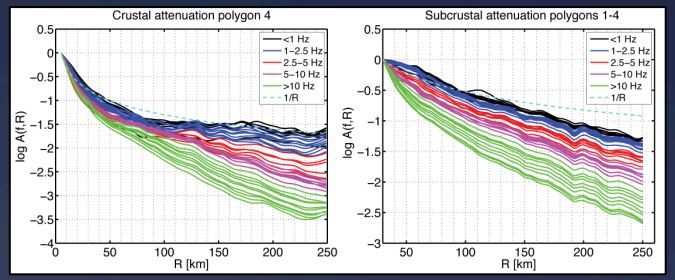




More than 53,000 records…

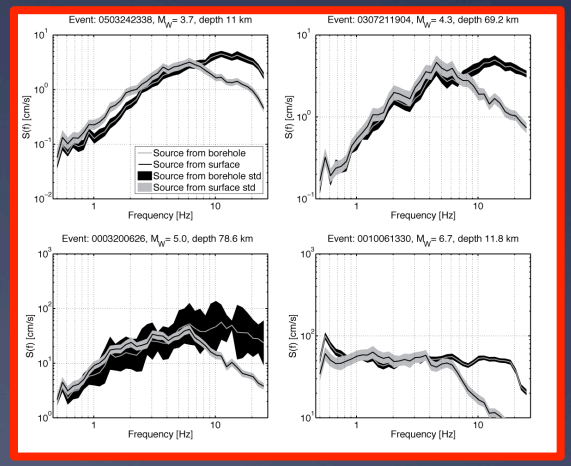


Site response (borehole and surface)



Attenuation

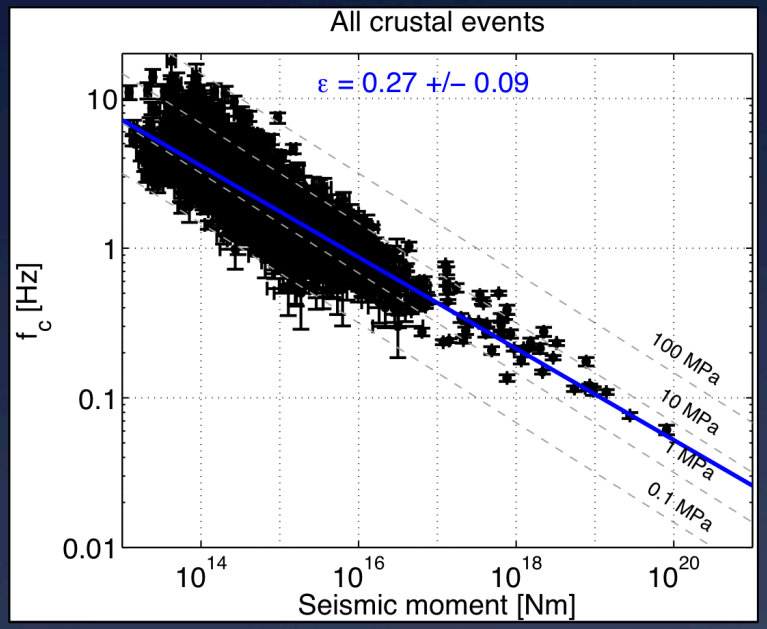
Inversion Scheme

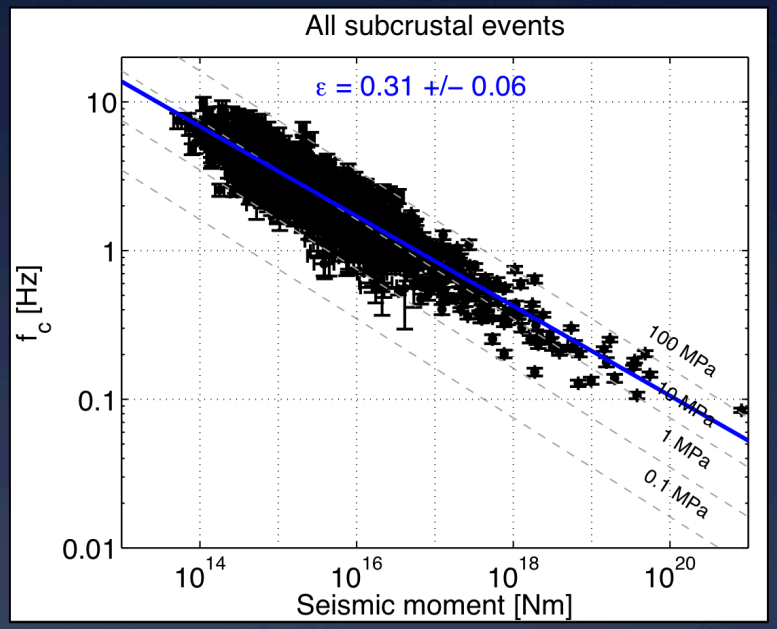


Source spectra

Basic stress drop & scaling observations

Average scaling behavior of stress drop ($\Delta\sigma$)





Scaling parameter ε :

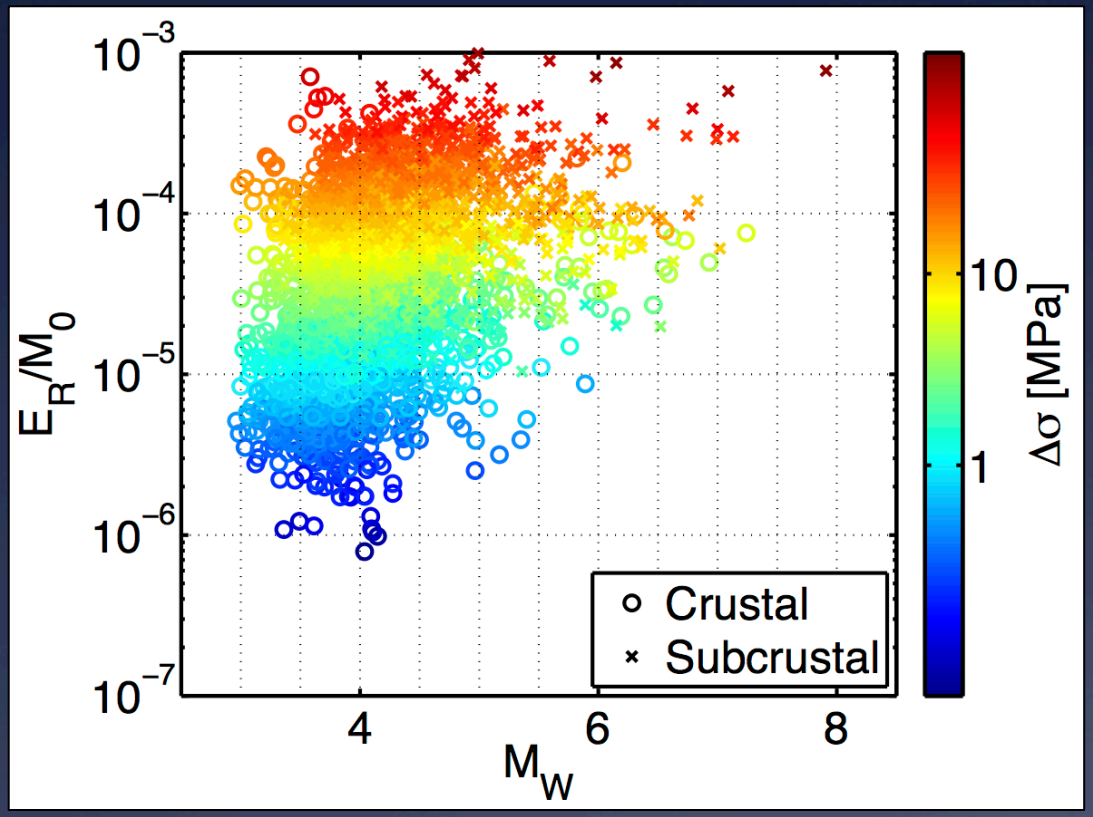
$$M_0 \propto f_c^{-(3+\varepsilon)}$$

(Kanamori & Rivera, 2004)

⇒ **$\varepsilon = 0$** in case of self-similar scaling

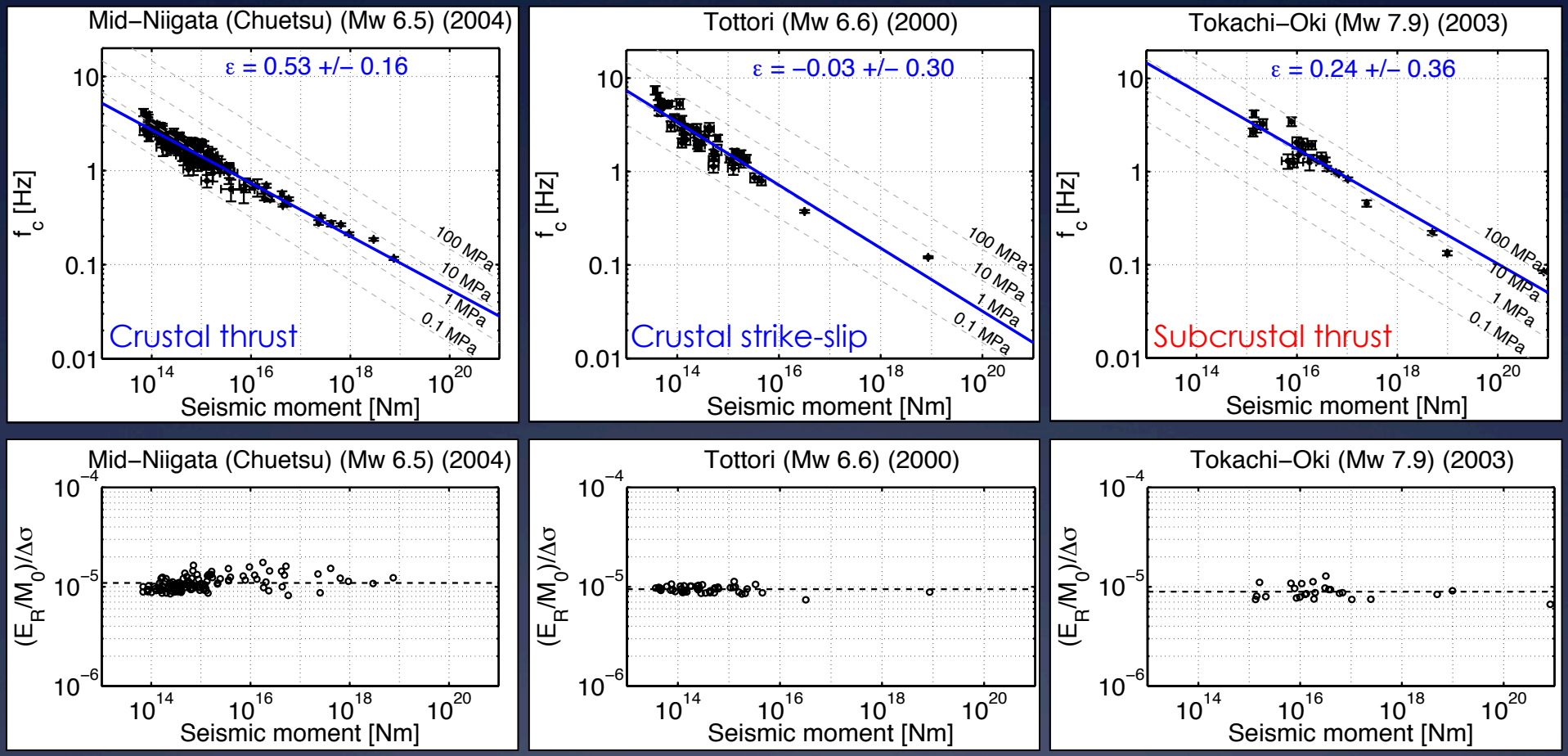
- **$\varepsilon > 0$, but not very far from self-similarity** (compare with previous study, Oth et al., 2010)
- Higher f_C resp. $\Delta\sigma$ for subcrustal (~10 MPa vs. ~1 MPa for crustal events)

What about scaled energy (E_R/M_0)?



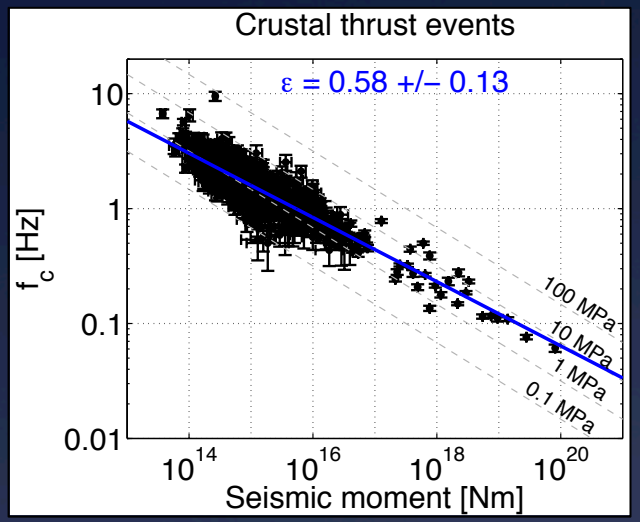
- **Scaled energy ⇒ correlation with $\Delta\sigma$**, no dependence on moment observed !
- **For that reason, I will concentrate the discussion on stress drop, results apply in similar way to scaled energy resp. apparent stress !**

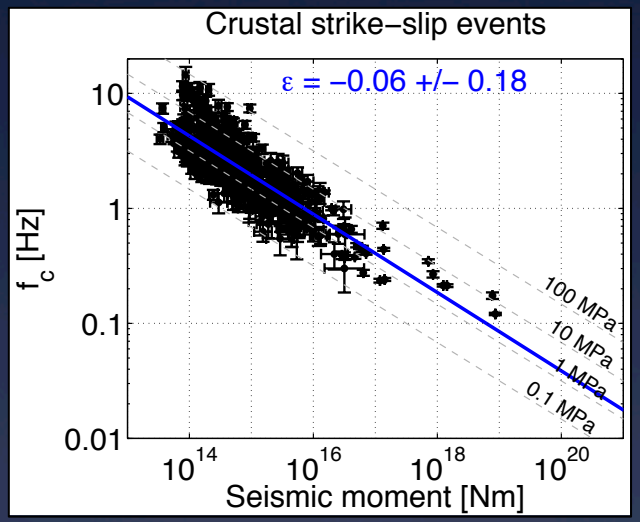
Scaling of individual sequences – Examples

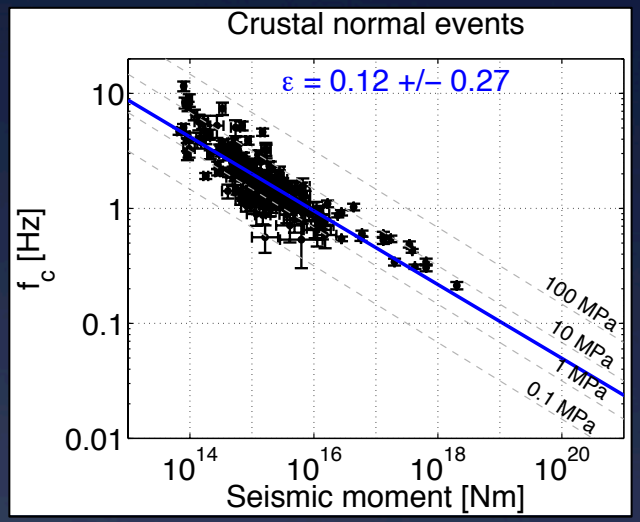


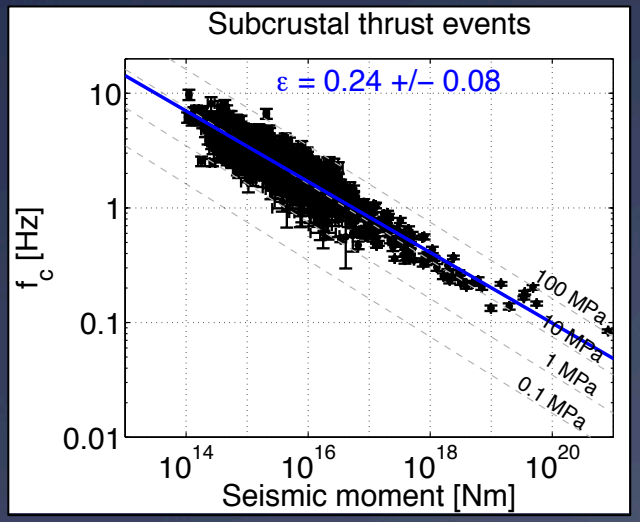
- Mid-Niigata (thrust): well-constrained break in self-similarity $\varepsilon > 0$
- Strike-slip sequences: tendency for $\varepsilon \leq 0$
- No trends in scaled energy apart from stress drop dependence (corrected)

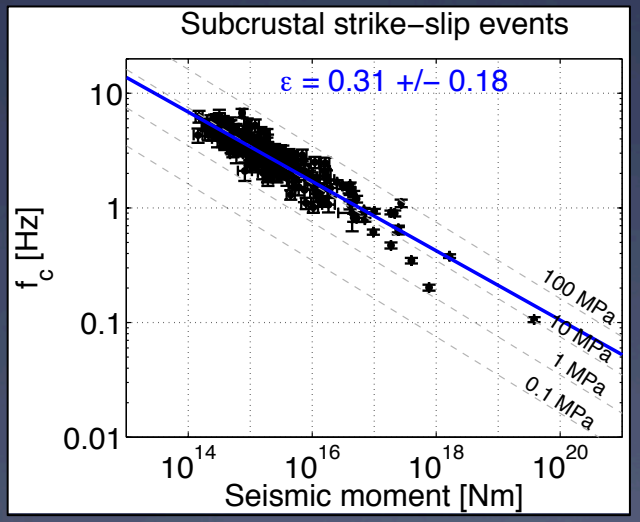
Scaling according to fault mechanism

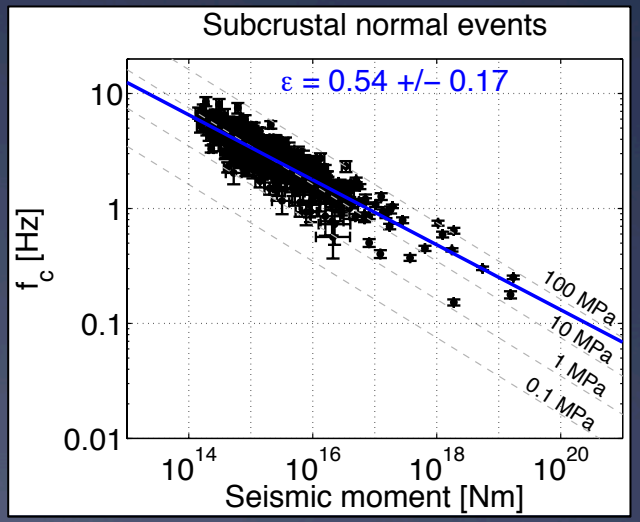




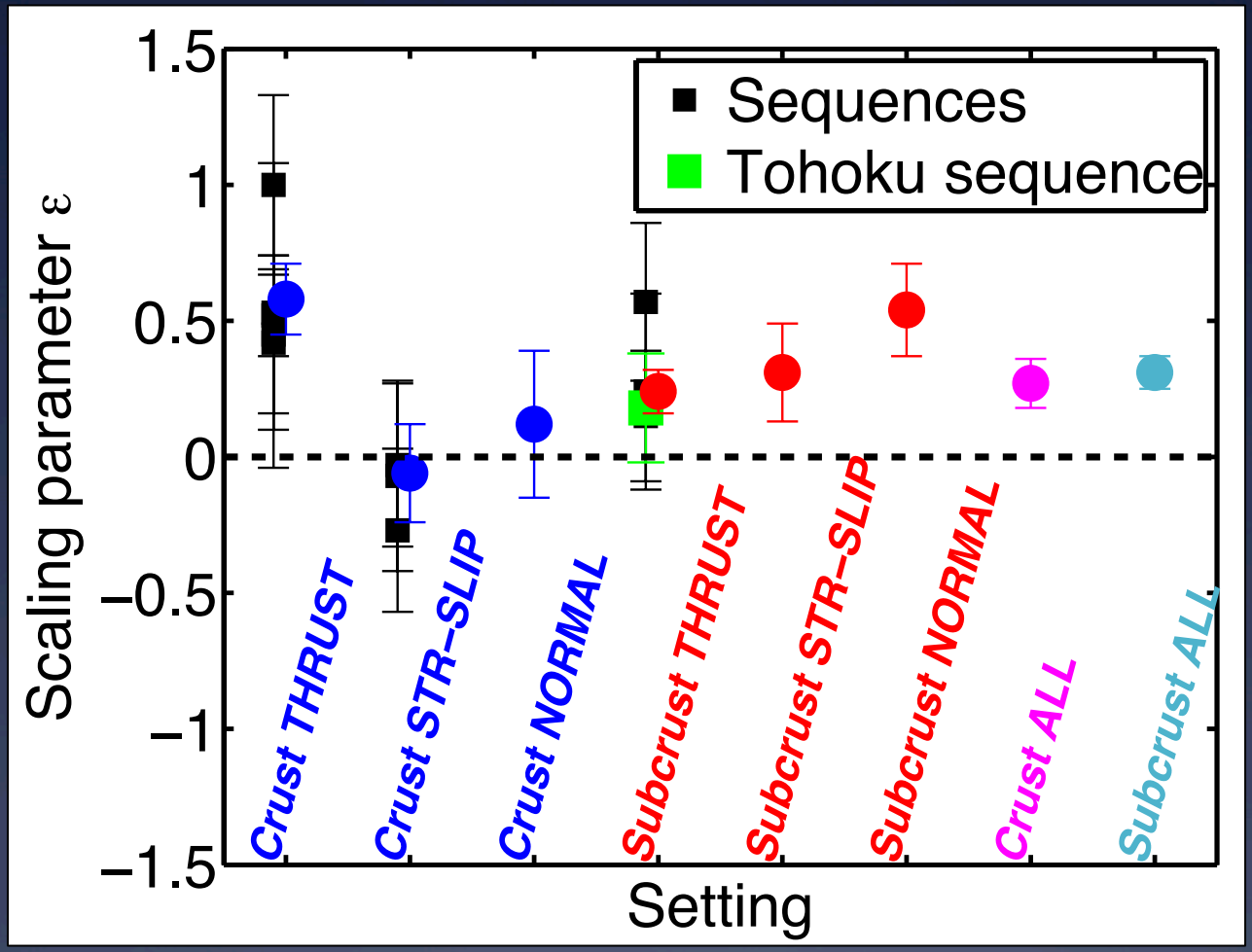






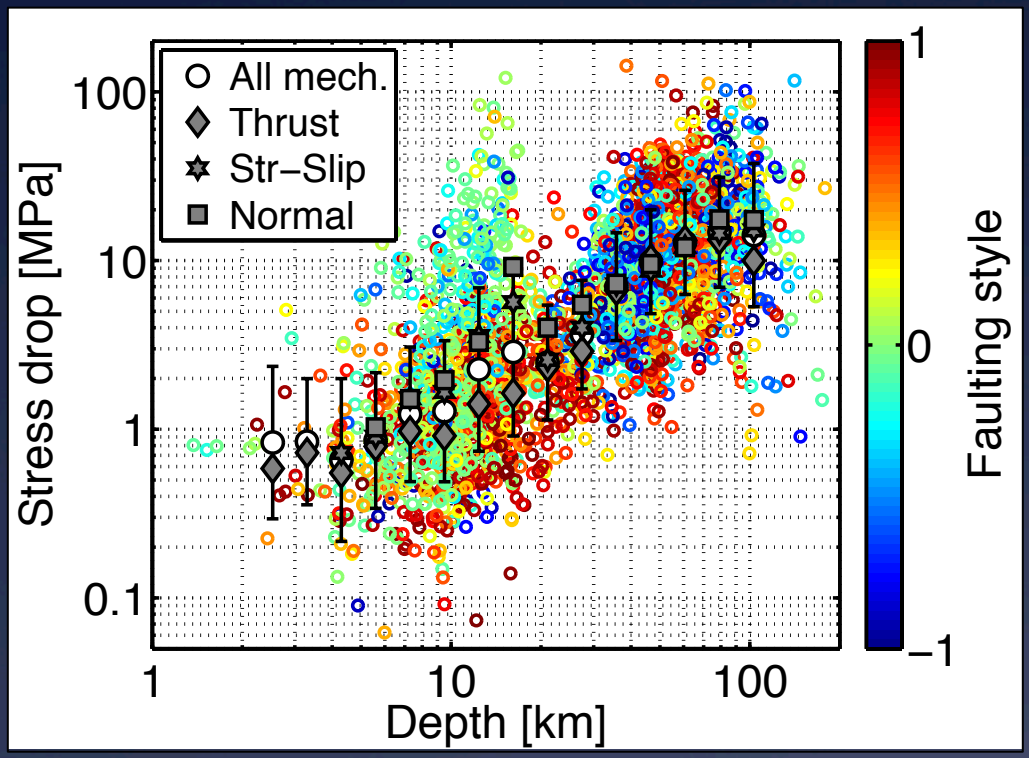


Scaling summary plot

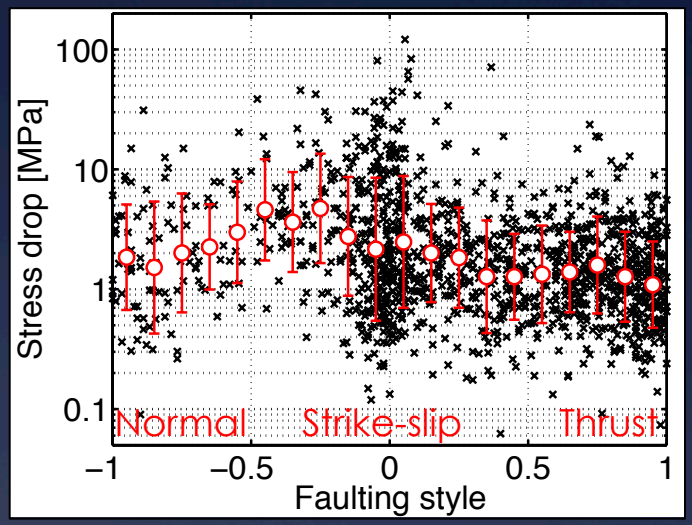


Beyond simple average trends: variability analysis

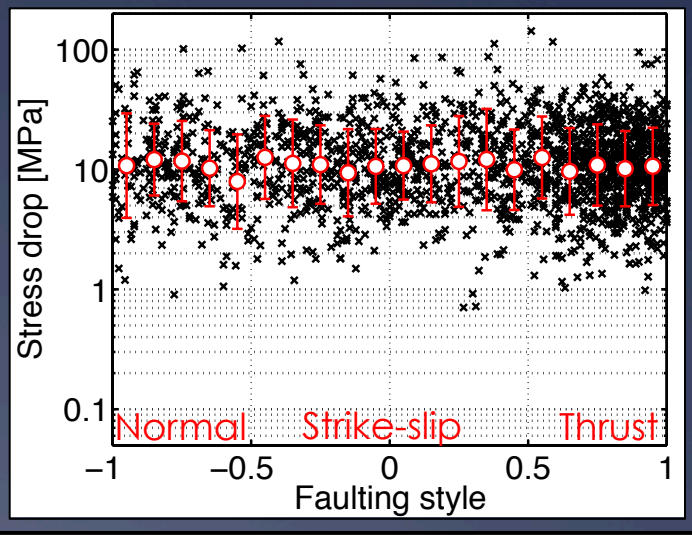
Δσ depth- and mechanism-dependence



Crustal events



Subcrustal events



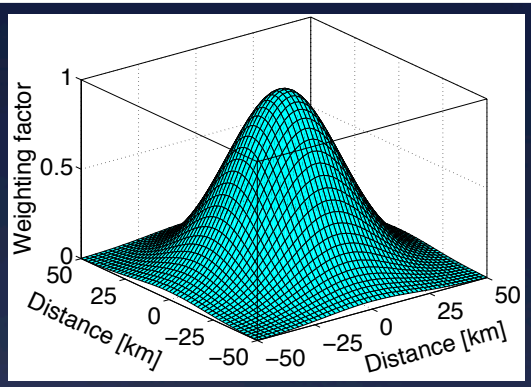
- **Increase of stress drop with depth**
- Apparent mechanism-dependence of stress drop for crustal earthquakes, large variability for strike-slip events
- Faulting style after Shearer et al. (2006)

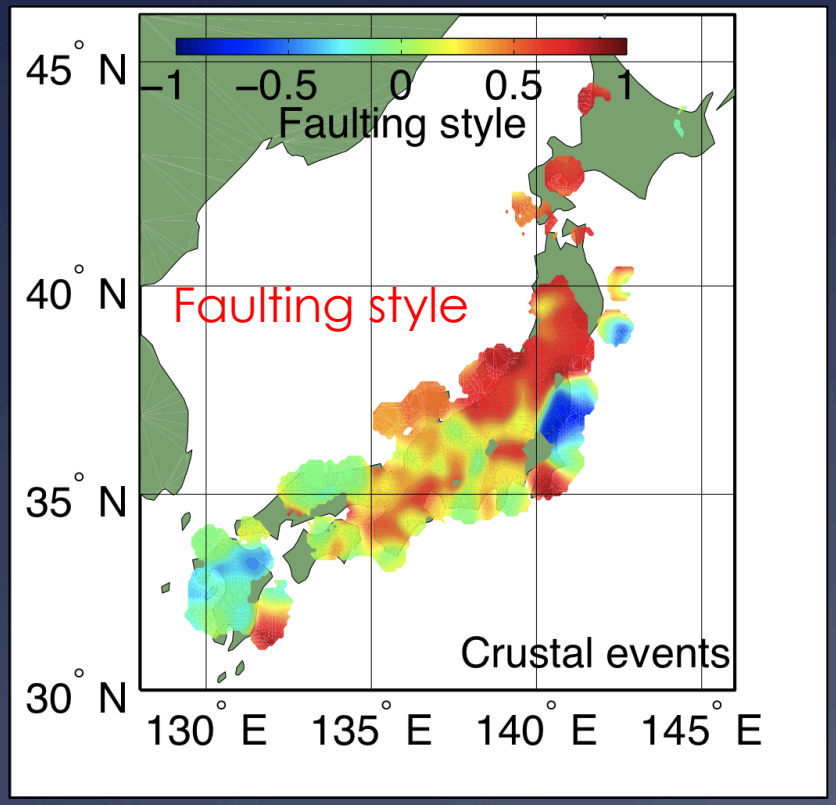
Lateral stress drop variations (crustal)

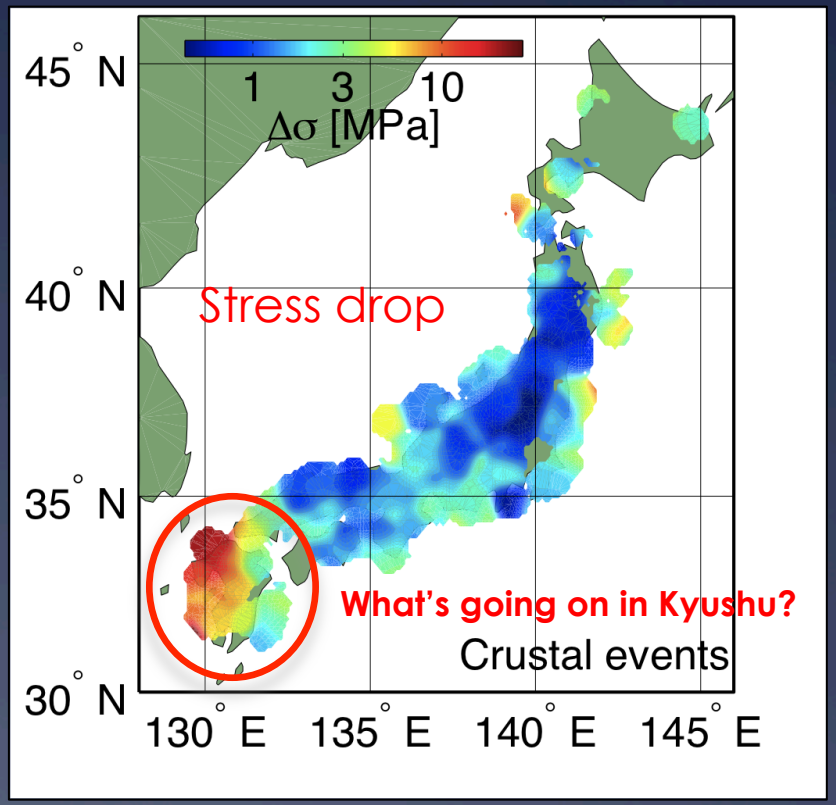
Spatial smoothing approach
(weighted average, only shown if at least 5 events in 50 km radius):

⇒ maps of the lateral variations

Evident pattern for crustal events !





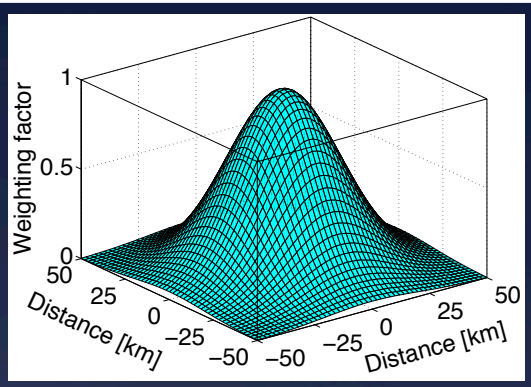


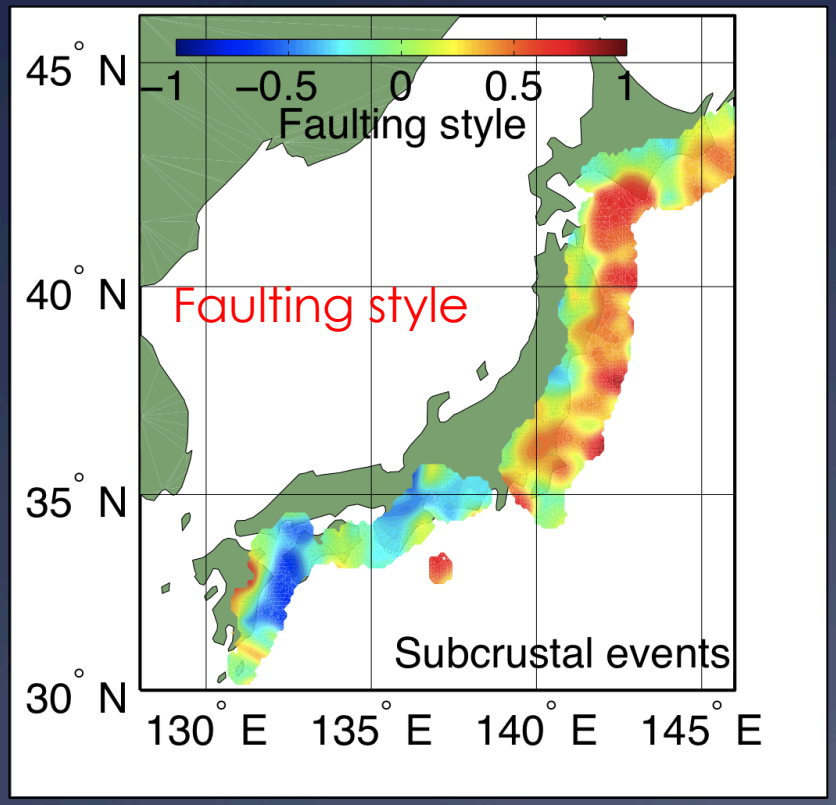
Lateral stress drop variations (subcrustal)

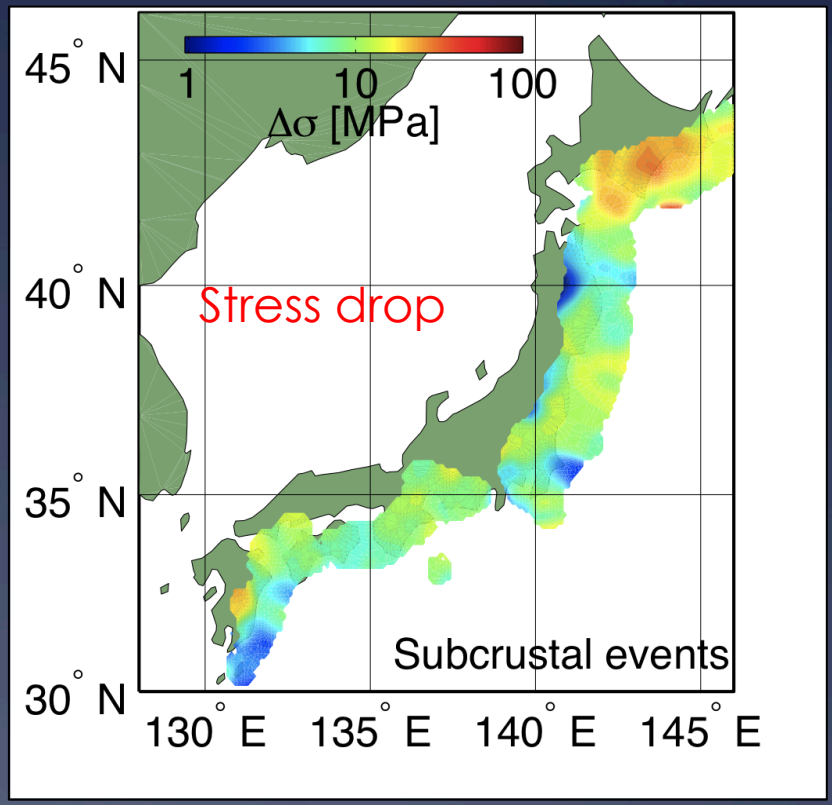
Spatial smoothing approach
(weighted average, only shown if at least 5 events in 50 km radius):

⇒ maps of the lateral variations

No clear pattern (apart off-Hokkaido)



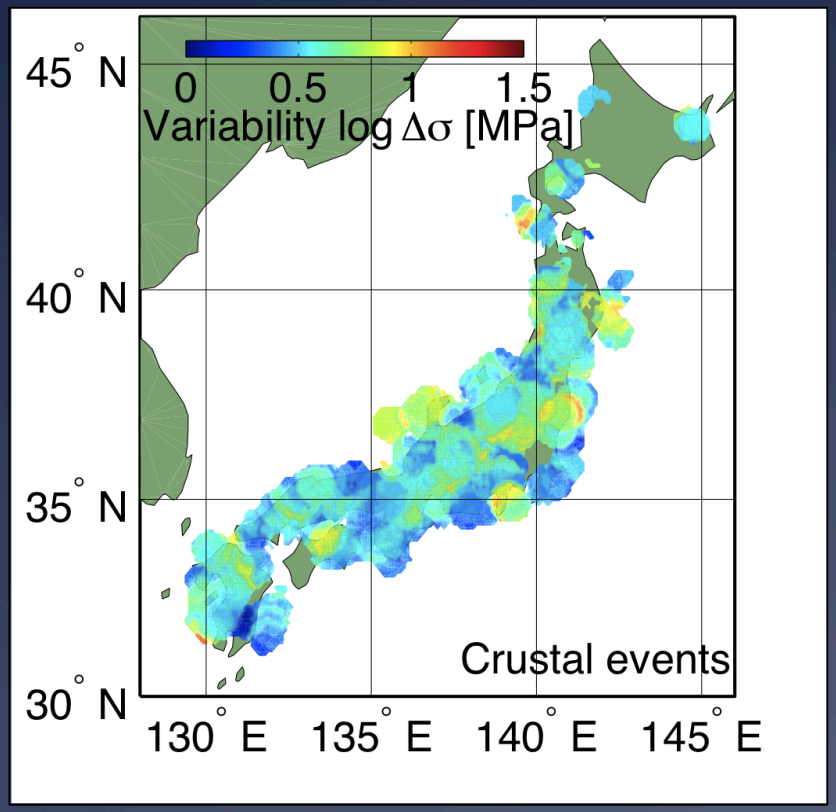


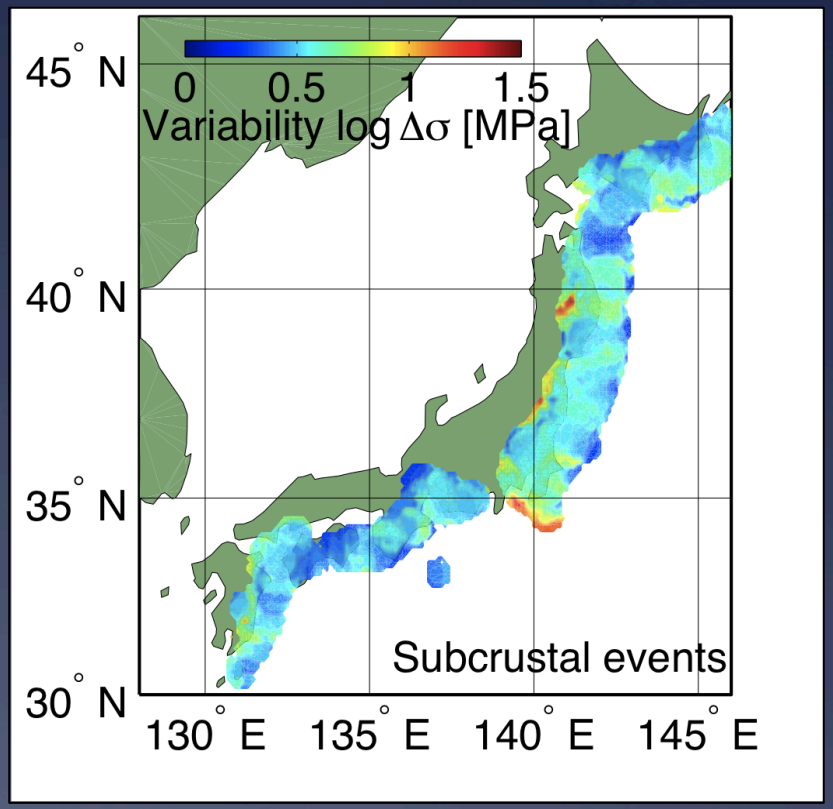


Lateral stress drop variations (variability)

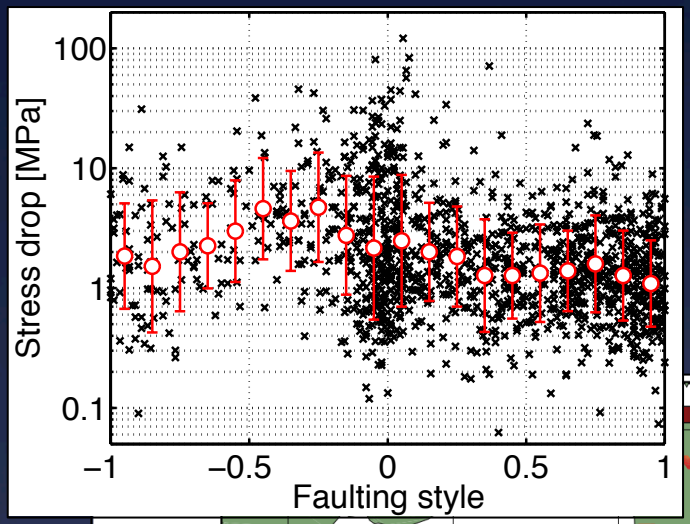
Local variability: defined as 84th – 16th percentiles of local sample (50 km radius around grid point)

Similar level throughout Japan and no clear spatial pattern !

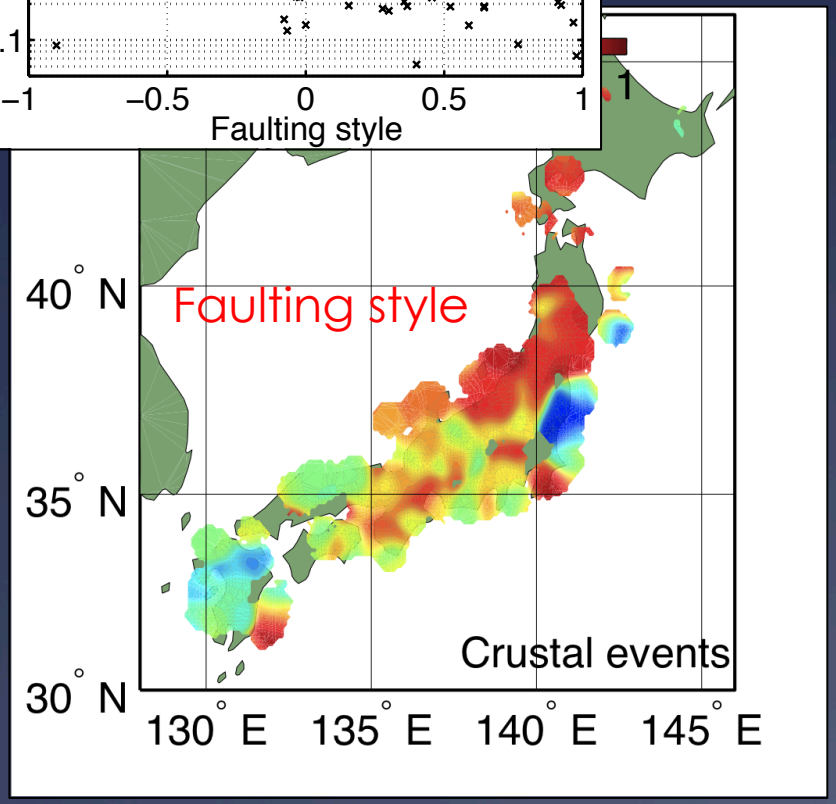


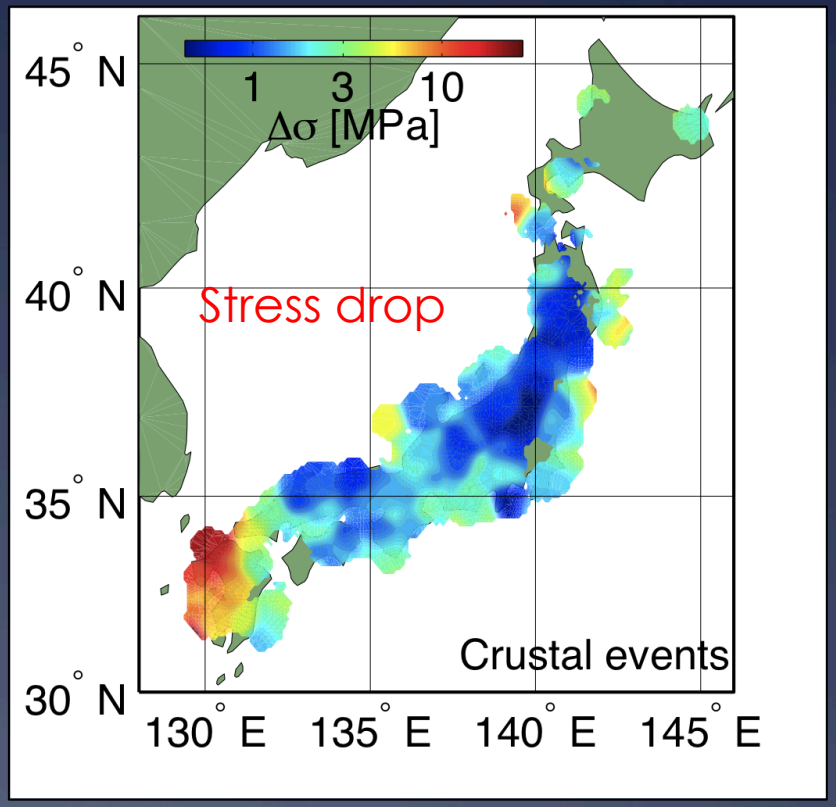


Back to apparent mechanism-dependence...

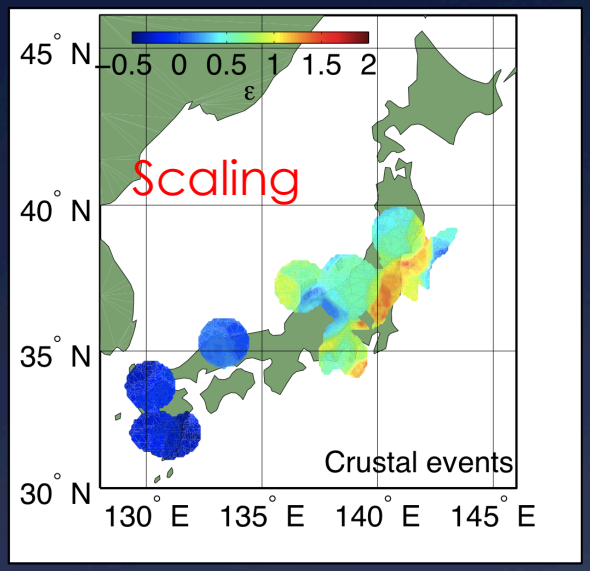


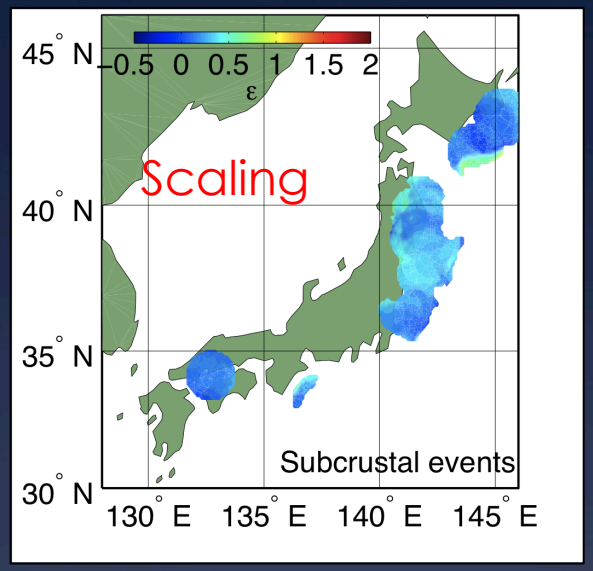
- Apparent mechanism-dependence may be a consequence of the lateral variations – or vice-versa...
- Chicken or egg ???

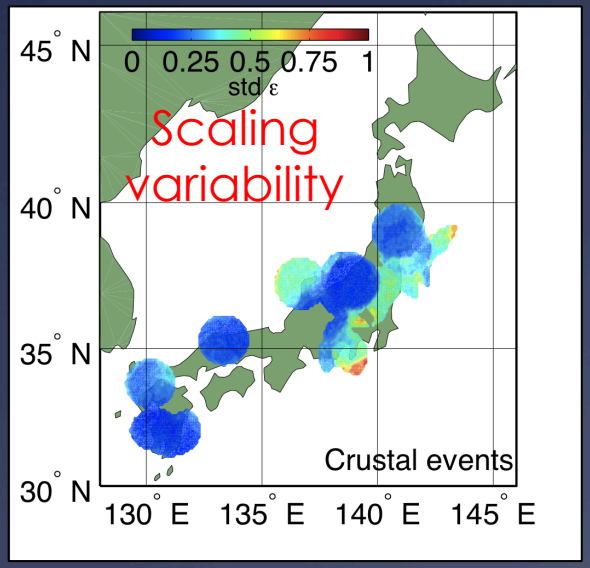


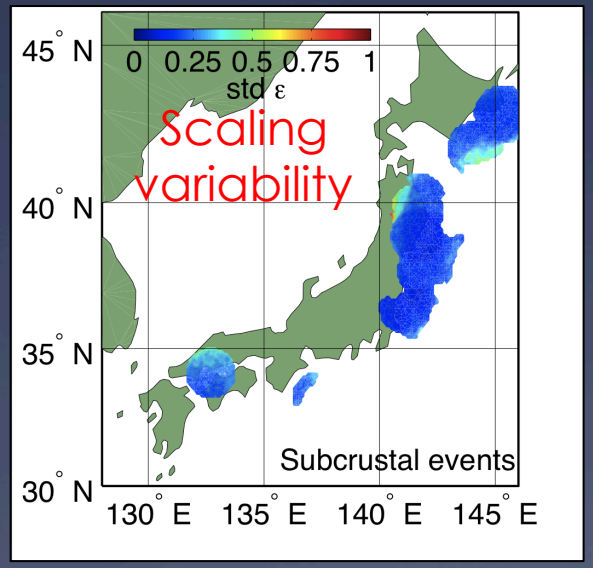


Lateral scaling variations









Local ε values:

estimated if within a radius of 100 km from grid point at least 5 sources covering 3 units of magnitude are available

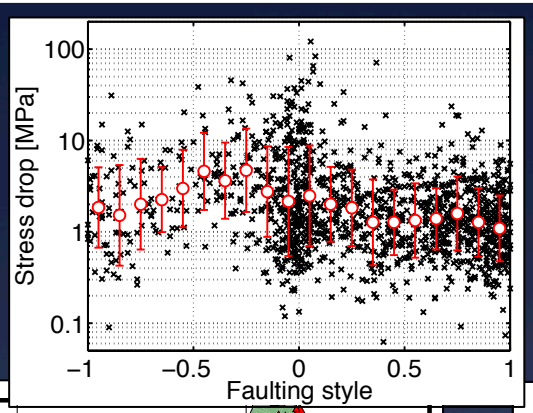
- Difference between normal and strike-slip events in southern compared to predominantly thrust in northern Honshu
- Small area of very large ε values up to 2

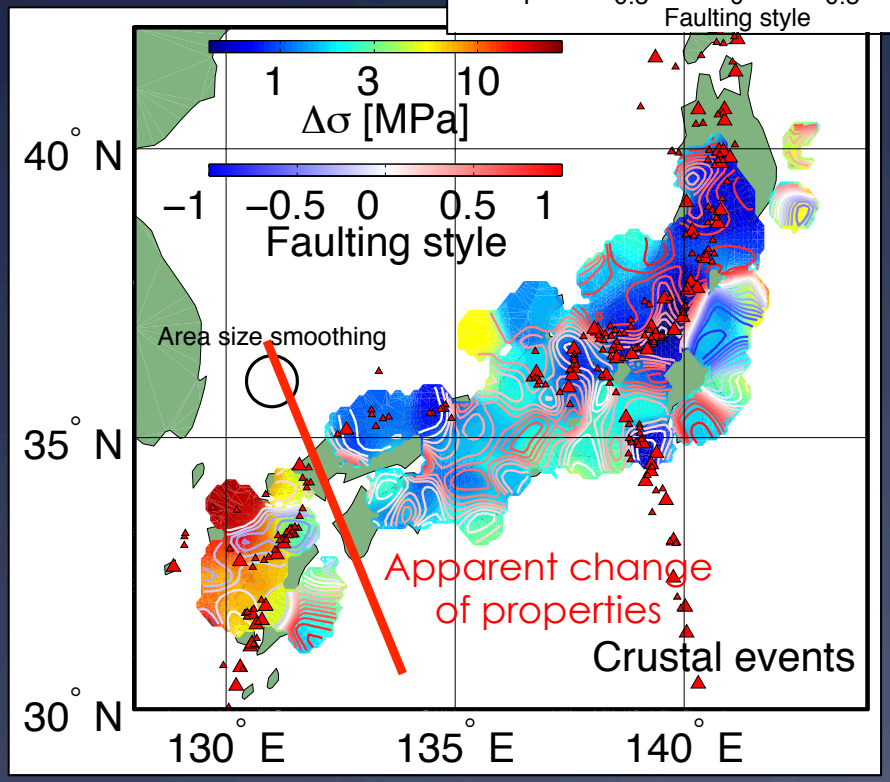
What could be the controlling factors of these observations ?

A look at the crustal earthquakes...

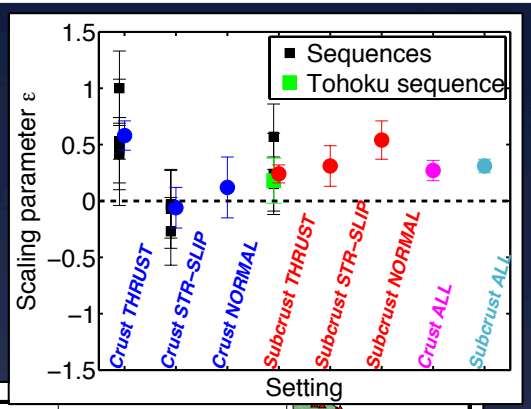
One more look at faulting style

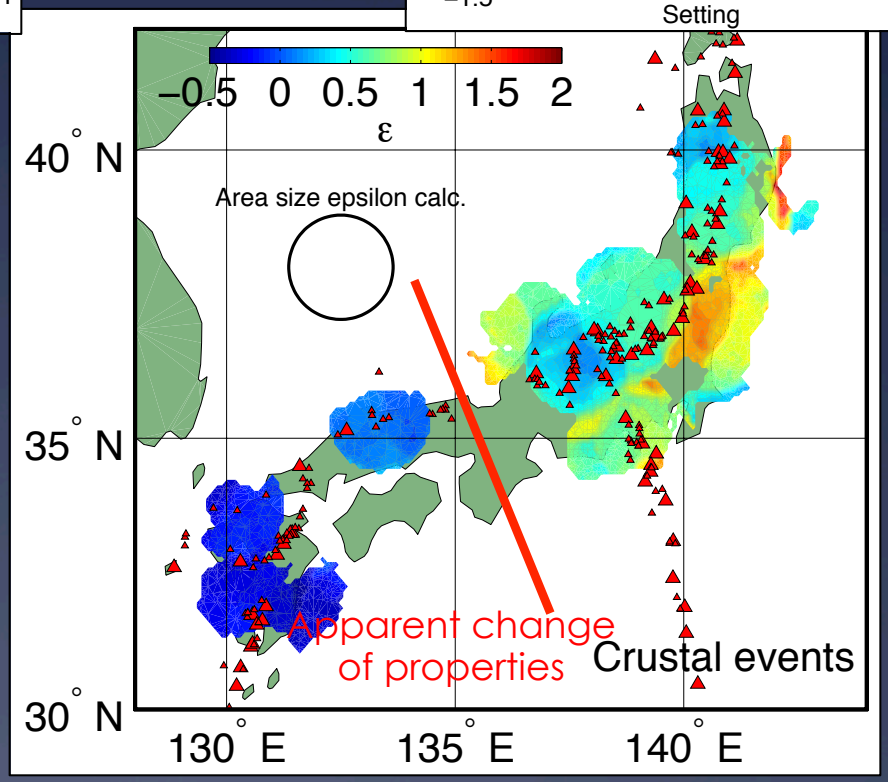
Stress drop with faulting style





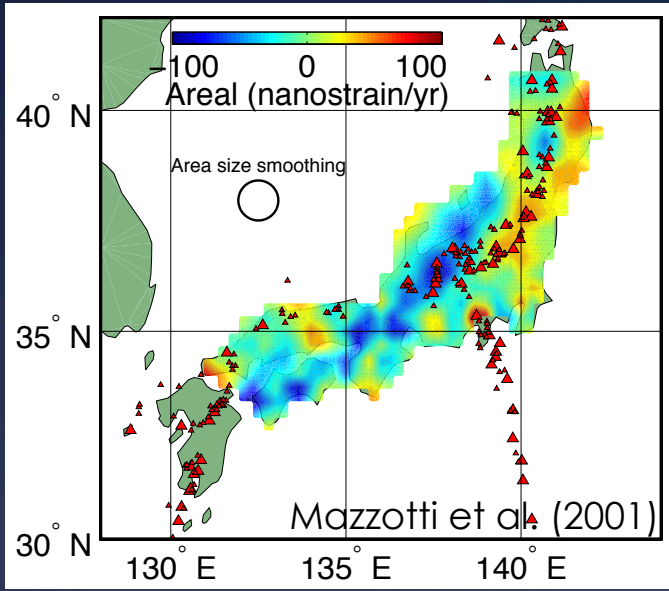
Scaling



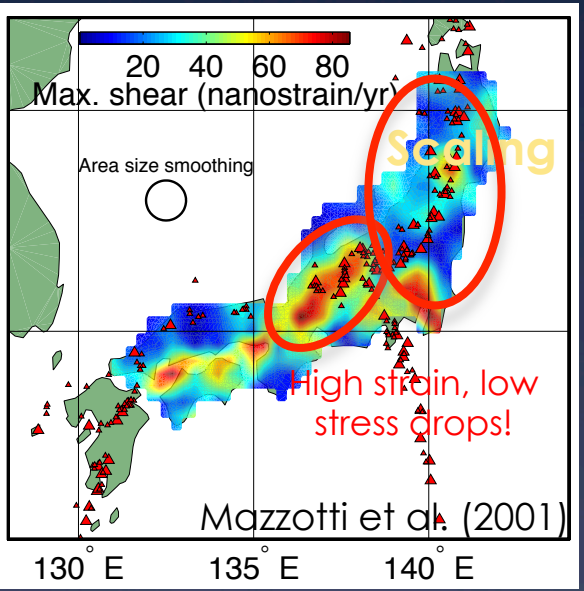


Strain rate data: not very convincing...

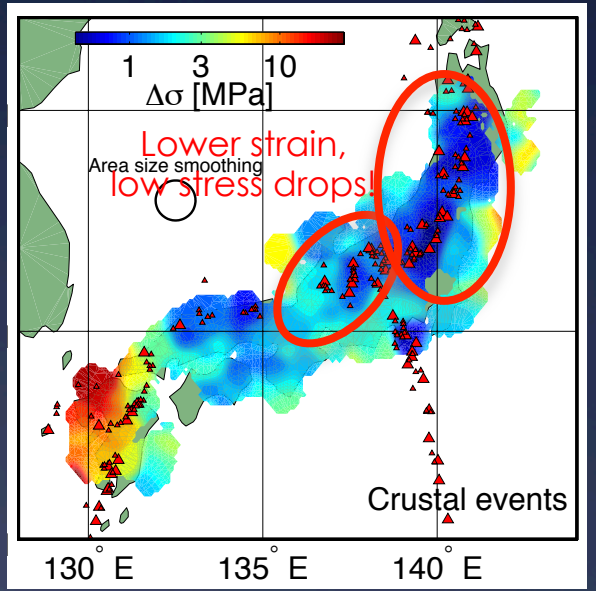
Areal strain rate



Shear strain rate



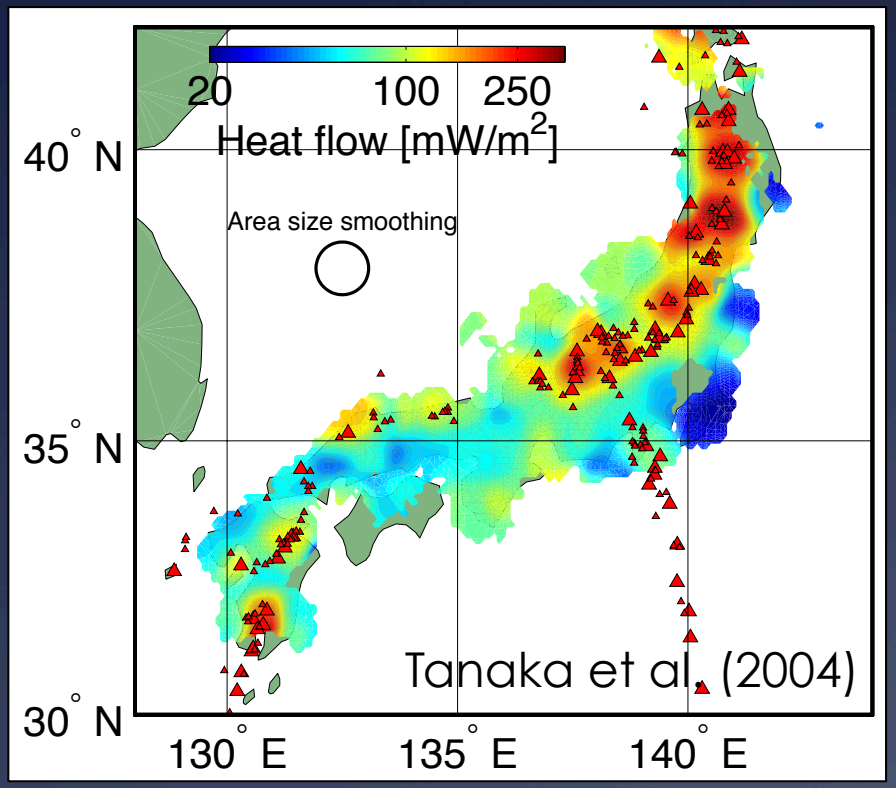
Stress drop

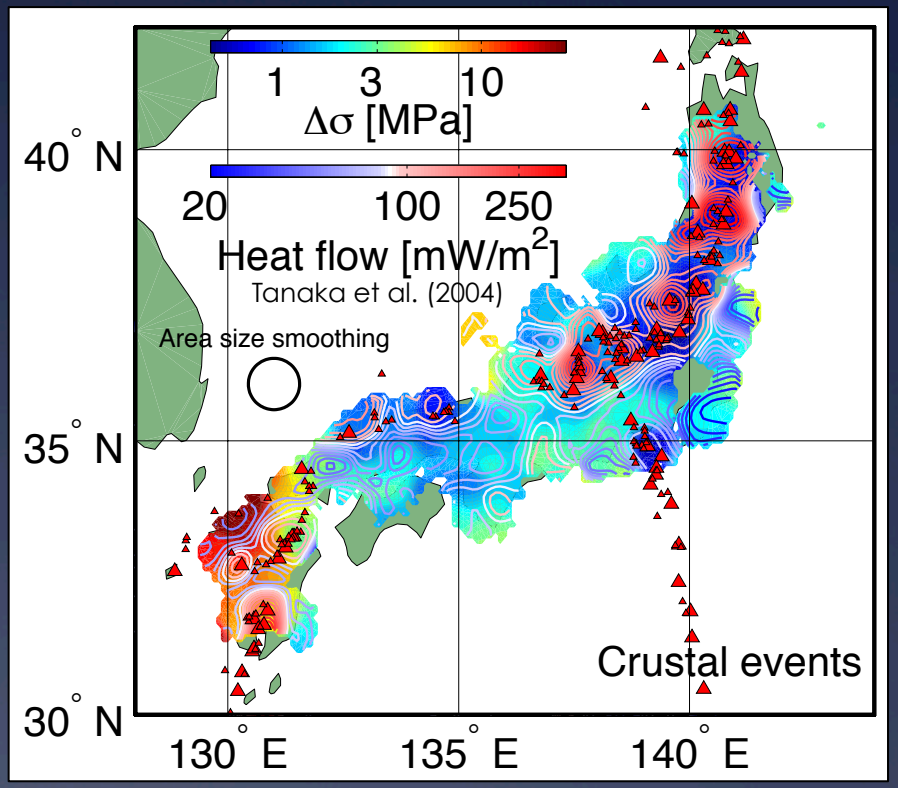


No convincing correlation between Δσ and geodetic strain rate estimates

The best candidate: heat flow & volcanic arc !

Co-location of regions with low Δσ and high heat flow is impressive, especially in northern Honshu !





But what is happening in Kyushu ?

There still seems to be a link, but not as clear and with generally higher Δσ

Some summarizing thoughts

- **Thermal structure of the crust seems to be to a large extend the controlling factor for earthquake stress release !**
- **Stress drop: significant difference between Honshu & Kyushu**
  - stress drop increase in Kyushu not easily explainable with change in thermal structure
  - Tectonics change to include an extensional component in Kyushu
  - Scaling markedly different in Kyushu as compared with Northern Honshu, but not that different from Southern Honshu, while stress drop levels are different!
  - We would not expect to see such high stress drops in normal faulting region, as is Kyushu
  - Significant fluid involvement in source properties is rather probable in Japan → volcanism !
  - Degree of fluid overpressure smaller in Kyushu? Different weakening mechanisms?

Conclusions

- **Source scaling in Japan seems to be mechanism-dependent, average is representative for a mix of these scaling behaviors** (dominated by thrust)
- **Crustal events** show marked **spatial patterns of $\Delta\sigma$**
- **No evident $\Delta\sigma$ – patterns in subcrustal dataset** (except maybe large values off-Hokkaido)
- **Individual sequences** can show **significant scaling breaks**
- **Local variability of stress drops** more or less constant throughout the Japanese islands
- **Thermal structure of crust seems to be controlling factor for stress drops**, while the scale-dependency seems to be more closely linked to faulting style
- **Clear difference of stress drops between Honshu & Kyushu !** Difference in fluid involvement in source processes ?