Systematic Seismic Rupture Responses to Background Loading: Insights from Source Time Functions of "Quasi-"Repeating Earthquakes

- Keisuke Yoshida[1] & Satoshi Ide[2]
- 1: Tohoku Univ. : 2: Univ. of Tokyo

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Special Collection:
Slow to fast earthquakes and the geology, structure, and rheology of their host subduction zones

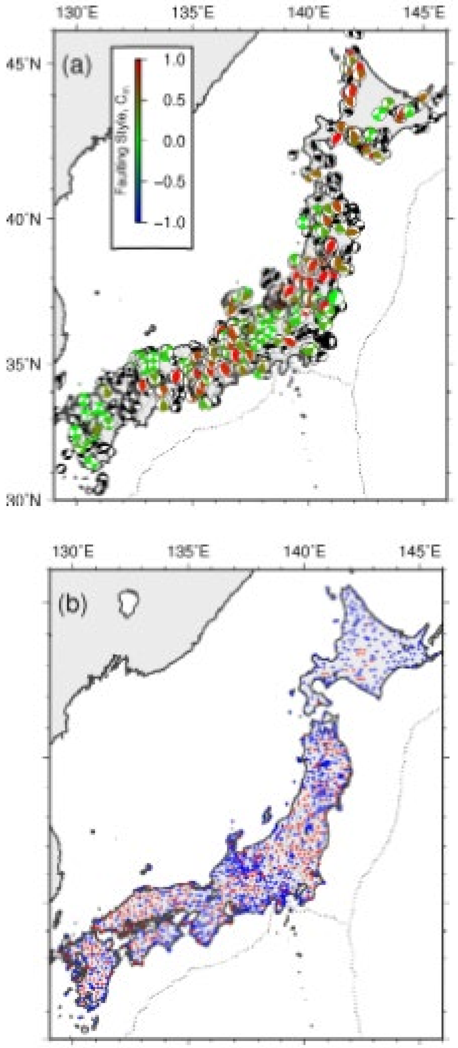
Highly Systematic Response of Seismic Rupture Patterns to Background Loading Rate: Insights From Repeating Earthquakes

Keisuke Yoshida[1] and Satoshi Ide[2]

[1]Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, Sendai, Japan, [2]Department of Earth and Planetary Science, The University of Tokyo, Tokyo, Japan

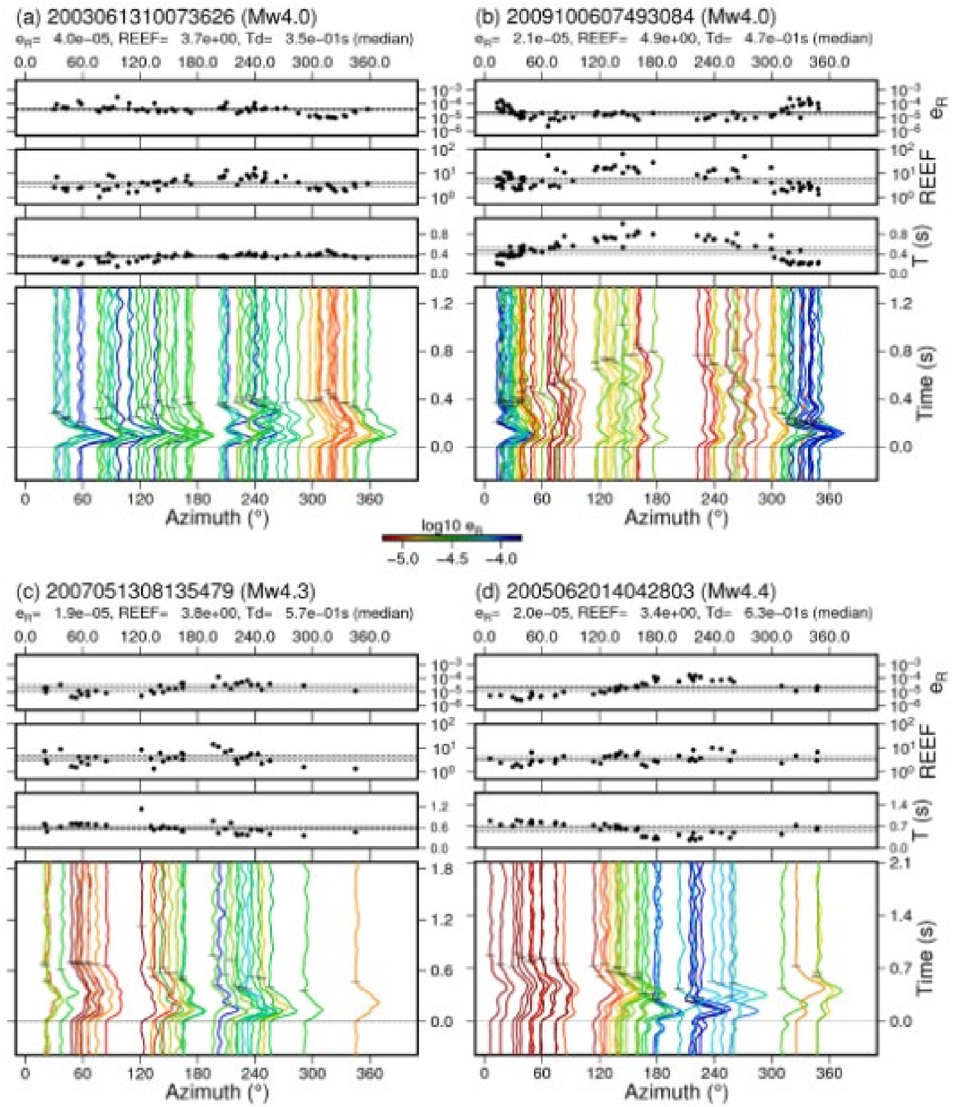
Resolving second-order source characteristics via Source Time Functions

Yoshida & Kanamori (2023, GJI), Yoshida (2019, Geosci. Let.)

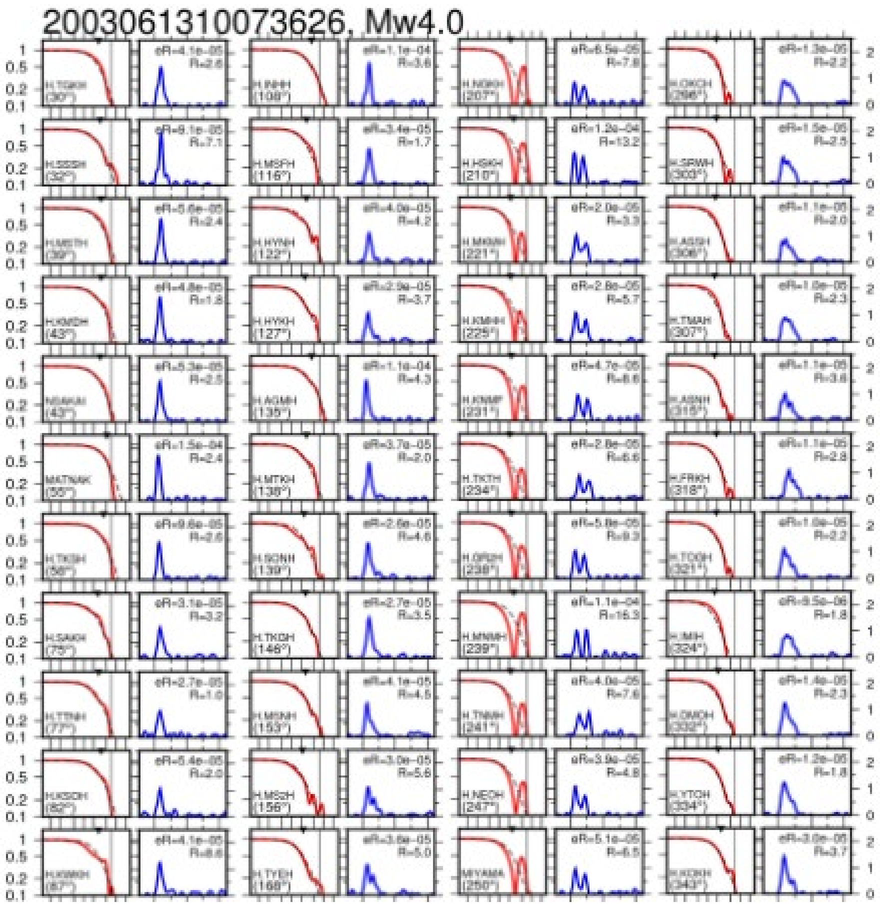


Seismic stations

Azimuthal Variations of Apparent Moment-rate functions (AMRFs) for Mw 4.0–4.5 Events



Spectral deviation from the omega-square model in complex events.



⇒ Data contain robust information about second-order source characteristics.

Diverse Repetition Patterns in Earthquakes

Simple, regular repetitions (characteristic earthquake)

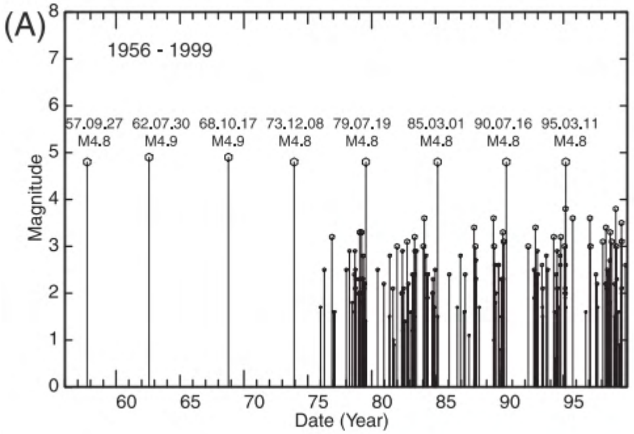
- ***Repeating earthquakes (REs)***: repeated ruptures on a **locked region (asperity).**

General case: diverse and complex repetition patterns

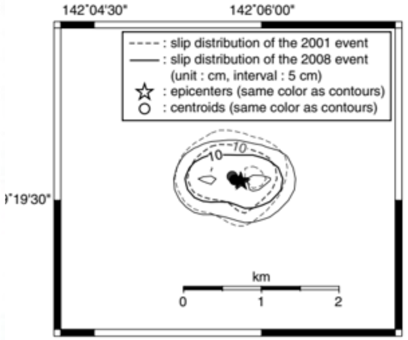
- Multiple asperities, sometimes in different combinations
- Growth across hierarchical structures

Goal: identify rupture growth–influencing factors

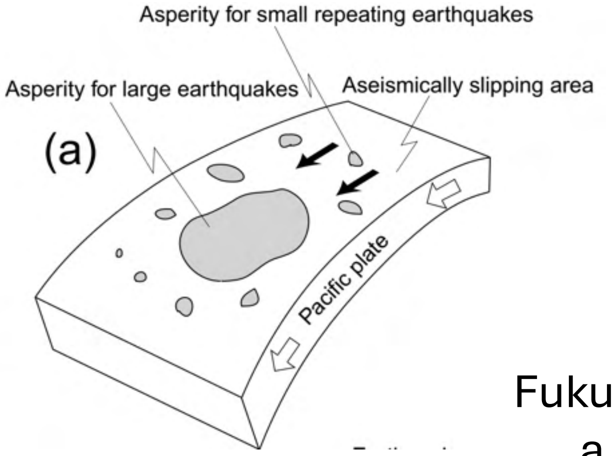
Kamaishi-Oki repeaters



Matsuzawa et al. (2003)

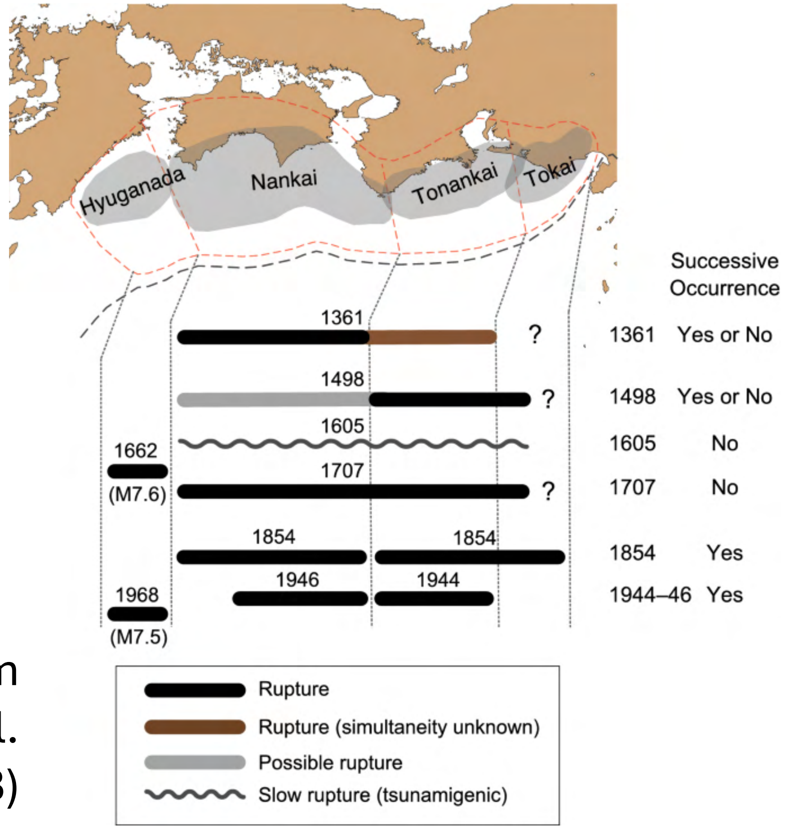


Shimamura et al. (2008)



Matsuzawa et al. (2004)

Fukushima et al. (2023)



Size diversity in repeating earthquakes: Wide magnitude range — what does it imply?

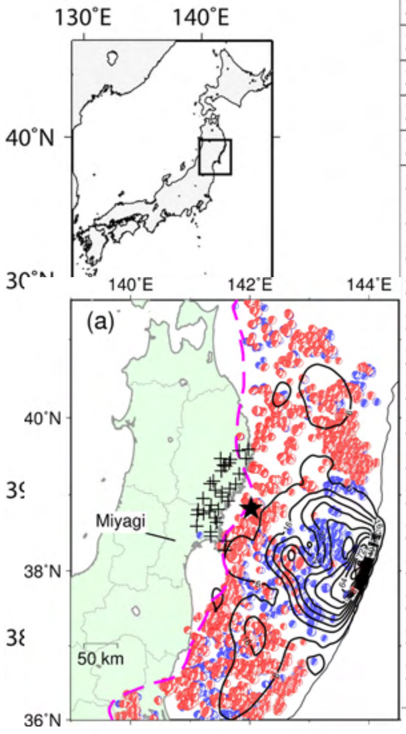
Shown in Fig. 1 of Igarashi (2020)

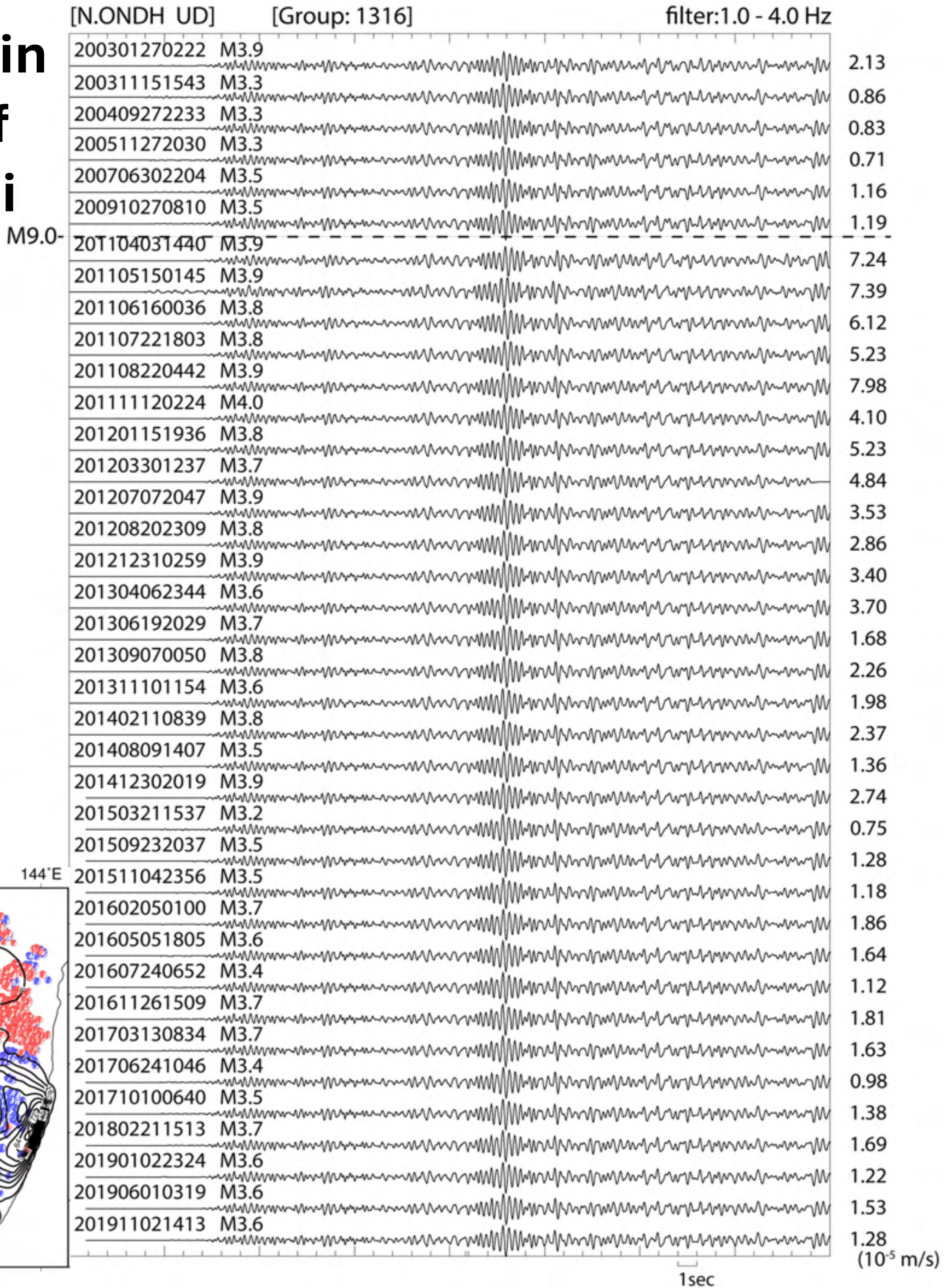
- A repeating earthquake sequence in Igarashi (2020): **M_{JMA} variability 3.2–4.0 within the same sequence**
  (A Mw difference of ΔMw = 0.8 corresponds to ~15 × in M_0)

Possible causes:

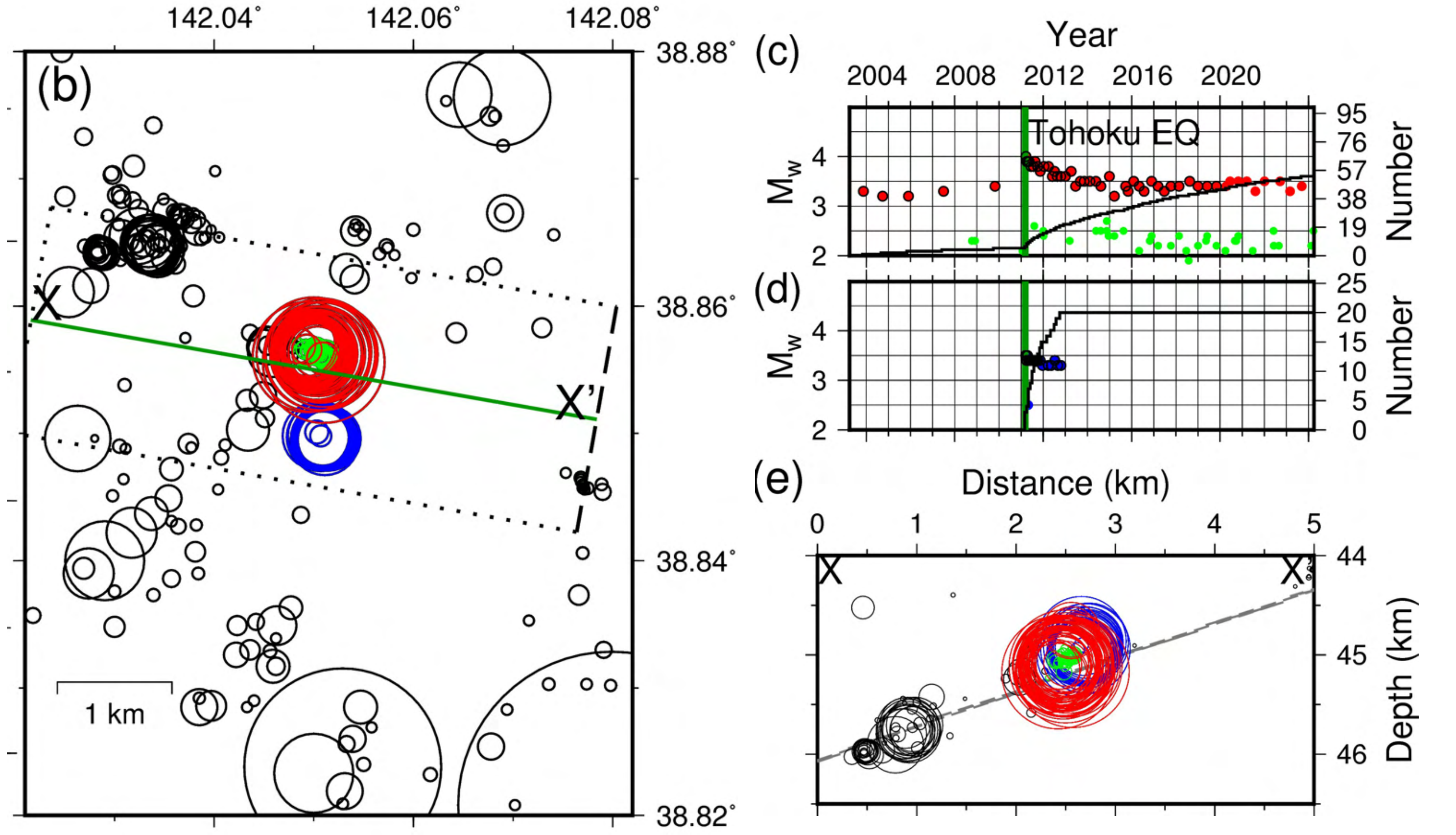
- Slip variation on the same patch (e.g., Lin et al., 2011)
- Change of rupture area (not true repeaters)
- Only dynamic property differences

⇒ Examine this sequence in detail





Hierarchical occurrence of earthquake repetitions and pronounced post-Tohoku temporal change in Mw



○ : target sequence (53 events)

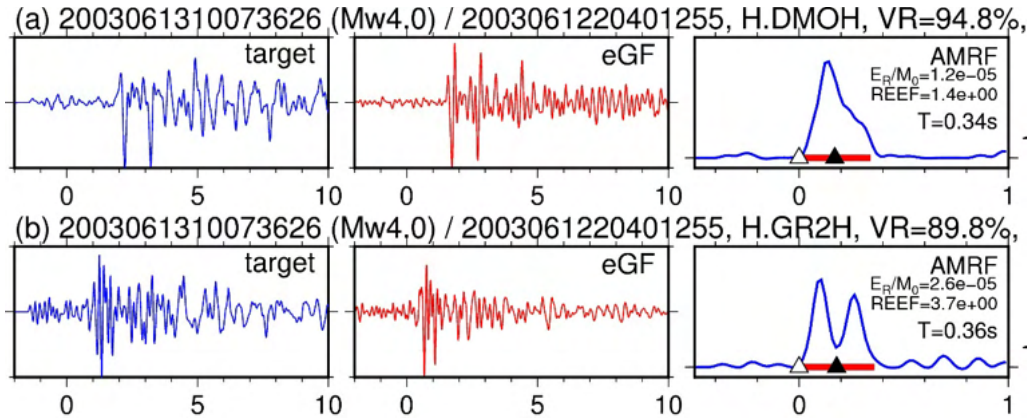
- ○ : small earthquakes inside the target repeater source region

○ : appeared after 2011 Tohoku EQ, then disappeared

Diverse source time functions even within the same sequence!

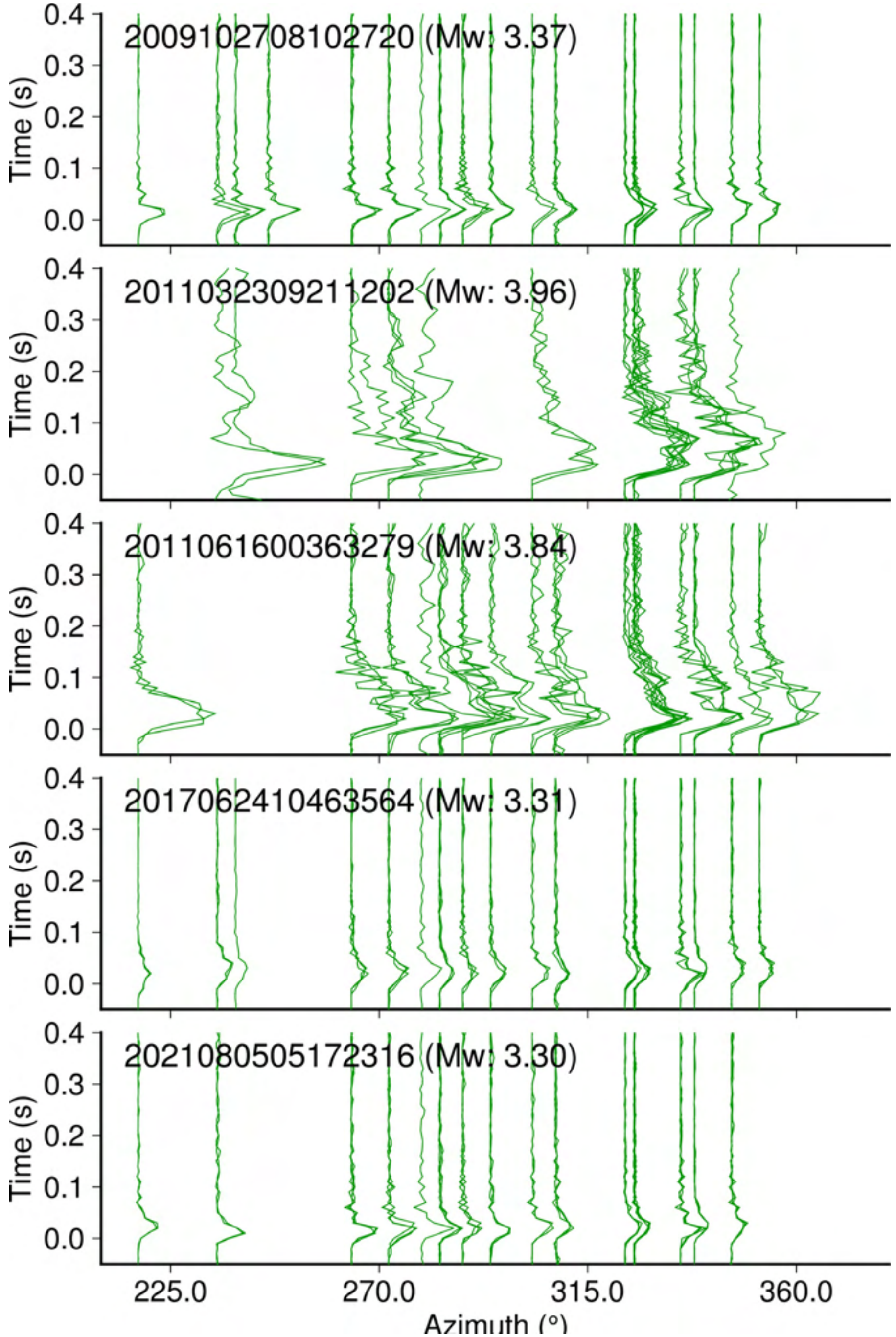
Deconvolution of sequence events using a common M1.8 waveform

Empirical Green's function (eGF)
- Method: Time-domain iterative deconvolution by Ligorria and Ammon (1999) after Kikuchi & Kanamori (1982)
- Positive value constraint
- S-wave obtained at velocity seismometers
- Cut-off frequency of Low-pass filter: 40 Hz

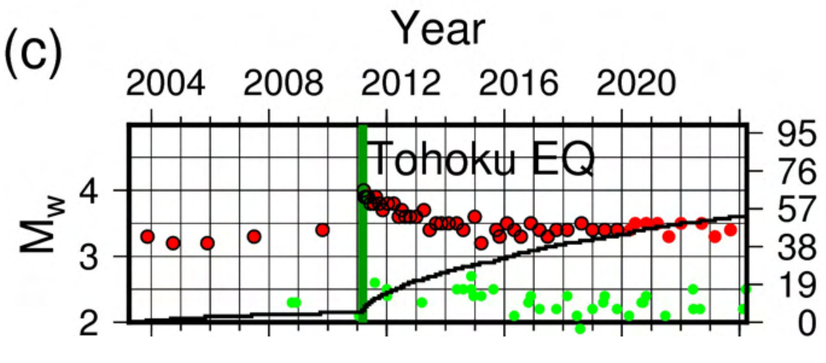


Yoshida & Kanamori (2023)

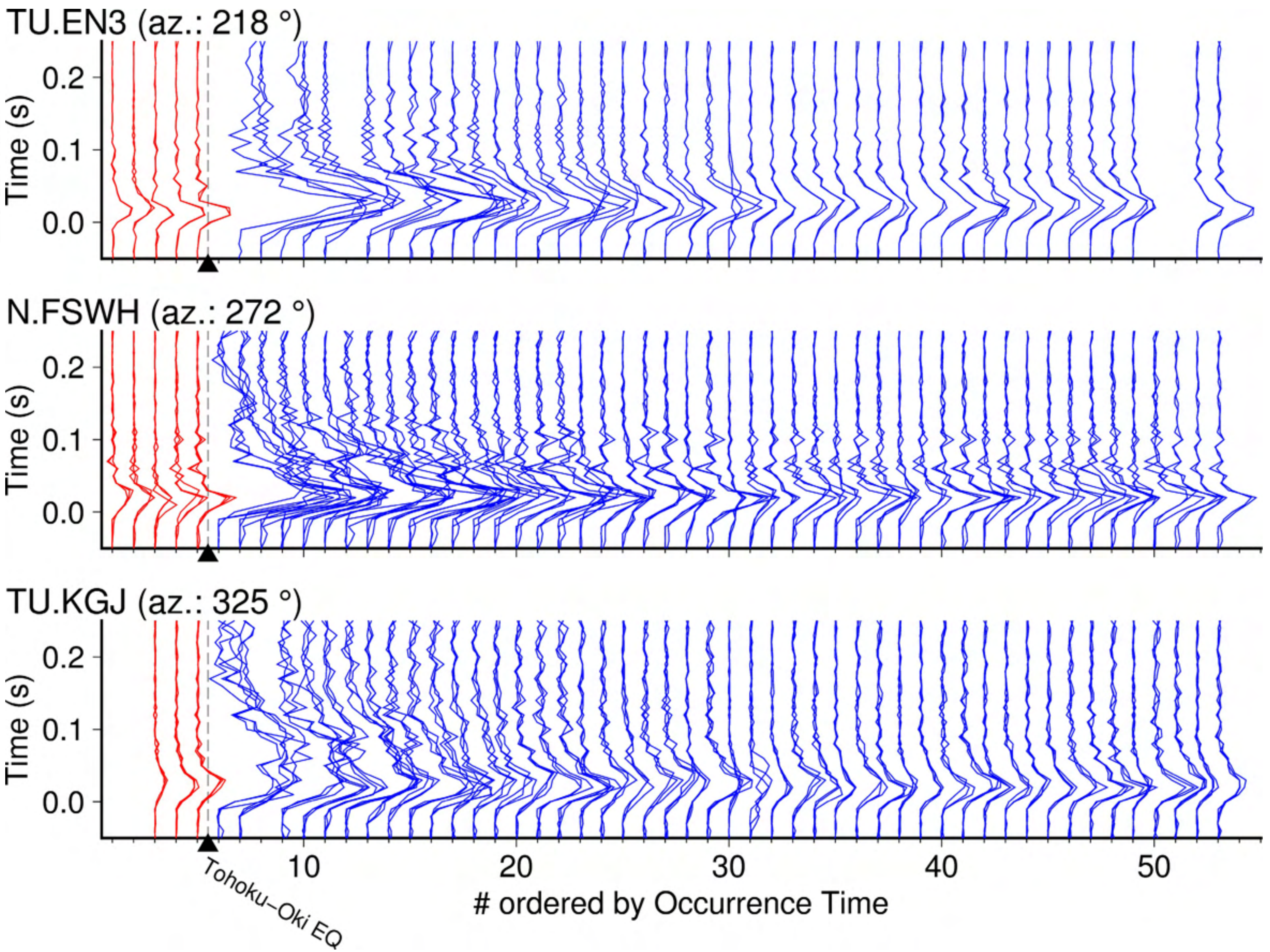
Example apparent moment rate functions (AMRFs) for five events at different stations



Highly Systematic Temporal Changes in AMRFs



Apparent moment-rate functions (AMRFs)



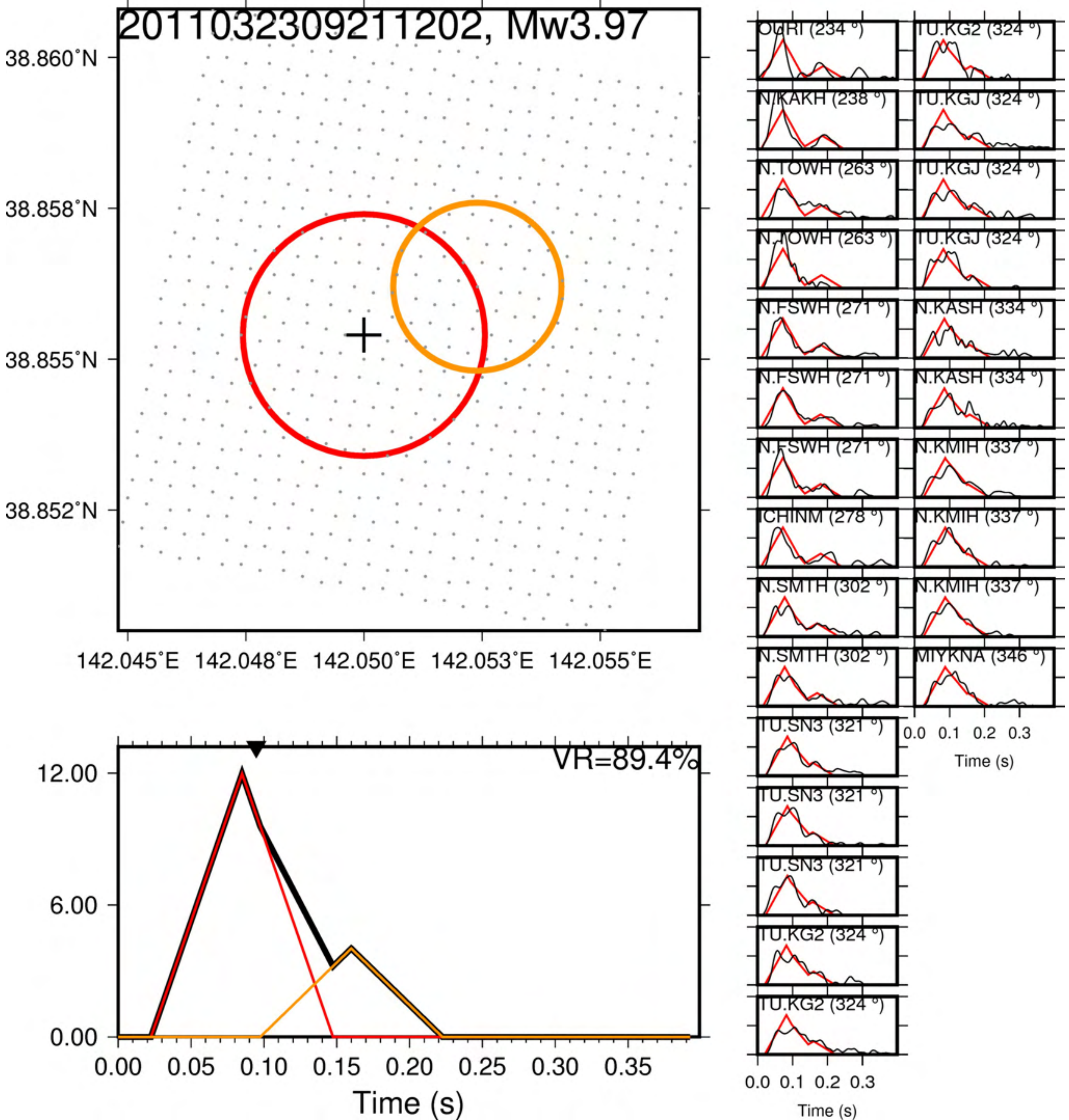
Mw > 3.7 events: double rupture seen at south stations (single at north)

→ 2nd rupture on southern patch;

similar directional dependence across events

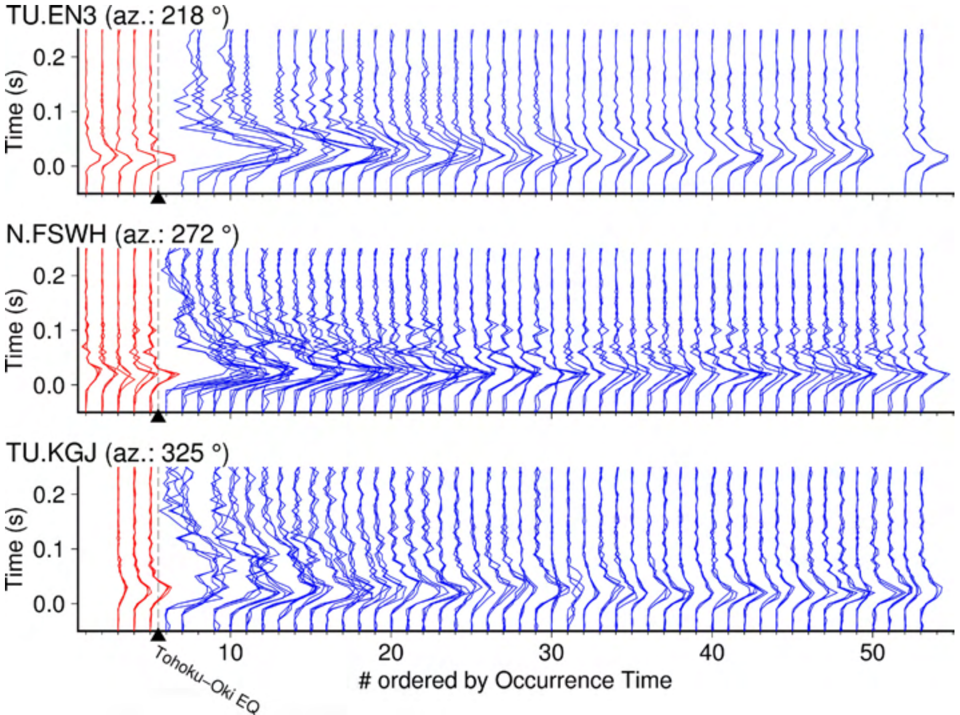
Simple Estimation of Rupture Patterns

- **Method**: Kikuchi & Kanamori (1982)
  Data: AMRFs from multiple stations
- **Approach**
- Place point sources on grid along plate boundary fault model
- Estimate $\mathbf{M_0}$ and **time delay** that best explain data
- Source: two subevents
- Source time functions: isosceles triangles with common duration
- Duration chosen by grid search
- Fault model: plate boundary geometry

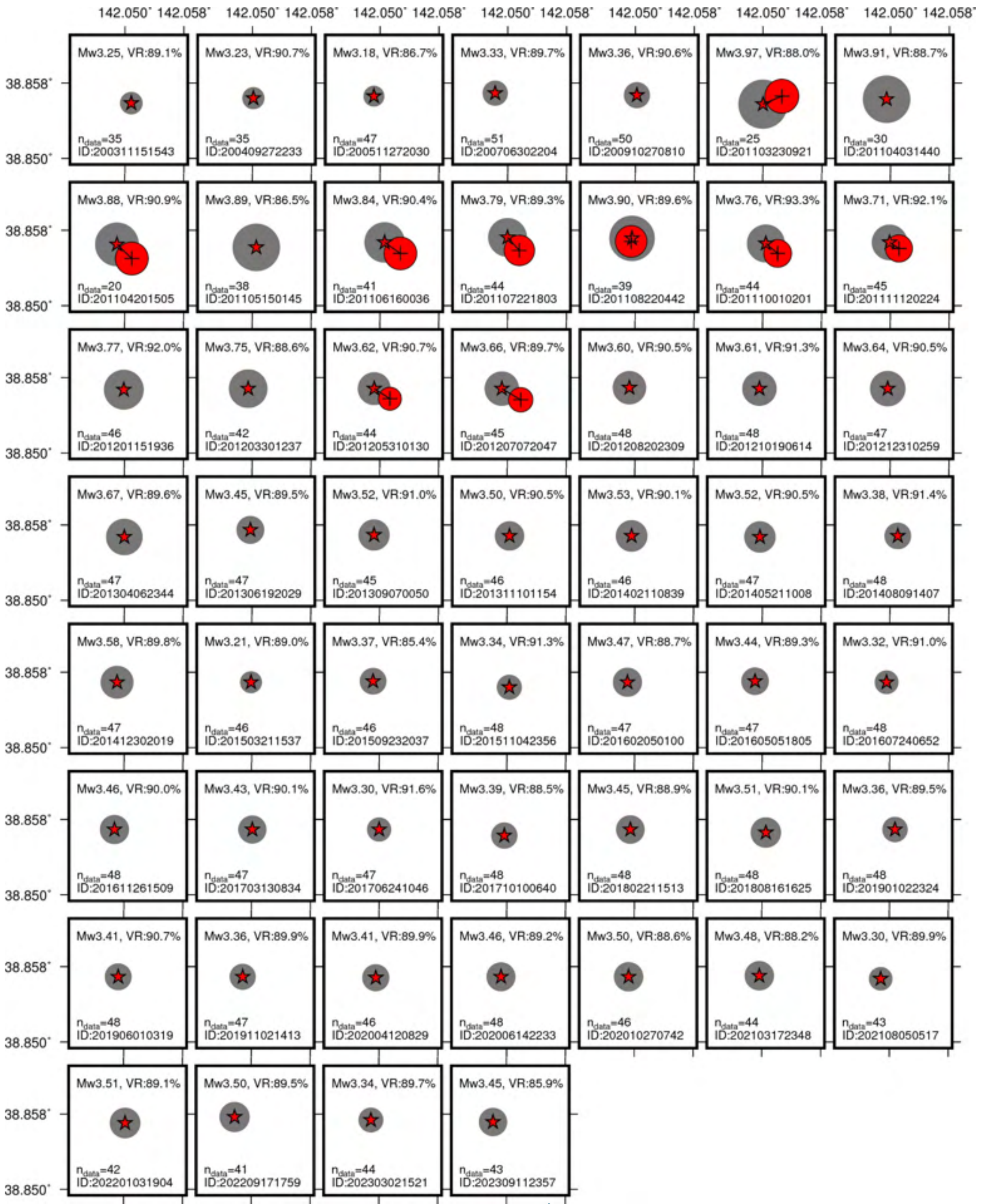


Larger final-Mw events already have a larger Mw in the first rupture

- First 15 post-Tohoku: 2nd rupture east → later single
- Fixed-order rupture → Similar directivity



Estimated source locations shown in **time order**

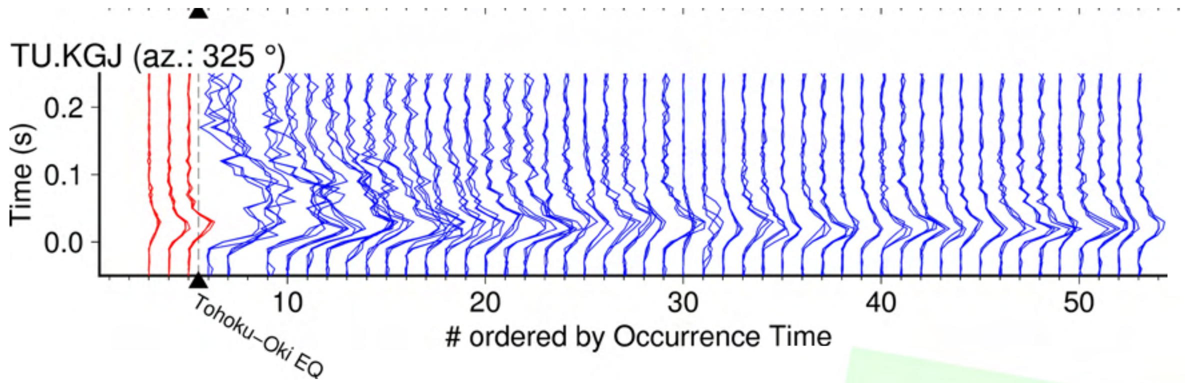


The second rupture is shown in red, only when it is significant.

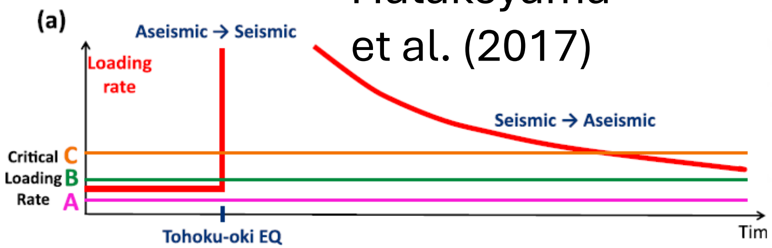
Changes in Mw and rupture patterns strongly depend on time since the Tohoku EQ → influence of afterslip

Increased loading rate ⇒ Reduce critical nucleation length and enhance rupture instability (e.g., Kato & Hirasawa, 1996 & 1997; Kaneko et al., 2017; Mclaskey & Yamashita 2017)

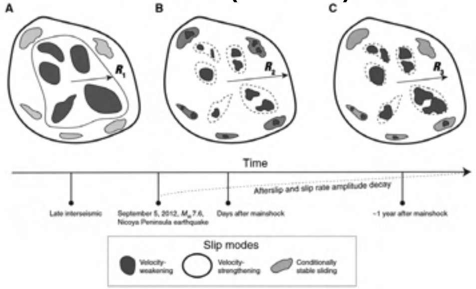
Harder to stop ⇒ surrounding slip ⇒ cascading ruptures



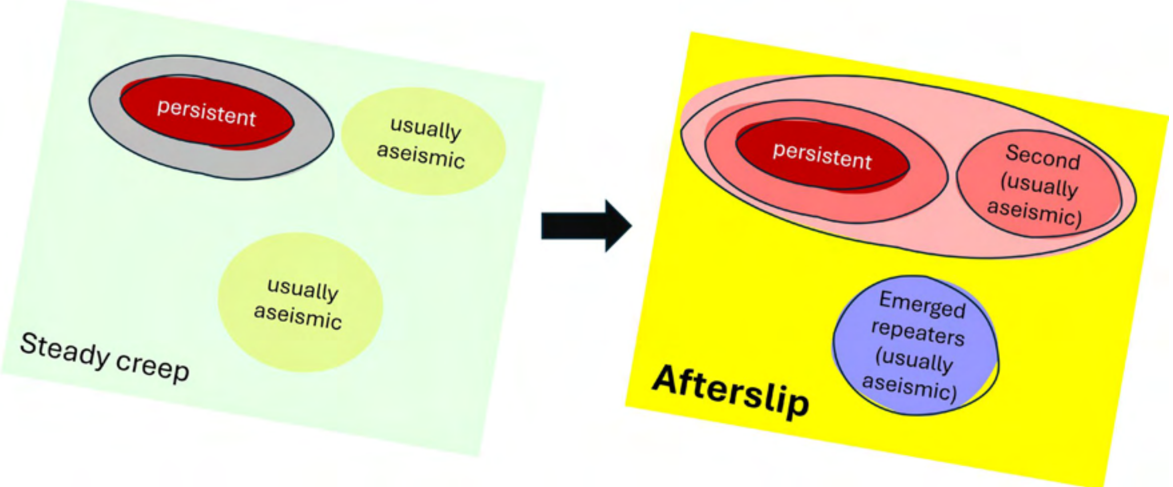
Hatakeyama et al. (2017)

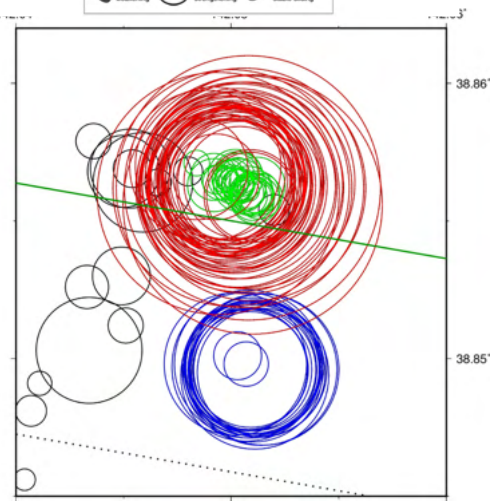


Chaves et al. (2020)



Changes in loading rate systematically affect rupture termination and final size, with remarkable reproducibility!



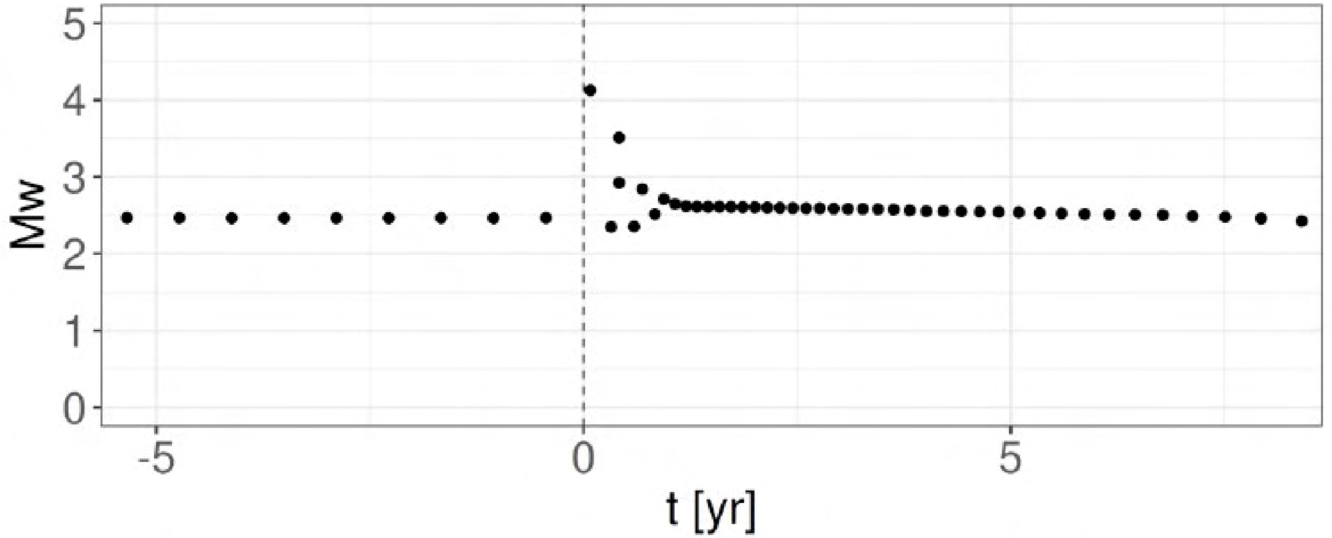


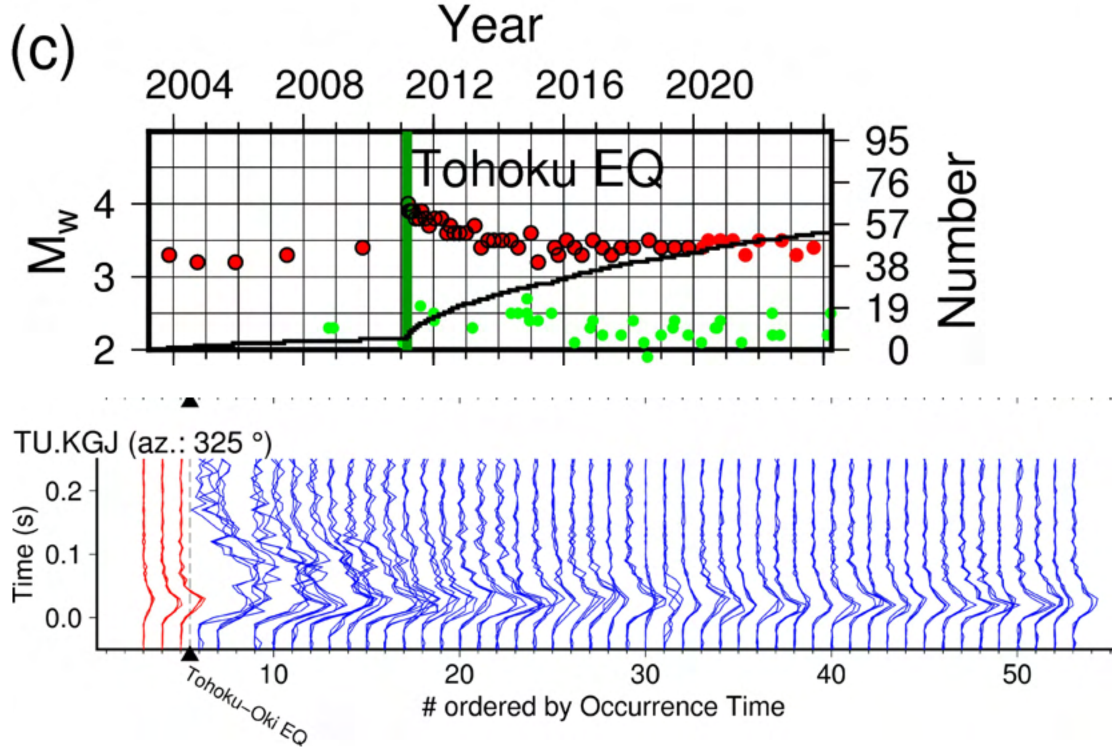
Weaker braking → rupture continued even in the same area

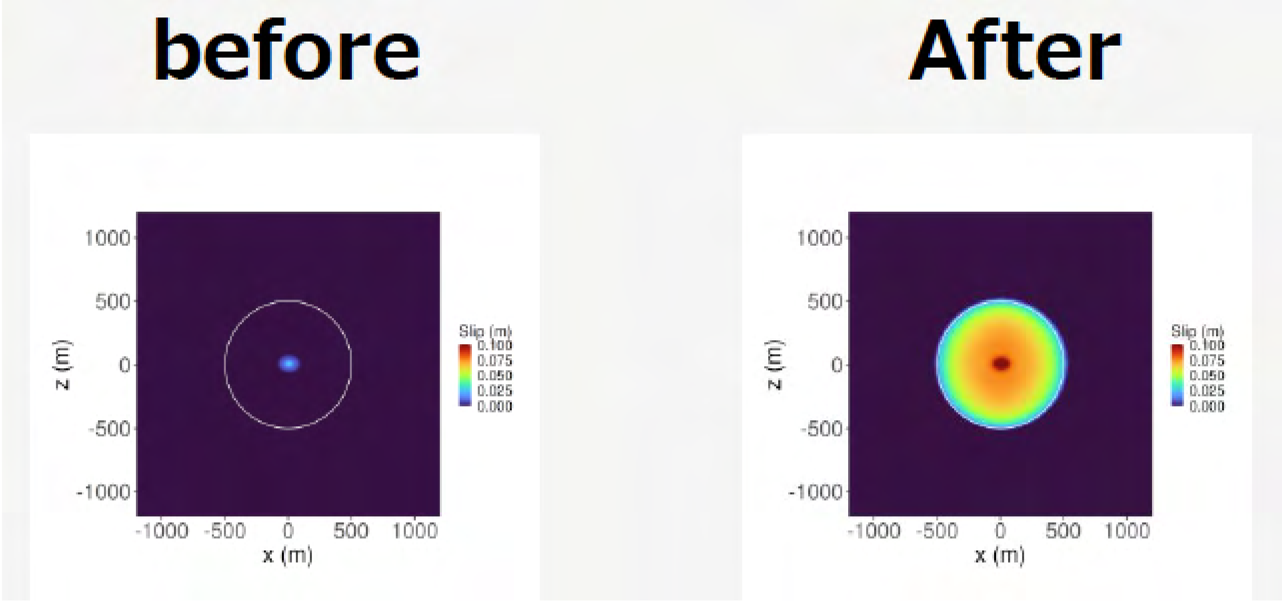
Ongoing Work: Numerical Simulations Based on Rate-and-State Friction

Watanabe, Kaneko, Yoshida (2025, AGU)

- How quantitatively our observations can be explained based on the rate-and-state friction law.
- Do we need additional physical mechanisms not yet incorporated into our current modeling framework?







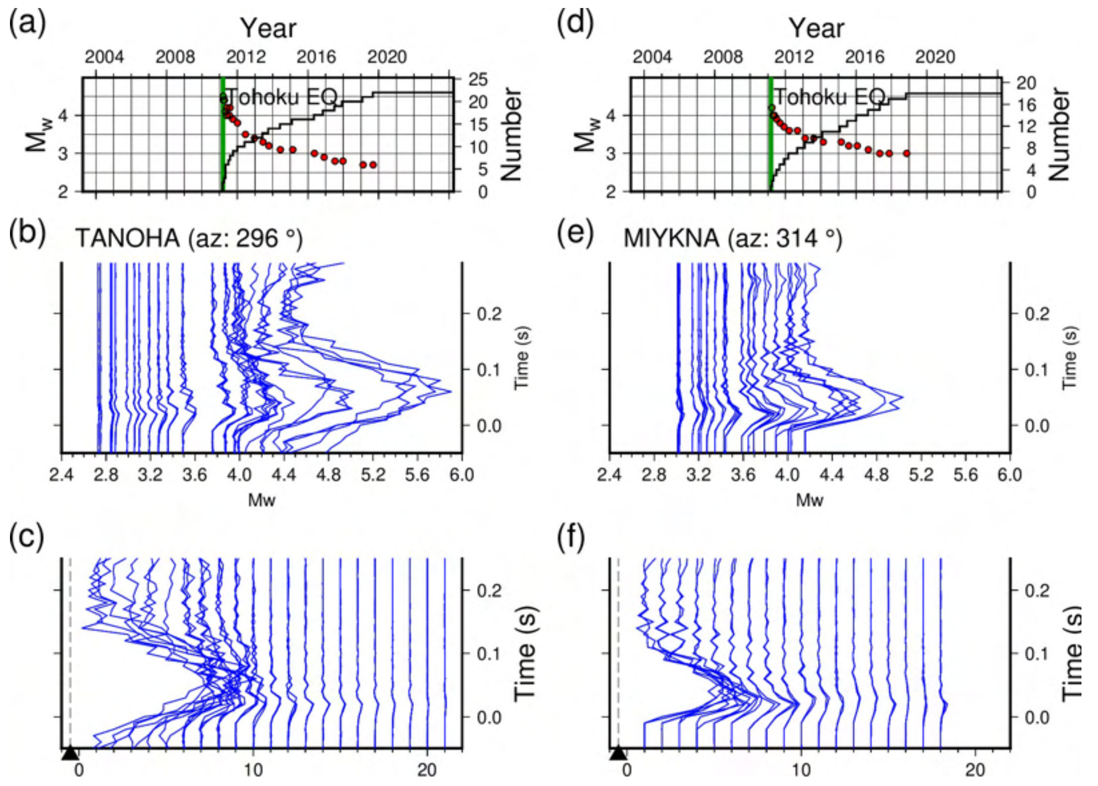
Conclusions

- **Magnitude diversity in repeaters can reflect physical process differences**
- In this case, the **same patch ruptured repeatedly**, but **Mw varies up to 0.8**
  - Not strict "repeaters," but provide clues to **rupture growth mechanisms**
  - Larger events → **increased final rupture area and slip amount**

Change closely followed time since the Tohoku EQ

→ Loading rate influences rupture termination, and thereby final size, in a surprisingly systematic manner

Similar phenomena seen in other regions (supple.)

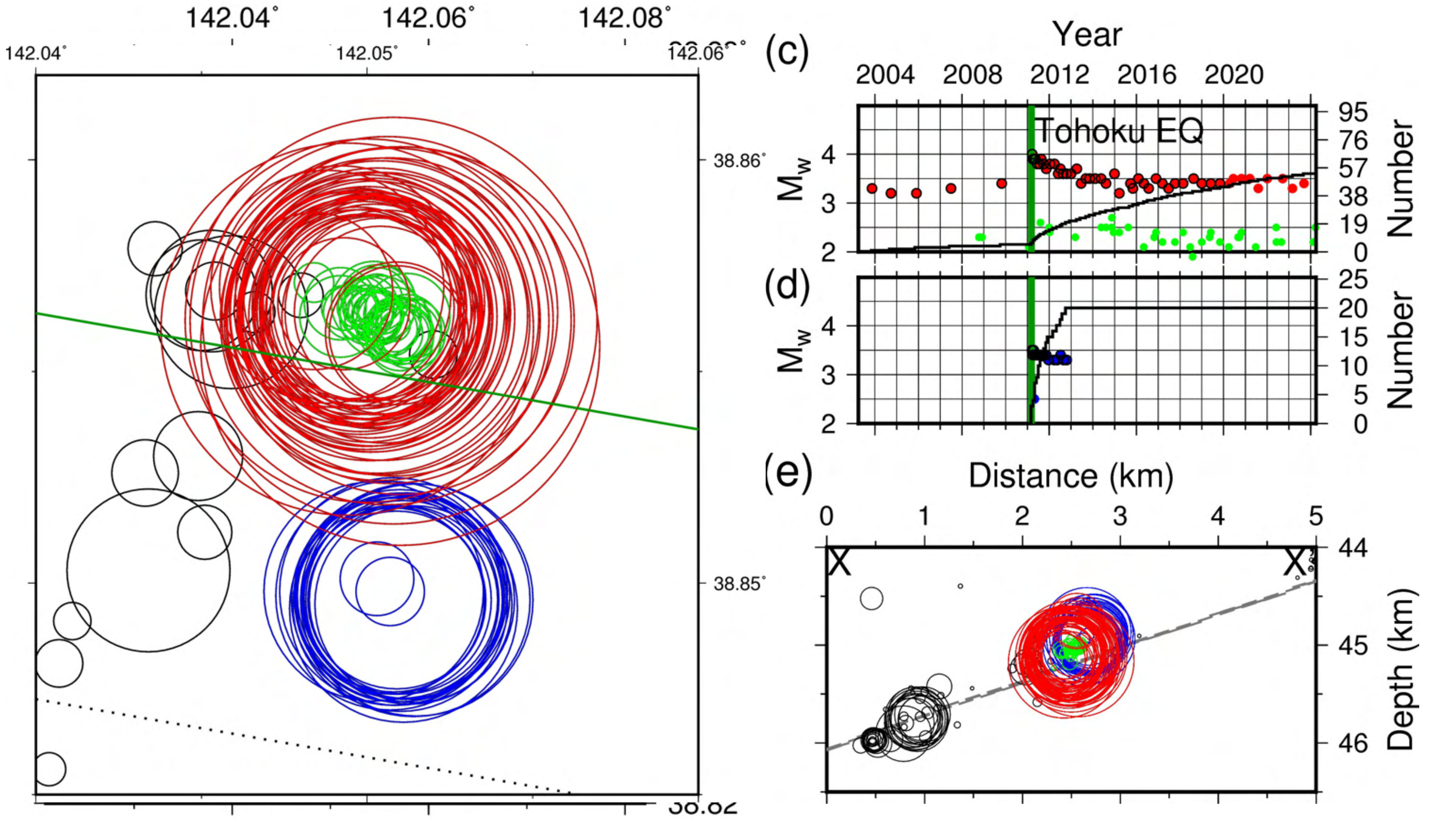


ordered by Occurrence Time

Questions? / Contact Information
Keisuke Yoshida
Email: keisuke.yoshida.d7@tohoku.ac.jp

I also welcome any further comments or detailed questions via email.

Hierarchical occurrence of earthquake repetitions and pronounced post-Tohoku temporal change in Mw

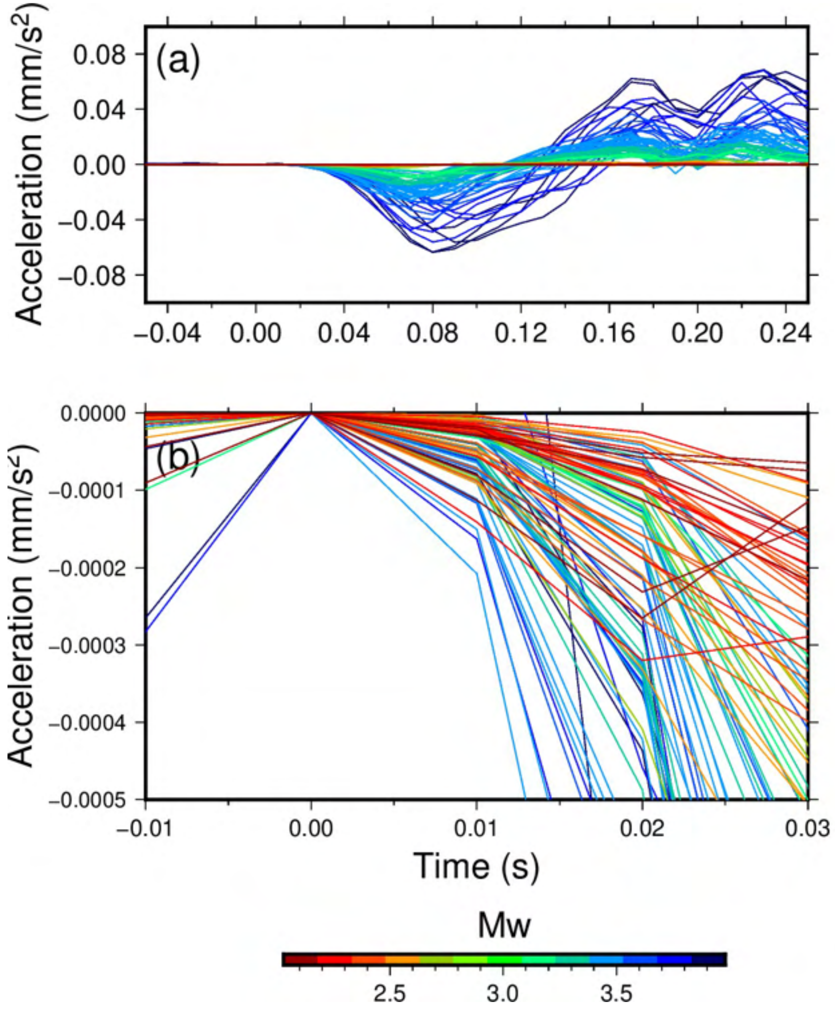


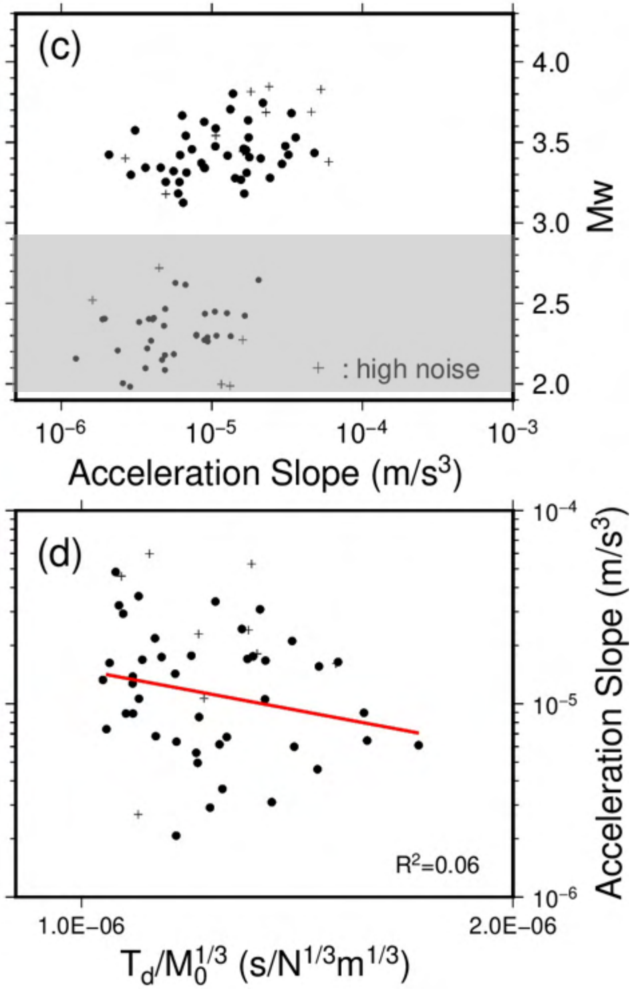
○ : target sequence (53 events)

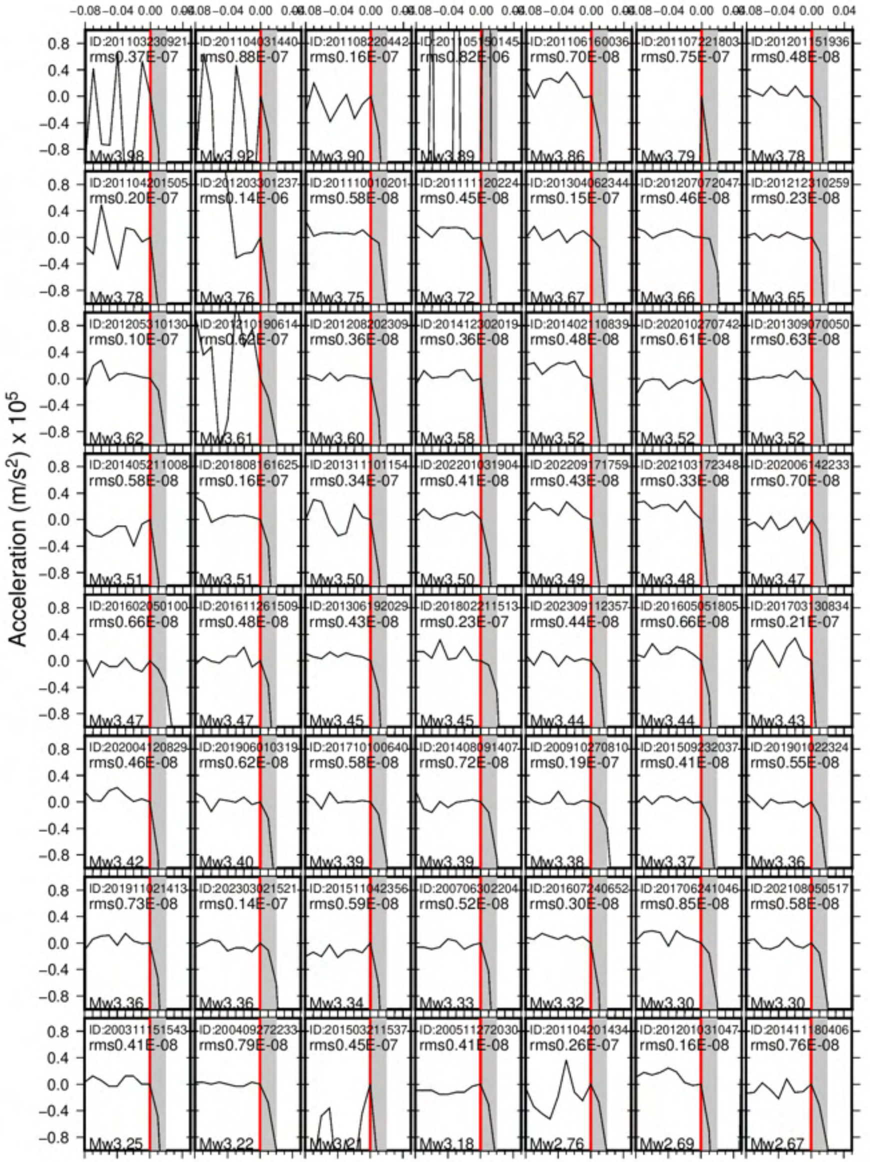
- ○ : small earthquakes inside the target repeater source region

○ : appeared after 2011 Tohoku EQ, then disappeared

No clear relation between Mw and initial acceleration

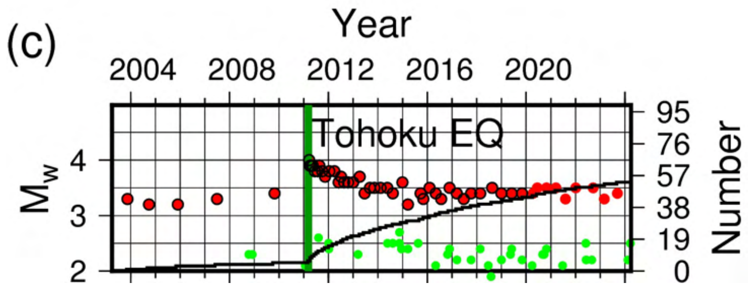






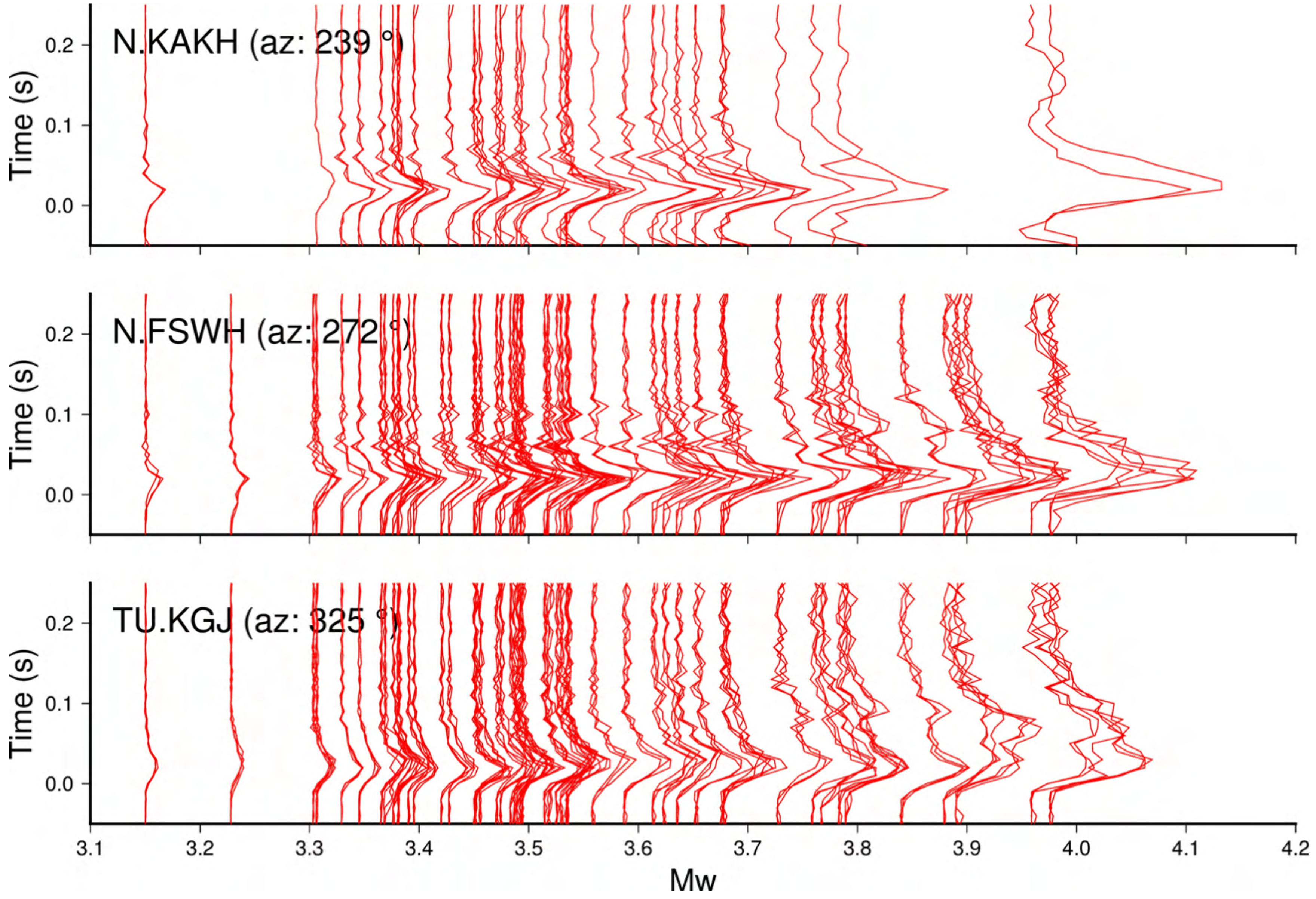
Measure P-wave slope in the first 0.02 s

Larger events show longer durations and multiple pulses



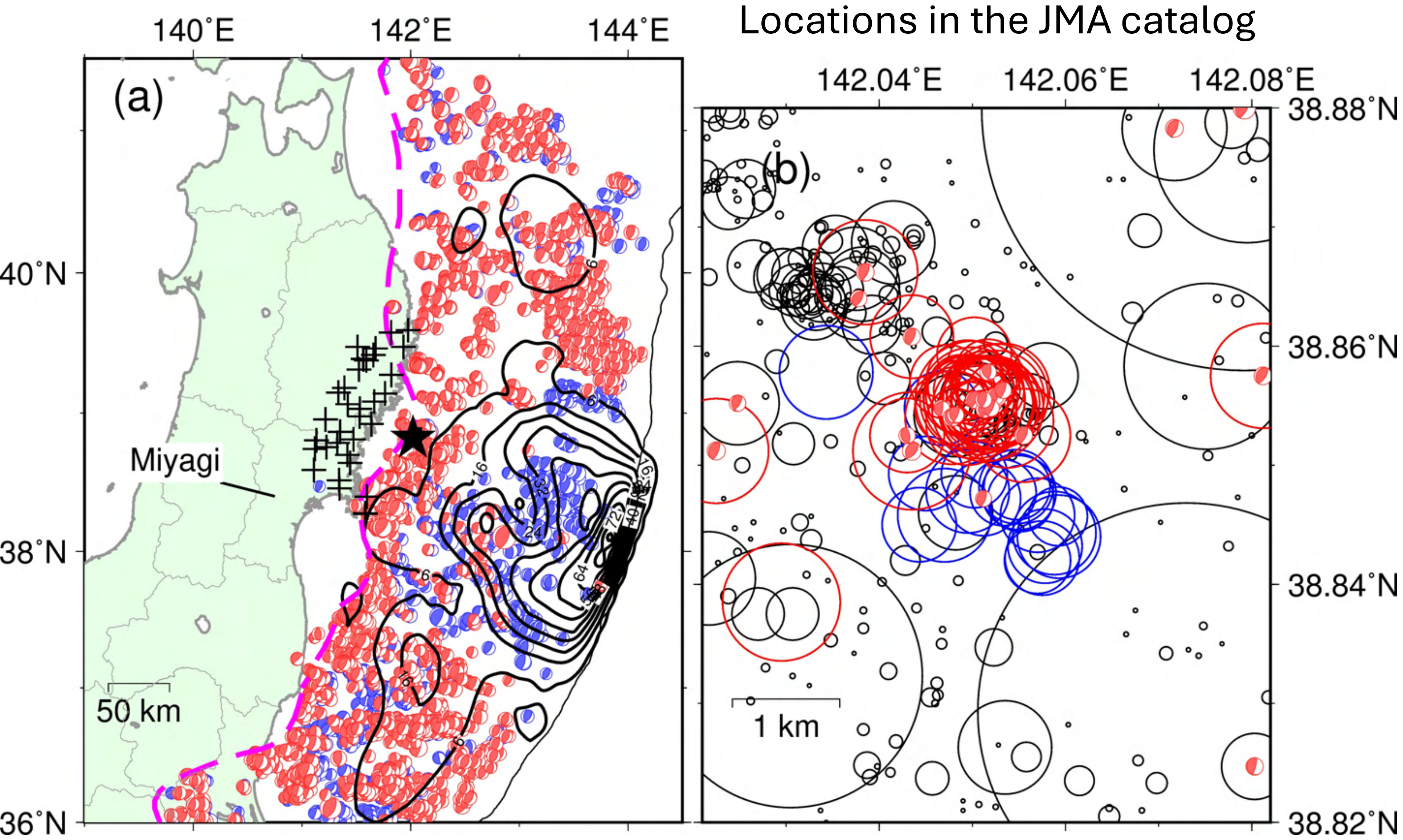
For larger events (Mw > 3.7):
South stations: double rupture
North stations: single rupture
Interpretation: 2nd rupture on southern patch after the 1st
Similar directional dependence seen across different events

Apparent moment-rate functions (AMRFs)



Earthquake (○) and Station (+) Distribution

- Red: Target sequence (Circle size: fault dimension for $\Delta\sigma$ = 3 MPa)



Approach

1. Centroid relocation
2. Mw estimation
3. Rupture pattern estimation
4. Initial rupture momentum characterization

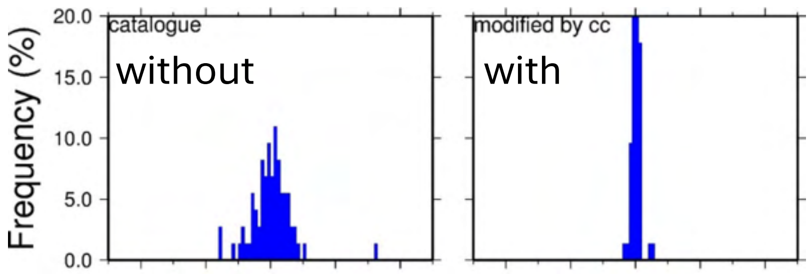
- Contours: 2011 Tohoku earthquake slip distribution (Iinuma et al., 2012)

Hypocenter relocations

Take advantage of waveform cross correlation to obtain the differential arrival time data

- Events: 347 events in the JMA catalogue (2003/3-2024/3)
- Quadratic Interpolation from 100 msec sampling to 10 msec
- Threshold of correlation coefficient: 0.8
- Number of obtained differential arrival times
  - P-wave: 24913 , S-wave: 24992
- Number of catalogue-derived differential arrival time data
  - P-wave: 685021 , S-wave: 481040

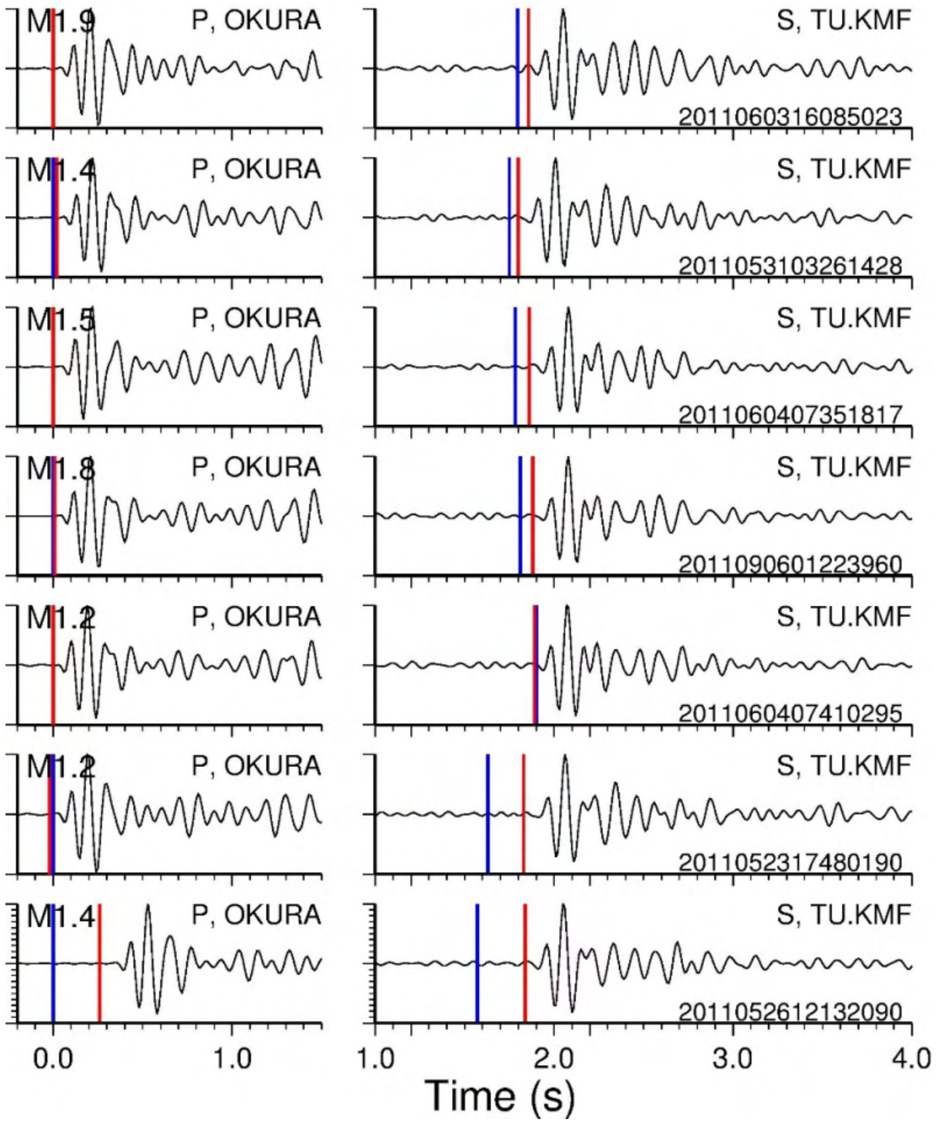
Examples of modification of S-P times based on the cross-correlation derived differential time



We apply the double-difference hypocenter relocation technique (Waldhauser & Ellsworth, 2000) to the differential arrival time data.

Examples of waveform

Yoshida & Hasegawa (2018)



Blue：arrival times listed in the JMA unified catalogue

Red：arrival times modified by cross-correlation

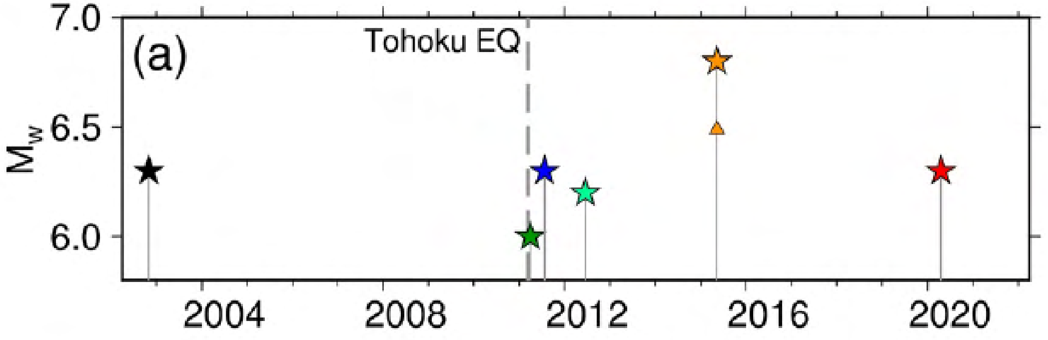
Large Numbers of Small 'Quasi-Repeating' Earthquakes as a Window into Repetition Patterns

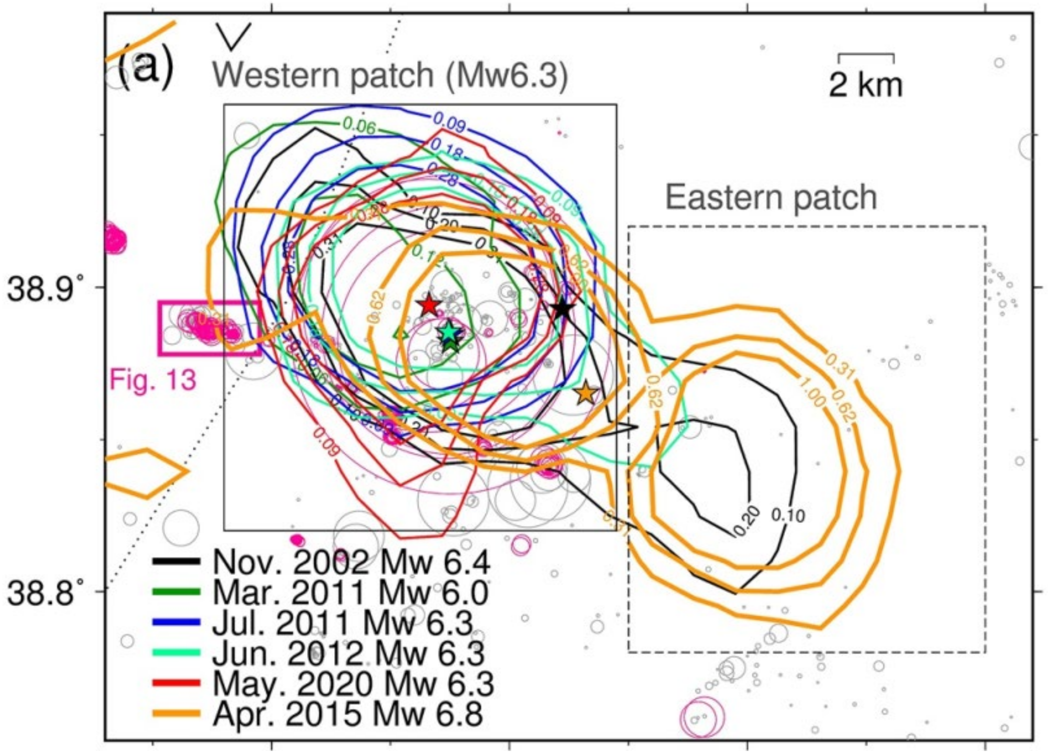
Quasi-Repeating Earthquakes:

- Earthquakes involving the same area, but with subtle variations in rupture extent or slip amount.
- Along the **Japan Trench**, repeaters increased after the 2011 Tohoku EQ
- Some sequences show **diverse magnitudes** (*Uchida et al., 2015; Yoshida, 2023, JGR*)

Identify factors influencing earthquake growth, termination, and its final size

An example (Mw 6–6.8, Yoshida 2023 JGR): Seismic patches not isolated → interaction matters





Pronounced temporal change in Mw

Select pairs with centroids distances < 0.3 times the mean fault radius and M differences of ≤ 0.8 (loose standard)