Recurring slow slip events and earthquake nucleation in the source regions of the M7 Ibaraki-Oki earthquakes inferred from seismicity

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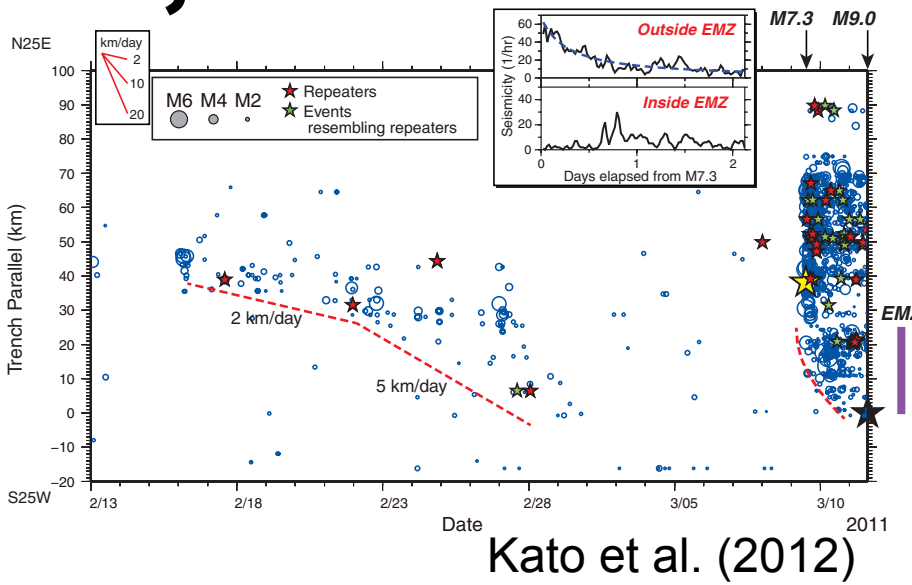
Slow slip, foreshock, and swarm

- SSEs often trigger ordinary earthquakes
- **Foreshock**
  - 2011 M9 Tohoku

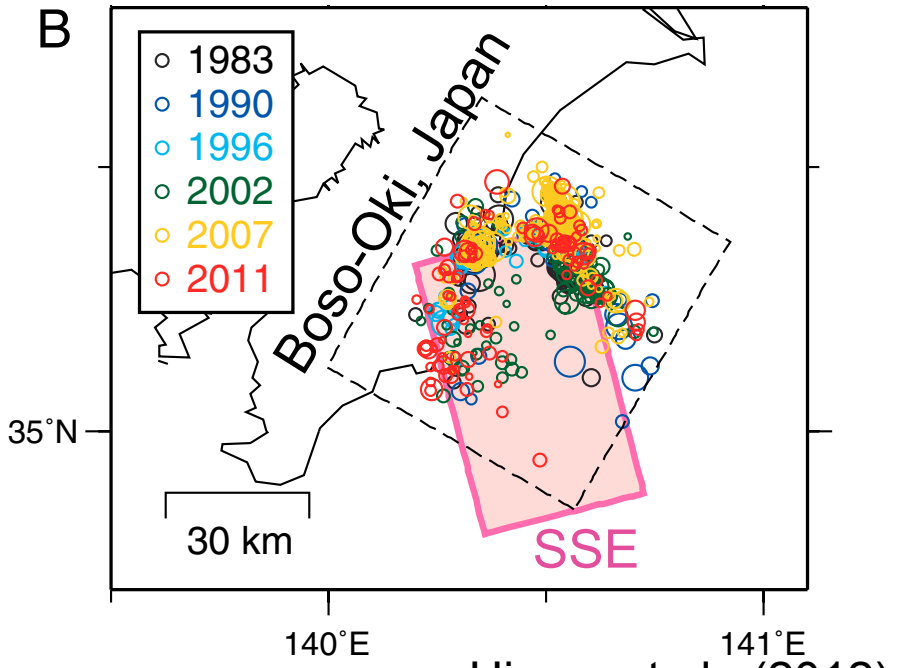
  e.g., Kato et al. (2012)
- **Earthquake swarm**
  - Boso-Oki SSEs

  e.g., Ozawa et al. (2003); Hirose (2012)
- We can use foreshocks and swarms as potential indicators of SSEs!

  e.g., Marsan et al. (2013)



Kato et al. (2012)



Hirose et al. (2012)

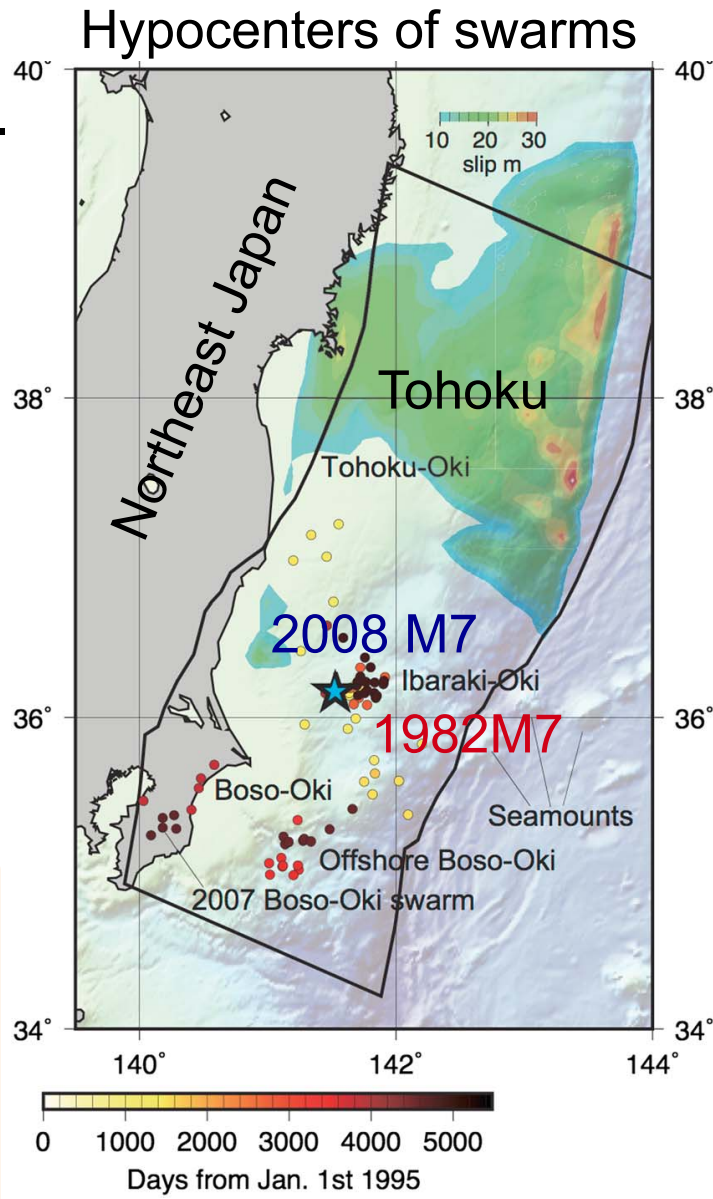
Recurring SSEs in Ibaraki-Oki?

- Recurring **swarms** and **foreshocks** are found in Ibaraki-Oki (Nishikawa and Ide, 2017)
  - Swarms in 1999, 2002, and 2006
  - Foreshocks in 1982 and 2008

- Close to the hypocenters of the 1982 and 2008 M7 Ibaraki-Oki EQs

Questions

- Unknown SSEs trigger these swarms and foreshocks?
- The unknown SSEs are related to the M7 Ibaraki-Oki EQs?



Nishikawa and Ide (2017)

Objectives

- We further investigate the possibility of recurring SSEs in Ibaraki-Oki, the Japan Trench
  - Reveal a more detailed history of swarm activity in Ibaraki-Oki using a longer local catalog (JMA)
  - Detect missing small events using Matched filter technique (Shelly et al., 2007)
  - Detect repeating earthquakes (Nadeau and Johnson, 1998) and reveal the history of aseismic slips
- We discuss the difference between the swarms and the foreshocks in Ibaraki-Oki
  - Important for earthquake predictability
- We discuss the relationship between the SSEs and the 1982 and 2008 M7 Ibaraki-Oki EQs

How to detect swarms

Nishikawa and Ide (2017)

- Earthquake swarms have much higher seismicity rates than predicted by ETAS model because swarms are triggered by **phenomena other than earthquake-earthquake triggering**

ETAS model ① Background + ② Omori law

$$\lambda(t,x,y) = \mu(x,y) + \sum_{\{k:\ t_k<t\}} \kappa(m_k) g(t-t_k) f(x-x_k, y-y_k; m_k)$$

Seismicity rate

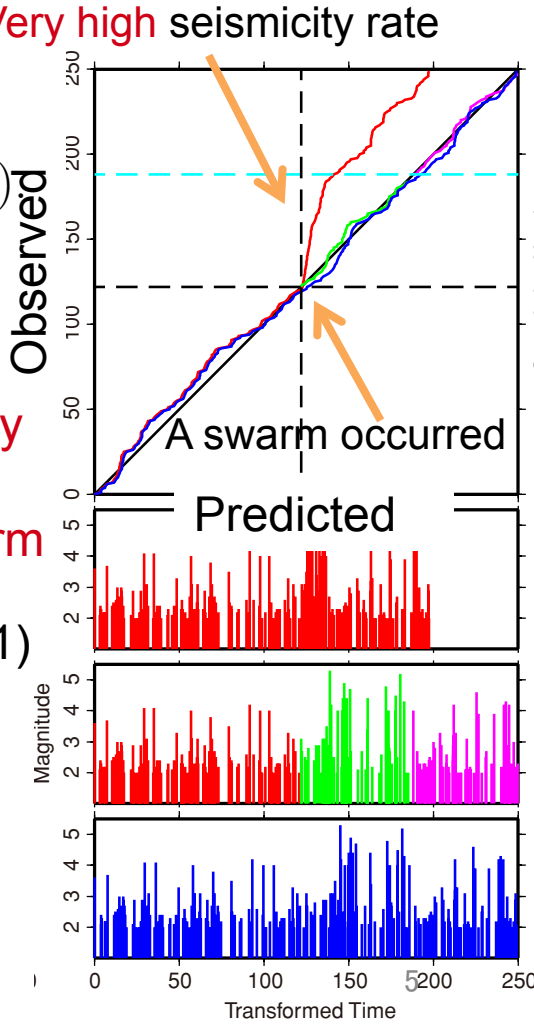
Ogata (1998); Zhuang et al. (2002)

Number of events predicted by ETAS

$$\tau_i = \int_0^{t_i} \lambda(s)\, \mathrm{d}s$$

Red: number of events predicted by the ETAS model based on pre-swarm catalog.

Okutani and Ide (2011)



- We can detect earthquake swarms as seismic sequences with anomalously high seismicity rates inexplicable by ETAS

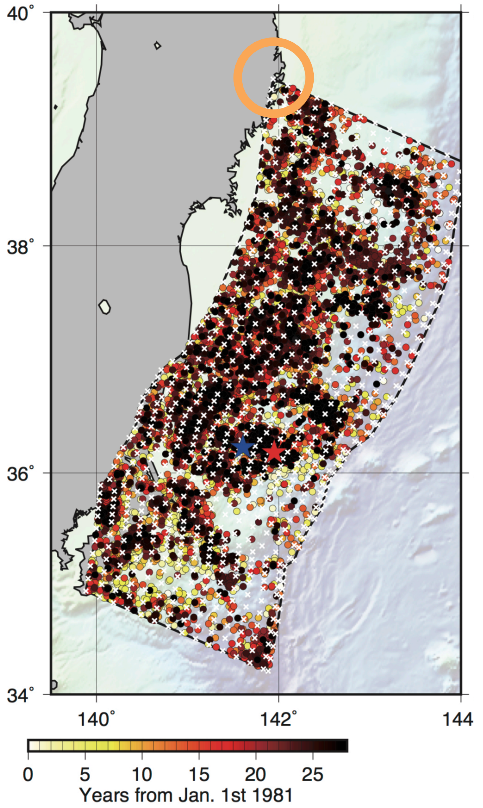
Method to detect swarms

1. Fit the ETAS model in the Japan Trench
   - 500km along strike
   - 200km dip
   - From 1981 to 2008
2. Calculate number of events expected by the ETAS model
   - Each circle with 30km radius
   - 15 km interval
3. Detect seismic sequences with anomalously high seismicity rates as swarms

Predicted number of events

$$\tau_i = \int_0^{t_i} \lambda(s)\, \mathrm{d}s$$

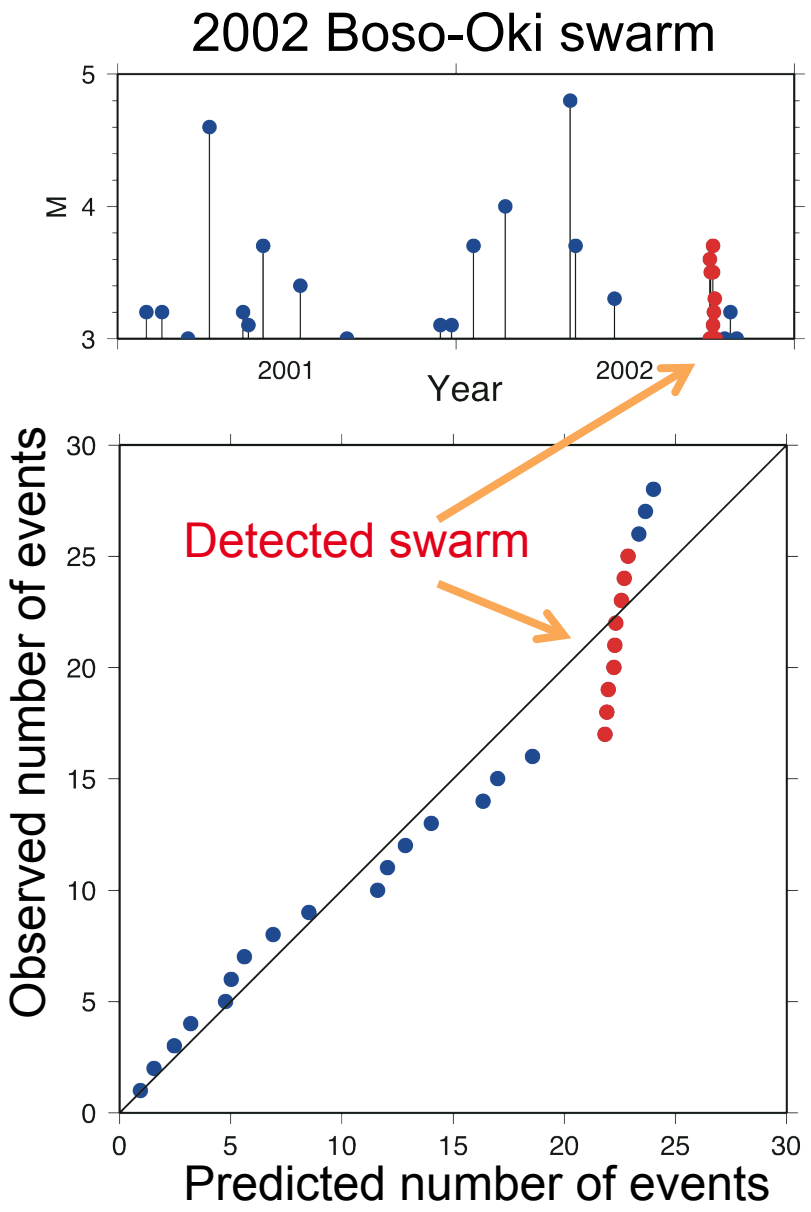
The Japan Trench JMA M ≥ 3



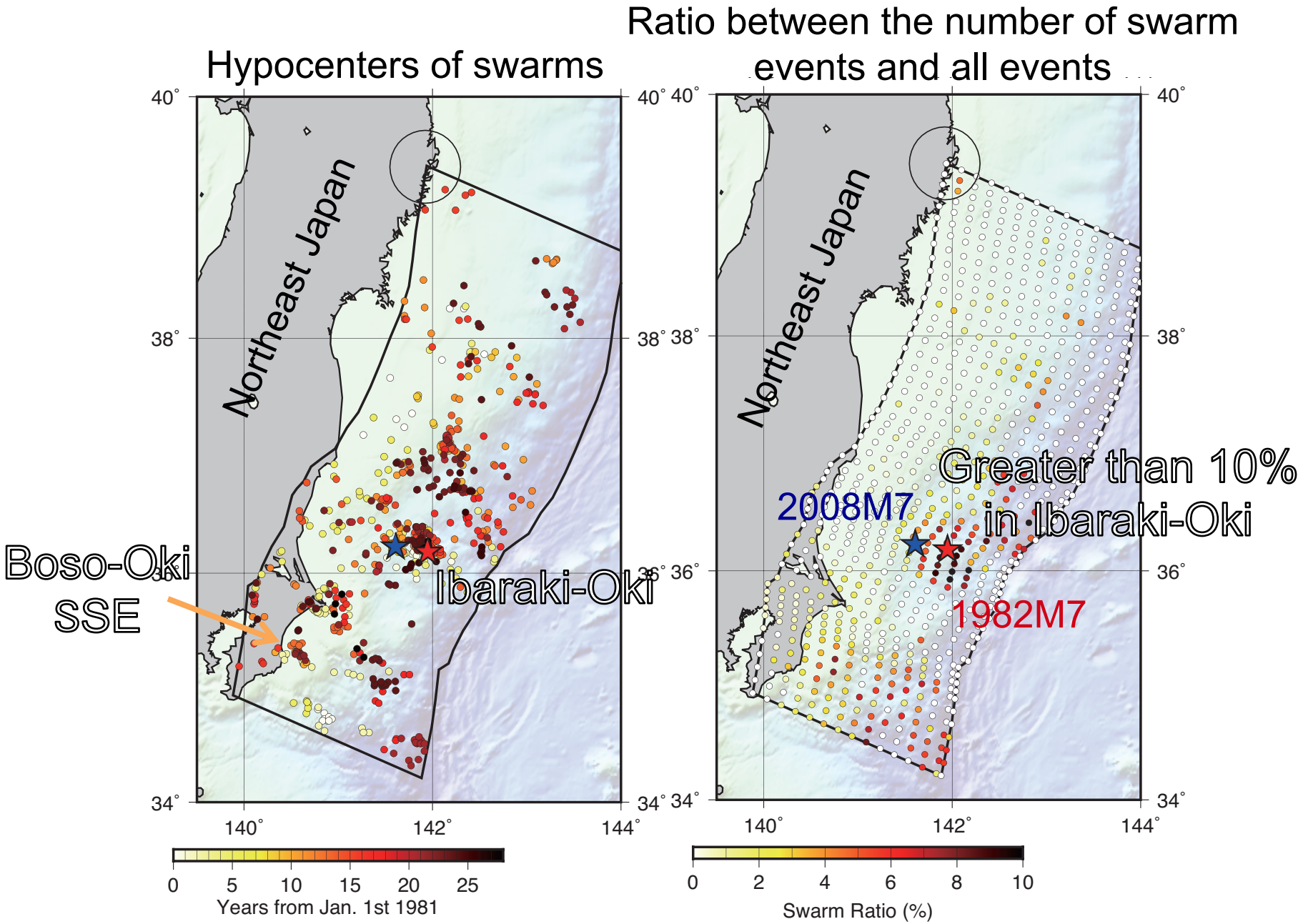
For details of the method, see Nishikawa and Ide (2017) JGR

Detection criteria and Catalog

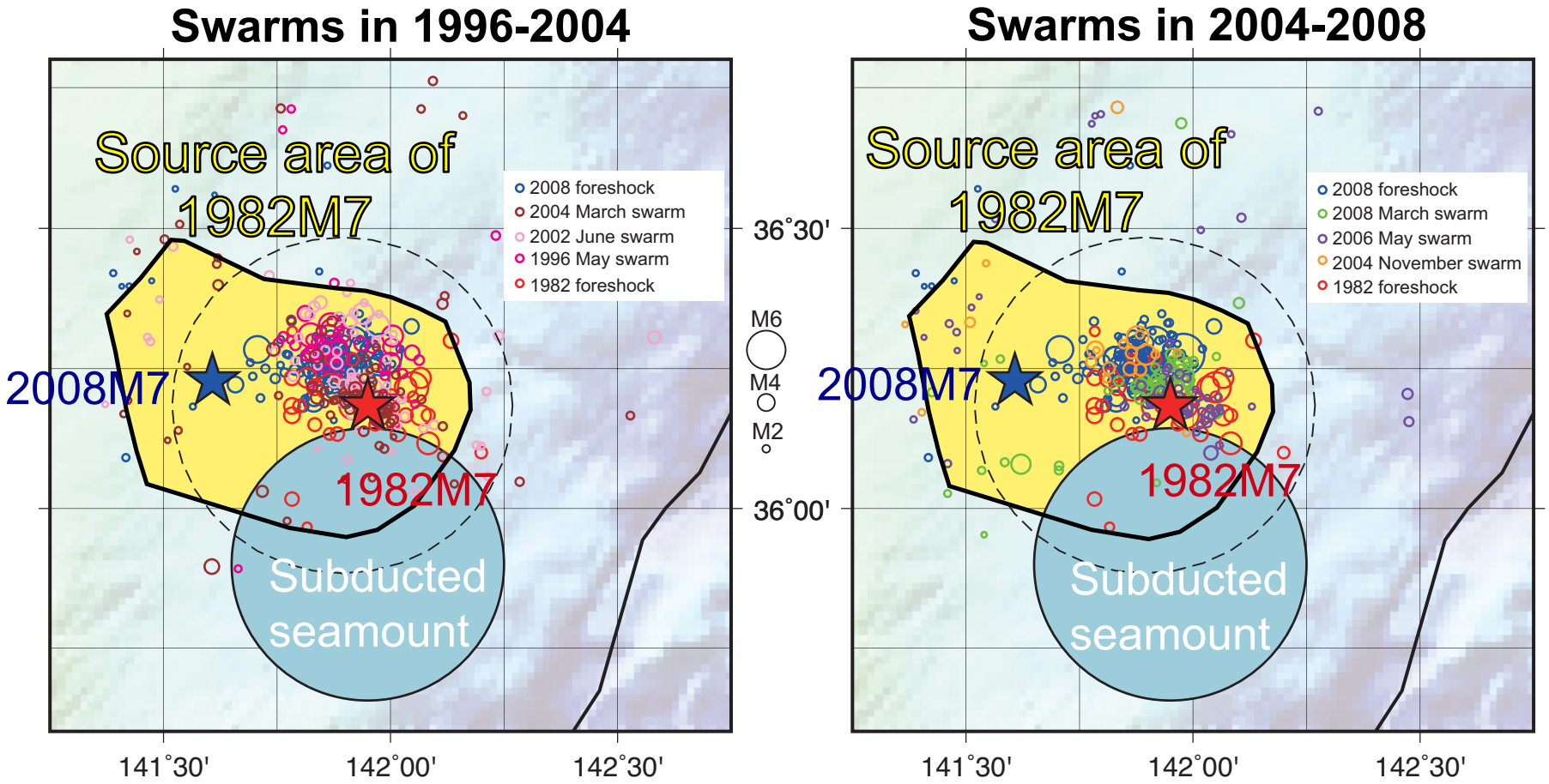
- Criteria for detection
  - "Expected number of earthquakes does not exceed 1 in the time interval between two earthquakes even though considering 1.5σ error"
  - This continuously occurs four times or more
  - The probability that 5 events following the ETAS have such a high seismicity rate is 2.39×10^{-3}
  - The first event of each swarm is not an aftershock (i.e., the probability of being aftershock is less than 50%)
- Earthquake Catalog
  - 1981-2008 JMA (M ≥ 3)
- Study region
  - The Japan Trench



Earthquake swarms during 1981-2008

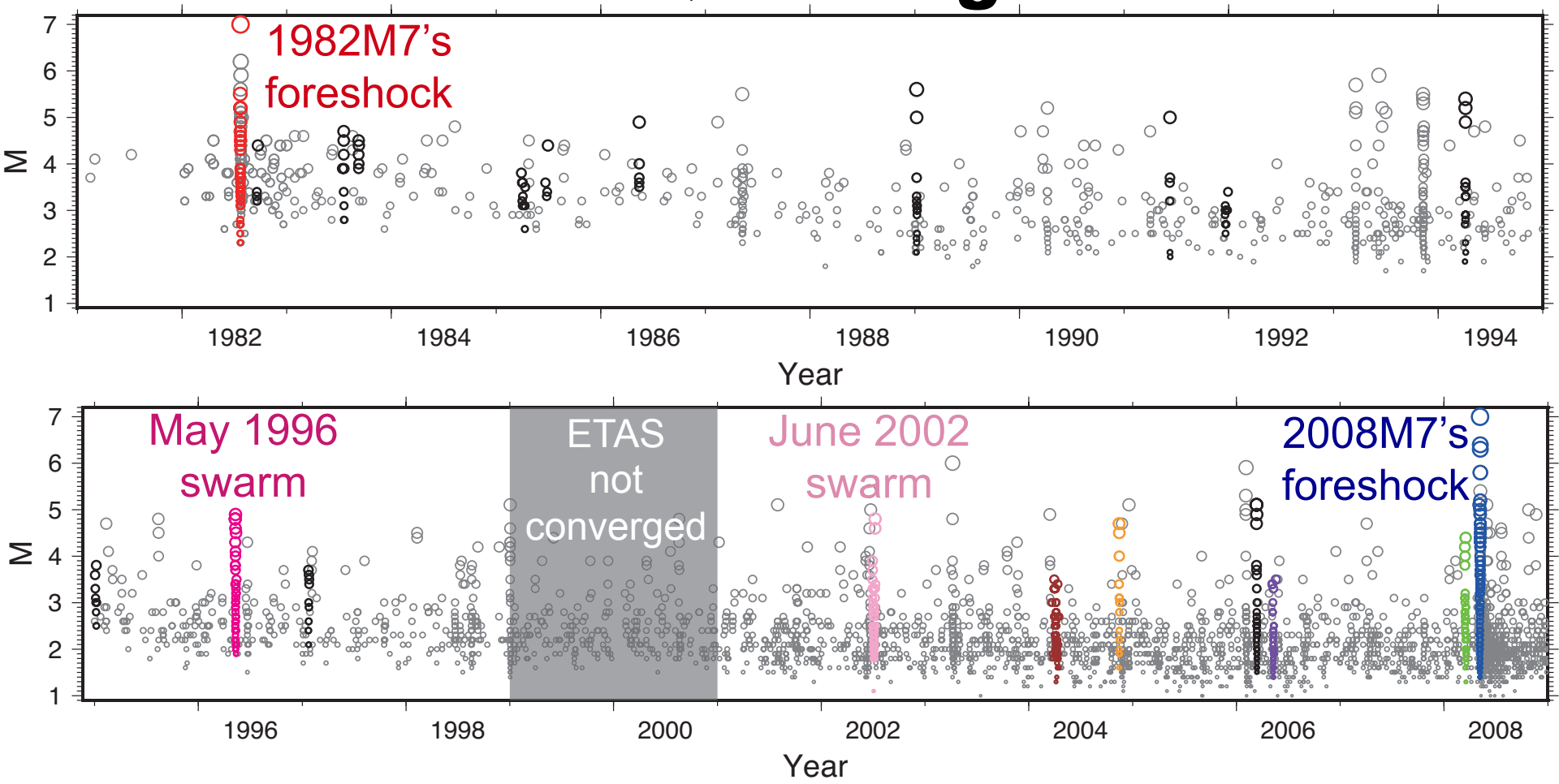


Swarms in the source area of the M7 Ibaraki-Oki EQs



- Swarms are concentrated in the foreshock area of 1982 and 2008 Ibaraki-Oki EQs (36.1-36.3N, 141.8-142.0E)
- Close to a subducted seamount (Mochizuki et al., 2008)

Swarms in the source area of the M7 Ibaraki-Oki EQs during 1981-2008



- 19 swarm sequences during 1981-2008
- The 1982 foreshock is also classified as swarm-like foreshock

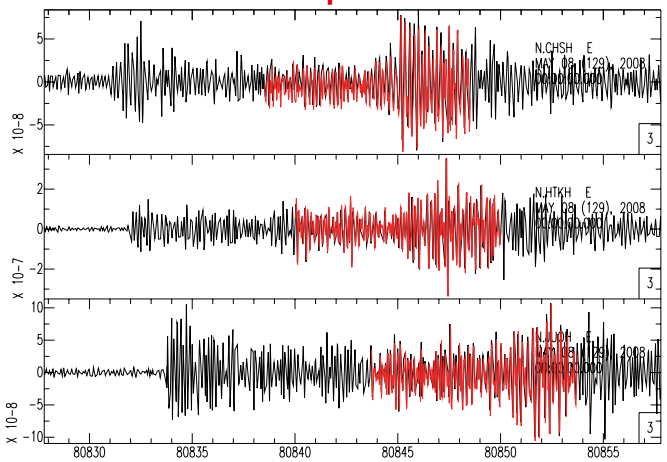
Matched filter technique

- Detect missing small events

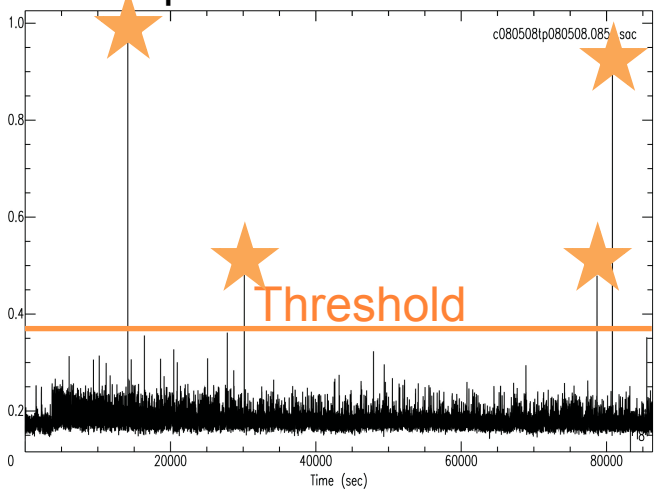
Shelly et al. (2007)

- Templates
  - Swarm events and 500 aftershocks of the 2008 M7
  - 10 s window starting from 5 s before S arrival
  - 4-12 Hz
- Waveform of Hi-net
  - 16 stations in Ibaraki prefecture
- Larger than 17 scaled mad

Templates

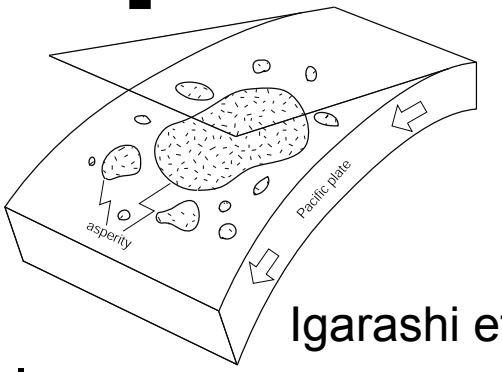


Averaged correlation over components and stations

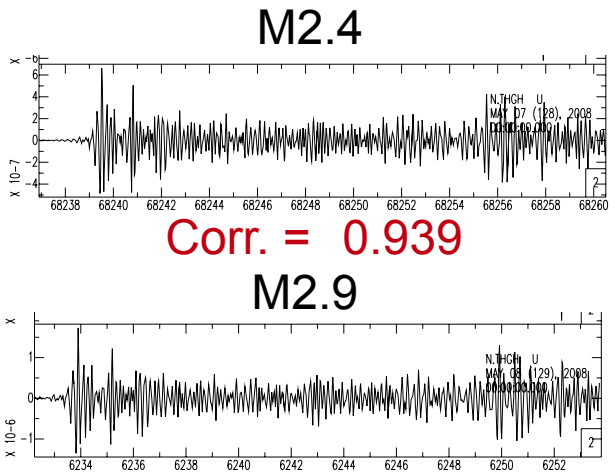


Repeating earthquake

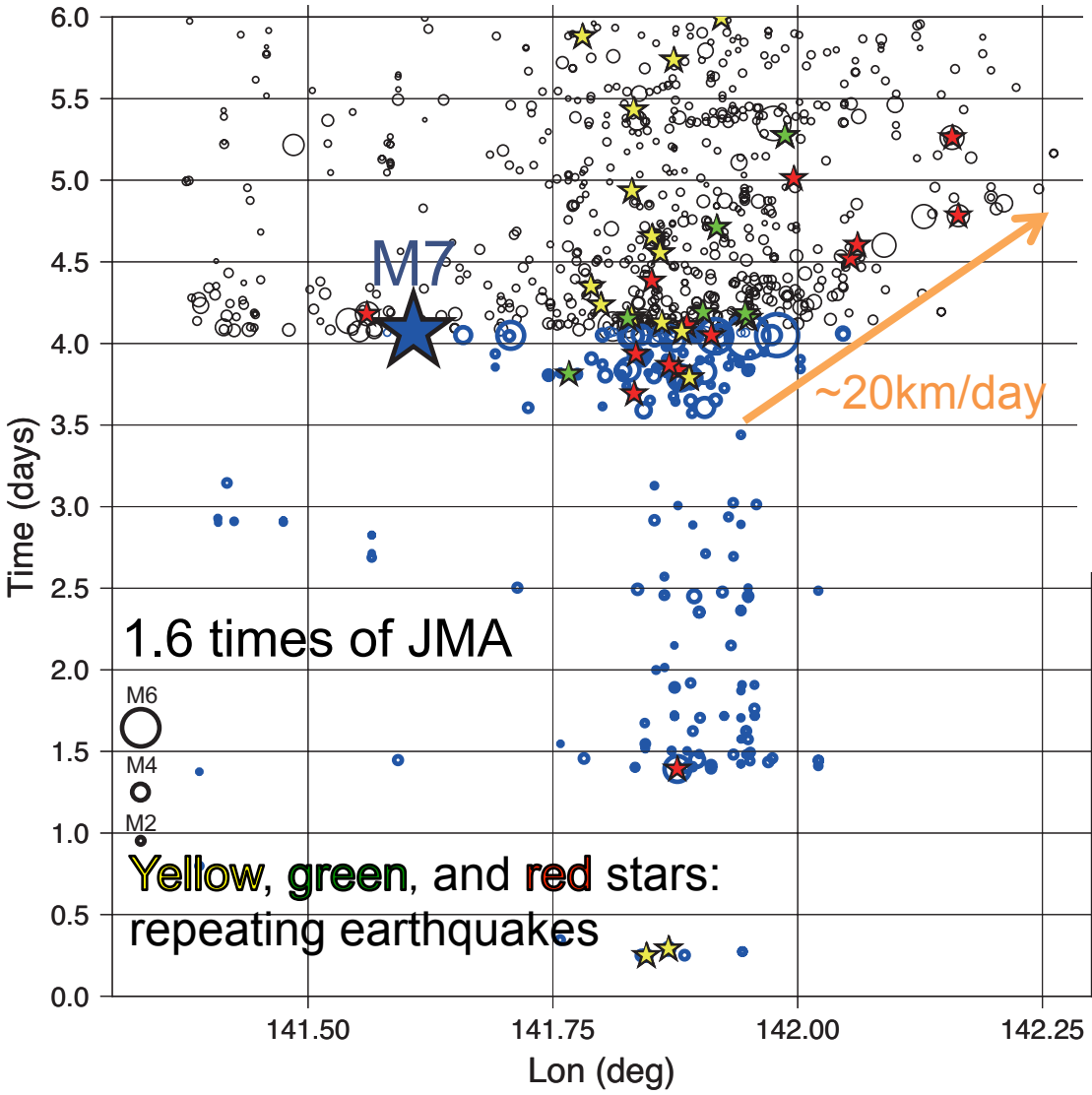
- Catalog
  - Catalog made by Matched filter
- Waveform
  - From P arrival to 3 s after S arrival
  - 1-4 Hz, 2-8Hz, and 4-16 Hz
- Detection criterion
  - Cross-correlations larger than 0.95 at two or more stations
- Analysis time period
  - Time period of each swarm
  - Repeaters not in the swarm periods are based on a repeater catalog by Uchida et al. (2016)



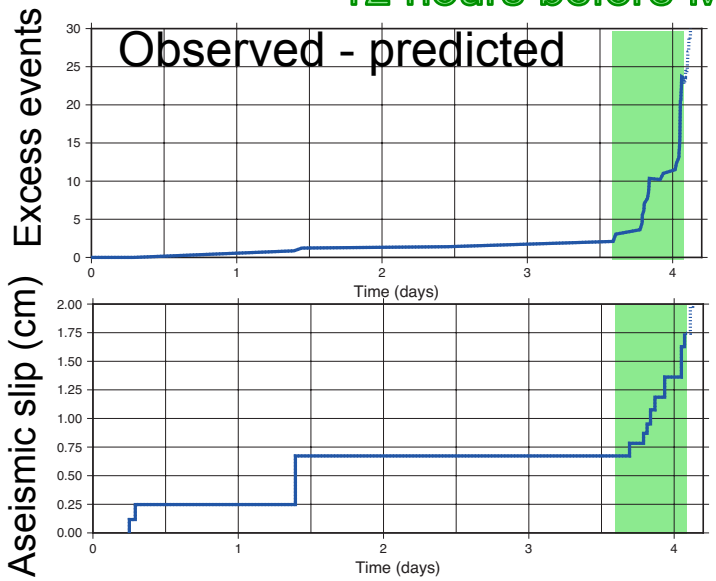
Igarashi et al. (2003)

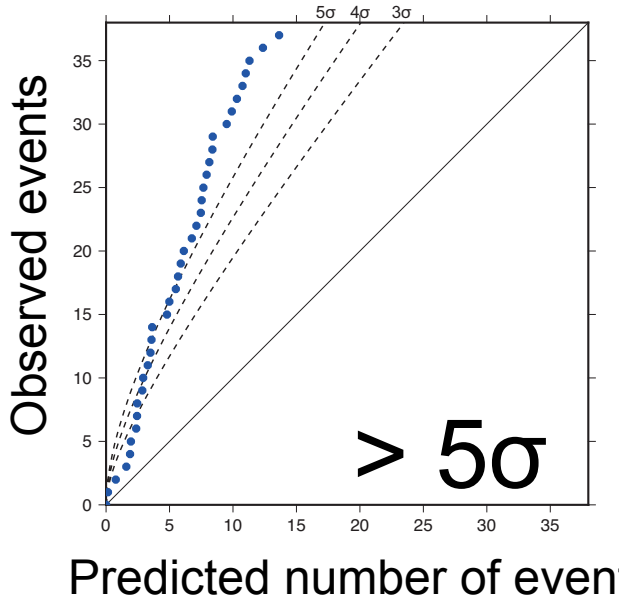


Foreshock in 2008

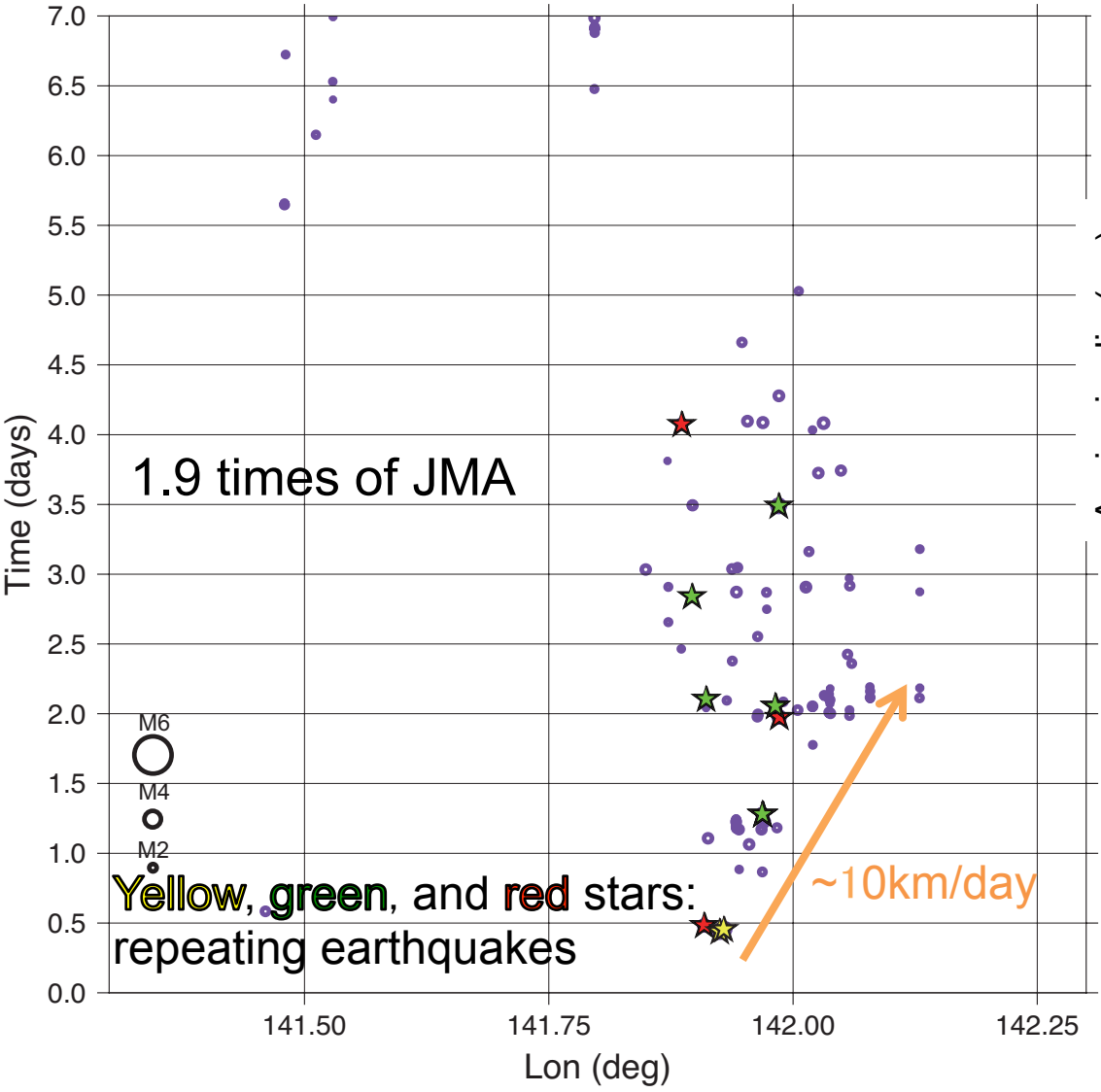


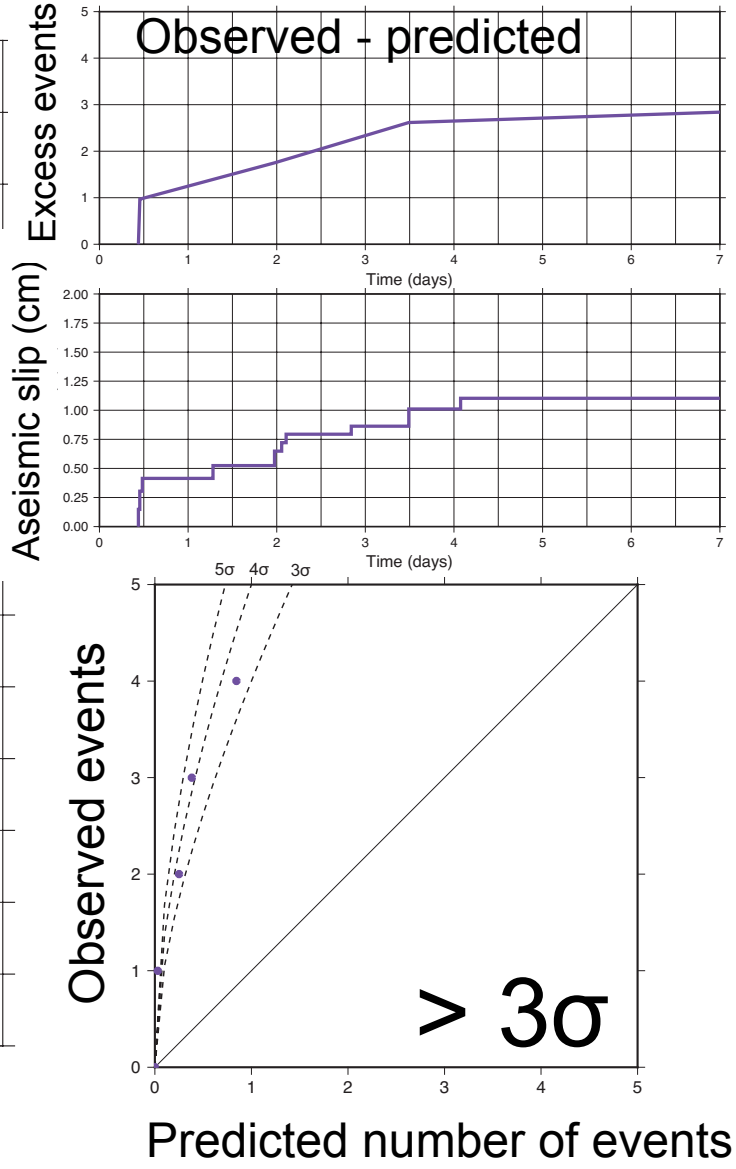
12 hours before M7



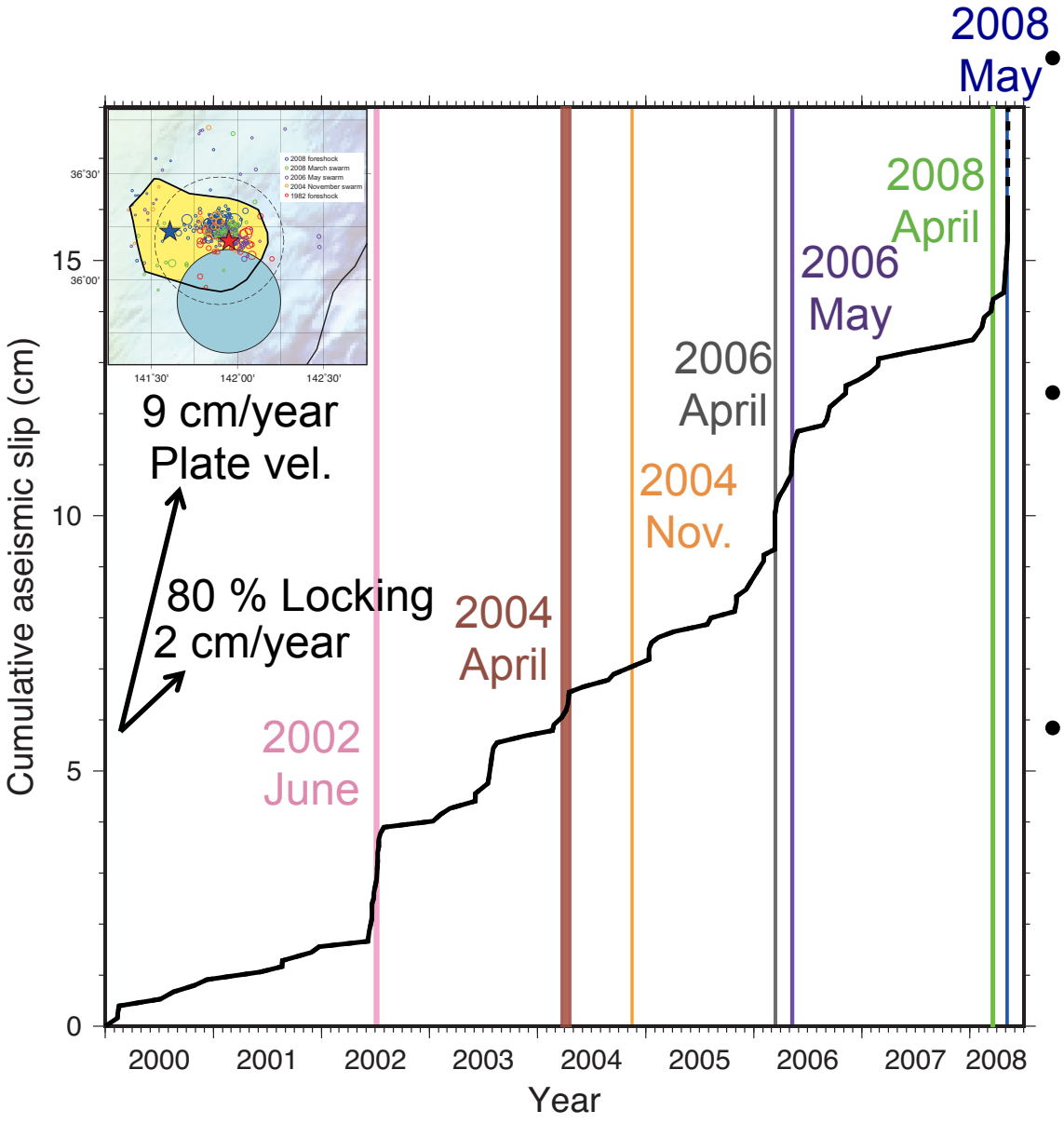


Earthquake swarm in 2006





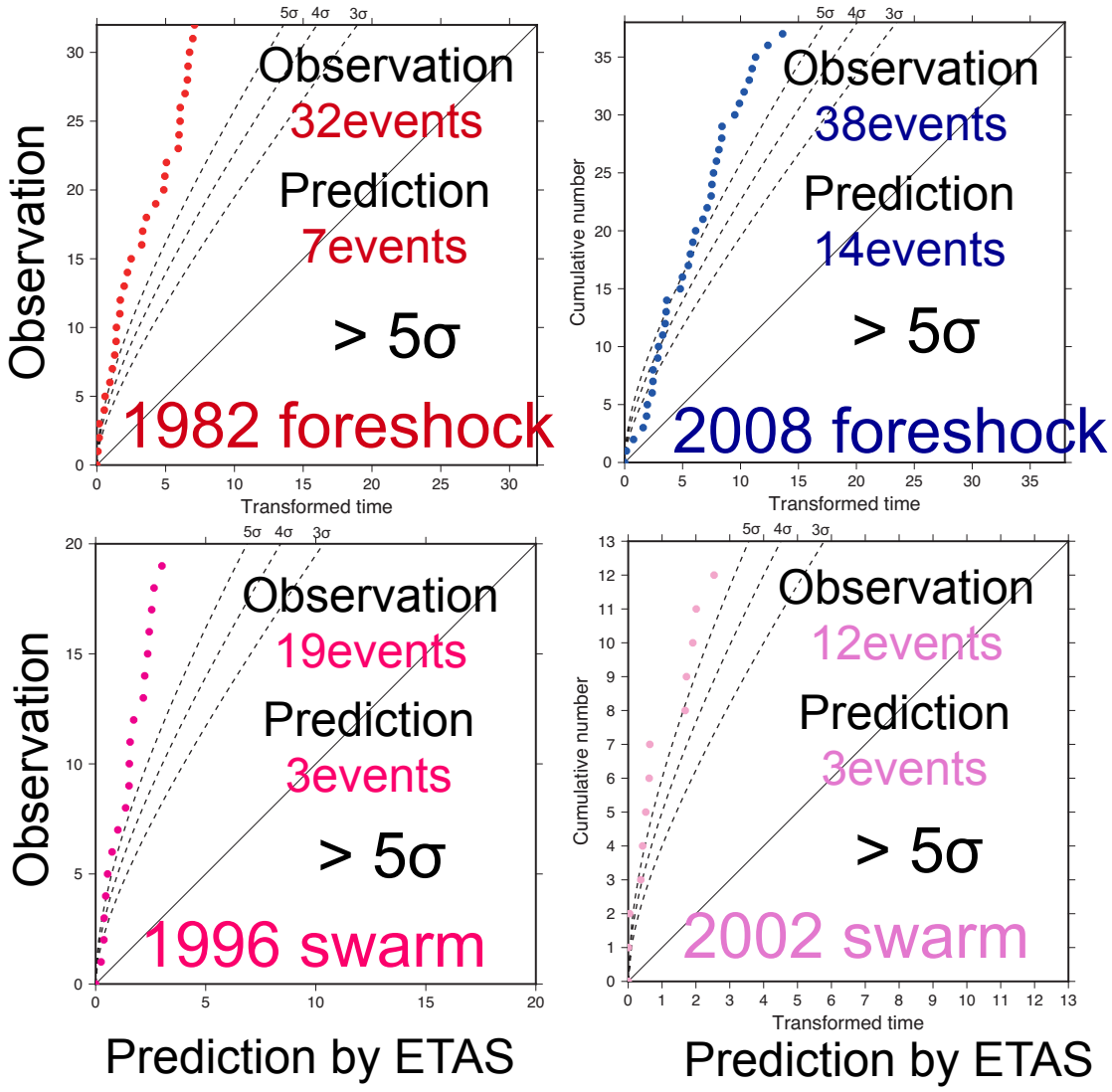
Swarms and increases in aseismic slip



- Long-term repeater catalog by Uchida et al. (2016)
  - 98 repeater groups
- Estimate aseismic slips using the scaling law of Nadeau and Johnson (1998)
- Except Nov. 2004, swarms correspond with step-like increases in aseismic slips
  - SSE

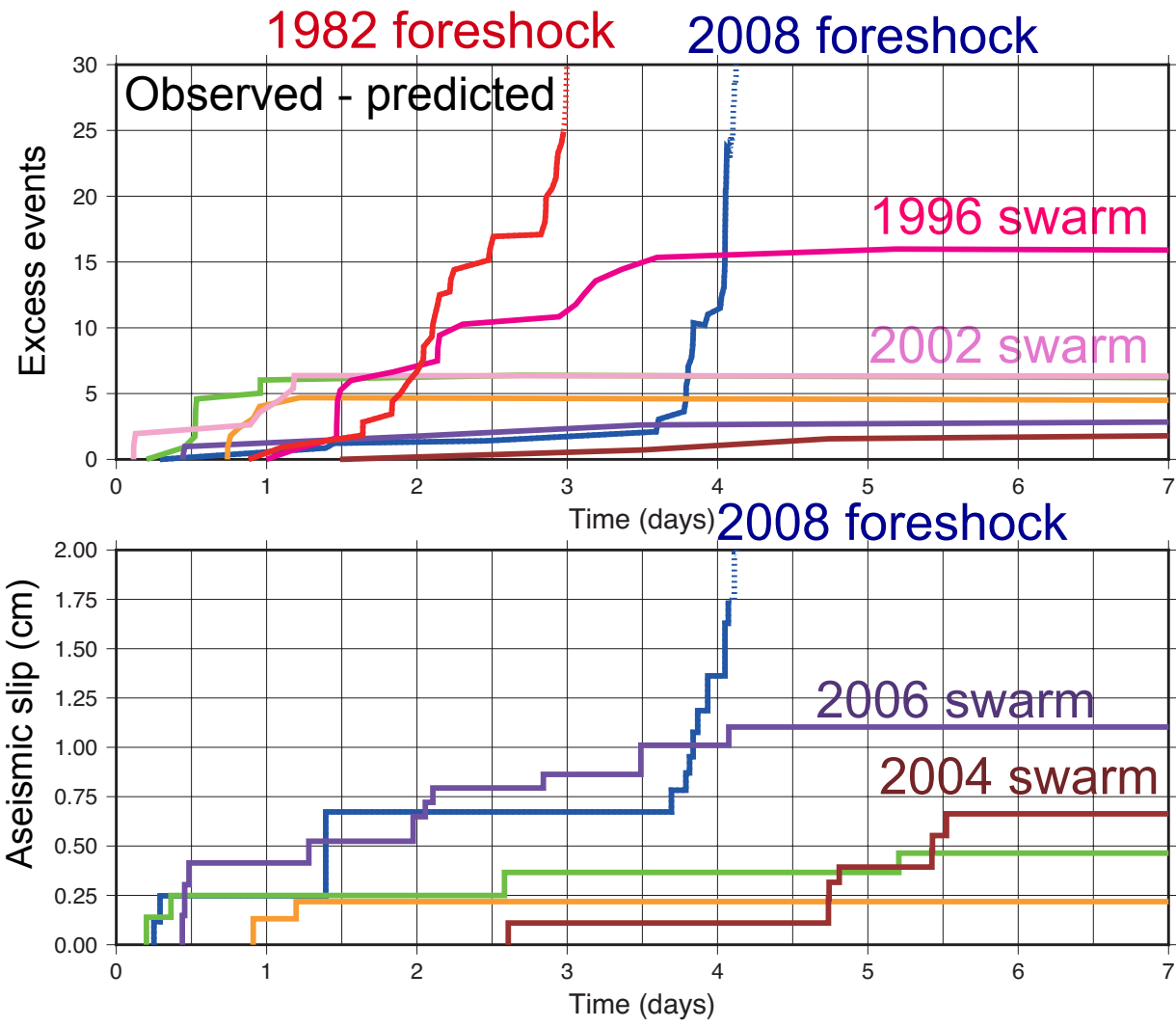
Comparison between foreshocks and swarms

- 5σ anomaly inexplicable by ETAS
  - 1982 foreshock
  - 2008 foreshock
  - 1996 swarm
  - 2002 swarm
- Triggered by phenomena other than earthquake-earthquake triggering
  - SSE



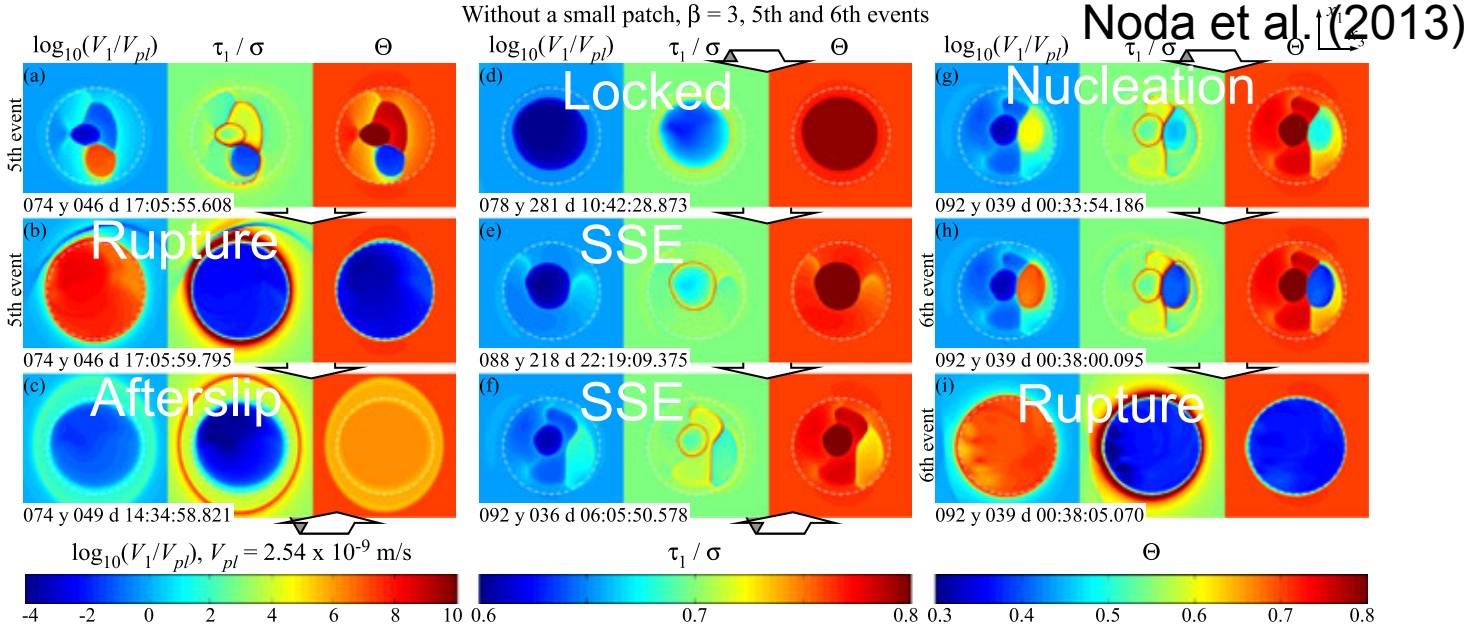
Further comparison between foreshocks and swarms

- 1982 foreshock and 2008 foreshock have the largest number of events inexplicable by ETAS
- Aseismic slip is the largest during 2008 foreshock
- SSEs preceding the 1982 and 2008 M7 may be larger than other SSEs that triggered swarms



SSEs related to unlocking of M7

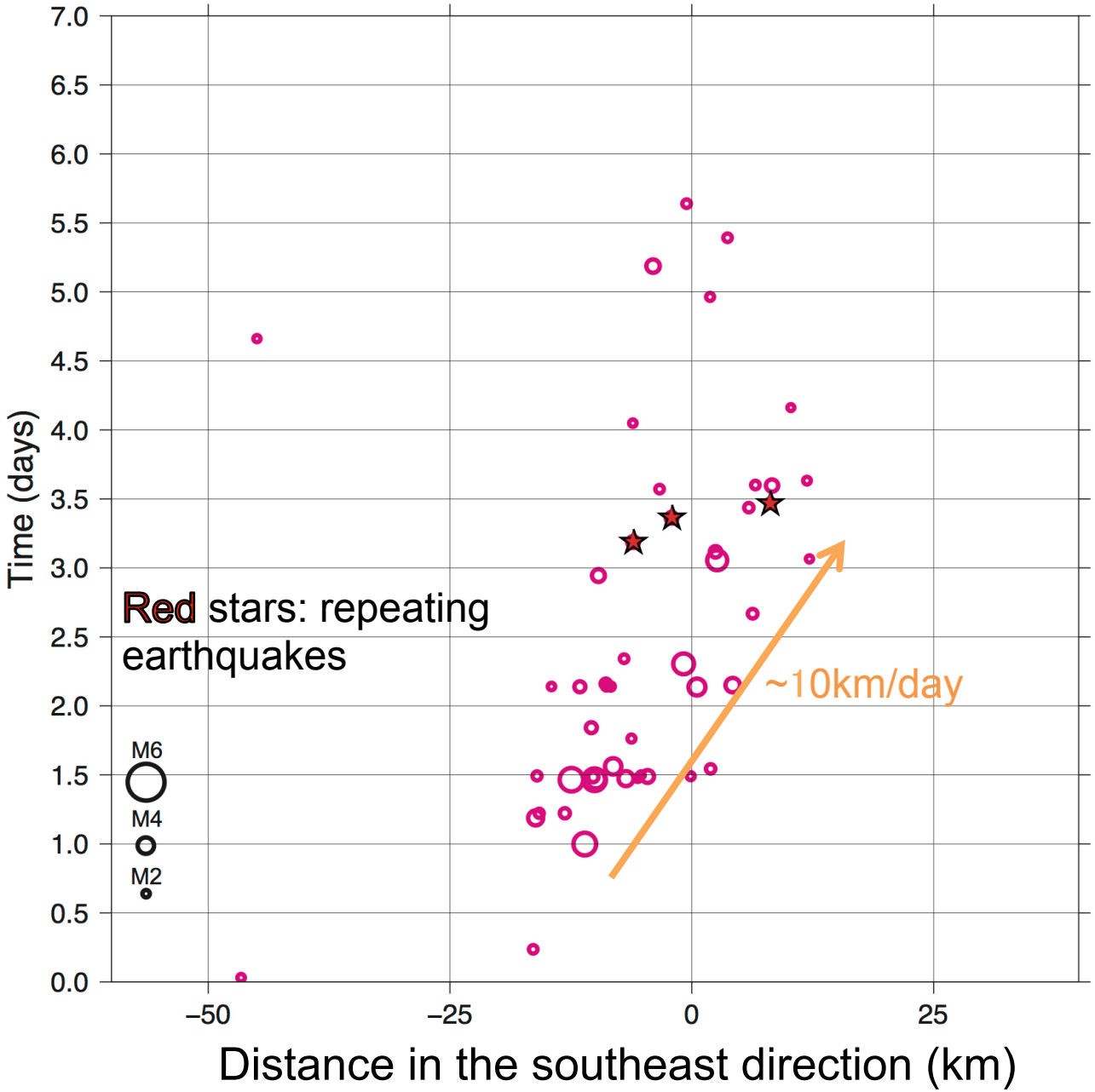
- Both ETAS and repeating earthquakes suggested recurring of SSEs in the source region of the M7 Ibaraki-Oki EQs
  - SSEs preceding the 1982 and 2008 M7 may be the largest
- SSEs spontaneously occur as the locked region shrinks due to plate loading e.g., Lapusta and Liu (2009); Noda et al. (2013)
  - One of SSEs grows and leads to the nucleation



Summary

- We investigated the possibility of recurring SSEs in Ibaraki-Oki
  - Reveal the history of swarm activity using ETAS during 1981-2008
  - Detect missing small events using Matched filter
  - Estimate the amount of aseismic slip using repeating earthquakes
- Both ETAS and repeaters suggested recurring of SSEs in the source region of the M7 Ibaraki-Oki EQs
  - Highly anomalous seismicity inexplicable by ETAS
  - Step-like increases in aseismic slip
  - SSEs preceding the 1982 and 2008 M7 might be the largest
- These SSEs can be interpreted as SSEs related to unlocking of the M7 source region
  - One of the SSEs might have grown and led to the nucleation of the 2008 M7 Ibaraki-Oki earthquake

Swarm in 1996



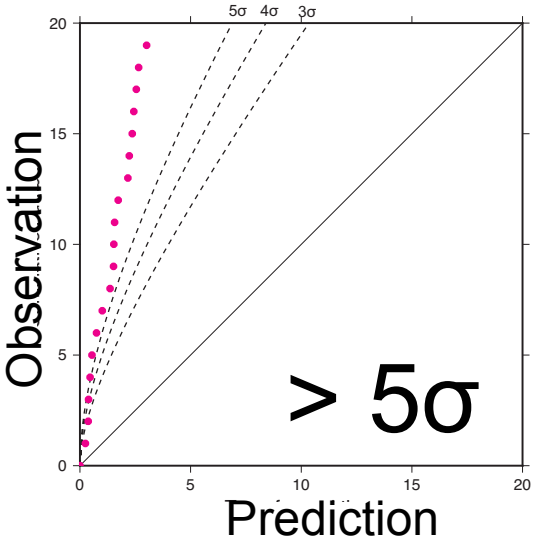
Swarm migrated to southeast

- About 10 km/day

The most anomalous event during 1981-2008

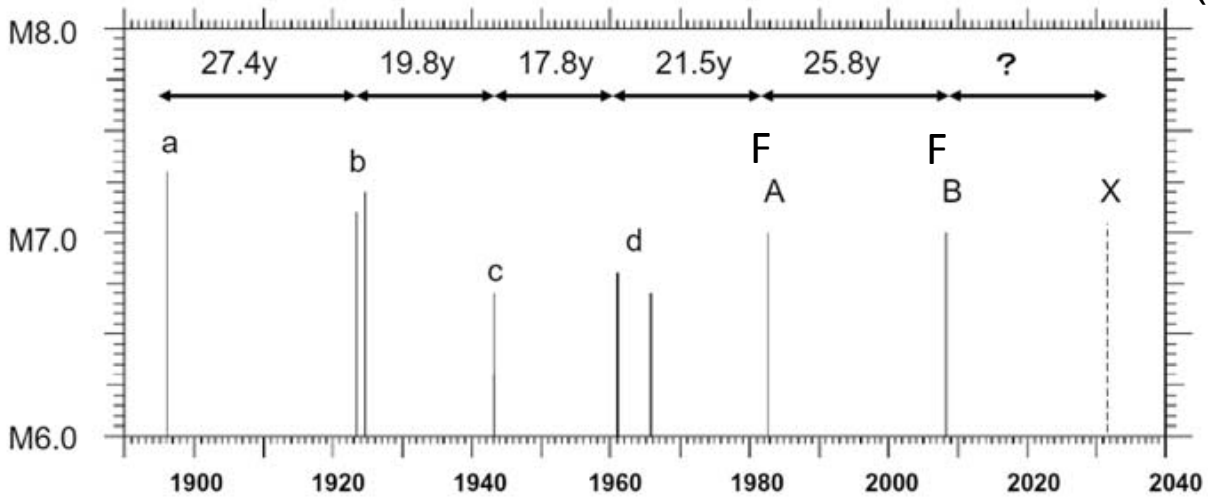
Observation
19events

Prediction
3events

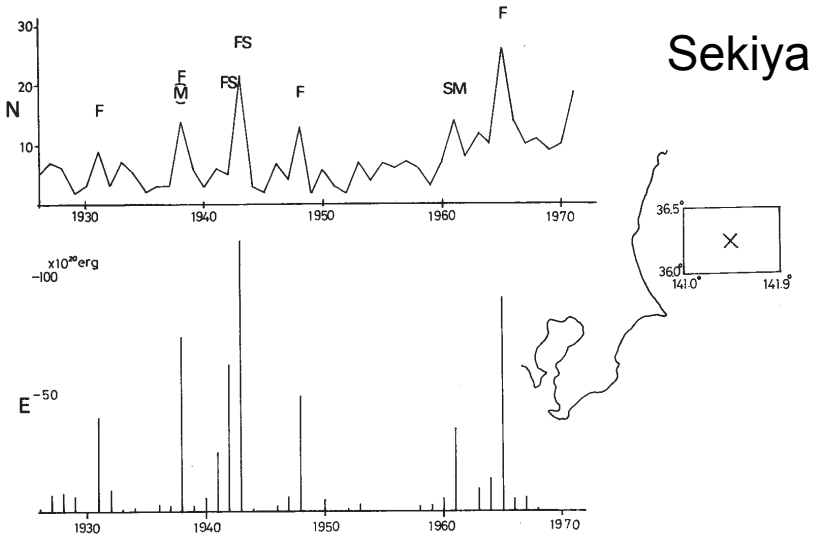


Supplement

Matsumura (2010)



Sekiya (1973)



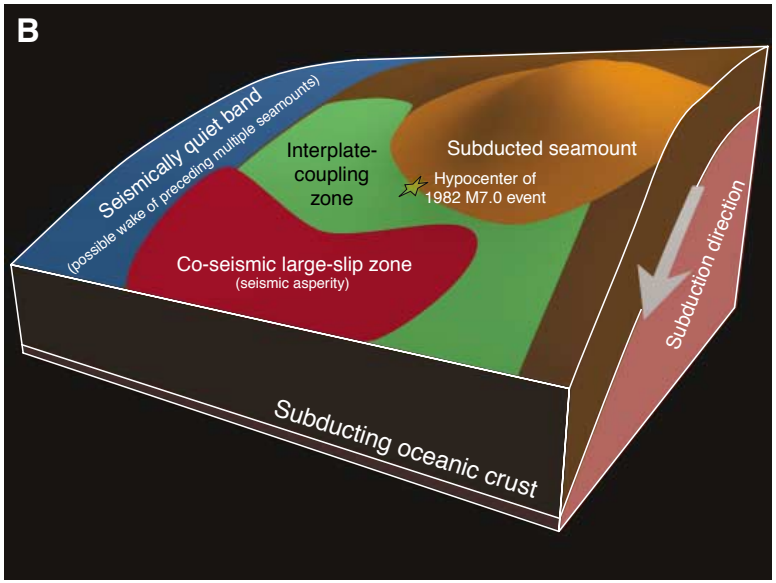
第 3 図　茨城県沖（ ×域 ）における地震活動の変動

Fig. 3　Variation of seismic activities in region X
(N: Number of earthquakes, E: Energy)

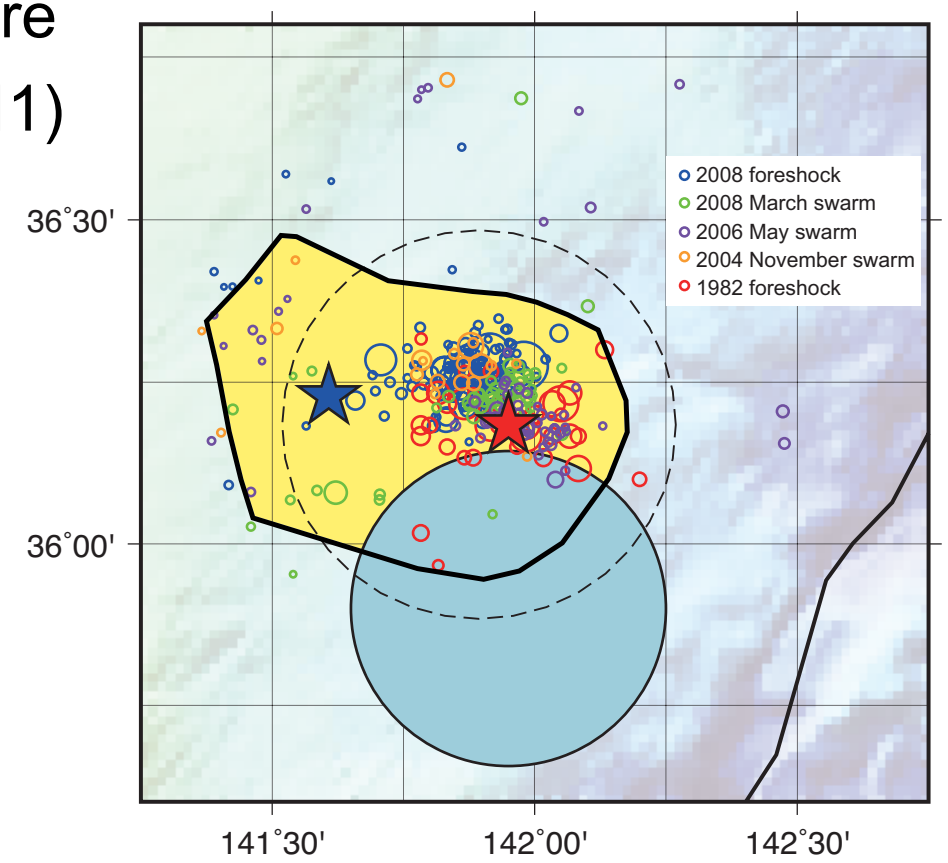
Supplement

Why do SSEs frequently occur in the Ibaraki-Oki?

- High pore-fluid pressure caused by subducted seamounts (Mochizuki et al., 2008)
- SSEs tend to occur in regions with high pore-fluid pressure (Saffer and Tobin, 2011)



Mochizuki et al. (2008)



Supplement

- Space Time ETAS model Ogata (1998)

$$\lambda(t,x,y) = \mu(x,y) + \sum_{\{k:\ t_k<t\}} \kappa(m_k) g(t-t_k) f(x-x_k, y-y_k; m_k).$$

Expected number of aftershocks

$$\kappa(m) = Ae^{\alpha(m-m_0)}$$

Probability density of aftershock lag times

$$g(t) = \frac{p-1}{c}(1+\frac{t}{c})^{-p}$$ ∵Modified Omori law

Probability density of aftershock locations

$$f(x,y;m) = \frac{q-1}{\pi D^2 e^{\gamma(m-m_0)}} \left(1 + \frac{x^2+y^2}{D^2 e^{\gamma(m-m_0)}}\right)^{-q}$$

Zhuang et al. (2005)