Systematic Investigation of Dynamic Earthquake Triggering in Japan

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Research Background

- Dynamically induced earthquakes might be less likely to occur in Japan than in other seismically active regions, as California and Greece (Harrington and Brodsky, 2006)

- In California, stress changes σ_d ~ 0.1 kPa trigger seismicity, in Japan 30 kPa or larger are required (van der Elst and Brodsky, 2010)

- However, in the case of the 2016 Kumamoto earthquake (M_{JMA}7.3), the triggering occurred at stress levels of just a few kPa (Enescu et al., 2016): Did the stress threshold level in Japan changed after the M9.0 Tohoku-oki earthquake?

Purpose

- Investigating the occurrence of dynamically triggered earthquakes in Japan after large earthquakes

- Investigating whether the threshold of dynamic triggering may have changed due to the 2011 Tohoku-Oki earthquake and why this threshold might have changed

Why This Research is Important

- By capturing changes in the occurrence of dynamically induced earthquakes, it is possible to understand the crustal seismogenic conditions (i.e., stress levels)
- Since in some rare occasions some relatively large earthquakes might be dynamically triggered (Fred et al., 2012, Tamura and Miyazawa, 2017), the study is also important for hazard assessment.

Current Investigation

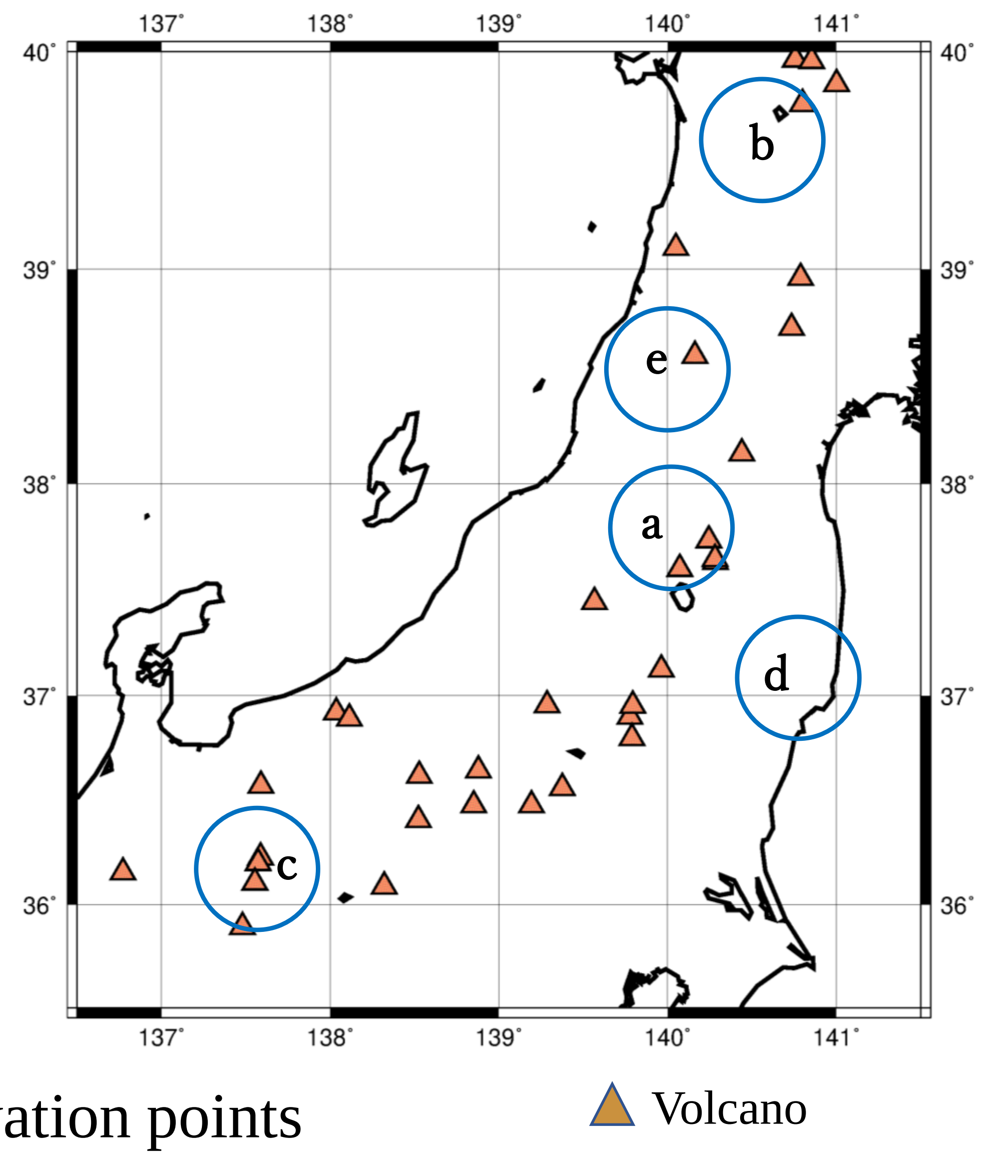
- Dynamic triggering of earthquakes in 5 regions of NE Japan, following 31 large earthquakes occurred worldwide, from 2004 to 2020. In all 5 regions earthquake swarms occurred following the 2011 M9.0 Tohoku-oki earthquake. Waveform data at Hi-net, V-net and F-net stations belonging to NIED were used for the analysis.

Data

Target areas

a. Yamagata-Fukushima border
b. Southwest side of Mt. Akita-Komagatake
c. Hida (Nagano - Gifu border)
d. Iwaki
e. Central Yamagata

In all these regions, earthquake swarms have occurred after the 2011 M9.0 Tohoku-oki earthquake (i.e., the triggering environment may have been also changing).



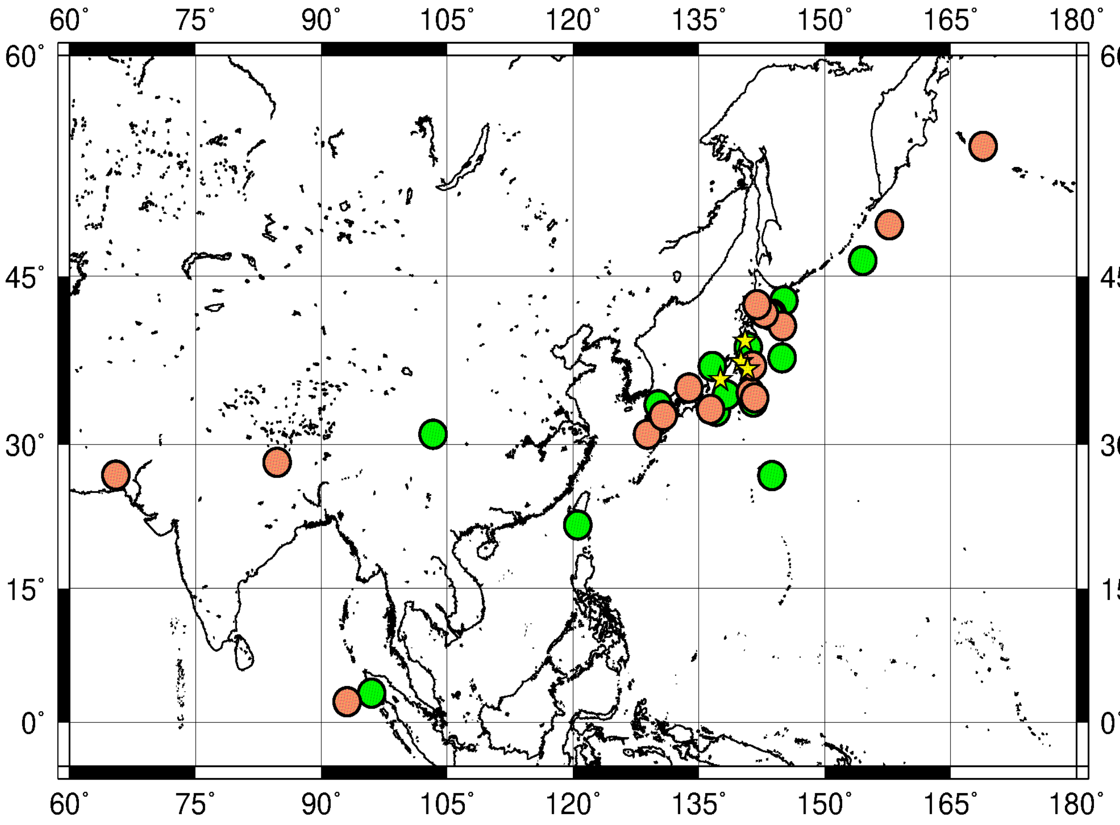
Remote EQs (see next slide):

- Depth ≦ 100 km
  → In order to observe surface waves
- Earthquakes more than 300 km away from the observation points
  → To minimize the effects of static stress changes and aftershocks
- Dynamic stress changes induced at the observation sites of $\sigma_d \geqq 1.0$kPa
  → It is quite unlikely to observe triggered seismicity for stress changes smaller than this threshold

Data Remote earthquakes

Before

Date & (Lat, Long)	Place	Mw
2004/05/30 & (34.251, 141.406)	East Off Kanto, Japan	6.5
2004/09/05 & (33.184, 137.071)	Southeast Off Mie Pref., Japan	7.4
2004/11/29 & (43.006, 145.119)	Off Kushiro, Japan	7.0
2004/12/26 & (3.295, 95.982)	Off Sumatra, Indonesia	9.0
2005/01/19 & (34.064, 141.491)	Eastern Off Kanto, Japan	6.6
2005/03/20 & (33.807, 130.131)	Western Off Fukuoka Pref., Japan	6.6
2005/11/15 & (38.107, 144.896)	Off Sanriku, Japan	7.0
2006/12/26 & (21.799, 120.547)	Taiwan	7.1
2007/01/13 & (46.243, 154.524)	East of Kuril Islands, Russia	8.1
2007/03/25 & (37.336, 136.588)	Off the Noto Peninsula, Japan	6.7
2008/05/12 & (31.002, 103.322)	Wenchuan, China	7.9
2008/06/14 & (39.030,140.881)	Iwate-Miyagi, Japan	6.9
2008/09/11 & (41.892, 143.754)	Off Tokachi, Japan	6.8
2009/06/05 & (41.824, 143.445)	Off Tokachi, Japan	6.4
2009/08/11 & (34.743, 138.264)	Suruga Bay, Japan	6.2
2010/12/22 & (26.901, 143.698)	Near Chichijima Island, Japan	7.4



:Before 2011 Tohoku-oki

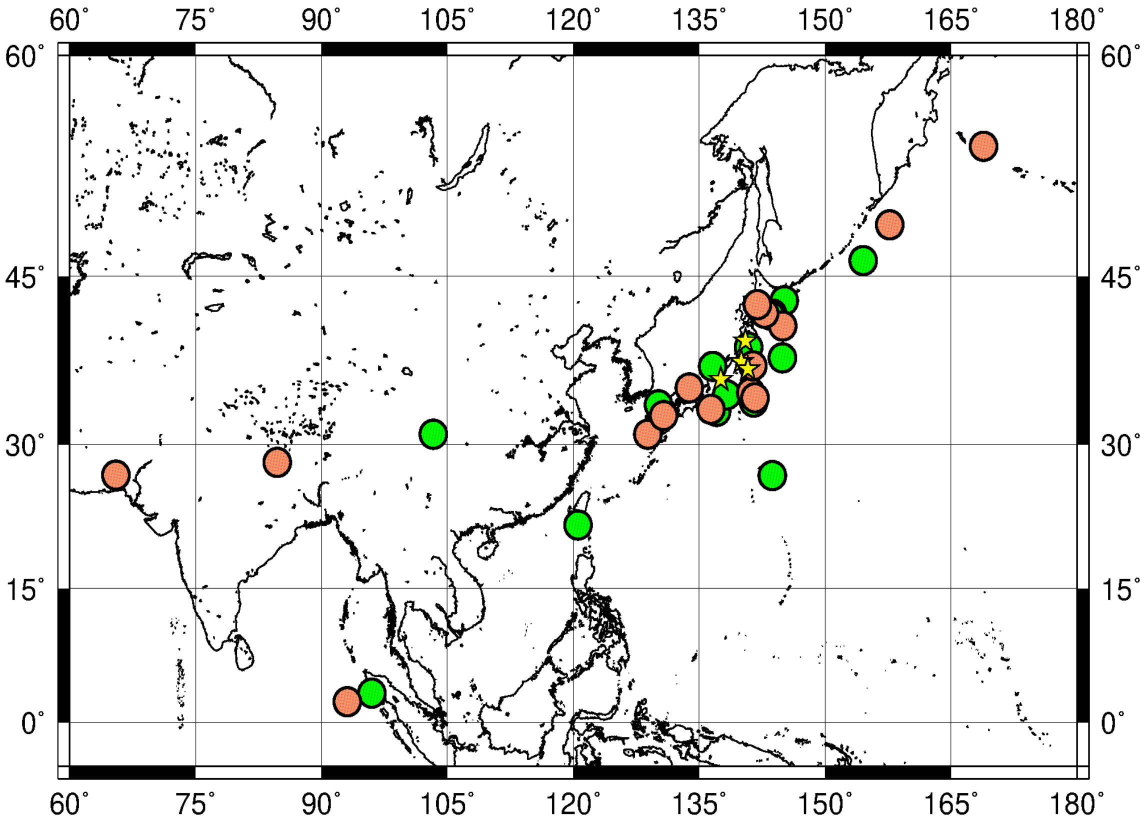
:After 2011 Tohoku-oki

:Local areas (previous slide)

Data Remote earthquakes

After

Date & (Lat, Long)	Place	Mw
2012/03/14 & (40.887, 144.944)	Off Sanriku, Japan	7.0
2012/04/11 & (2.327, 93.063)	Off Northern Sumatra, Indonesia	8.6
2012/06/06 & (34.943, 141.132)	Off Chiba Prefecture, Japan	6.1
2013/09/24 & (26.951, 65.501)	Pakistan	7.7
2015/04/25 & (28.231, 84.731)	Nepal	7.8
2015/11/14 & (31.001, 128.873)	Off Satsuma Peninsula, Japan	6.7
2016/01/14 & (41.972, 142.781)	Off Urakawa, Japan	6.7
2016/04/01 & (33.381, 136.390)	SE Off Mie Prefecture, Japan	5.9
2016/04/16 & (32.791, 130.754)	Kumamoto, Japan	7.0
2016/09/23 & (34.462, 141.637)	Eastern Off Kanto, Japan	6.2
2016/10/21 & (35.374, 133.809)	Central Tottori, Japan	6.2
2016/11/22 & (37.393,141.387)	Off Fukushima, Japan	6.9
2017/07/18 & (54.443, 168.857)	Commander Islands, Russia	7.7
2018/09/06 & (42.686, 141.929)	Middle Eastern Iburi, Japan	6.6
2020/03/25 & (48.964, 157.696)	Northwest Pacific	7.5



:Before 2011 Tohoku-oki

:After 2011 Tohoku-oki

:Local areas (previous slide)

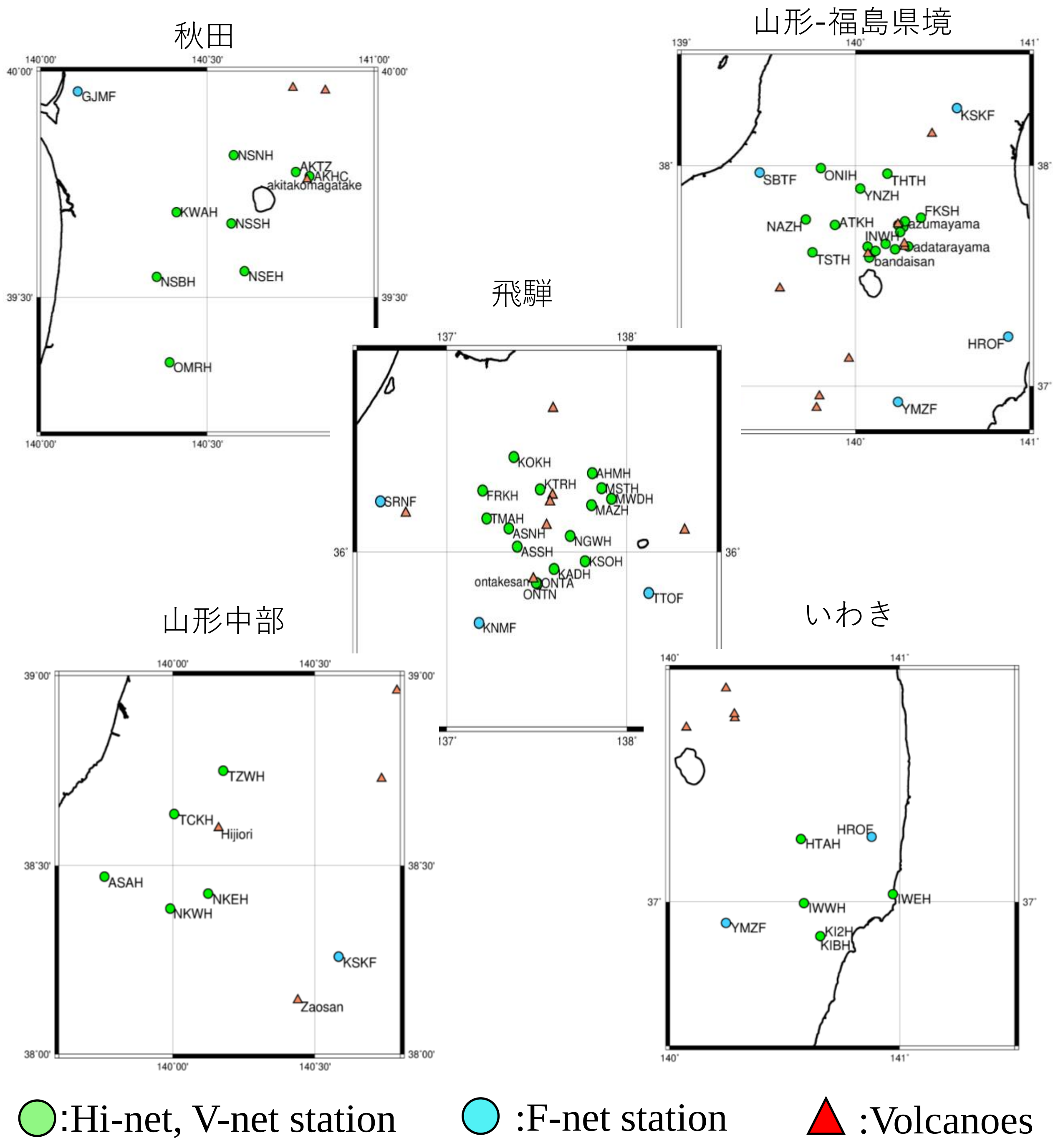
Data

Hi-net, V-net, F-net networks data (NIED)

- Data from 5 hours before to 1 hour after the arrival of P-wave
- Hi-net, V-net data filtered from 10-30Hz, F-net from 0.01 to 0.2Hz (for surface waves)

Methods (summary)

- Exclude cases of visually quasi-constant seismicity from further analysis
- Consider only Ts – Tp < 5s to define local EQs
- Compare timing of local EQs with surface wave train to define potentially triggered EQs – previous slide
- Calculate β-values (for the stations where local earthquakes were observed) – see next slide
- Calculate dynamic stresses σ_d – slide after the next
- Perform K-S 2-sample test to test for differences in triggering stress levels before/after 2011 Tohoku-oki EQ – slide after the next



Methods

④ β-value calculation

$$\beta = \frac{Na - N(\frac{Ta}{T})}{\sqrt{N(\frac{Ta}{T})(1-\frac{Ta}{T})}}$$

Na : No. of EQs occurred after the mainshock P-wave arrival
N : Total number of detected EQs (before and after P-wave)
Ta : Length of window, after P-wave arrival
T : Total length of time window (before + after)

(Aiken and Peng, 2014)

Analysis steps:
① Exclude from analysis cases of visually constant seismicity (as observed at Hi-net, V-net stations)
② Earthquake detection
③ Surface wave & local EQs: comparison
↓
④ β-value calculation (at the observation station)

Time window

Before： from 5 hours before the arrival of the P-wave to the arrival of the P-wave

After : from the arrival of 5 km/s wave until
- (i) the arrival of 2 km/s wave (if larger than 1000 s) OR
- (ii) 1000 s otherwise

$\beta \geq 1.96$:
the increase is statistically significant at 5% significance level (Hill and Prejean, 2018)

Methods

Analysis steps:
① Exclude from analysis cases of visually constant seismicity (as observed at Hi-net, V-net stations)
② Earthquake detection
③ Surface wave & local EQs: comparison
④β-value (at the observation station)
⑤ σ_d calculation
⑥ K-S 2-sample test

⑤ Maximum dynamic stress calculation σ_d

（for β≧1.96 stations only）

$$\sigma_d = \frac{Gu'}{V_{ph}}$$

G：Shear modulus
u'：peak particle velocity
V_{ph}：Phase velocity

(Jaeger and Cook 1979)

G=30GPa
V_{ph}=4.1km/s (Love waves)
V_{ph}=3.5km/s (Rayleigh waves)

(e.g., Enescu et al., 2016)

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⑥ Kolmogorov-Smirnov 2-sample test

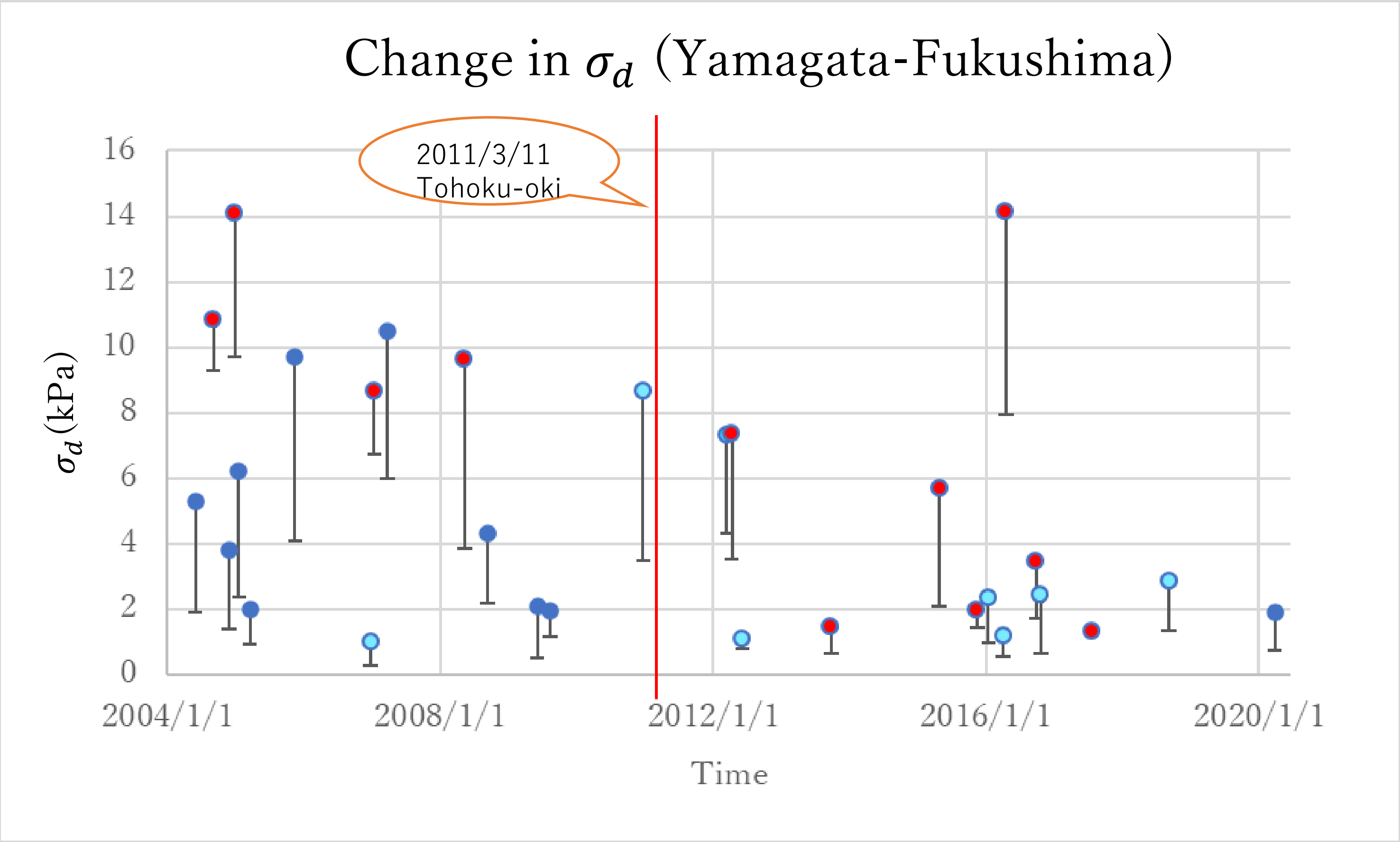
- A nonparametric tests to determine if the two distributions are different

Null hypothesis: "The distribution of σ_d for the triggered earthquakes that occurred before and after the Tohoku-Oki earthquake is the same"

→ If the p value is 0.05 or less, the null hypothesis can be rejected at the significance level of 5%.

Results

Largest σ_d at stations in the Yamagata-Fukushima border region, at the passage of surface waves from remote earthquakes, from 2004 – 2020 (bar reflects range of values).



<u>Minimum σ_d at which triggering was detected:</u>

- Before Tohoku-oki: 8.7kPa
- After Tohoku-oki: 1.3kPa

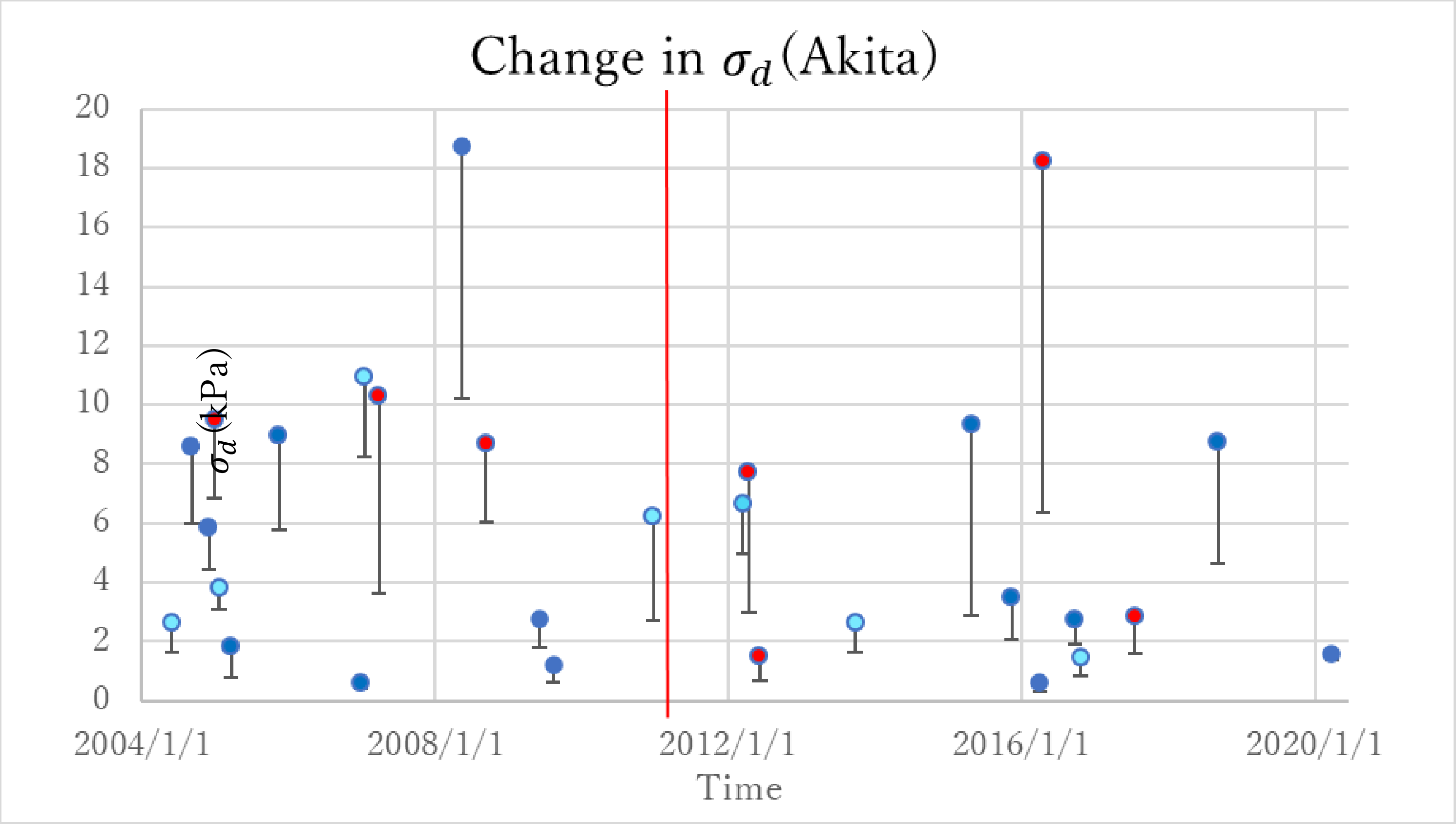
K-S 2-sample test:
p-value: 0.03

→ Significance at 5% level

: Triggered earthquakes (β≥1.96)
: Earthquakes detected, but β<1.96
: No earthquakes were detected

Results

Largest σ_d at stations in the SW side of Akita-Komagatake volcano region, at the passage of surface waves from remote earthquakes, from 2004 – 2020 (bar reflects range of values).



- : Triggered earthquakes (β≥1.96)
- : Earthquakes detected, but β<1.96
- : No earthquakes were detected

<u>Minimum σ_d at which triggering was detected:</u>

・Before Tohoku-oki: 8.7kPa

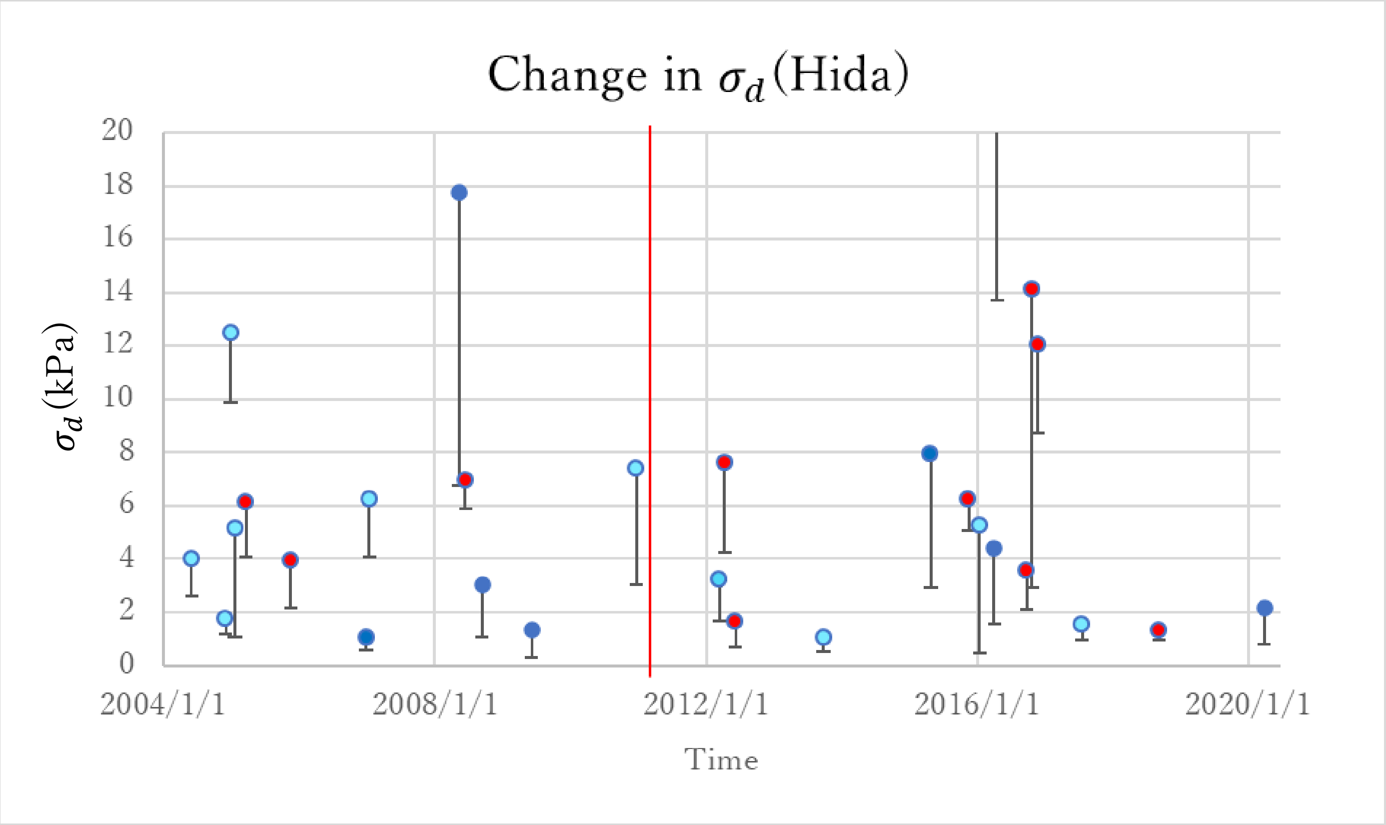
・After Tohoku-oki: 1.5kPa

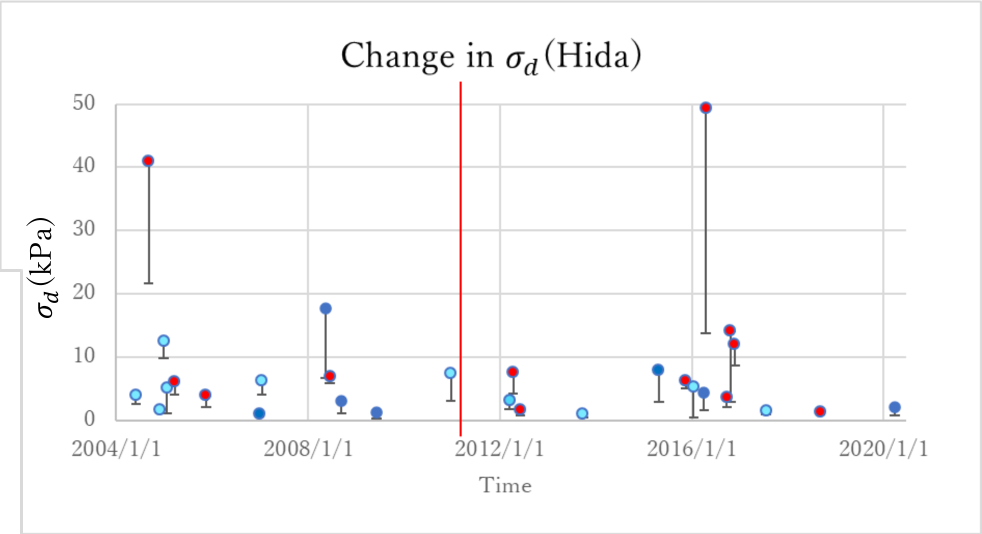
K-S 2-sample test:
p-value: 0.23

→ Does not pass the significance test at 5% level

Results

Largest σ_d at stations in the Hida region, at the passage of surface waves from remote earthquakes, from 2004 – 2020 (bar reflects range of values).





- : Triggered earthquakes (β≥1.96)
- : Earthquakes detected, but β<1.96
- : No earthquakes were detected

<u>Minimum σ_d at which triggering was detected:</u>

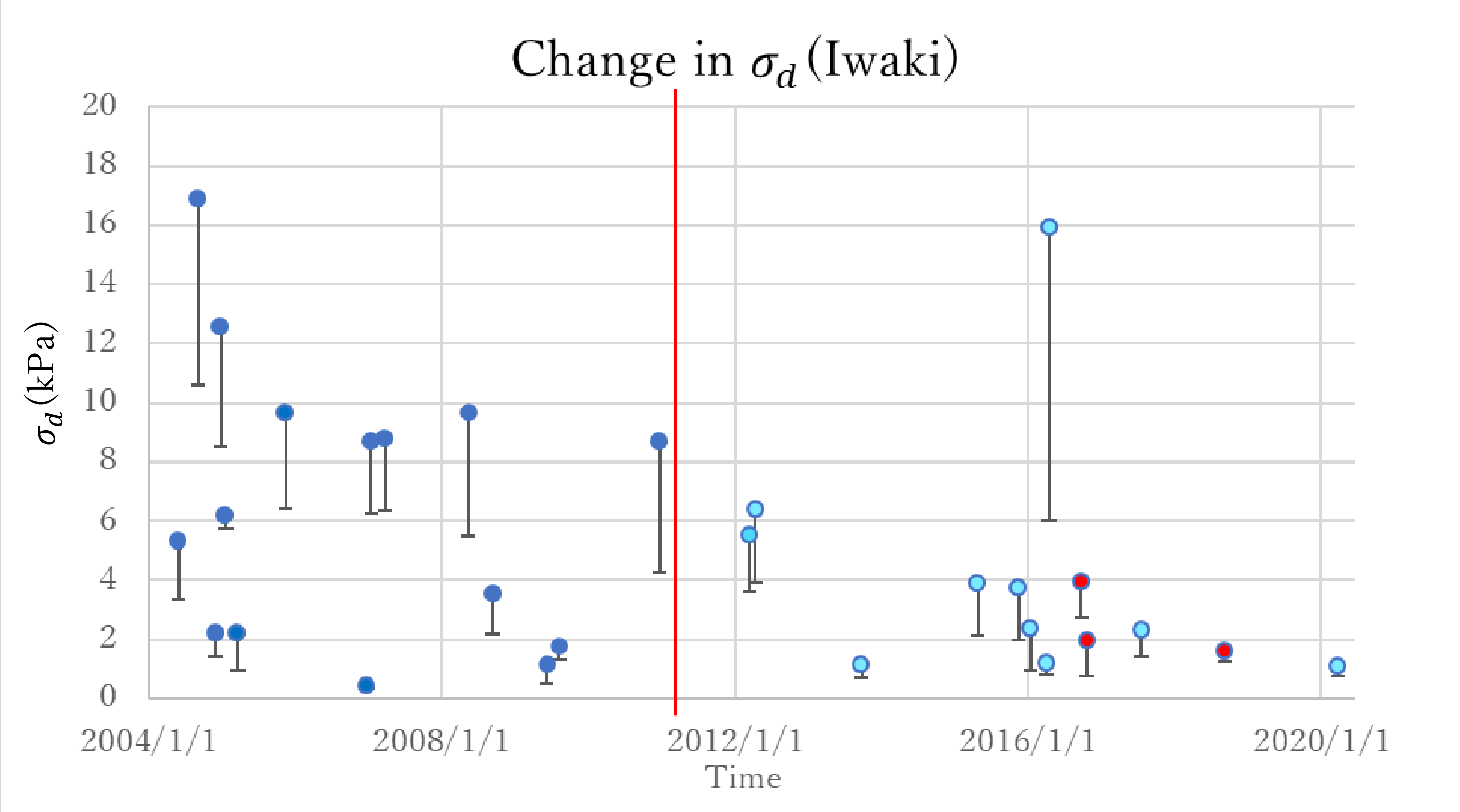
- Before Tohoku-oki: 3.9kPa
- After Tohoku-oki: 1.3kPa

K-S 2-sample test:
p-value: 0.84

→ Does not pass the significance test at 5% level

Results

Largest σ_d at stations in the Iwaki region, at the passage of surface waves from remote earthquakes, from 2004 – 2020 (bar reflects range of values).



<u>Minimum σ_d at which triggering was detected:</u>

- Before Tohoku-oki: ー
- After Tohoku-oki: 1.6kPa

→ Change in triggering environment

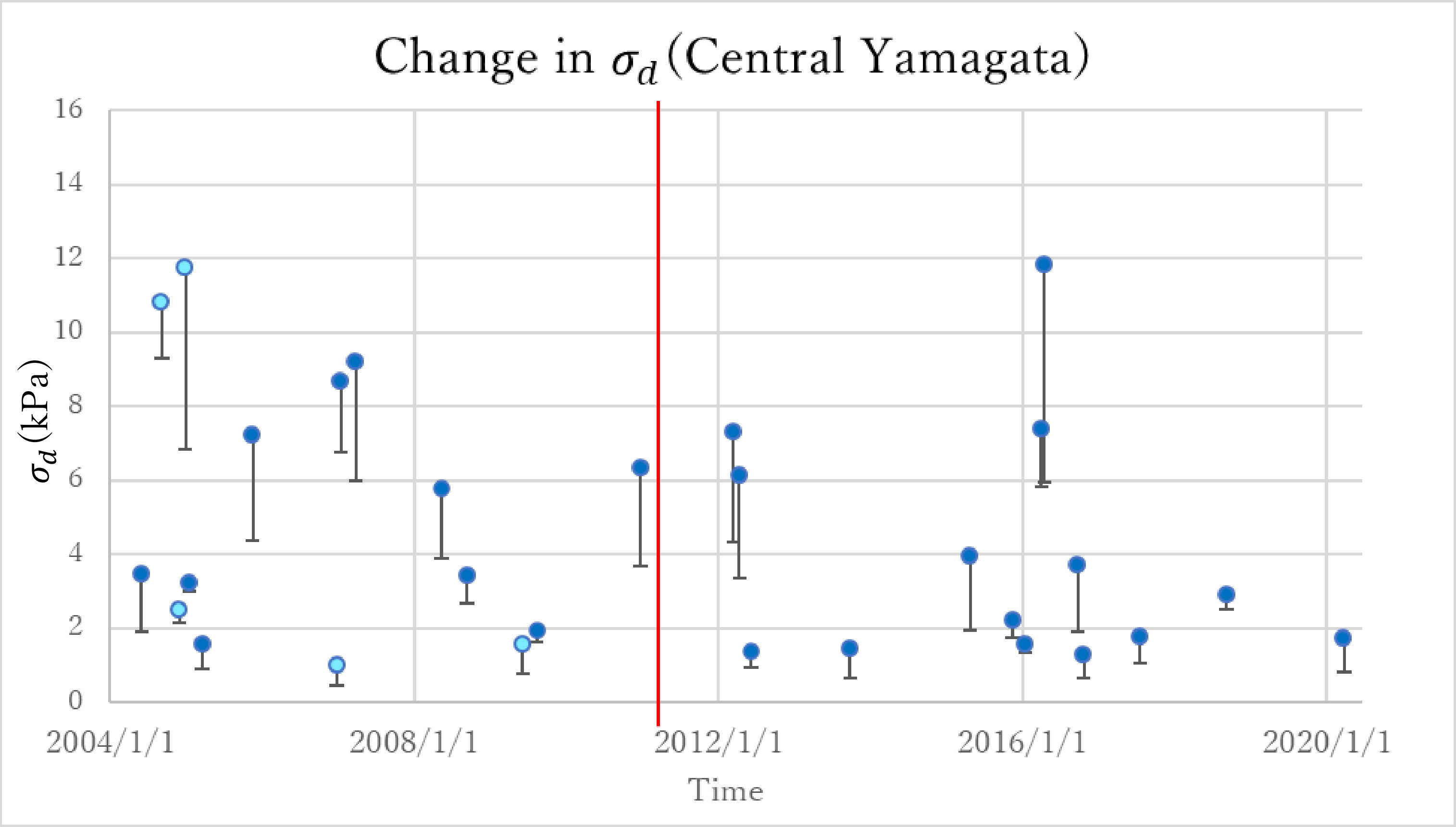
: Triggered earthquakes (β≥1.96)

: Earthquakes detected, but β<1.96

: No earthquakes were detected

Results

Largest σ_d at stations in the central Yamagata region, at the passage of surface waves from remote earthquakes, from 2004 – 2020 (bar reflects range of values).



→ No triggering

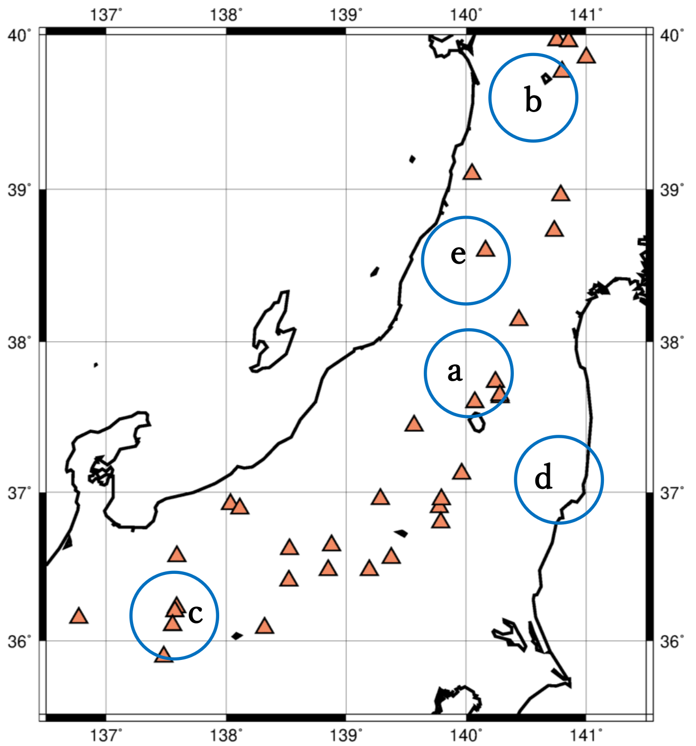
: Triggered earthquakes (β≥1.96)

: Earthquakes detected, but β<1.96

: No earthquakes were detected

Discussion Largest σ_d and p − value (summary)

Place	Dynamic stresses before Tohoku-oki EQ (kPa)	Dynamic stresses after Tohoku-oki EQ (kPa)	p-value
a. Yamagata-Fukushima border	8.7 kPa	1.3 kPa	0.03
b. SW of Akita-Komagatake volcano	8.7 kPa	1.5 kPa	0.23
c. Hida	3.9 kPa	1.3 kPa	0.84
d. Iwaki	— kPa	1.6 kPa	—
e. Central Yamagata	— kPa	— kPa	—



a~d regions together, p-value = 0.04: statistically significant

➢ Yamagata-Fukushima・Akita・Hida : values smaller than in previous studies

Possible reasons:

- Few studies of earthquake dynamic triggering at low thresholds
- This study also includes triggered earthquakes that are slightly delayed (up to 1 hour)

➢ The threshold after the Tohoku-oki earthquake was smaller than before the Tohoku-oki earthquake, except for the central part of Yamagata.

Discussion

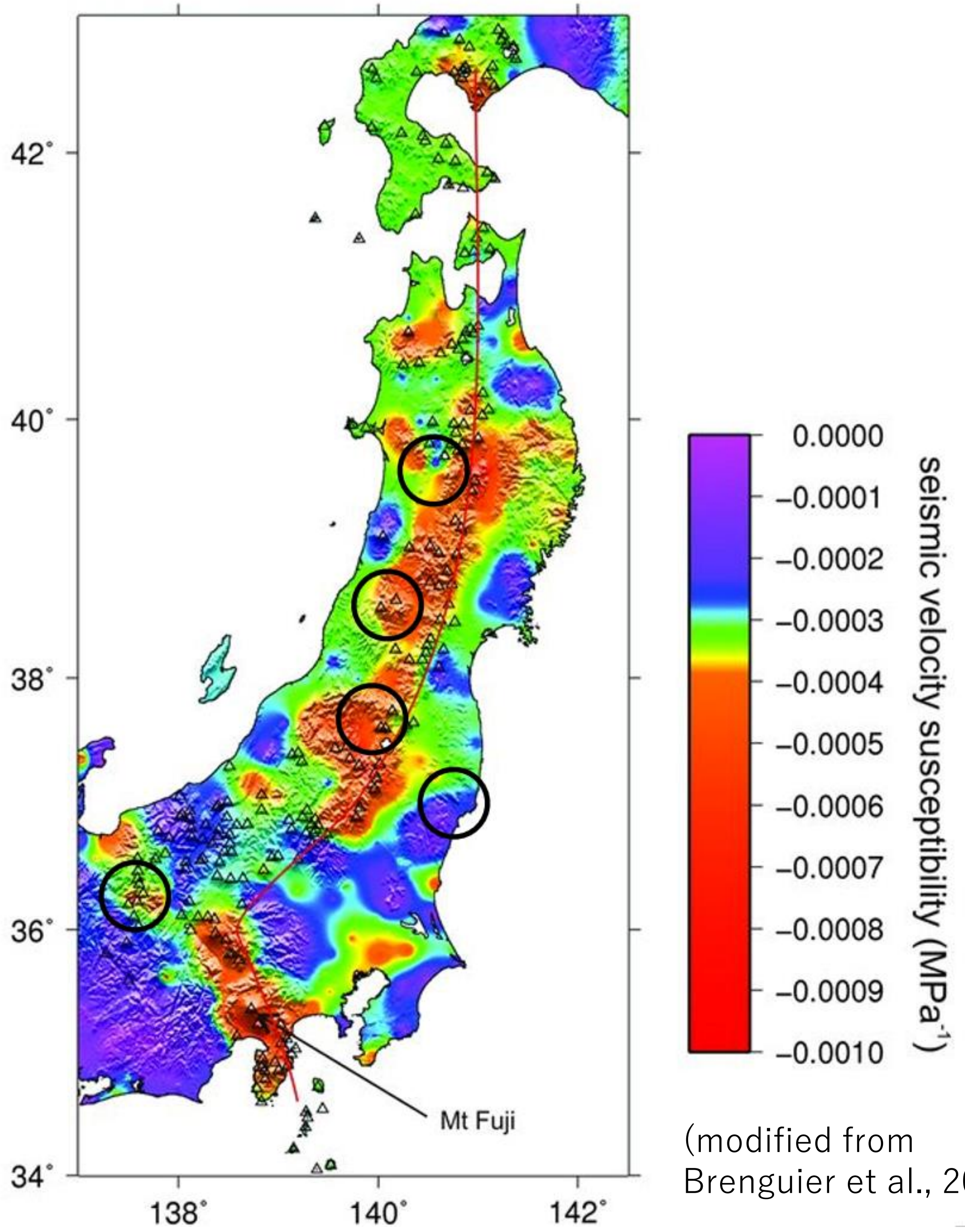
- Pressurized crustal fluids in volcanic regions

- Areas of decreased seismic velocity susceptibility after Tohoku-oki EQ - Red areas may indicate decrease in normal stress and increase in pore water pressure (Brenguier et al., 2014)

  ⇒ Fault strength decreased, making triggered earthquakes more likely to occur

- Central Yamagata is a red area, but the triggering environment did not change

- In the Iwaki area, the triggering environment has changed, although it is not a red area



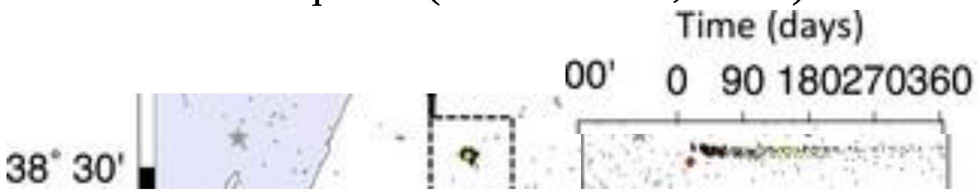
(modified from Brenguier et al., 2014)

Discussion

Central Yamagata region

- The trigger environment may have changed only at short times after
- Brenguier et al. (2014) uses data from the first 5 days after Tohoku-oki EQ

The earthquake swarm subsided 360 days after the Tohoku-oki earthquake (Okada et al., 2015)



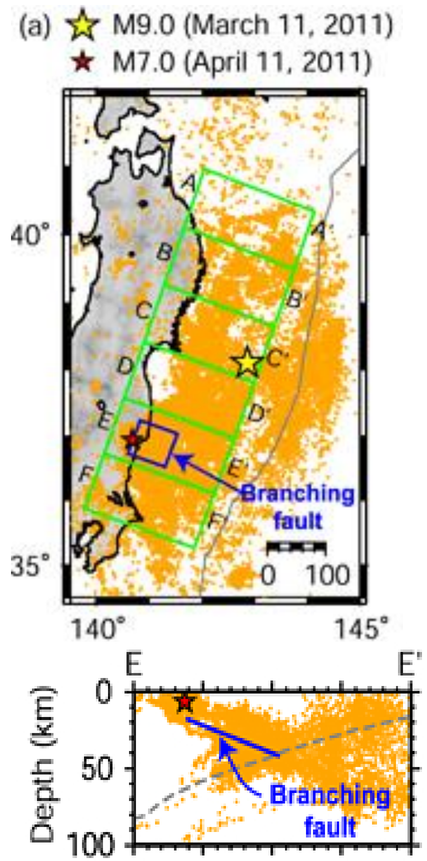
(modified from Okada et al., 2015)

The first remote EQ used in this study occurred on March 14, 2012

→ Possibility of returning to previous state within one year

Iwaki region

- Branching fault formed from the subduction zone near Iwaki to Fukushima-Ibaraki border (Imanishi et al., 2012)
- Hot spring water spilled after the Iwaki earthquake on April 11, 2011 (Sato et al., 2020)
- Branching fault may play a role in raising fluid from the subduction zone (Togo et al., 2014)

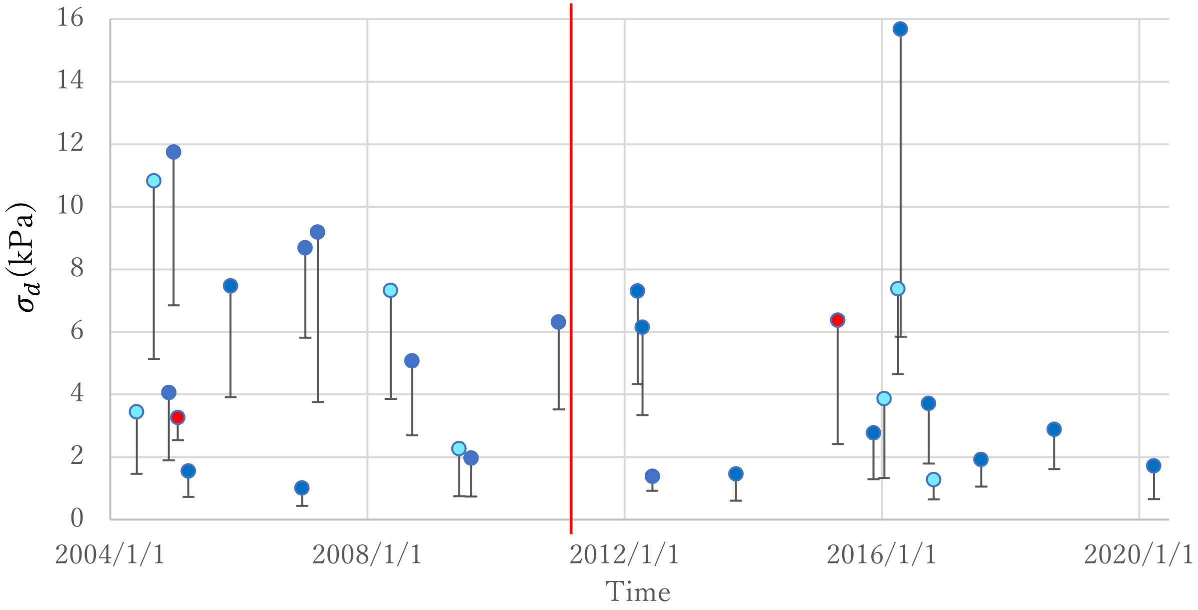


(Imanishi et al., 2012)

→ The branching fault contributed to increase the pore water pressure and changed the triggering environment

Discussion

Area that is not red and without earthquake swarms (Miyagi)



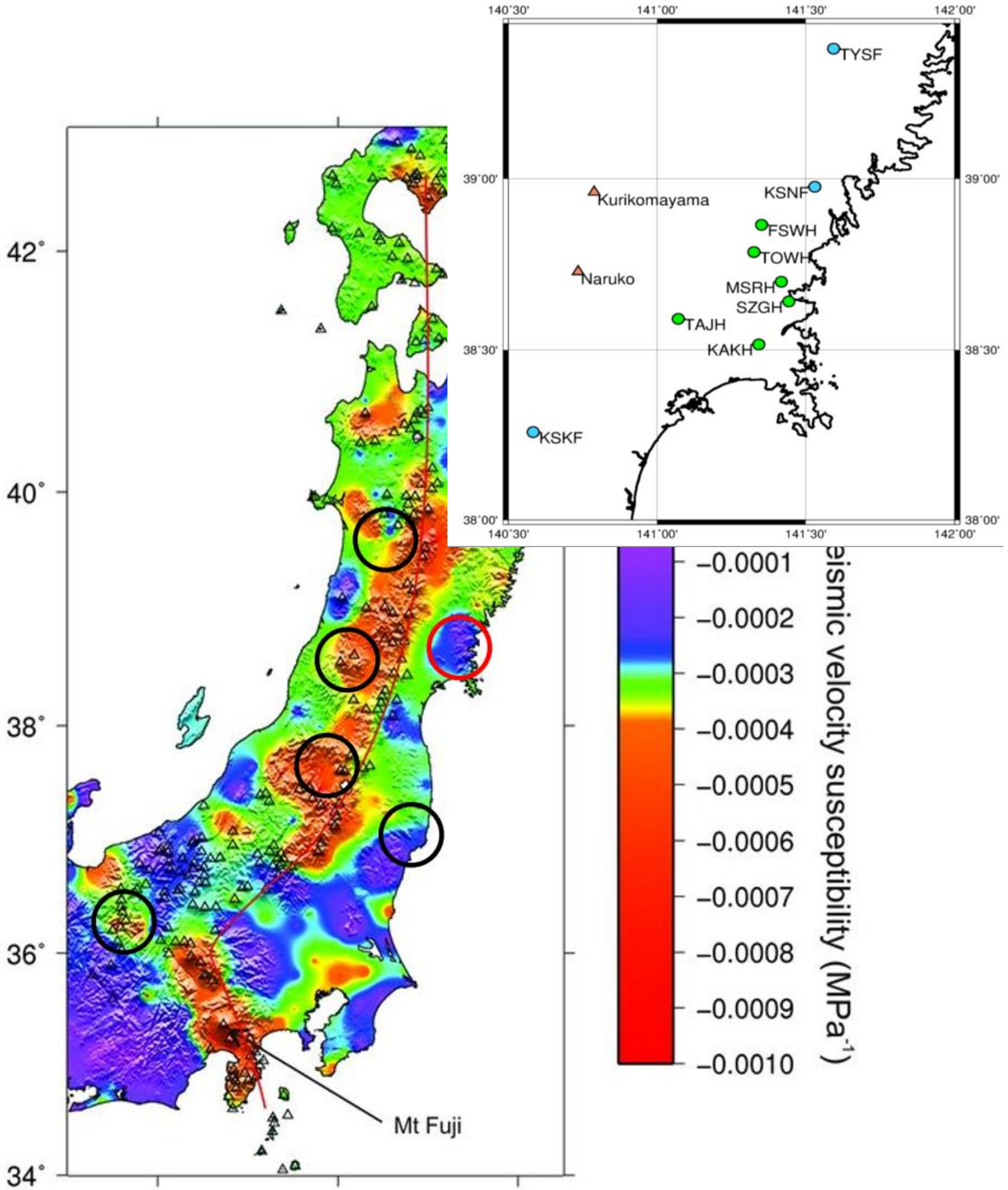
- ● : Triggered earthquakes (β≥1.96)
- ● : Earthquakes detected, but β<1.96
- ● : No earthquakes were detected

<u>Minimum σ_d at which triggering was detected:</u>

・Before Tohoku-oki: 3.3 kPa

・After Tohoku-oki: 6.4 kPa

No decrease of σ_d



(modified from Brenguier et al., 2014)

Conclusions

- We investigated the occurrence of triggered earthquakes in six regions of northeast Japan after 31 large earthquakes that occurred worldwide, between 2004 and 2020. The dynamic stress change triggering threshold was one order smaller than in previous studies for Japan, but larger than for California.

- The dynamic stress change threshold in three volcanic areas where earthquake swarms occurred after the 2011 Tohoku-oki earthquake was smaller after the before the megathrust event.

- Crustal pressurized fluids in volcanic areas, after the 2011 Tohoku-oki earthquake, and the "branching fault" acting as a conduit for the rise of fluids in the Iwaki region may have contributed to the change of the triggering environment.