~~Remote triggering in Japan before and after the 2011 M9.0 Tohoku-oki earthquake: Study cases and implications for earthquake nucleation~~

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National Central University, Taiwan, 2018

Remote triggering of earthquakes as a possible stress-meter: the case of the 2016 M7.3 Kumamoto (Japan) mainshock

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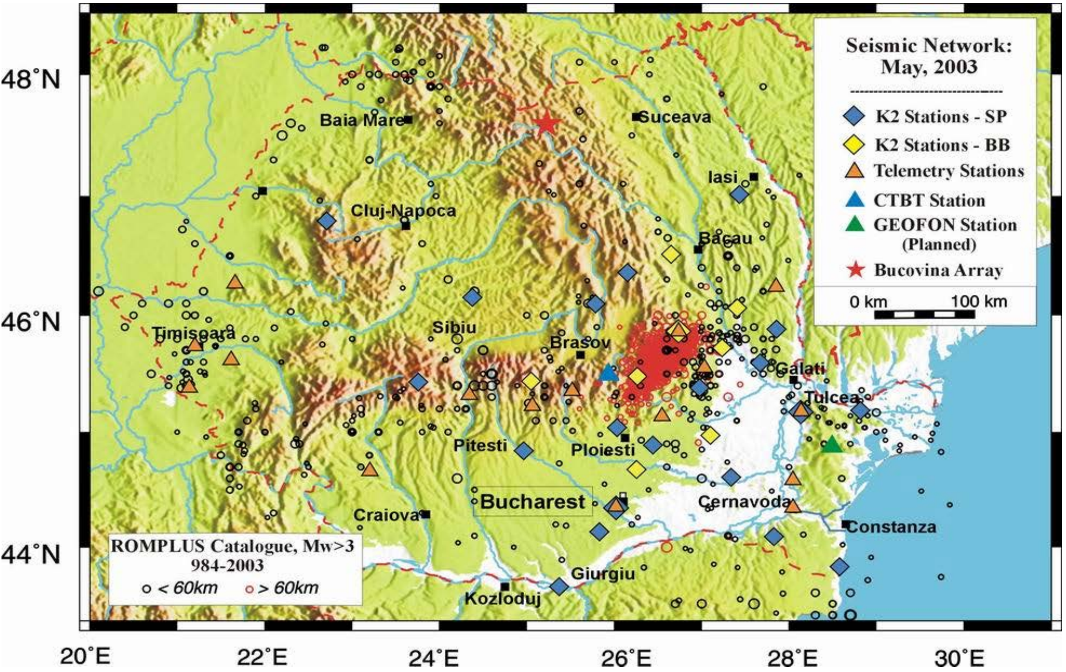
Reference papers:

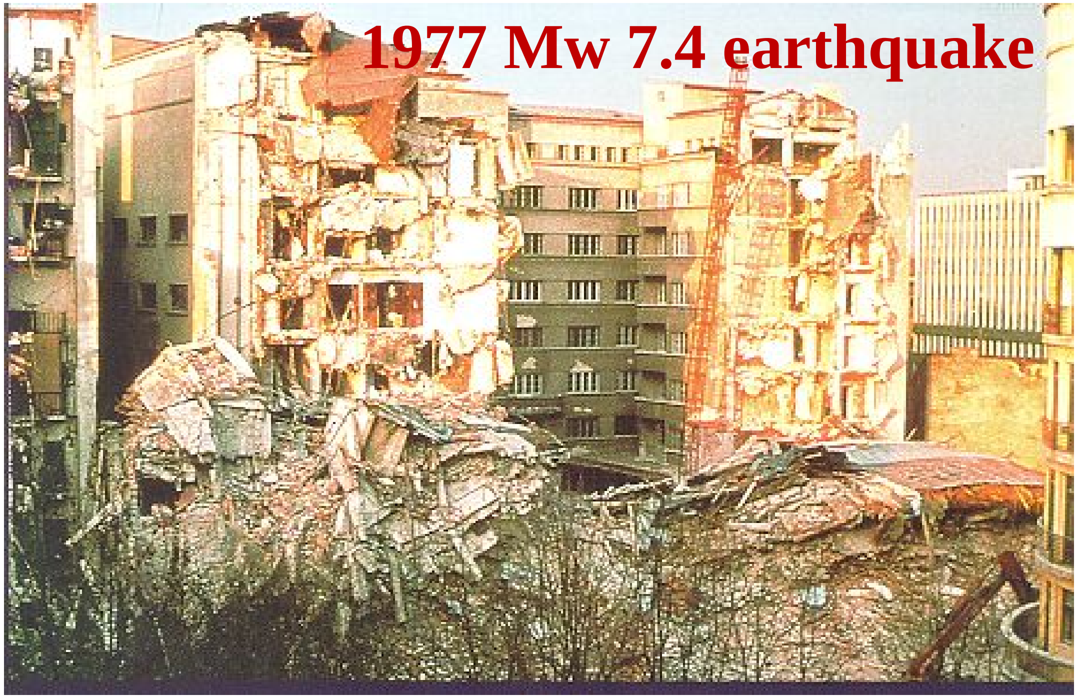
Enescu, B., K. Shimojo, A. Opris & Y. Yagi, Remote triggering of seismicity at Japanese volcanoes following the 2016 M7.3 Kumamoto earthquake, Earth, Planets and Space, 68:165, DOI: 10.1186/s40623-016-0539-5, 2016.

Opris, A., Enescu, B., Yagi, Y., and J. Zhuang, Triggering and decay characteristics of dynamically activated seismicity in Southwest Japan, Geophys. J. Int., 212, 2, 1010-1021, doi: 10.1093/gji/ggx456, 2018.



Romania is a seismic country, known for its intermediate-depth (60 – 200 km) earthquakes.

The largest earthquakes (like the 1977 Mw7.4 Vrancea earthquake) can be very destructive.



1977 Mw 7.4 earthquake

Career steps…

Education:

- 1995年6月 ： 学士, 国立Bucharest大学（Romania）地球物理学 部地質・地球物理学科
- 2001年12月: 物理学博士, 国立Bucharest大学 大学院物理学研究科
- 2004年3月 ： 博士（理学）, 京都大学 大学院理学研究科

Work:

- 1995年7月ー2000年3月：研究員, 国立地球物理学研究所（Romania）地震研究部
- 2004年4月ー2007年2月：特別研究員, 京都大学防災研究所
- 2007年3月ー2008年8月：特別研究員, 地球科学研究センター（GFZ）（Germany）
- 2008年9月ー2012年7月 ：特別研究員, (独) 防災科学技術研究所 (NIED)
- 2012年8月一2016年3月 ： 准教授, 筑波大学命環境科学研究科地球進化科学専攻
- 2016年4月 ～ ： 准教授,京都大学 大学院 理学研究科 攻地球物理学教室

Main directions of study

1. <u>早期余震活動の研究</u>
   ・本震発生から1日以内に発生した余震
   ・Hi-netの地震波形データ及び気象庁（JMA）地震Catalogを使用
   (e.g., Enescu et al., JGR, 2007; Enescu et al., BSSA, 2009; Marsan & Enescu, JGR, 2012; Sawazaki & Enescu, JGR, 2014; Shimojo et al., GRL, 2014)

2. <u>地震及び非火山性微動の静的・動的Triggering　（誘発地震）</u>
   地震活動と応力変化の関係；応力変化から地震活動レートを予測
   (e.g., Enescu & Ito, Tectonophysics, 2005; Aoi et al., Nature Geoscience, 2010; Toda & Enescu, EPS, 2011; Enescu et al., GRL, 2012; Enescu et al., 2016)

3. <u>地震活動の時空間パターン（特に大地震の前後）</u> (e.g., Enescu & Ito, Tectonophysics, 2001; Tormann et al., Nature Geoscience, 2015)

4. <u>高分解能三次元速度構造と震源決定</u>
   (e.g., Enescu & Ito, Tectonophysics, 2005; Koulakov et al., G3, 2010)

5. <u>測地記録と地震波干渉法を利用した地殻構造の時間変化</u>
   (Enescu et al., 2010; Ueno et al., JGR, 2010)

EQ Triggering

Near-field: within a few fault-length distance from the mainshock

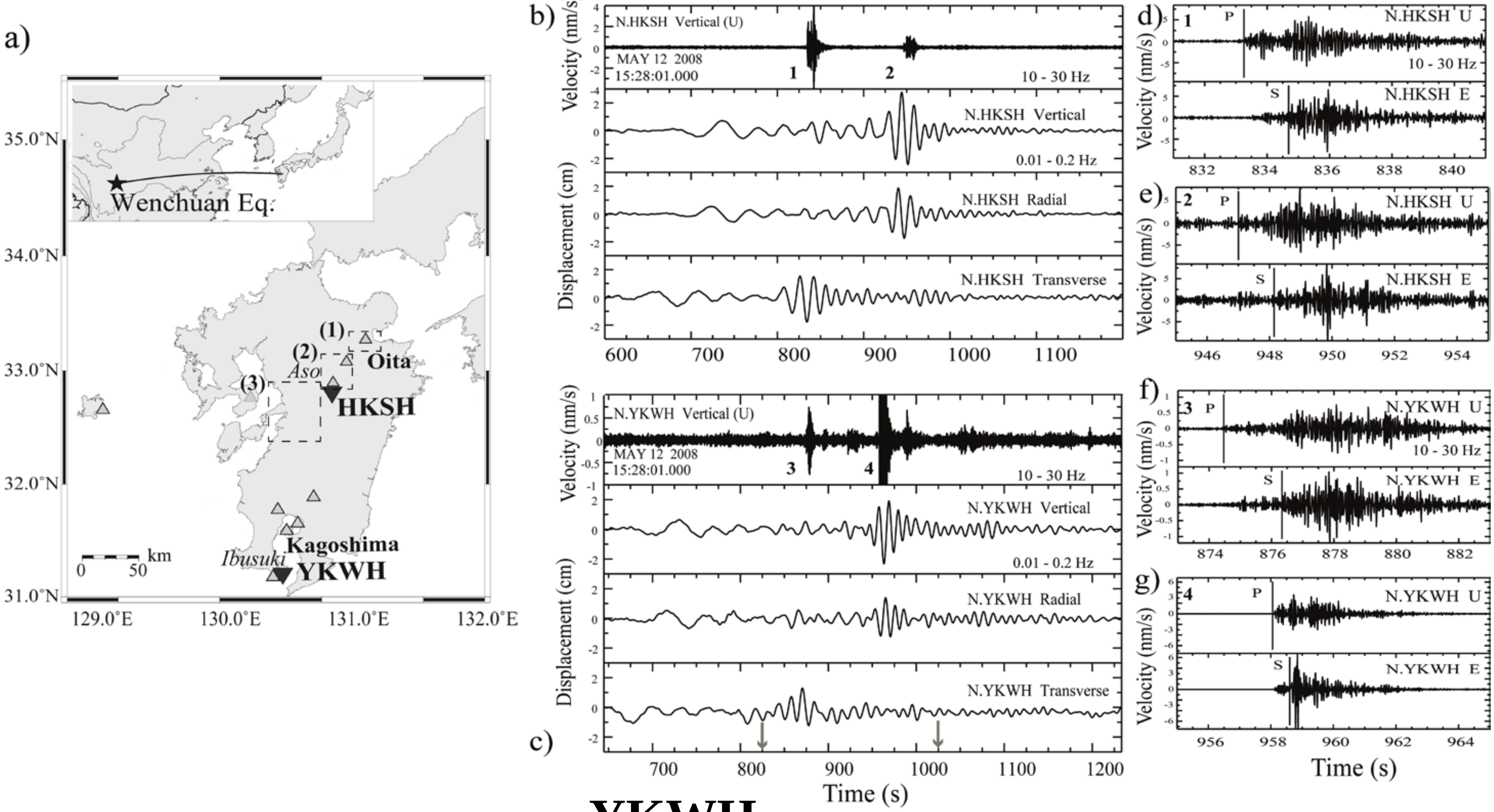
- Triggering by static (permanent) stress changes (ΔCFS or ΔCFF), due to **co- and post-seismic slip** on the mainshock fault; static stress attenuates relatively fast with distance, as ~D^{-3};
- Triggering due to excitation of crustal fluids (e.g., a reduction of **normal stresses** after a large mainshock and the existence of **high pressure fluids** may facilitate fluid migration within the fault zone, thus triggering EQs).

Far-field: up to thousands of kilometers from a large earthquake

- Triggering by dynamic stresses due to passage of seismic waves; in general, triggers small earthquakes (e.g., the 2008 M8.0汶川大地震 earthquake triggered small events in Kyushu, Japan); dynamic stress attenuates slower with Distance, as ~$D^{-3/2}$, for the surface waves;
- Triggering by fluid movement, excited by the passage of surface waves.

Evidence of dynamic triggering in **Kyushu** from the 2008 Mw7.9 **Wenchuan** earthquake

HKSH



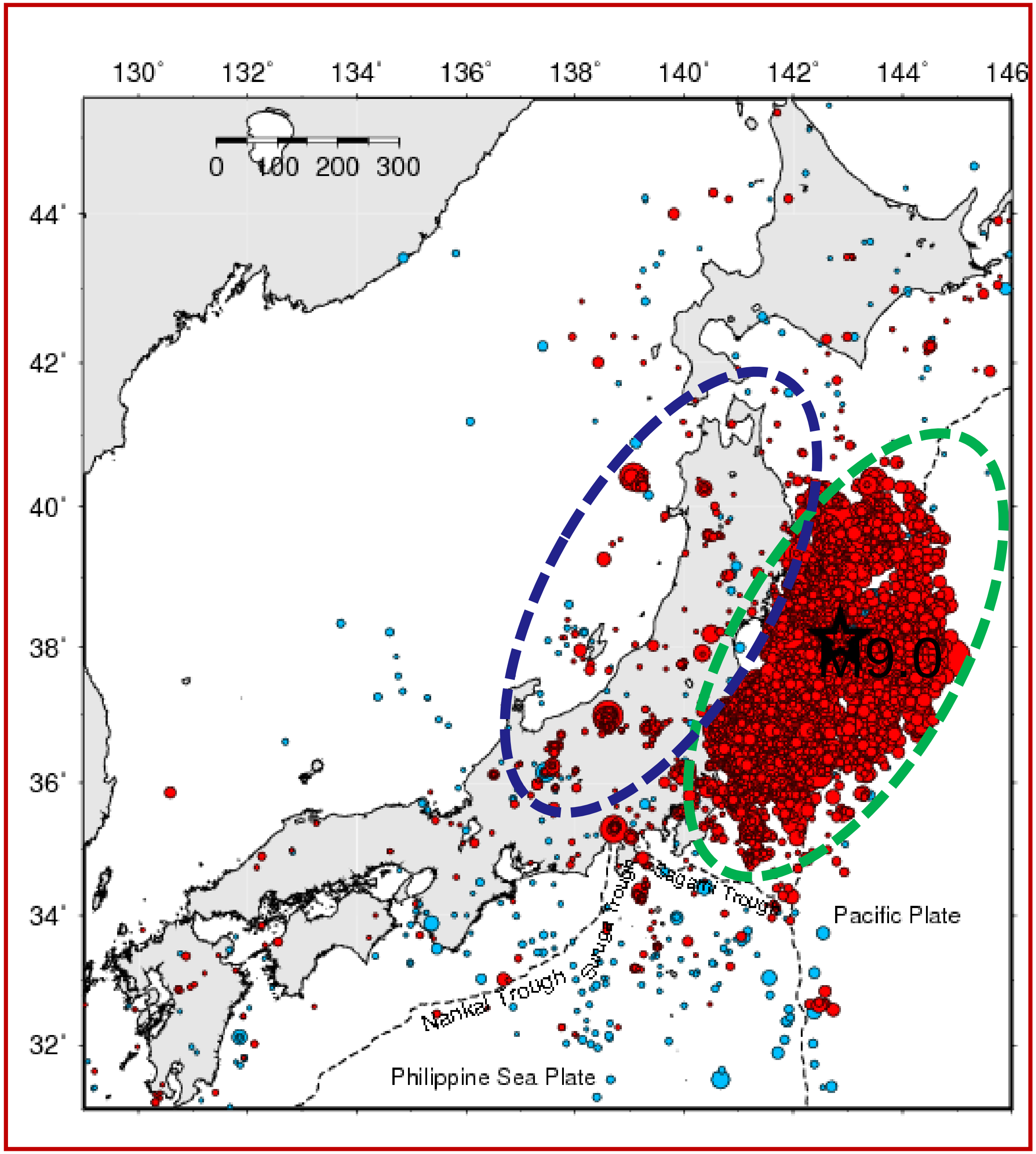
YKWH

Opris et al., 2018

Activation of seismicity following the M9.0 Tohoku-oki earthquake:

- off-shore (aftershocks);
- inland & short-range (Tohoku region);
- remote activation (as far as Kyushu, about 1350 km away from the Tohoku earthquake hypocenter)

Seismicity Pattern After the 2011 Tohoku-oki EQ (1)



JMA catalog:

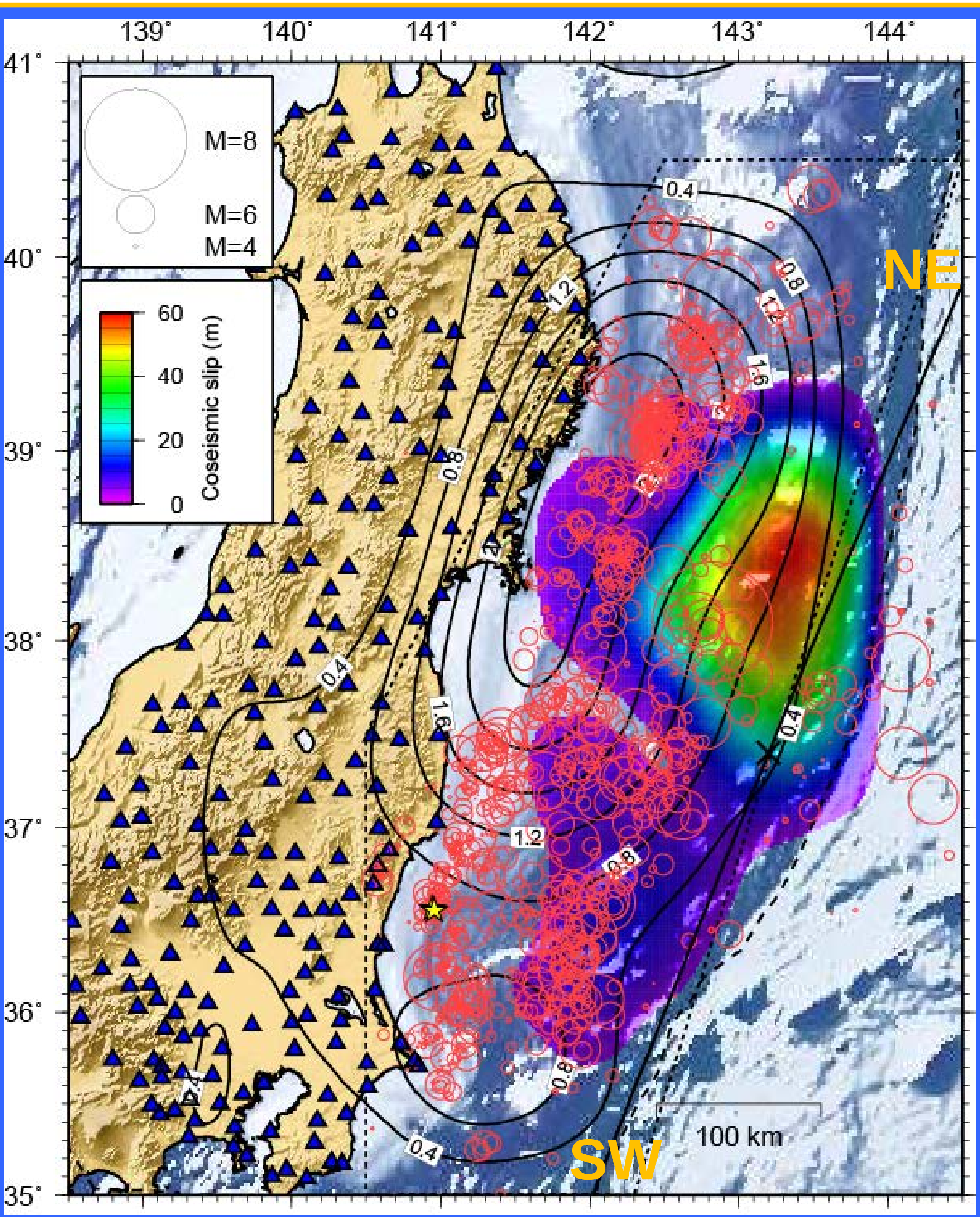
🔵 - one month before Tohoku eq.

🔴 - one month after Tohoku eq.

M ≥ 2.5

Clear activation of inland seismicity (Toda et al., 2011, Hirose et al., 2011, Enescu et al., 2011)

早期余震活動の研究

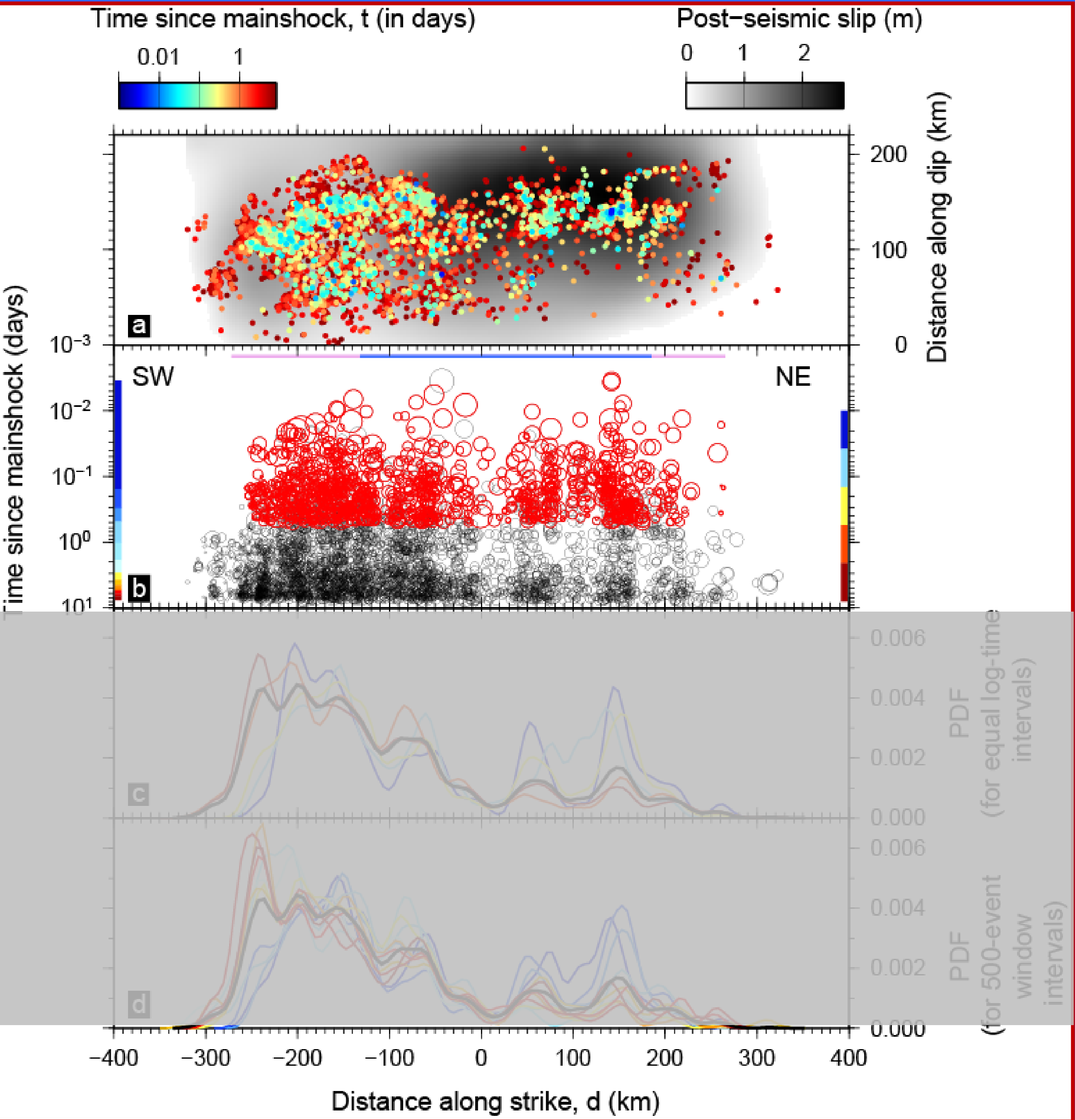


Decay and expansion of the early aftershock activity, following the 2011, Mw9.0 Tohoku earthquake

Lengline, Enescu, Peng & Shiomi, GRL, 2012

Distribution of Hi-net catalog aftershocks occurred in the first eight days from the Tohoku-oki mainshock (red circles), slip (colored) and afterslip distribution (Ozawa et al., Nature, 2011)

早期余震活動の研究

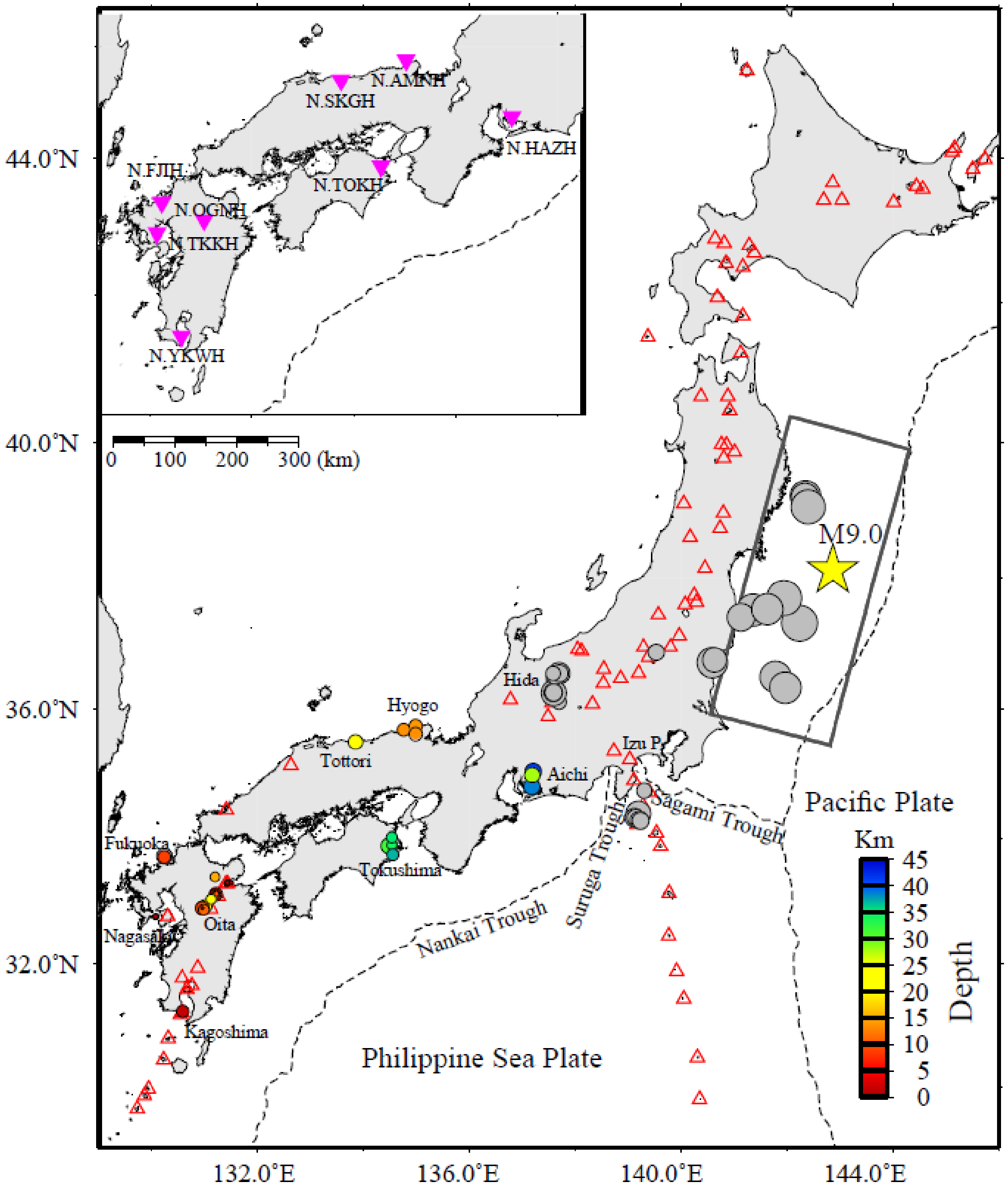


2011 Tohoku-oki earthquake (M9.0):

Aftershock area expansion

Lengline, Enescu, Peng & Shiomi, *GRL*, 2012

Remotely activated in SW of Japan after the 2011 Tohoku-oki earthquake



Immediate activation of seismicity after the M9.0 Tohoku-oki earthquake

1. Correlation between the occurrence of early post-Tohoku-oki events and the passage of both **Rayleigh and Love** waves from the mainshock.
2. Relatively short temporal extent (about 10 days)

△ Volcanoes

★ M9.0 2011 Tohoku-oki mainshock

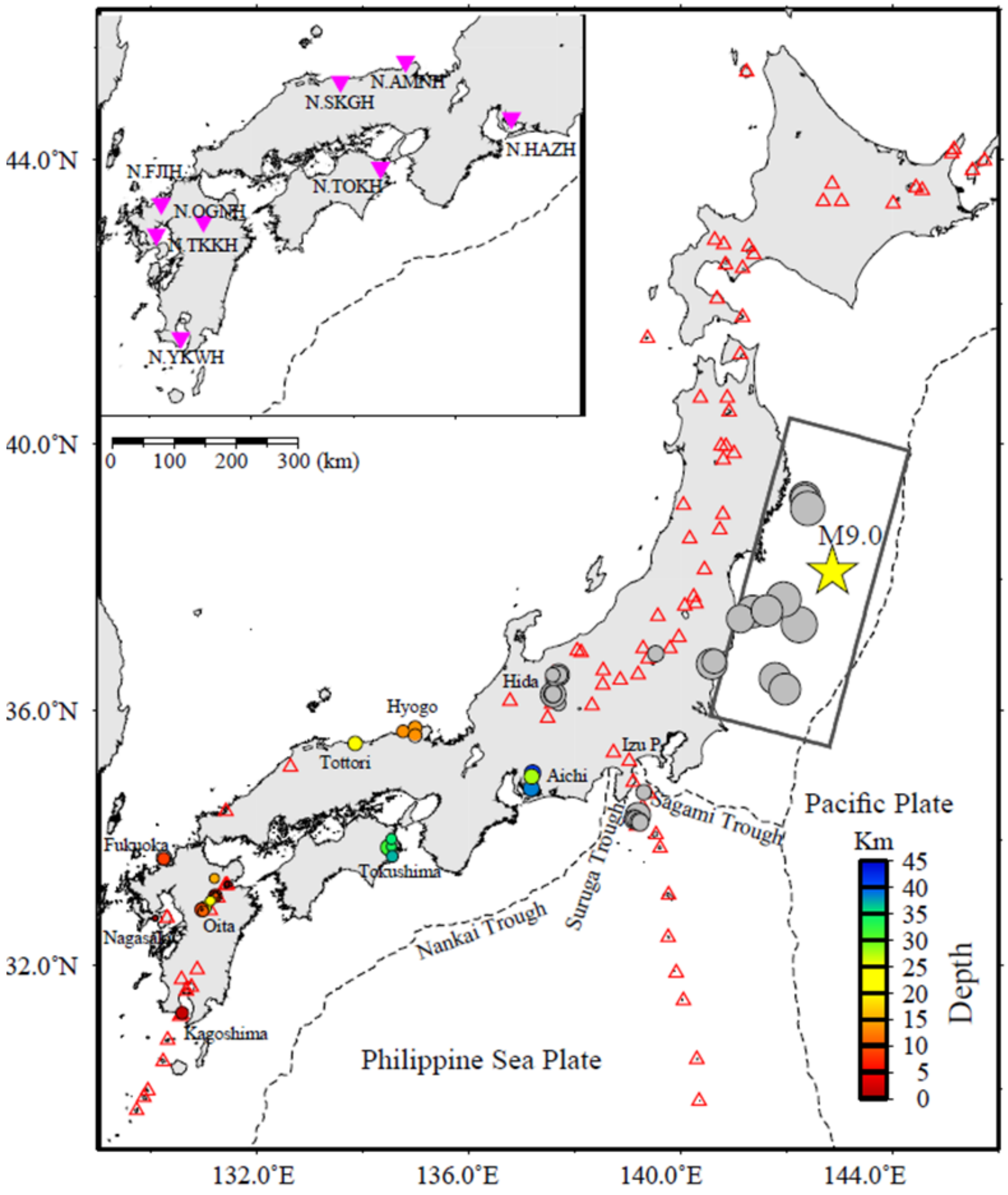
▲ Hi-net stations

● JMA early aftershocks

● Remotely triggered earthquakes

Opris et al., 2018

Remotely activated in SW of Japan after the 2011 Tohoku-oki earthquake



Immediate activation of seismicity after the M9.0 Tohoku-oki earthquake

Remotely activated areas:

Aichi
Tokushima → Subduction

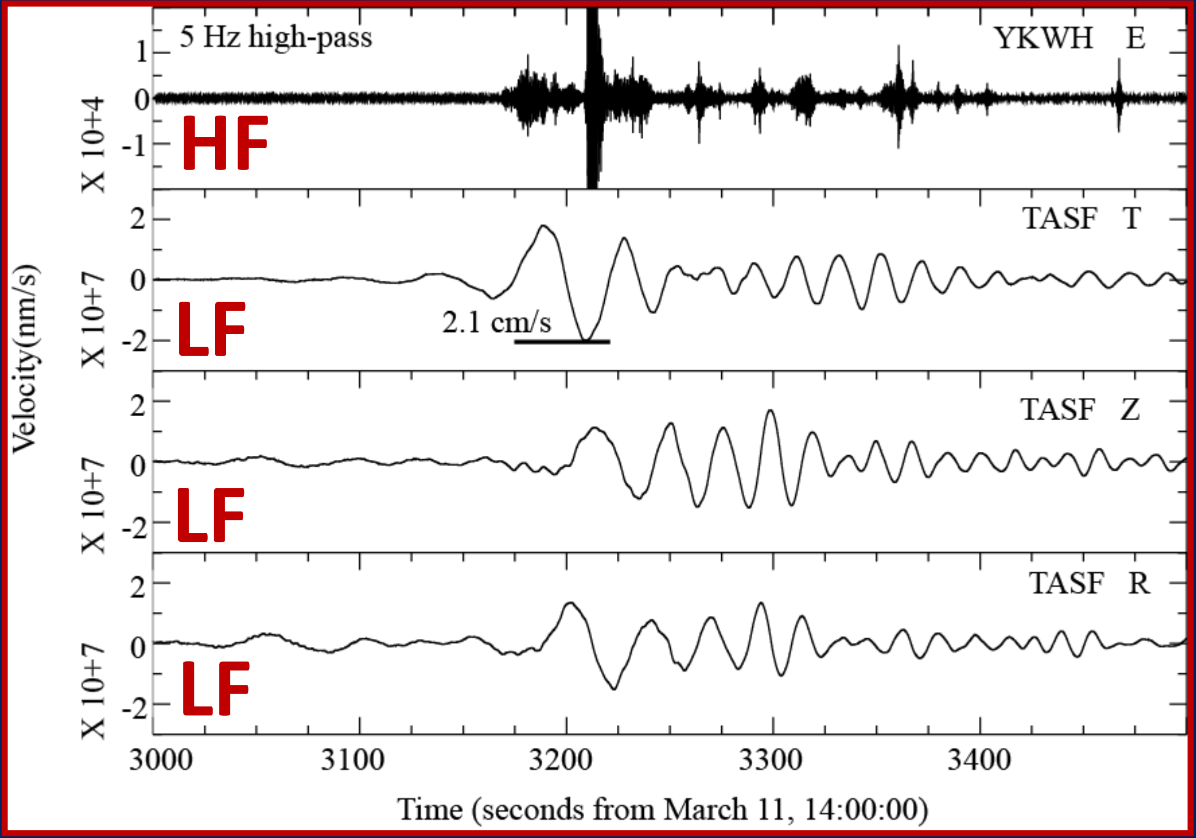
Hyogo
Tottori
Fukuoka → Strike-slip

Nagasaki
Oita
Kagoshima → Volcanic/ geothermal

△ Volcanoes
☆ M9.0 2011 Tohoku-oki mainshock
▲ Hi-net stations
● JMA early aftershocks
● Remotely triggered earthquakes

Opris et al., 2018

Dynamic stresses during the passage of surface waves from mainshock (S. Kyushu, ~ 1350 km from Tohoku epicenter)



$$\sigma_d = \frac{G\dot{u}}{v_s}$$

G – shear modulus (30 GPa)

Vs – phase velocity $\left(4.1\,{}^{km}/{}_{s}\right)$

$\dot{u}$ – peak particle velocity $\left(2.1\,{}^{cm}/{}_{s}\right)$

σ_d = 154 kPa
(0.15 MPa)

The Coulomb static stress changes (ΔCFS) are on the order of 0.002 MPa (about 100 times less than the dynamic ones).

Remote activation of seismicity following the 2016 M7.3 Kumamoto earthquake

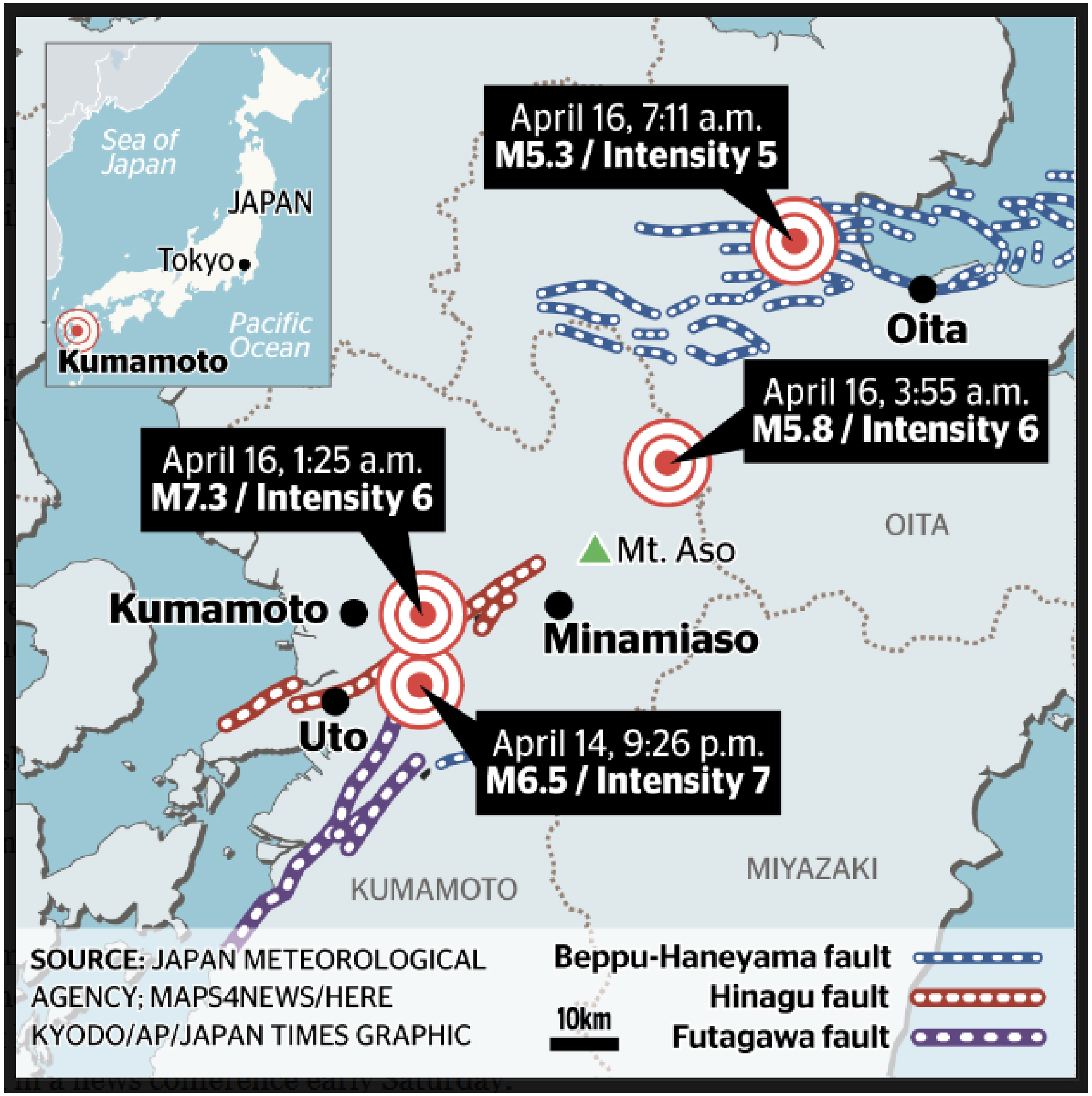
Research background

(1) Remote activation of seismicity due to the passage of seismic waves from large earthquakes is well-documented (Hill et al., 1993), **BUT**

(2) Such distant **EQ** triggering is scarce in Japan (e.g., Harrington and Brodsky, 2006), with the exception of the remote **EQs** activated after the 2011 M9.0 Tohoku-oki earthquake (e.g., Enescu et al., 2011; Miyazawa, 2011; Yukutake et al., 2011).

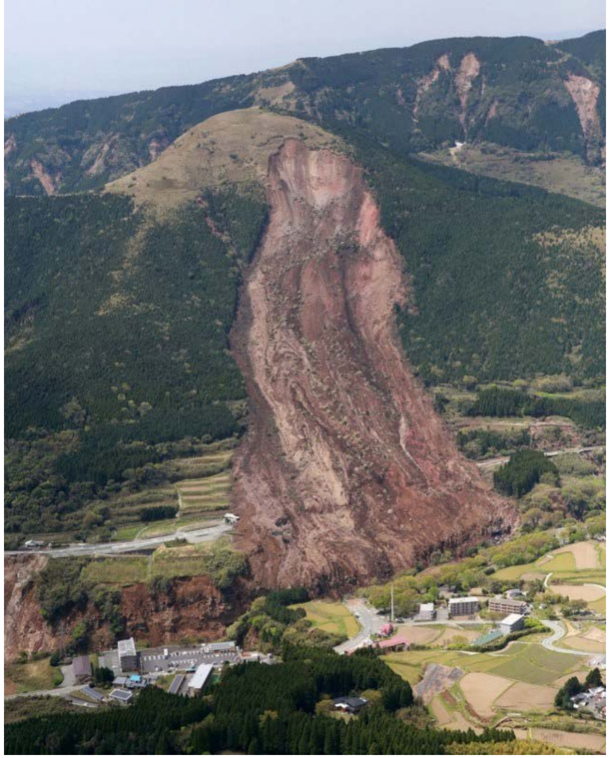
(3) Responsible physical processes are unclear (e.g. Hill & Prejean,2007).

The 2016 Kumamoto earthquakes （熊本地震について）(1)



SOURCE: JAPAN METEOROLOGICAL AGENCY; MAPS4NEWS/HERE
KYODO/AP/JAPAN TIMES GRAPHIC

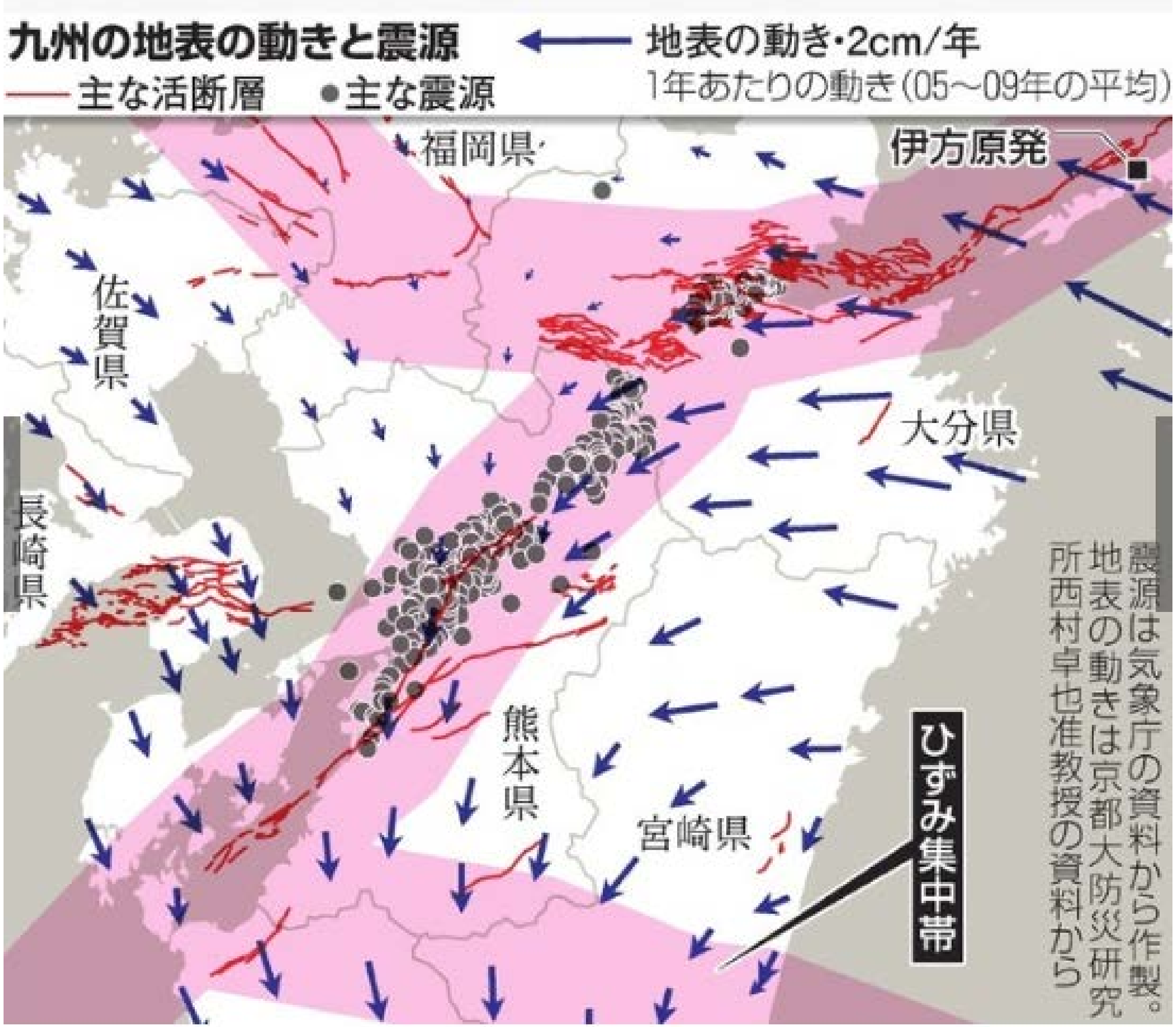
Japan Meteorological Agency（気象庁）



The 2016 Kumamoto earthquakes （熊本地震について）(2)

The 2016 Kumamoto earthquakes （熊本地震について）(3)

九州の地表の動きと震源



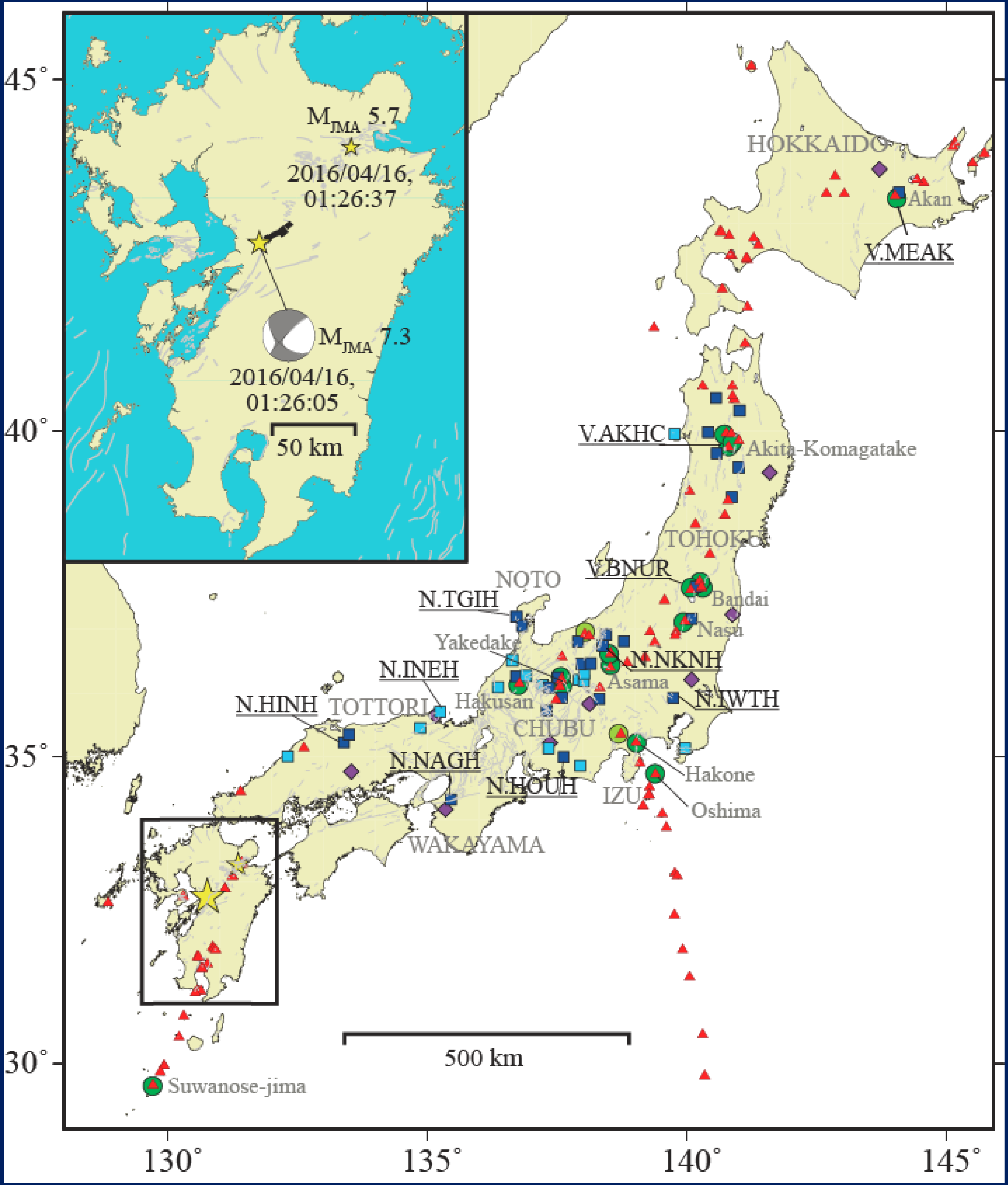
震源は気象庁の資料から作製。地表の動きは京都大防災研究所西村卓也准教授の資料から

The earthquakes occurred on the “High Strain Rate Area of Japan”

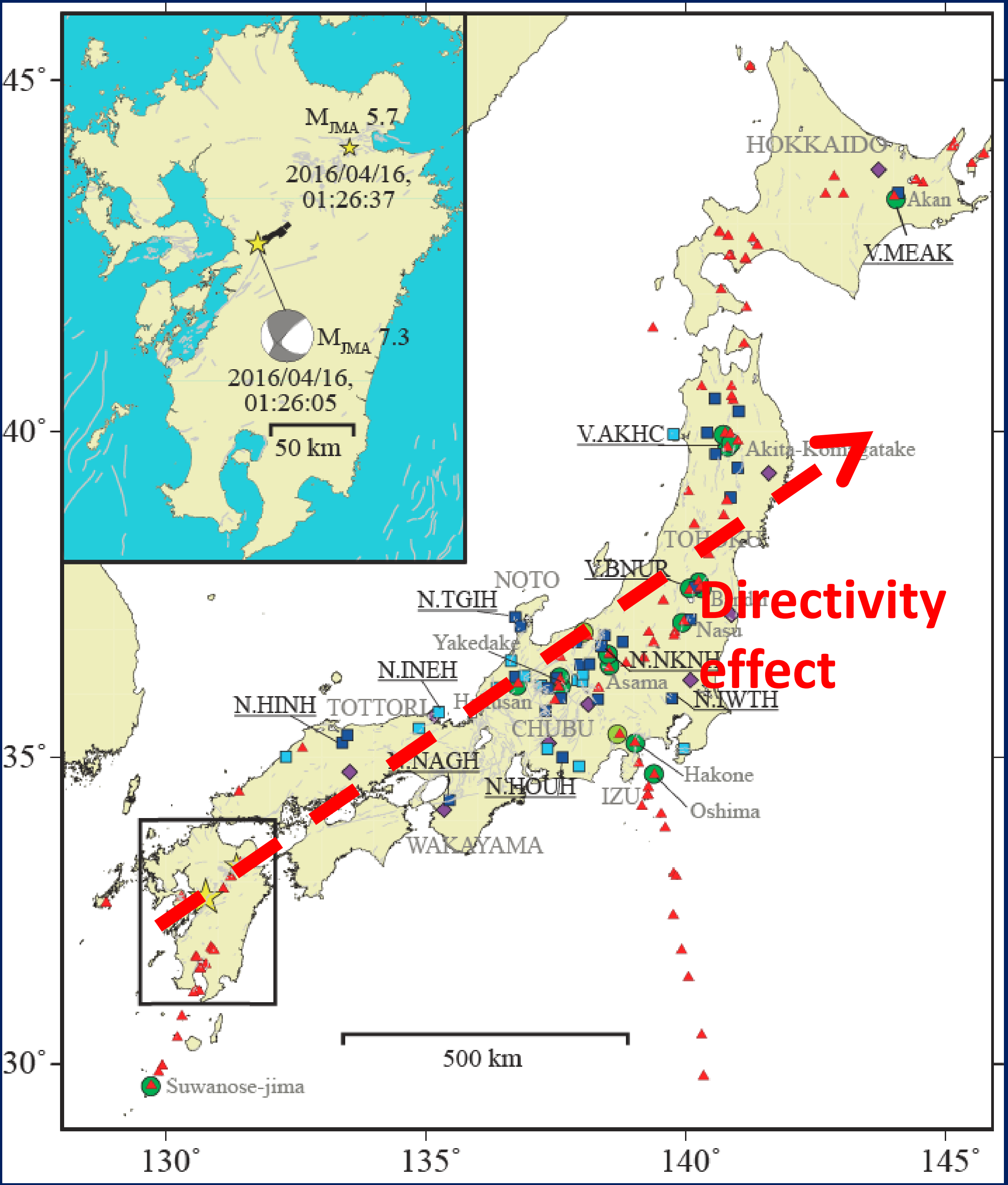
Method. In order to detect remote triggering following the 2016 M7.3 Kumamoto EQ we have examined the continuous waveform data at more than 1000 seismic stations (Hi-net, JMA volcano stations, V-net) all over Japan.

We have also computed dynamic stresses using a relatively simple approach, based on the peak particle velocity.

Wide-spread triggering in Japan, following the 2016 M7.3 Kumamoto EQ



- ■ **Hi-net borehole seismic stations**
- ● **JMA seismic stations at volcanoes**
- ◆ **F-net Broadband stations**
- ▲ **Volcanoes**



Volcanoes:

Hokkaido: Akan

Tohoku: Akita-Komatagatake; Bandai; Nasu

Chubu: Yakedake; Asama; Hakusan

Izu Peninsula: Hakone; Oshima

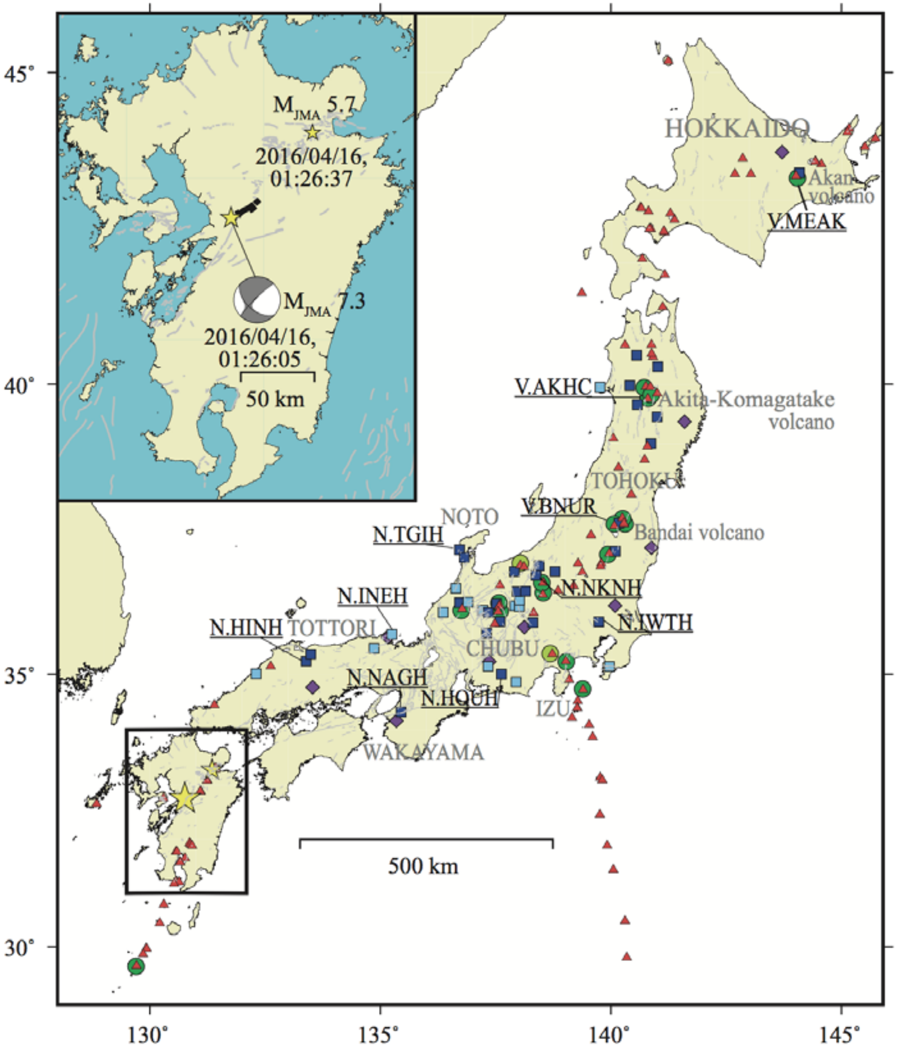
Kyushu: Suwanose-jima

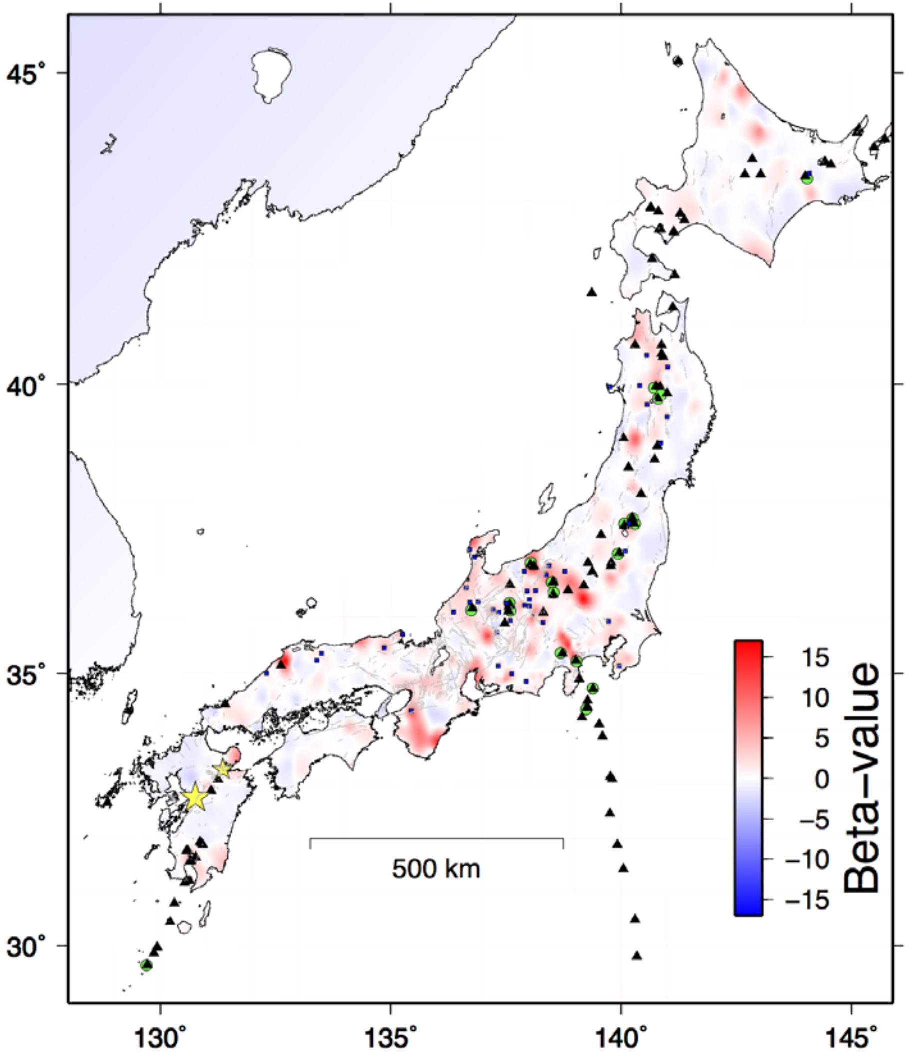
Active faults

Wakayama, Tottori and Noto

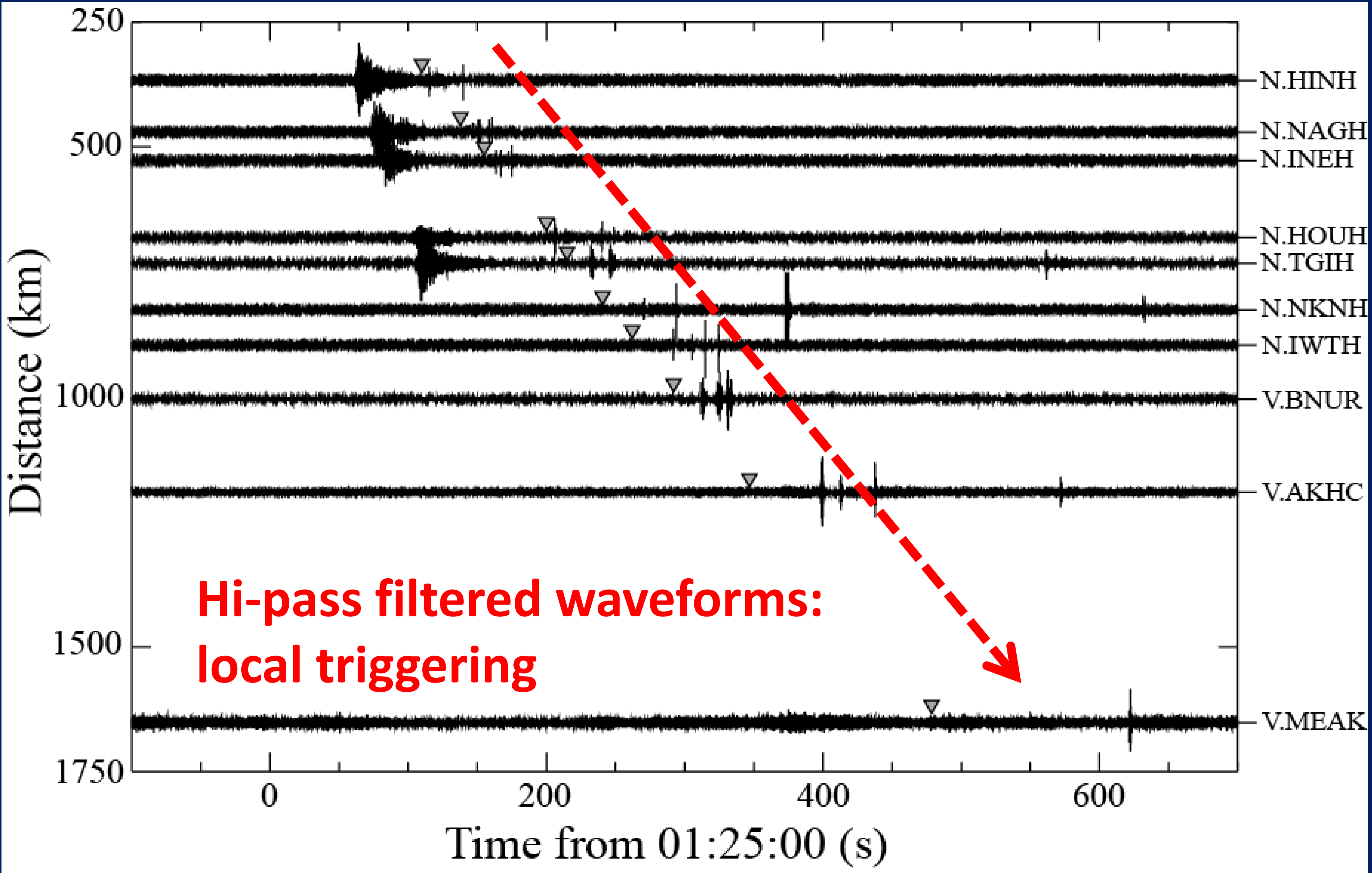
Comparison with the beta-value statistics map

Beta-value quantifies the change of envelope-waveform amplitudes after the Kumamoto EQ compared to the level before the mainshock, for 1000s windows.



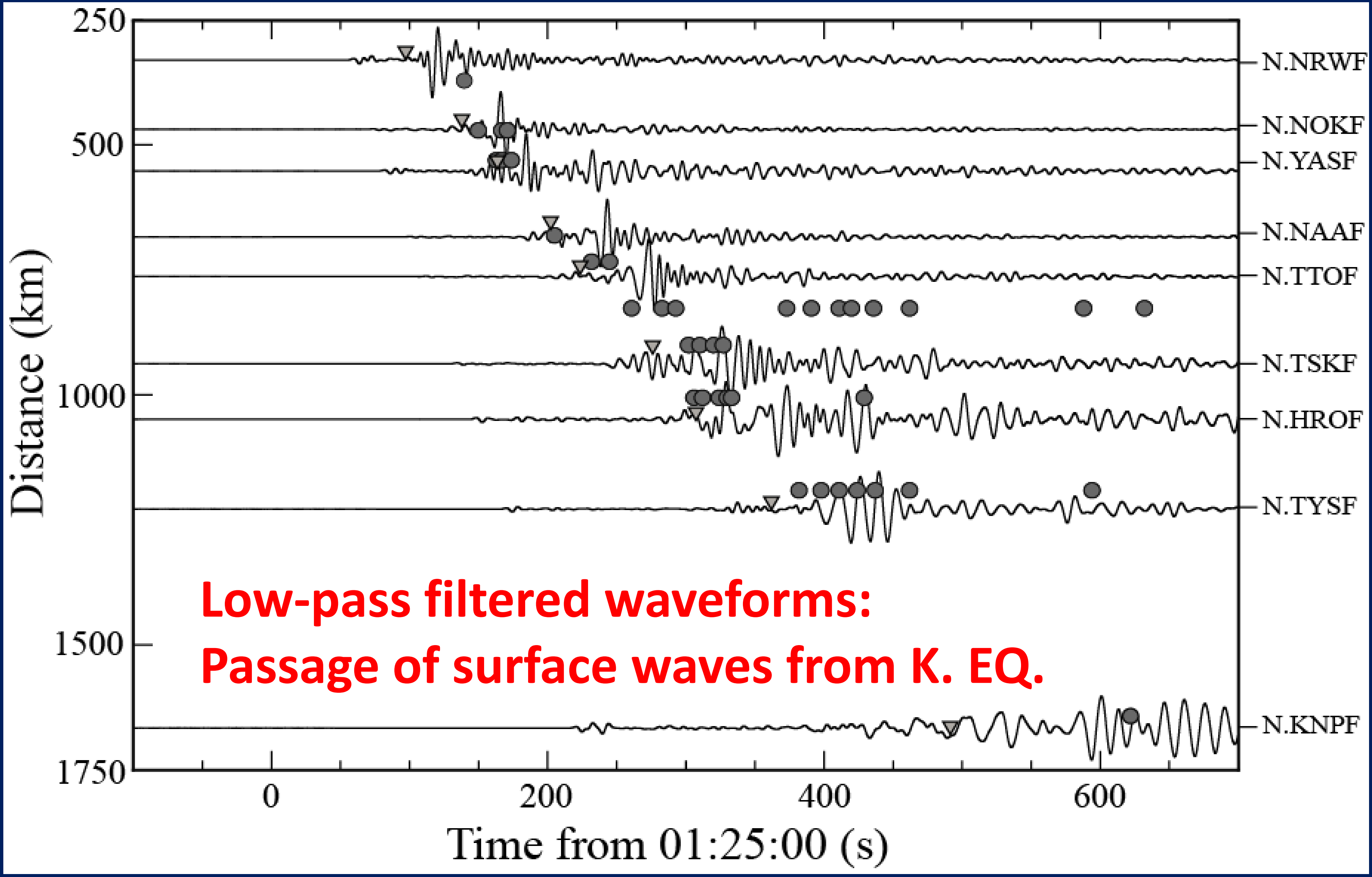


Remote triggering in Japan, following the Kumamoto EQ



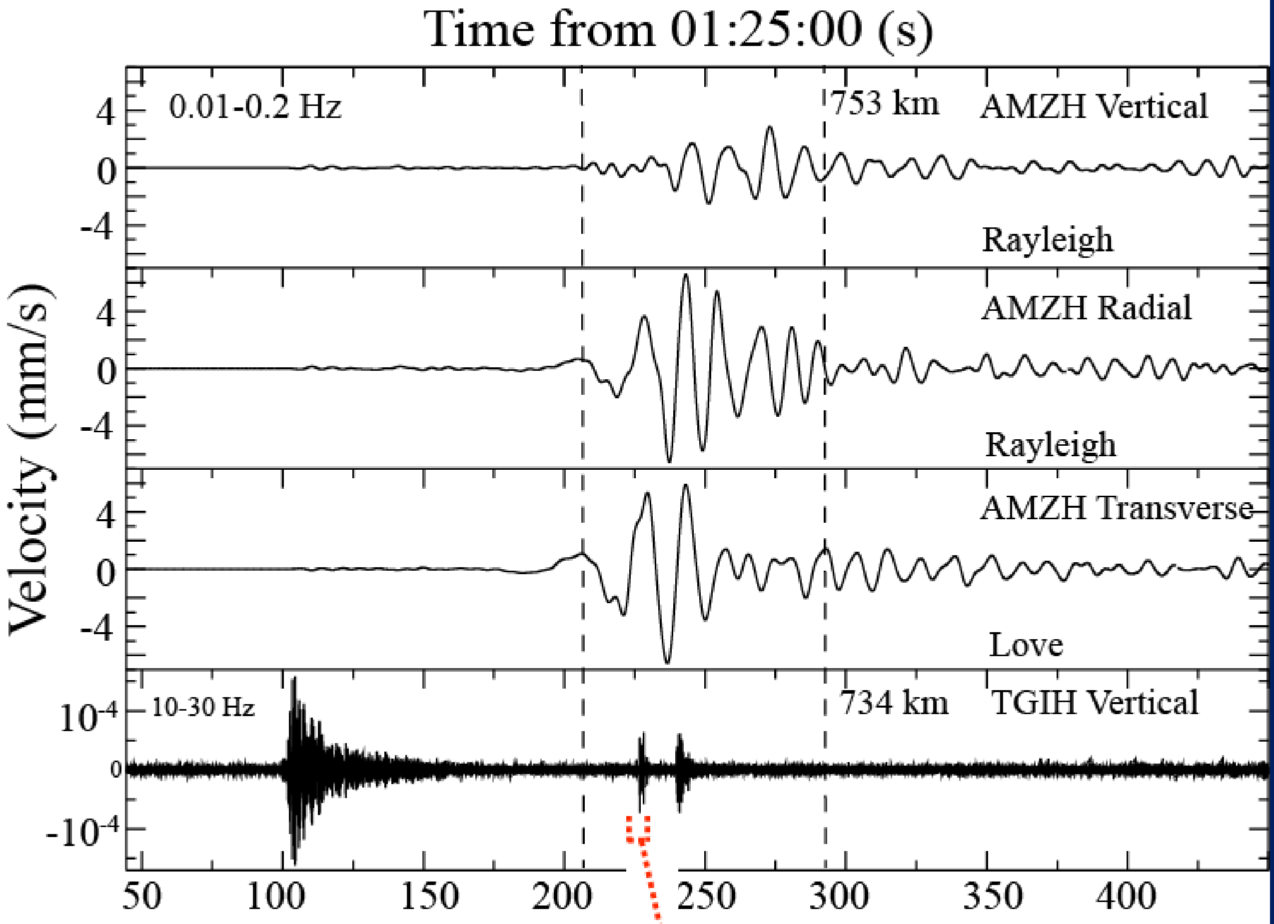
Hi-pass filtered waveforms:
local triggering

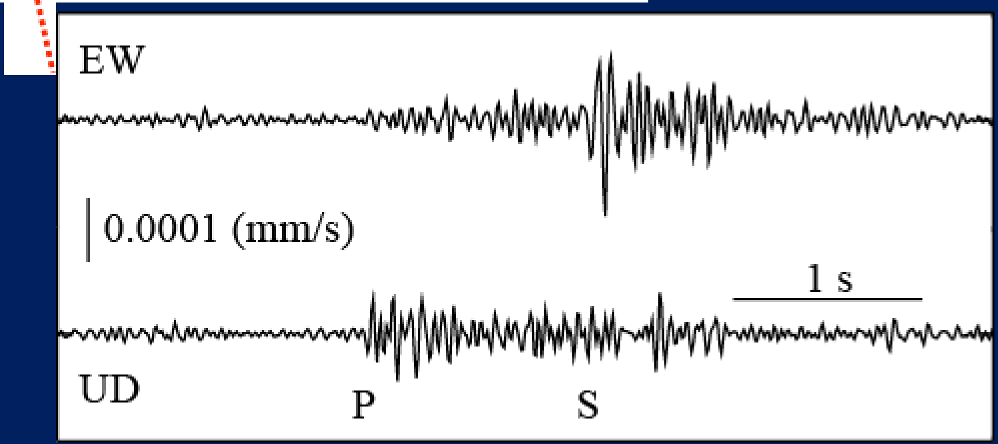
Remote triggering in Japan, following the Kumamoto EQ



Low-pass filtered waveforms:
Passage of surface waves from K. EQ.

Remote seismicity triggering in Noto Peninsula



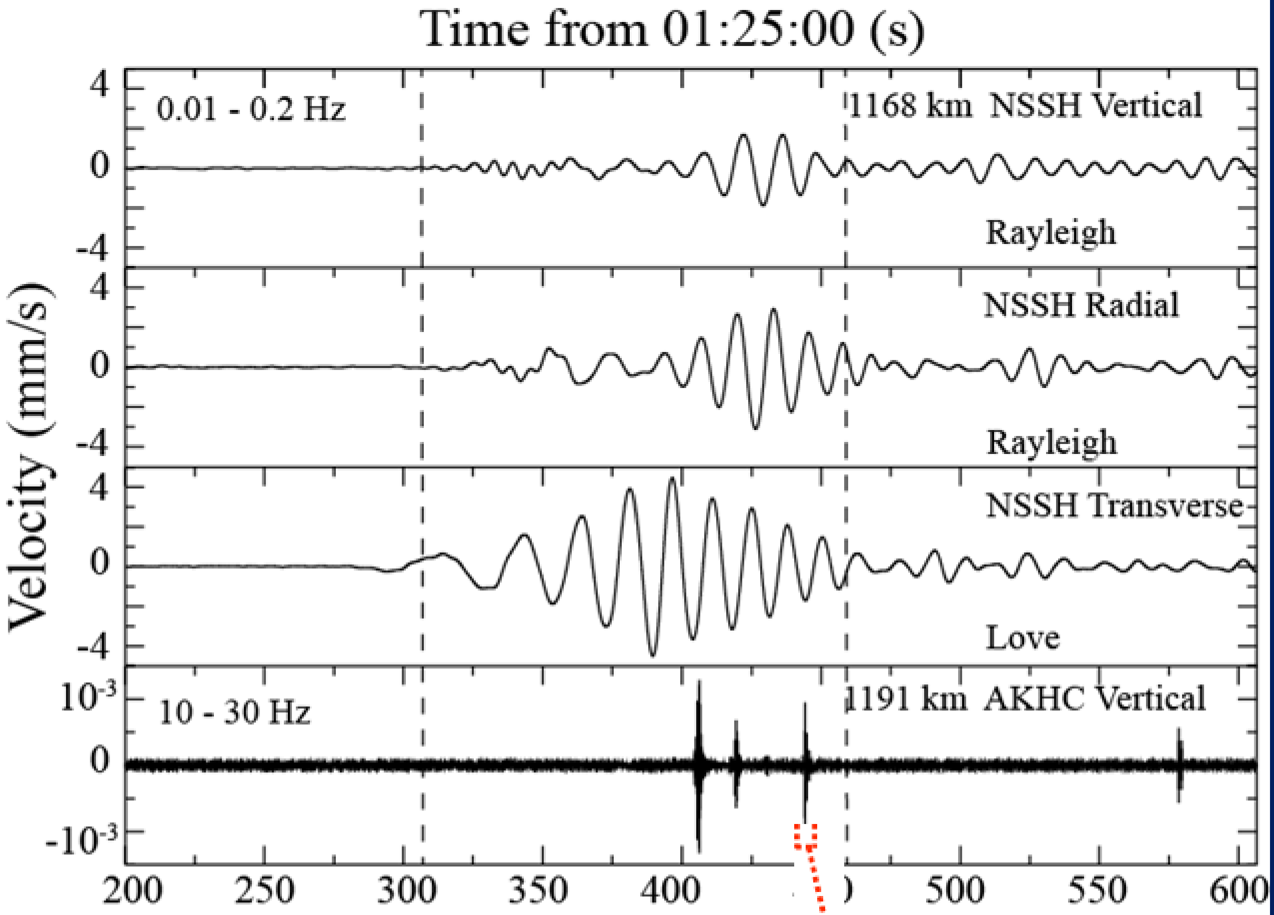


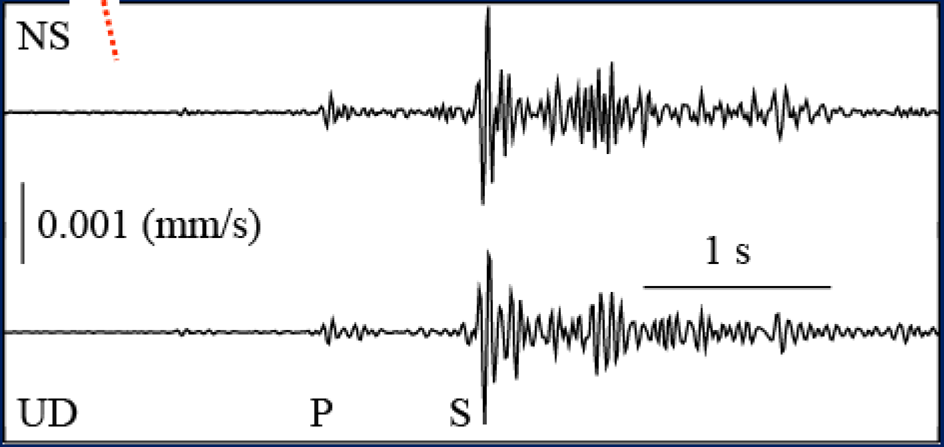
LOVE ??

Hypocentral distance = 753 km

Remote seismicity triggering in Tohoku region (at the Akita-Komagatake volcano)

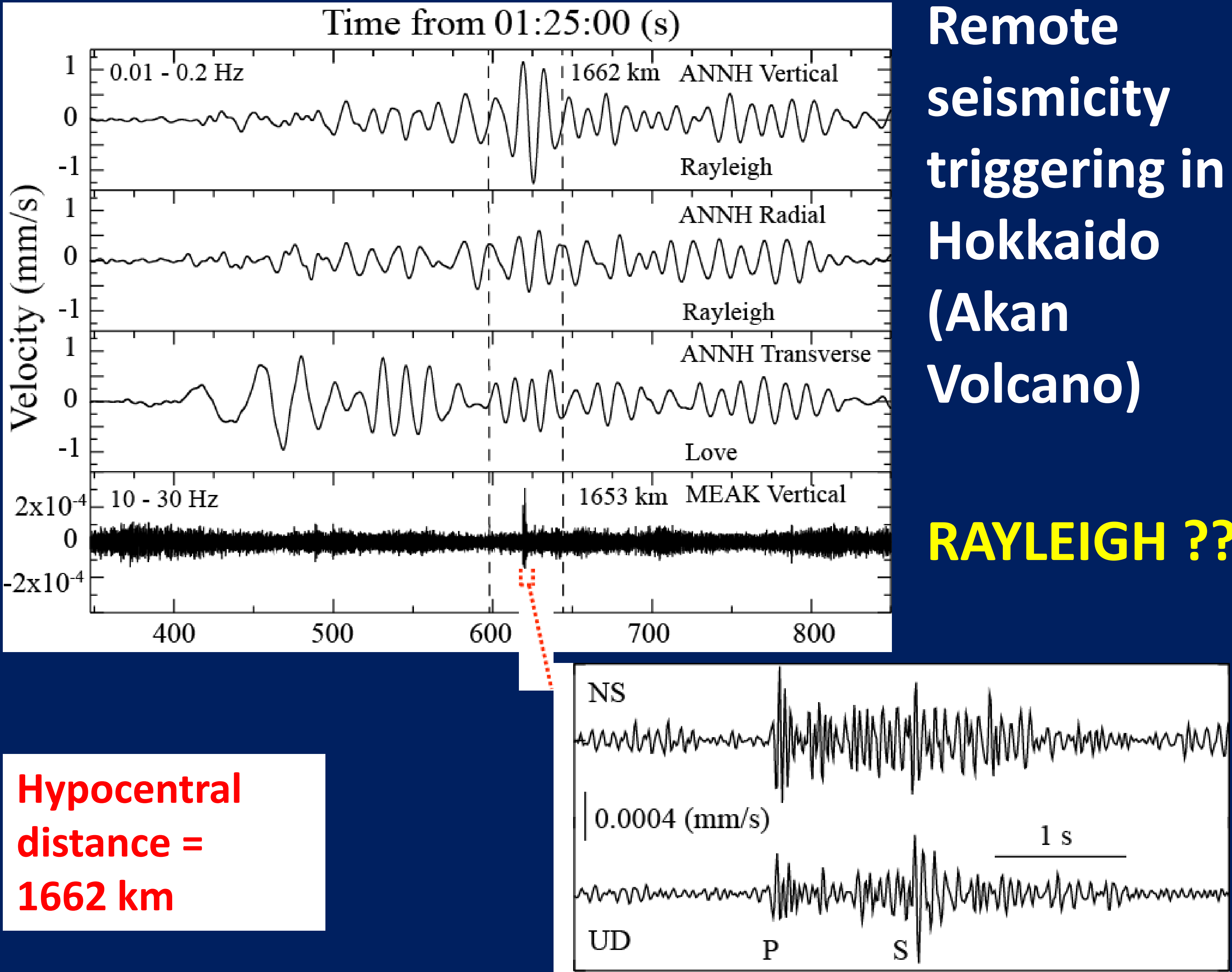
RAYLEIGH ??





Hypocentral distance = 1168 km

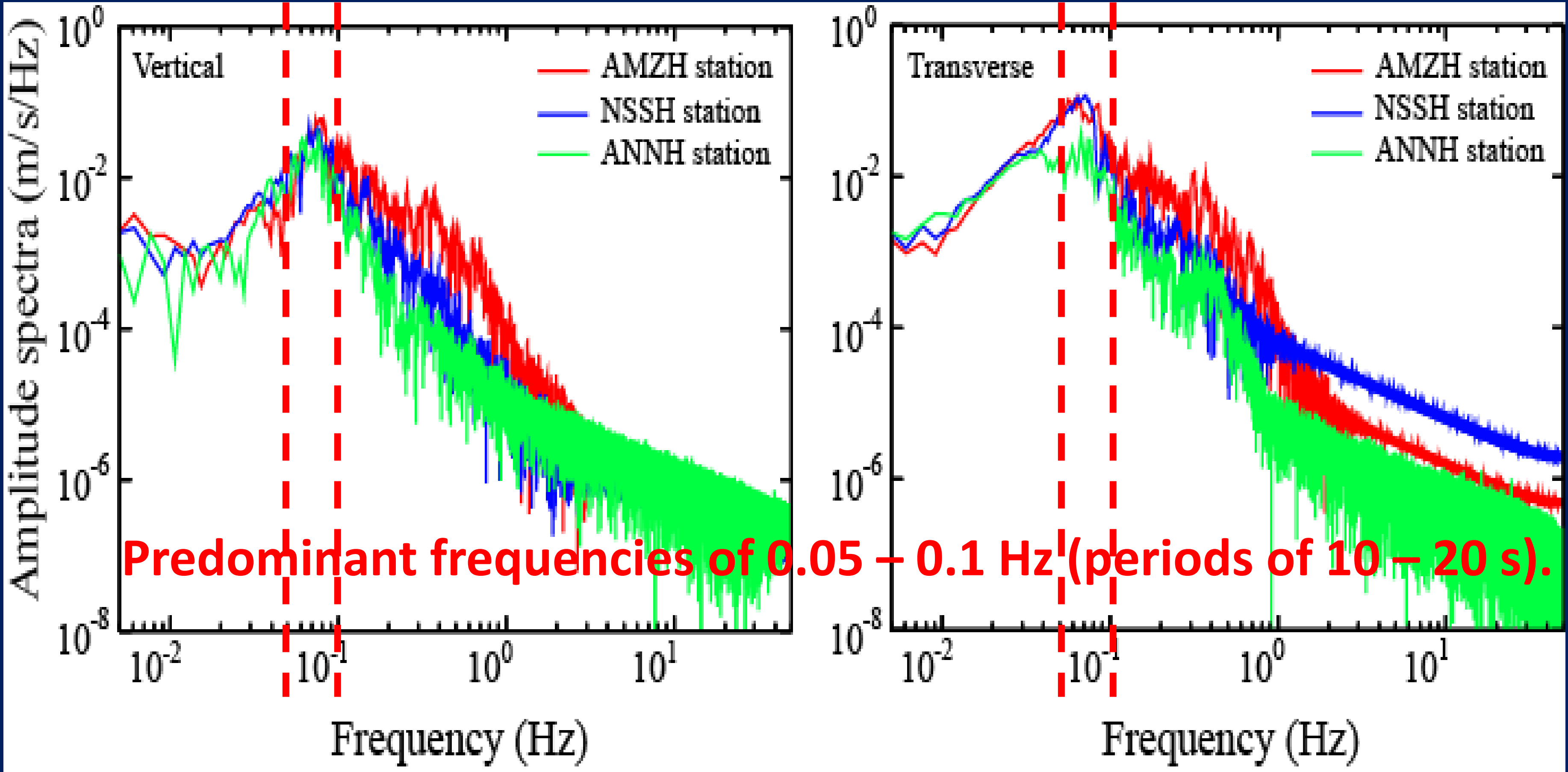
Remote seismicity triggering in Hokkaido (Akan Volcano)



RAYLEIGH ??

Hypocentral distance = 1662 km

Predominant frequencies – previous 3 cases



Predominant frequencies of 0.05 – 0.1 Hz (periods of 10 – 20 s).

Velocity spectra for the vertical (left) and transverse (right) waveform components at the Hi-net stations AMZH (red), NSSH (blue) and ANNH (green) during a 500 s window, starting 10 s before the observed surface wave arrival.

Discussion and Interpretation

Velocity peak-amplitudes

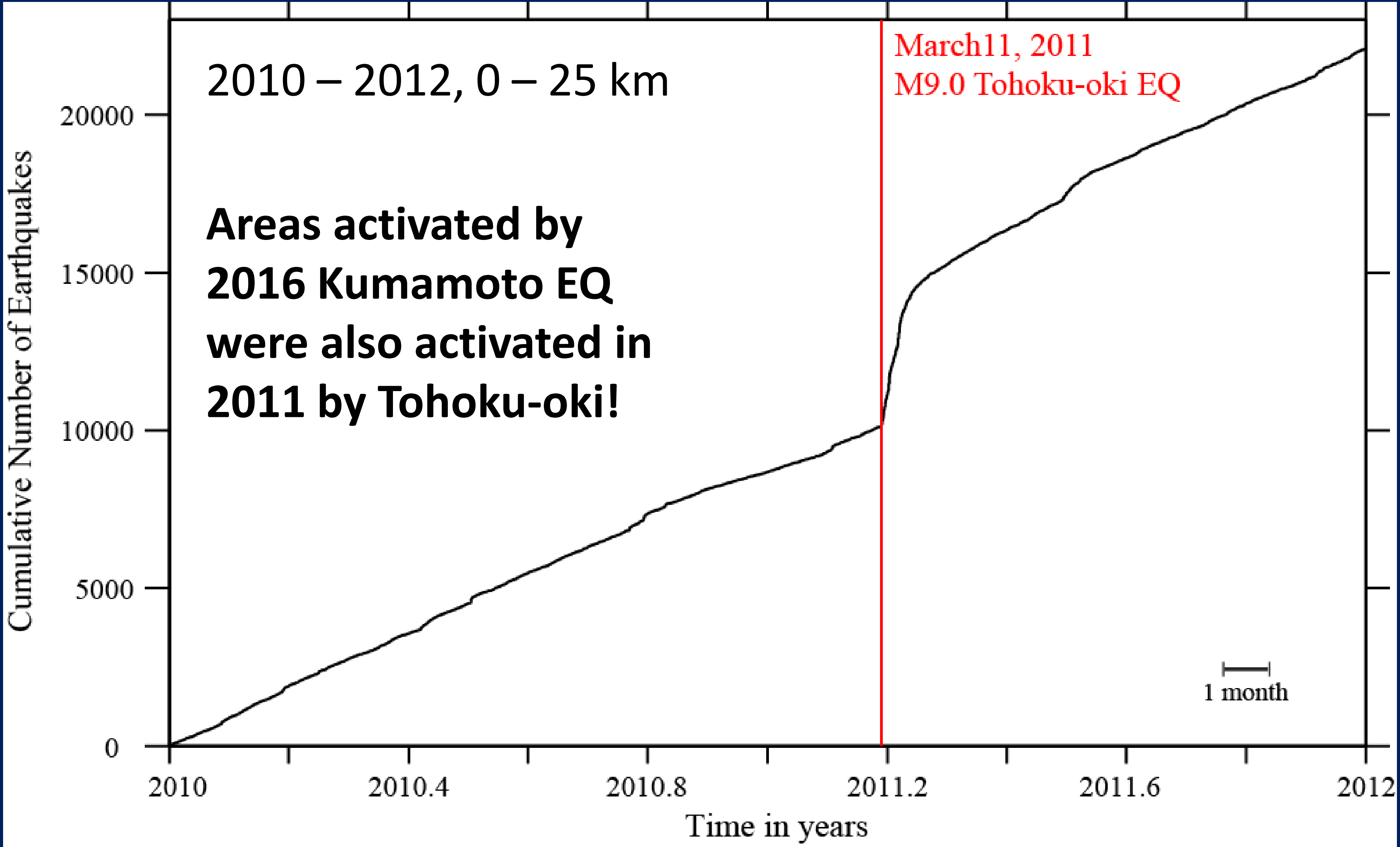
These amplitudes are typically equal or above 0.2 cm/s, with the exception of Hokkaido, where smaller peak amplitudes (of ~0.1 cm/s) have been recorded.

Harrington and Brodsky (2006): for the case of the 2004 Sumatra earthquake (peak amplitudes of 0.25 – 0.7 cm/s in Japan), only the largest amplitudes (~0.7 cm/s) triggered seismicity in Kyushu.

Dynamic stresses

Several kPa to tens of kPa:
thresholds comparable to others reported worldwide, but unusually small for Japan (e.g., Van der Elst and Brodsky, 2010).

Seismicity change in the JMA catalogue



Areas activated by 2016 Kumamoto EQ were also activated in 2011 by Tohoku-oki!

Selection of earthquakes in all areas where we observed remote triggering after Kumamoto EQ

Discussion and Conclusions

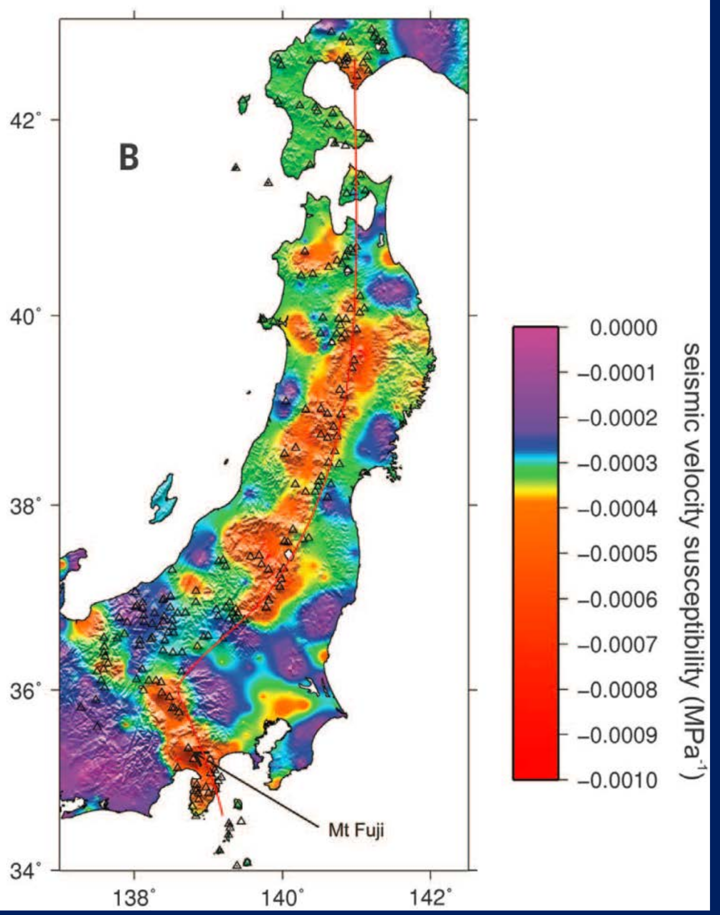
1. **The 2016 M7.3 Kumamoto EQ triggered unprecedented seismicity (M ~ 1.0) in many areas of Japan, as far as Hokkaido, in particular at volcanoes in Hokkaido, Chubu and Tohoku regions.**

2. **Dymamic stresses in the areas of remote triggering range from a few kPa to tens of kPa, at threshold levels significantly smaller than found before for Japan.**

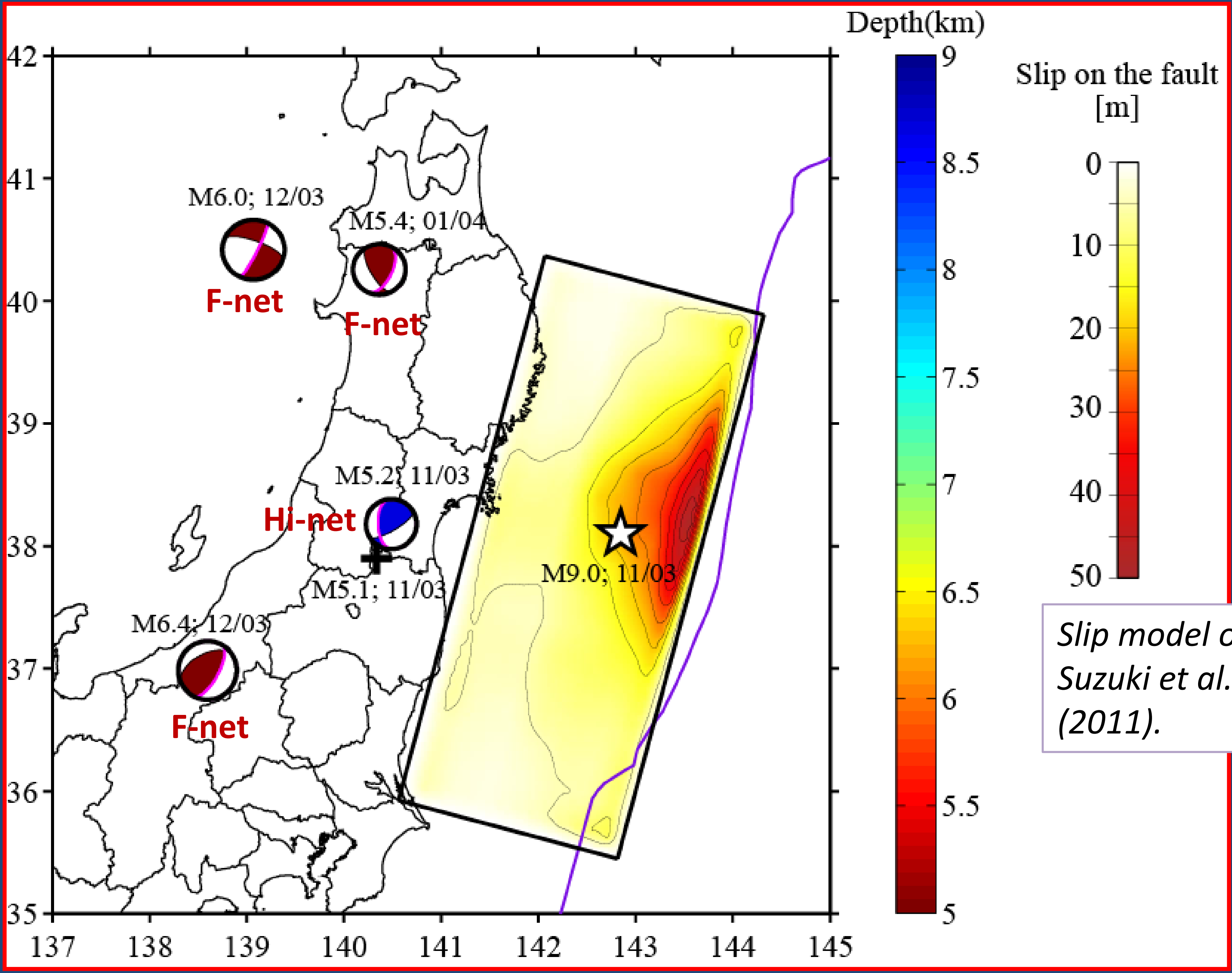
3. Triggering mechanisms: excitation of fluids at volcanoes, strong directivity effect.

4. **Many volcanic areas in NE Japan may be more triggerable after the 2011 Tohoku-oki earthquake than before!**

Brenguier et al., Science, 2014

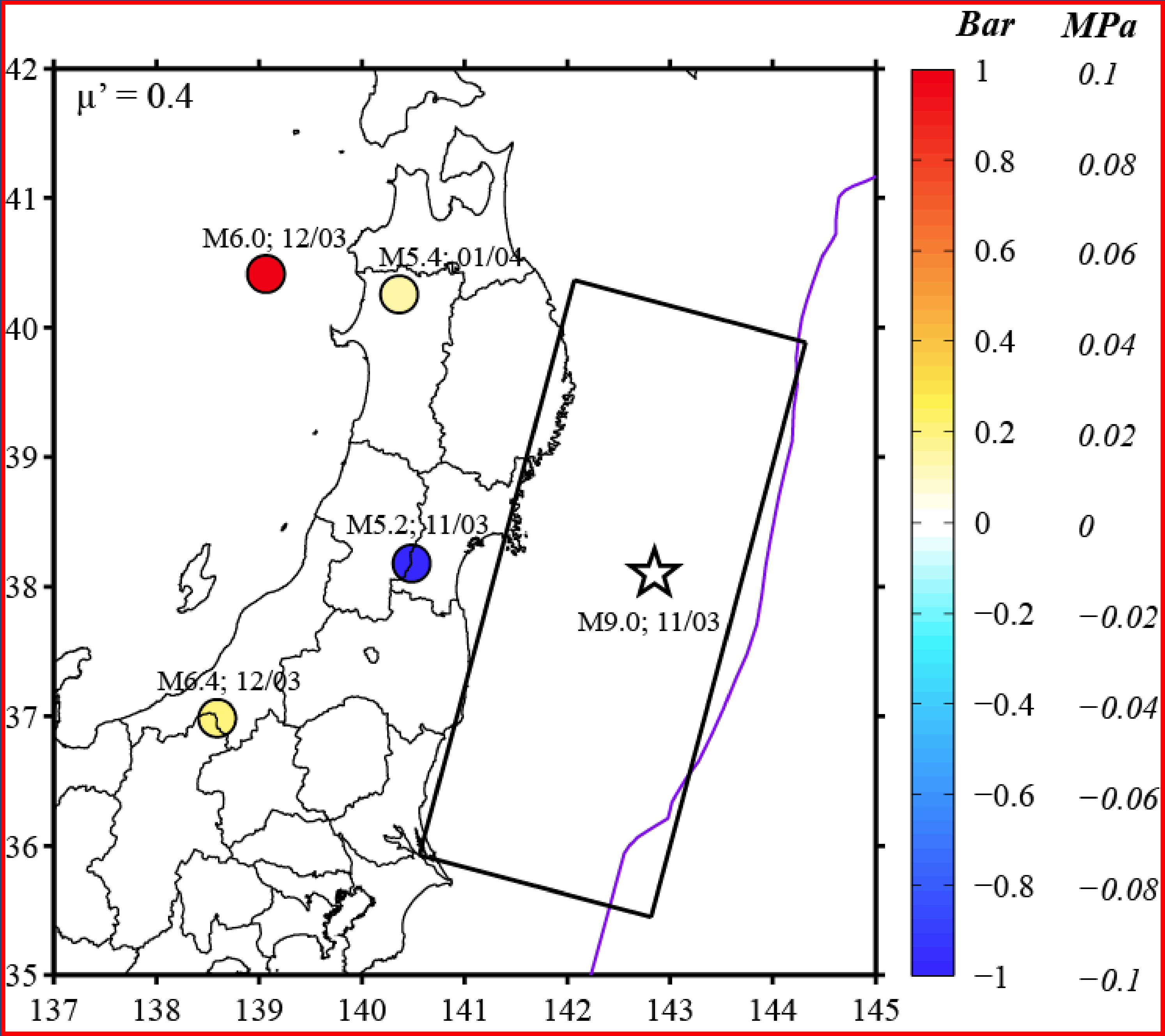


Earthquakes of M ≥ 5.0. occurred in NE Japan, within one month from M9.0 2011 Tohoku-oki earthquake

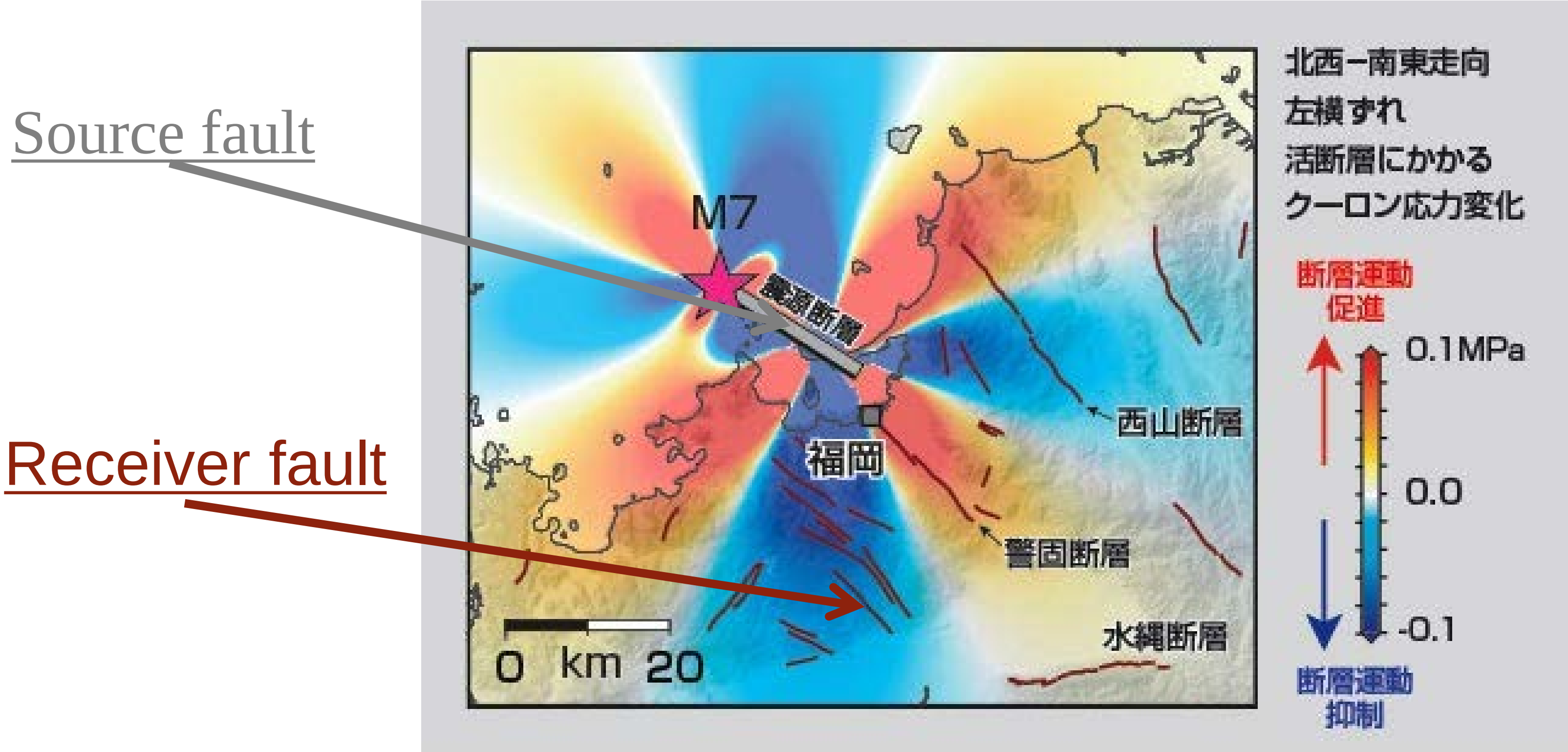


Slip model of Suzuki et al. (2011).

Maximum Coulomb stress changes (ΔCFF) on nodal planes



地震の静的 Triggering



Source fault

Receiver fault

Toda, 2005

ΔCFF -負の場合: Receiver断層 is getting easier to slip，
ΔCFF -正の場合: Receiver断層 is getting difficult to slip。

In general, small earthquakes were observed to be triggered on nearby **receiver faults** when the ΔCFF is larger than 0.01 MPa.

地震の静的Triggering

Coulomb static stress model:

$$\Delta \mathrm{CFF} = \Delta\tau + \mu'\Delta\sigma$$

$\Delta \mathrm{CFF}$ – Coulomb破壊応力変化 (Coulomb Failure Stress Change)

$\Delta\tau$ – 断層のすべりの向きへの剪断変化 (shear stress change)

$\Delta\sigma$ – 断層面に垂直な法線応力 (normal stress change)

μ' – みかけ摩擦係数 (apparent coefficient of friction)

$\Delta \mathrm{CFF}$ -負の場合: Receiver断層 is getting easier to slip，
$\Delta \mathrm{CFF}$ -正の場合: Receiver断層 is getting difficult to slip.