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International Symposium on Earthquake Forecast
5th International Workshop on Earthquake Preparation Process
~ Observation, Validation, Modeling, Forecasting ~

Empirical forecast of occurrence of mainshocks based on foreshock activities

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Procedure for Selecting Foreshock Candidates

(1) To Eliminate **Small Aftershocks**

- Condition for Distance: $\log L \leq 0.5 M_m - 1.8$
- Condition for Time: $t \leq 10^{[0.17+0.85(M_m-4.0)]/1.3} - 0.3$
- Condition for Magnitude: $M_a < M_m - M_d \quad (where\ M_d = 1.0)$

(2) To Segment Investigated Area

- Size of Segmentation **D°** (Latitude) × **D°** (Longitude)

(3) To Define Number of Earthquakes for Foreshock Candidates

- Magnitude Threshold of Foreshock Candidates: $M \geq Mf_0$
- Time Window for Counting Earthquakes: **Tf**
- Number of Earthquakes to Define Foreshock Candidates: **Nf**

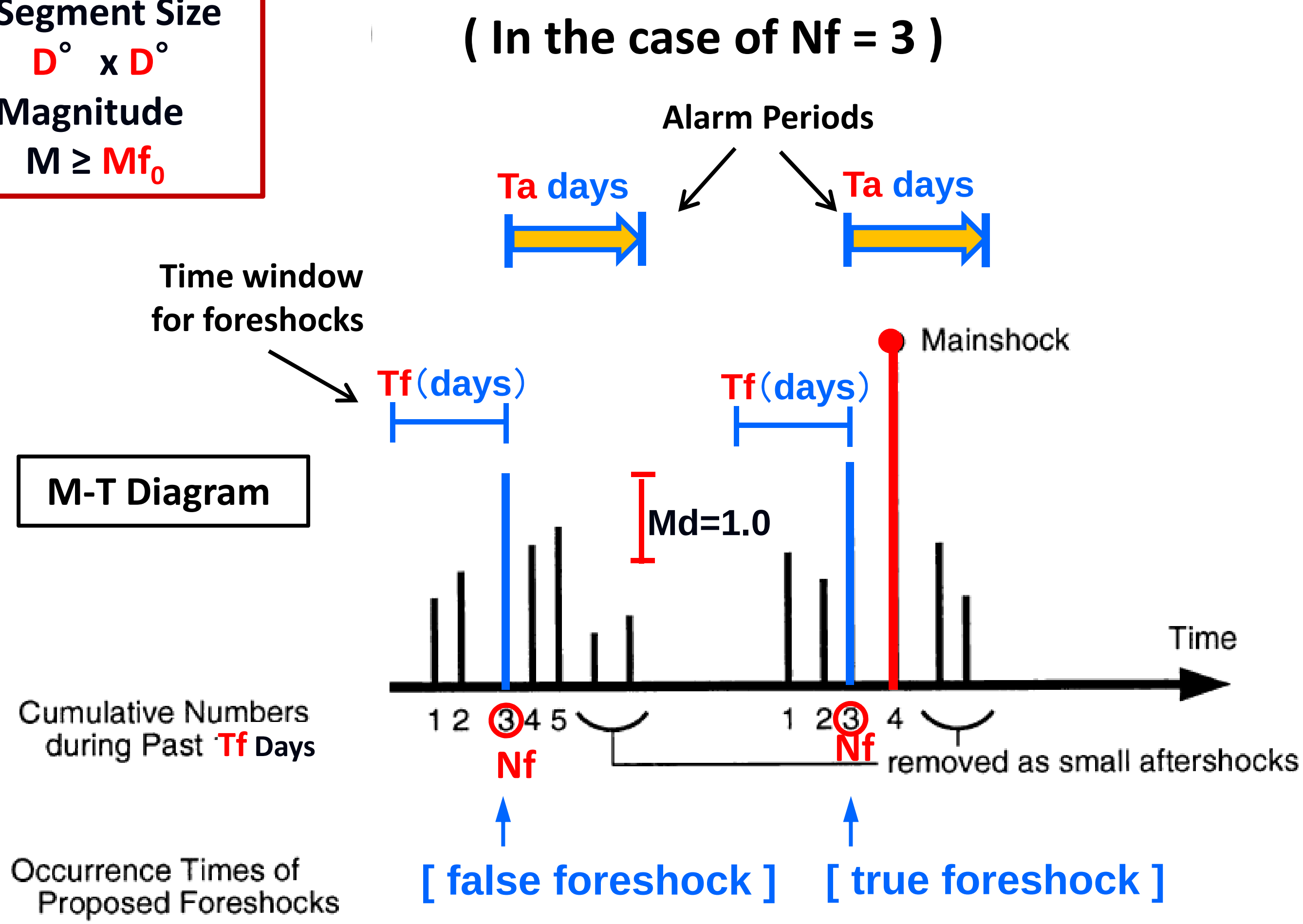
(4) To Define Alarm Period for Mainshocks

Alarm period = Ta (days)

(Mainshocks: $M \geq Mm_0$, All aftershocks are removed. → Target $M \geq \max(Mm_0, Mf_{max})$)

Schematic Diagram for Foreshock Candidates and Alarm Period

- Segment Size
  D° x D°
- Magnitude
  M ≥ Mf_0



Indices for Prediction Performance

- Alarm Rate（AR）＝（ Number of Alarmed Mainshocks）
  /（Total Number of Mainshocks）

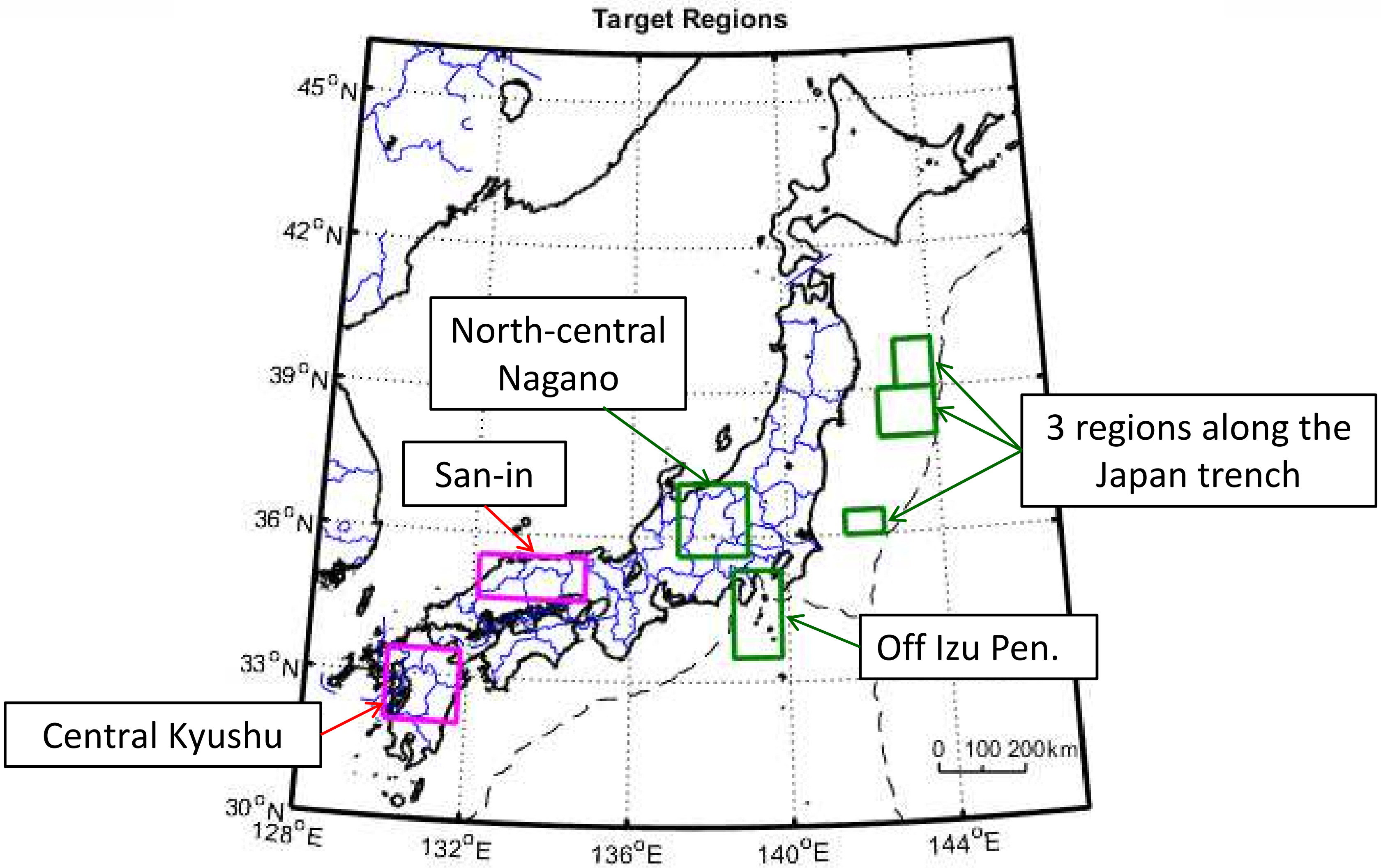
- Truth Rate（TR）＝（Number of True Foreshocks）
  /（Number of Proposed Foreshocks）

- Probability Gain（PG）＝
  （Occurrence Rate of M.S. in Predicted Space-Time）
  /（Background Occurrence Rate of M.S.）

- dAIC＝(AIC for the Stationary Poisson Model)
  - (AIC for the Foreshock-based Prediction Model)

↑ The larger, the better.

Target Regions



Estimating the Best Parameters by Grid Search

(Example for 3 Regions along the Japan Trench)

Optimized period:
1961 – 2010

The range of grid search for Mm ≥ 6.0

Mf:
4.0, 5.0, 6.0

D:
0.25, 0.5, 1.0°

Tf:
10 days

Nf:
1, 2, …, 10

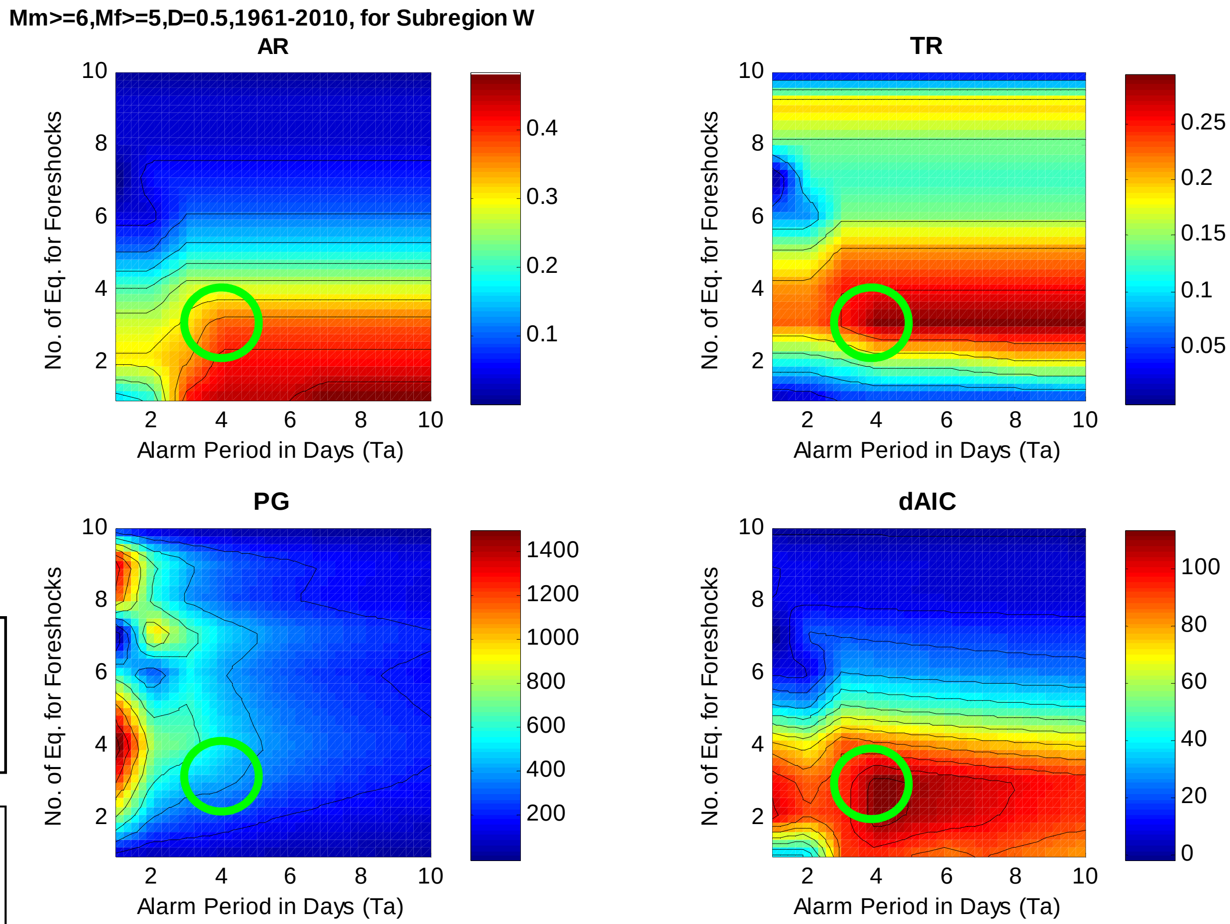
Ta:
1, 2, …, 10 days

Optimized parameters
- Mf ≥ 5.0 ・D = 0.5 °
- Tf = 10d ・Nf = 3 ・Ta = 4d

Performance
- Alarm rate = 38% (=11/29)
- Trueth rate = 30% (=13/44)
- PG = 380, ・dAIC = 115

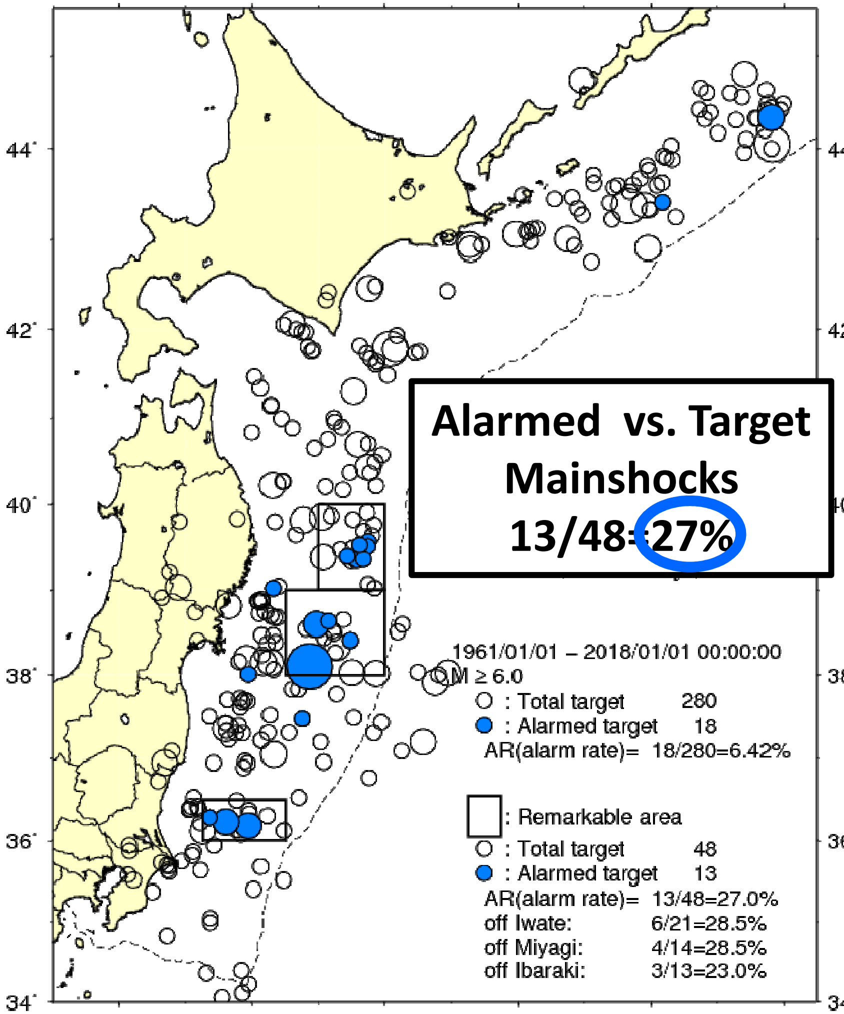
An example of grid search for Nf and Ta

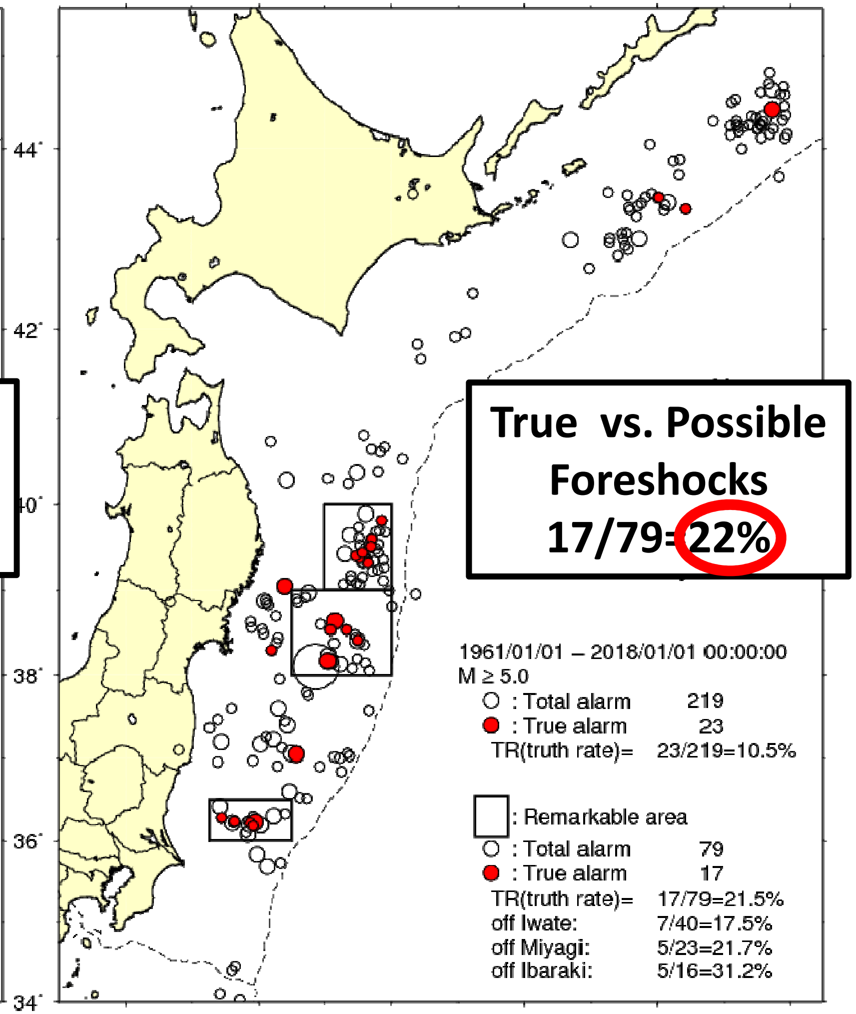
（In the case of Mm ≥ 6.0, Mf ≥ 5.0, D = 0.5°, and Tf = 10days）



Prediction Performance for the 3 Regions along the Japan Trench

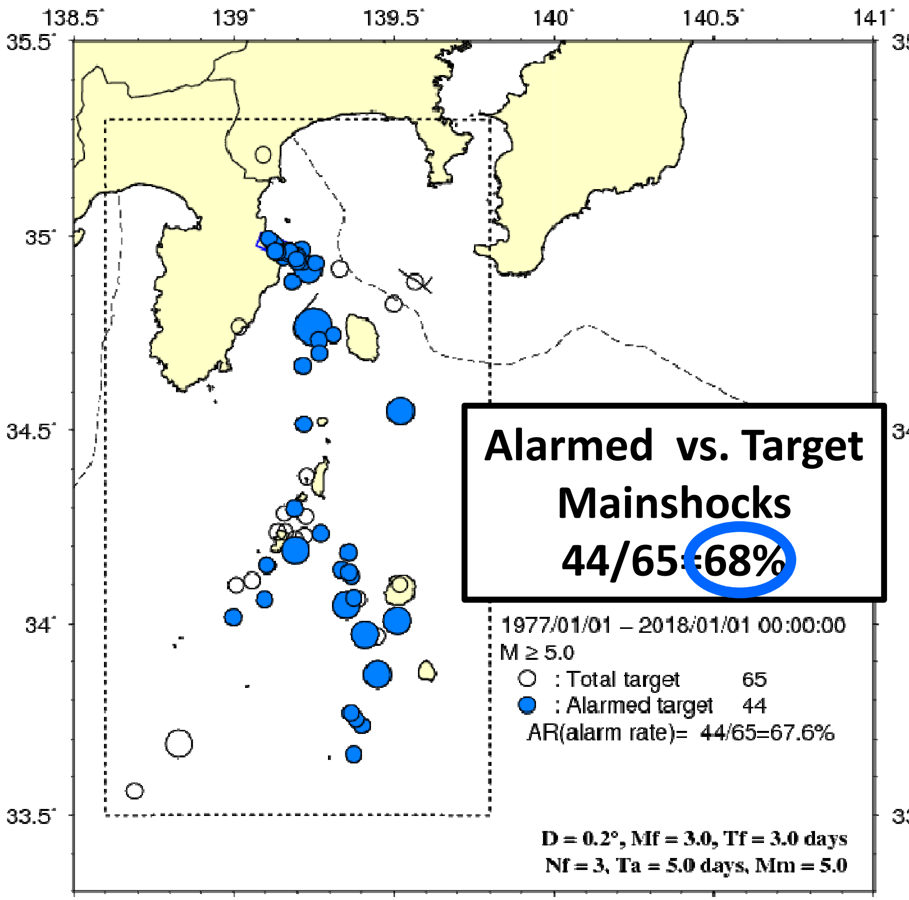
Best parameters: D = 0.5°, Mf ≥ 5.0, Tf = 10d, Nf = 3, Ta = 4d for Mm ≥ 6.0
(Target period: 1961 – 2017/12/31; Optimized period: 1961 – 2010)

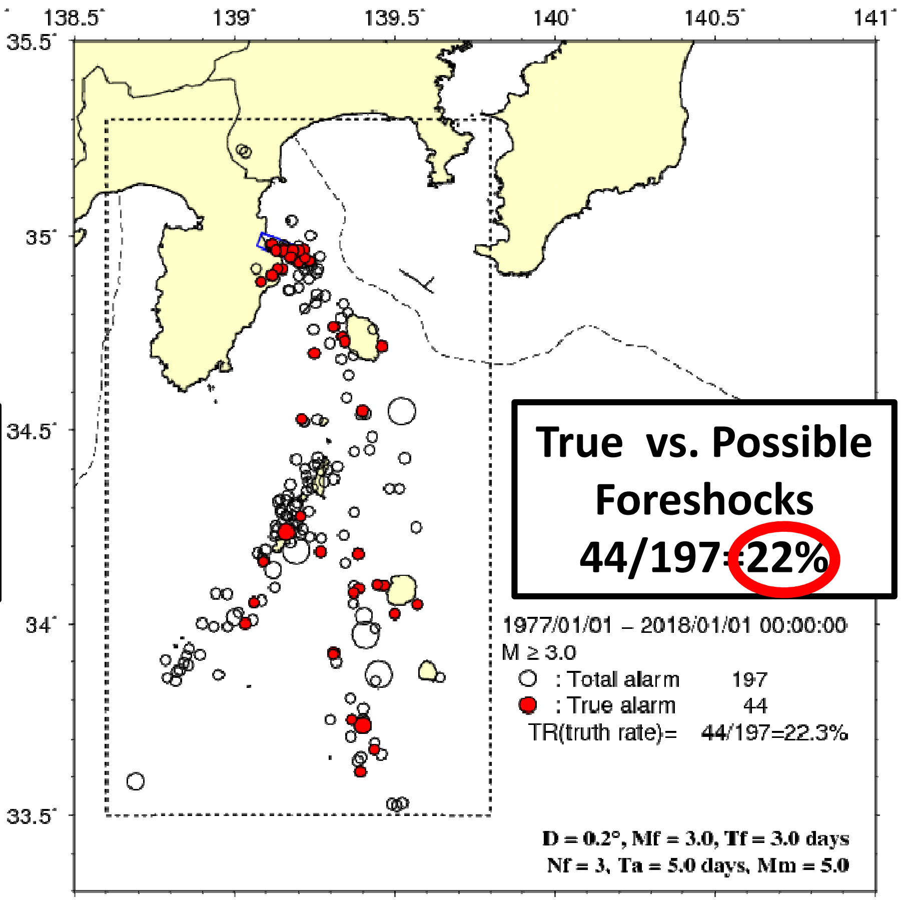




Prediction Performance for off the Izu Peninsula

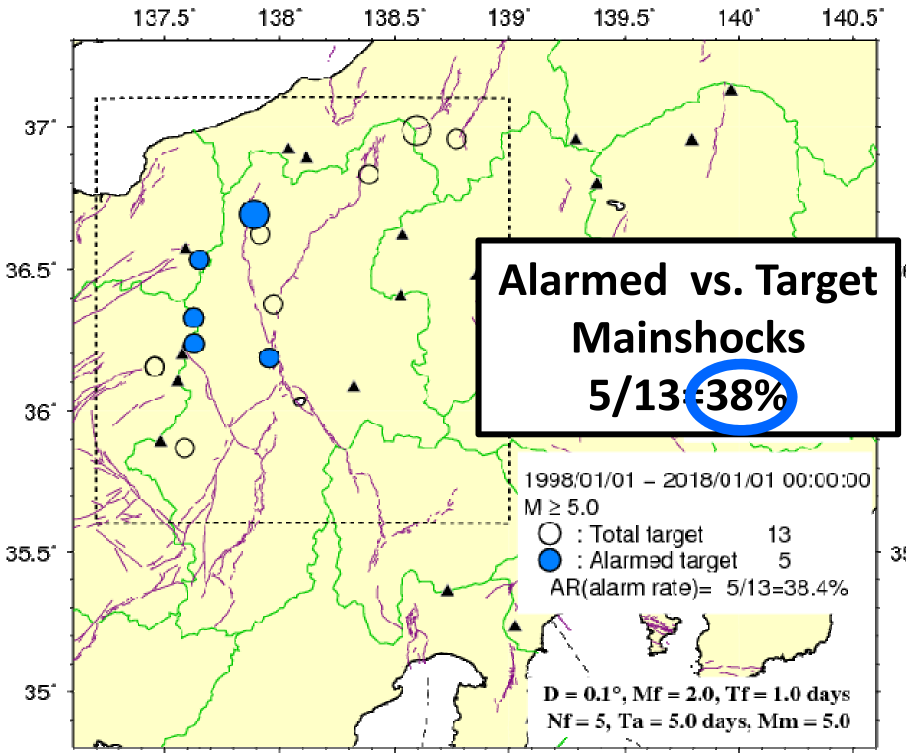
Best parameters: D = 0.2°, Mf ≥ 3.0, Tf = 3d, Nf = 3, Ta = 5d for Mm ≥ 5.0
(Target period: 1977 – 2017/12/31; Optimized period: 1977 – 2013/6)

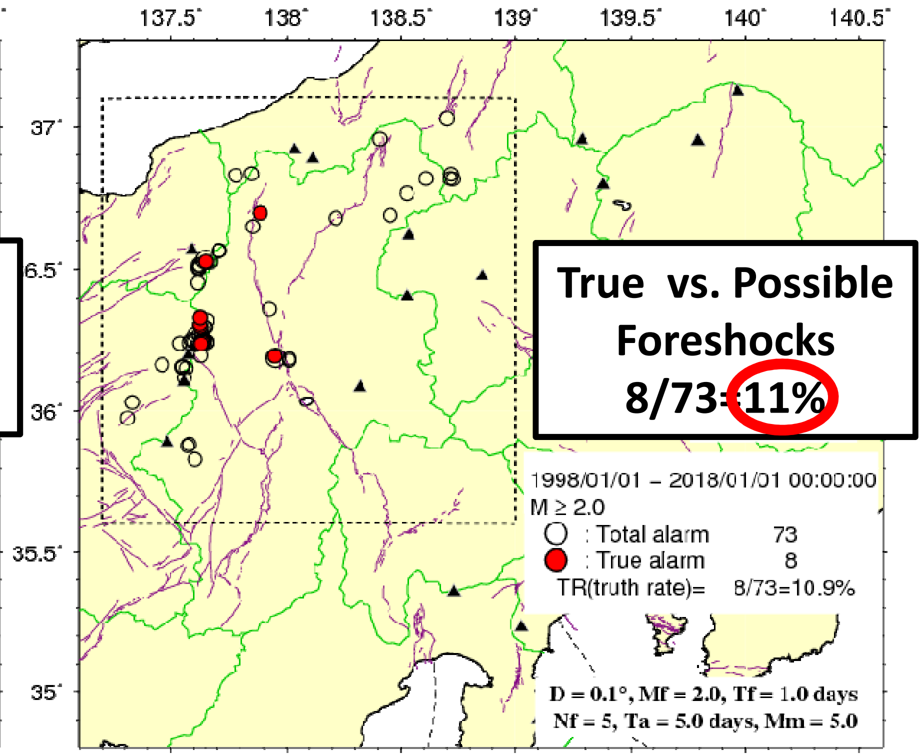




Prediction Performance for North-central Nagano Prefecture

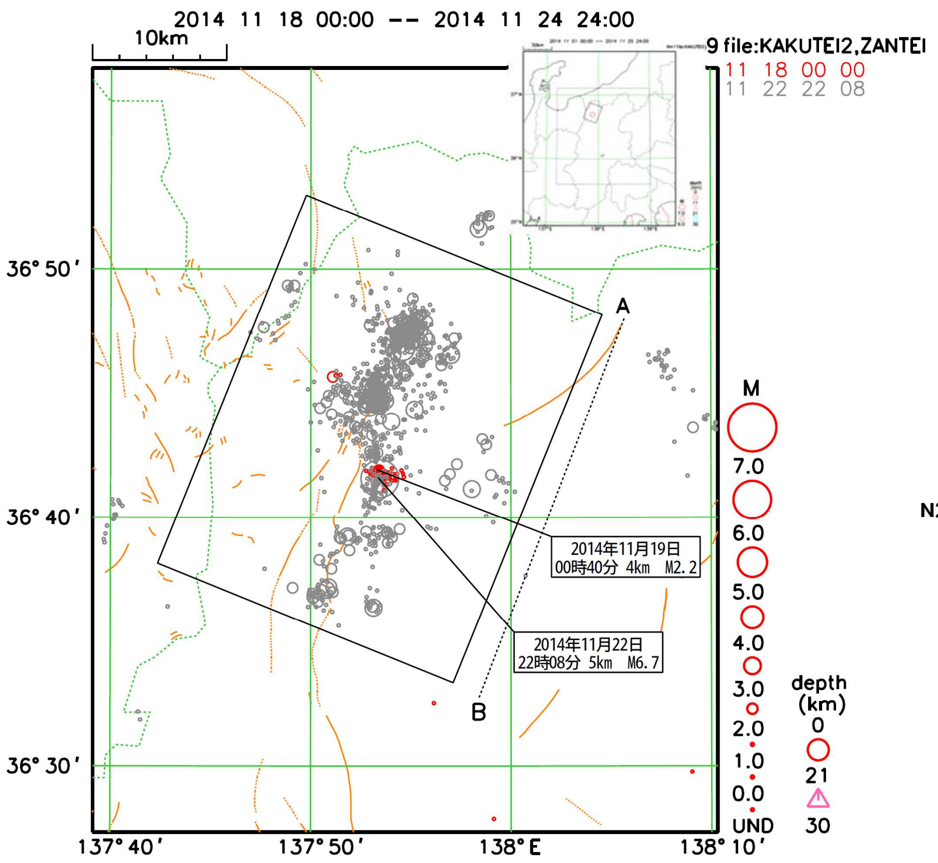
Best parameters: D = 0.1°, Mf ≥ 2.0, Tf = 1d, Nf = 5, Ta = 5d for Mm ≥ 5.0
(Target period: 1998 – 2017/12/31; Optimized period: 1998 – 2014)

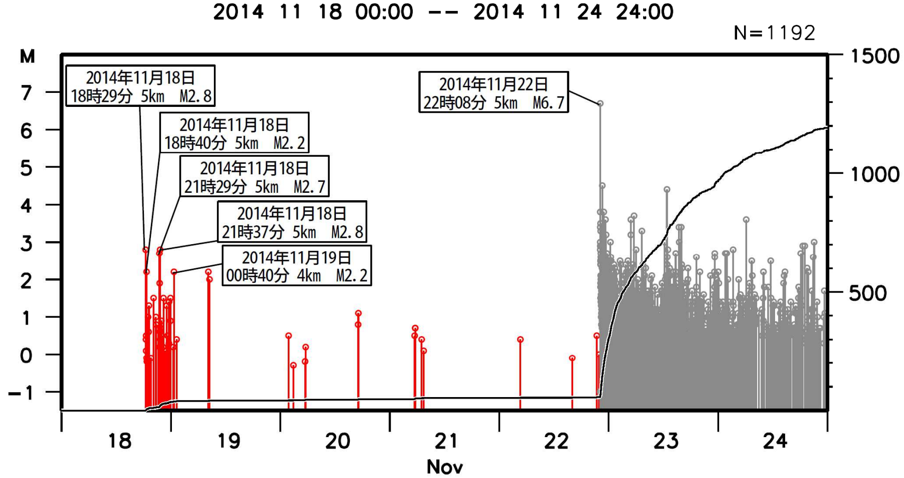


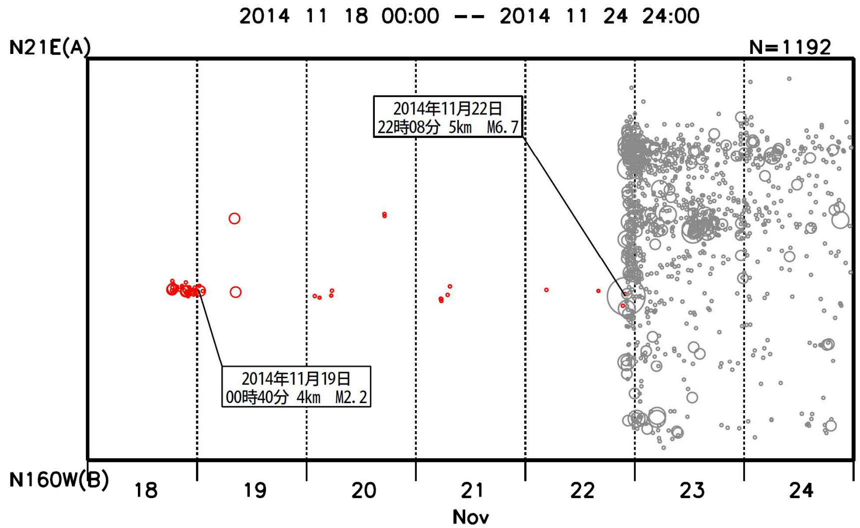


Foreshock Activity before the 2014 Northern Nagano Earthquake (M6.7)

Best parameters: D = 0.1°, Mf ≥ 2.0, Tf = 1d, Nf = 5, Ta = 5d for Mm≧5.0

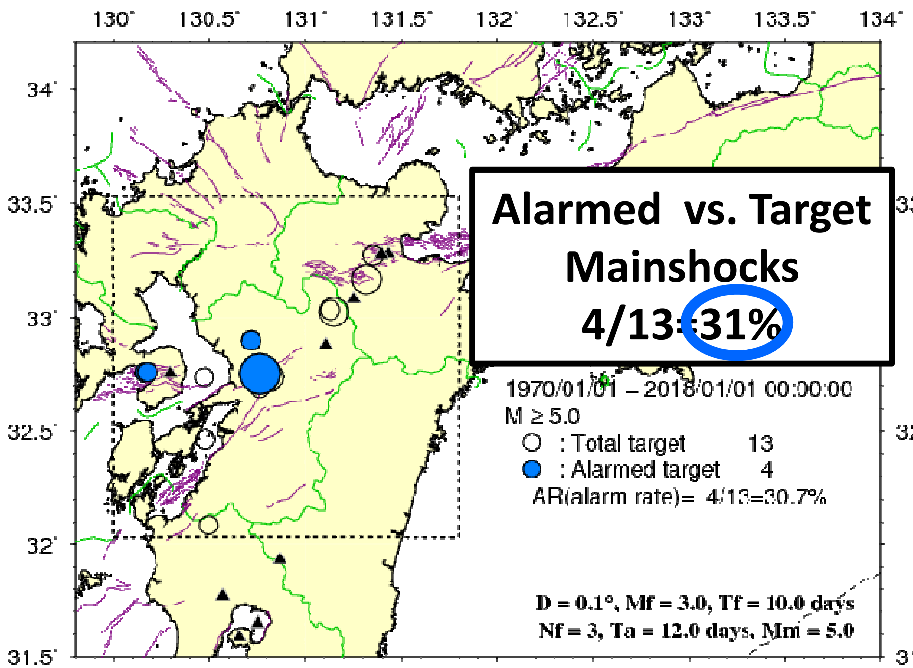


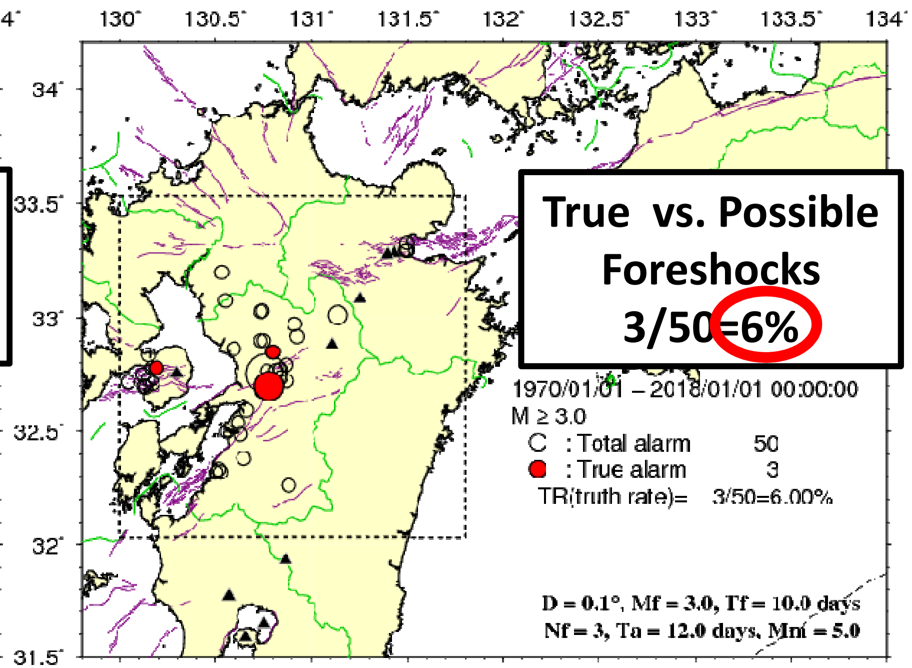




Prediction Performance for the Central Kyushu Region

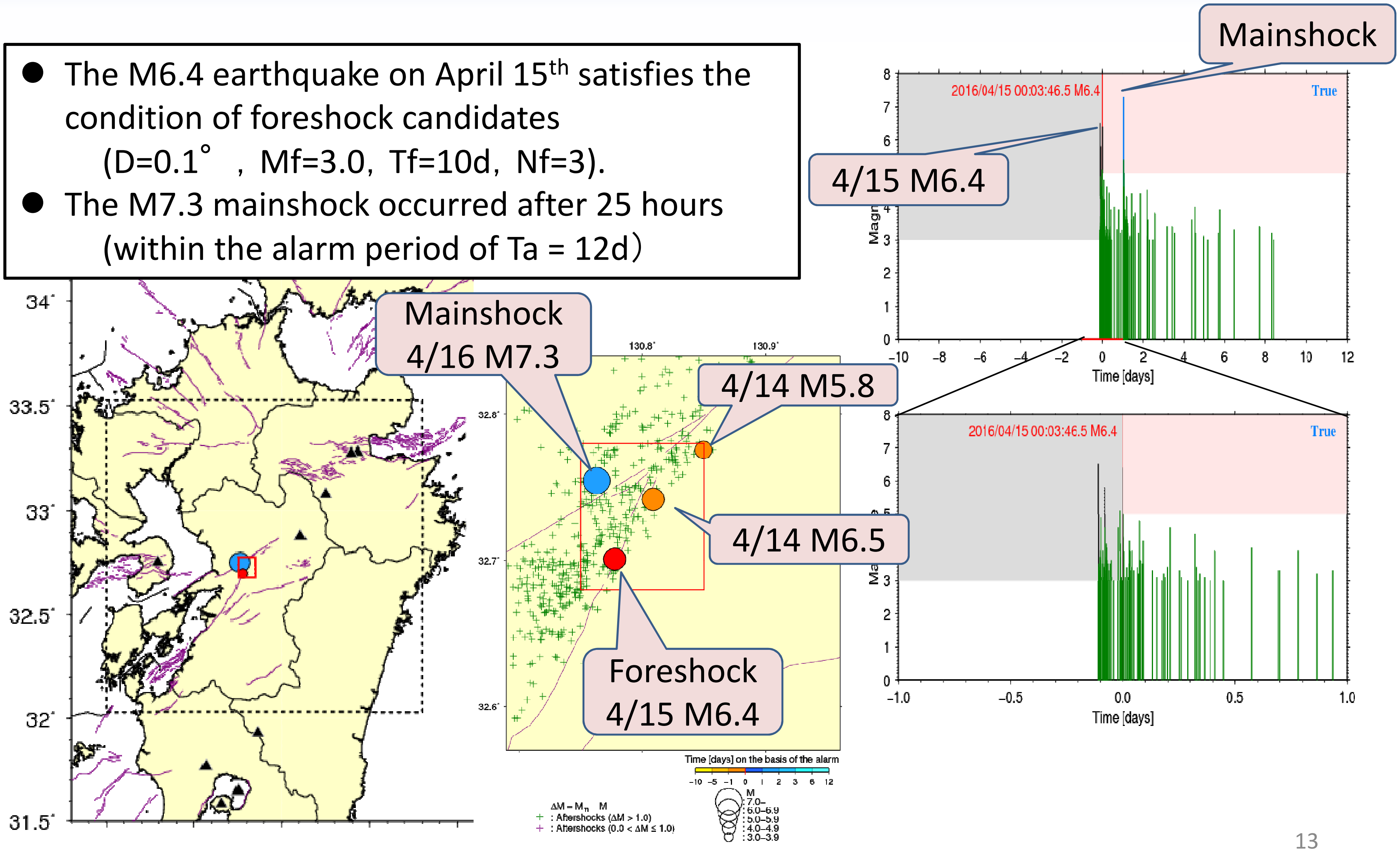
Best parameters: D = 0.1°, Mf ≥ 3.0, Tf = 10d, Nf = 3, Ta = 12d for Mm ≥ 5.0
(Target period: 1970 – 2017/12/31; Optimized period: 1970 – 2016/5)





Foreshock Activity before the 2016 Kumamoto Earthquake (M7.3)

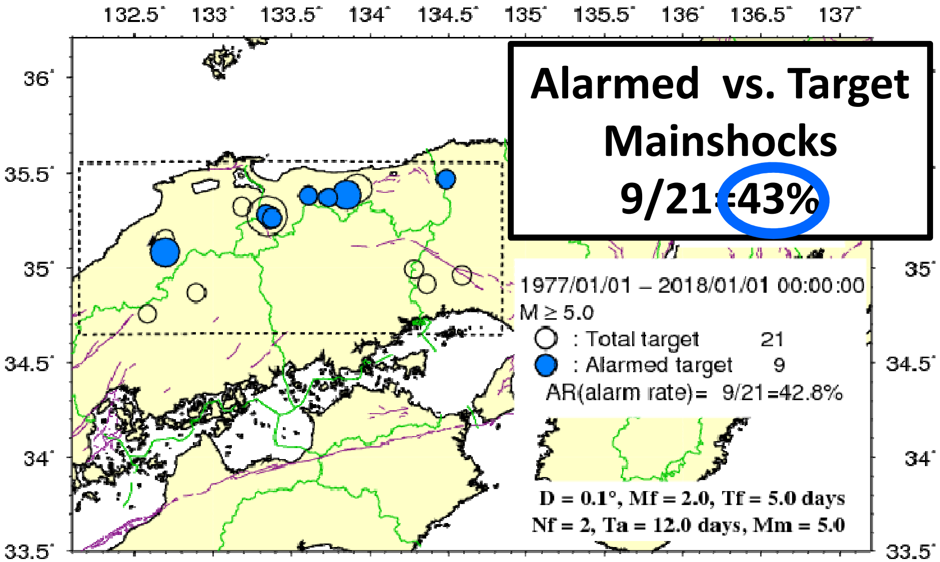
- The M6.4 earthquake on April 15th satisfies the condition of foreshock candidates (D=0.1°, Mf=3.0, Tf=10d, Nf=3).
- The M7.3 mainshock occurred after 25 hours (within the alarm period of Ta = 12d)

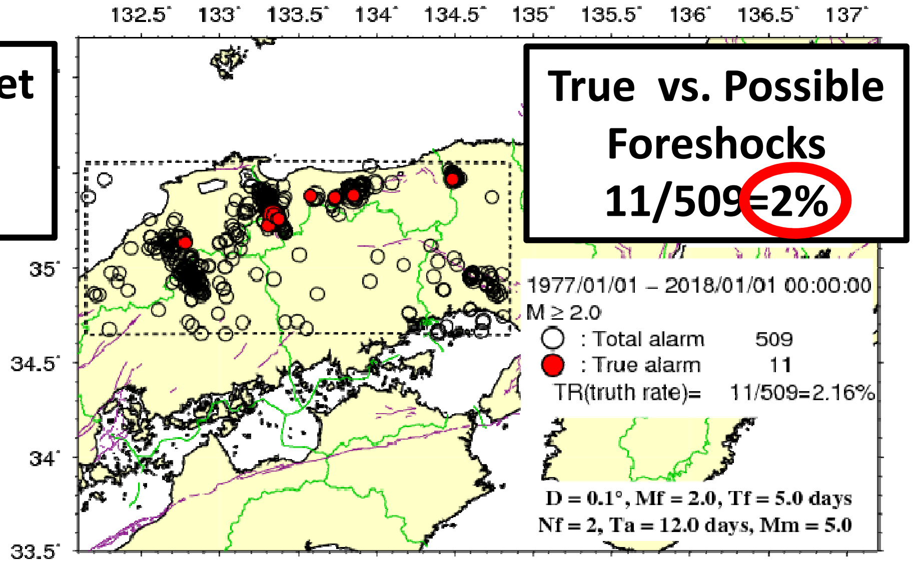


Prediction Performance for the San-in Region

(Using parameters giving maximum dAIC)

Best parameters: D = 0.1°, Mf ≥ 2.0, Tf = 5d, Nf = 2, Ta = 12d for Mm ≥ 5.0
(Target period: 1977 – 2017/12/31; Optimized period: 1977 – 2016)

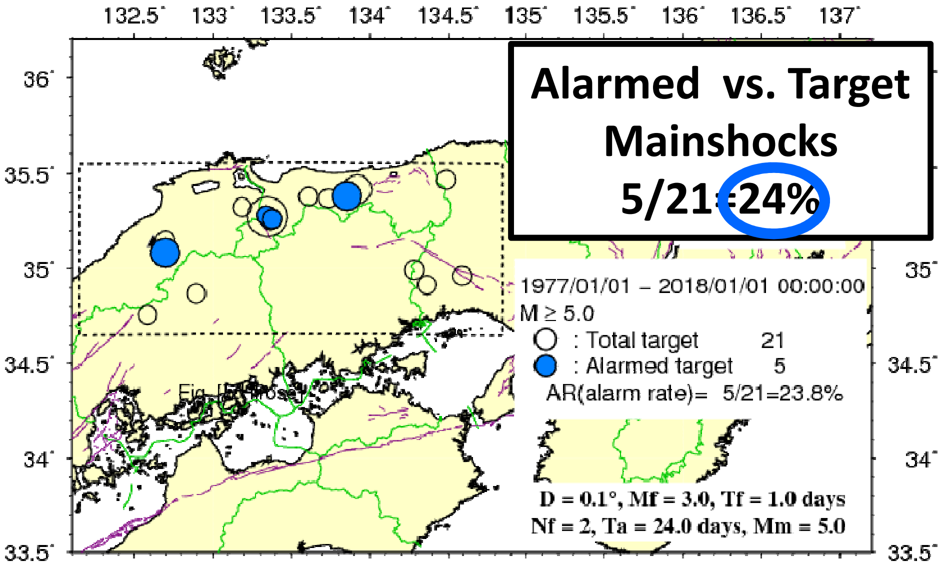


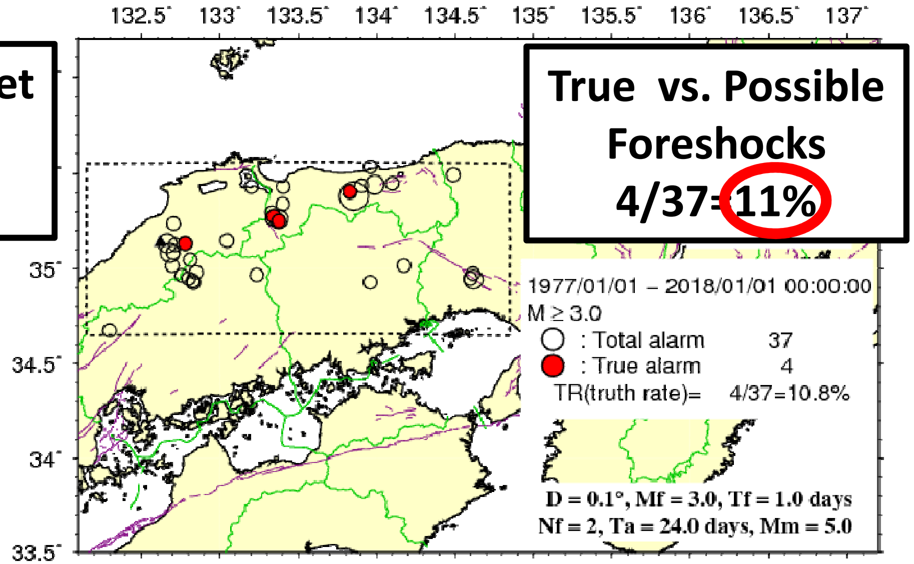


Prediction Performance for the San-in Region

(Using parameters with constrain of TR ≥ 5%)

Best parameters: D = 0.1°, Mf ≥ 3.0, Tf = 1d, Nf = 2, Ta = 24d for Mm ≥ 5.0
(Target period: 1977 – 2017/12/31; Optimized period: 1977 – 2016)

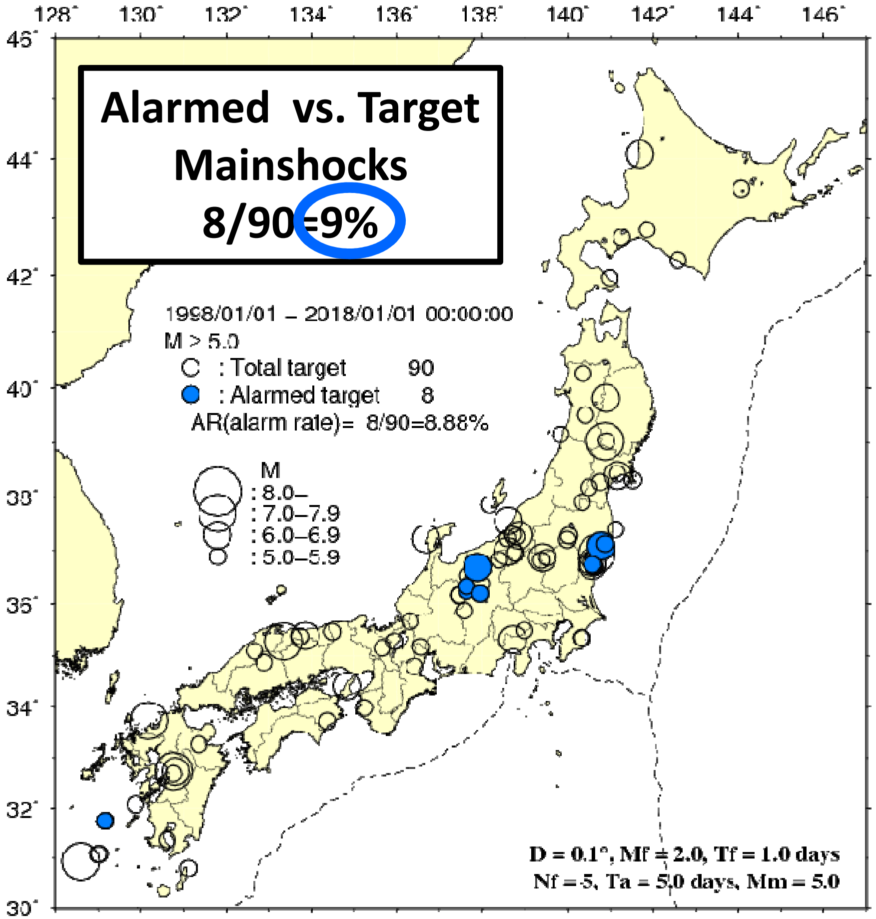


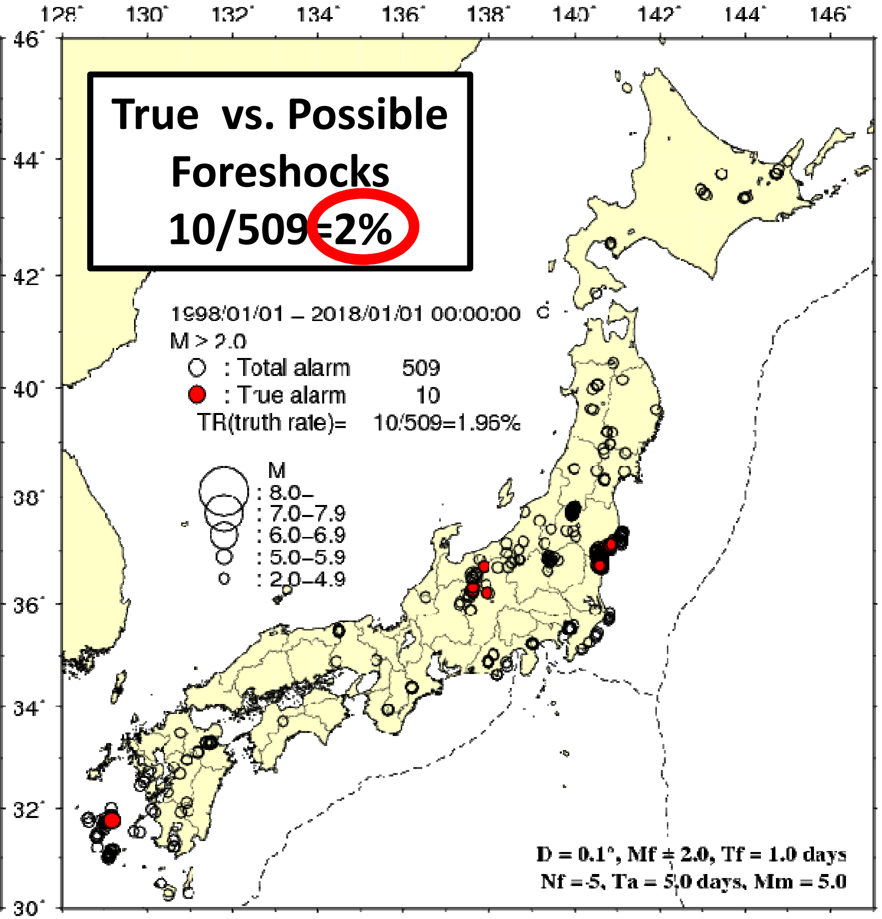


Prediction Performance for Inland Japan

(Using parameters for off the N.C. of Nagano)

Best parameters: D = 0.1°, Mf ≥ 2.0, Tf = 1d, Nf = 5, Ta = 5d for Mm ≥ 5.0
(Target period: 1998 – 2017/12/31; Optimized for N.C. of Nagano)

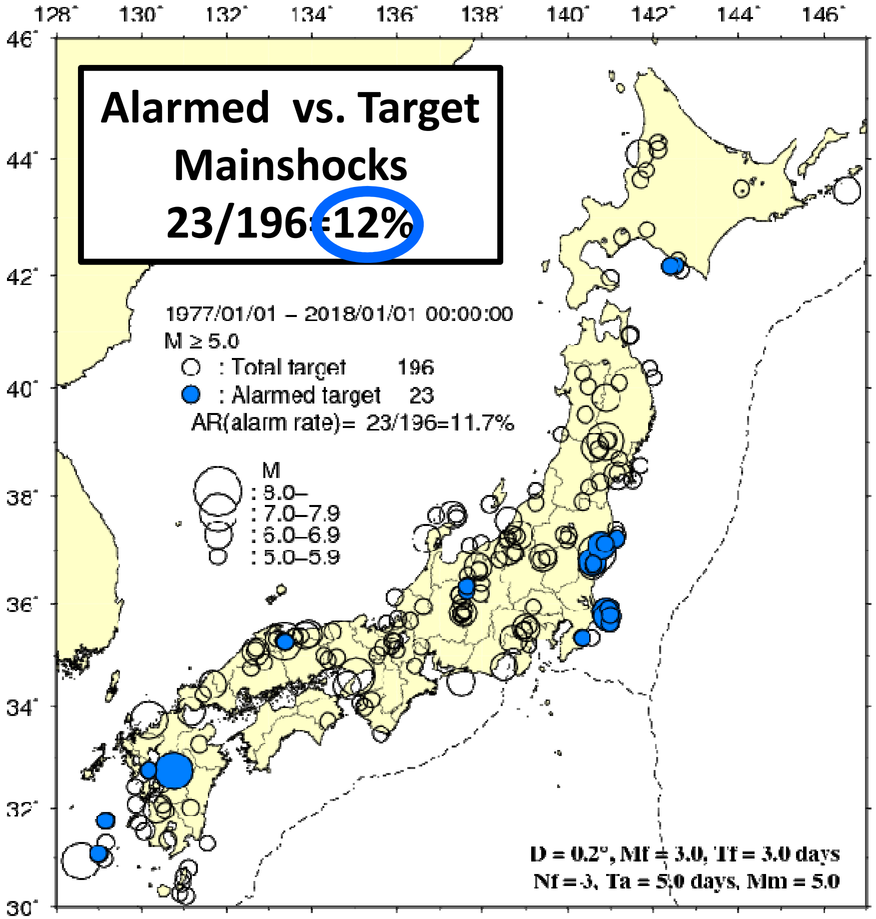


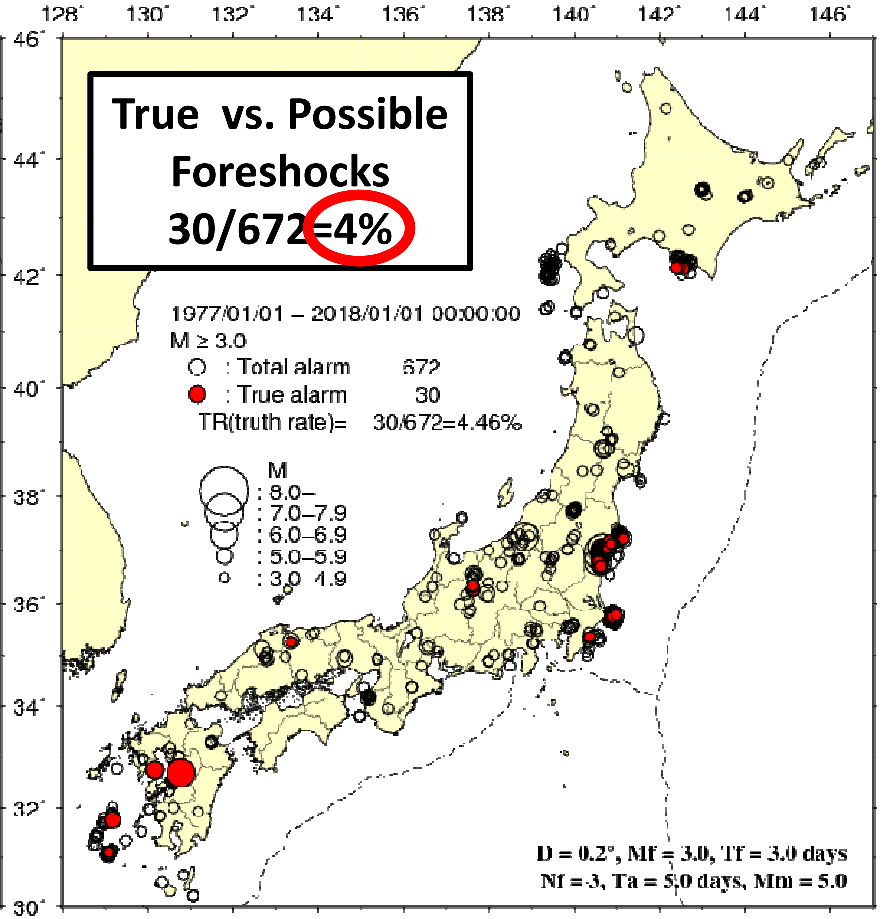


Prediction Performance for Inland Japan

(Using parameters for off the Izu peninsula)

Best parameters: D = 0.2°, Mf ≥ 3.0, Tf = 3d, Nf = 3, Ta = 5d for Mm ≥ 5.0
(Target period: 1977 – 2017/12/31; Optimized for off the Izu peninsula)





Summary of Prediction Performance

Target Regions	Target Periods	Best Parameters D, Mf_0, Tf, Nf, Ta, Mm_0 (optimized period)	Alarm Rates	Truth Rates	PG (for optimized period)
3 regions along the Japan trench	1961～*	0.5, 5.0, 10, 3, 4, 6.0 (1961～2010)	27% (=13/48)	22% (=17/79)	380
Off the Izu pen.	1977～*	0.2, 3.0, 3, 3, 5, 5.0 (1977～2013/6)	68% (=44/65)	22% (=44/197)	225
N.C. of Nagano	1998～*	0.1, 2.0, 1, 5, 5, 5.0 (1998～2014)	38% (=5/13)	11% (=8/73)	333
Central Kyushu	1970～*	0.1, 3.0, 10, 3, 12, 5.0 (1970～2016/5)	31% (=4/13)	6% (=3/50)	365
San-in	1977～*	0.1, 2.0, 5, 2, 12, 5.0 (1977～2016)	43% (=9/21)	2% (=11/509)	89
		0.1, 3.0, 1, 2, 24, 5.0 (under TR ≥ 5%)	24% (=5/21)	11% (=4/37)	120
Inland of Japan (not optimized)	1998～*	0.1, 2.0, 1, 5, 5, 5.0 (from Nagano case)	9% (=8/90)	2% (=10/509)	-
	1977～*	0.2, 3.0, 3, 3, 5, 5.0 (from Izu case)	12% (=23/196)	4% (=30/672)	-

* 2017/12/31

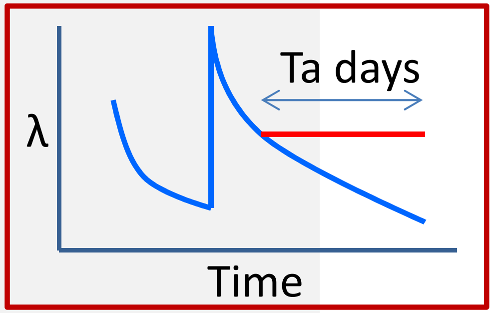
Comparison with the ETAS Model

t

Procedure of calculating probability based on the ETAS model

1. Estimate the b-value and parameters of the ETAS model
   data: $M \geq M_{th}$, optimized for each region

2. Calculate the expected occurrence rate of the target events
   target period: Ta days after each event
   target M: $M \geq \max (Mm_0 , Mf_{max})$
   target area: all area within the each region
   magnitude distribution: G-R model
   constant rate during Ta days



3. Calculate probability assuming Poisson process during Ta days
   $P(n \geq 1) = 1 - e^{-\lambda * Ta}$

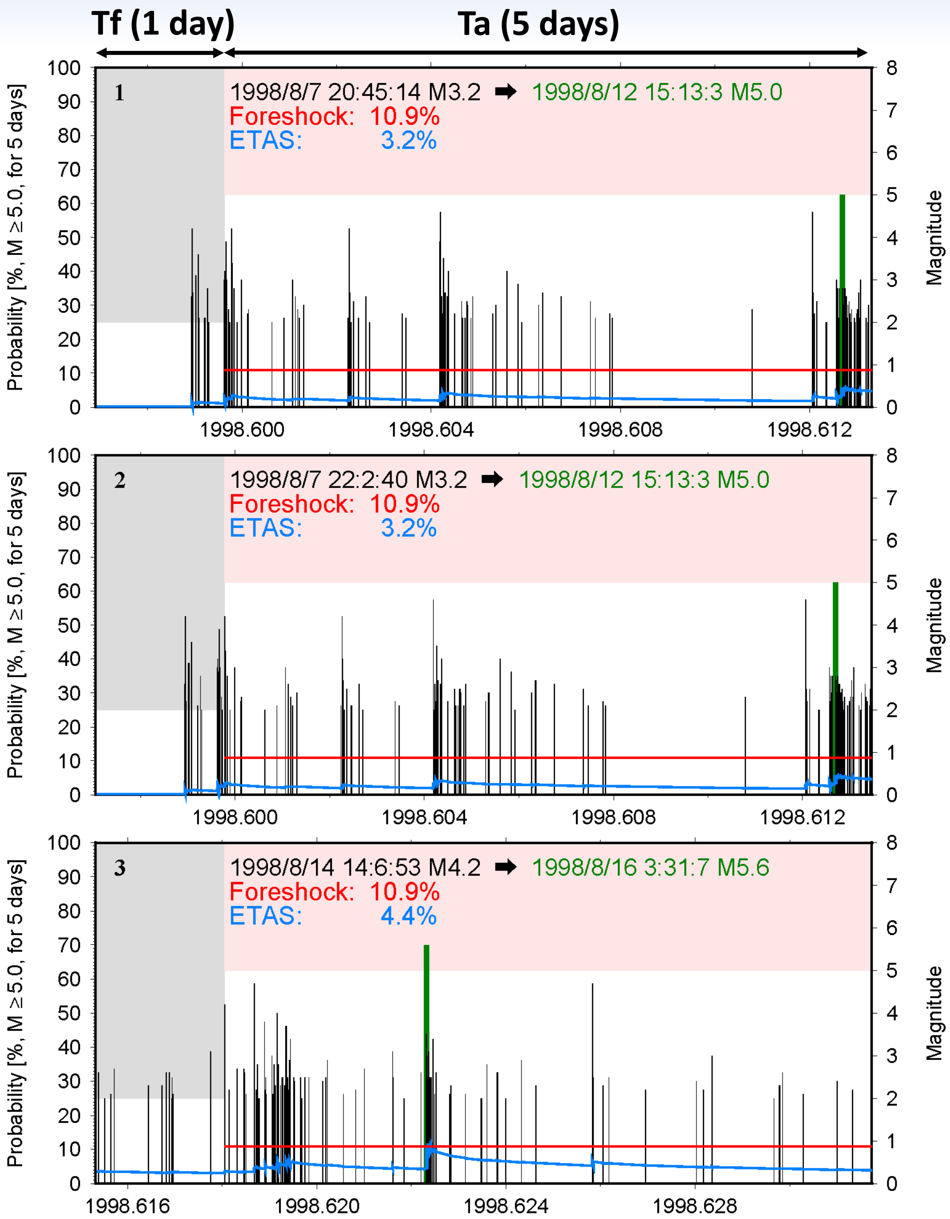
Foreshocks vs. ETAS Model

(N-C. Nagano Prefecture)

- 8 cases are successful
- target period: 5 days
- target M:
  M ≥ max (5.0, Mf_{max})
- Red line: Truth rate of the foreshock model（10.9%）
- Blue line: Probability by the ETAS model
- The ETAS value is at just before the target event

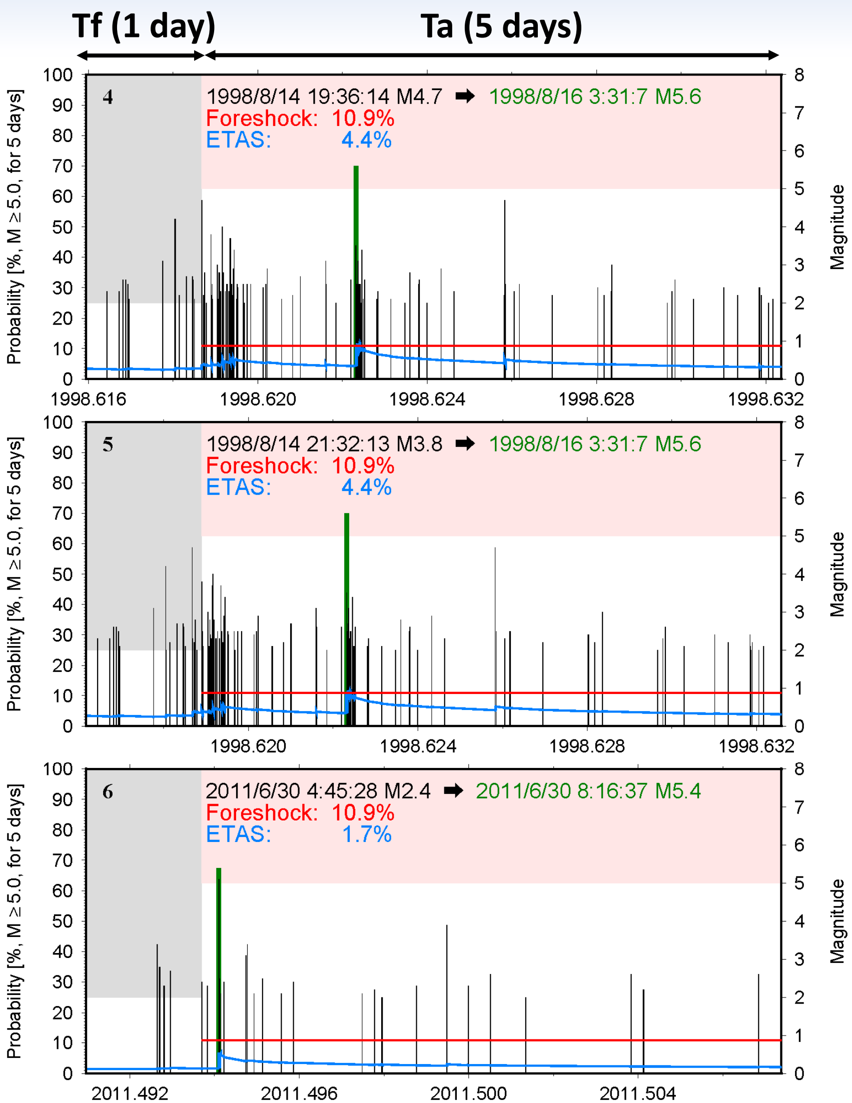
ETAS Parameters
Region : N-C. Nagano
Period : 1998-2014/10
M_{th} = 1.95
b = 0.84
μ = 0.14
K = 0.0191
c = 0.0012
α = 1.30
p = 1.05

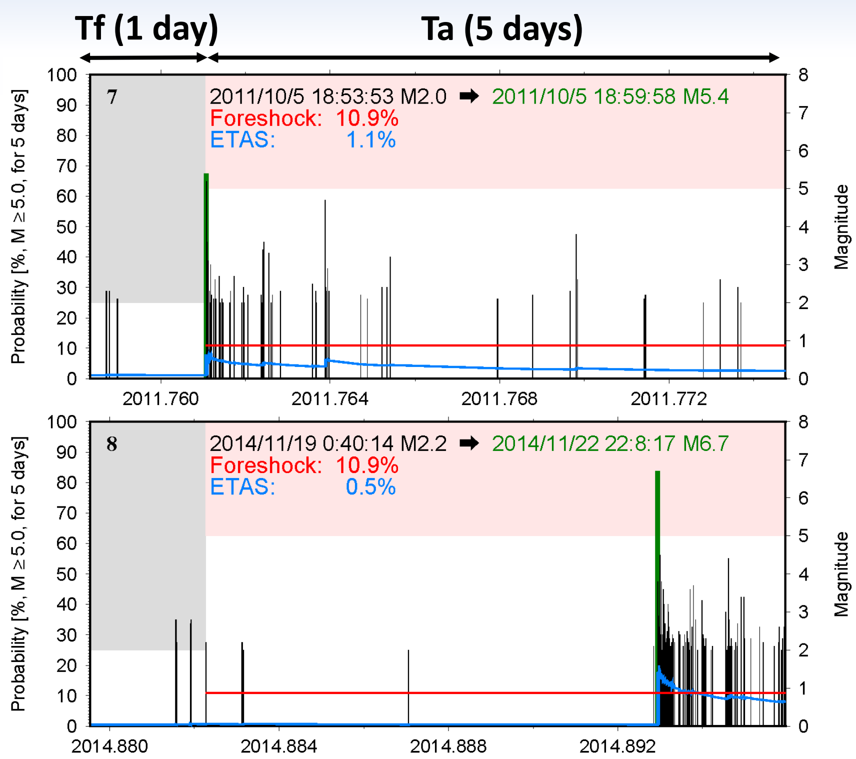
Foreshock Parameters
1998-2014
D = 0.1°
Mf ≥ 2.0
Tf = 1d
Nf = 5
Ta = 5d
Mm ≥ 5.0



Foreshocks vs. ETAS Model

(N-C. Nagano Prefecture) (continued)





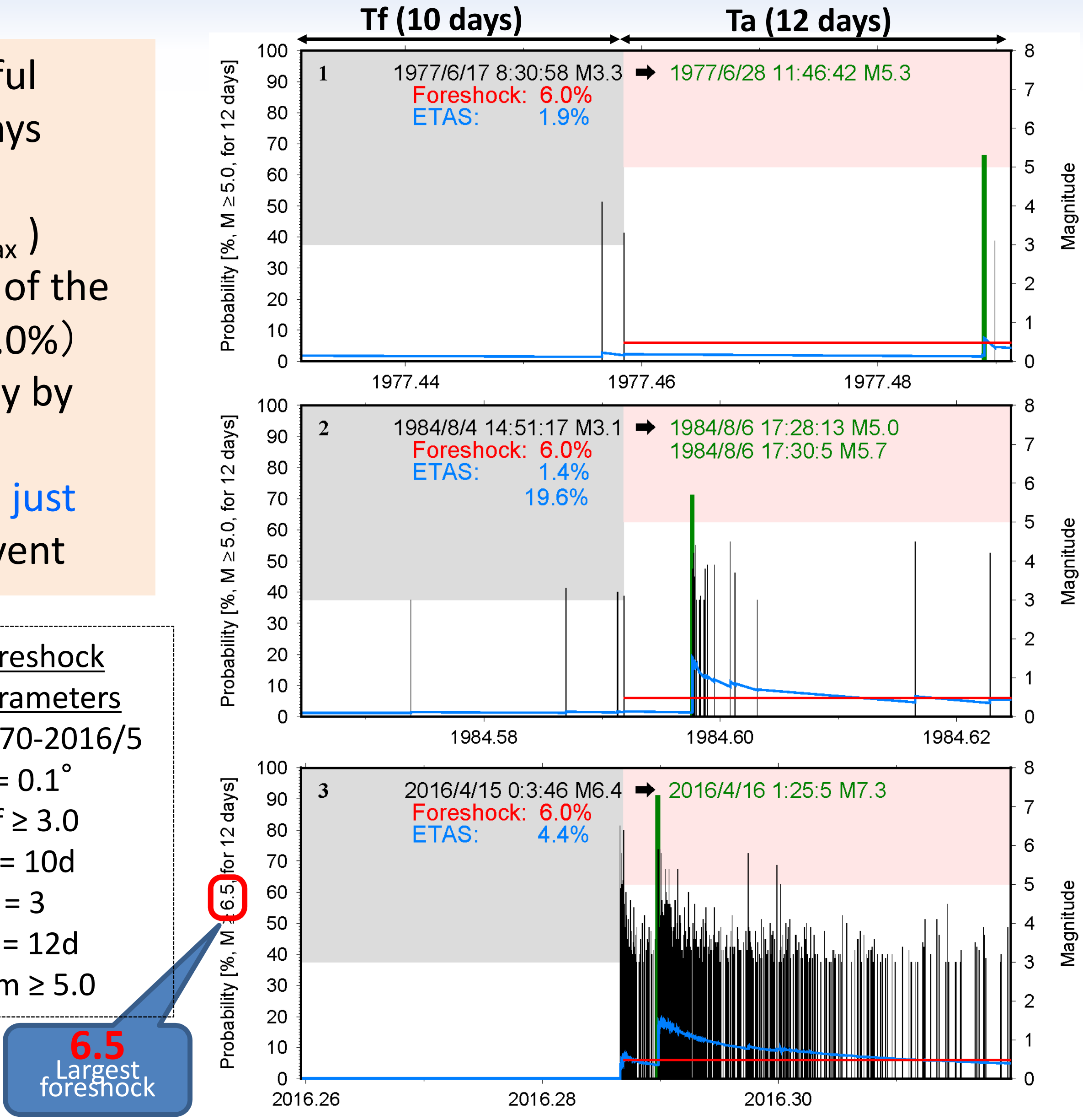
- The ETAS values are lower than the truth rate of the foreshock model for all the 8 cases.

Foreshocks vs. ETAS Model
(Central Kyushu District)

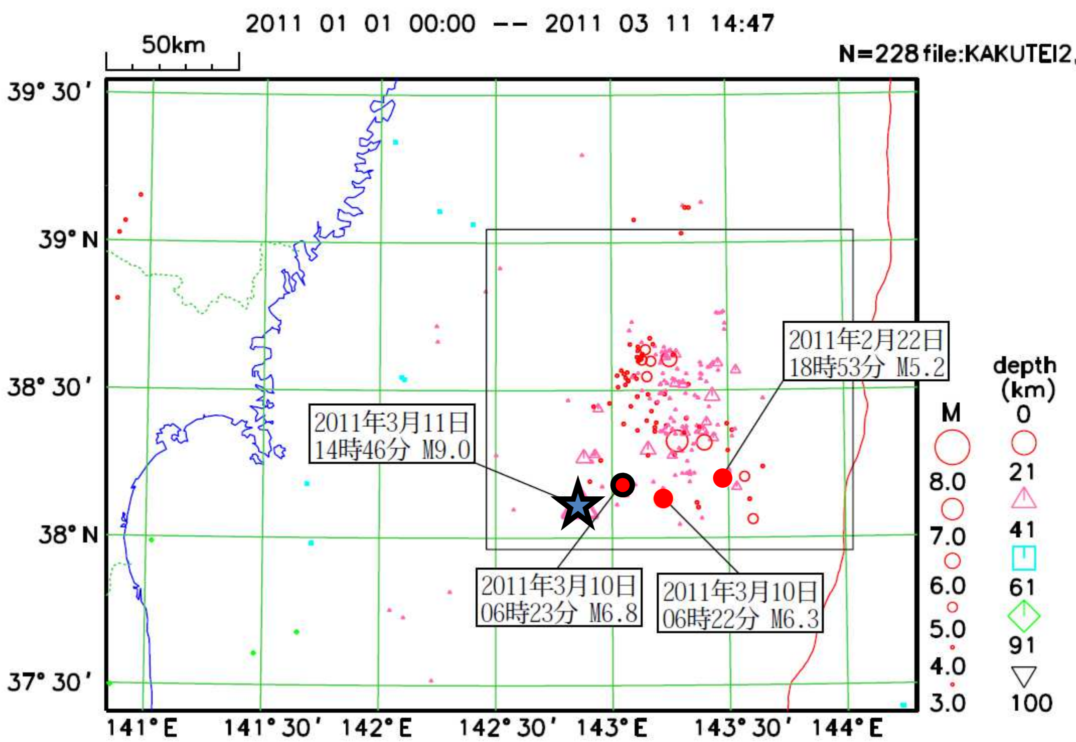
- 3 cases are successful
- target period: 12 days
- target M:
  M ≥ max (5.0, Mf_{max})
- Red line: Truth rate of the foreshock model（6.0%）
- Blue line: Probability by the ETAS model
- The ETAS value is at just before the target event

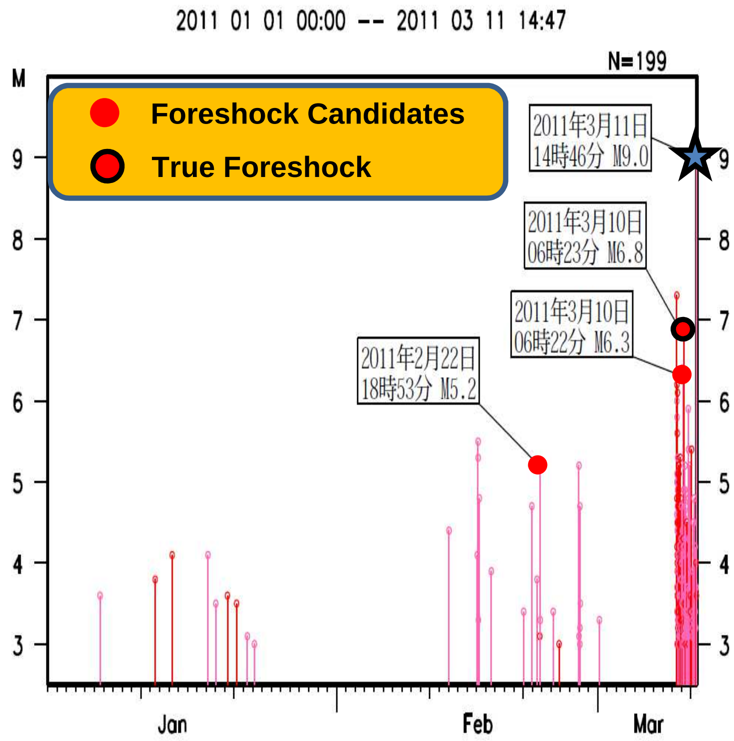
<u>ETAS Parameters</u>
Region： C. Kyushu
Period： 1970-2016/3
M_{th} = 2.95
b = 0.74
μ = 0.03
K = 0.0104
c = 0.0074
α = 1.38
p = 1.11

<u>Foreshock Parameters</u>
1970-2016/5
D = 0.1°
Mf ≥ 3.0
Tf = 10d
Nf = 3
Ta = 12d
Mm ≥ 5.0



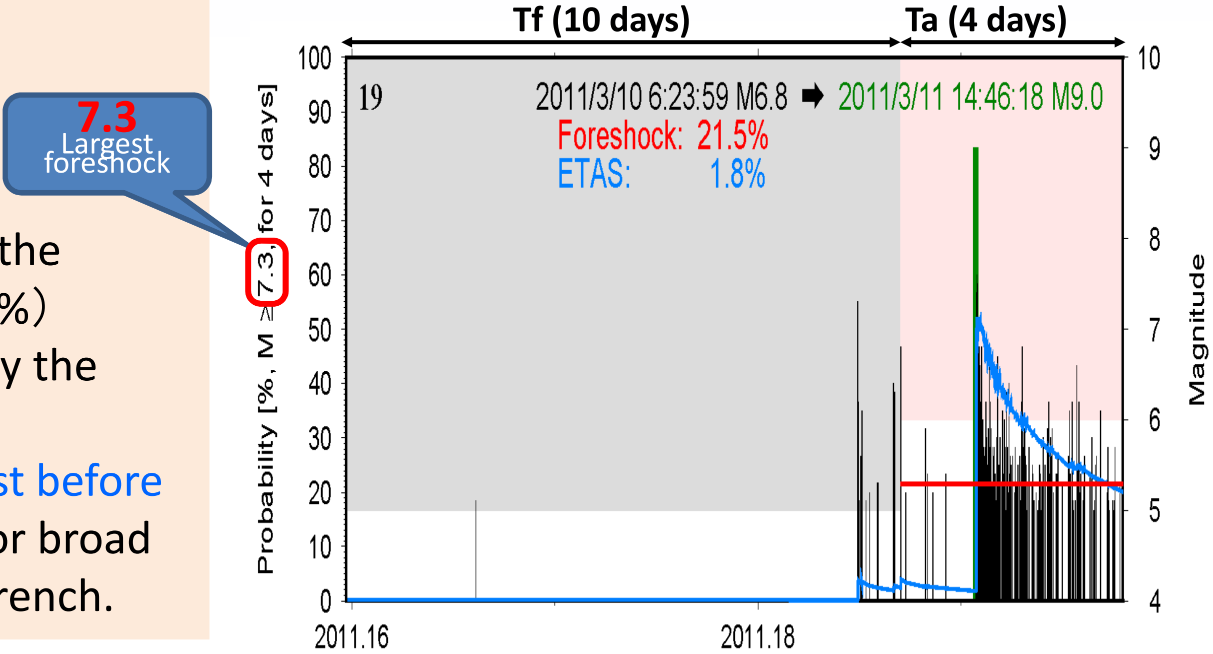
Foreshocks before the 2011 Off Tohoku Eq.
(2011/3/11 14:46, M9.0)





Foreshocks vs. ETAS Model
(2011 Off Tohoku Eq. (M9.0))

- Case: 2011.3.11 M9.0
- target period: 4 days
- target M:
  M ≥ max (6.0, Mf_{max})
- Red line: Truth rate of the foreshock model（21.5%）
- Blue line: Probability by the ETAS model (1.8%)
- The ETAS value is at just before the target event and for broad area along the Japan trench.

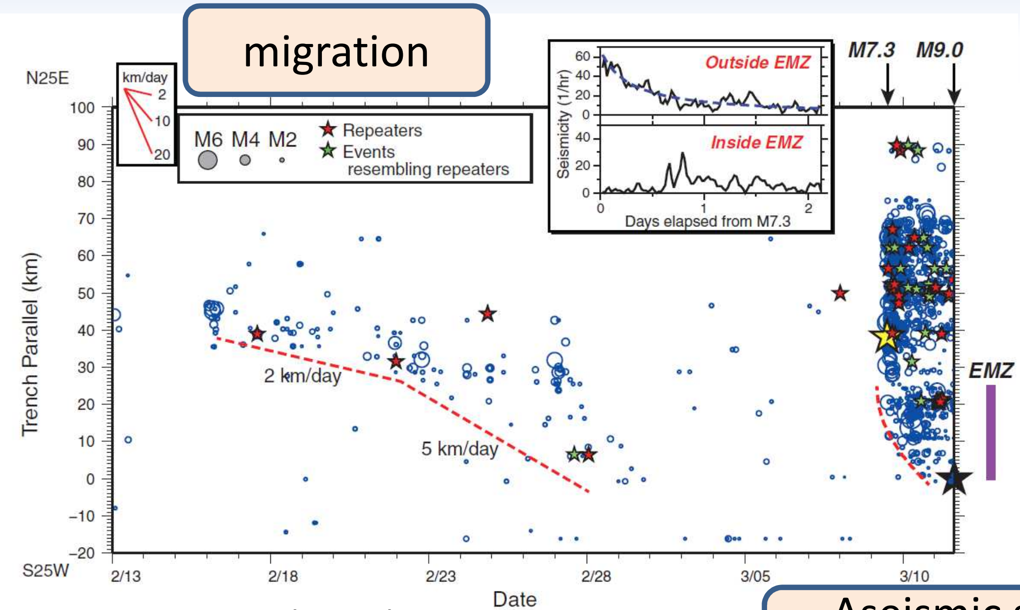


ETAS Parameters
Region : along the Japan trench
Period : 1961-2011/2
M_{th} = 4.95
b = 0.99
μ = 0.06
K = 0.0184
c = 0.0265
α = 1.76
p = 1.10

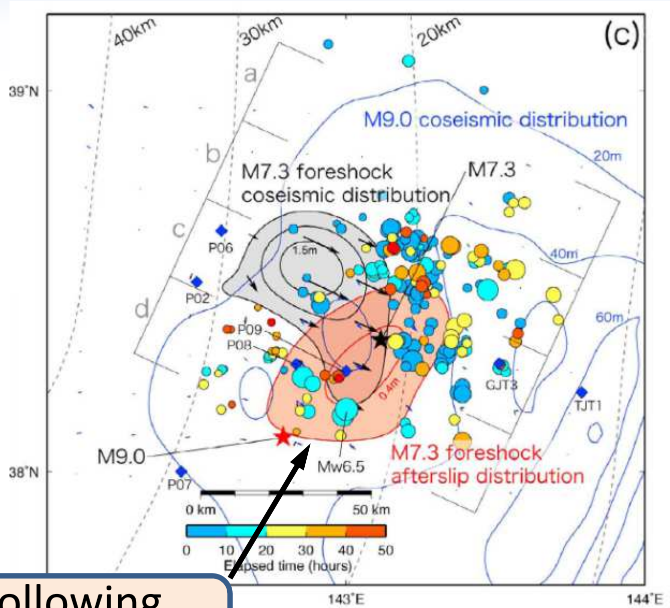
Foreshock Parameters
1961-2010
D = 0.5°
Mf ≥ 5.0
Tf = 10d
Nf = 3
Ta = 4d
Mm ≥ 6.0

Aseismic Slip during Foreshock Activity
(2011 Off Tohoku Eq. (M9.0))

migration

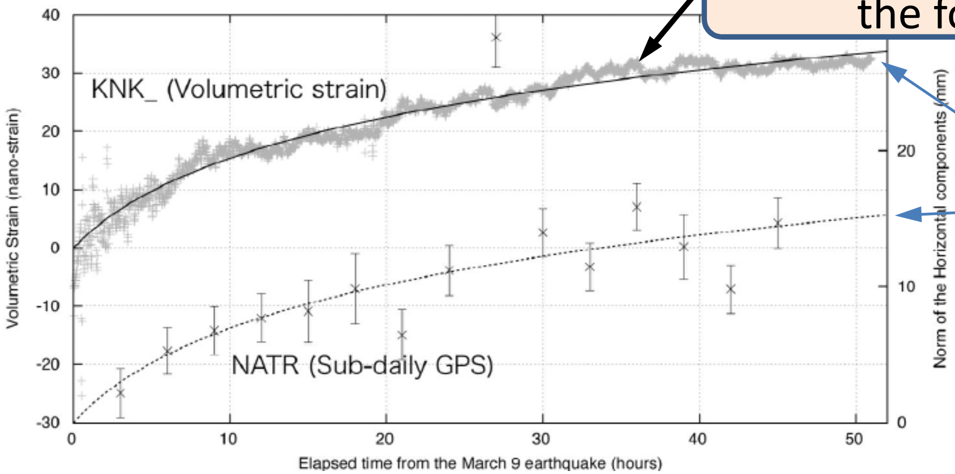


[Kato et al. (2012)]

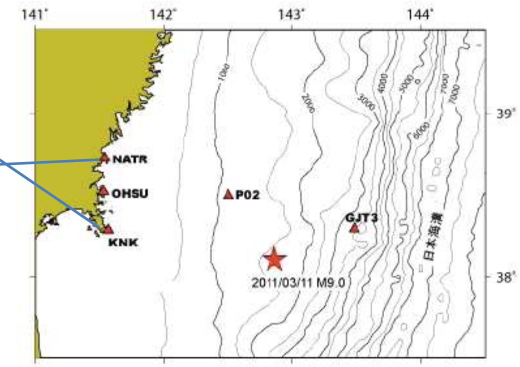


Aseismic slip following the foreshock

[Ohta et al. (2012)]

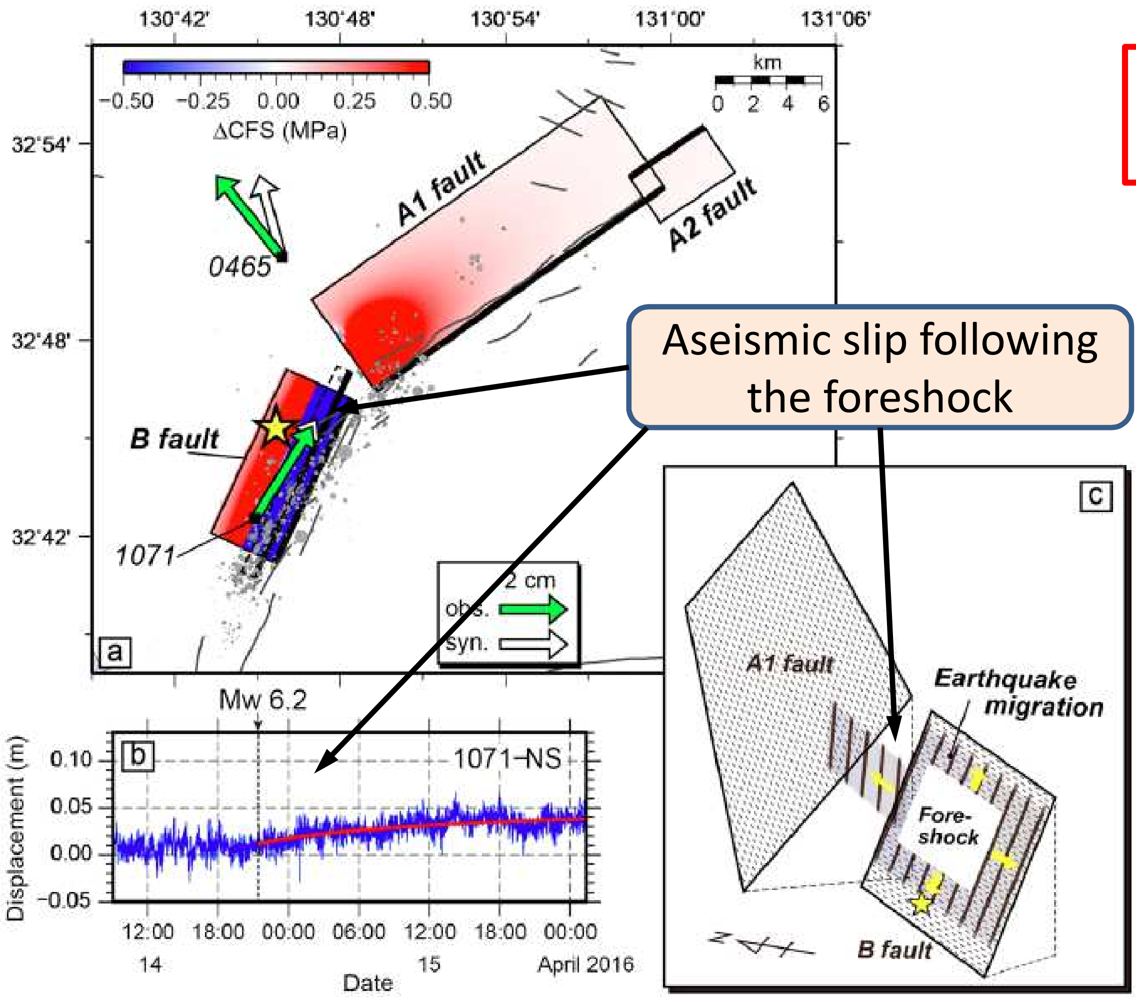


[Ohta et al. (2012)]



[Tohoku Univ. (2011)]

Aseismic Slip during Foreshock Activity
(2016 Kumamoto Eq. (M7.3))



[Kato et al. (2016)]

Aseismic slip may be an additional or a main triggering source.

A prediction model should take this effect into account appropriately.

One of the reason why our foreshock model gives higher probability than ETAS may be that our model may implicitly include this effect more appropriately than ETAS.

Summary

- **We have proposed a method to select foreshock candidates, which produces relatively high performance for predicting mainshocks.**
- **For example, the performance are**

AR = 27%, TR= 22%, PG=380 for 3 regions along the Japan Trench
AR = 68%, TR= 22%, PG=225 for off the Izu Peninsula
AR = 38%, TR= 11%, PG=333 for the North-central Nagano Prefecture
AR = 31%, TR= 6%, PG=365 for the Central Kyushu District

- **Our model tend to calculate higher probability values at the mainshock occurrence time than those by the ETAS model.**
- **Aseismic slip during foreshock activity may have an important role to trigger a mainshock, which should be taken into account appropriately in the model.**