

第200回地震予知連絡会重点検討課題  
「地震の短期予測の現状と評価」

# 短期予測と統計モデル

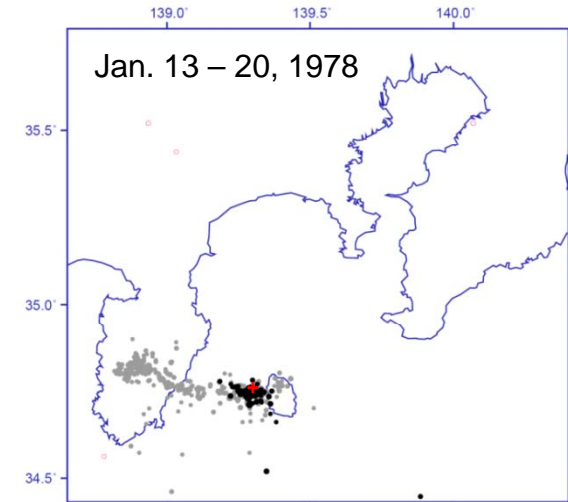
尾形良彦

# 1978年1月14日12時24分 伊豆大島近海の地震 (M7.0)

宇津 (1978予知連会報)

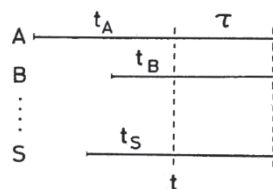


予測地震を  $M6\frac{1}{2}$  以上としての  
前兆確率の試算



- 項目A: 1976年初からの隆起域の広がり等から考えて、  
隆起が始ってから 5 年以内にかかる確率  $1/3$  (0.02% per day)
- 項目B: 石廊崎と網代の埋込式体積ひずみ計に現れた異常や伊豆半島でのラドン、井戸水位等の異常、前年の12月中旬から1か月以内にかかる確率  $1/10$  (0.3% per day)
- 項目C: 1月14日午前大島西方の地震活動、前震確率  $1/10$ 。  
始ってから3日以内にかかる確率  $1/35$  (1% per day)
- 項目O: 大地震の基礎確率  $P_0$ : 対象地域内で  
30年に1回の割合で起っている場合 (Case I) (0.009% per day)  
100年に1回の割合で起っている場合 (Case II) (0.003% per day)

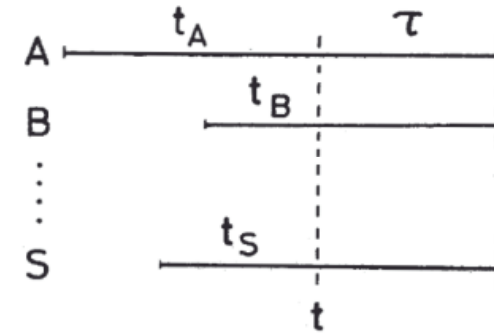
複合的確率予測公式 (宇津, 1977「地震」)



$$P = \frac{1}{1 + \left(\frac{1}{P_A} - 1\right) \left(\frac{1}{P_B} - 1\right) \left(\frac{1}{P_C} - 1\right) \cdots \left(\frac{1}{P_S} - 1\right) / \left(\frac{1}{P_0} - 1\right)^{N-1}}$$

# 伊豆大島近海の地震 (M7.0) の前兆確率の試算

$$P = \frac{1}{1 + \left(\frac{1}{P_A} - 1\right) \left(\frac{1}{P_B} - 1\right) \left(\frac{1}{P_C} - 1\right) / \left(\frac{1}{P_0} - 1\right)^{N-1}}$$



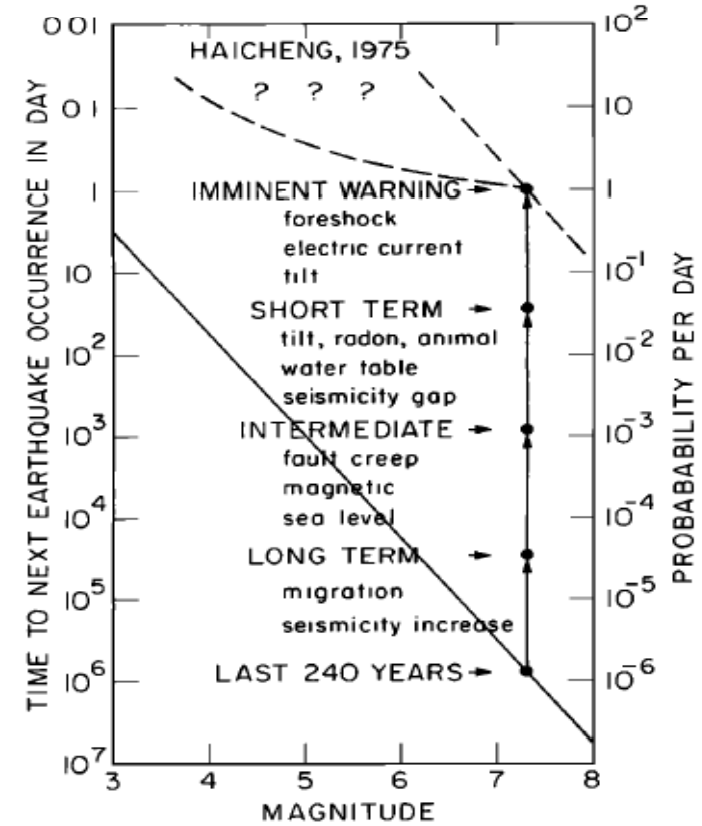
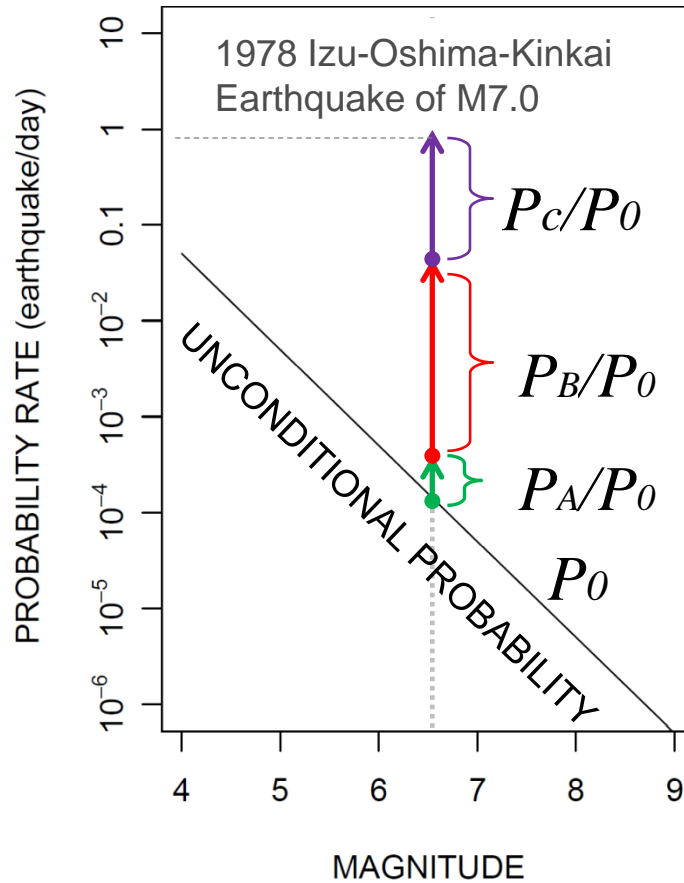
$\tau$		3 hours	1 day	3 days
隆起	$P_A$	0.0000228	0.000183	0.000548
前震	$P_B$	0.00119	0.00952	0.0286
歪、水位	$P_C$ ラドン	0.000417	0.00333	0.01
$P_0$	Case I	0.0000114	0.0000913	0.000274
	Case II	0.00000342	0.0000274	0.0000821
$P(A \cap B \cap C)$	Case I	0.080 (0.011)	0.41 (0.081)	0.68 (0.21)
	Case II	0.49 (0.11)	0.89 (0.49)	0.96 (0.75)
$P(A \cap B)$	Case I	0.0024	0.019	0.056
	Case II	0.0079	0.060	0.16
$P(B \cap C)$	Case I	0.042	0.26	0.52
	Case II	0.13	0.54	0.78

$$P(M | A, B, C, \dots, S) = \frac{1}{1 + \left(\frac{1}{P_A} - 1\right)\left(\frac{1}{P_B} - 1\right)\left(\frac{1}{P_C} - 1\right) \dots \left(\frac{1}{P_S} - 1\right) / \left(\frac{1}{P_0} - 1\right)^{N-1}} \approx P_0 \cdot \frac{P_A}{P_0} \frac{P_B}{P_0} \frac{P_C}{P_0} \dots \frac{P_S}{P_0}$$

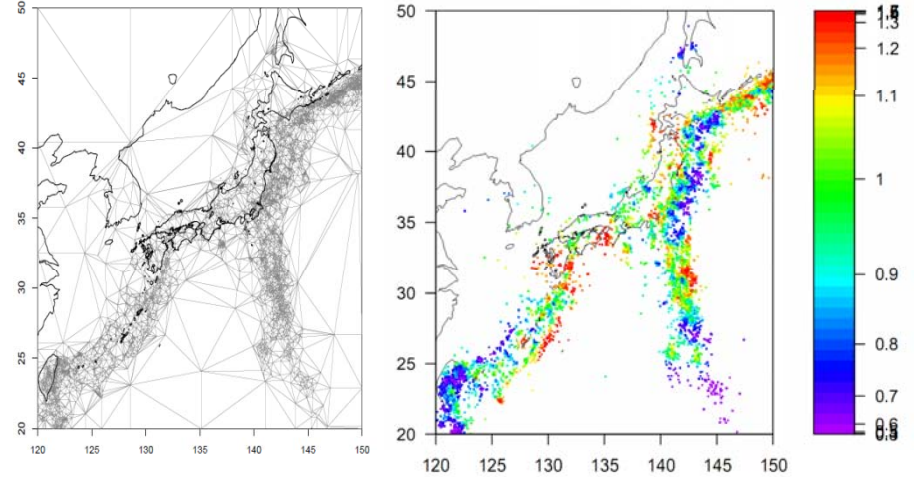
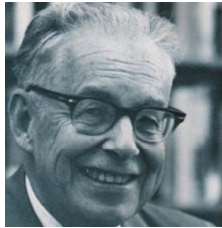
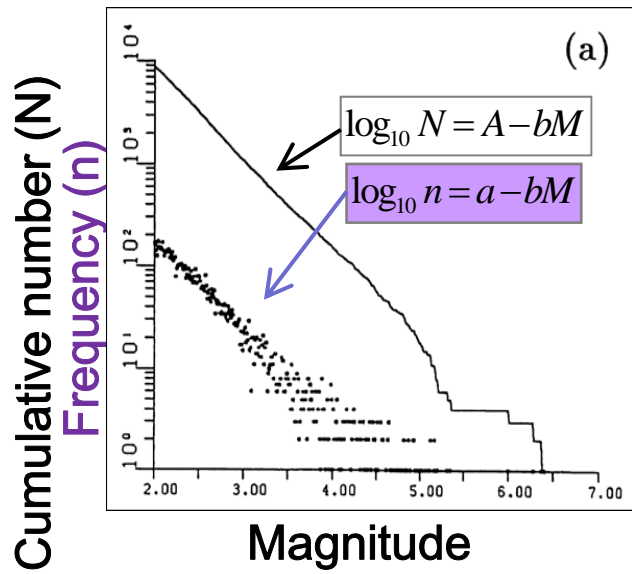


Aki (1981, Ewing series)

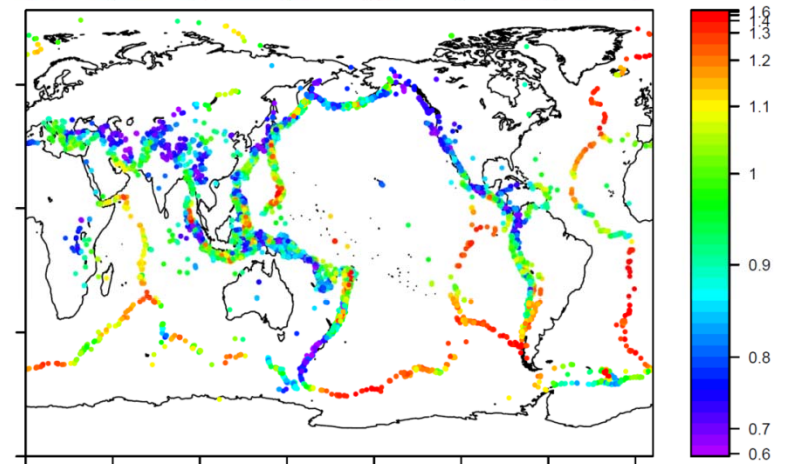
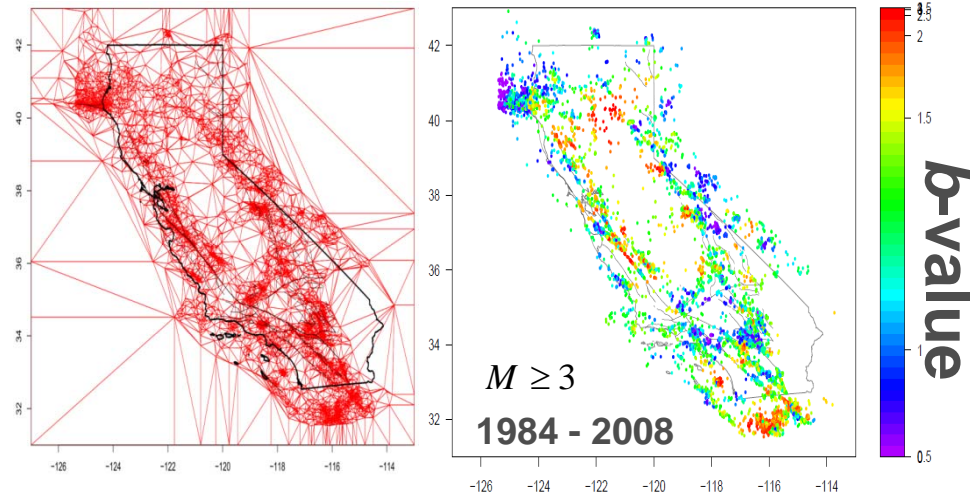
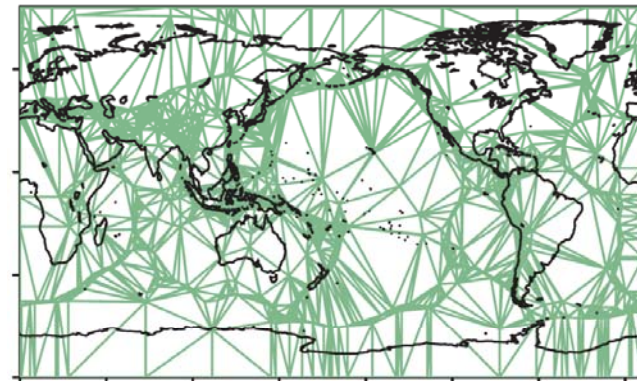
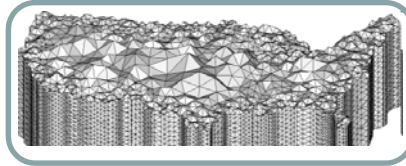
確率利得 =  $\frac{\text{異常現象が大地震の前兆である確率}}{\text{大地震の基礎確率}}$



# マグニチュード分布 Gutenberg-Richter Law :



$$\lambda(M) = 10^{a(x,y) - b(x,y)(M - M_c)}$$

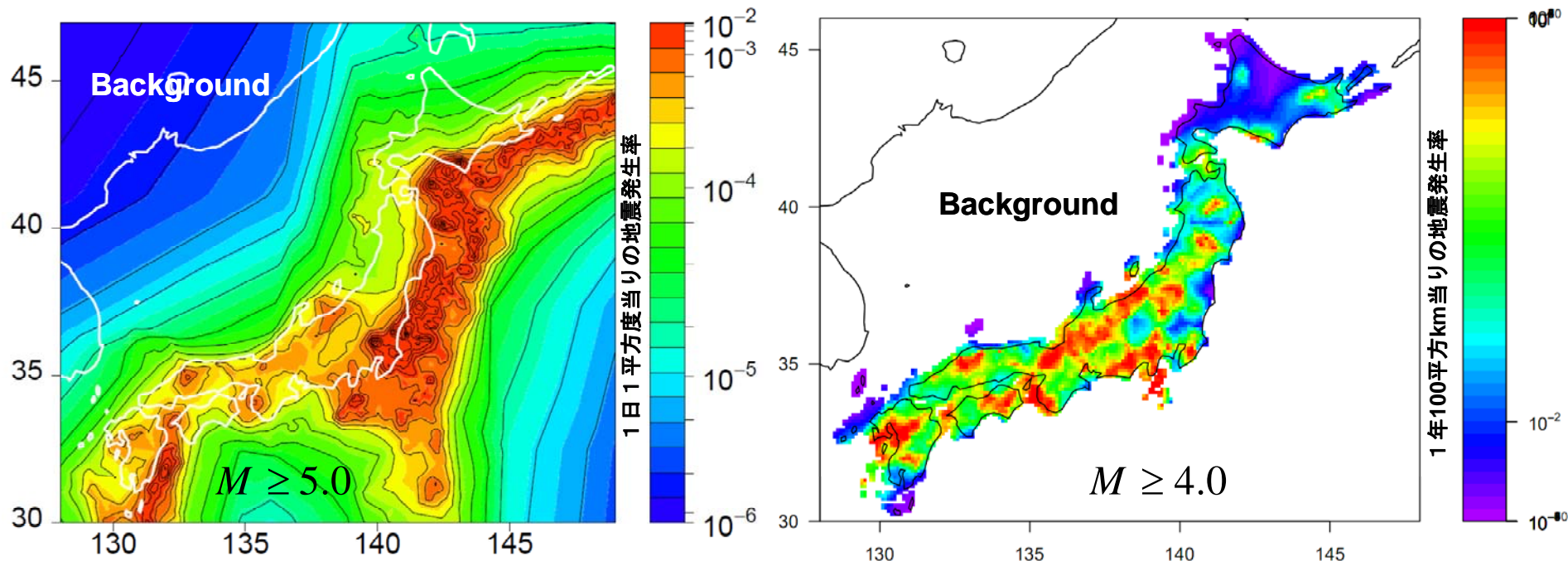
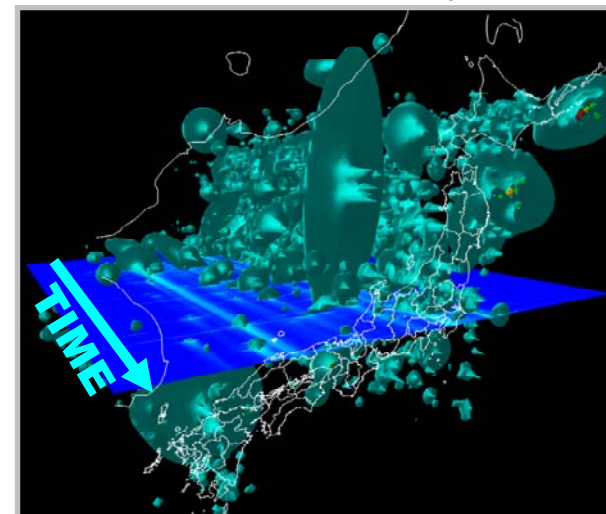


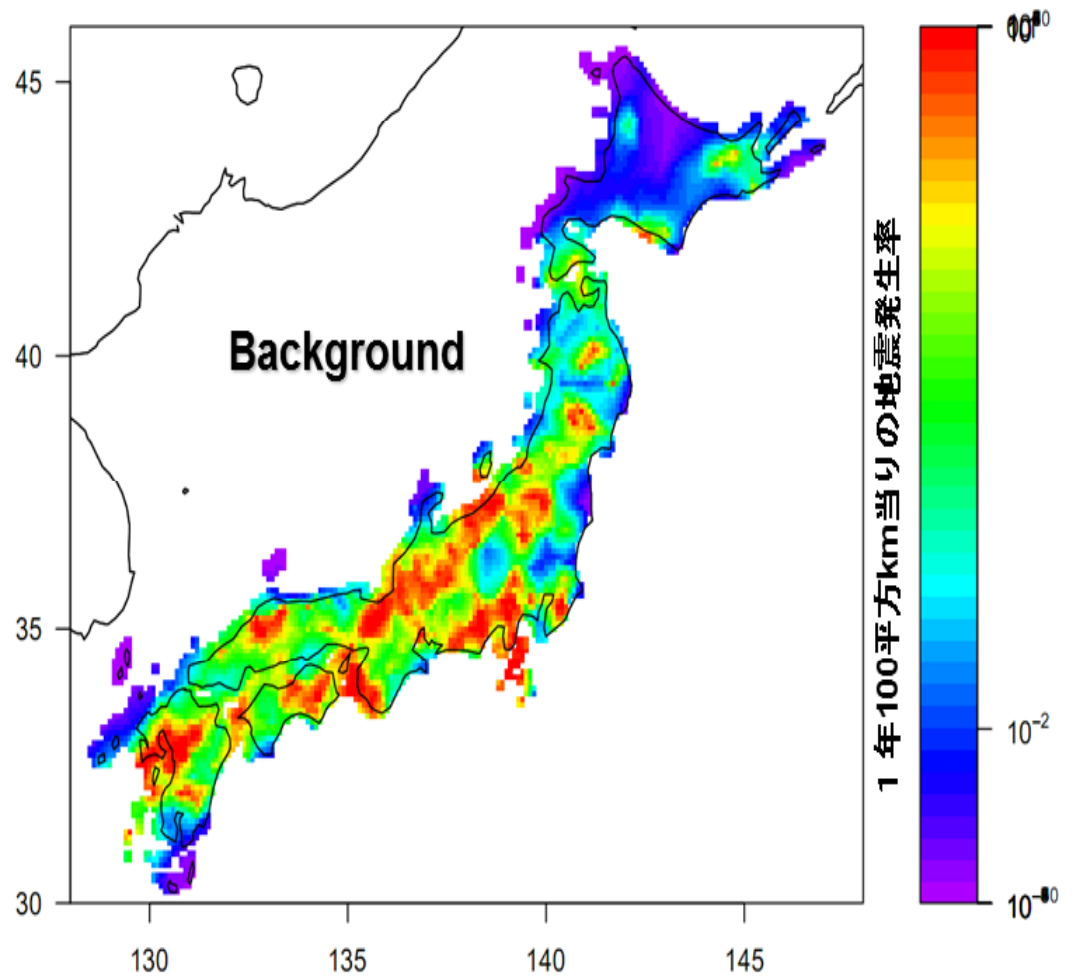
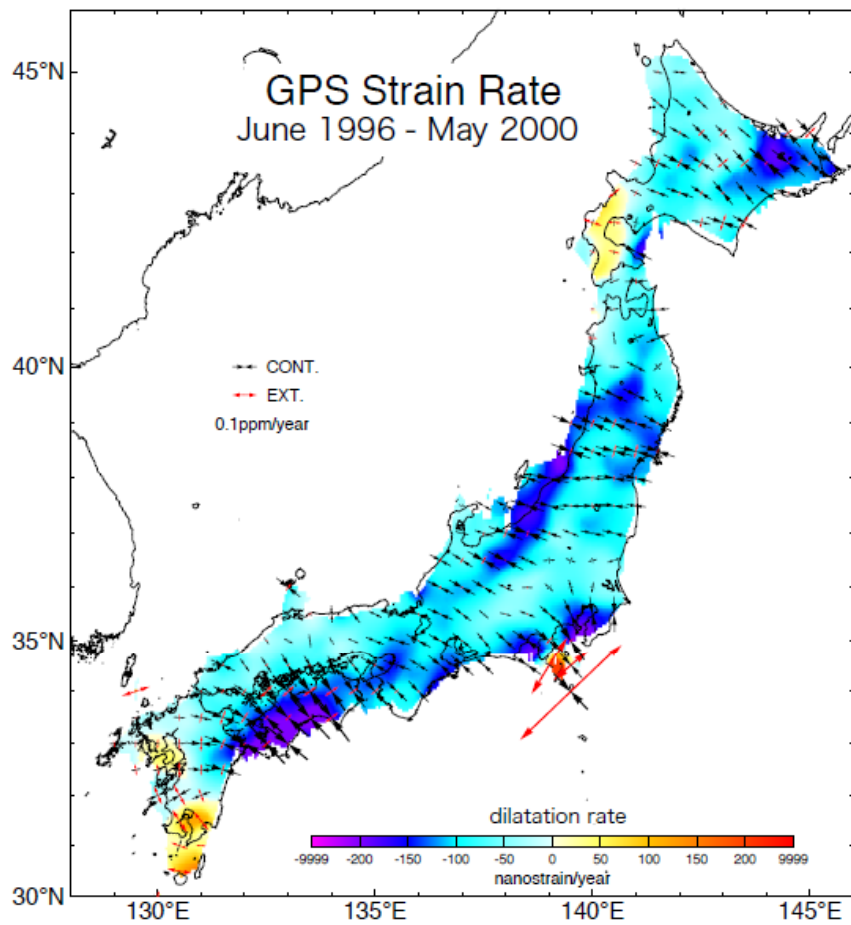
# A baseline probability model

Hierarchical space-time ETAS model

$$\lambda(t, x, y) = \mu(x, y) + \sum_{\{j; t_j < t\}} \frac{K(x, y)}{(t - t_j + c)^{p(x, y)}} \times \left[ \frac{(x - x_j, y - y_j) S_j(x - x_j, y - y_j)^t}{e^{\alpha(x, y)(M_j - M_c)}} + d \right]^{-q(x, y)}$$

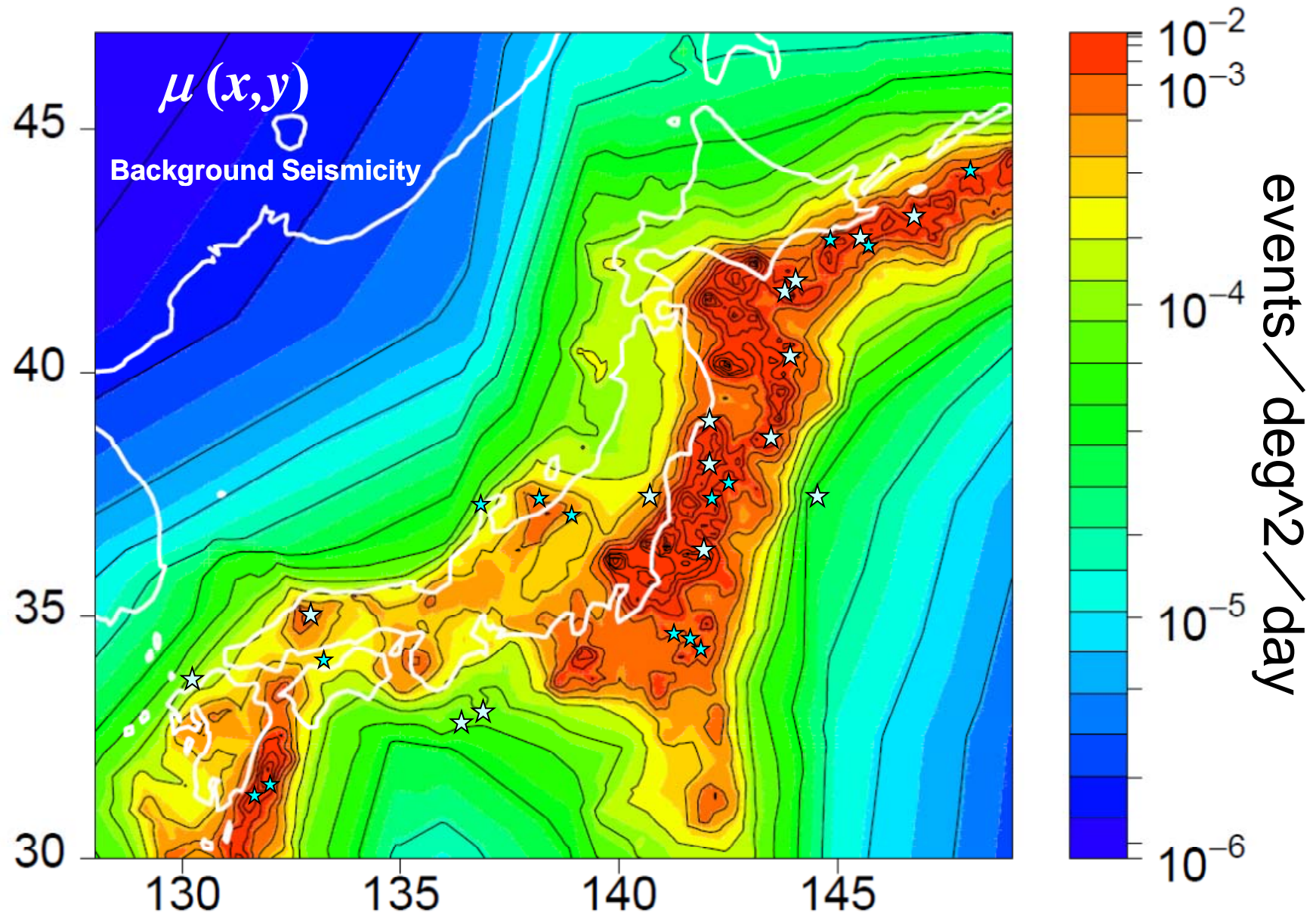
Isosurface of  $\lambda(t, x, y)$





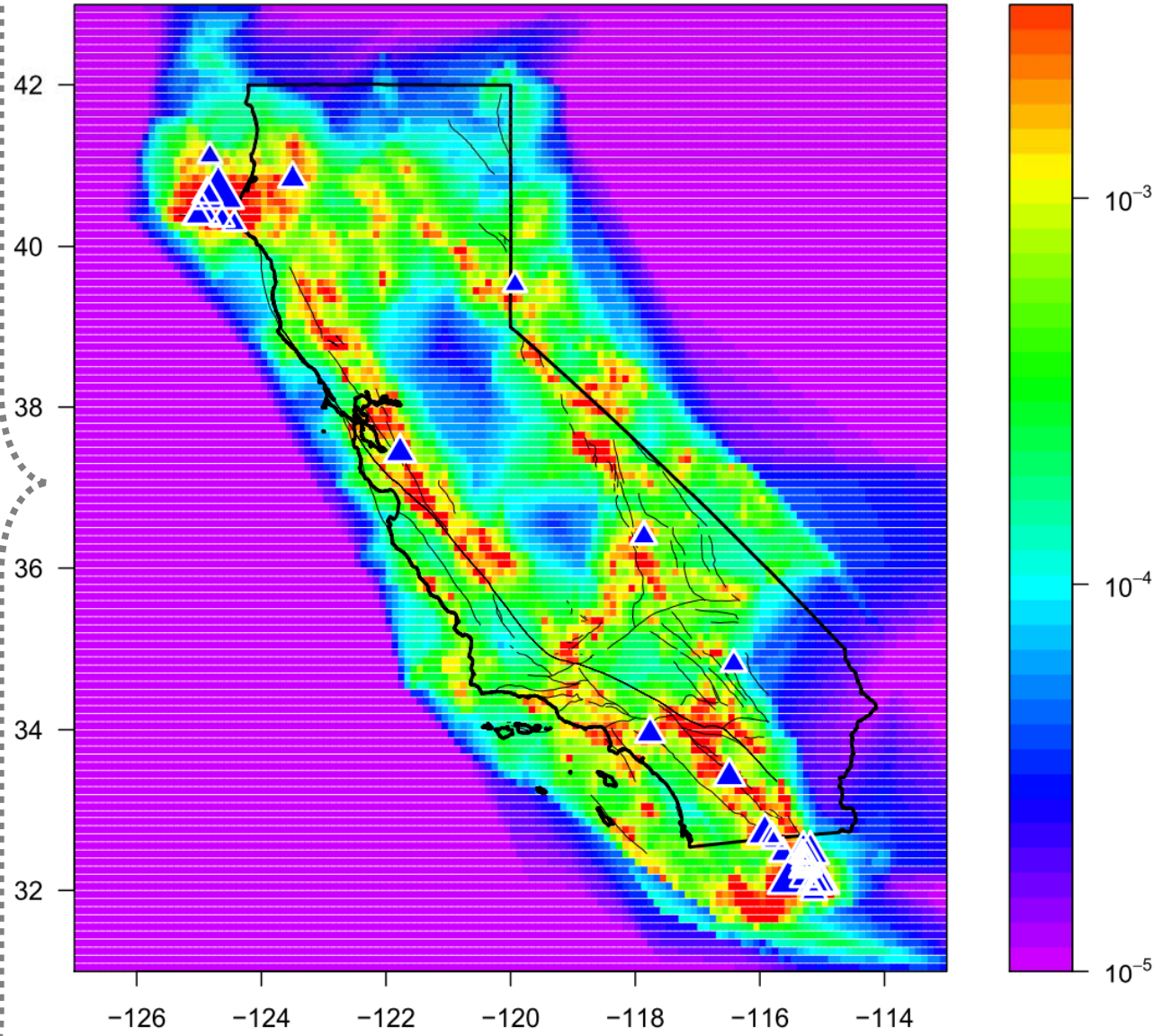
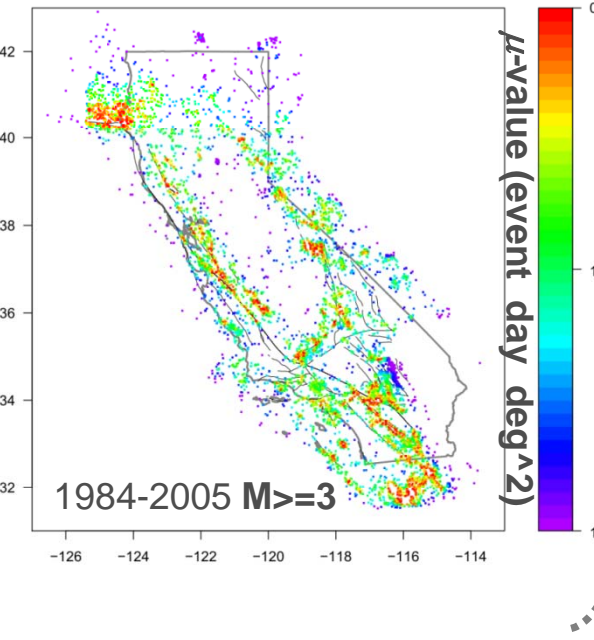
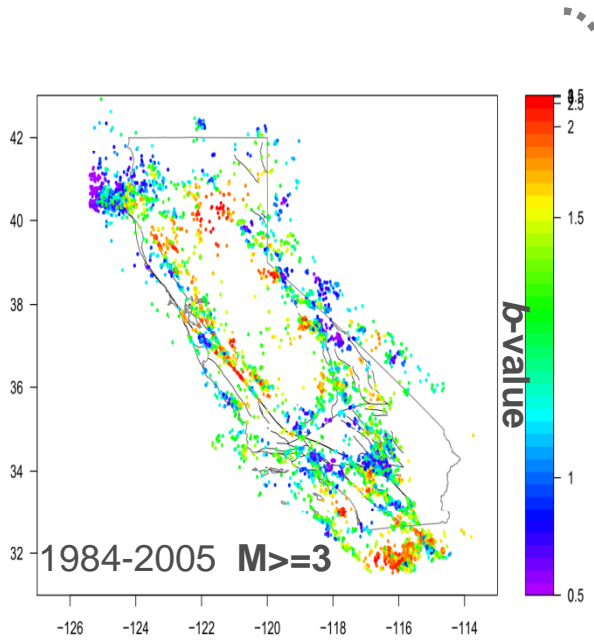
# Estimated from $M \geq 5.0$ for 1926-1995

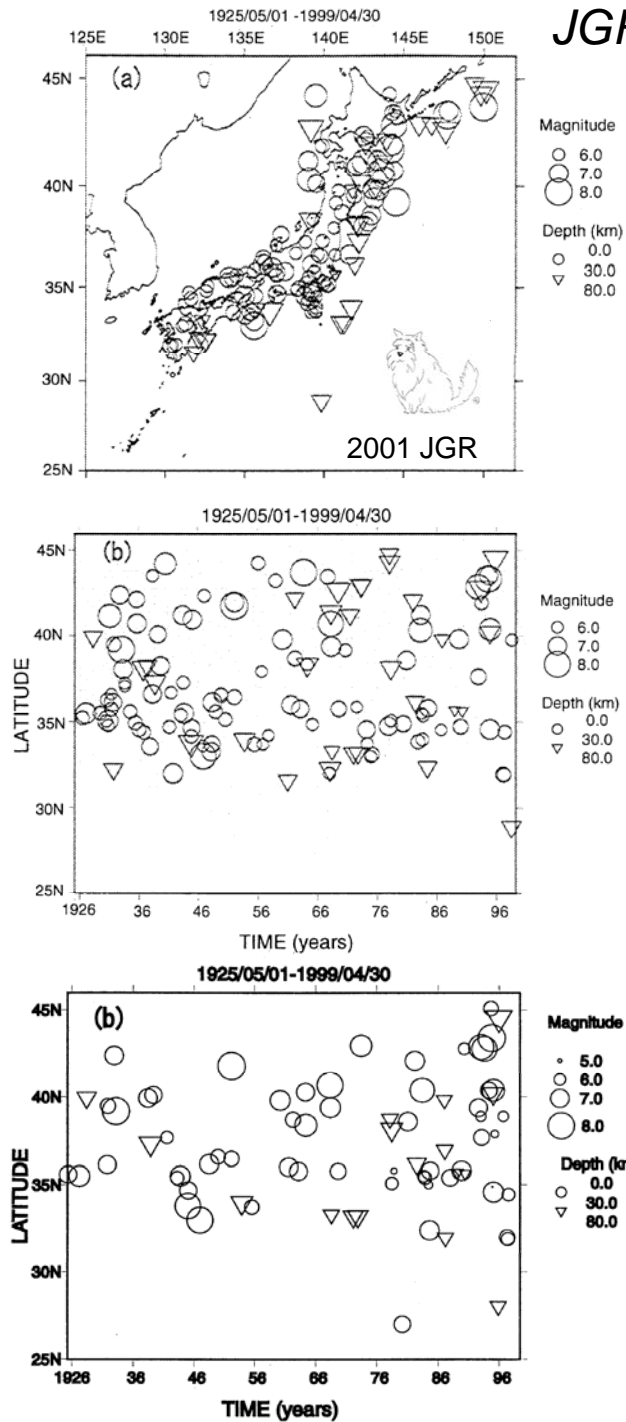
★ = earthquakes of  $M \geq 6.7$  during 1996 - 2011 Mar





**▲ = 2006 – 2011, M $\geq$ 5 earthquakes**

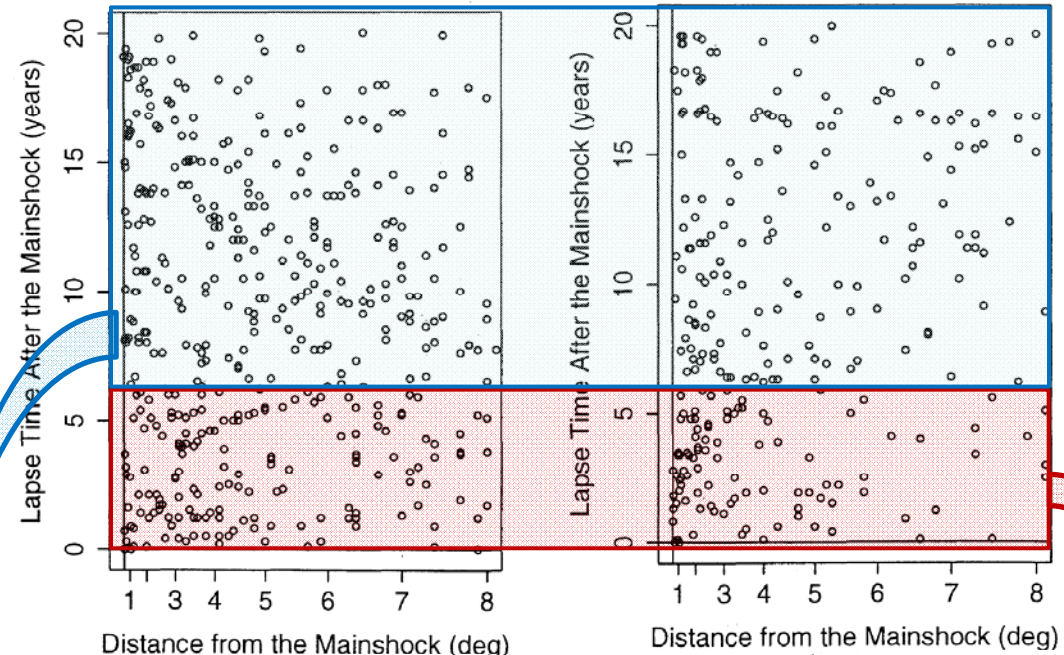




# JGR 2001

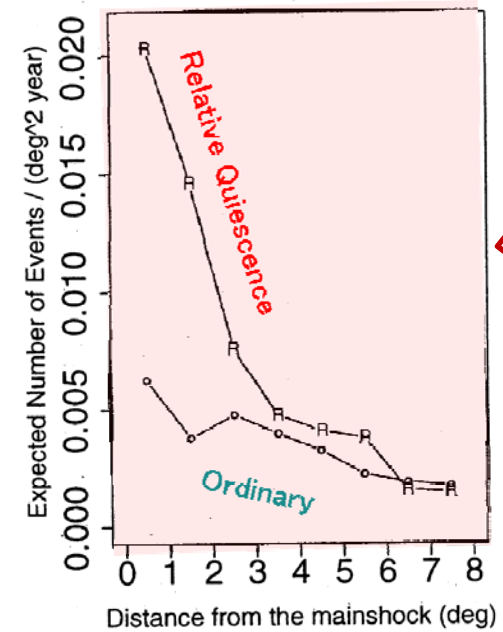
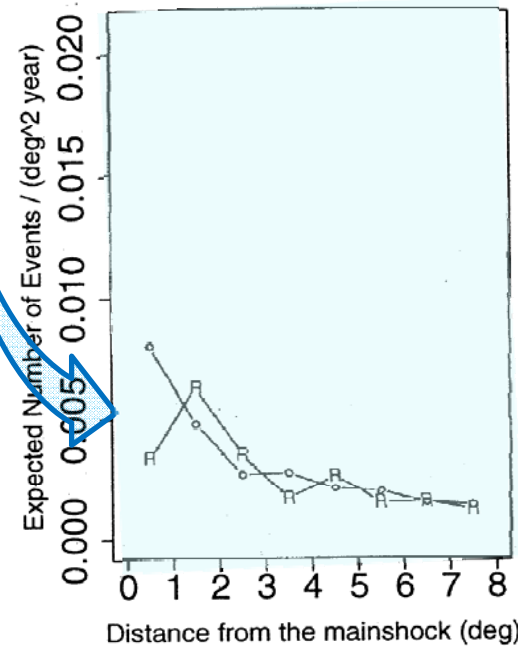
(a) No change-point

(b) Relative quiescence

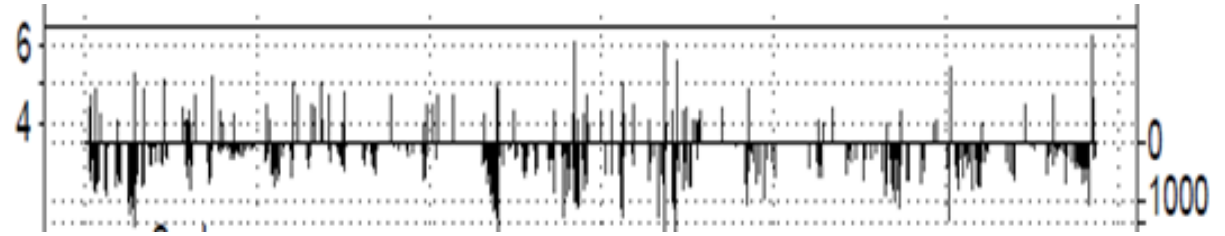
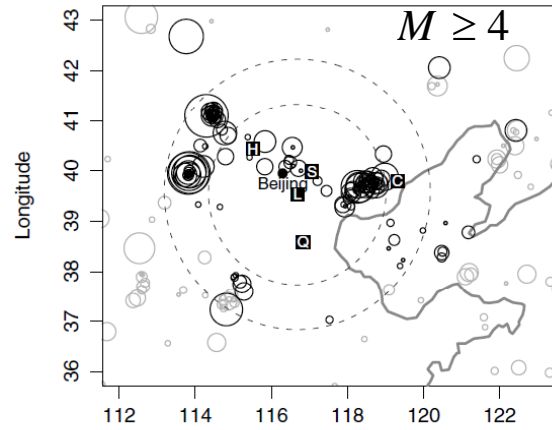


(b) next 14 years span

(a) first 6 years span



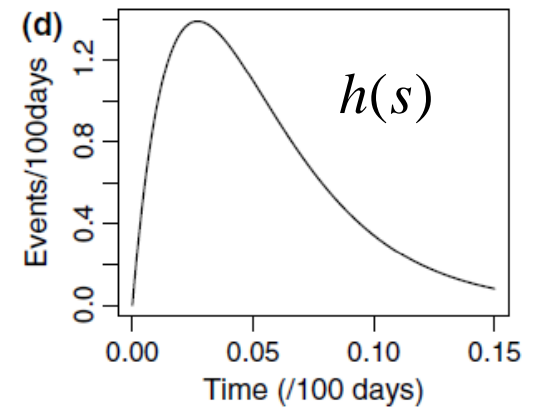
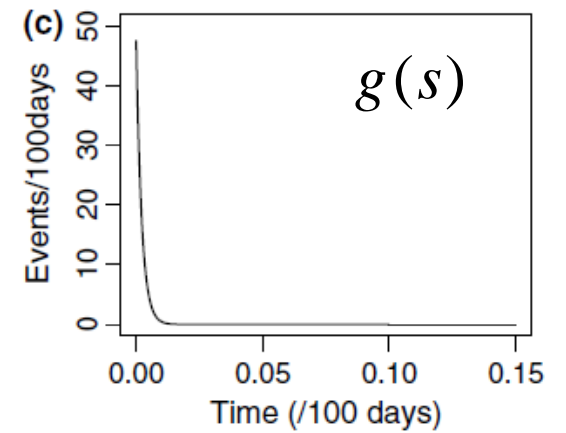
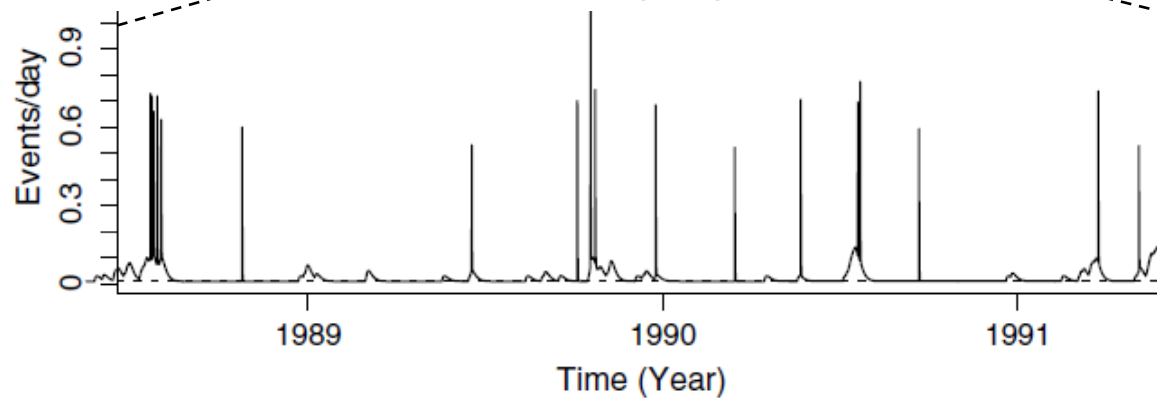
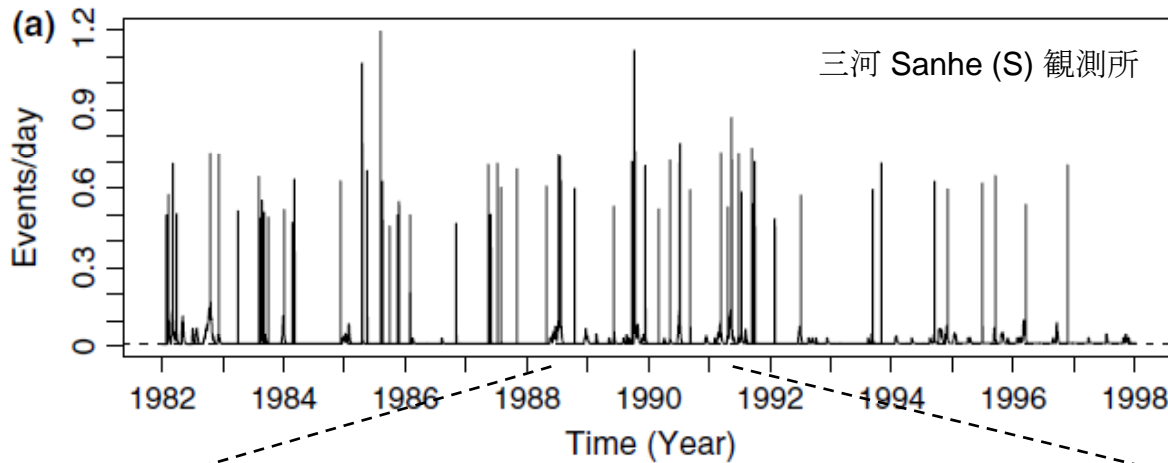
Zhuang et al. (2005, *PAGEOPH*)



$$\lambda(t | H_t) = \mu + \int_0^t g(t-s) dN_s + \int_0^t h(t-s) dM_s$$

$$= \mu + \sum_{\{i; t_i < t\}} g(t-t_i) + \sum_{\{j; \tau_j < t\}} h(t-\tau_j)$$

Latitude 1日当たりのM4以上の地震の発生率



# 短期予測

# 前震の識別

Ogata, Utsu & Katsura, *GJI*, 1996

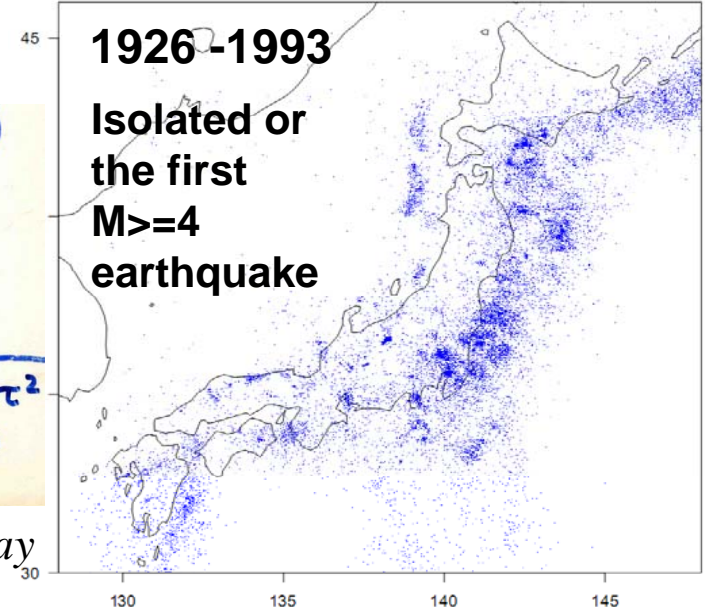
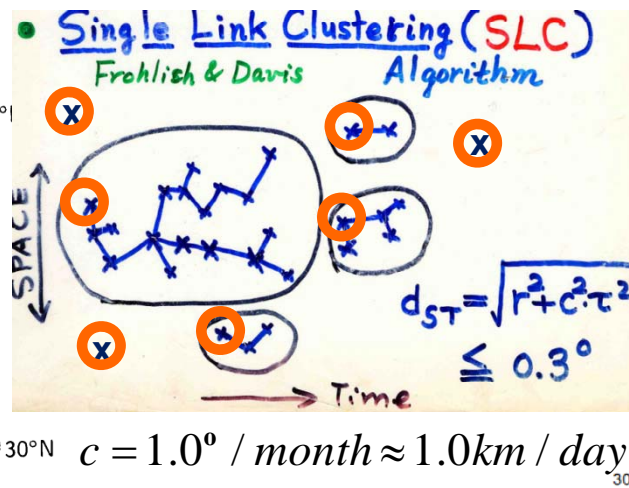
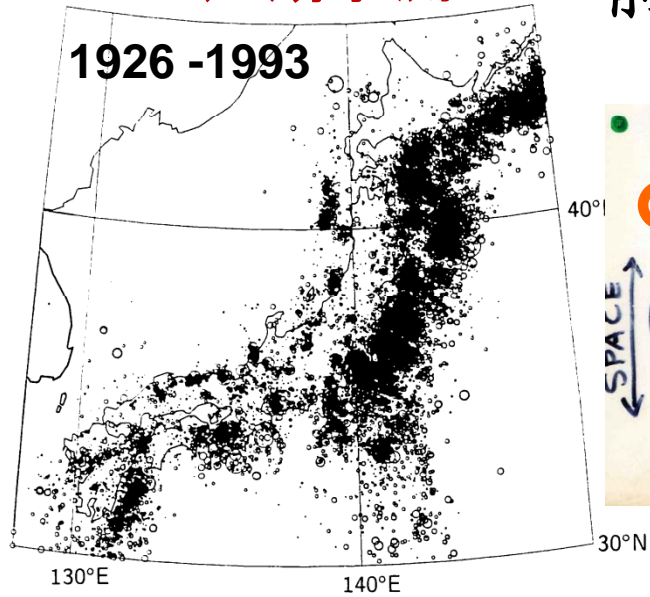
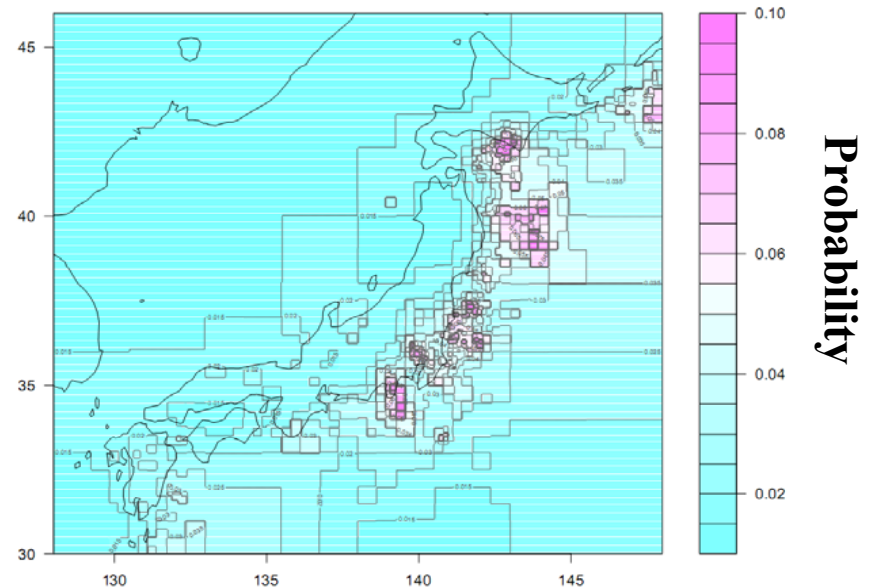
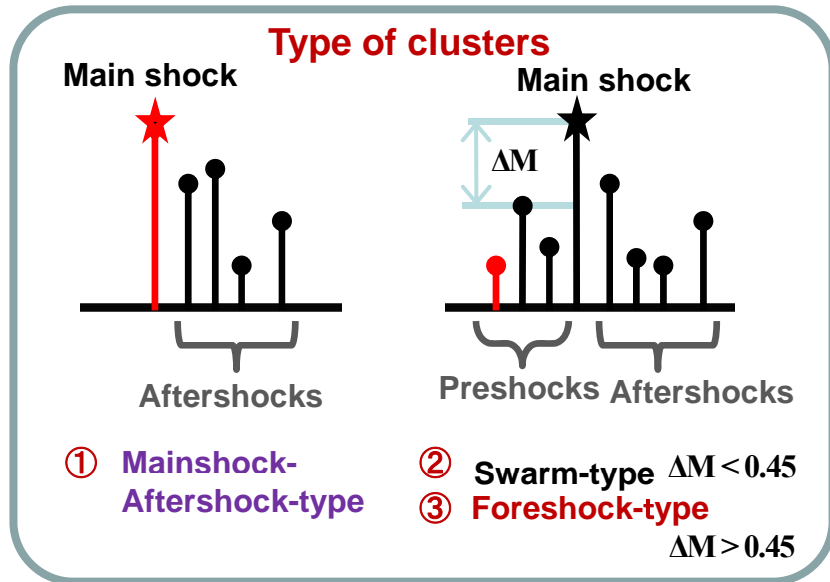


Figure 1. Epicentres of earthquakes ( $M_j \geq 4.0$ , depth  $\leq 100$  km) in the JMA catalog (1926–91).

孤立地震または群れの先頭の地震が前震である予報確率 1926 – 1993



# 時間間隔、相互距離、マグニチュード差 の単位立方体への非線形変換

Ogata, Utsu & Katsura, *GJI*, 1996

時間間隔:  $t_{i,j}^c = t_j^c - t_i^c$

相互距離:  $r_{i,j}^c = \sqrt{(x_i^c - x_j^c)^2 + (y_i^c - y_j^c)^2}$

マグニチュードの差:  $g_{i,j}^c = M_j^c - M_i^c$

$(t_{i,j}^c, r_{i,j}^c, g_{i,j}^c)$



$(\tau_{i,j}^c, \rho_{i,j}^c, \gamma_{i,j}^c) \in [0,1]^3$

## ① 時間間隔の変換: $t \rightarrow \tau$

$$\tau = \begin{cases} 0 & \text{for } t \leq 0.01 \\ \log(100t) / \log(3000) & \text{for } 0.01 < t \leq 30 \\ 1 & \text{for } 30 \leq t \end{cases}$$

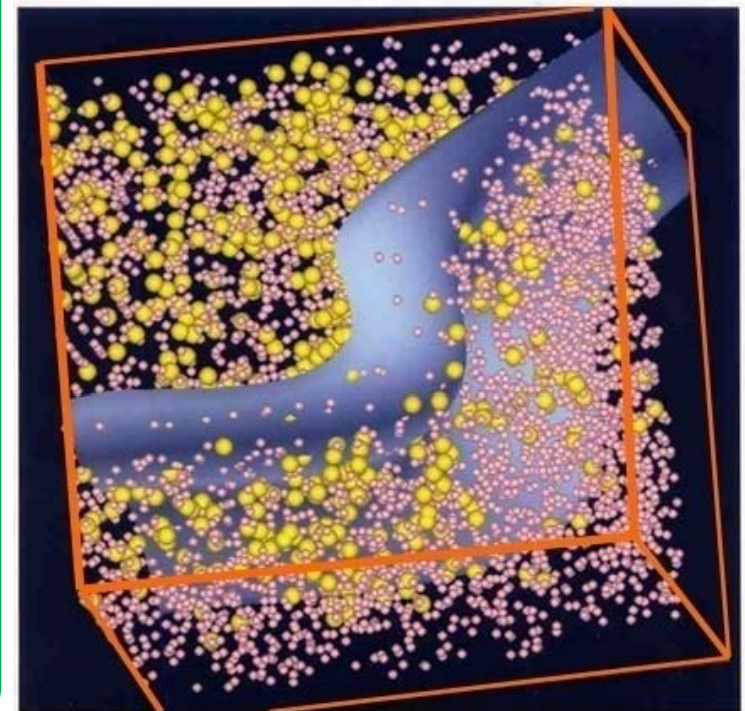
## ② 相互距離の変換: $r \rightarrow \rho$

$$\rho = 1 - \exp\{-\min(r, 50) / 20\}$$

## ③ マグニチュード差の変換: $g \rightarrow \gamma$

$$\gamma = \begin{cases} (2/3) \exp\{g/\sigma_1\} & \text{for } g \leq 0 \\ (2/3) + (1/3)[1 - \exp\{-g/\sigma_2\}] & \text{for } g > 0 \end{cases}$$

ただし  $\sigma_1 = 6709, \sigma_2 = 0.4456$



# Algorithm of foreshock probability calculations in case of plural earthquakes in a cluster

Ogata, Utsu &  
Katsura, *GJI*, 1996

For plural earthquakes in a cluster, time differences  $t_{i,j}$  (days), epicenter separation  $r_{i,j}$  (km), magnitude difference  $g_{i,j}$  are transformed into the unit cube

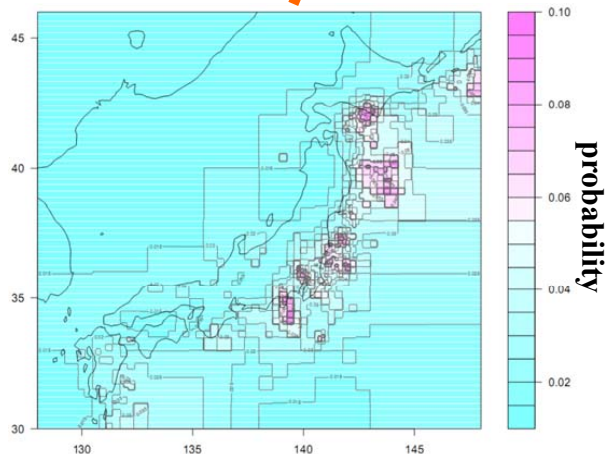
$$(t_{i,j}, r_{i,j}, g_{i,j}) \rightarrow (\tau_{i,j}, \rho_{i,j}, \gamma_{i,j}) \in [0,1]^3$$

Probability  $p_c$  is calculated sequentially

$$p = \frac{1}{1 + e^f} \Leftrightarrow f \equiv \mathbf{logit}(p) \equiv \ln \frac{1-p}{p}$$

$$\mathbf{logit}(p_c) = \mathbf{logit} \{ \mu(x_1, y_1) \} + \frac{1}{\#\{i < j\}} \sum_{i < j} \left[ a_1 + \sum_{k=1}^3 b_k \gamma_{i,j}^k + \sum_{k=1}^3 c_k \rho_{i,j}^k + \sum_{k=1}^3 d_k \tau_{i,j}^k \right]$$

$\mu(x, y)$  indicates probability of initial earthquake at location  $(x, y)$ .

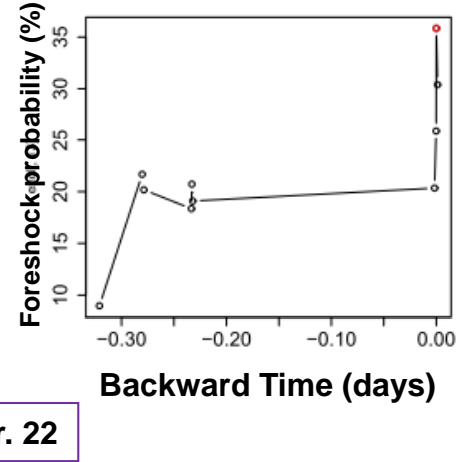
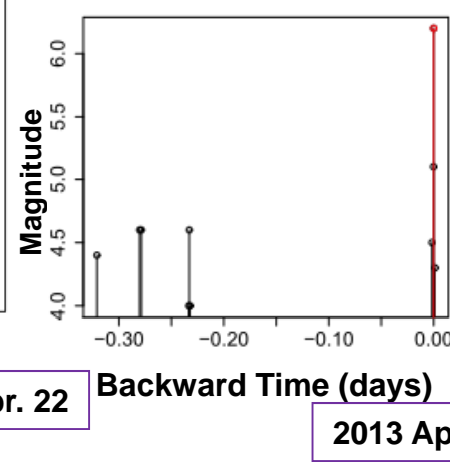
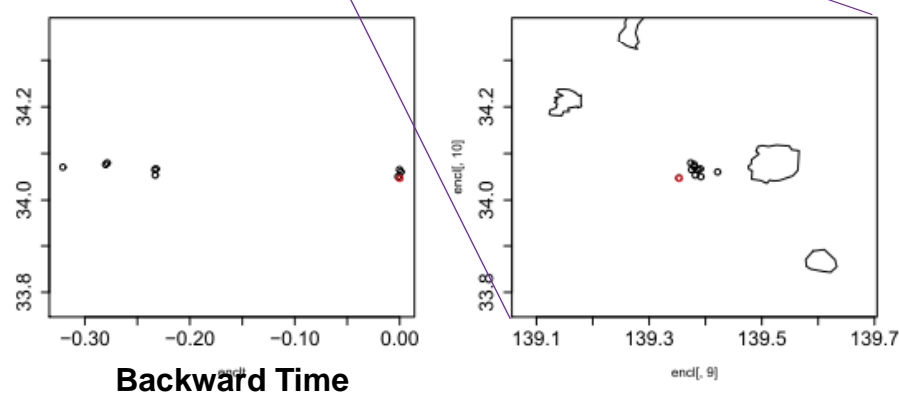
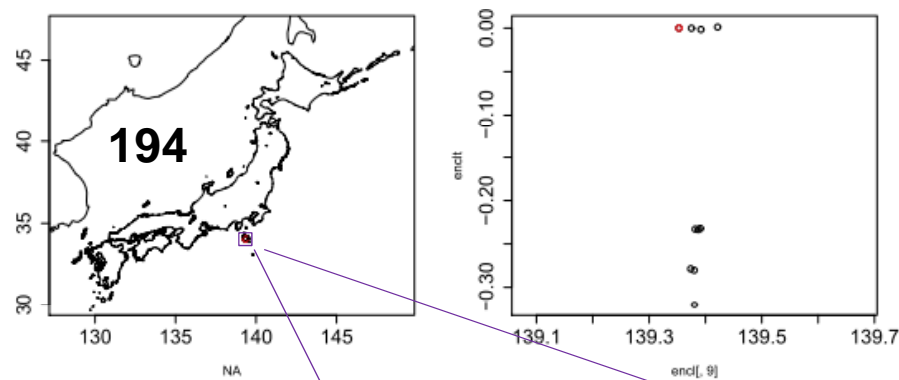
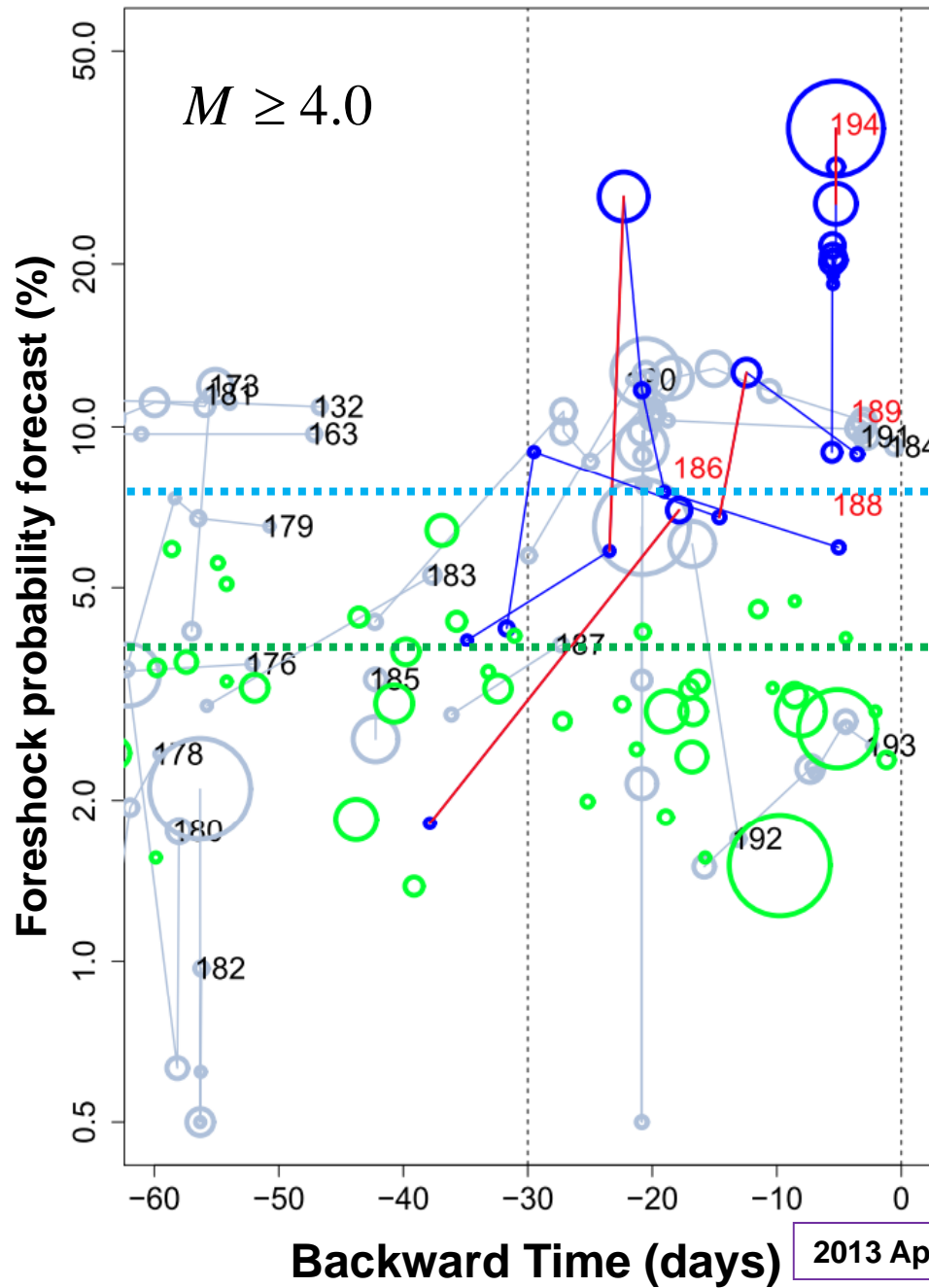


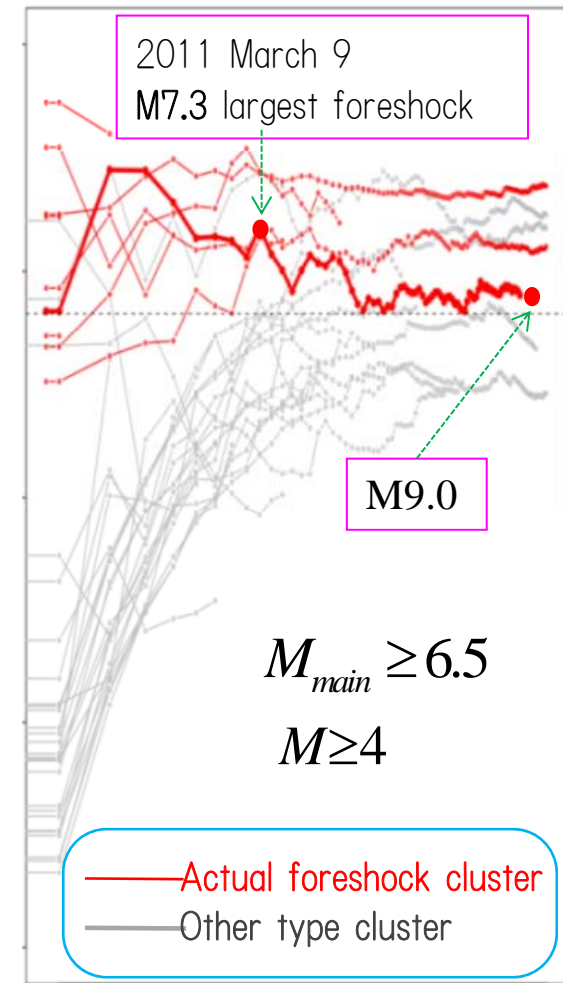
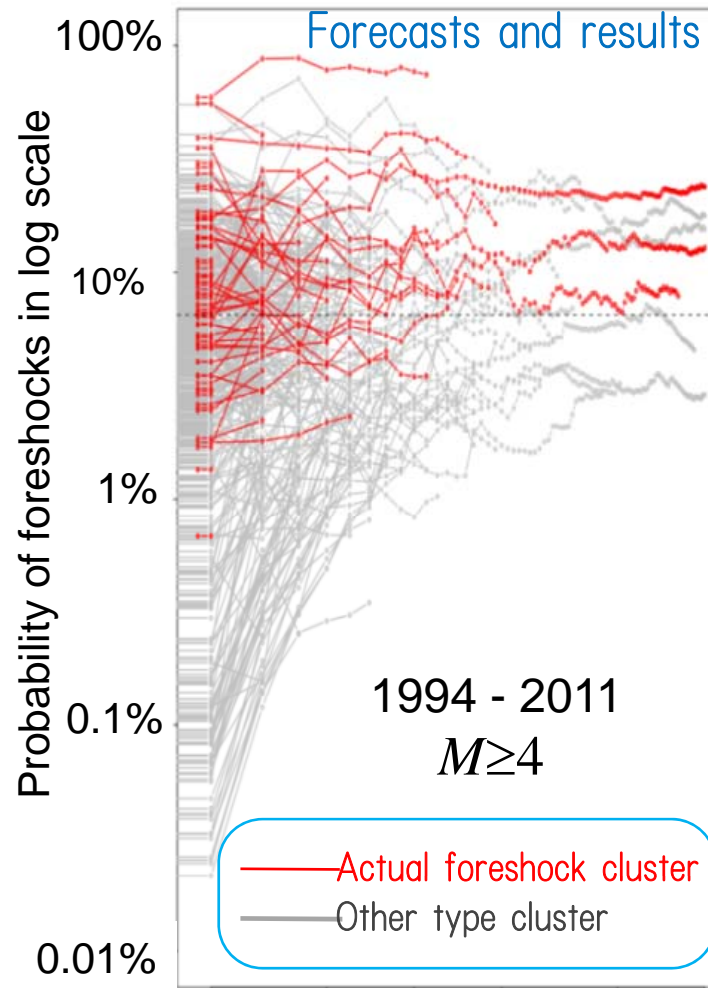
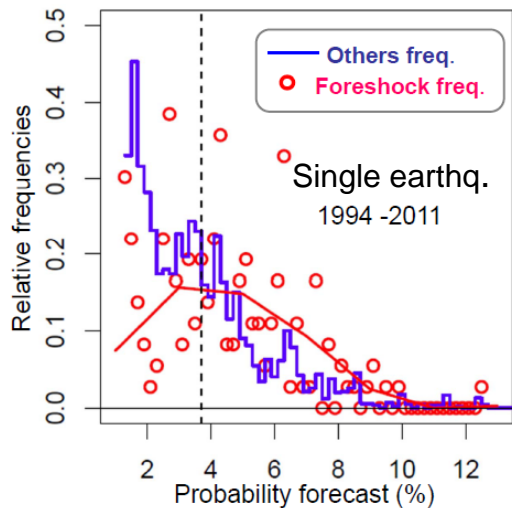
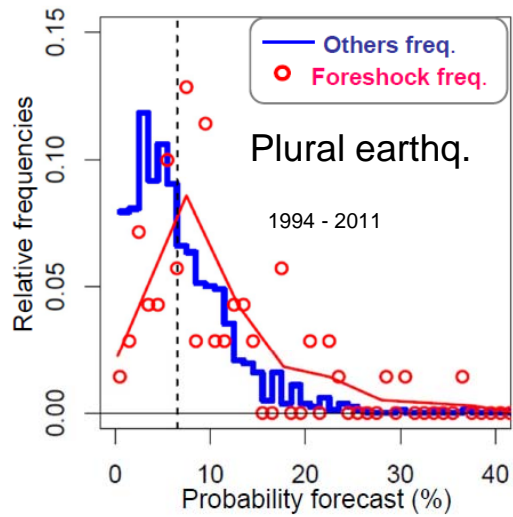
Arithmetic mean of polynomials of the normalized space-time magnitude variables for all pairs of earthquakes ( $i < j$ ) in a cluster.

The coefficients  $a, b, c, d$  are estimated by the maximum likelihood method together with the AIC.

Ogata, Utsu and Katsura, 1996, *GJI*)

$k$	$a_k$	$b_k$	$c_k$	$d_k$
1	8.018	33.25	-1.490	-10.92
2		62.77	2.805	295.09
3		37.66	-2.190	-1161.5

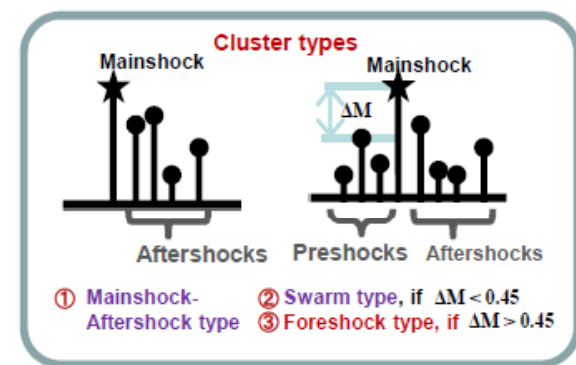




Forecast & performance 1994年 - 2011年

Predicted probability	2.5	5%	10%	15%	
Foreshock	4	10	30	12	14   70
Others	179	211	263	115	51   819
Relative Frequency	2.2	4.5	10.2	9.4	21.5   7.9

Ogata & Katsura,  
GJI, 2012





## まとめ

④ 地震予知の特効薬はなく、複雑で多様な地震発生を予測するには、**確率予測**が避けられない。

④ 各地域に適した**基準の地震活動**の確率予測(長期・短期予測の**相場**の**モデル**)を与える(CSEPの**目標**)。

→ 統計的**点過程モデル**の改訂を進める必要がある。

④ **異常現象**が、大地震の**前兆**なのか、どの程度切迫性があるのかなどの不確定さを見積もる。

→ 大地震の発生確率を、基準のもの比べて、この範囲、この期間、この程度まで増加させる(**確率利得**)と言えるようになればよい。これらを偏りなく見積もる必要がある。

→ **異常現象と大地震の因果性を記述する点過程モデルの作成**

④ 大地震を少しでも高い確率で予測するために、各種の観測データの有意な異常現象を多数考慮して、**確率利得を高め、複合的に予測**することが有力である。