地震活動異常と地殻変動異常と前駆的非地震性すべり

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Anomalies in seismic activity and transient crustal deformation

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ETAS model:

$$\lambda(t) = \mu + \sum_{\{j\,:\,t_j<t\}} e^{\alpha\{Mj-M_c\}}\,\nu(t-t_j)$$

where

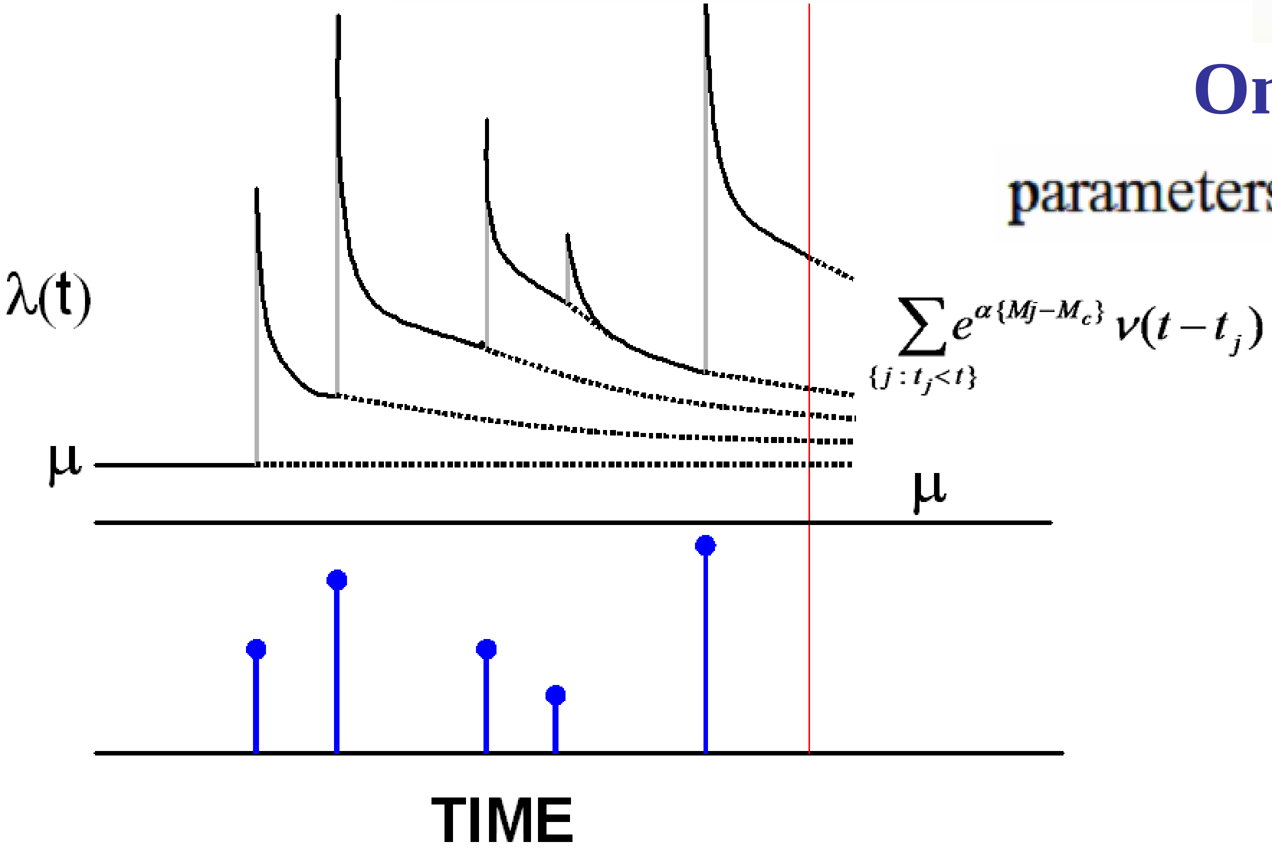
t_j is occurrence time of jth event;

M_j is magnitude of jth event;

$$\nu(t) = \frac{K}{(t+c)^p}$$

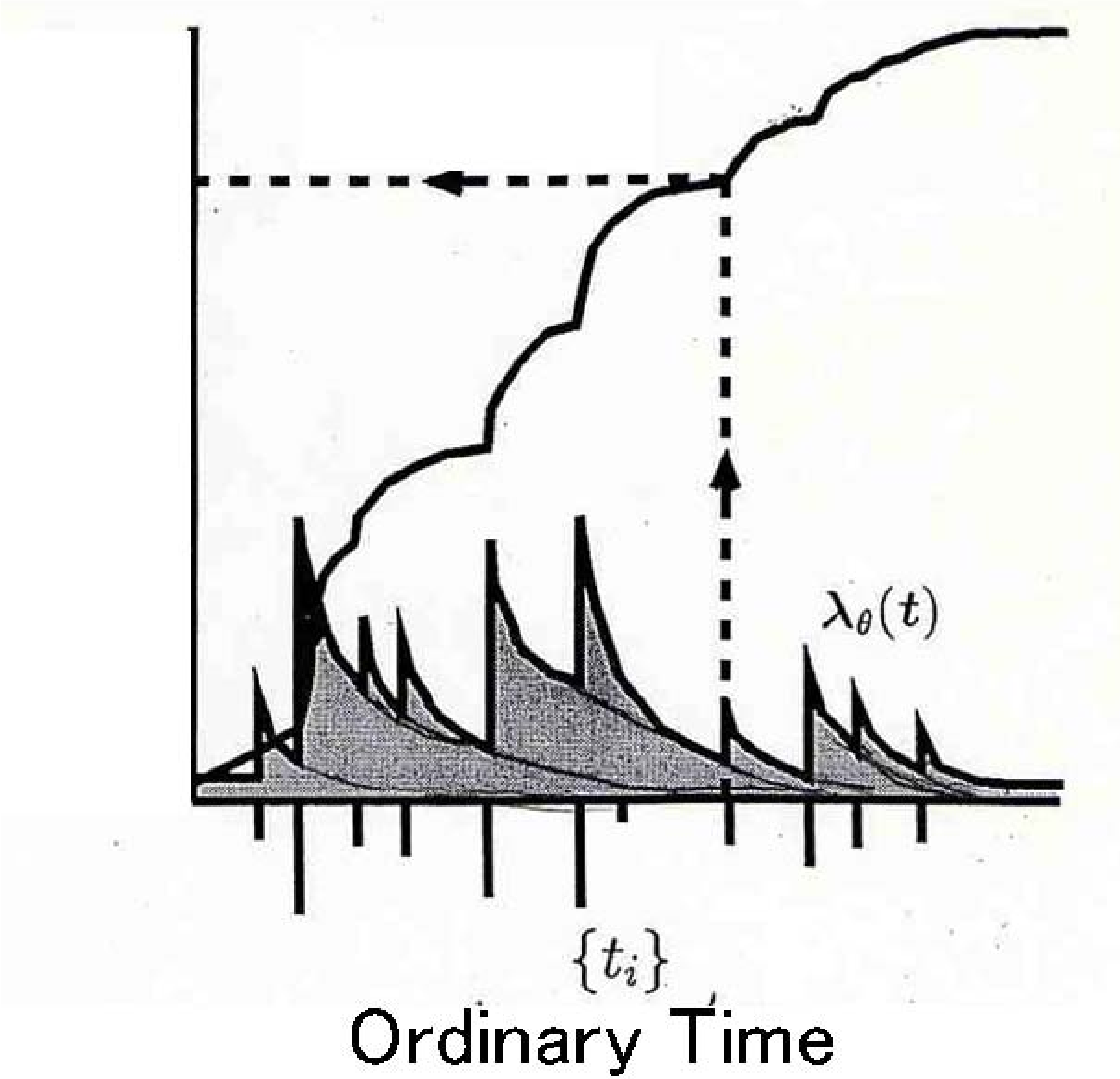
Omori-Utsu formula

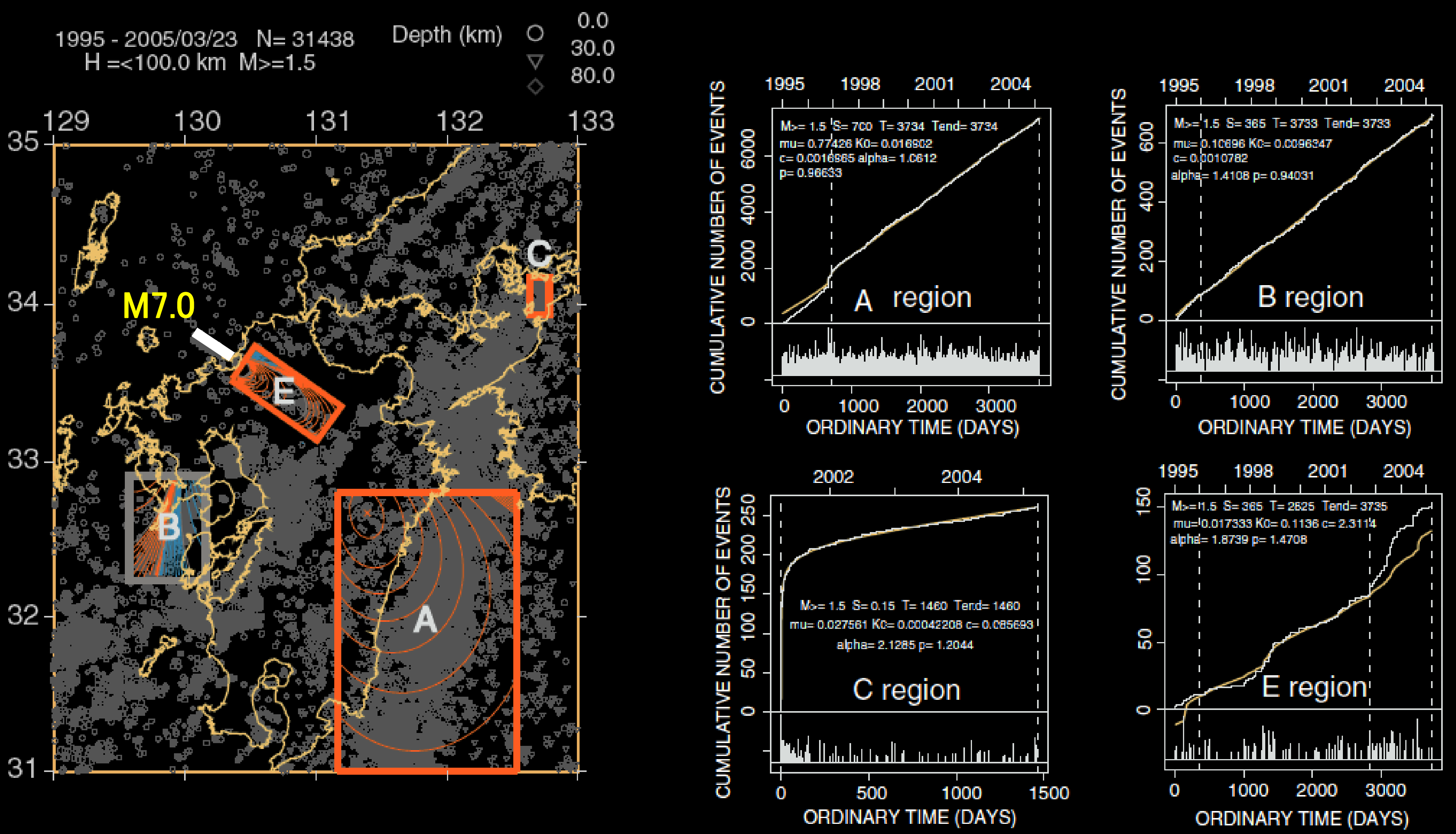
parameters are (μ, K, c, α, p).

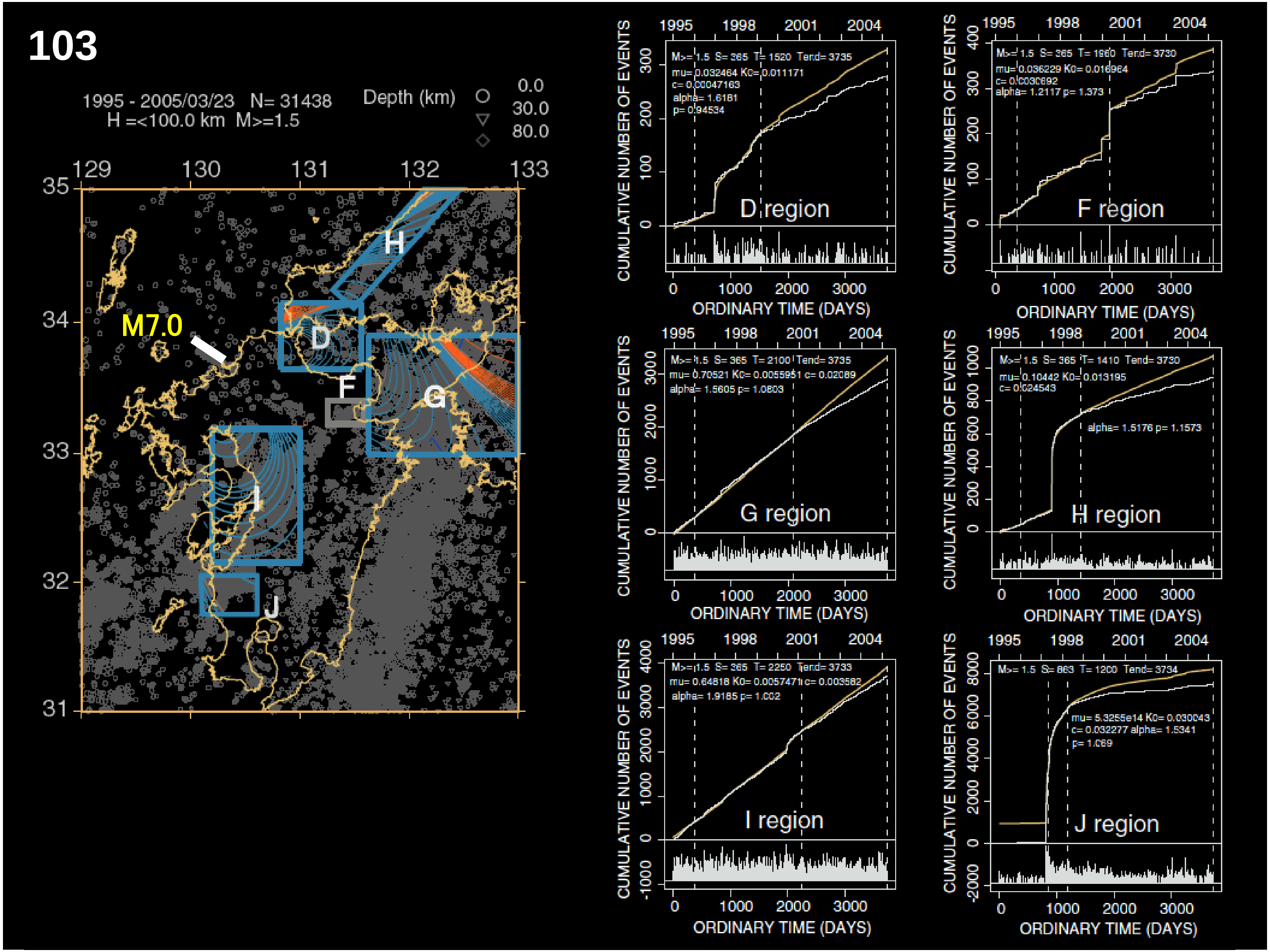


Theoretical cumulative number of the events:

$$\Lambda(t) = \int_0^t \lambda(s)\, ds$$

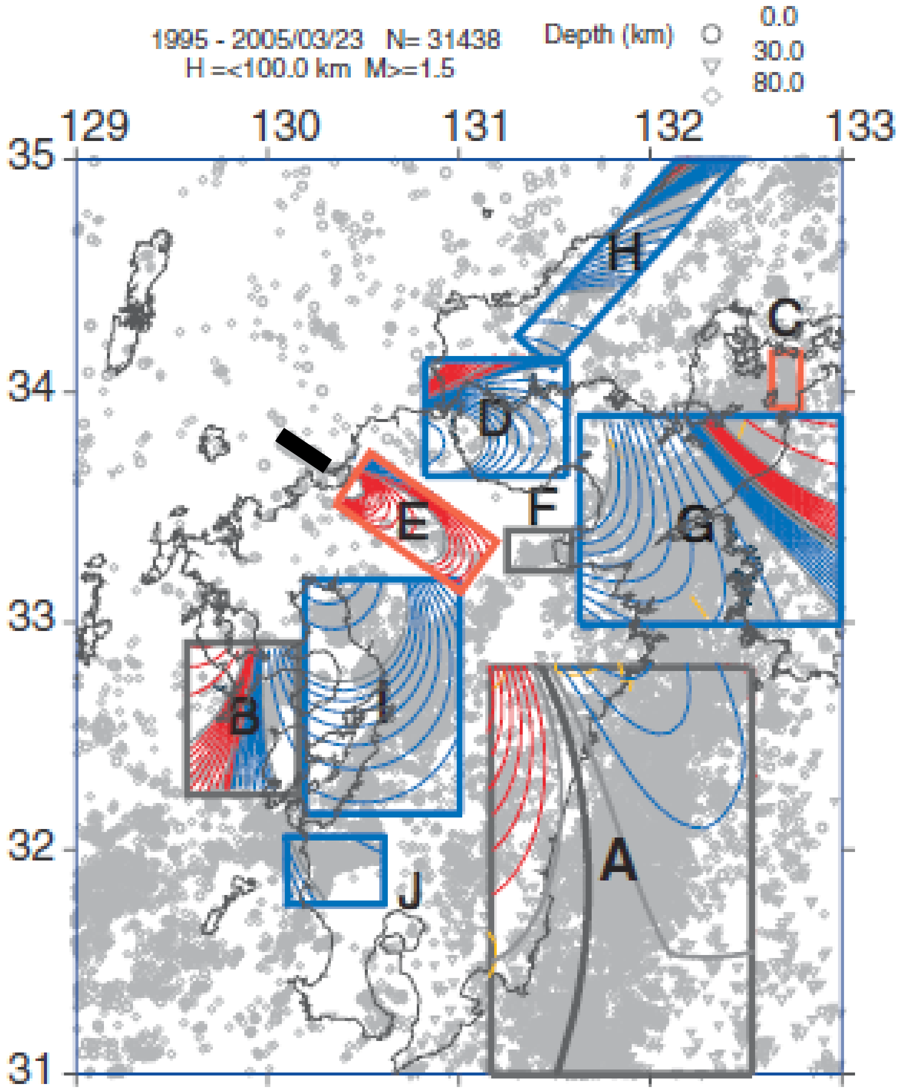



1995 - 2005/03/23 N= 31438
H =<100.0 km M>=1.5
Depth (km)
0.0
30.0
80.0
129
130
131
132
133
35
34
33
32
31
M7.0
A
B
C
E
1995
1998
2001
2004
M>= 1.5 S= 700 T= 3734 Tend= 3734
mu= 0.77426 K0= 0.016902
c= 0.0016985 alpha= 1.0612
p= 0.98633
A region
CUMULATIVE NUMBER OF EVENTS
0
2000
4000
6000
0
1000
2000
3000
ORDINARY TIME (DAYS)
M>= 1.5 S= 365 T= 3733 Tend= 3733
mu= 0.10696 K0= 0.0096347
c= 0.0010782
alpha= 1.4108 p= 0.94031
B region
200
400
600
2002
2004
M>= 1.5 S= 0.15 T= 1460 Tend= 1460
mu= 0.027561 K0= 0.00042208 c= 0.085693
alpha= 2.1285 p= 1.2044
C region
50
100
150
250
500
1500
M>= 1.5 S= 365 T= 2625 Tend= 3735
mu= 0.017333 K0= 0.1136 c= 2.3114
alpha= 1.8739 p= 1.4708
E region



103
1995 - 2005/03/23 N= 31438
H =<100.0 km M>=1.5
Depth (km)
0.0
30.0
80.0
M7.0
H
D
F
G
I
J
D region
F region
G region
H region
I region
J region
CUMULATIVE NUMBER OF EVENTS
ORDINARY TIME (DAYS)

福岡県西方沖のすべり



豊後水道のすべり

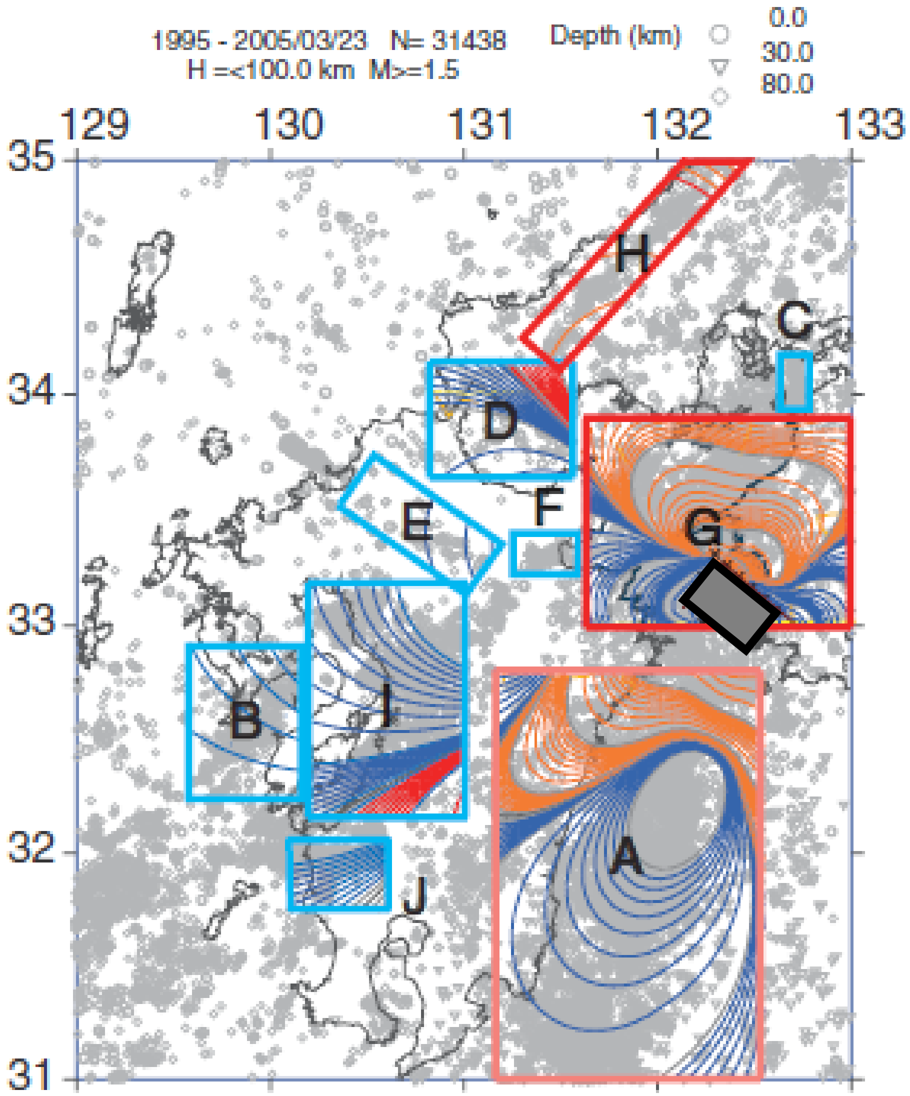


表 1　受け手の断層パラメタとΔCFS 値

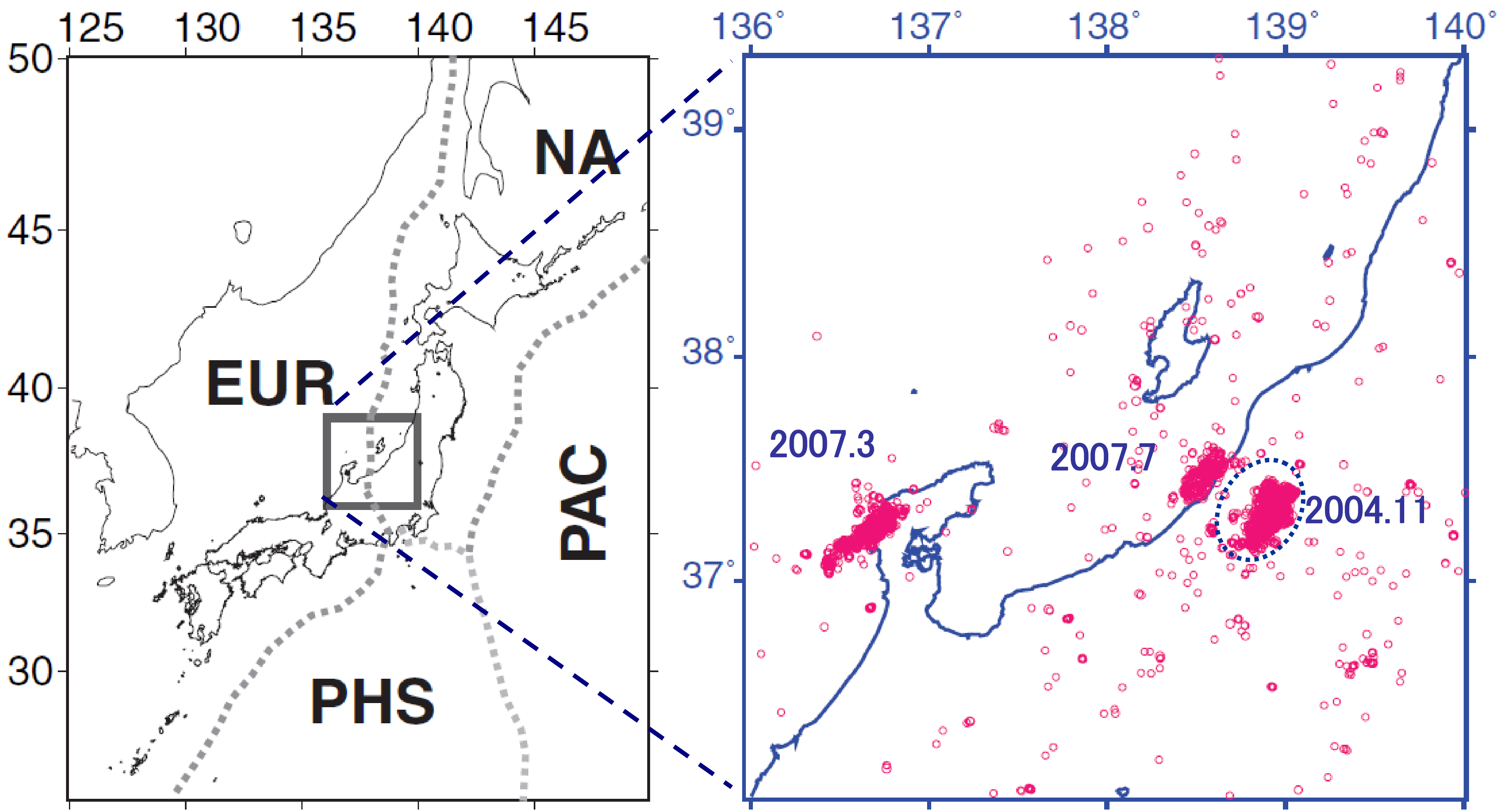
Table 1.　Assumed receiver fault configurations and ΔCFS values

領域	Strike (deg.)	Dip (deg.)	Rake (deg.)	Depth (km)	ΔCFS *(milli-bars)		Seismicity change (ΔAIC**)
					福岡県西方沖	豊後水道	
A	210	30	90	--	0.	-50. ～ +150.	Normal
B	45	90	180	10	0.	-2.	Normal
	90	45	- 90		0.	-1.	
C	179	55	- 82	45	+4.	-8.	Normal
D	135	90	0	10	-2.	-7.	Quiet (- 7.8)
E	135	90	0	10	+5. ～ +50.	- 4.	Activate (+3.1)
F	90	90	180	10	-1.	- 20.	Quiet (- 1.8)
	90	45	- 90		+1.	- 8.	
G	170	75	- 90	--	0.	-1. ～ +1. (bar)	Quiet (- 75.2)
	330	35	- 110		0.	-1. ～ +1. (bar)	
H	45	90	180	10	- 1.	+8.	Quiet (- 65.6)
I	225	45	180	10	- 4.	- 2.	Quiet (- 29.2)
	45	90	180		- 4.	- 4.	
	90	80	- 50		- 4.	- 2.	
	90	45	- 90		- 3.	- 1.	
J	280	90	0	10	- 1.	-0.3	Quiet (- 194.2)

(*) 福岡県西方沖の場合は本震の10%分の前駆すべり量を仮定している。

(**) 正常な場合の ETAS と変化がある場合の 2 つ分の ETAS モデルの変化点補正済みの AIC の差（変化点パラメタの調節に対して約 3.0 のペナルティを課している[2,3]）。

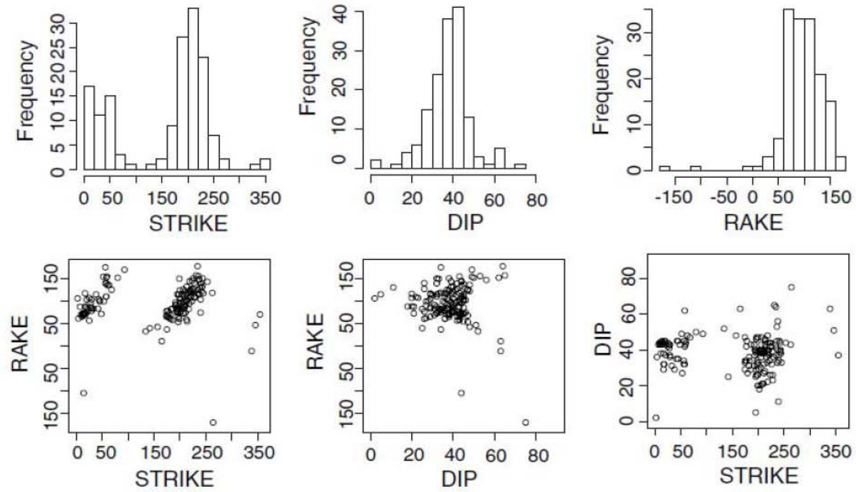
2004 Chuetsu M6.8



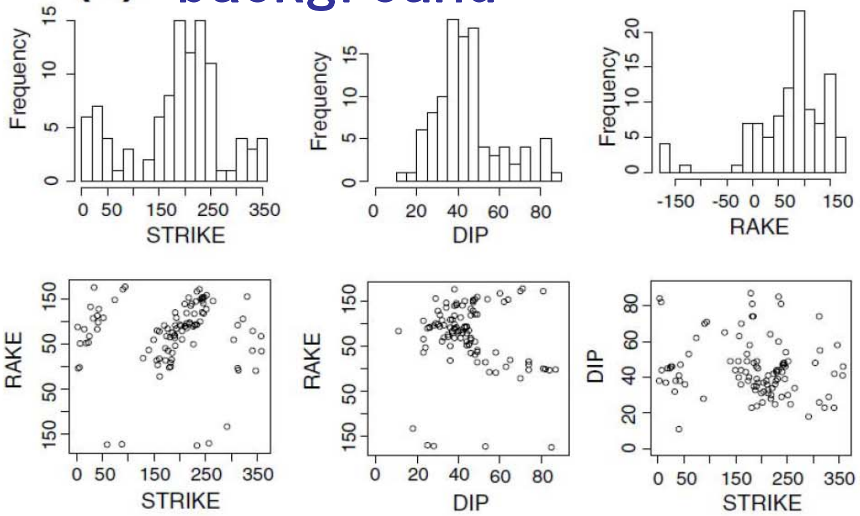
1997/01/01 - 2004/10/30 Number of events = 4060

Depth =< 25.0 km, M >= 2.0

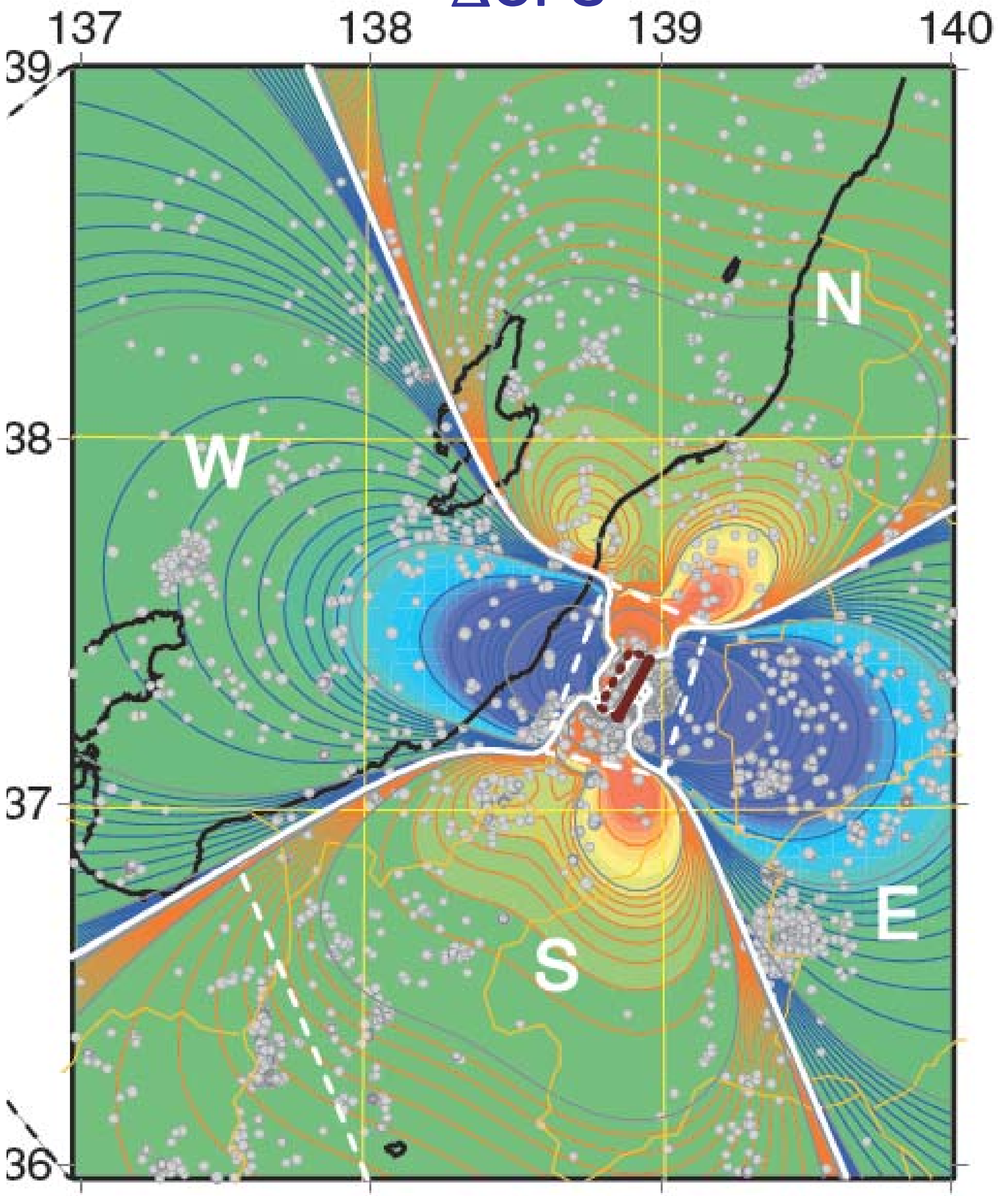
(a) aftershocks



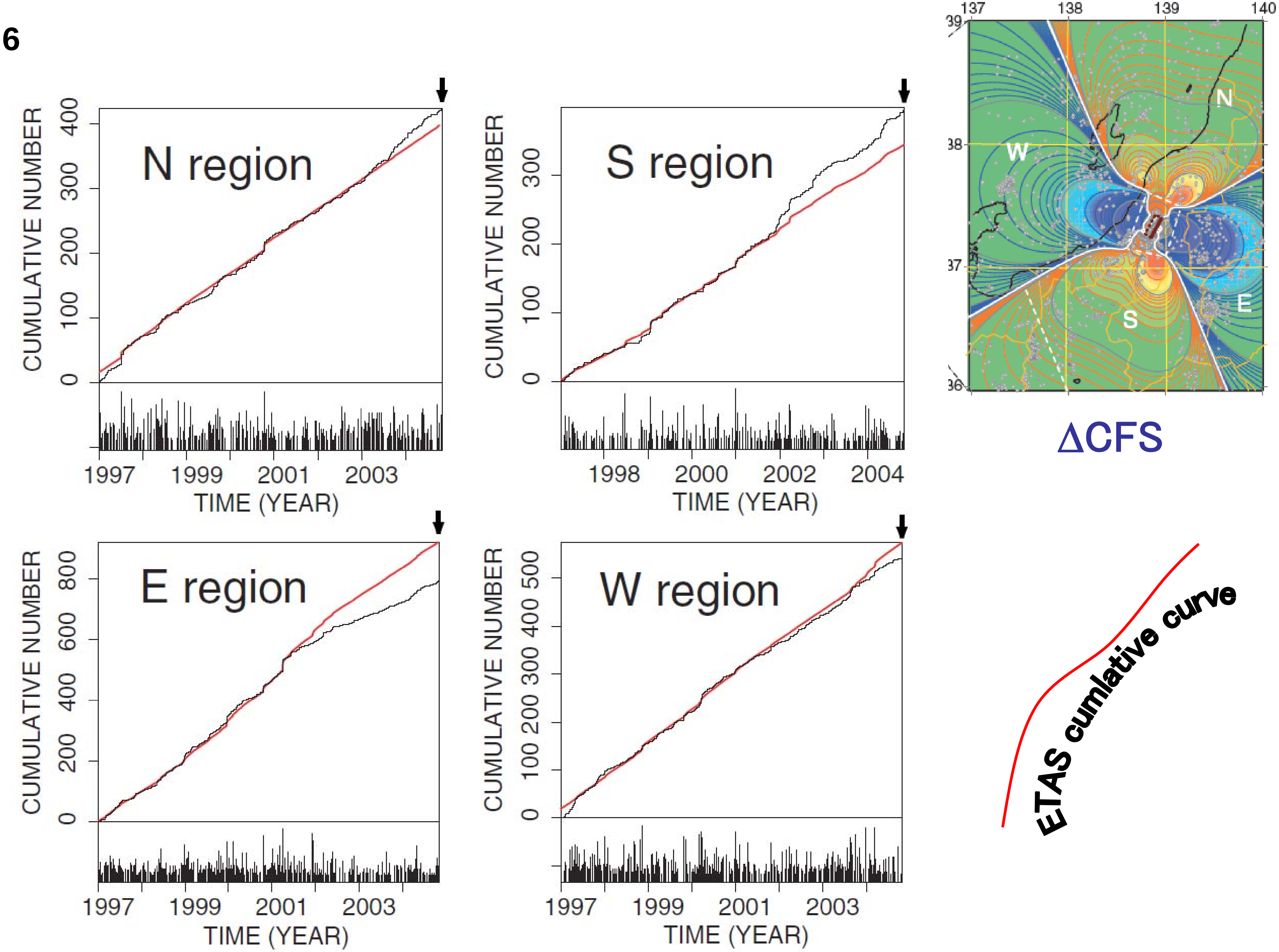
(b) background



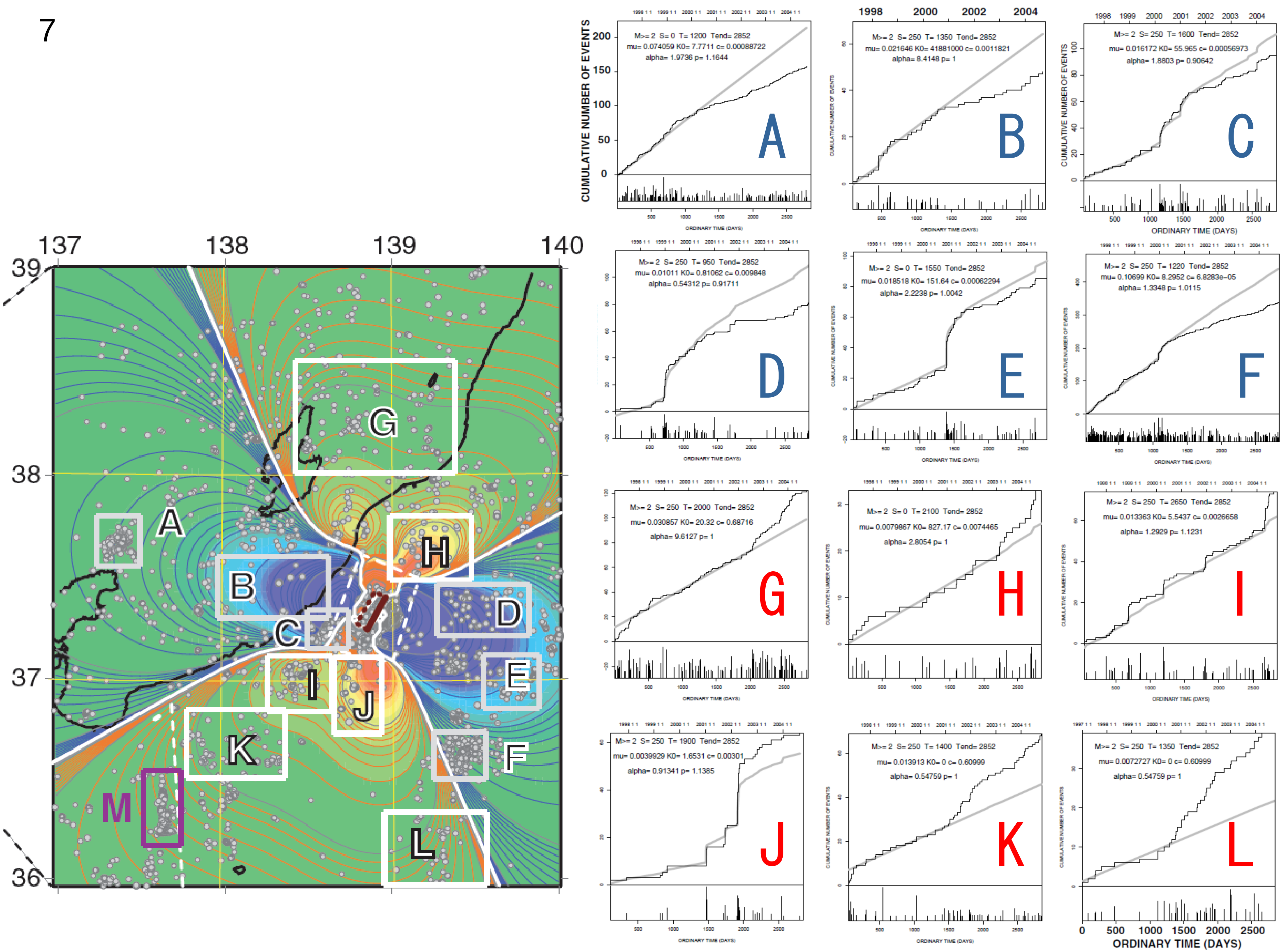
ΔCFS

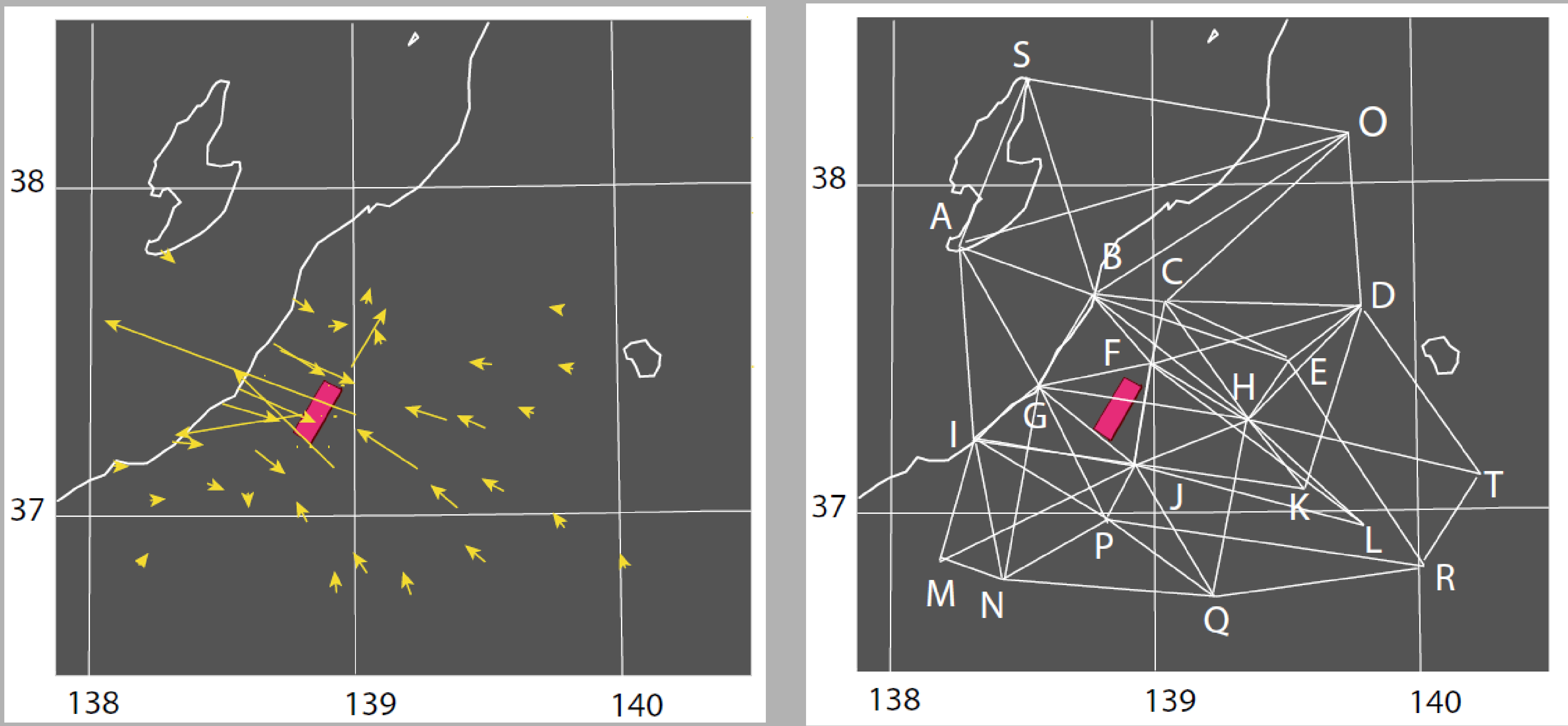


6


N region
S region
E region
W region
CUMULATIVE NUMBER
TIME (YEAR)
0
100
200
300
400
500
600
800
1997
1998
1999
2000
2001
2002
2003
2004
137
138
139
140
39
38
37
36
N
W
S
E
ΔCFS
ETAS cumlative curve

7


137
138
139
140
39
38
37
36
A
B
C
D
E
F
G
H
I
J
K
L
M
CUMULATIVE NUMBER OF EVENTS
ORDINARY TIME (DAYS)
M>= 2 S= 0 T= 1200 Tend= 2852
mu= 0.074059 K0= 7.7711 c= 0.00088722
alpha= 1.9736 p= 1.1644
M>= 2 S= 250 T= 1350 Tend= 2852
mu= 0.021646 K0= 41881000 c= 0.0011821
alpha= 8.4148 p= 1
M>= 2 S= 250 T= 1600 Tend= 2852
mu= 0.016172 K0= 55.965 c= 0.00056973
alpha= 1.8803 p= 0.90642
M>= 2 S= 250 T= 950 Tend= 2852
mu= 0.01011 K0= 0.81062 c= 0.009848
alpha= 0.54312 p= 0.91711
M>= 2 S= 0 T= 1550 Tend= 2852
mu= 0.018518 K0= 151.64 c= 0.00062294
alpha= 2.2238 p= 1.0042
M>= 2 S= 250 T= 1220 Tend= 2852
mu= 0.10699 K0= 8.2952 c= 6.8283e-05
alpha= 1.3348 p= 1.0115
M>= 2 S= 250 T= 2000 Tend= 2852
mu= 0.030857 K0= 20.32 c= 0.68716
alpha= 9.6127 p= 1
M>= 2 S= 0 T= 2100 Tend= 2852
mu= 0.0079867 K0= 827.17 c= 0.0074465
alpha= 2.8054 p= 1
M>= 2 S= 250 T= 2650 Tend= 2852
mu= 0.013363 K0= 5.5437 c= 0.0026658
alpha= 1.2929 p= 1.1231
M>= 2 S= 250 T= 1900 Tend= 2852
mu= 0.0039929 K0= 1.6531 c= 0.00301
alpha= 0.91341 p= 1.1385
M>= 2 S= 250 T= 1400 Tend= 2852
mu= 0.013913 K0= 0 c= 0.60999
alpha= 0.54759 p= 1
M>= 2 S= 250 T= 1350 Tend= 2852
mu= 0.0072727 K0= 0 c= 0.60999
alpha= 0.54759 p= 1


38
37
138
139
140
S
O
A
B
C
D
F
E
H
G
I
J
K
L
T
P
R
M
N
Q

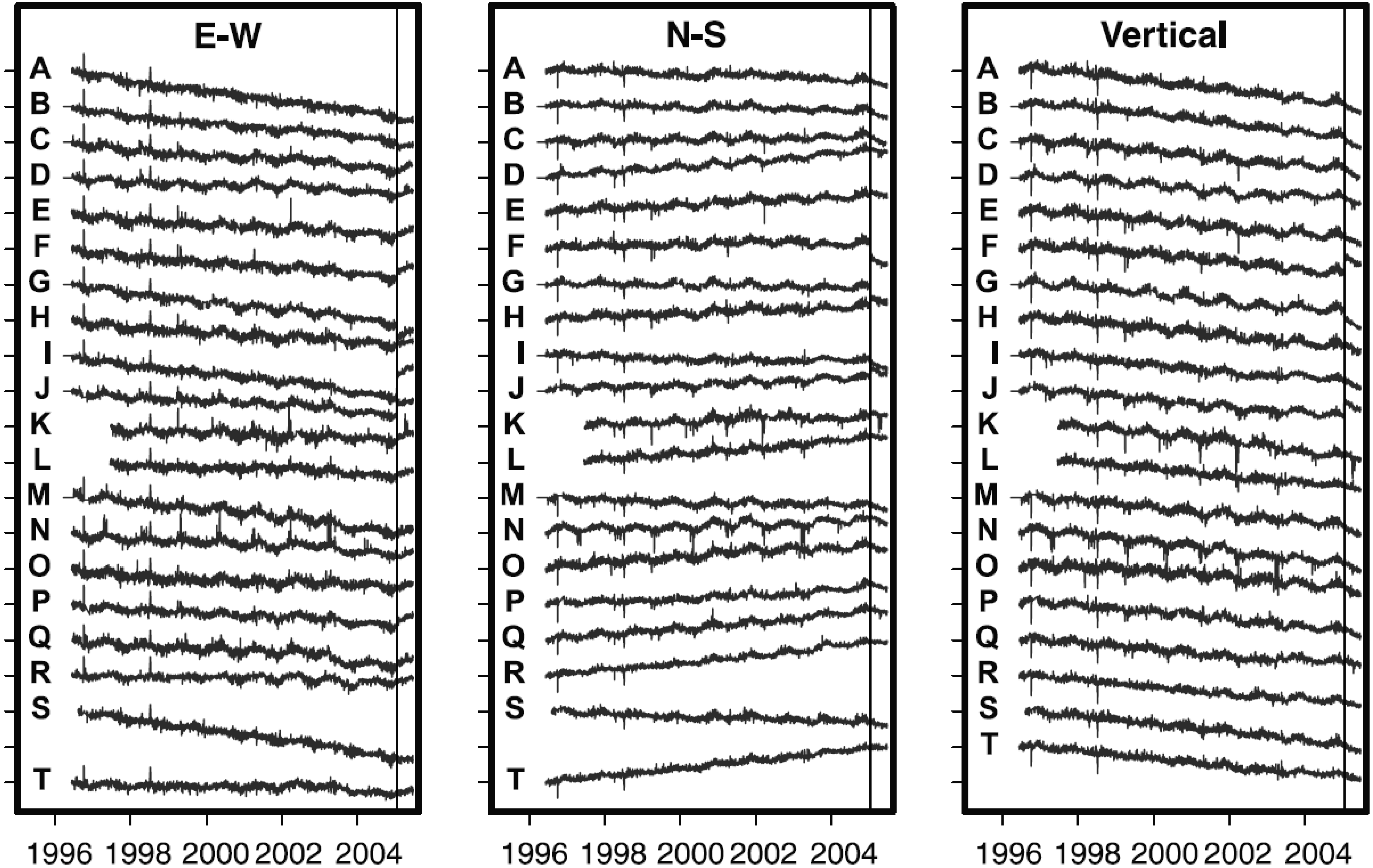
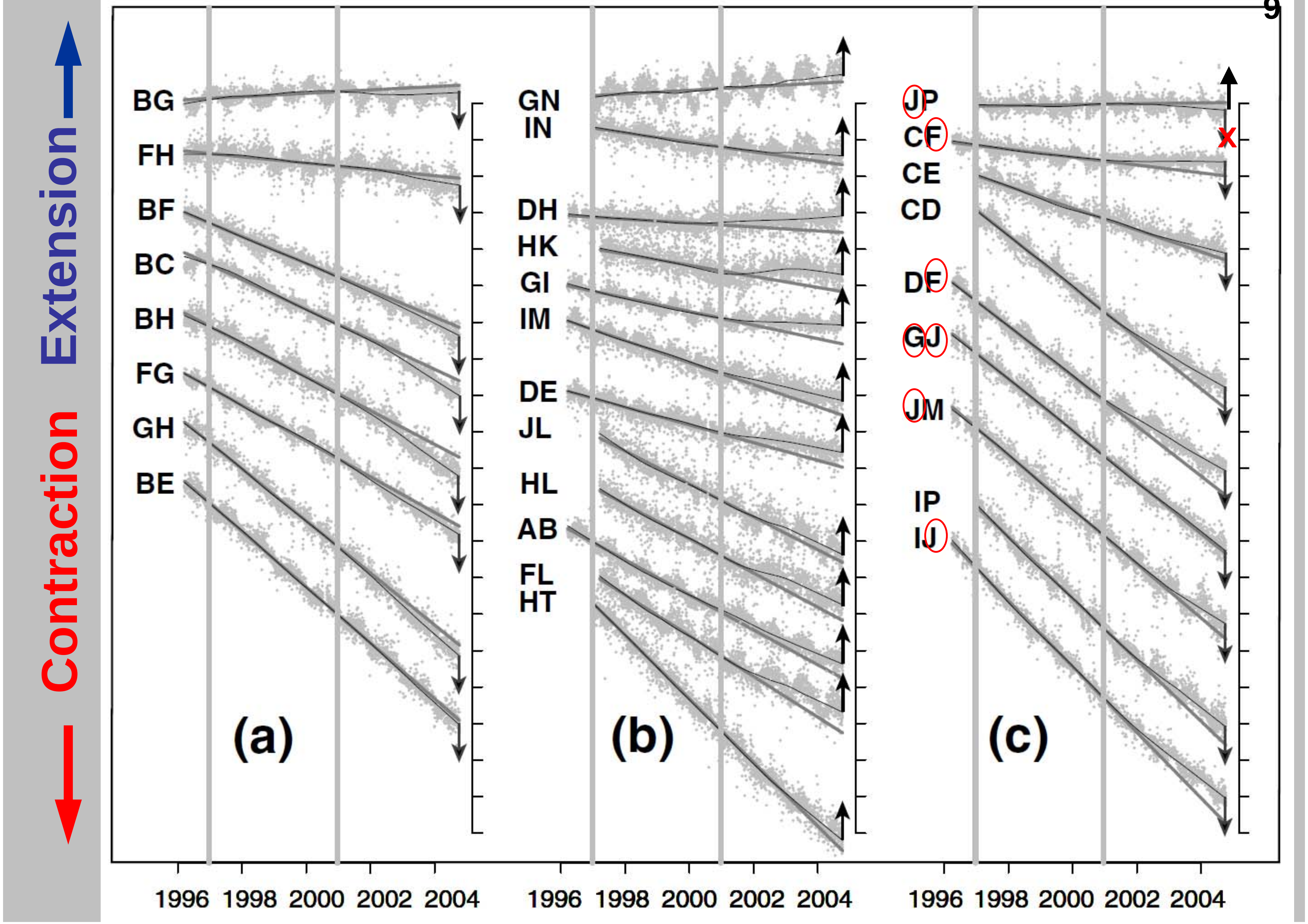
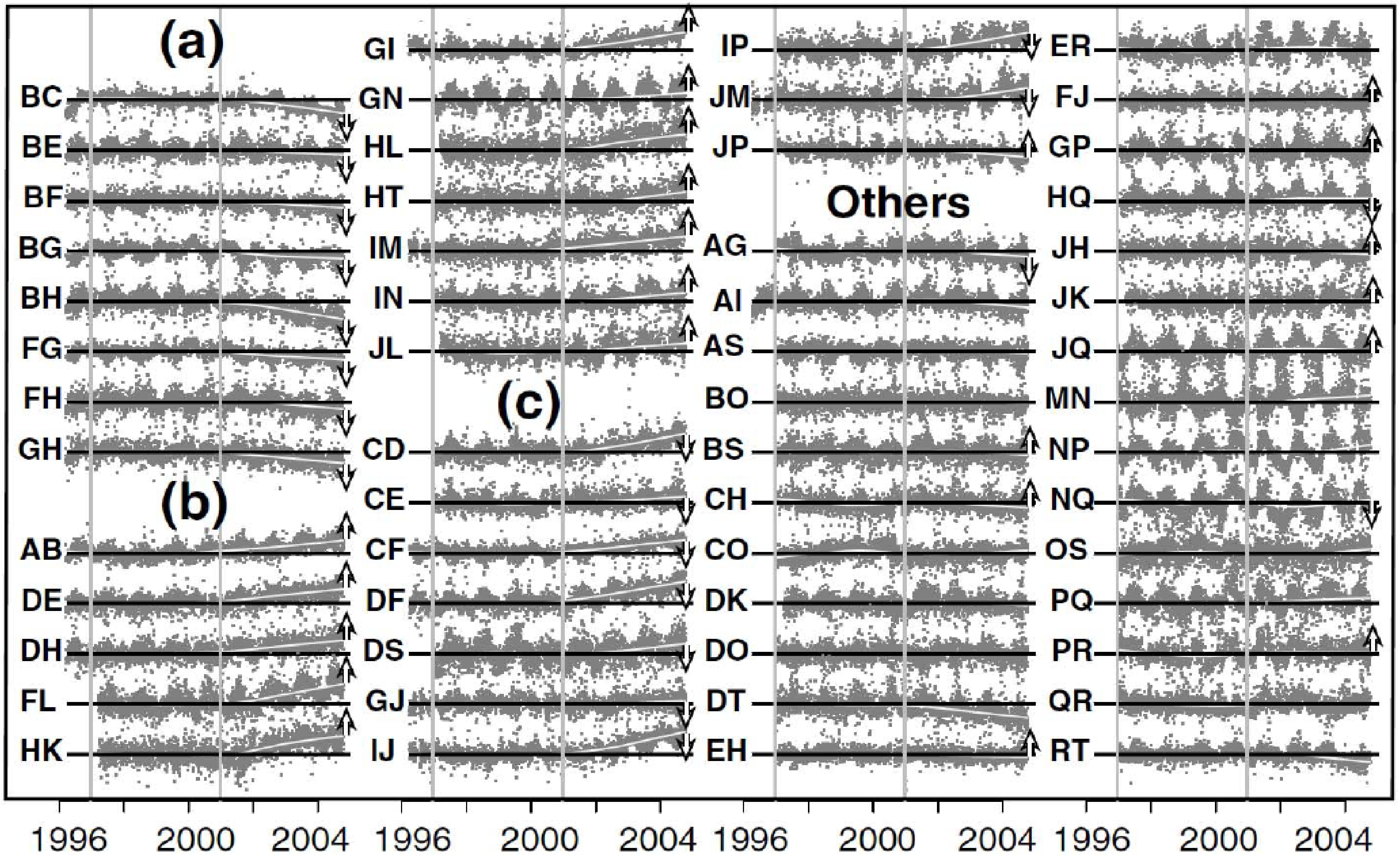


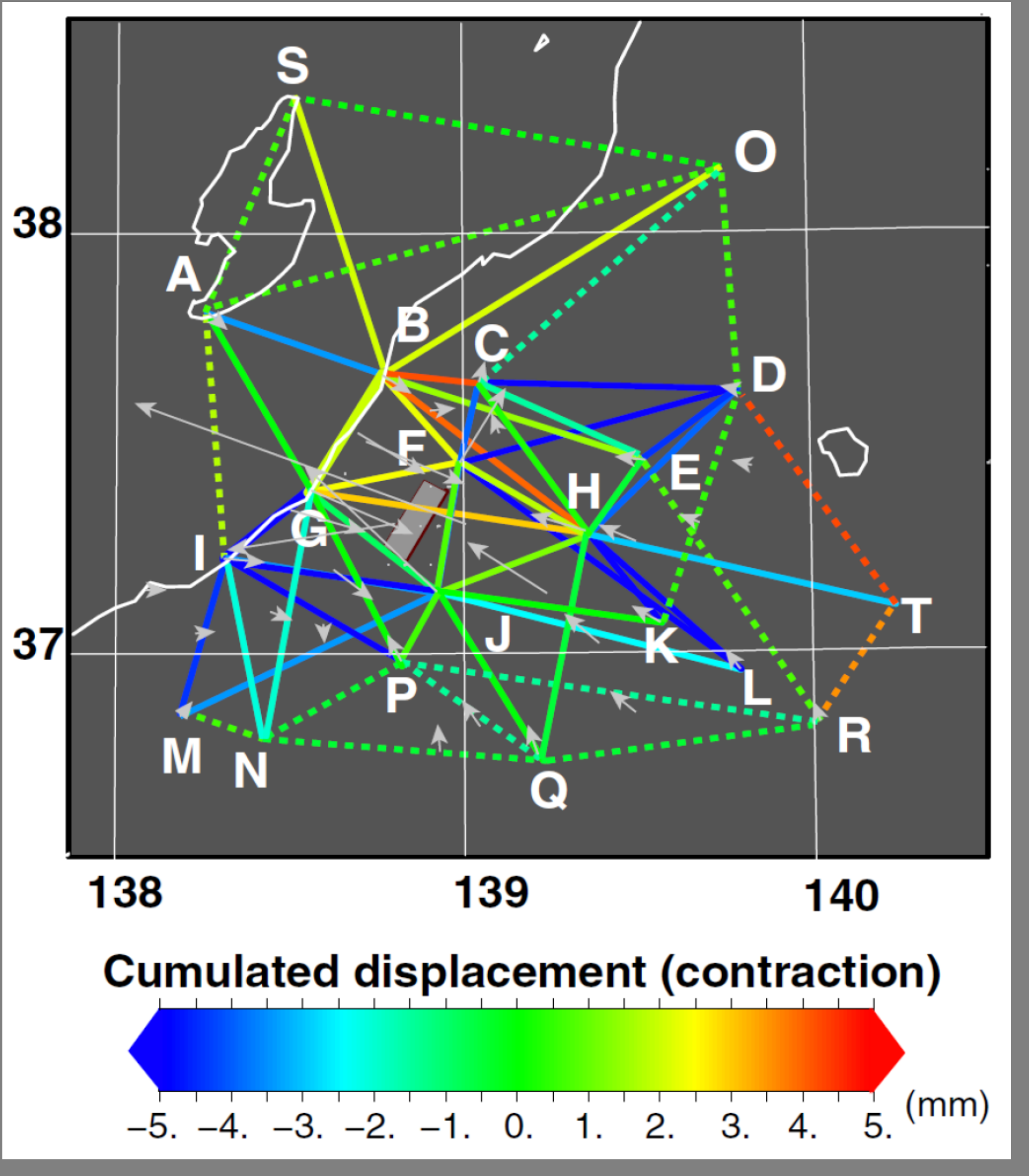
Figure 7. Daily position estimates for the (left) horizontal west-east, (middle) horizontal north-south, and (right) vertical coordinates of the GEONET stations A–T relative to their medians. The marked unit in vertical axis indicates 10 cm in distance. The thin vertical lines in 2004 indicate the occurrence time of the Chuetsu earthquake.

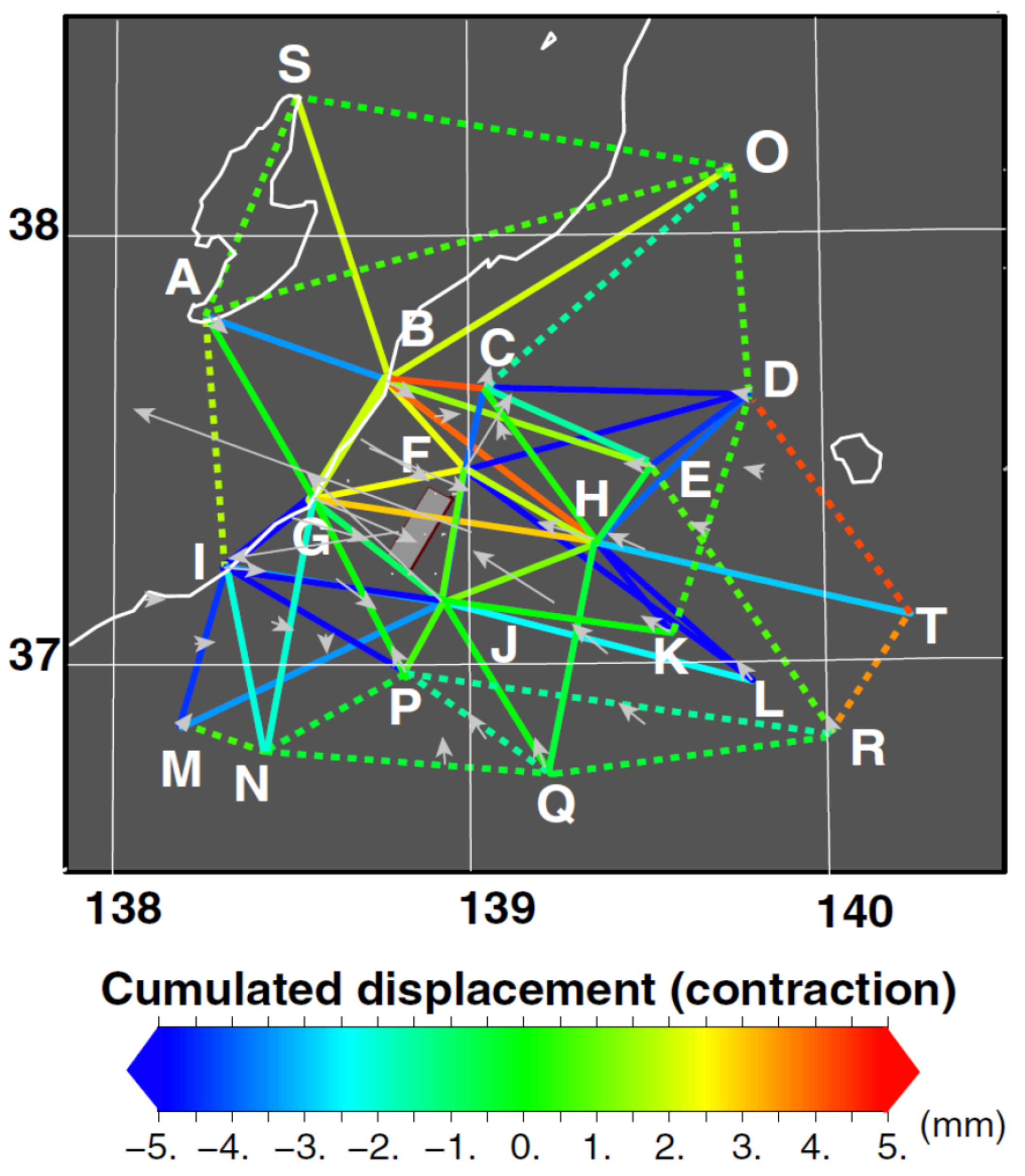
Daily time series of distance between stations

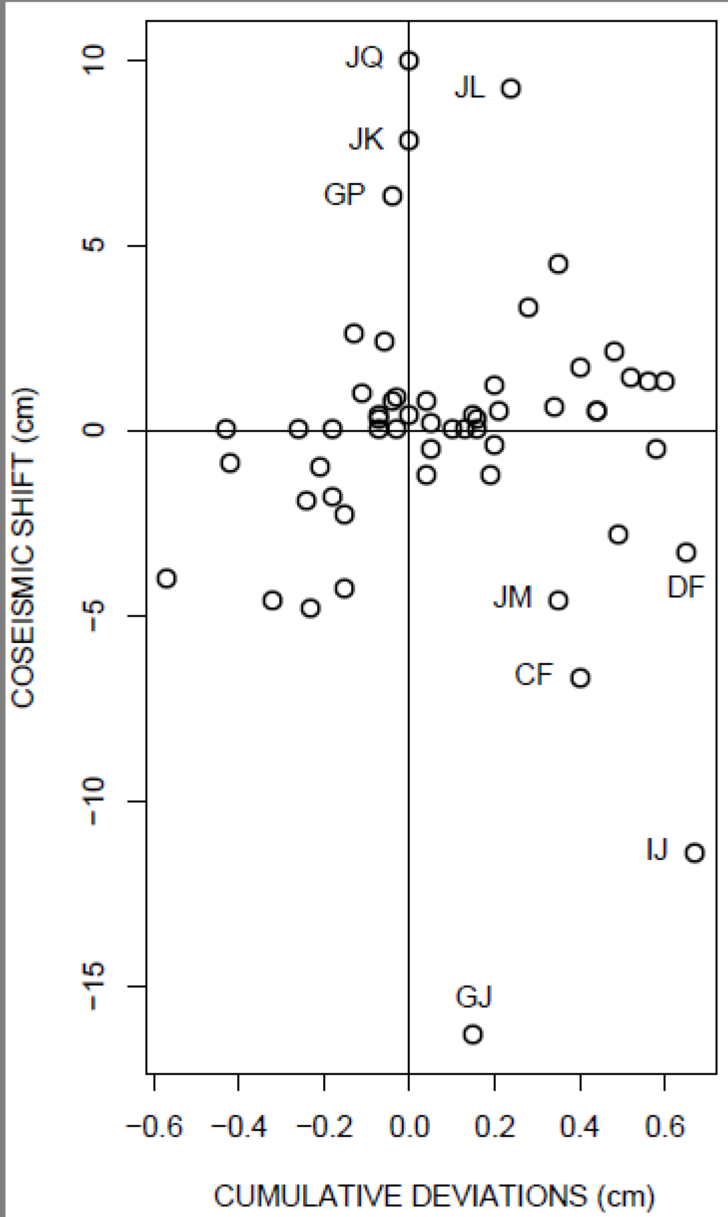


Residual time series of distances

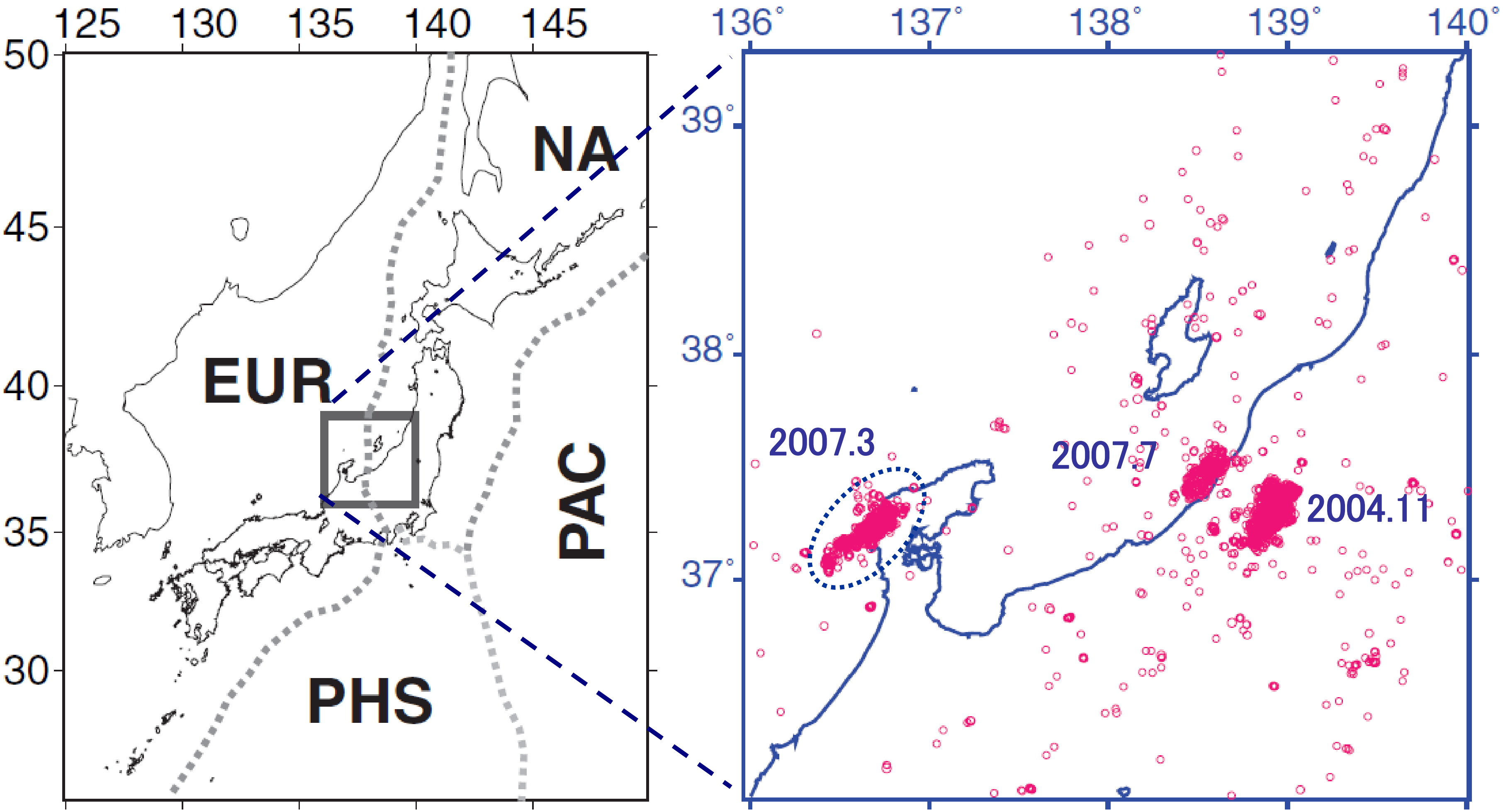


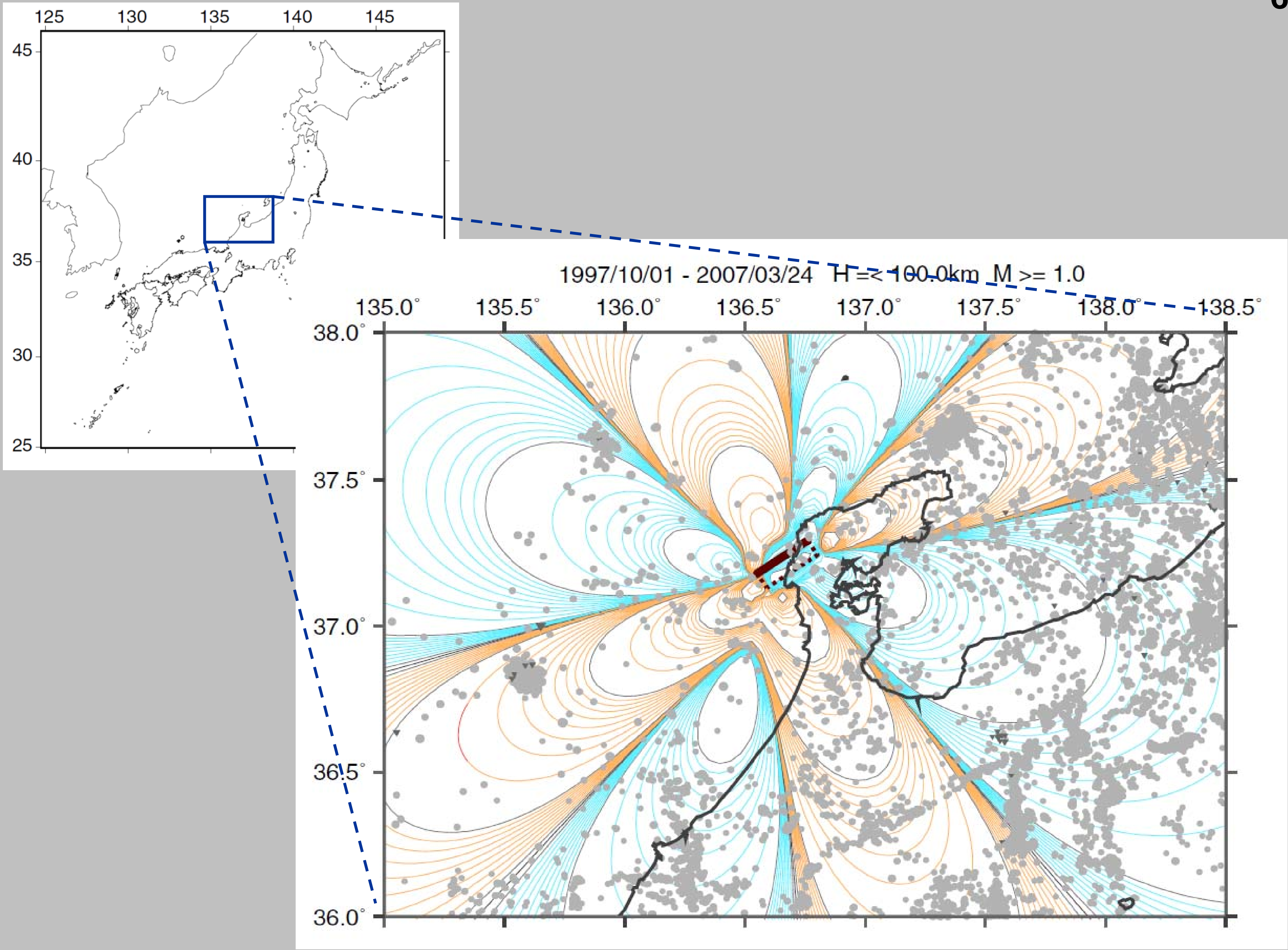

S
O
38
A
B
C
D
E
F
H
G
I
J
K
T
37
L
P
R
M
N
Q
138
139
140
Cumulated displacement (contraction)
−5. −4. −3. −2. −1. 0. 1. 2. 3. 4. 5.
(mm)

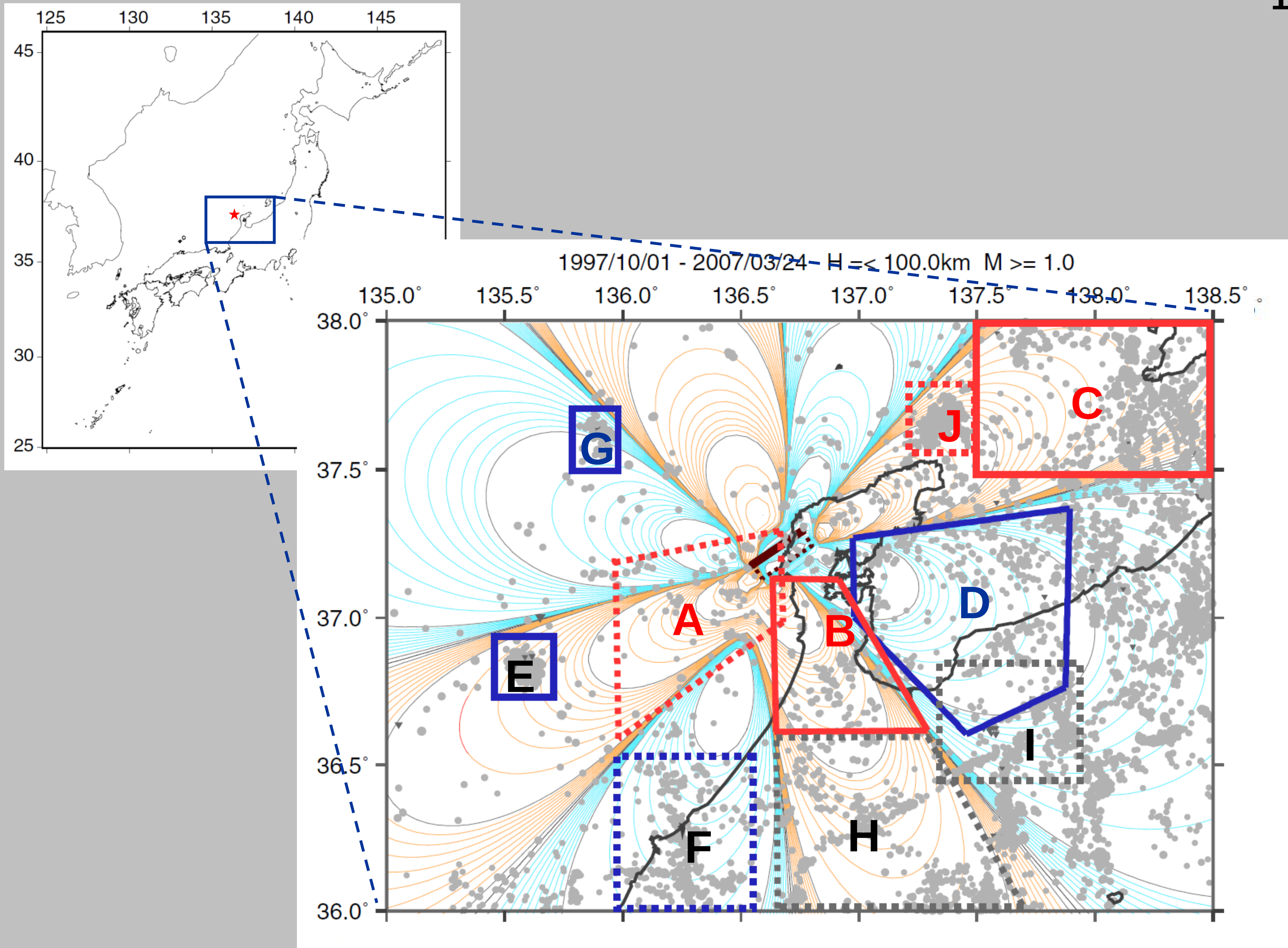

S
O
A
B
C
D
E
F
G
H
I
J
K
L
M
N
P
Q
R
T
38
37
138
139
140
Cumulated displacement (contraction)
–5. –4. –3. –2. –1. 0. 1. 2. 3. 4. 5.
(mm)

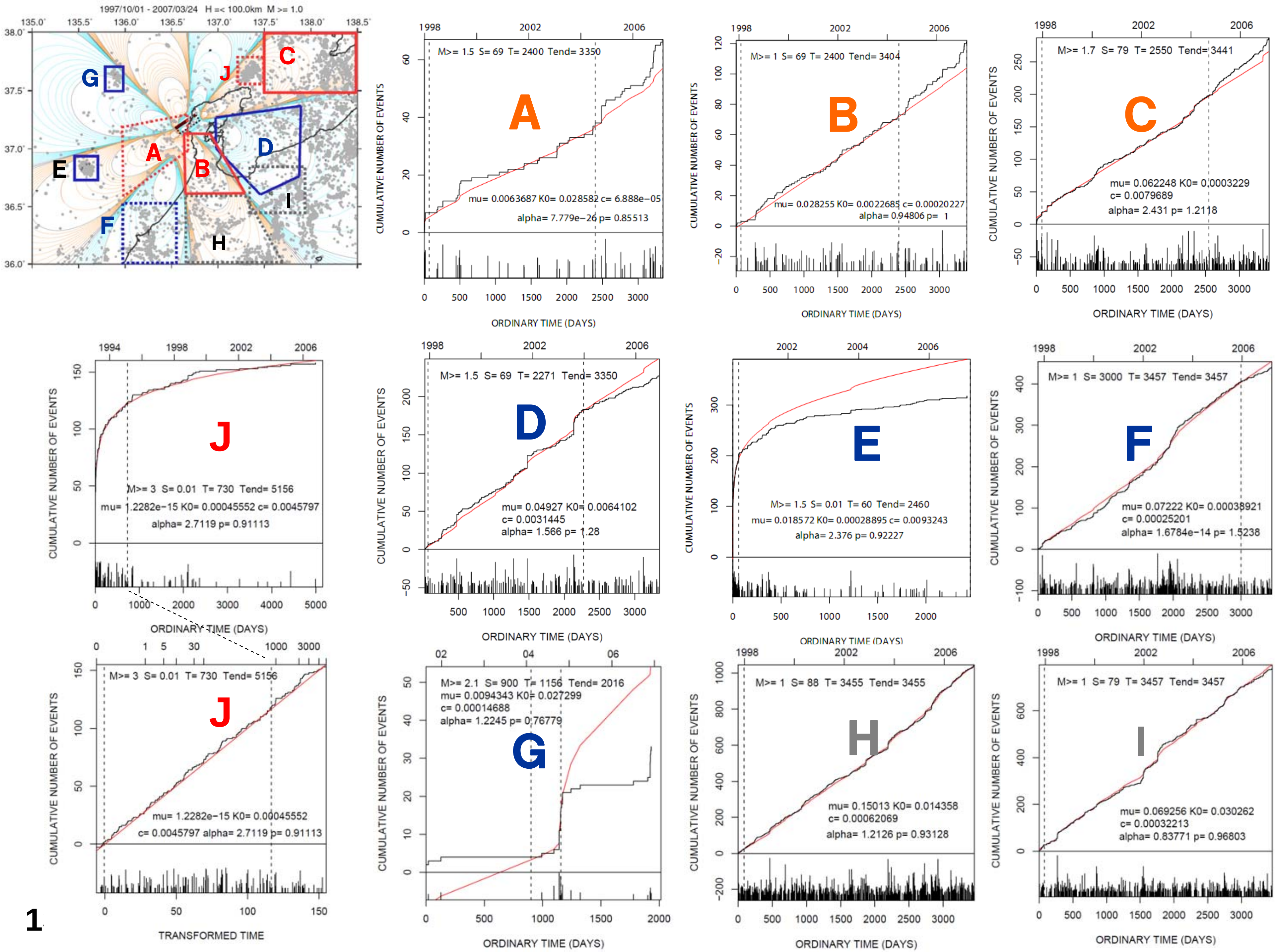

JQ
JL
JK
GP
JM
DF
CF
IJ
GJ
10
5
0
–5
–10
–15
COSEISMIC SHIFT (cm)
−0.6 −0.4 −0.2 0.0 0.2 0.4 0.6
CUMULATIVE DEVIATIONS (cm)

2007 Noto Peninsula M6.9



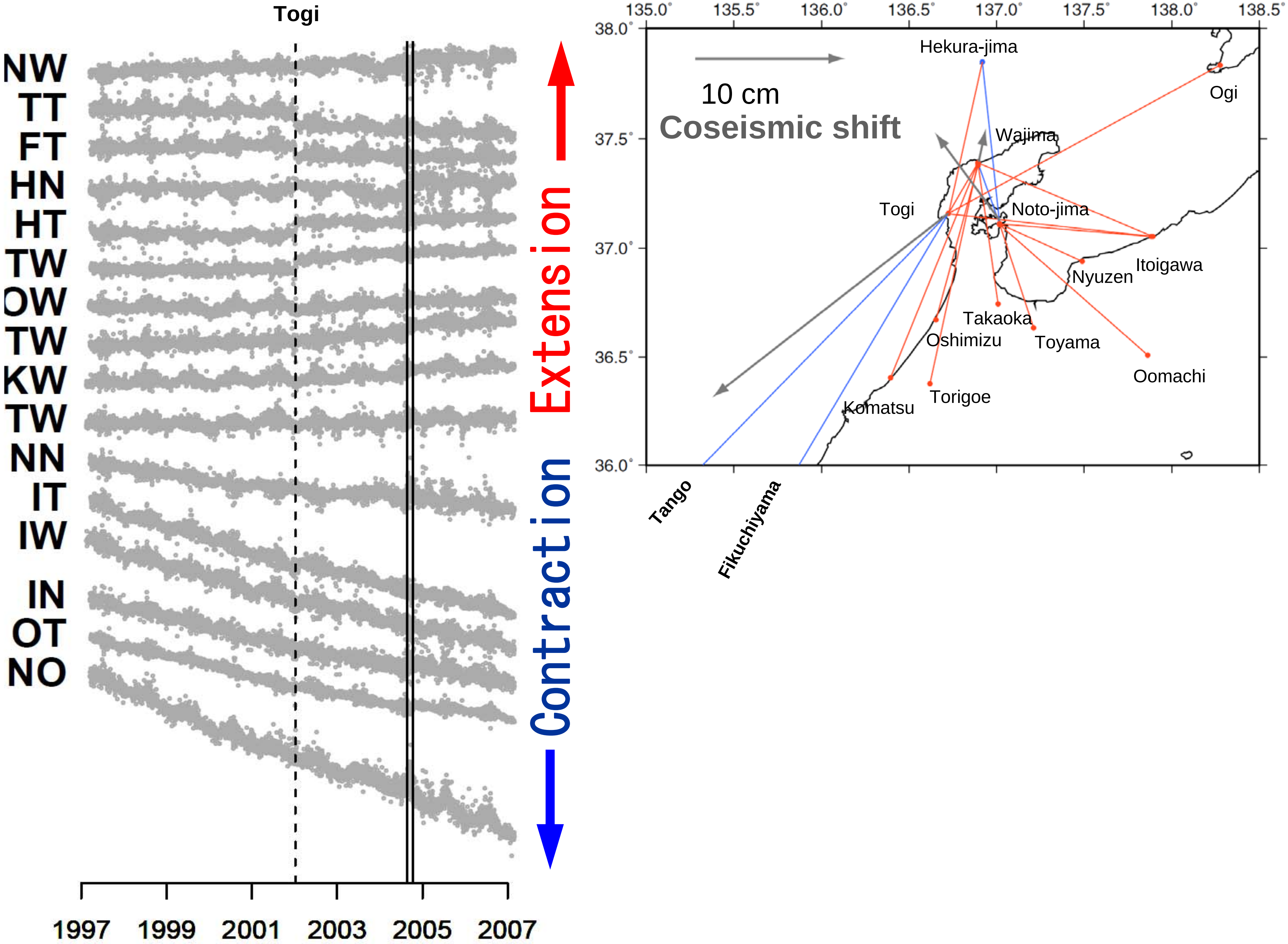

125
130
135
140
145
45
40
35
30
25
1997/10/01 - 2007/03/24 H =< 100.0km M >= 1.0
135.0°
135.5°
136.0°
136.5°
137.0°
137.5°
138.0°
138.5°
38.0°
37.5°
37.0°
36.5°
36.0°


125
130
135
140
145
45
40
35
30
25
1997/10/01 - 2007/03/24 H =< 100.0km M >= 1.0
135.0°
135.5°
136.0°
136.5°
137.0°
137.5°
138.0°
138.5°
38.0°
37.5°
37.0°
36.5°
36.0°
A
B
C
D
E
F
G
H
I
J

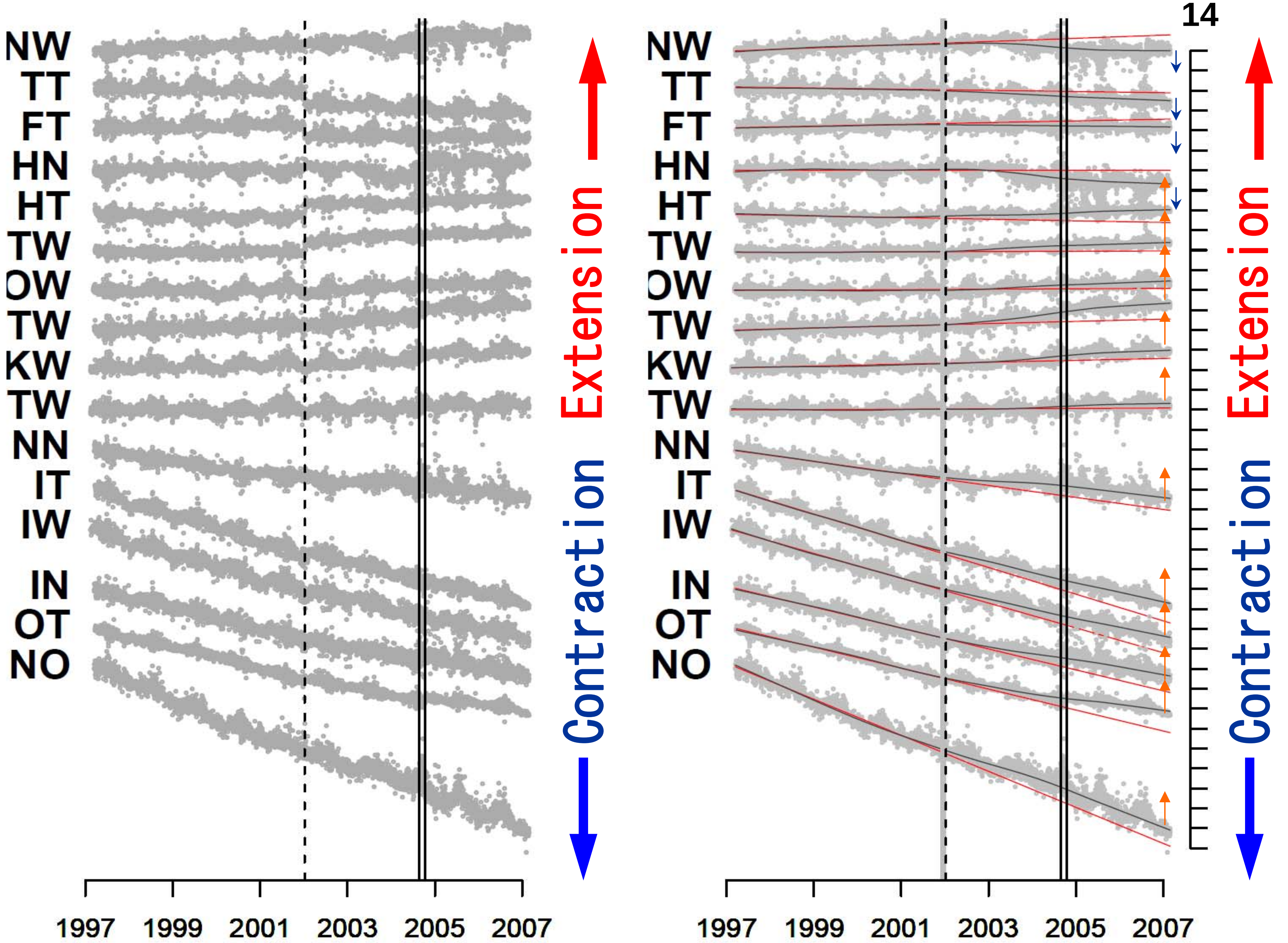


1997/10/01 - 2007/03/24 H =< 100.0km M >= 1.0
135.0° 135.5° 136.0° 136.5° 137.0° 137.5° 138.0° 138.5°
38.0° 37.5° 37.0° 36.5° 36.0°
A B C D E F G H I J
M>= 1.5 S= 69 T= 2400 Tend= 3350
mu= 0.0063687 K0= 0.028582 c= 6.888e−05
alpha= 7.779e−26 p= 0.85513
M>= 1 S= 69 T= 2400 Tend= 3404
mu= 0.028255 K0= 0.0022685 c= 0.00020227
alpha= 0.94806 p= 1
M>= 1.7 S= 79 T= 2550 Tend= 3441
mu= 0.062248 K0= 0.0003229
c= 0.0079689
alpha= 2.431 p= 1.2118
M>= 3 S= 0.01 T= 730 Tend= 5156
mu= 1.2282e−15 K0= 0.00045552 c= 0.0045797
alpha= 2.7119 p= 0.91113
M>= 1.5 S= 69 T= 2271 Tend= 3350
mu= 0.04927 K0= 0.0064102
c= 0.0031445
alpha= 1.566 p= 1.28
M>= 1.5 S= 0.01 T= 60 Tend= 2460
mu= 0.018572 K0= 0.00028895 c= 0.0093243
alpha= 2.376 p= 0.92227
M>= 1 S= 3000 T= 3457 Tend= 3457
mu= 0.07222 K0= 0.00038921
c= 0.00025201
alpha= 1.6784e−14 p= 1.5238
M>= 3 S= 0.01 T= 730 Tend= 5156
mu= 1.2282e−15 K0= 0.00045552
c= 0.0045797 alpha= 2.7119 p= 0.91113
M>= 2.1 S= 900 T= 1156 Tend= 2016
mu= 0.0094343 K0= 0.027299
c= 0.00014688
alpha= 1.2245 p= 0.76779
M>= 1 S= 88 T= 3455 Tend= 3455
mu= 0.15013 K0= 0.014358
c= 0.00062069
alpha= 1.2126 p= 0.93128
M>= 1 S= 79 T= 3457 Tend= 3457
mu= 0.069256 K0= 0.030262
c= 0.00032213
alpha= 0.83771 p= 0.96803
CUMULATIVE NUMBER OF EVENTS
ORDINARY TIME (DAYS)
TRANSFORMED TIME

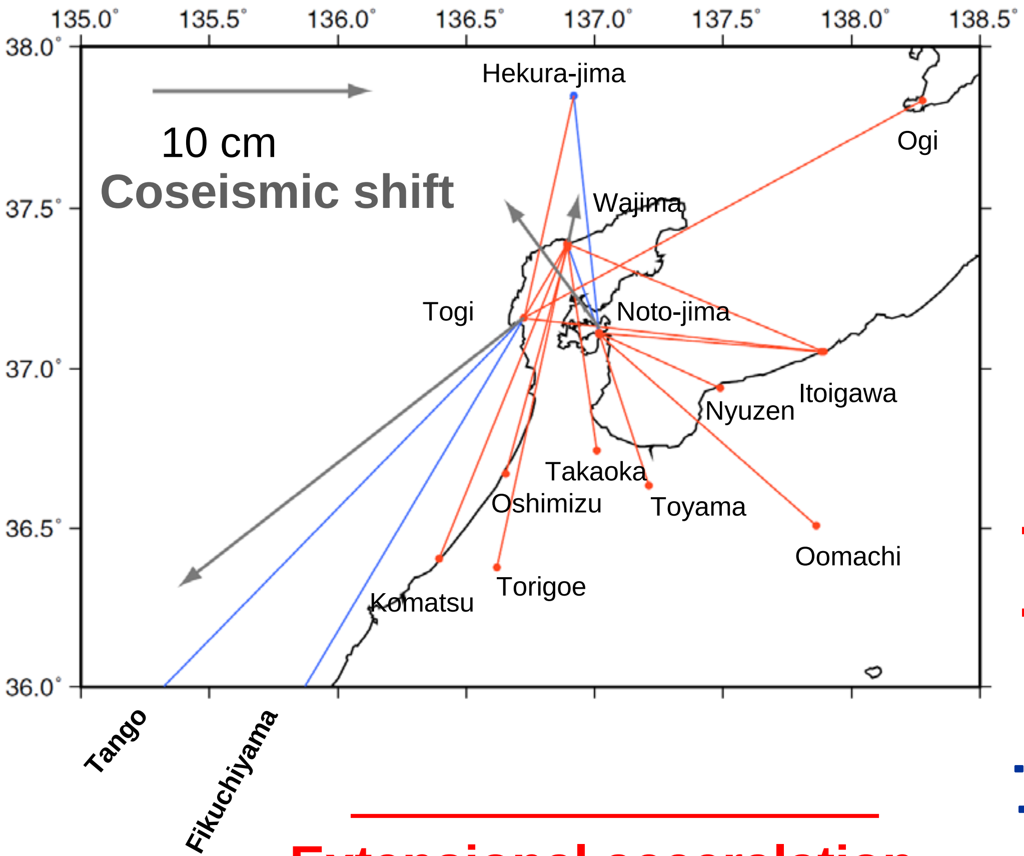
1



Togi
NW
TT
FT
HN
HT
TW
OW
TW
KW
TW
NN
IT
IW
IN
OT
NO
1997
1999
2001
2003
2005
2007
Extension
Contraction
135.0°
135.5°
136.0°
136.5°
137.0°
137.5°
138.0°
138.5°
38.0°
37.5°
37.0°
36.5°
36.0°
10 cm
Coseismic shift
Hekura-jima
Ogi
Wajima
Togi
Noto-jima
Itoigawa
Nyuzen
Takaoka
Oshimizu
Toyama
Oomachi
Torigoe
Komatsu
Tango
Fikuchiyama

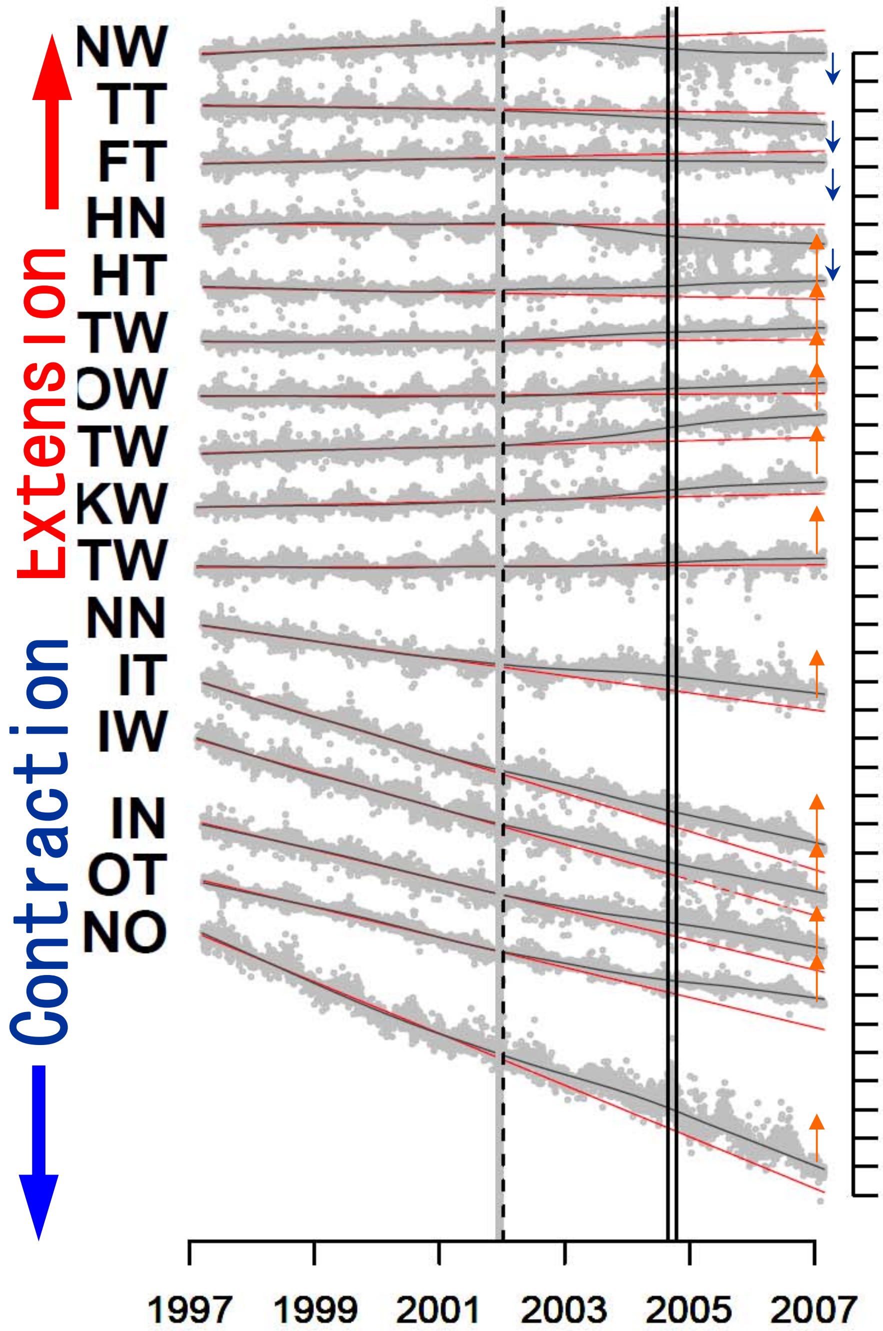


NW
TT
FT
HN
HT
TW
OW
TW
KW
TW
NN
IT
IW
IN
OT
NO
1997
1999
2001
2003
2005
2007
Extension
Contraction
14

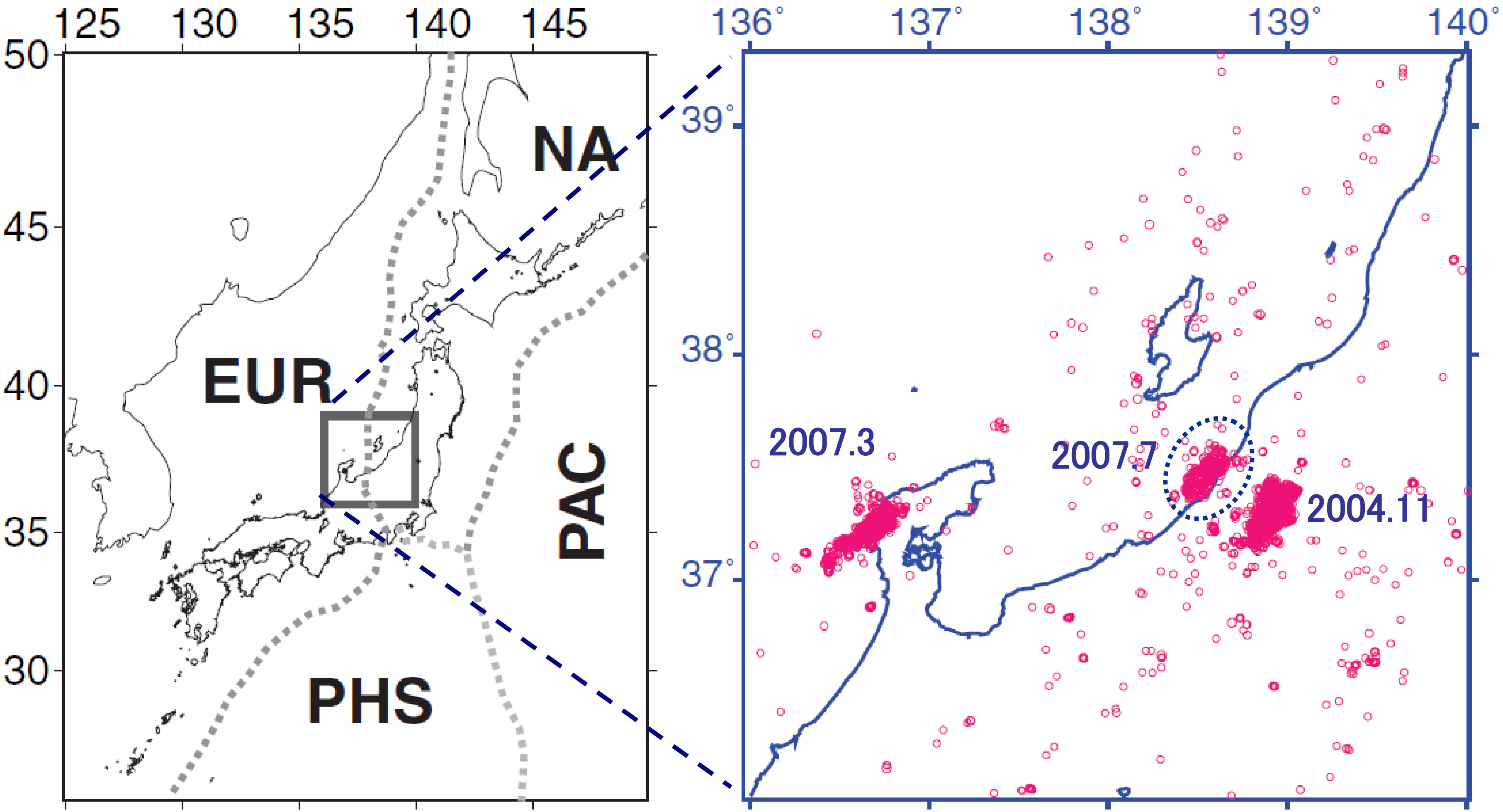


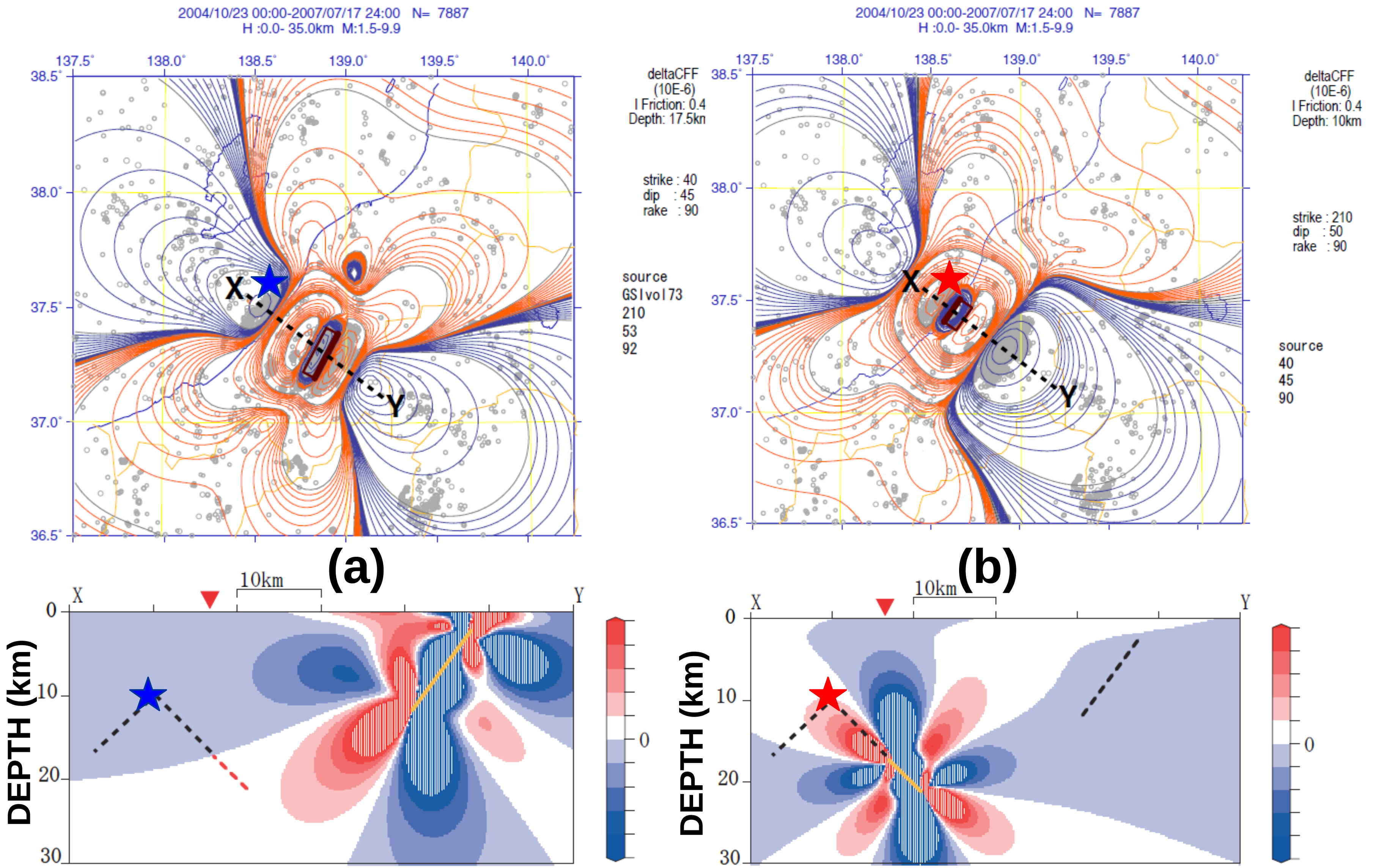
Extensional acceralation
Contractional deceralation

Extensional
deceralation

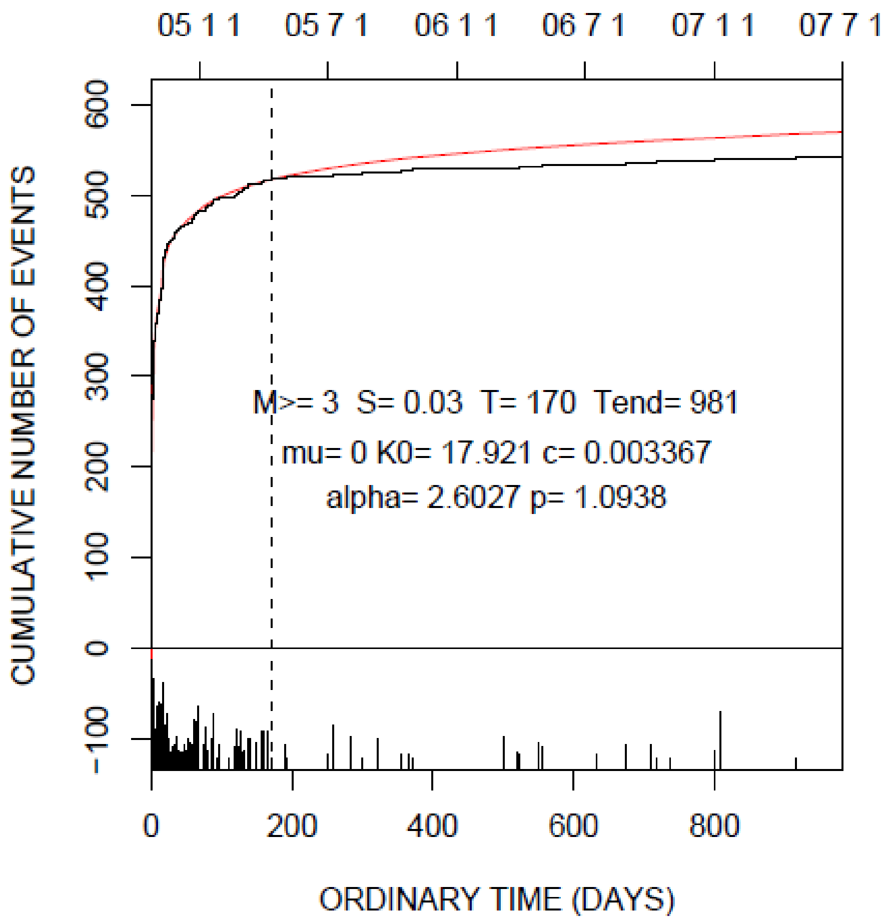


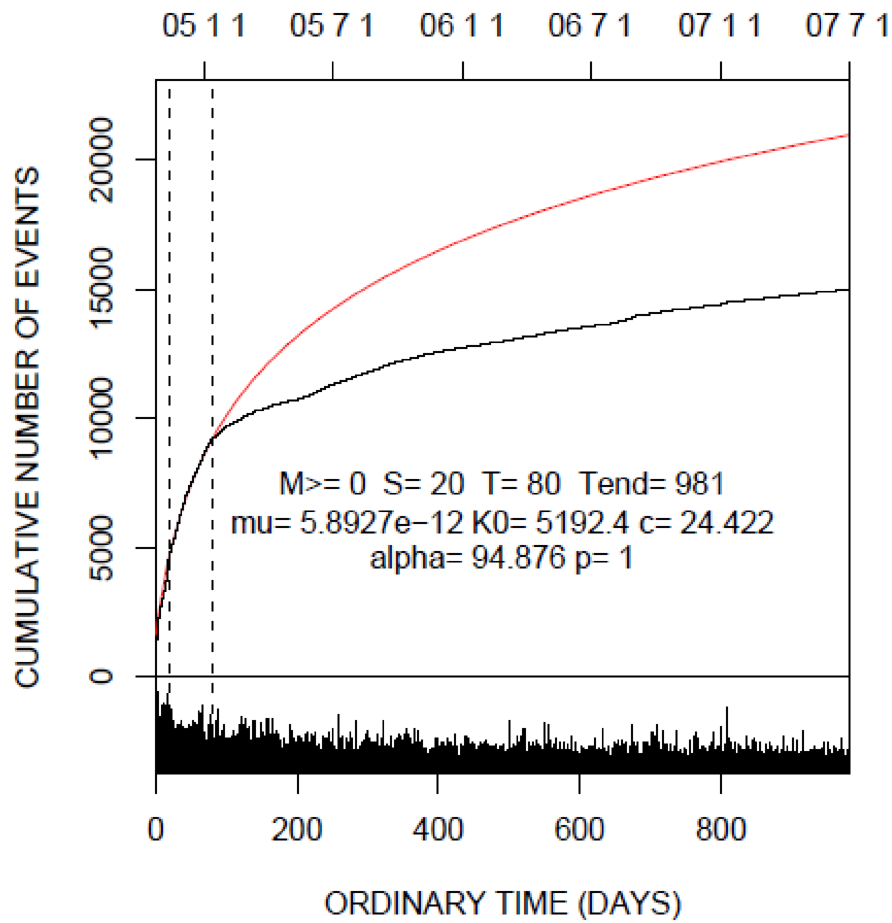
2007 Chuetsu-Oki M6.8

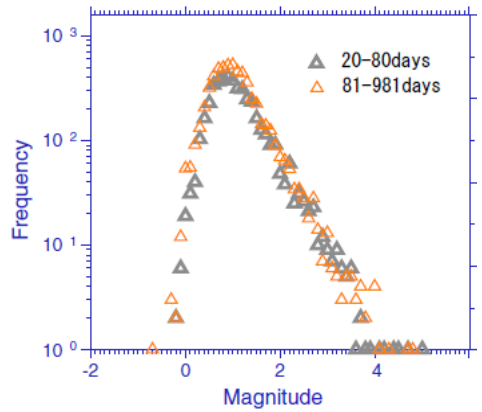


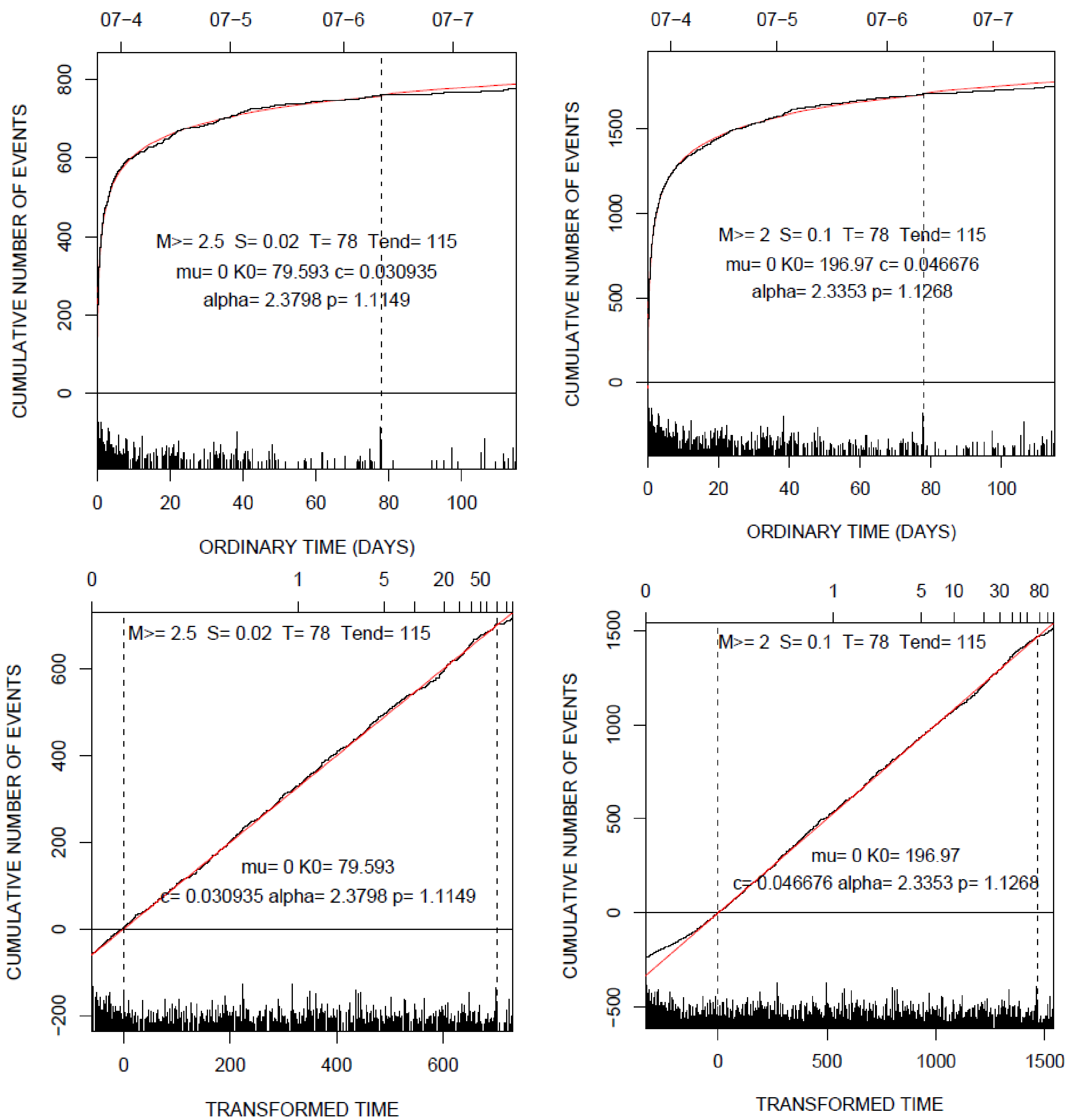


2004/10/23 00:00-2007/07/17 24:00 N= 7887
H :0.0- 35.0km M:1.5-9.9
137.5° 138.0° 138.5° 139.0° 139.5° 140.0°
38.5° 38.0° 37.5° 37.0° 36.5°
deltaCFF
(10E-6)
I Friction: 0.4
Depth: 17.5kn
strike : 40
dip : 45
rake : 90
source
GSIvol73
210
53
92
X
Y
(a)
2004/10/23 00:00-2007/07/17 24:00 N= 7887
H :0.0- 35.0km M:1.5-9.9
deltaCFF
(10E-6)
I Friction: 0.4
Depth: 10km
strike : 210
dip : 50
rake : 90
source
40
45
90
(b)
10km
DEPTH (km)
0
10
20
30


05 1 1
05 7 1
06 1 1
06 7 1
07 1 1
07 7 1
CUMULATIVE NUMBER OF EVENTS
M>= 3 S= 0.03 T= 170 Tend= 981
mu= 0 K0= 17.921 c= 0.003367
alpha= 2.6027 p= 1.0938
ORDINARY TIME (DAYS)

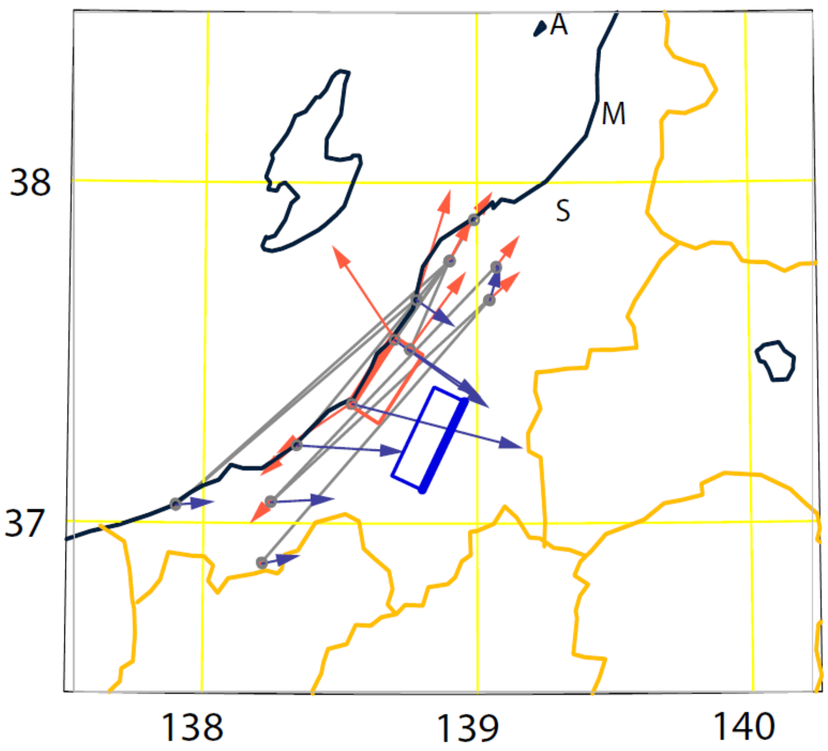

05 1 1
05 7 1
06 1 1
06 7 1
07 1 1
07 7 1
CUMULATIVE NUMBER OF EVENTS
M>= 0 S= 20 T= 80 Tend= 981
mu= 5.8927e−12 K0= 5192.4 c= 24.422
alpha= 94.876 p= 1
ORDINARY TIME (DAYS)

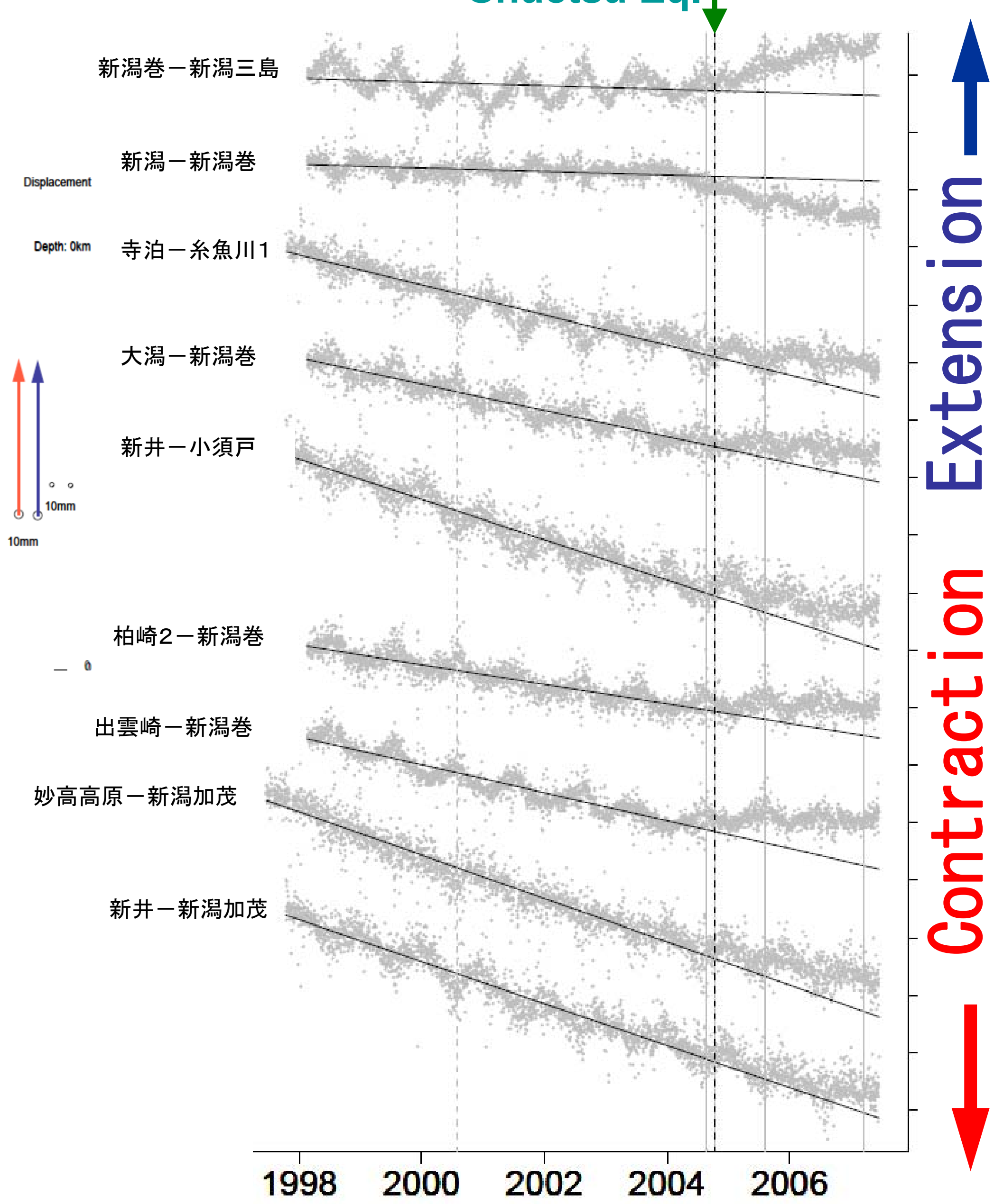

20-80days
81-981days
Frequency
Magnitude



2007年能登半島地震の余震活動

の2007年7月20日までの，MT図と累積関数。**右側図**は下限マグニチュードがM2.5で，左側はM2.0の余震。赤い累積曲線は，本震後一定の時間（**右側図**は0.02日で**左側図**は0.1日）から変化点（78日）までの余震データにETASモデルをあてはめて残りの期間を予測した，理論的累積曲線。横軸は，**上図**が通常の時間推移で，**下図**がETASモデルによる変換時間。


A
M
S
38
37
138
139
140
Displacement
Depth: 0km
10mm
10mm


Chuetsu Eq.
新潟巻ー新潟三島
新潟ー新潟巻
寺泊ー糸魚川1
大潟ー新潟巻
新井ー小須戸
柏崎2ー新潟巻
出雲崎ー新潟巻
妙高高原ー新潟加茂
新井ー新潟加茂
1998
2000
2002
2004
2006
Extension
Contraction

Summary

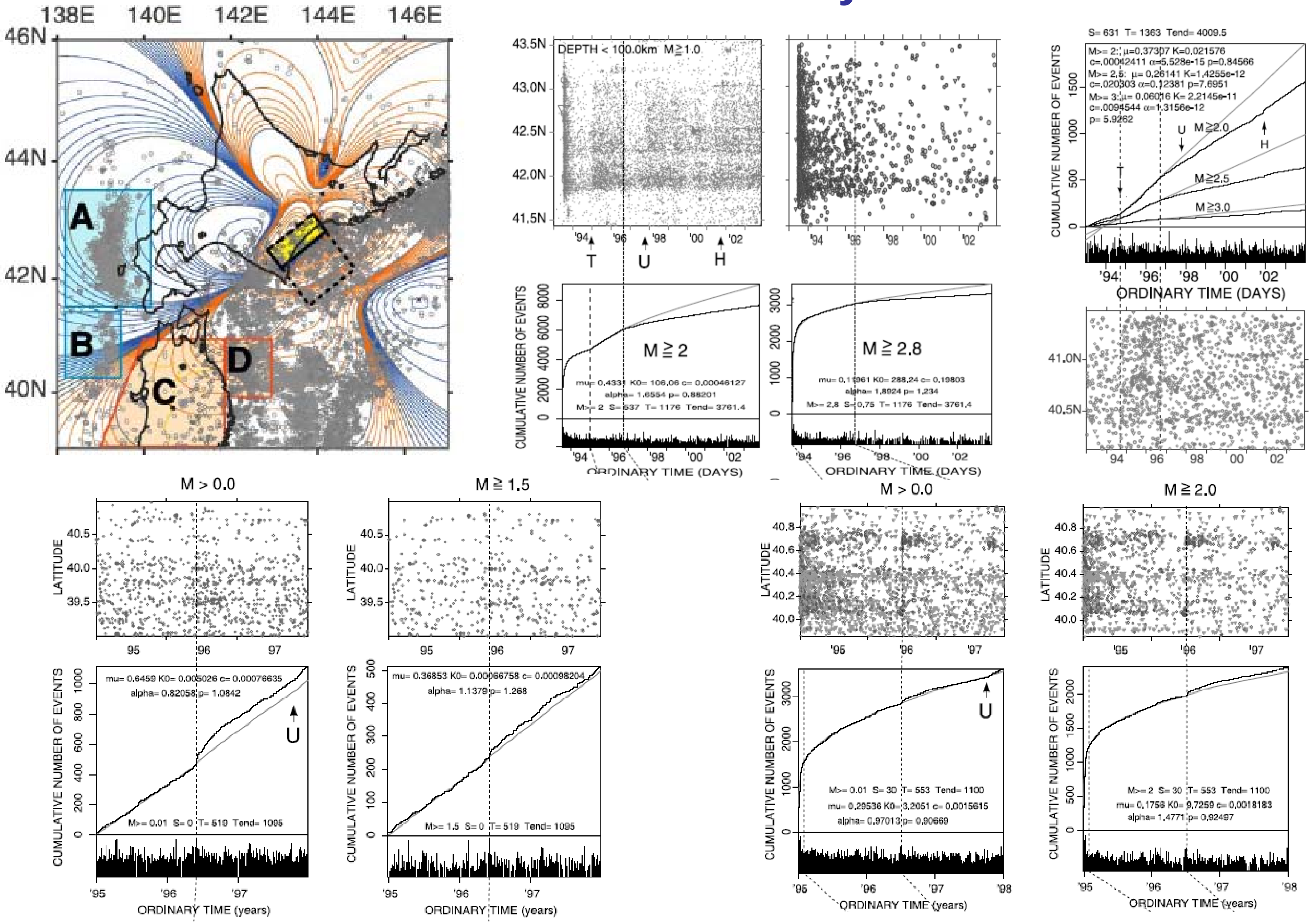
- **The ETAS model summarizes the seismicity due to triggering effect within the contiguous hierarchical complex faults.**
- **Deviations of the seismic activities from the predicted rate by the ETAS model are useful to detect regional stress changes.**
- **The respective deviations are explained by the changes in Coulomb failure stresses that are caused by seismic or aseismic slips.**
- **These are further supported by transient crustal movement around the source due to the aseismic slips preceding the ruptures.**

Software and manuals are available:

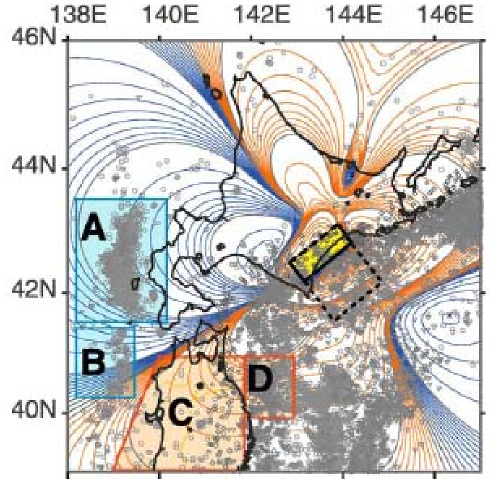
Search “SASeis2006” by Google

Ogata (2005, *JGR*)

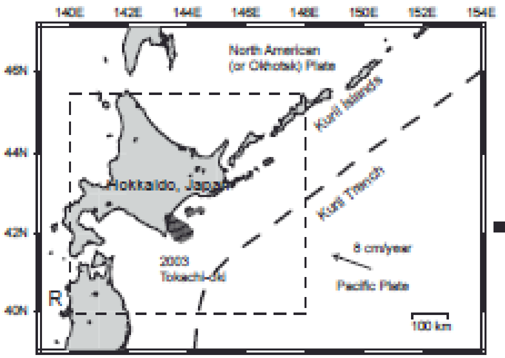
Period of anomaly: mid1996 ~ mid2003

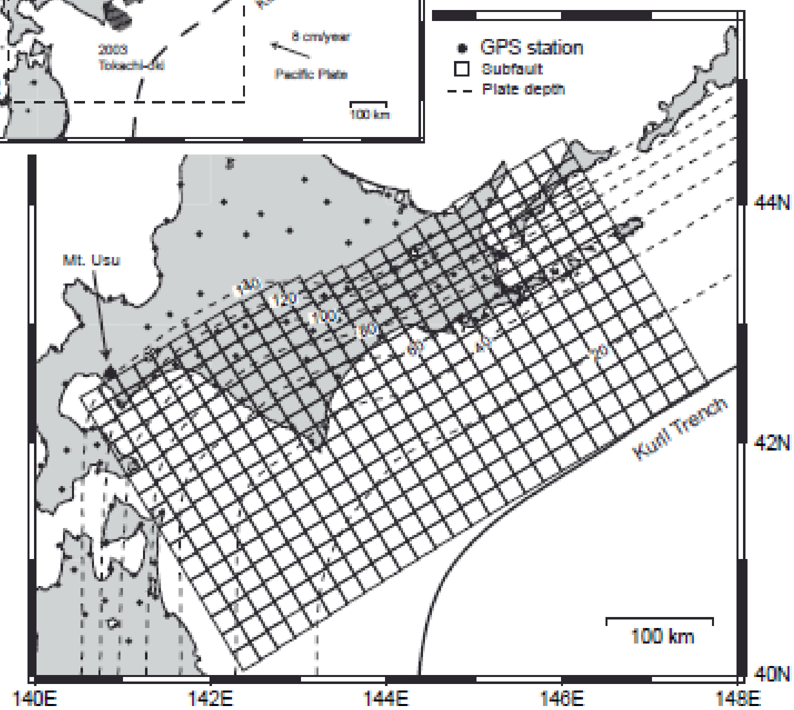


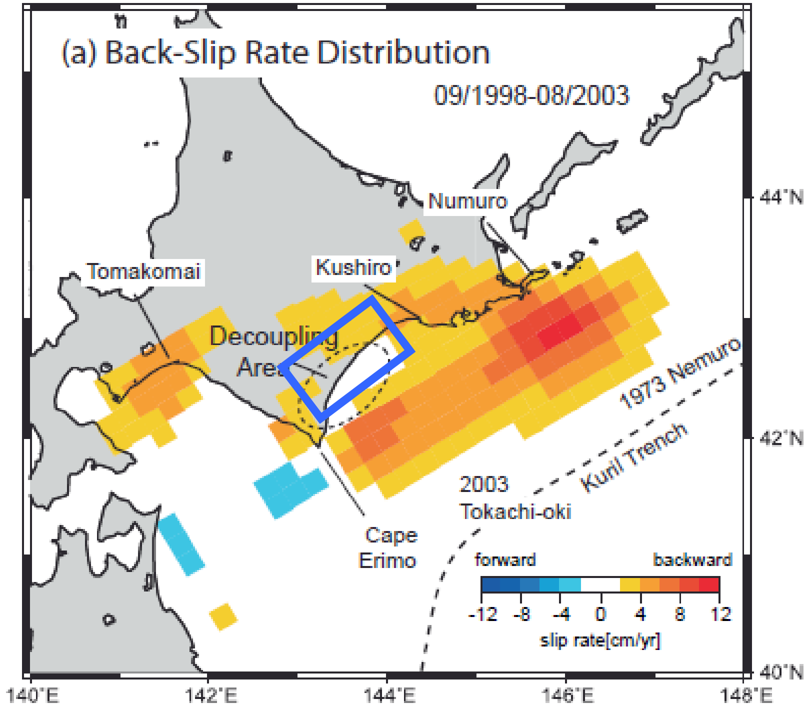
Back slip rate estimate during 1998-2003AUG by inversion of GPS network



Baba & Hori (2007)

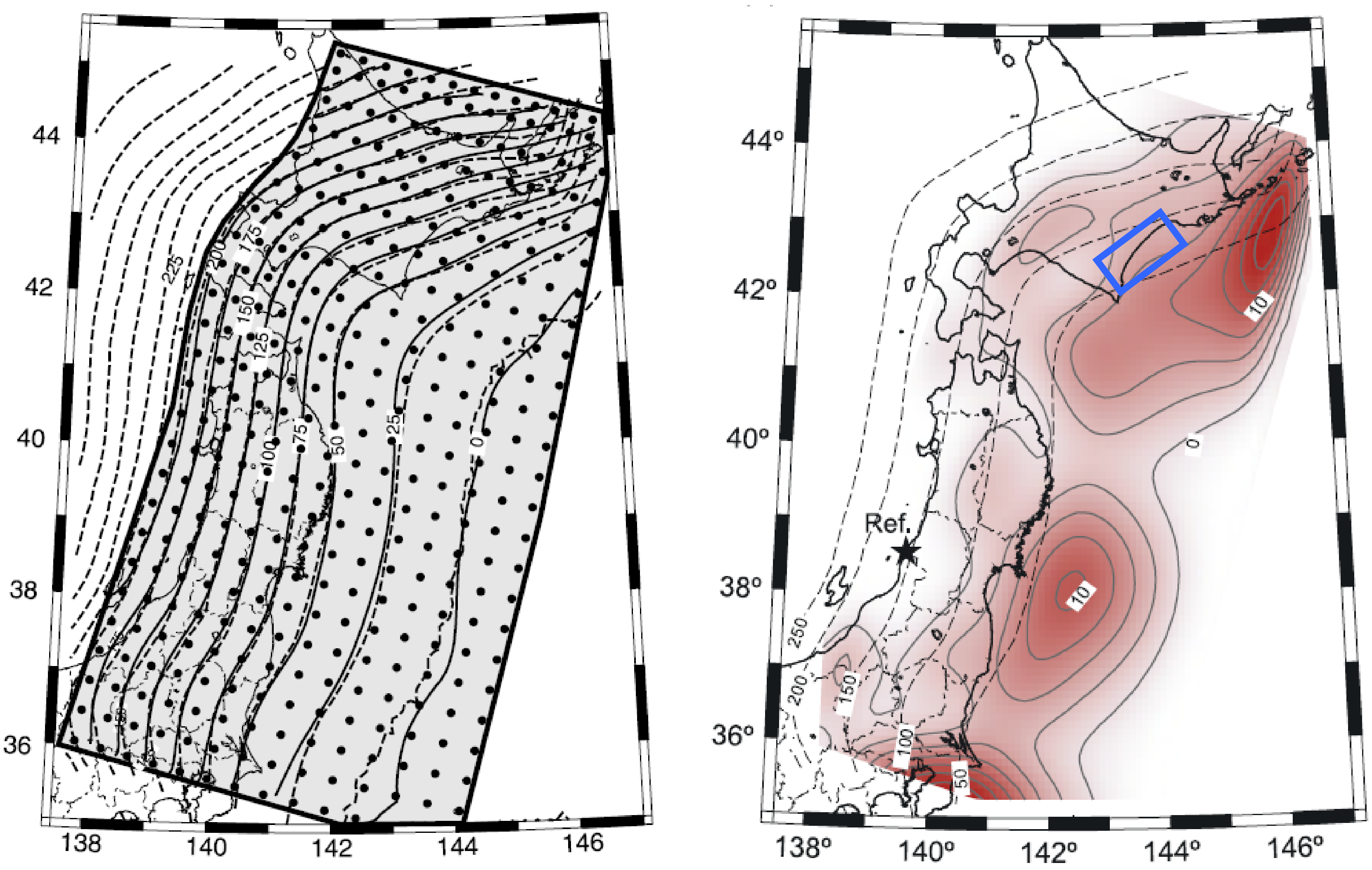






Suwa et al. (2006, JGR)

Back slip rate 1997-2001



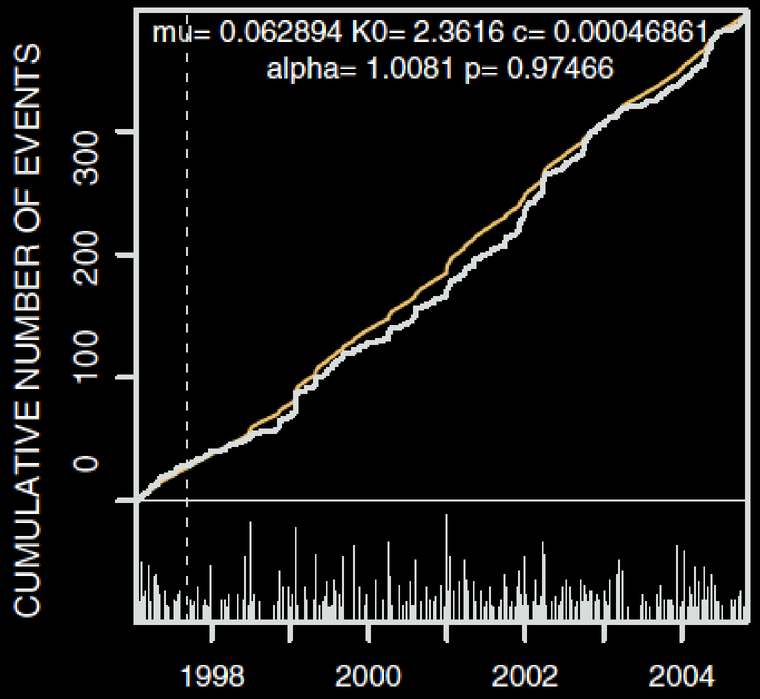
Thank you very much for listening

Software and manuals are available at

http://www.ism.ac.jp/~ogata/Ssg/softwaresE.html

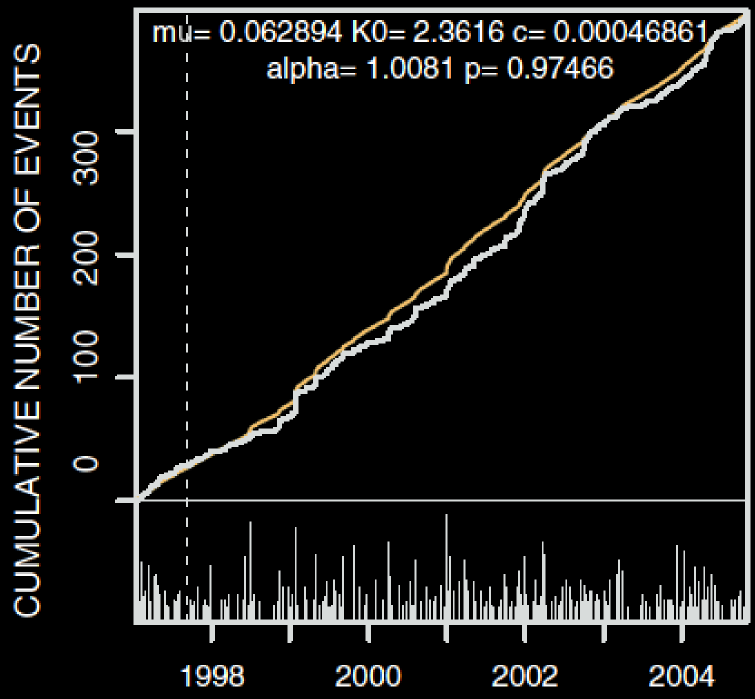
Search “SASeis2006” by Google

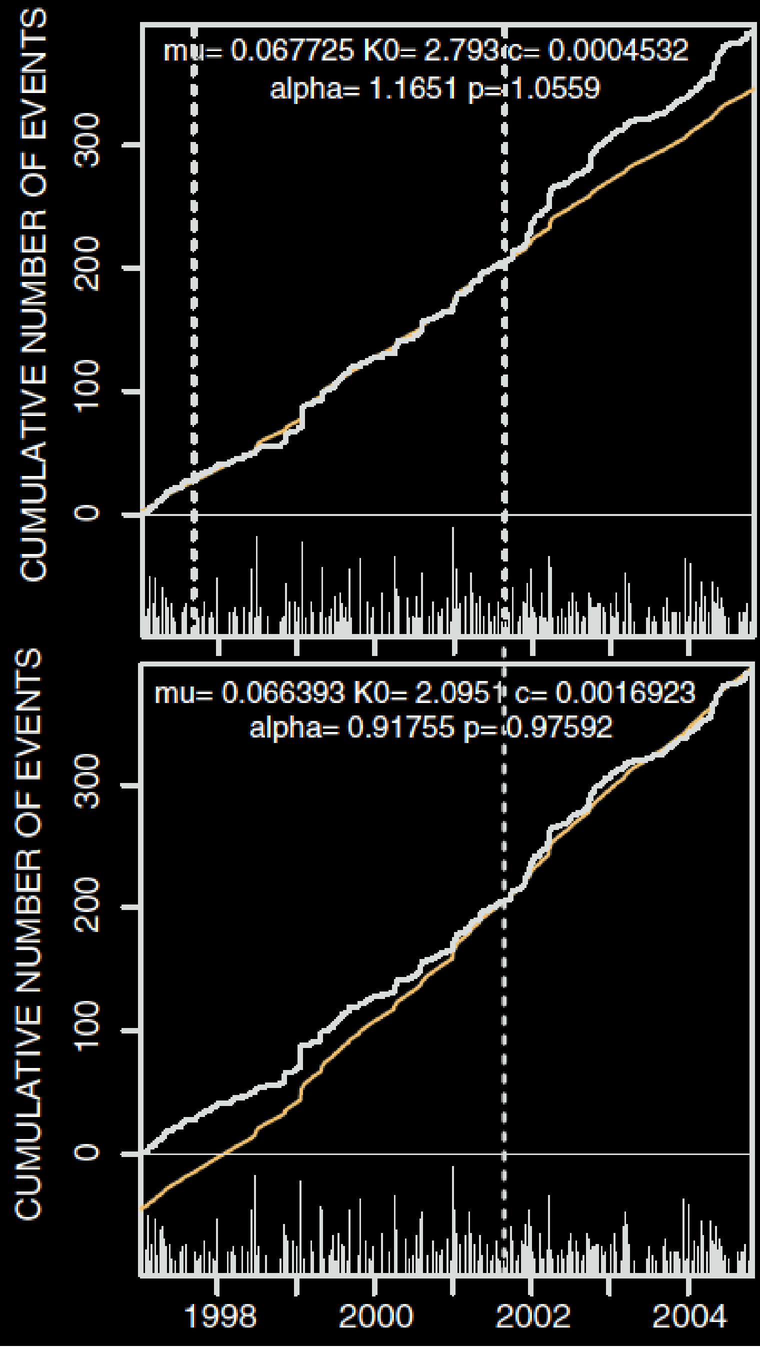
No-Change


mu= 0.062894 K0= 2.3616 c= 0.00046861
alpha= 1.0081 p= 0.97466
CUMULATIVE NUMBER OF EVENTS
0
100
200
300
1998
2000
2002
2004

A Change

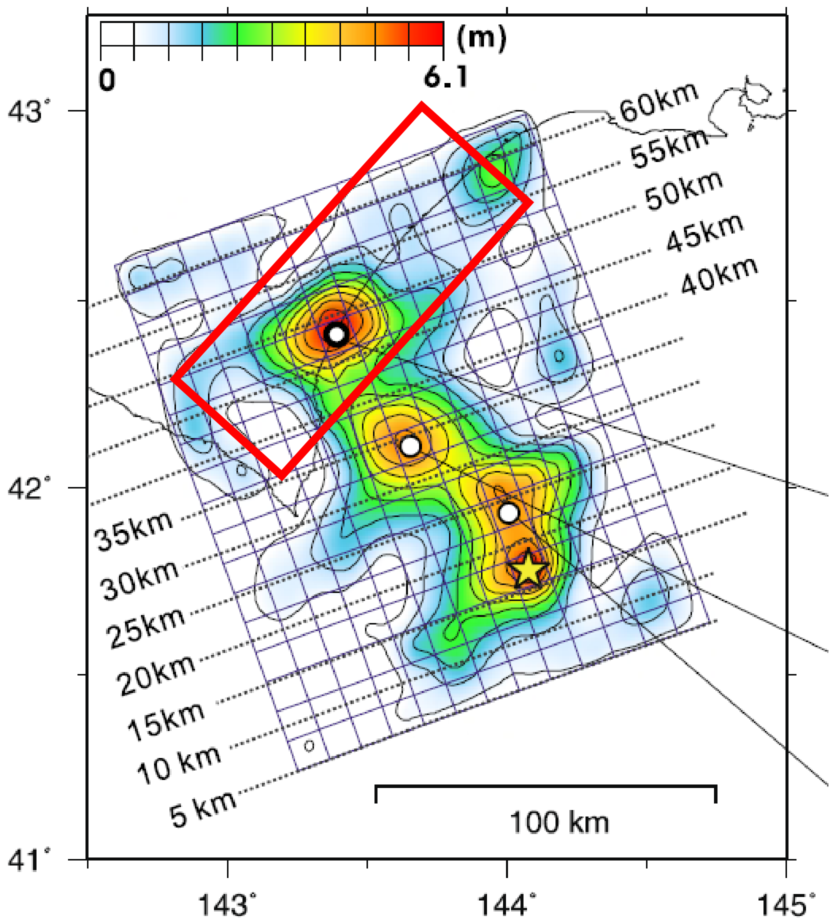
No-Change





Coseismic Slip duringthe first 60 seconds

Yagi (2004) EPS



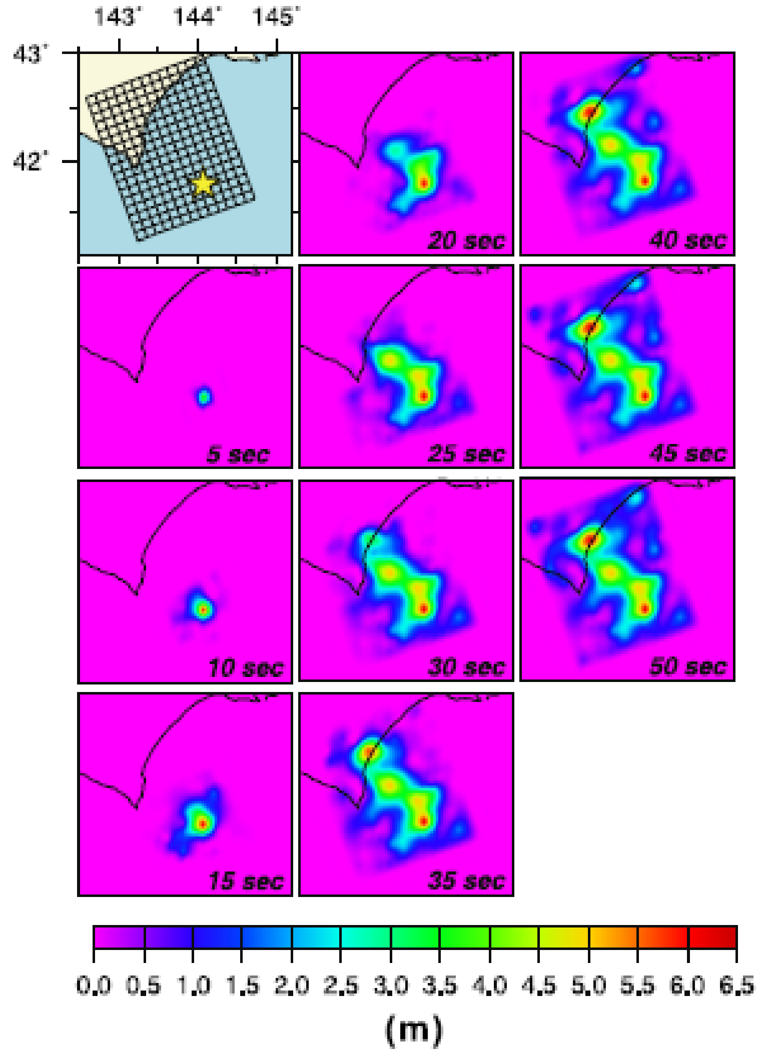
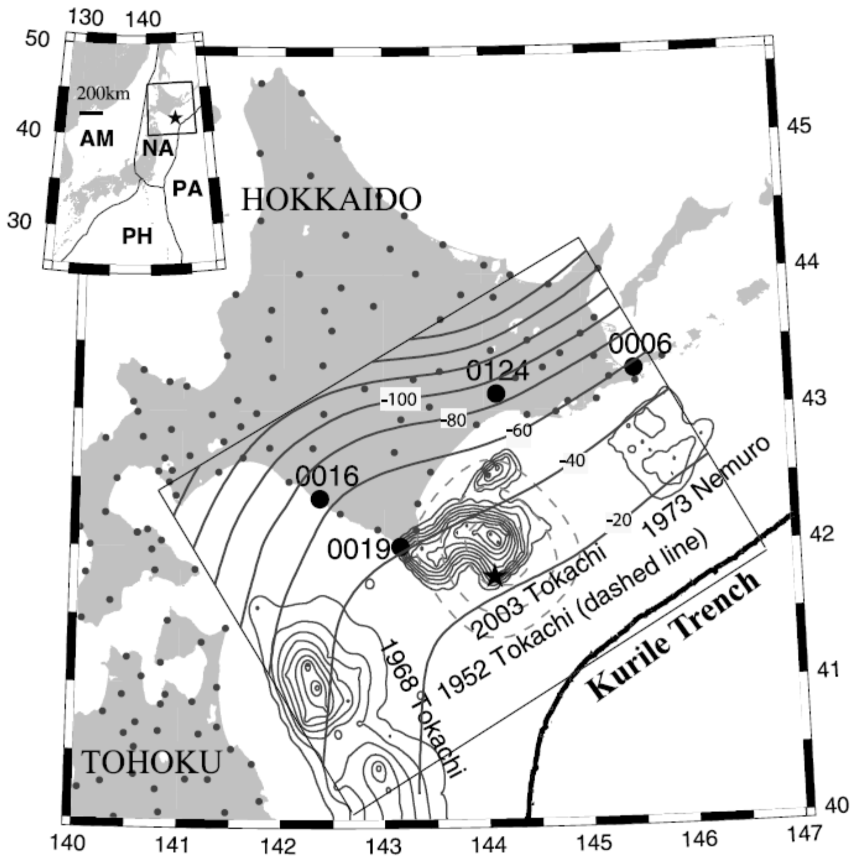
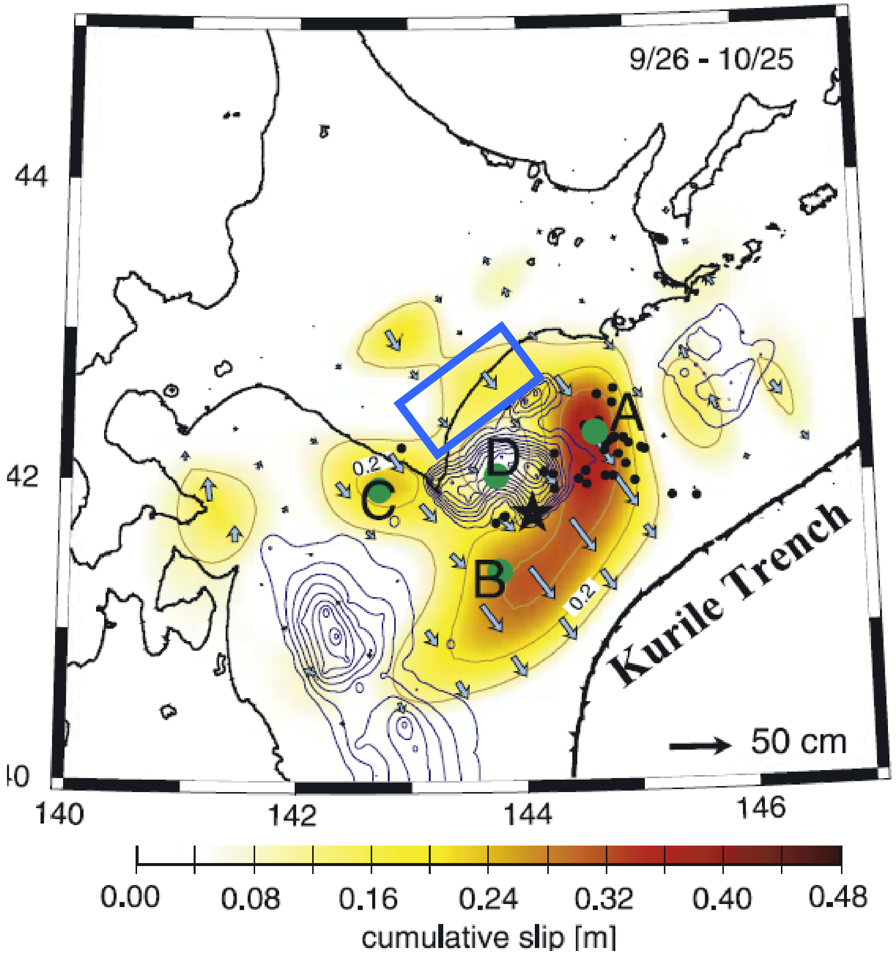


Fig. 6. Snapshots of surface projection of the dislocation at every 5 sec. The star indicates the epicenter.

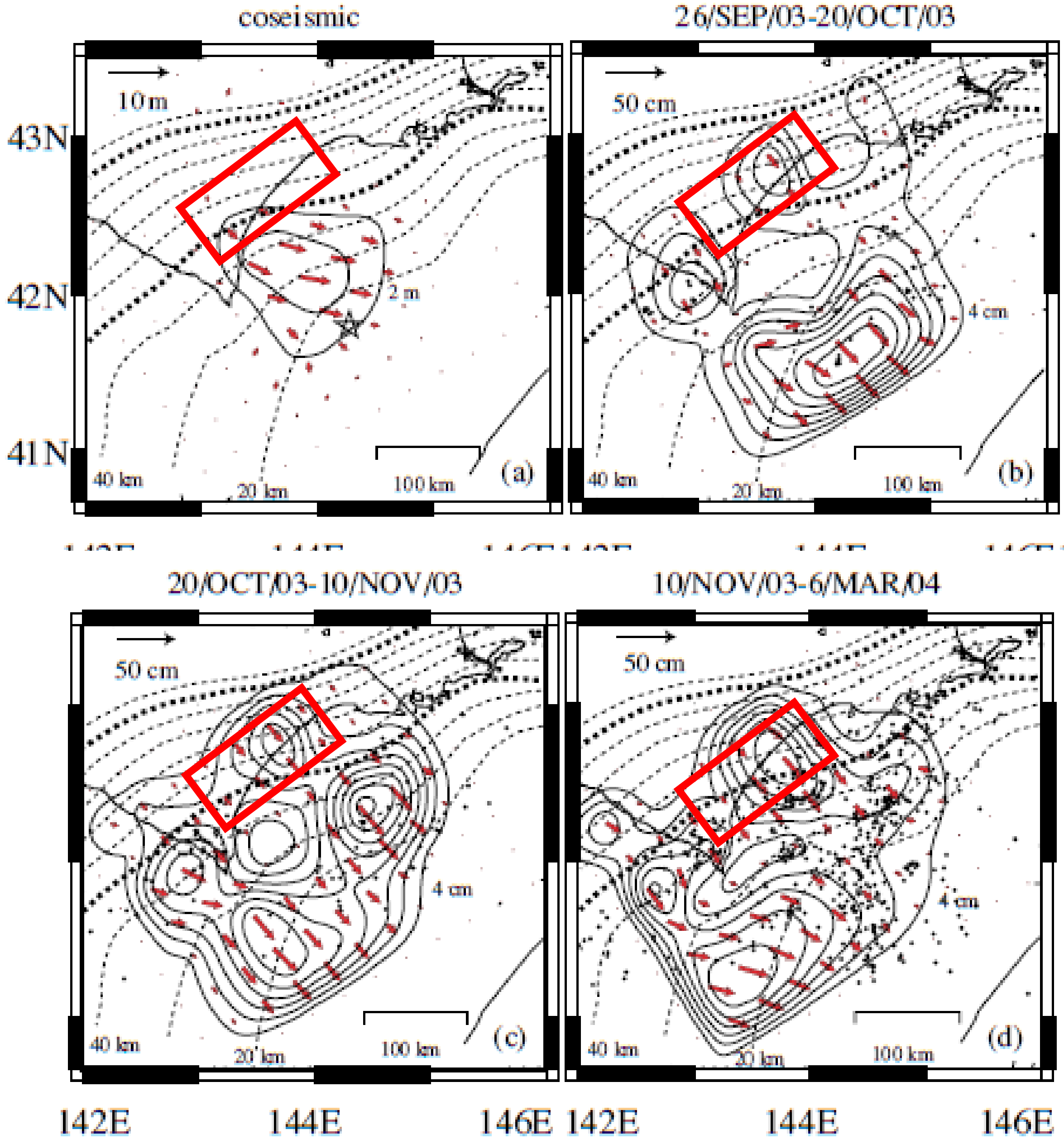
Cumulative Slip for 30days From the mainshock

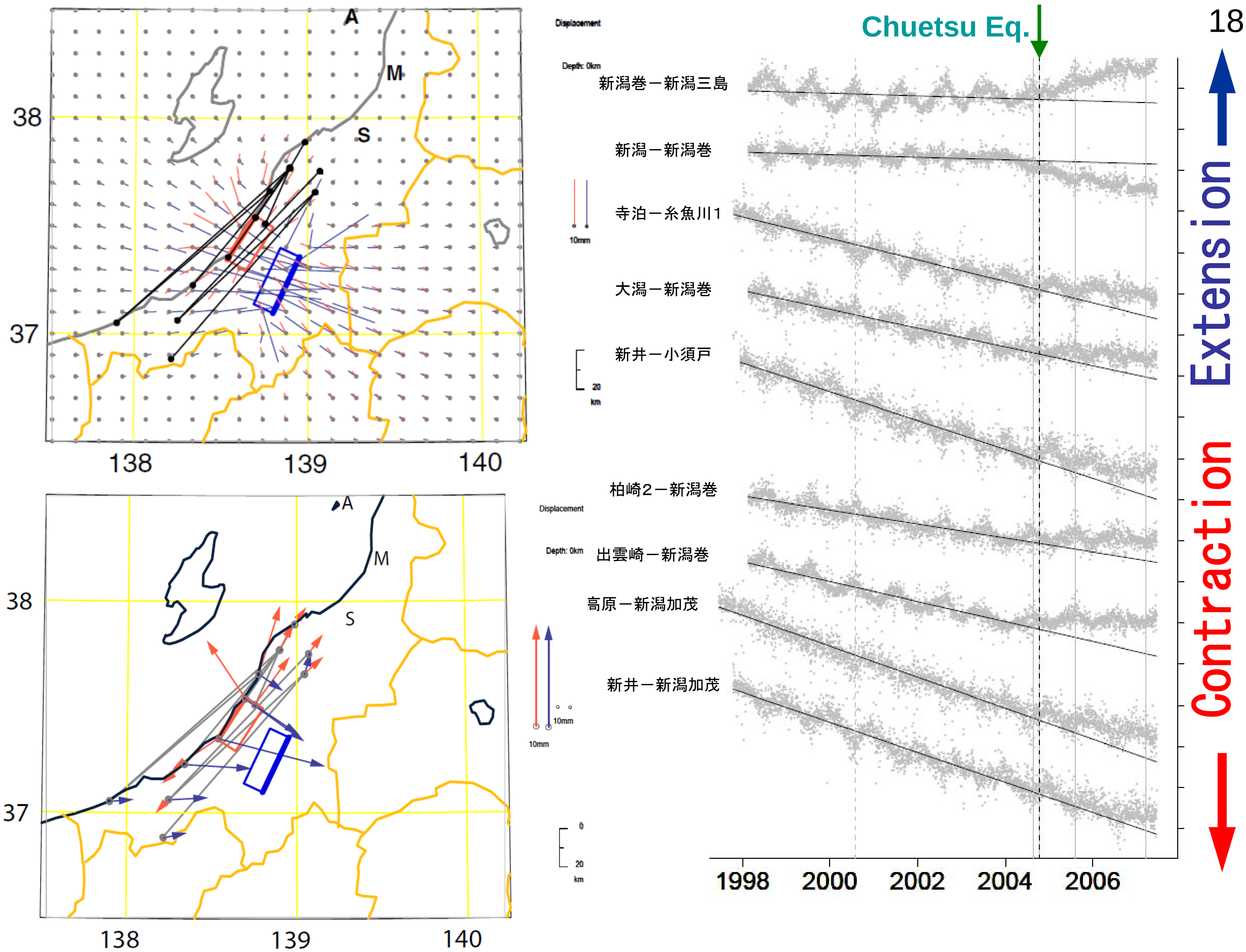
Miyazaki et al. (2004) GRL

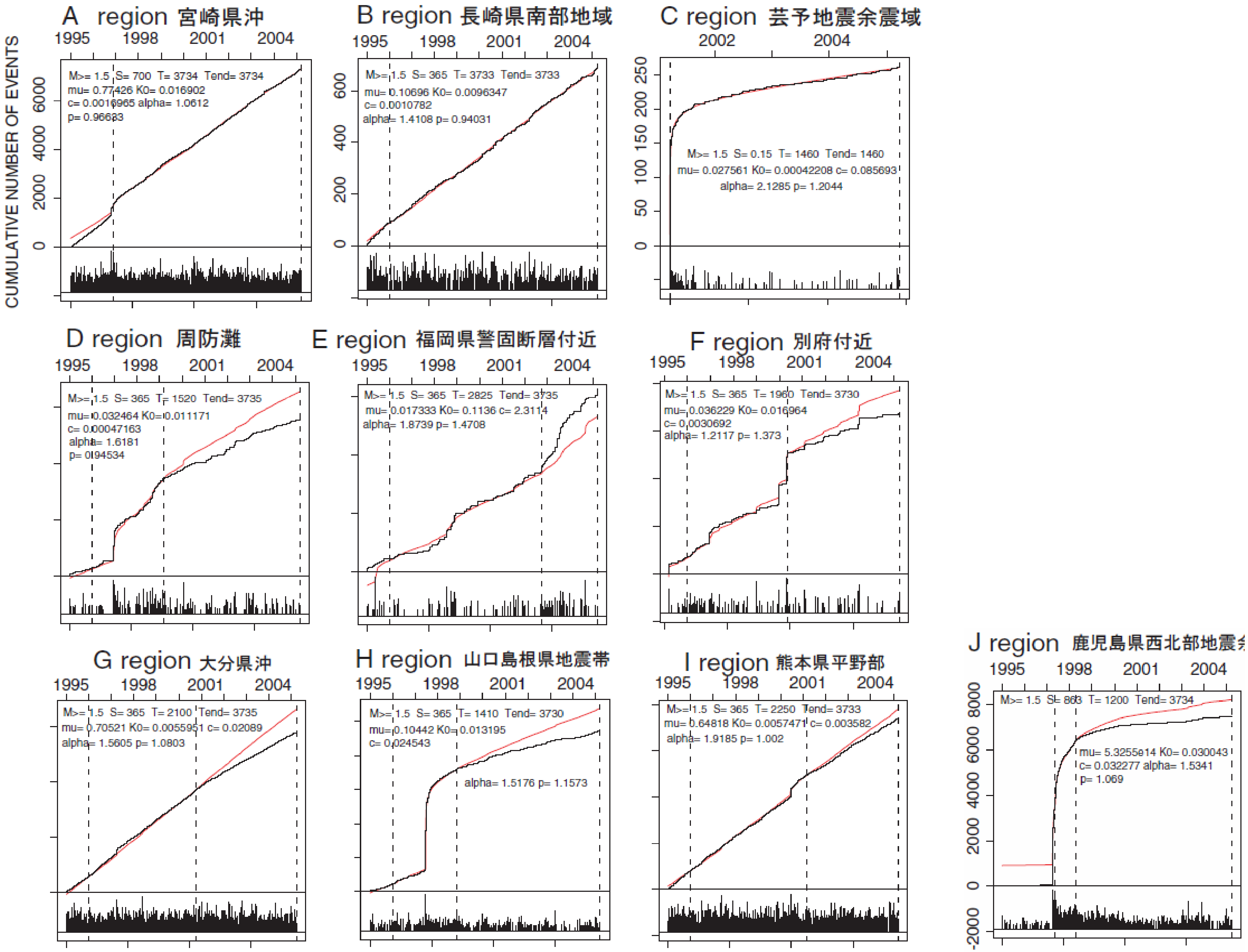


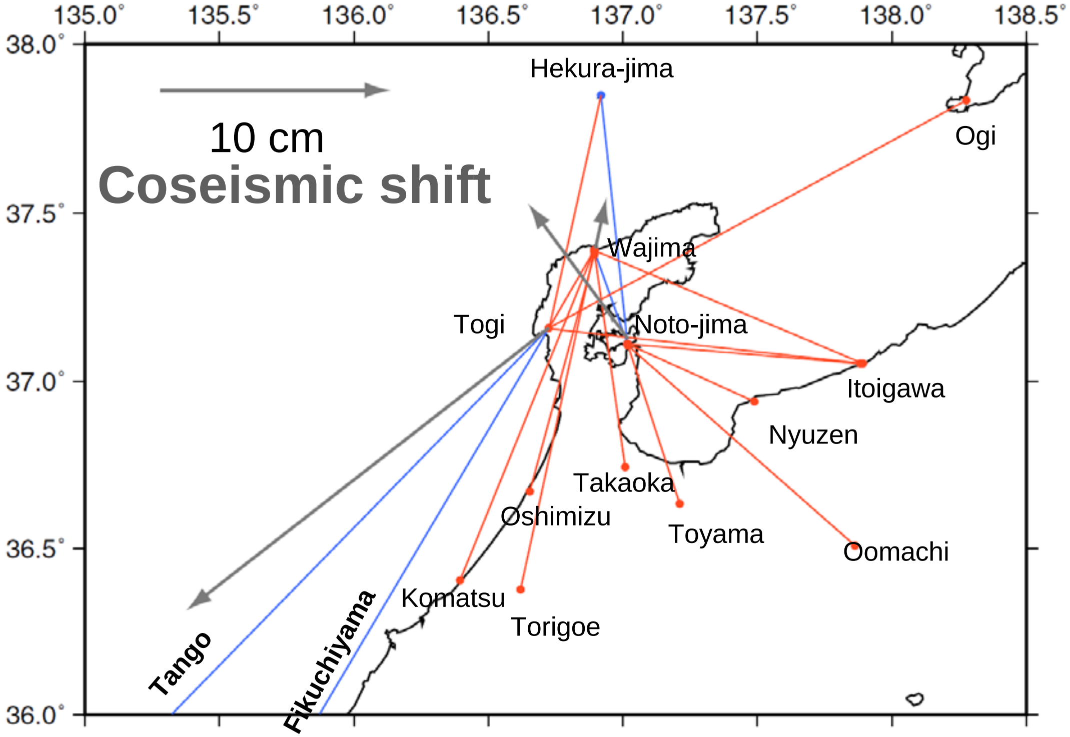


Co- & Post-seismic slip **Ozawa et al. (2004) EPS**




A
M
S
38
37
138
139
140
Displacement
Depth: 0km
10mm
20
km
Chuetsu Eq.
新潟巻－新潟三島
新潟－新潟巻
寺泊－糸魚川1
大潟－新潟巻
新井－小須戸
柏崎2－新潟巻
出雲崎－新潟巻
高原－新潟加茂
新井－新潟加茂
1998
2000
2002
2004
2006
Extension
Contraction


CUMULATIVE NUMBER OF EVENTS
A region 宮崎県沖
M>= 1.5 S= 700 T= 3734 Tend= 3734
mu= 0.77426 K0= 0.016902
c= 0.0016965 alpha= 1.0612
p= 0.96683
B region 長崎県南部地域
M>= 1.5 S= 365 T= 3733 Tend= 3733
mu= 0.10696 K0= 0.0096347
c= 0.0010782
alpha= 1.4108 p= 0.94031
C region 芸予地震余震域
M>= 1.5 S= 0.15 T= 1460 Tend= 1460
mu= 0.027561 K0= 0.00042208 c= 0.085693
alpha= 2.1285 p= 1.2044
D region 周防灘
M>= 1.5 S= 365 T= 1520 Tend= 3735
mu= 0.032464 K0= 0.011171
c= 0.00047163
alpha= 1.6181
p= 0.94534
E region 福岡県警固断層付近
M>= 1.5 S= 365 T= 2825 Tend= 3735
mu= 0.017333 K0= 0.1136 c= 2.3114
alpha= 1.8739 p= 1.4708
F region 別府付近
M>= 1.5 S= 365 T= 1960 Tend= 3730
mu= 0.036229 K0= 0.016964
c= 0.0030692
alpha= 1.2117 p= 1.373
G region 大分県沖
M>= 1.5 S= 365 T= 2100 Tend= 3735
mu= 0.70521 K0= 0.0055951 c= 0.02089
alpha= 1.5605 p= 1.0803
H region 山口島根県地震帯
M>= 1.5 S= 365 T= 1410 Tend= 3730
mu= 0.10442 K0= 0.013195
c= 0.024543
alpha= 1.5176 p= 1.1573
I region 熊本県平野部
M>= 1.5 S= 365 T= 2250 Tend= 3733
mu= 0.64818 K0= 0.0057471 c= 0.003582
alpha= 1.9185 p= 1.002
J region 鹿児島県西北部地震
M>= 1.5 S= 863 T= 1200 Tend= 3734
mu= 5.3255e14 K0= 0.030043
c= 0.032277 alpha= 1.5341
p= 1.069



Extensional acceleration
Contractional deceleration

Extensional deceleration