The pre-slip controversy: a review of the 1944 Tonankai and the 2011 Tohoku-oki cases and their implications (or no implication) for short-term prediction

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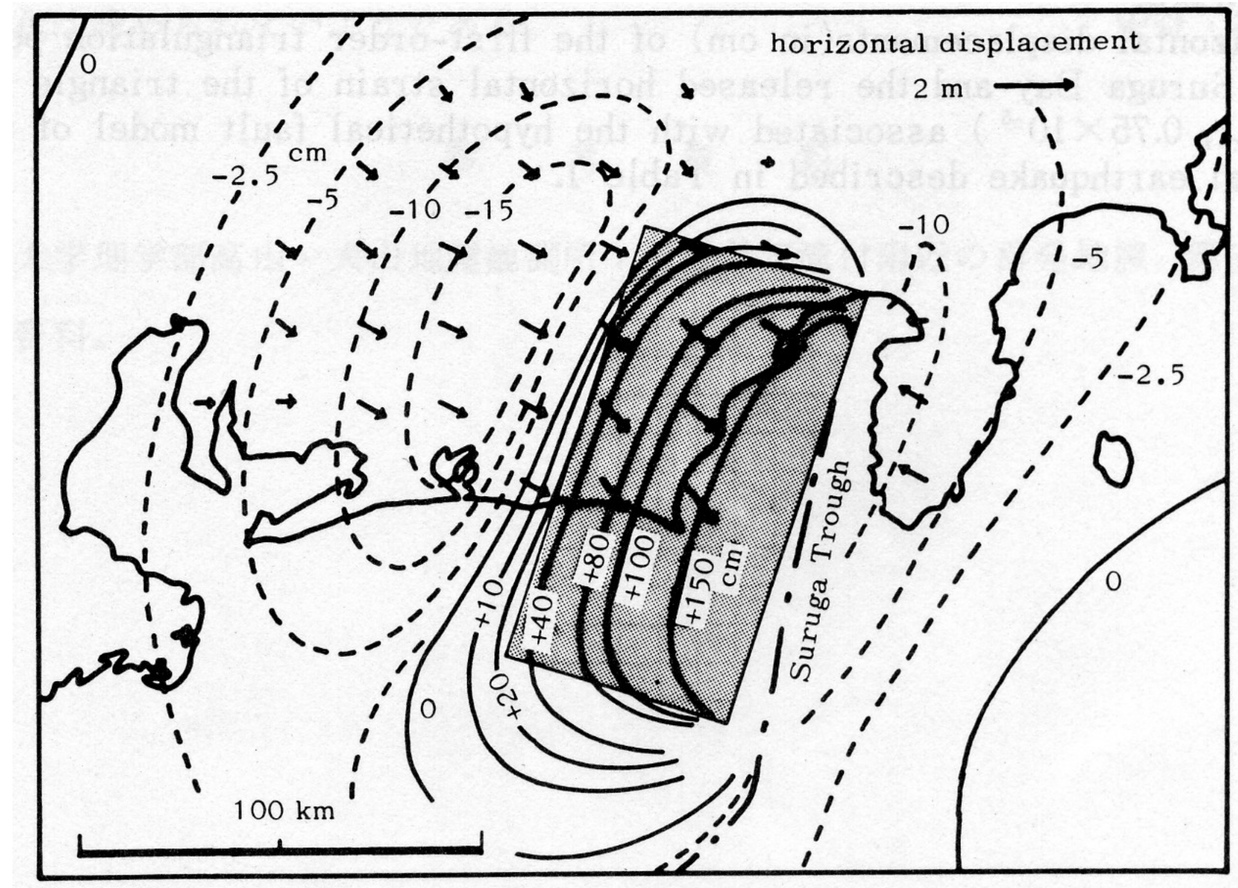
Earthquake prediction and pre-slip

- "Earthquake prediction"
  - Deterministic statement (high probability) about a future earthquake
  - Specification of "Time", "Location", and "Size (magnitude)"
  - Leads to issue an earthquake alert and/or an evacuation advisory
- Probability of large earthquakes is generally extremely low.
  - T~100 yrs : 3 days probability (Poissonian) = 0.01% for 3 days
- <u>Precursory phenomena are the key</u> to achieve a significant probability gain.
- Most of reported precursory phenomena are not considered to be reliable because their physical mechanisms are not well understood.
- "Pre-slip" has been considered a reliable precursor because it is consistent with an available physical model.

“Tokai Seismic Gap” experiment

- Ishibashi (1976) “Suruga-Bay earthquake” hypothesis
- Act on Special Measures Concerning Countermeasure for Large-Scale Earthquakes (Dai-shin-ho) (1978)
  - Disaster mitigation based on earthquake prediction
- The framework was abolished in 2017.

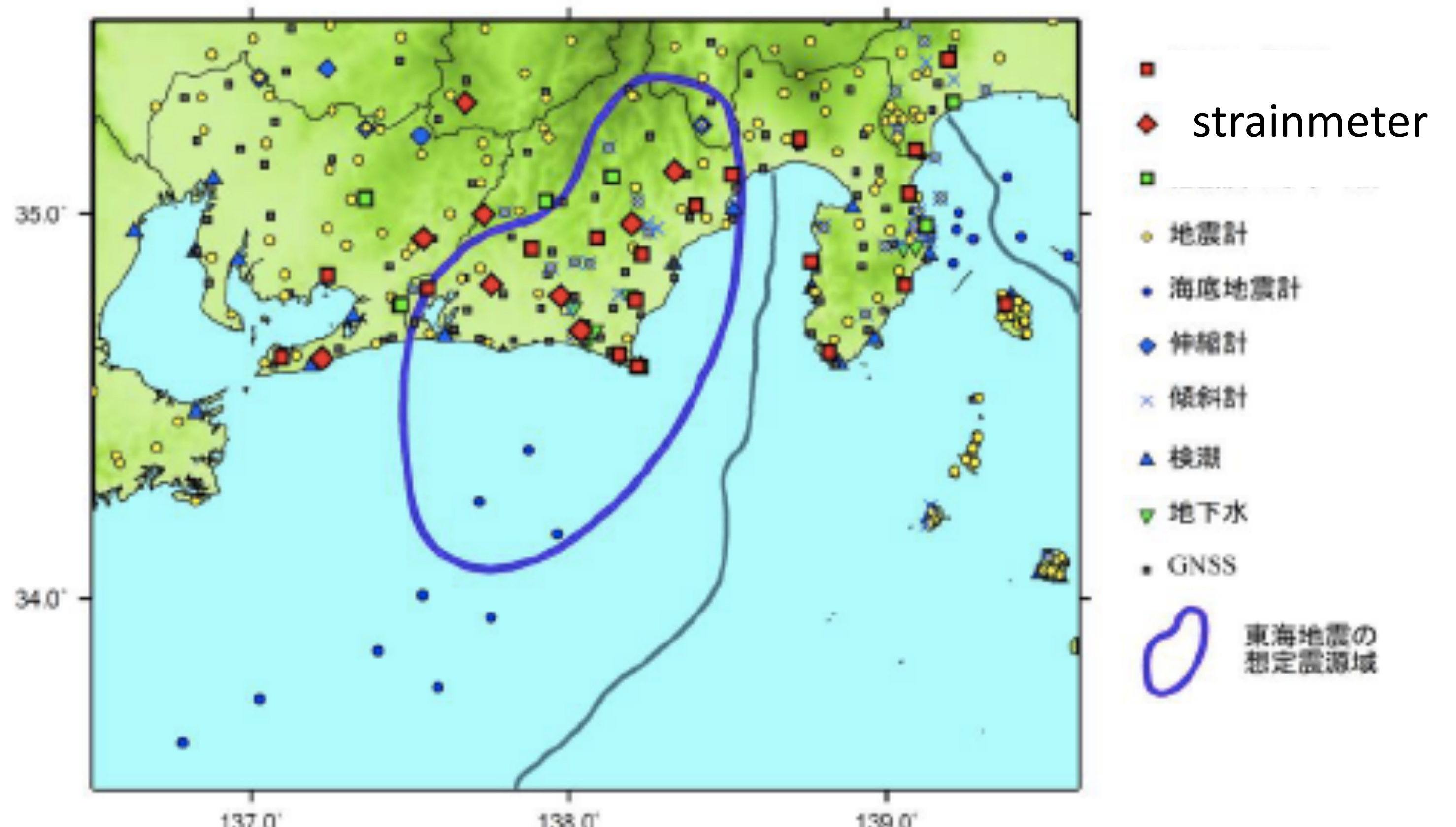


Three level information

Alert
(Yochi Joho)

Warning
(Chui Joho)

Normal
(Chosa Joho)



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On Prediction of "the Tokai Earthquake"

Investigations have revealed that the location and the size of the anticipated Tokai earthquake has been specified and its occurrence is imminent. Also the following facts are known.

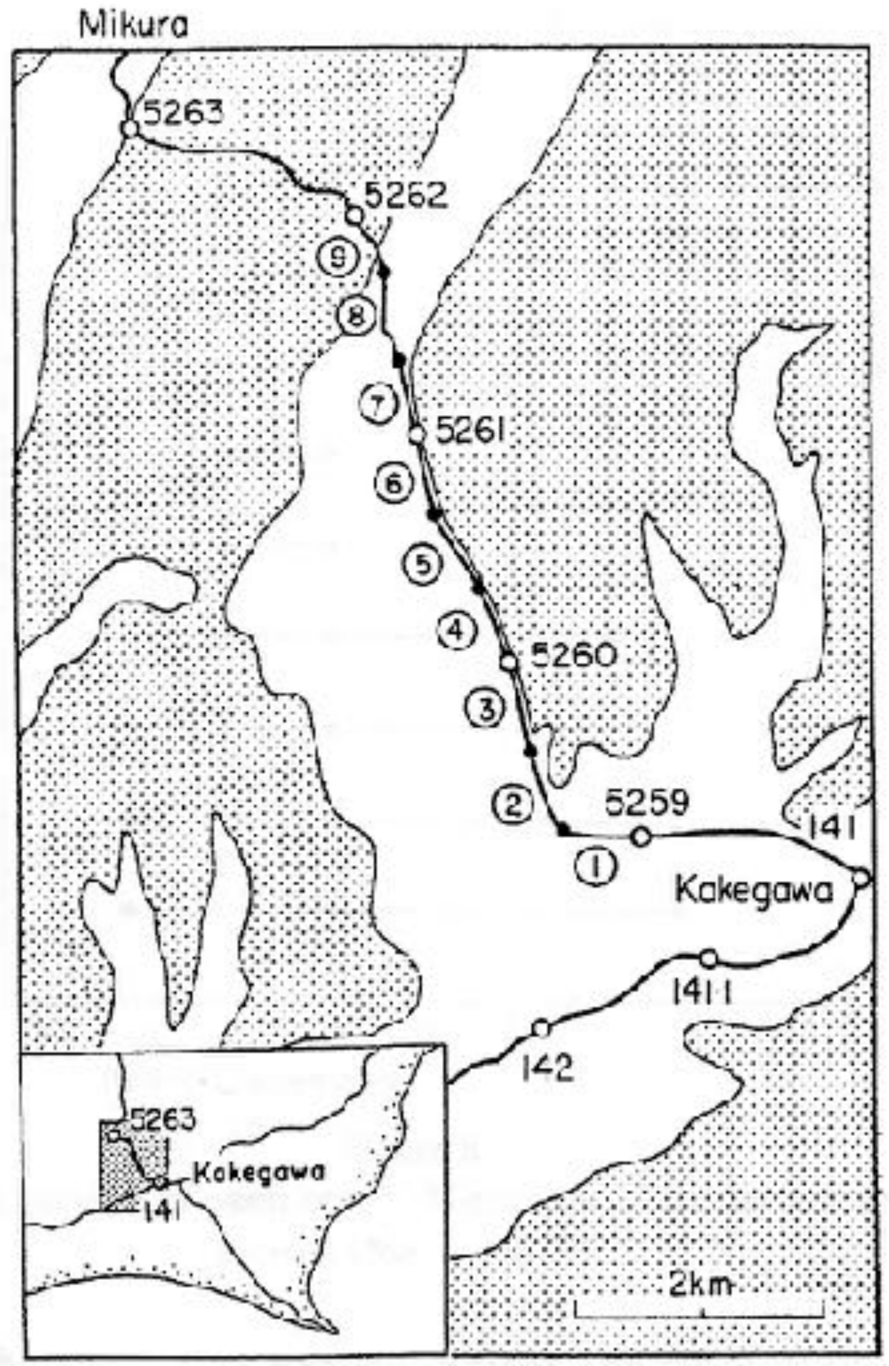
- **The Tokai Earthquake is possibly preceded by precursory phenomena.**
- **Expected source region of the Tokai Earthquake is located under the land or coastal region so that we deploy highly sensitive observation network above it.**
- **We can scientifically interpret observed anomalous phenomena with the "pre-slip model" if they are the expected earthquake precursors.**

Based on these facts, the Tokai Earthquake is the only earthquake in Japan we can possibly predict. On the other hand, other earthquakes do not satisfy the above three conditions, and are difficult to predict.
It should be also mentioned that it is impossible to specify the date and the time of the Tokai Earthquake with our current technology. We can just infer the Tokai Earthquake may happen in a few days.

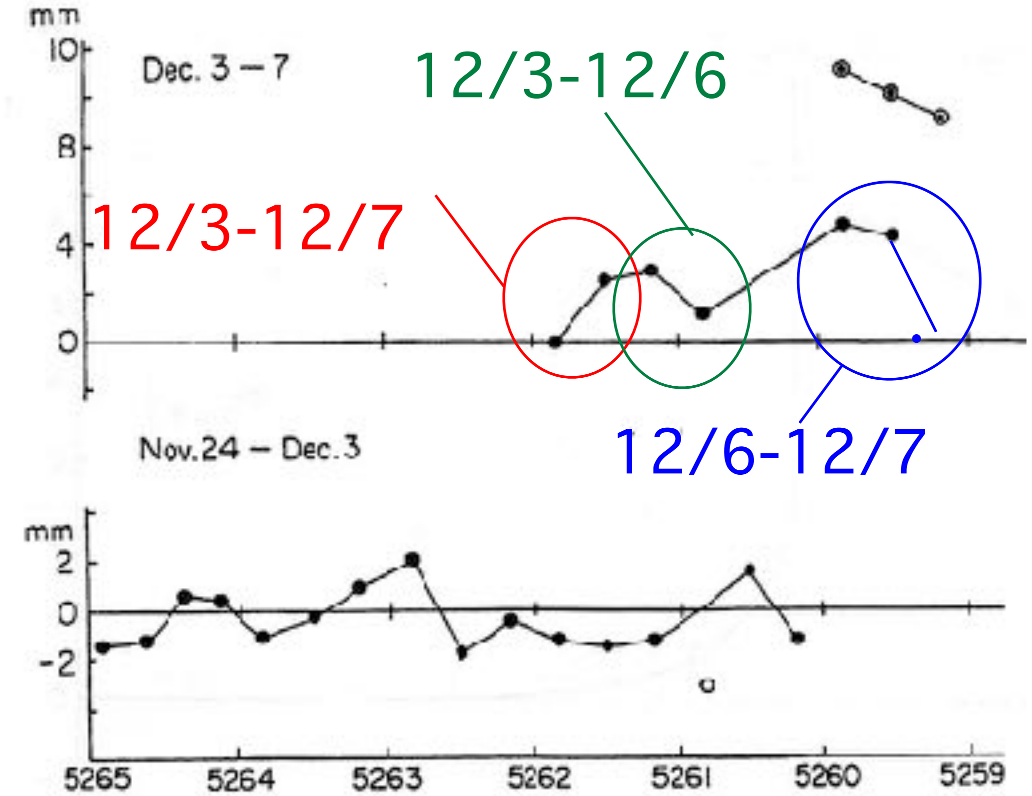
JMA web page (now deleted, translation by T. Sagiya)

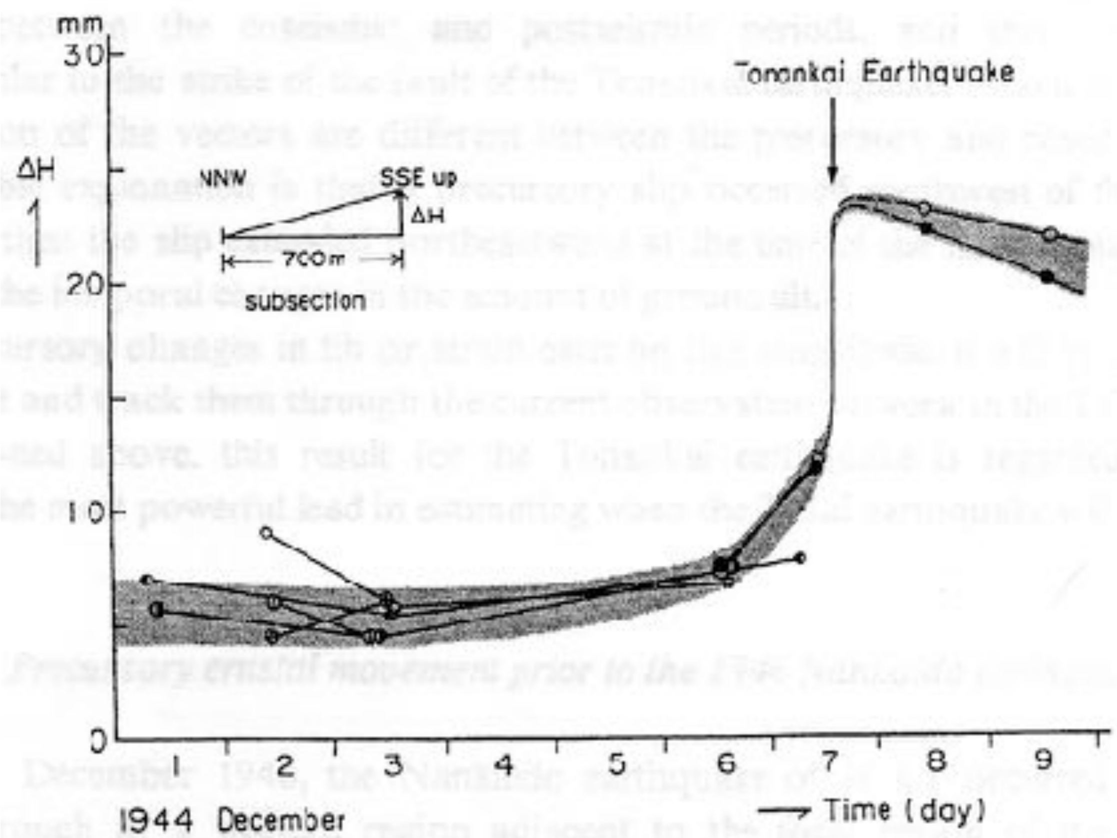
Precursory tilt change before the 1944 Tonankai Earthquake

Previous studies:
- Sato (1970)
- Sato (1977)



Mogi(1984)





South-up tilt change was accelerated from ~ 3days before the main shock

Based on leveling data and surveyor's essay (Koshiyama, 1976)

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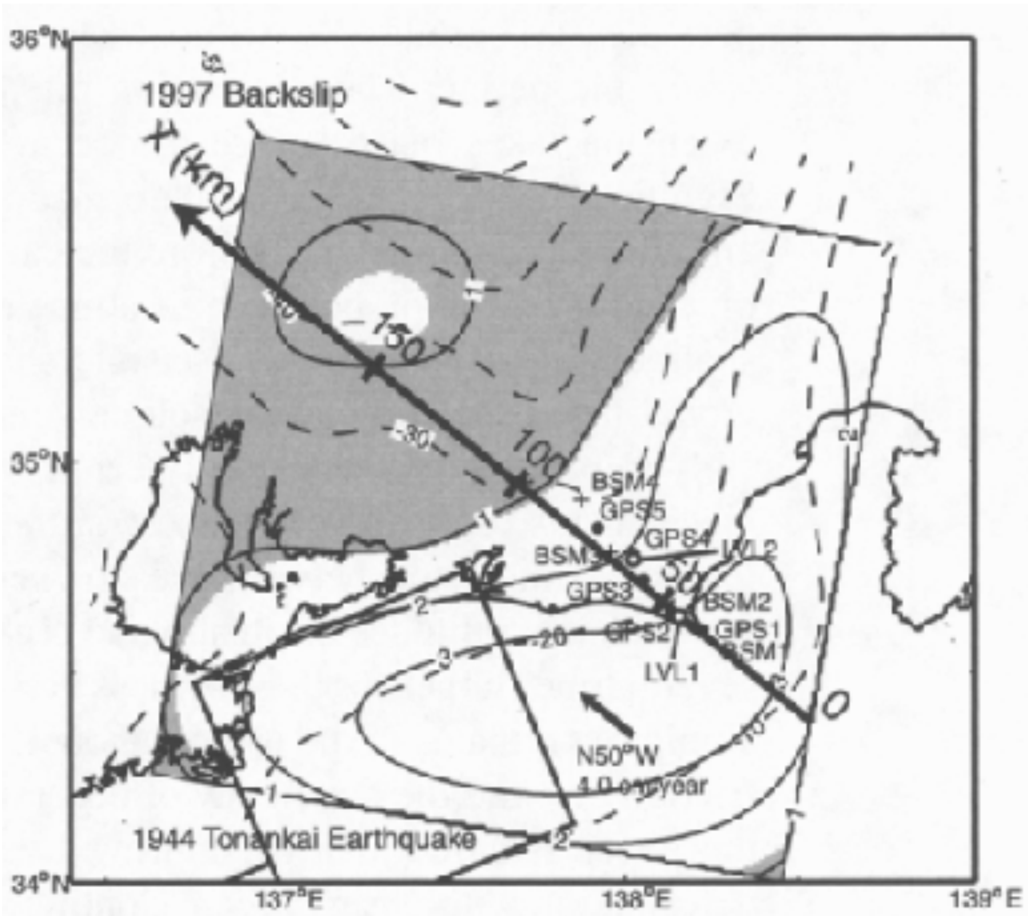
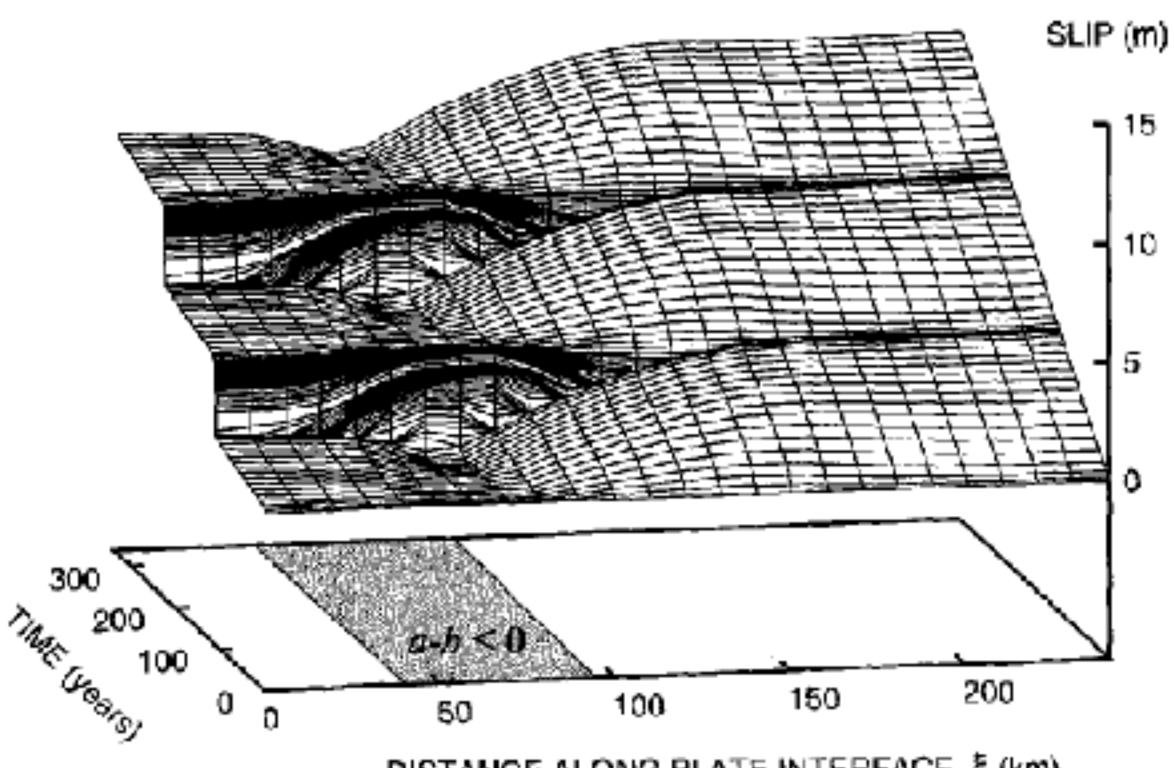
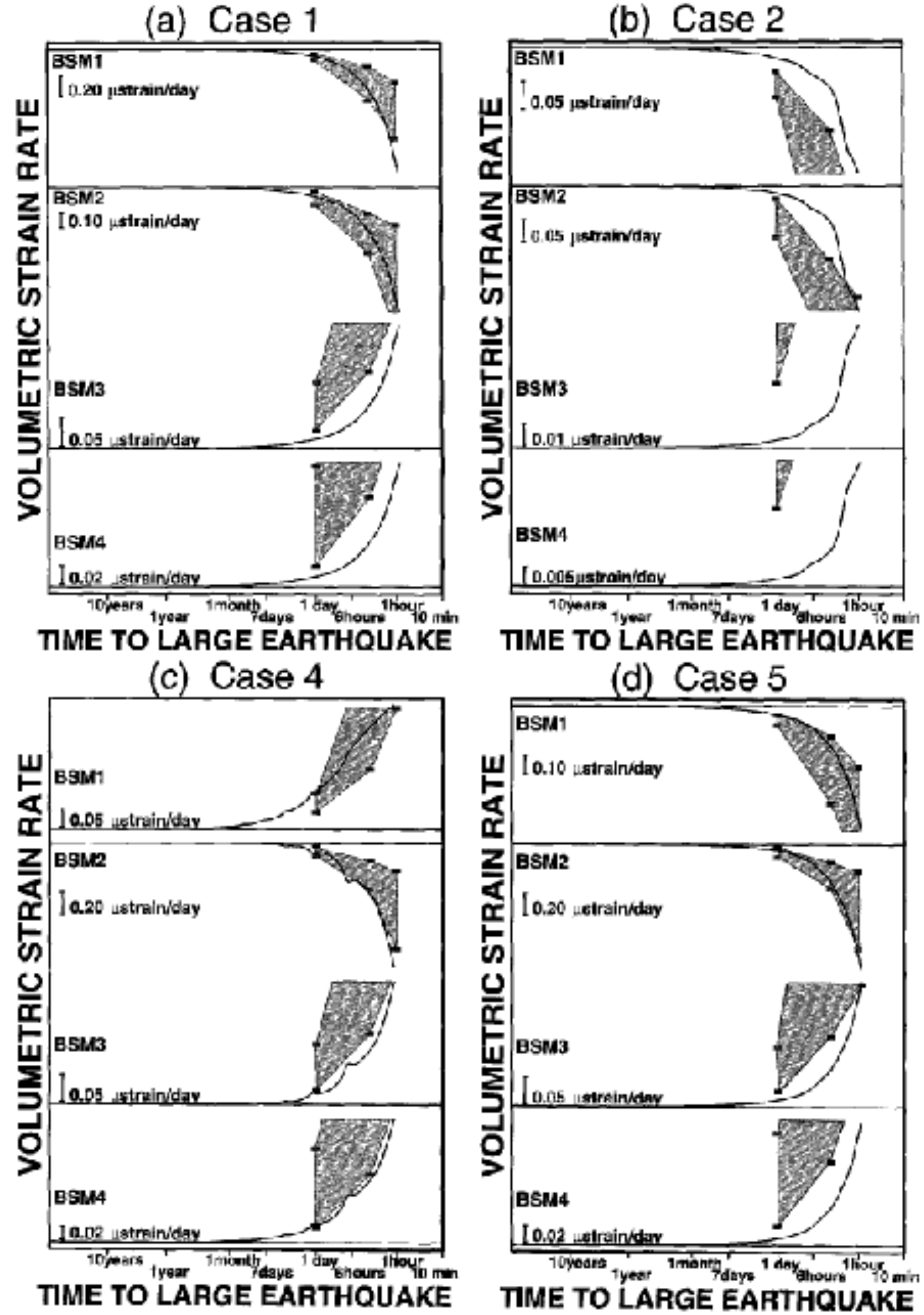
The Pre-slip model (Kato and Hirasawa, 1999)







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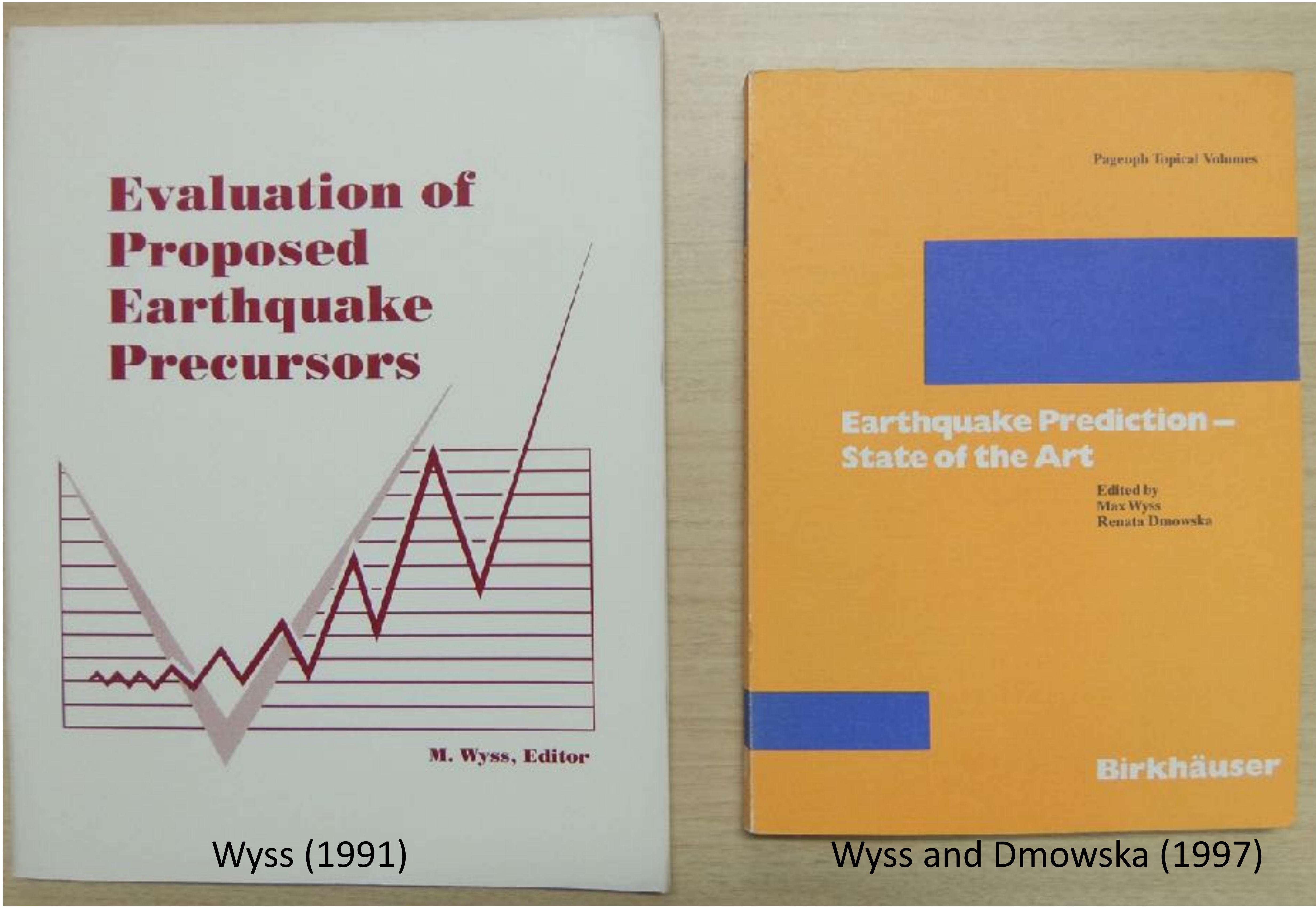
Was the 1944 pre-slip true?

- The JMA's explanation of predictability depends solely on the tilt anomaly before the 1944 Tonankai earthquake.
  - The only evidence about "observable precursors" for the Tokai earthquake
  - The only evidence about "the precursory time of a few days"

- Reliability of the 1944 observation was crucial to the earthquake prediction program

Evaluation of earthquake precursors by IASPEI



Wyss (1991)

Wyss and Dmowska (1997)

IASPEI evaluation: first round (Wyss, 1991)

- Accepted cases
  - Seismic quiescence before strong aftershocks (R.S. Matsu'ura)
  - 1975 M7.3 Haicheng earthquake: foreshocks (K.-T. Wu et al.)
  - 1978 M7.0 Izu-Oshima-Kinaki earthquake: radon (H. Wakita et al.)
- No decisions (pending)
  - 1923 M7.9 Kanto earthquake: strain (Y. Fujii and K. Nakane)
  - 1944 M7.9 Tonankai earthquake: tilt (H. Sato)
  - 1983 M7.7 Japan Sea earthquake: crustal movements (H. Ishii et al.), strain (A. T. Linde et al.), strain and tilt (S. Miura et al.)
- 14 rejected cases

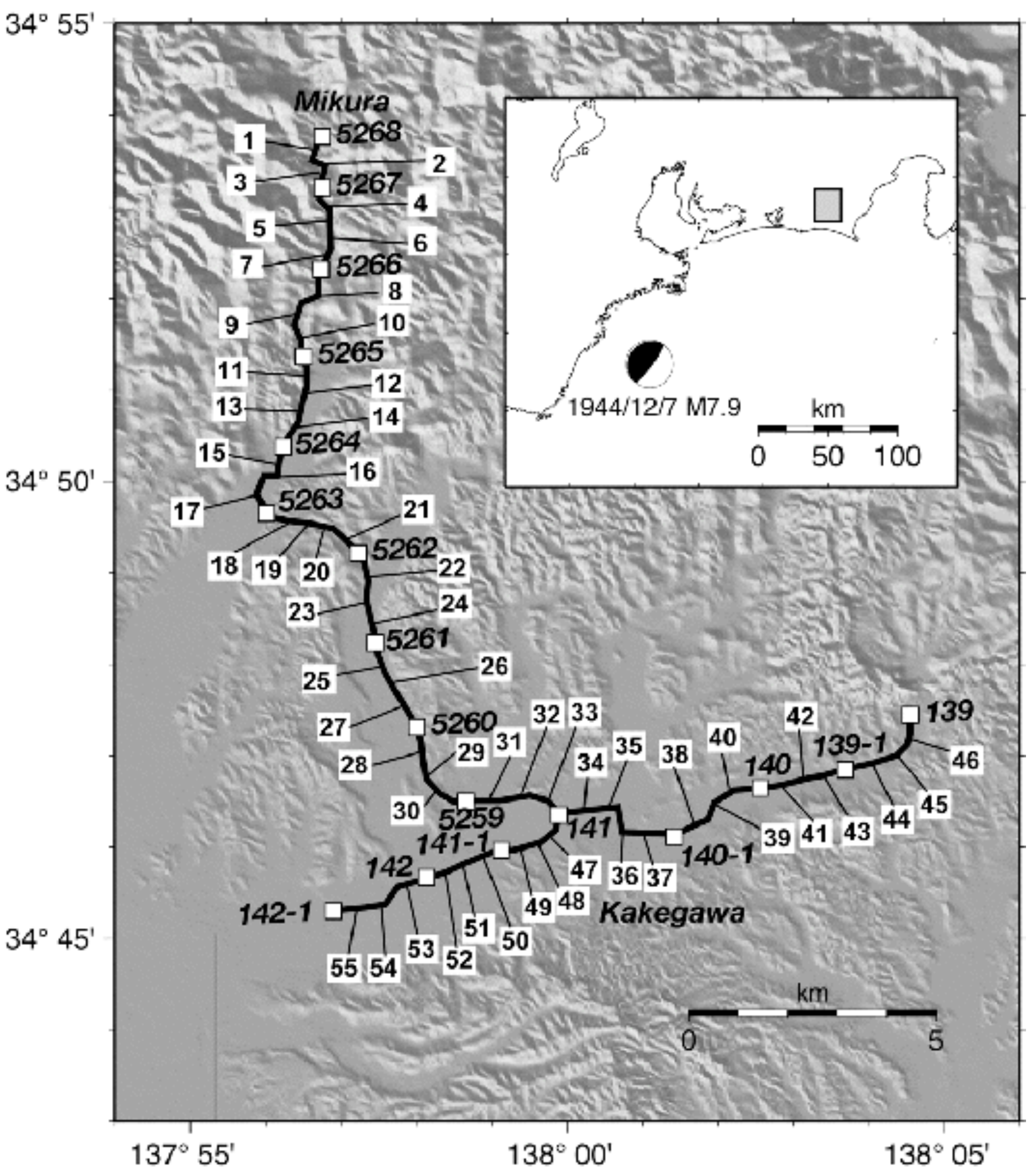
IASPEI evaluation: second round (Wyss and Dmowska, 1997)

- 5 significant precursors
  - 1975 Haicheng: foreshocks (K.-T. Wu et al.)
  - 1988 Tennant Creek, Australia: preshocks (J. R. Bowman)
  - Seismic quiescence before strong aftershocks (R. S. Matsu'ura)
  - 1978 Izu-Oshima-Kinkai earthquake: radon and temperature (H. Wakita et al.)
  - 1985 Kettleman Hills: ground water rise (E. Roeloffs and E. G. Quilty)
- The 1944 Tonankai tilt anomaly was placed in a list of "undecided" cases again.

Revisit to the 1944 leveling data

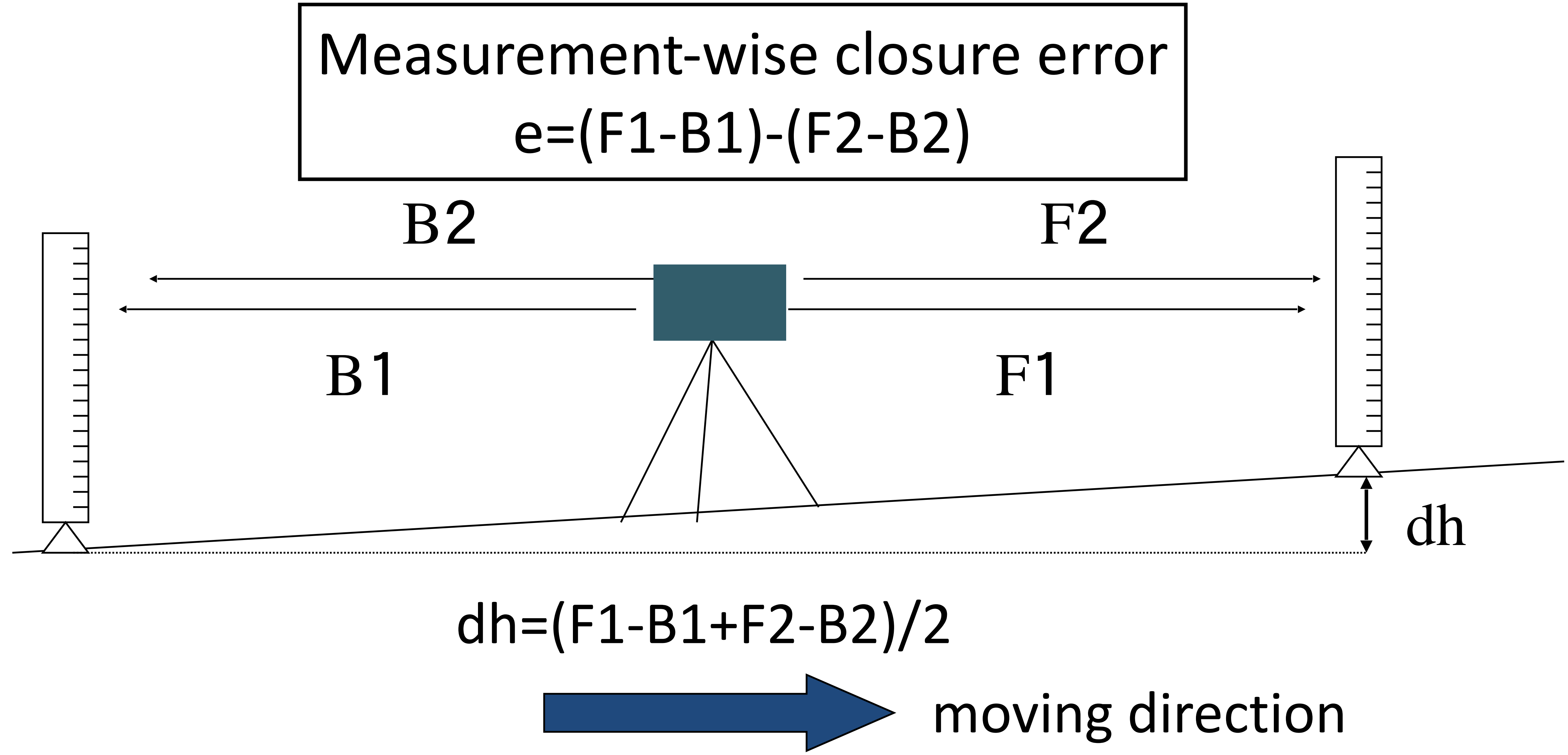
- Motivation
  - "Undecided" decision of the IASPEI committee
  - Thorough investigation of the all available data
  - Statistical testing about significance of the anomaly
  - Physical interpretation of the anomaly
- Approach
  - Reconstruct all the leveling data from original readings
  - Fault modeling of the observed deformation pattern

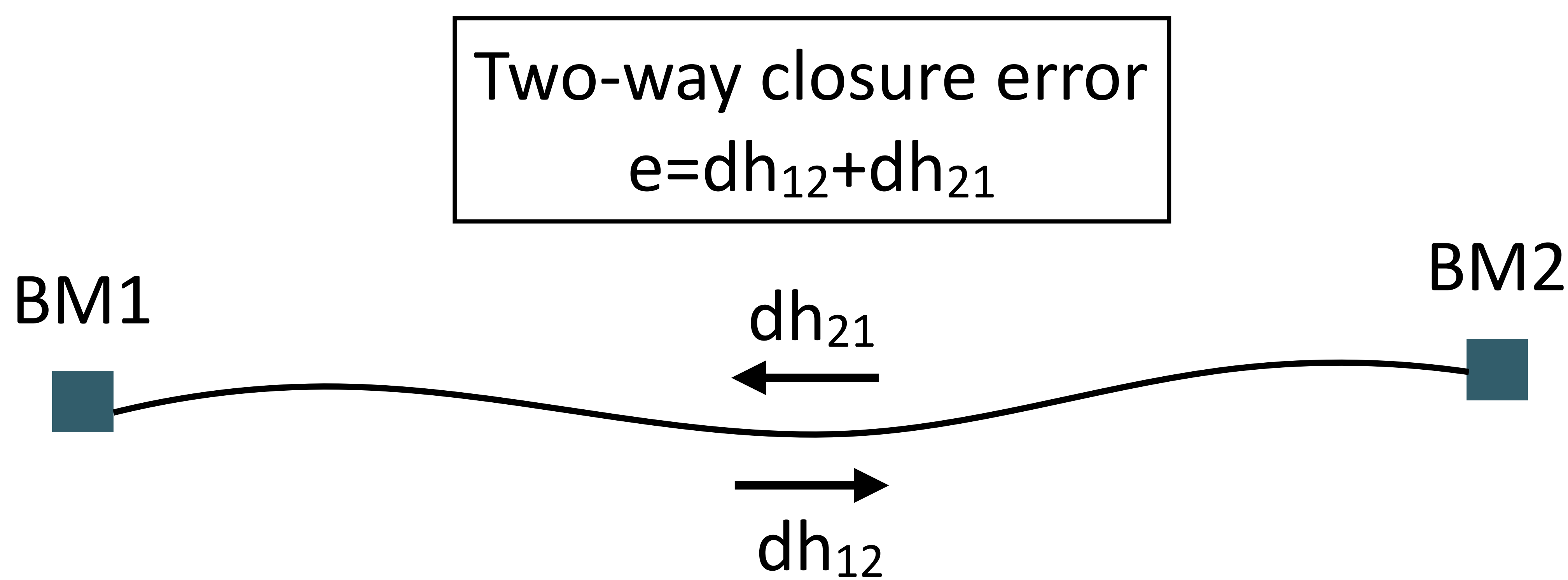
Leveling survey before and after the 1944 Tonankai earthquake



Sagiya (1998)、Sagiya(2004)

- The 1944 Tonankai earthquake (M7.9)
  - December 7, 1944
  - JST13:35
- Evaluate the whole survey record
  - Survey starts: November 24
  - Survey ends: December 25
- Two survey teams
  - Field log of only one team is analyzed
  - Field log of another team has been missing as early as in 1970
    - They construct a new survey line between Kakegawa and Omaezaki.


Measurement-wise closure error
e=(F1-B1)-(F2-B2)
B2
F2
B1
F1
dh
dh=(F1-B1+F2-B2)/2
moving direction


Two-way closure error
e=dh12+dh21
BM1
BM2
dh21
dh12

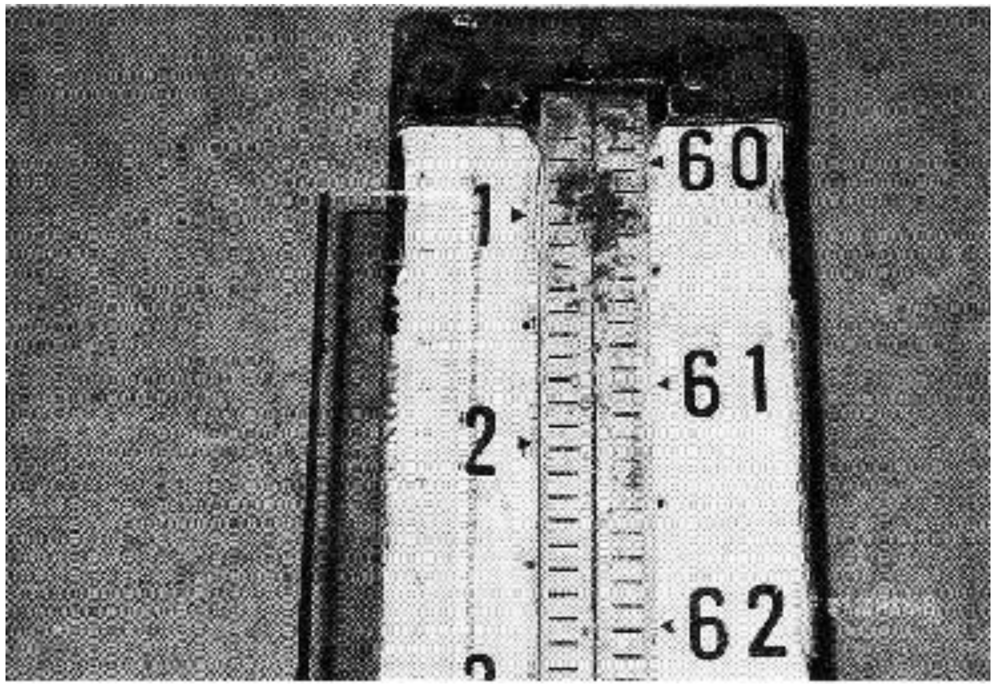
Checking field logs (Sagiya, 1998)

B1 F1 B2 F2

1	30		0.12	X	9.88	821	825			6.05	X	3.95	338	333		5268 11/24
		X	5.73		4.27	413	419	414	X	9.81		10.19	925	924	-578	1°
		X	5.85		4.15				X	5.86		4.14				7:30
2	39		2.03	X	7.97	622	624			7.96	X	2.04	104	103		
		X	6.61		3.39	237	232	377	X	0.69		9.31	700	722	-615	
		X	4.49		5.51				X	4.51		5.49				
3	40		1.71	X	8.29	603	601			7.64	X	2.36	32	29		
		X	6.83		3.17	532	540	32	X	0.90		9.10	102	106	-47	
		X	3.03		6.97				X	3.05		6.95				
4	40		1.51	X	8.49	423	421			7.43	X	2.57	832	831		
		X	5.77		4.23	946	949	-551	X	9.84		10.16	426	428	409	
		X	0.31		9.69				X	0.32		9.68				
5	40		1.27	X	8.73	321	323			7.19	X	2.81	736	743		
		X	6.24		3.76	608	607	-271	X	0.31		9.69	48	48	683	
		X	87.82		12.18				X	87.82		12.18				
6	40		1.32	X	8.68	521	522			7.25	X	2.75	21	8		
		X	8.74		1.26	843	846	-346	X	2.81		7.19	341	340	-352	
		X	87.88		12.12				X	87.88		12.12				
7	40		3.84	X	6.16	246	248			9.76	X	0.24	724	726		
		X	8.85		1.15	2	0	292	X	2.93		7.07	436	438	276	
		X	0.57		9.43				X	0.57		9.43				
8	40		4.01	X	5.99	452	443			9.93	X	0.07	946	949		
		X	7.57		2.43	347	346	102	X	1.65		8.35	848	848	99	
		X	2.15		7.85			49	X	2.15		7.85			-125	··· A
(a)	(b)		(c)		(d)	(e)	(f)	(g)		(h)		(I)	(j)	(k)	(l)	

R= -7.85000
mC= -0.00038
-7.85038
-3.92519
(m)

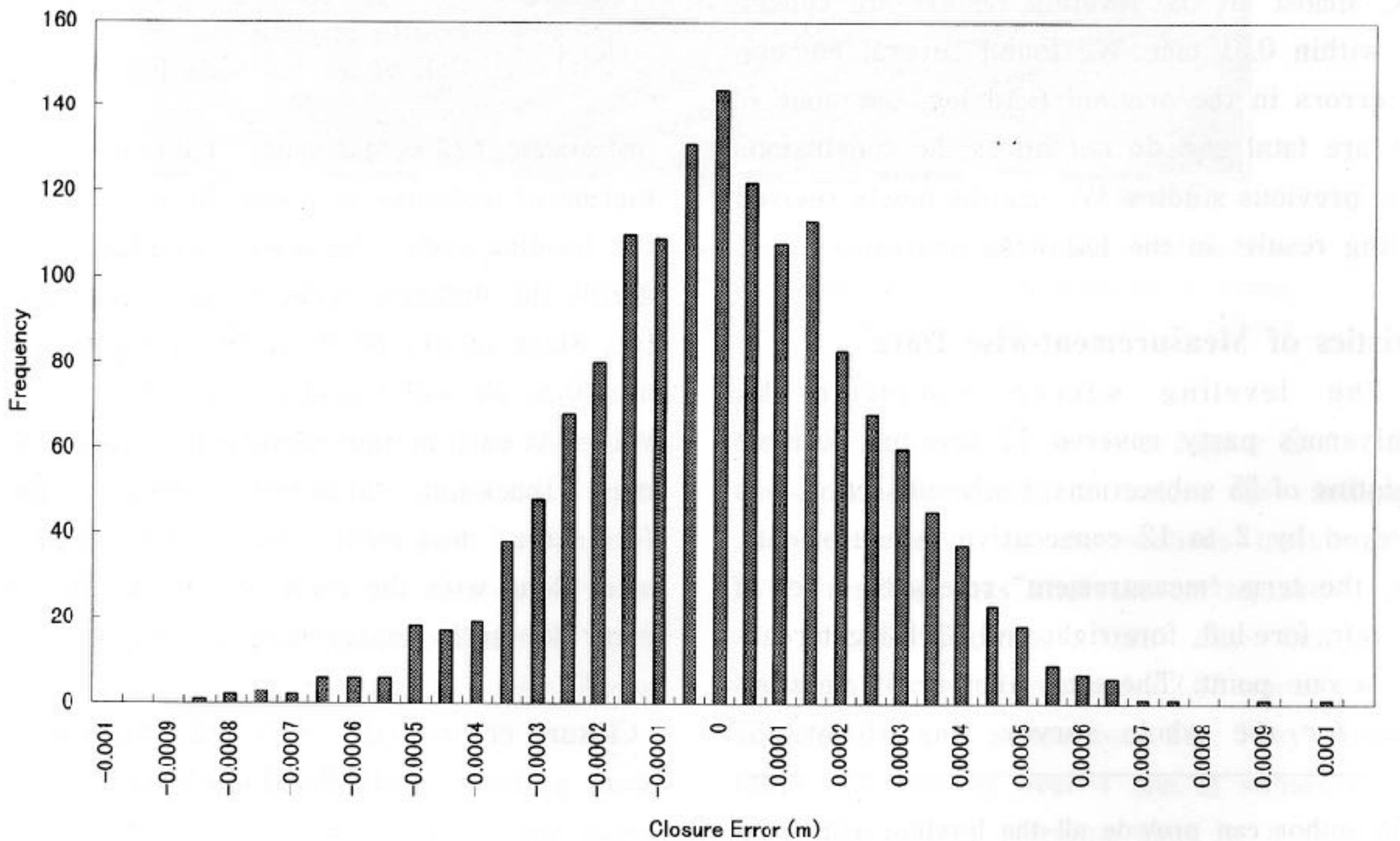
- Input all the data into Excel spreadsheet
- Check all the calculation
- No fatal calculation error



Sagiya(1998)

Frequency distribution of measurement-wise closure error

All the measurement-wise closure errors of the survey team during 1 month (Nov. 24 ~ Dec. 25, 1944)



Sagiya(1998)

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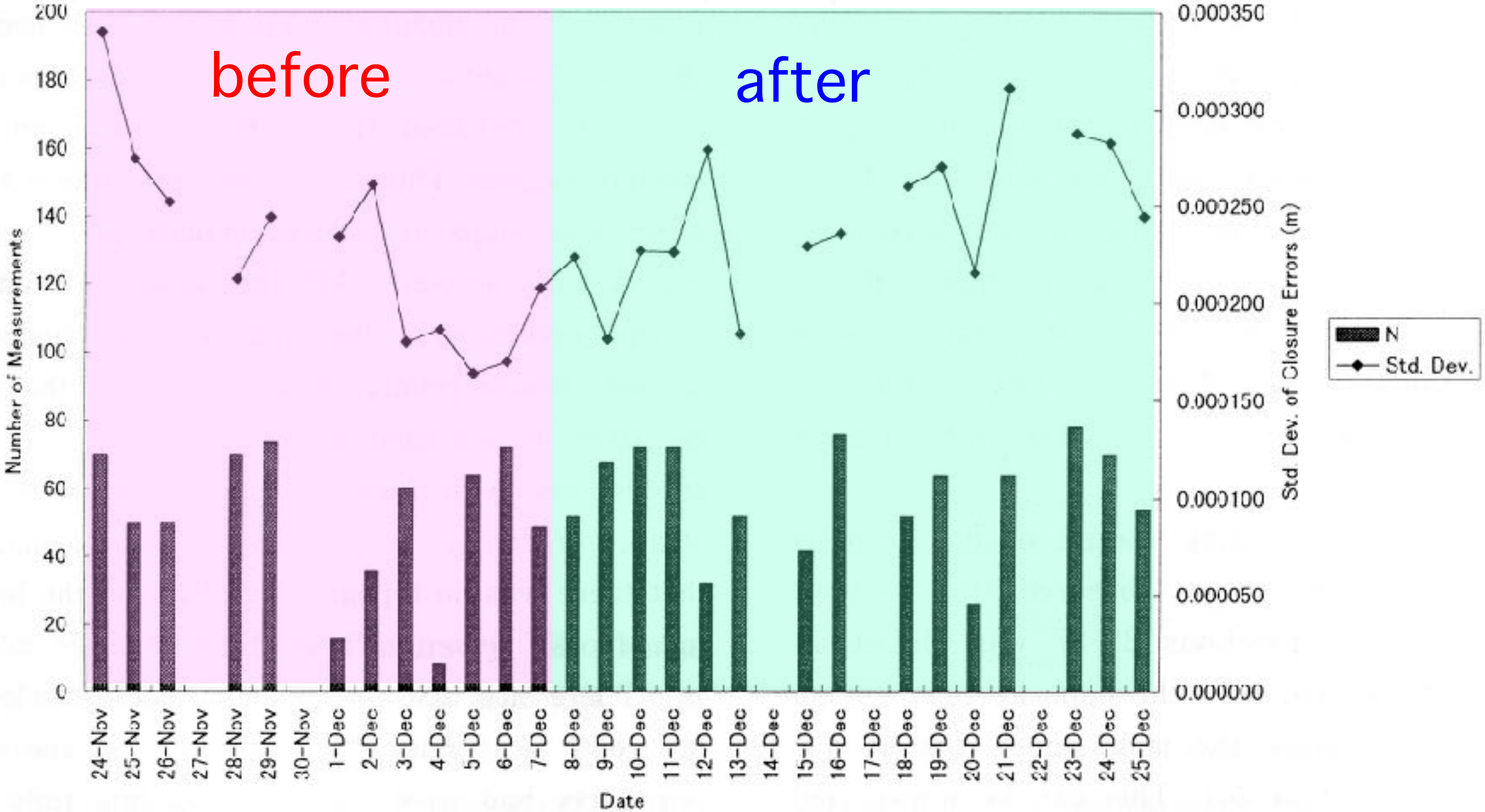
Day-by-day statistics of closure errors



Sagiya(1998)

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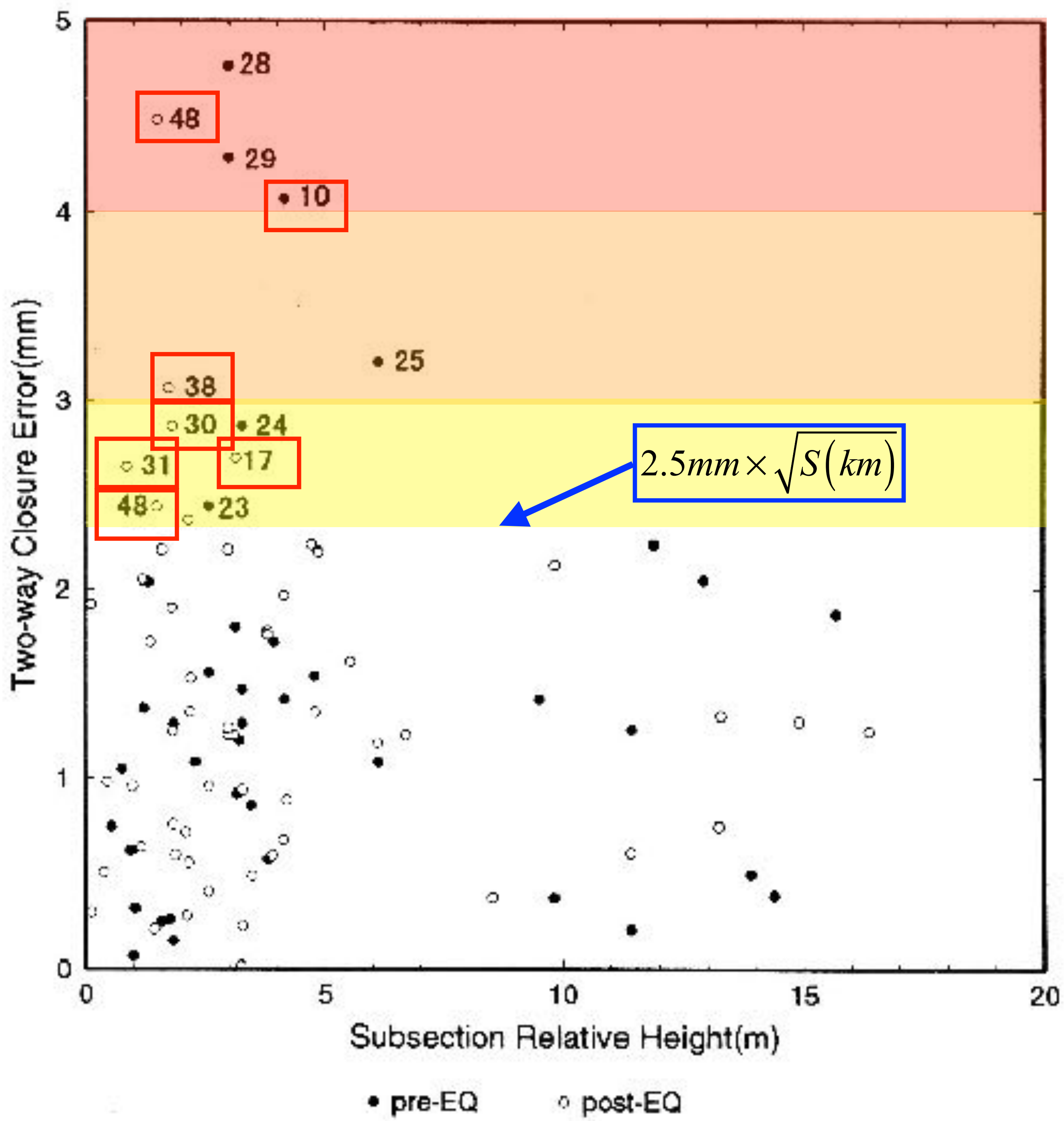
Leveling Data Summary



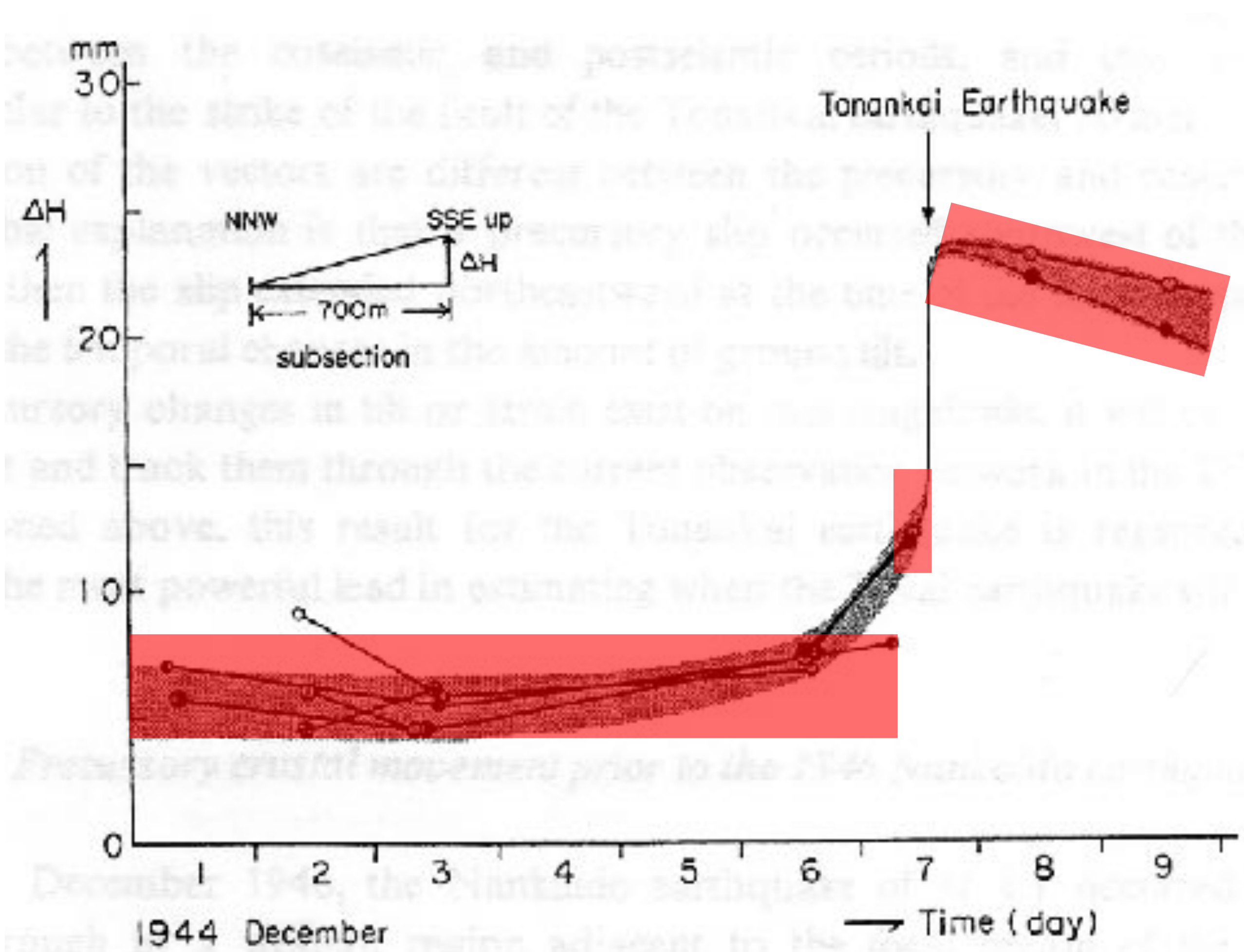
Large two-way closure errors irrelevant to the main shock precursor

Large closure errors themselves are not strong enough as a precursor.

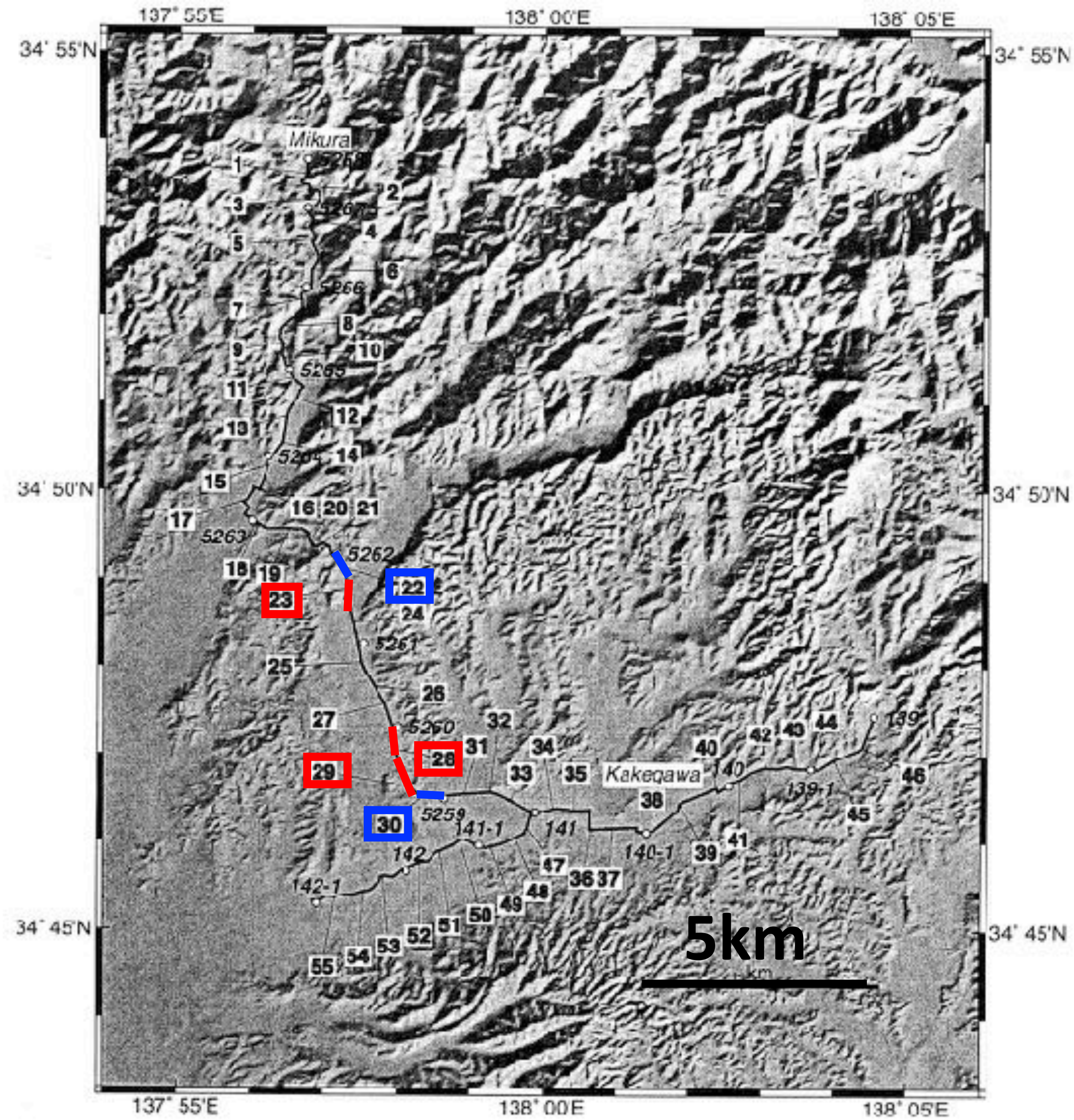
	Survey Date						Relative Height Changes (mm)				
section	A	B	C	D	E	F	A-B	B-C	Coseismic	D-E	E-F
1	11/24	11/26		12/24	12/24		+1.72			-1.62	
2	11/24	11/26		12/24	12/25		+2.24		-1.89	+0.38	
3	11/24	11/26		12/24	12/25		-1.80			+2.20	
4	11/24	11/26	11/26	12/24	12/25		-1.05	+1.20		+1.23	
5	11/24	11/26		12/24	12/25		-0.39		+2.78	-0.75	
6	11/24	11/25		12/24	12/25		-1.42			+1.97	
7	11/24	11/25					+0.62				
8	11/24	11/25		12/23	12/23		+0.38			+0.68	
9	11/24	11/25		12/23	12/23		-0.86		-3.09	+0.49	
10	11/25	11/25	11/28	12/23	12/24		+4.07	-1.42		-2.13	
11	11/25	11/28		12/23	12/23		-1.47		+0.79	+0.94	
12	11/28	11/28	11/29	12/23	12/23	12/25	-1.29	+0.70	+6.76	-1.25	+0.76
13	11/28	11/29		12/21	12/23	12/25	+0.58		+3.12	-1.78	-1.76
14	11/28	11/29		12/21	12/23		+0.25		-2.07	-2.21	
15	11/28	11/29		12/21	12/21		-1.20		-3.71	+1.23	
16	11/28	11/29		12/21	12/21		+0.26			+0.60	
17	11/28	11/29		12/21	12/21		+0.92		+2.76	-2.70	
18	11/29	12/4		12/19	12/19		+0.07		+3.28	-0.96	
19	11/29	12/4		12/19	12/19		+2.05			+1.33	
20	11/29	12/4		12/19	12/19		-1.87		+17.21	+1.25	
21	11/29	12/3		12/19	12/19		-0.50			+1.30	
22	12/1	12/3	12/7	12/18	12/20		-1.26	-0.21	+10.12	-0.61	
23	12/1	12/3	12/7	12/18	12/20		-1.56	+2.44	+5.19	-0.96	
24	12/2	12/3	12/6	12/18	12/20		-1.29	+2.87	-5.69	+0.23	
25	12/2	12/3	12/6	12/18	12/18		-3.21	+1.09	+17.82	+1.19	
26	12/2	12/3		12/18	12/18		+1.54		-5.77	+1.35	
27	12/2	12/3		12/18	12/18		-1.37		+17.40	-2.05	
28	12/6	12/7		12/8	12/9		+4.77		+12.84	-1.23	
29	12/6	12/7		12/8	12/9	12/9	+4.29		+11.56	-2.21	+1.27
30	12/6	12/7		12/8	12/9	12/9	-0.15		+7.84	-1.90	+2.87
31	12/6			12/8	12/9				+2.33	-2.65	
32	12/6			12/8	12/9				+4.18	+0.98	
33	12/6			12/8	12/9				+3.51	+0.60	
34	12/5	12/5		12/12			+0.75				
35	12/5	12/5		12/12			-2.04		+2.00		
36	12/5	12/5		12/12			+1.00				
37	12/5	12/5		12/12			-0.32				
38				12/13	12/13					+3.07	
39				12/13	12/13					-1.35	
40				12/13	12/13					-0.89	
41				12/16	12/16					-0.21	
42				12/15	12/16					+2.24	
43				12/15	12/16	12/16				-2.37	-0.56
44				12/15	12/16					+0.02	
45				12/15							
46				12/15							
47				12/10	12/11					-0.41	
48				12/10	12/10	12/11				-4.49	+2.44
49				12/10	12/10	12/11				-1.92	+0.30
50				12/10	12/10					+0.72	
51				12/10	12/10					-1.72	
52				12/10	12/10					-0.64	
53				12/11	12/11					+0.51	
54				12/11	12/11					+1.53	
55				12/11	12/11					-0.28	

Was the tilt accelerated?

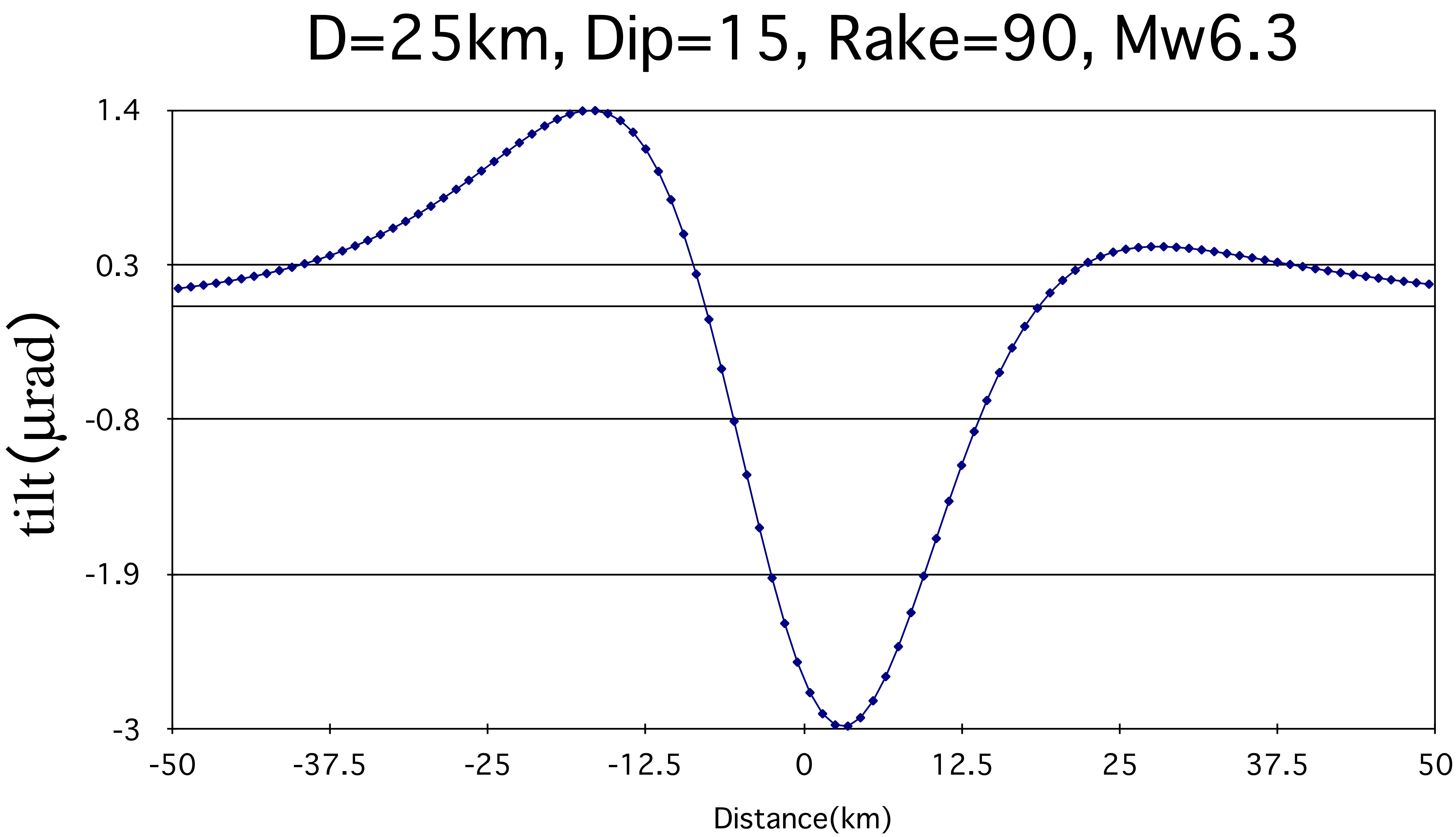
- Morning survey on December 7
  - 7:10am 23: +2.44mm (12/3)
  - 9:10am 22: -0.21mm (12/3)
  - 9:40am 28: +4.77mm (12/6)
    - 29: +4.29mm (12/6)
  - 12:13am 30: -0.15mm (12/6)
- Monotonous acceleration is not
- Step-wise tilt change is also possible.



Mogi (1984)



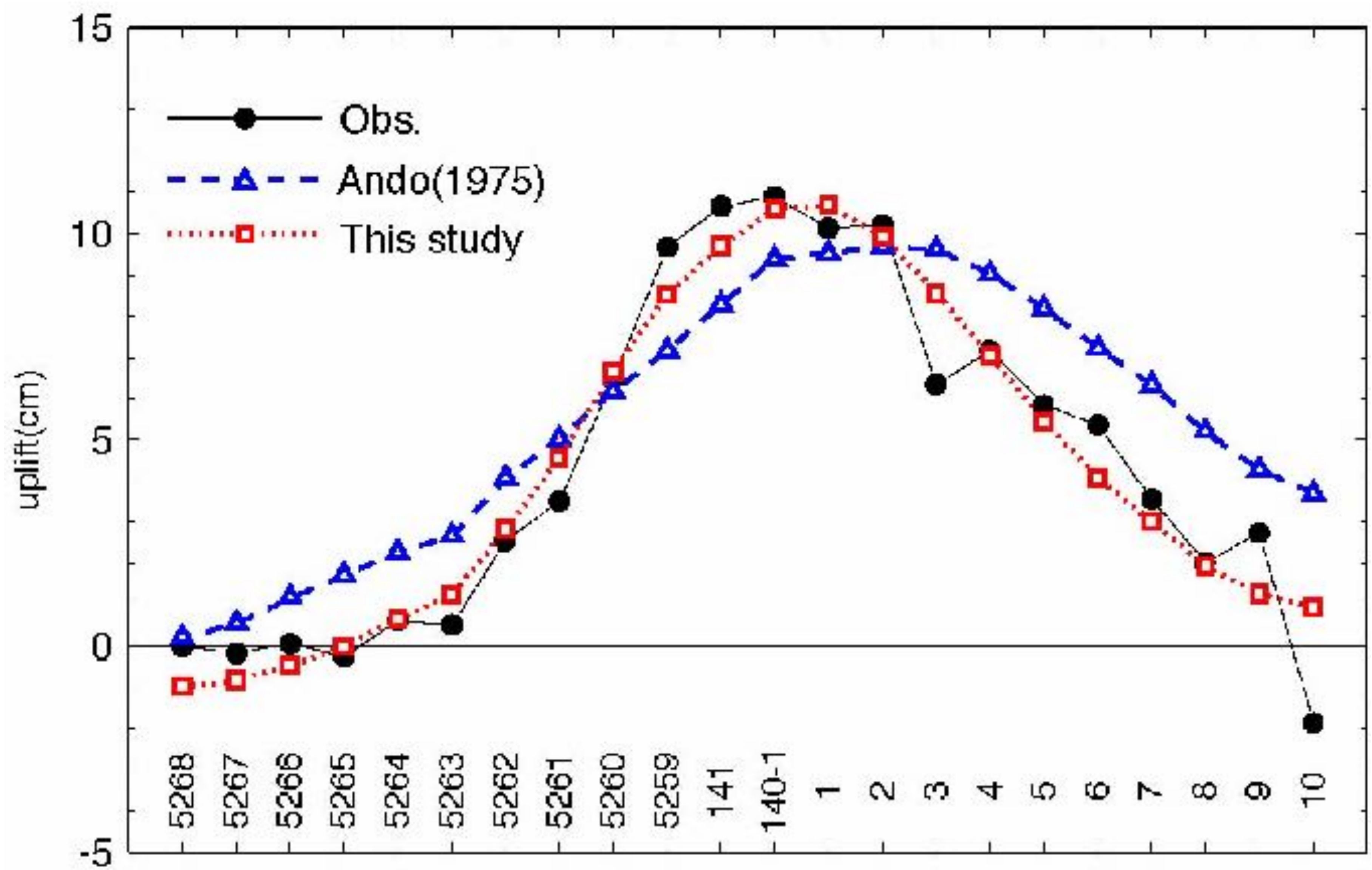
Was the tilt change originated at plate boundary?

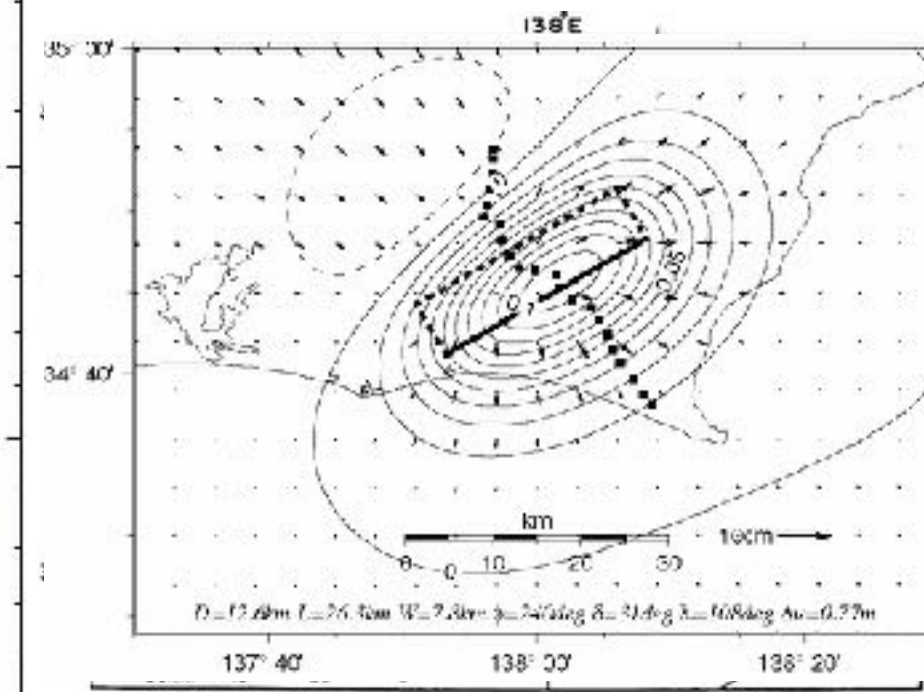


Tilt change originated from plate boundary should have a long wavelength pattern.

Coseismic uplift of the 1944 Tonankai earthquake

- Faulting at the plate interface does not explain the preseismic and coseismic uplift pattern.
- Depth range:12.6~16.6km, L=26.3km, W=7.8km, slip=0.8m (Mw6.4)





Benchmarks between Kakegawa and Omaezaki (1~10) are assumed to be located at current positions.

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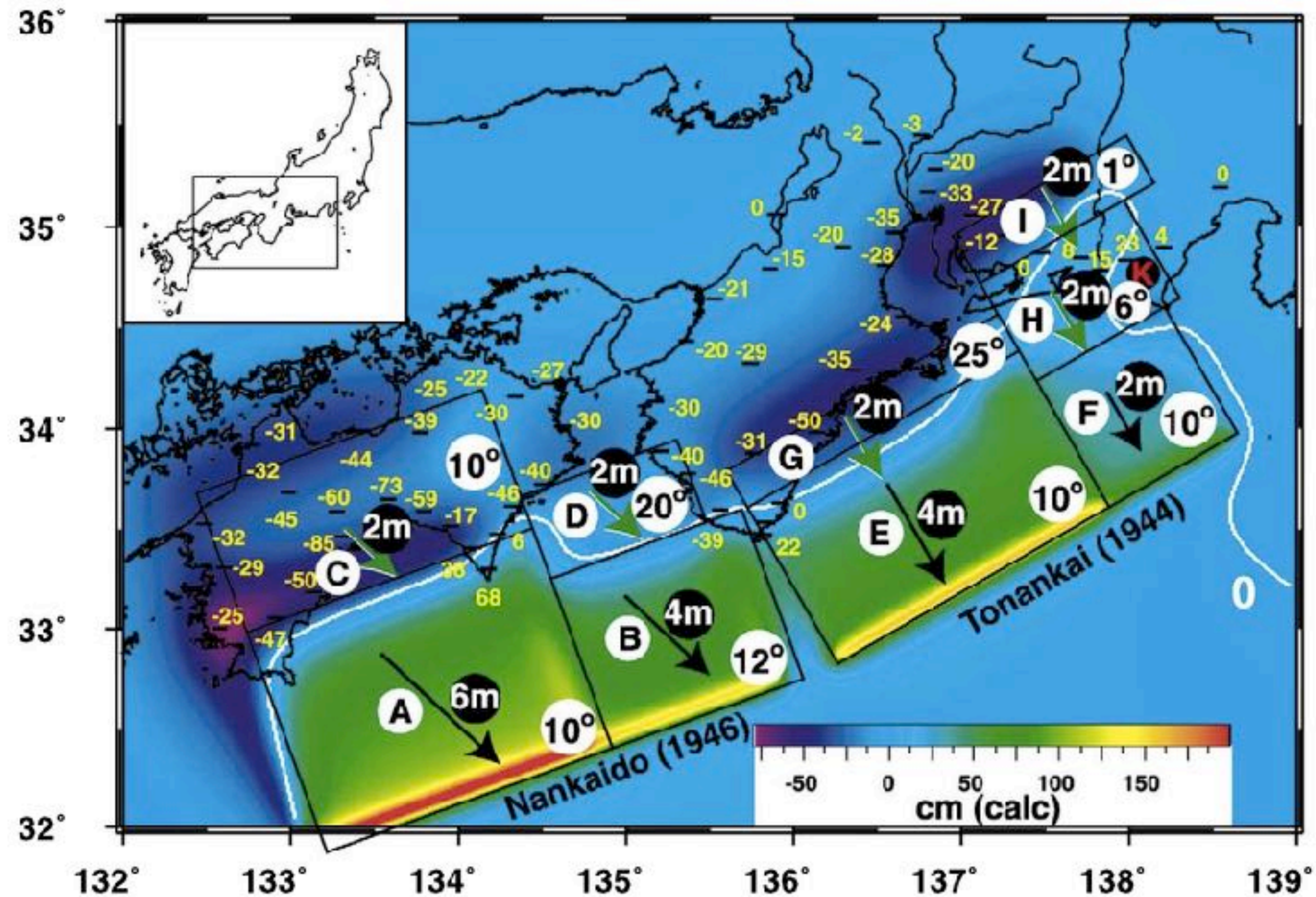
One interpretation of anomaly



Linde and Sacks (2002)

Precursory slip at the deeper extension of the whole 1944 and 1946 rupture.
No significant change was observed in tidal record before the 1944 Tonankai earthquake (Kobayashi et al., 2002).

Additional problems

- Surveyor's Essay (Koshiyama, 1976)
- Is this scientific evidence?
  - Essay first appeared in 1976 (32 years after the earthquake).
  - Referred in Sato (1977) and Mogi (1984).
  - No report in Imamura (1945) who asked the survey.
  - No mentioning until 1970.
  - How good is his memory?
  - Psychological bias?

Koshiyama (1996)

Summary of the 1944 Tonankai tilt anomaly

- ✦ The reported tilt anomaly is not rejected but not strong enough.
  - The case can be interpreted in both positive and negative ways.
- ✦ "Undecided" decision by the IASPEI committee is correct.

- ✦ The case does not provide a strong scientific basis for the Tokai seismic gap experiment.
- ✦ The pre-slip duration of a few days is thus questioned.

- ✦ The 1944 case has become **obsolete**.
  - Scientists should look for other evidence with more precise and reliable observations.

List of reported precursory crustal deformation

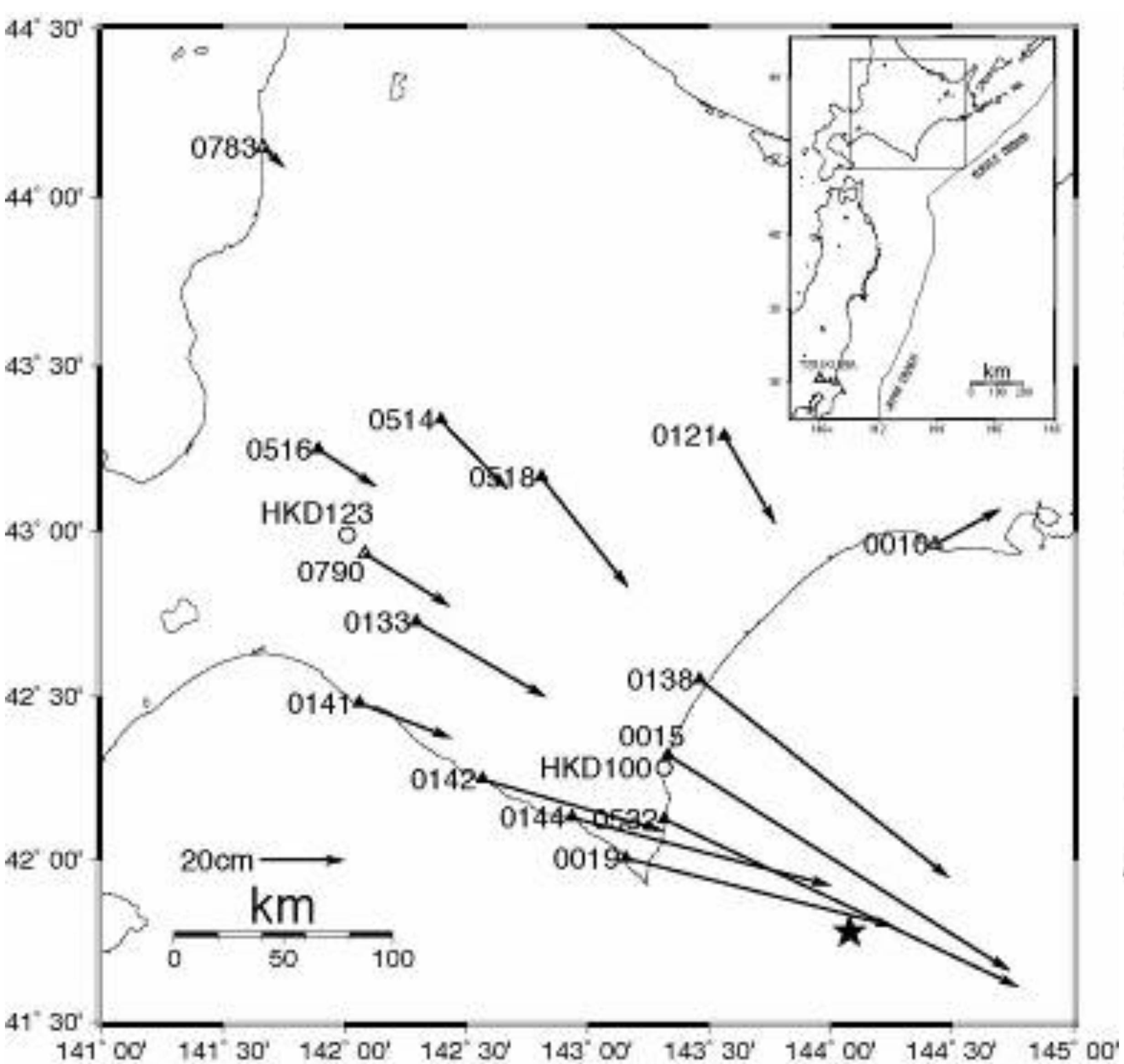
Earthquake	year	M	Location	Fault	Data	Duration
Ajigasawa	1793	6.9	Japan Sea	Reverse	Tide (1m)	4 hours
Sado	1802	6.6	Japan Sea	Reverse	Tide (1m)	4 hours
Hamada	1872	7.1	Inland	?	Tide (2m)	0.5 hour
Shonai	1894	7.0	Inland	Reverse	Tide (0,5m)	15 days
Kanto	1923	7.9	Sagami	Reverse	Tide, strain	3 years
Tango	1927	7.3	Inland	Strike slip	Tide (1.5m)	2,5 hours
Oga	1939	6.8	Japan Sea	Reverse	Tide (3m)	3 hours
Tottori	[illegible]	[illegible]	Inland	Strike slip	Tilt	6 hours
Tonankai	1944	8.0	Nankai	Reverse	Tilt (level)	3 days
Nankai	1946	8.0	Nankai	Reverse	Tide (0.1m)	2 days
Hyuganada	[illegible]	[illegible]	Nankai	Reverse	[illegible]	5 years
Kita-Mino	[illegible]	[illegible]	[illegible]	Strike slip	[illegible]	10 years
Niigata	1964	7.5	Japan Sea	Reverse	Level (0.05m)	10 years
Gifu-Chubu	1969	6.6	Inland	Strike slip	Level (0.02m)	5 years
SE Akita	1970	6.2	Inland	Reverse	Level (0.03m)	10 years
Izu-Oshima-Kinkai	1978	7.0	Inland	Strike slip	Strain	30 days
Urakawa	1982	7.1	Inland	Reverse	Level (0.03m)	10 years
Japan-Sea	1983	7.7	Japan Sea	Reverse	Level (3cm)	5 years
Japan-Sea	1983	7.7	Japan Sea	Reverse	Strain (0.05ppm)	5 months
Kobe	1995	7.2	Inland	Strike slip	Triangulation	100 years

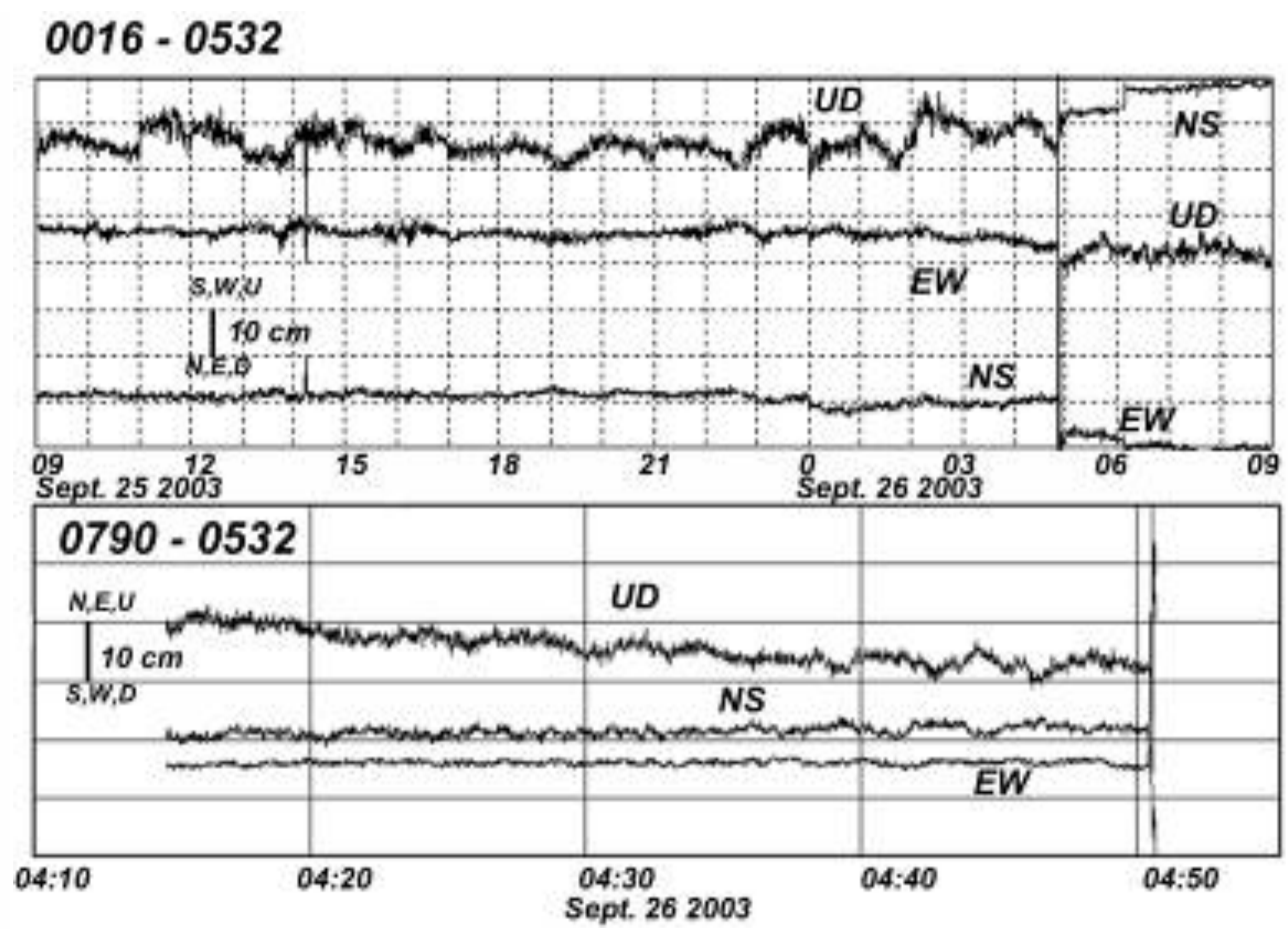
As time goes, more and more precise observation is possible. But reported anomalies become smaller in their magnitudes and longer in their duration:

This is a typical signature of a false signal detection.

The 2003 M_w8.3 Tokachi-oki earthquake

- The first M8-class megathrust earthquake after GEONET started.
- No sign of pre-slip.
- My personal motivation for re-revisiting the 1944 tilt anomaly.

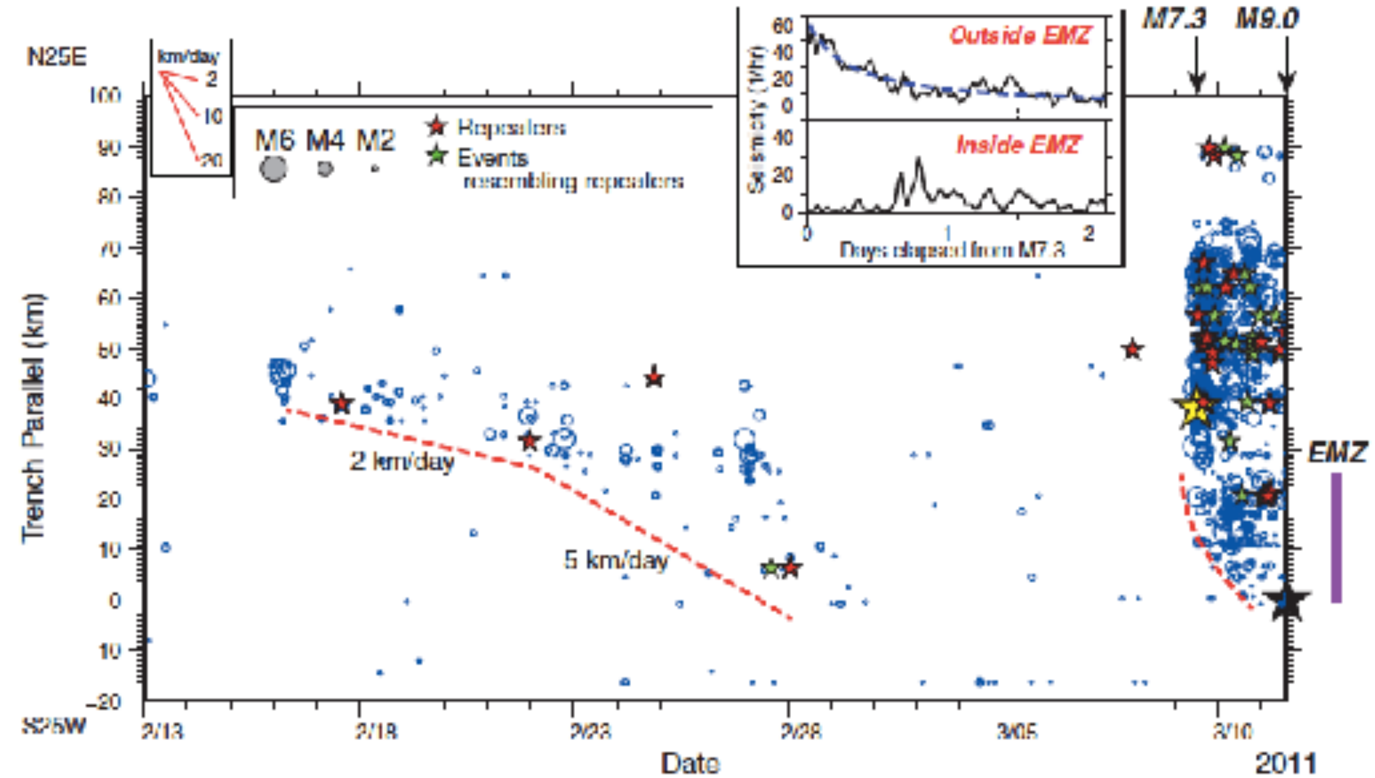


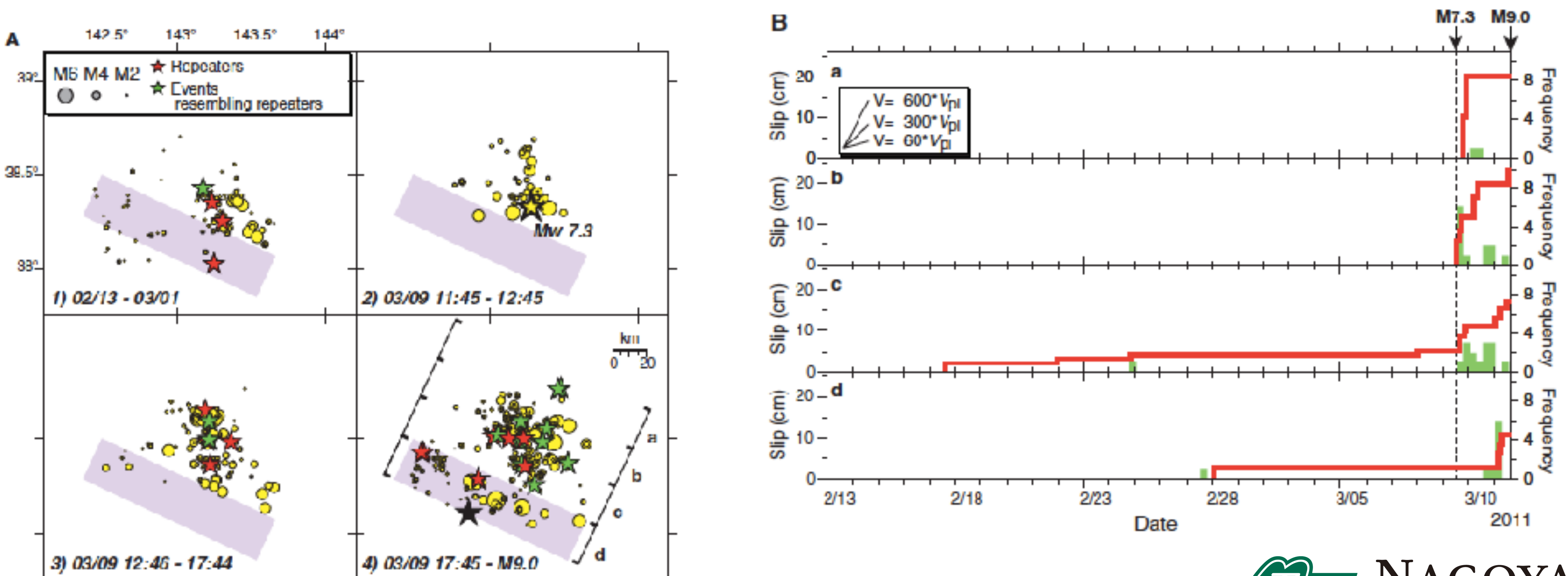


Irwan et al. (2003)

The 2011 M_w9.0 Tohoku-oki earthquake

- ✦ Propagation of slow slip in the hypocentral region
  - Based on repeating earthquakes
- ✦ Accelerated slip after the large foreshock (M7.3) with seismicity.
- ✦ Afterslip of the foreshock?





Kato et al. (2012)

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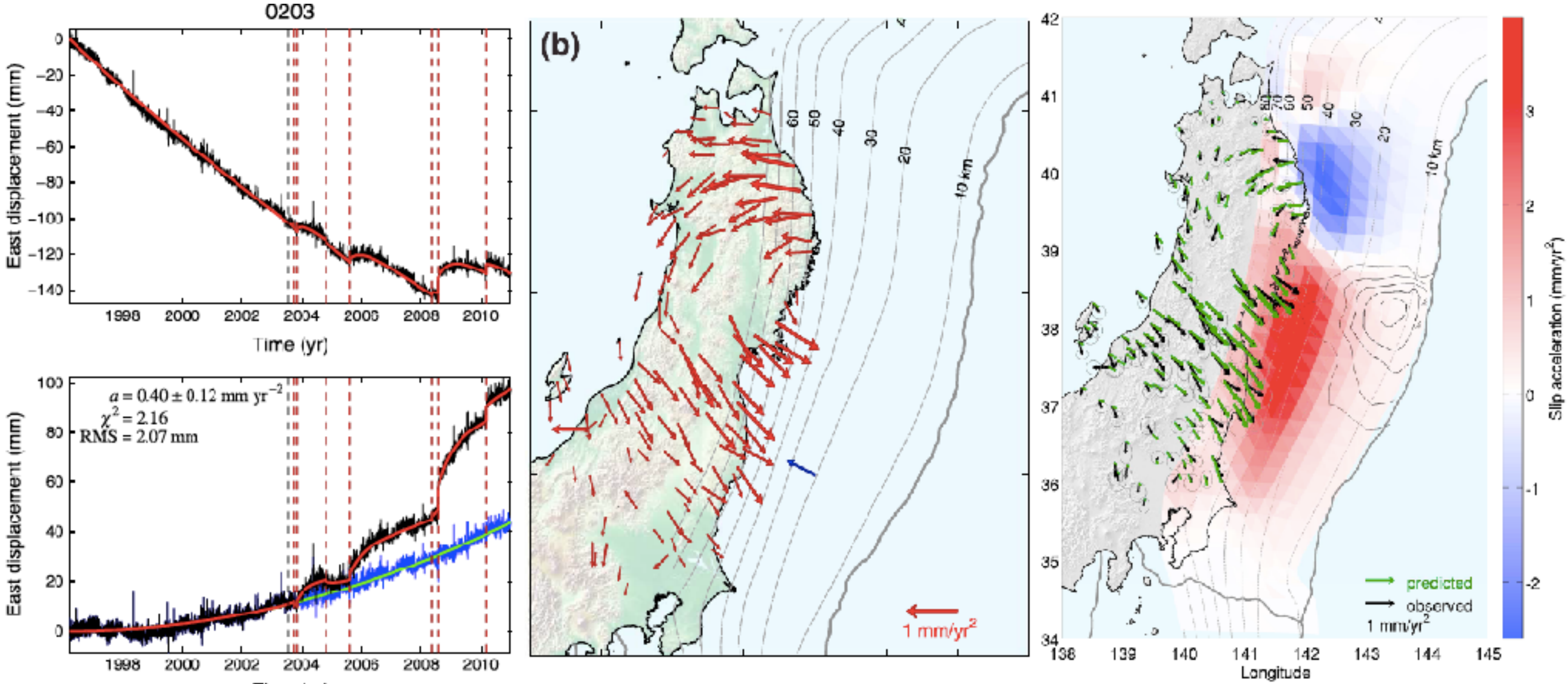
Slip acceleration before the 2011 Tohoku-oki earthquake



Mavrommatis et al. (2014)

- GPS Horizontal coordinates showed trench-ward acceleration along the 2011 Tohoku-oki source region.
- Possibility of accelerated plate boundary slip
- GPS vertical signal?

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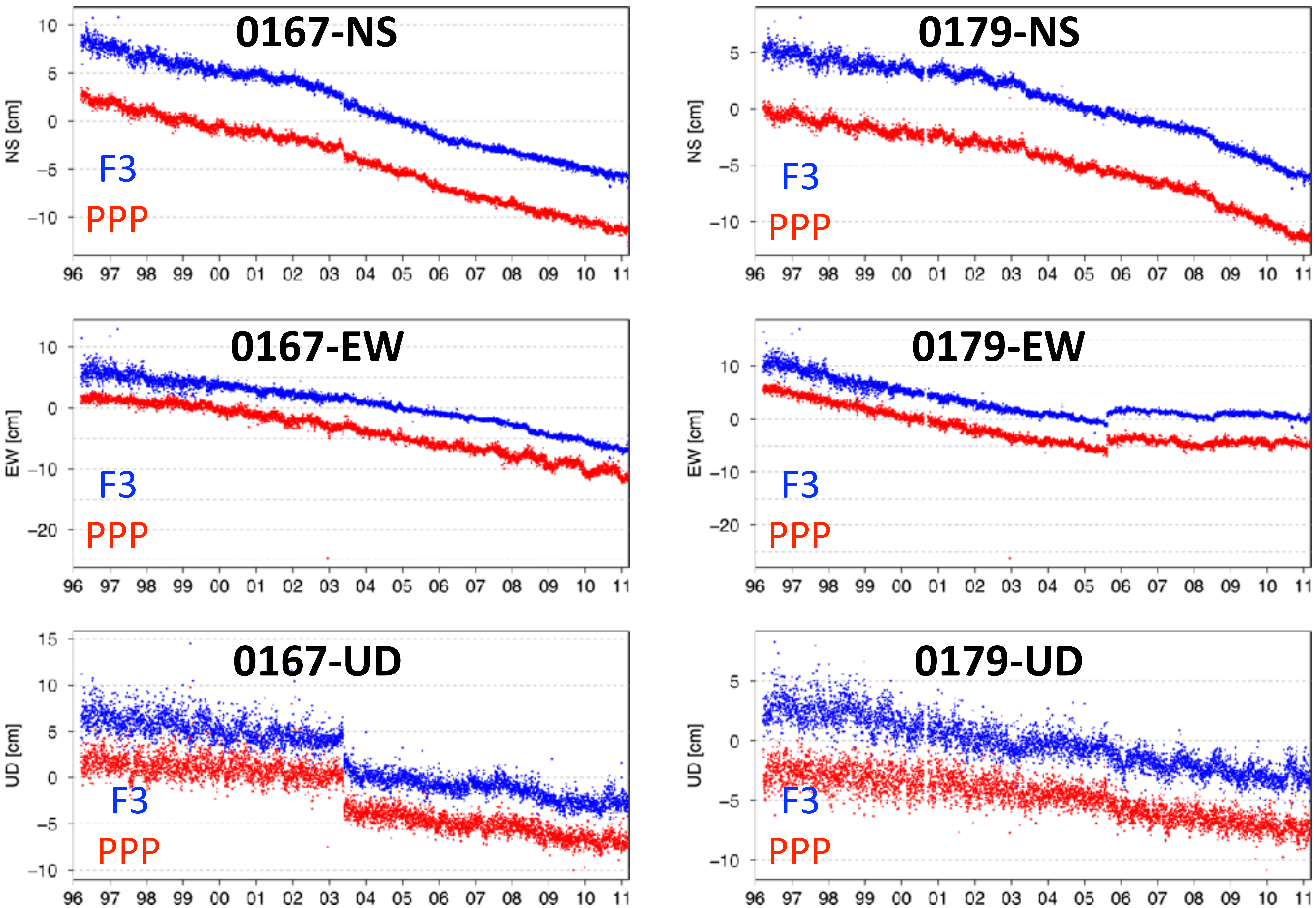
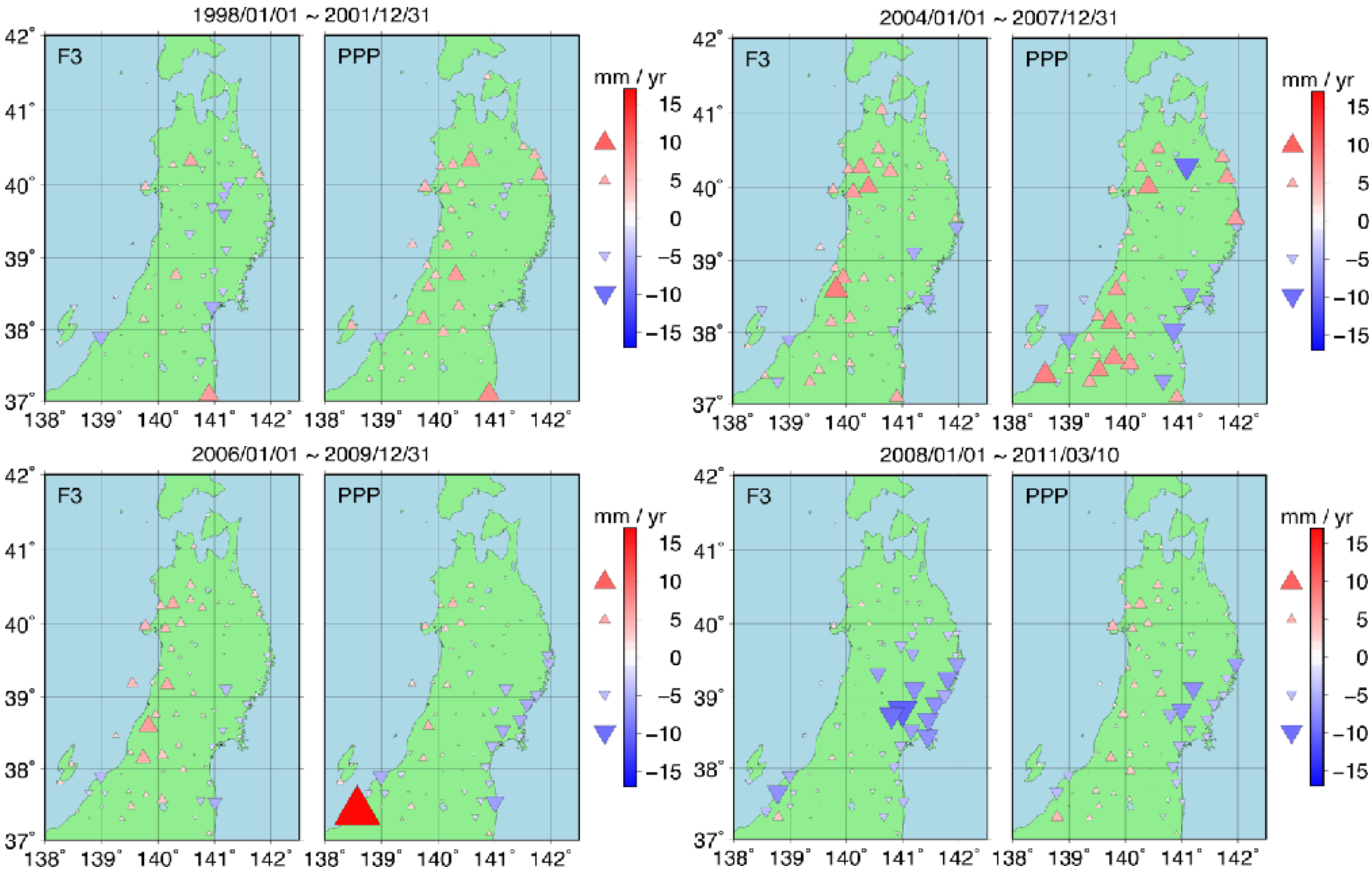
Coordinate time series (F3 vs. PPP solutions)



Vertical GPS velocity



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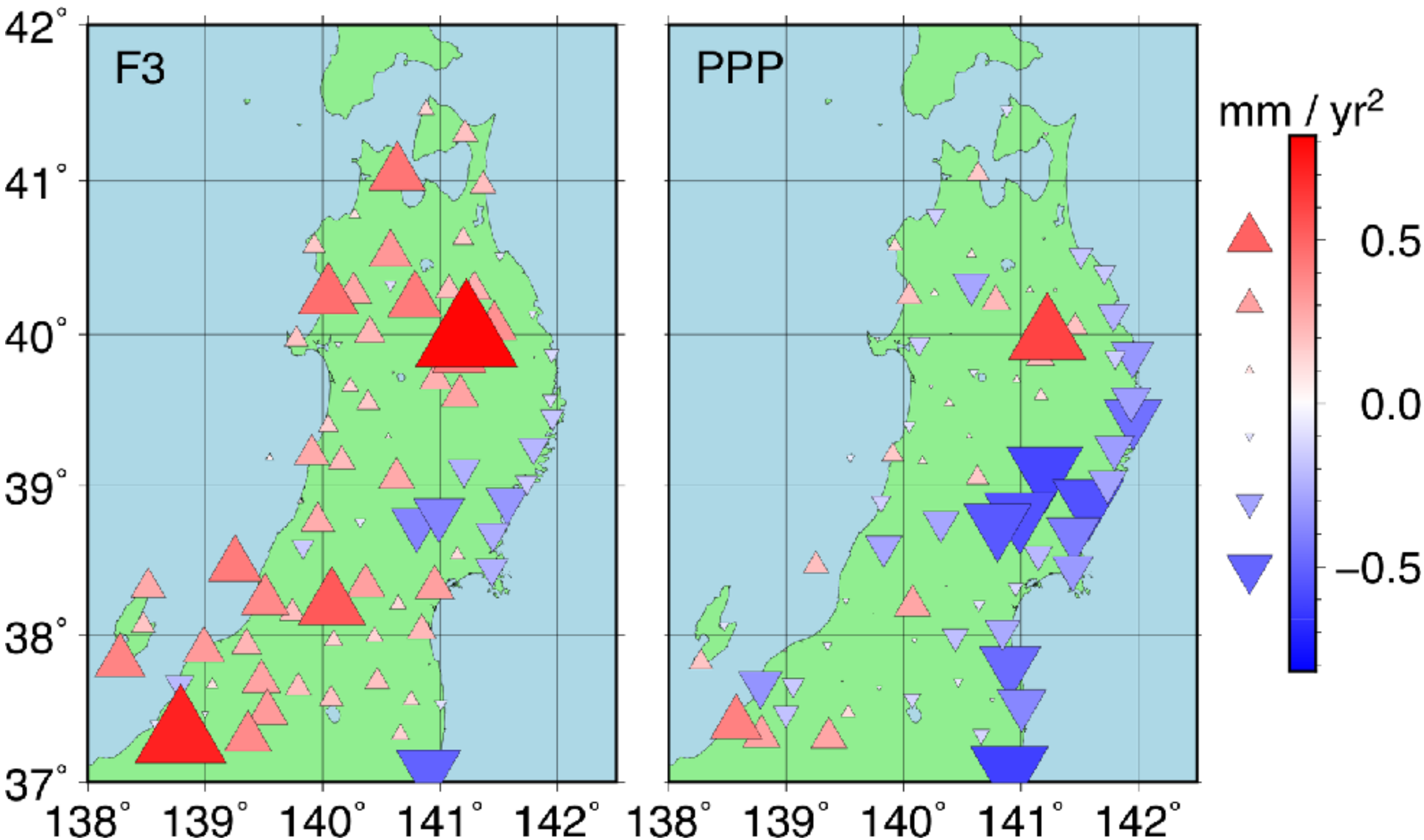
Vertical Acceleration



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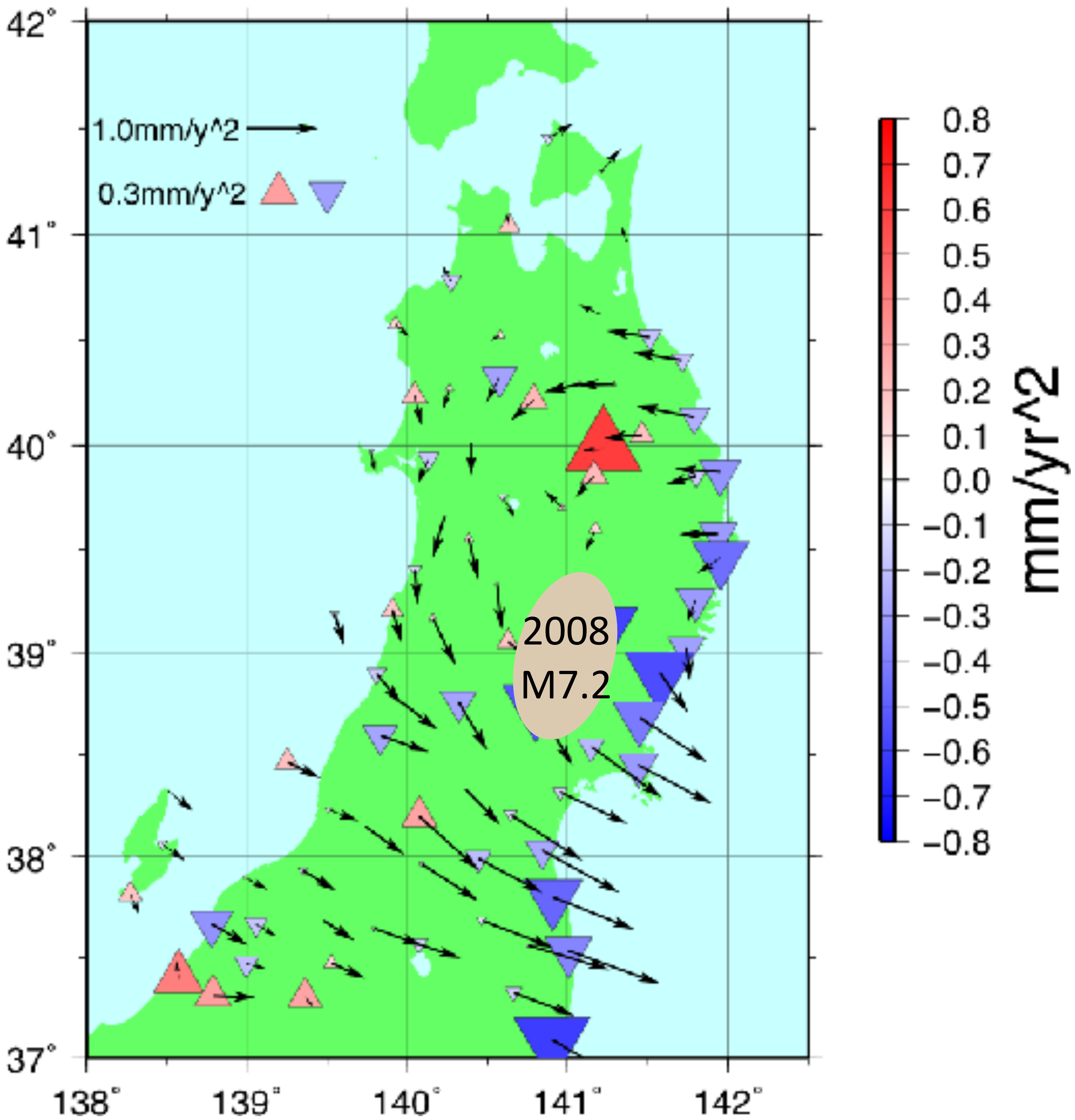
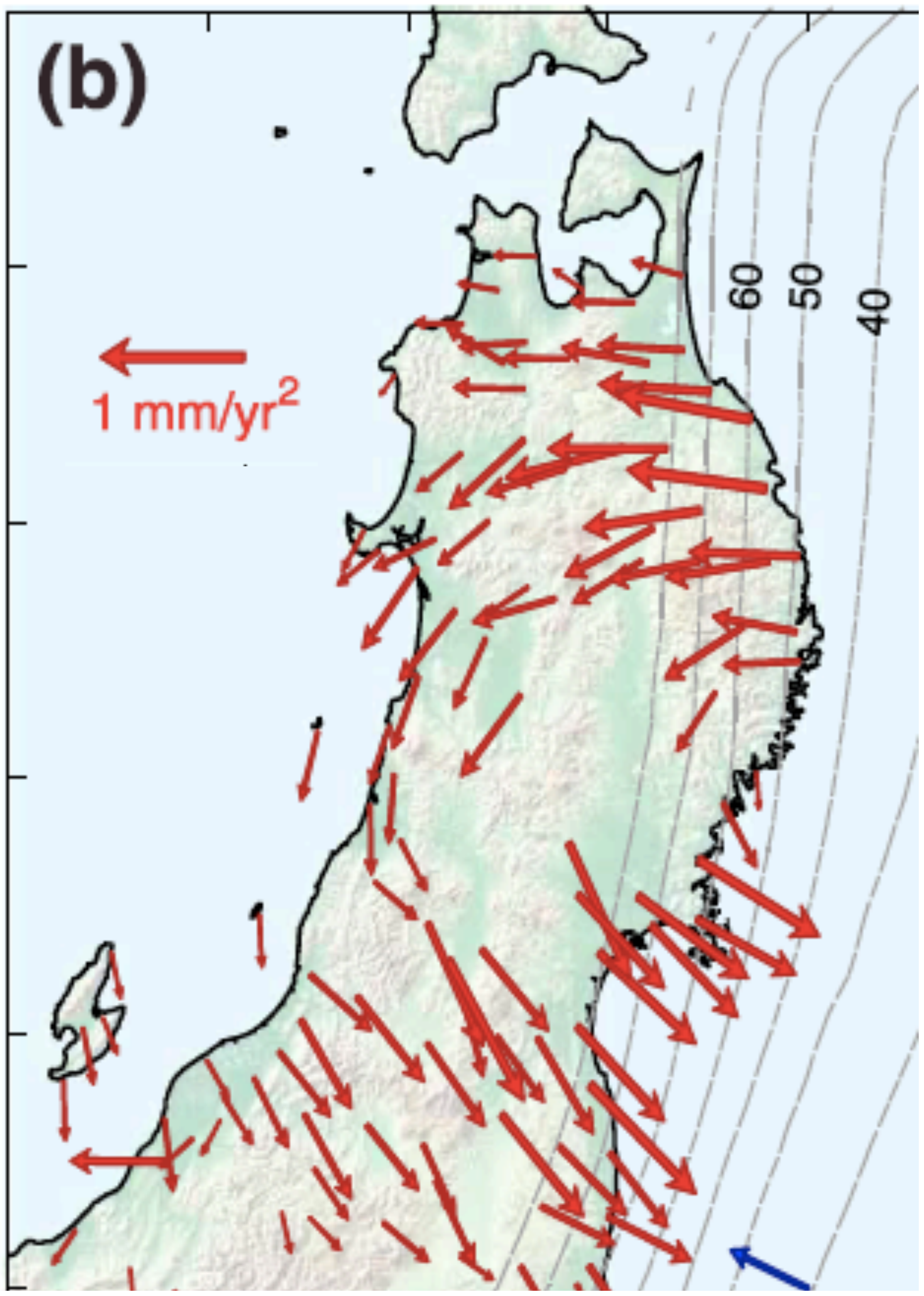
3-D acceleration





Mavrommatis et al. (2014)

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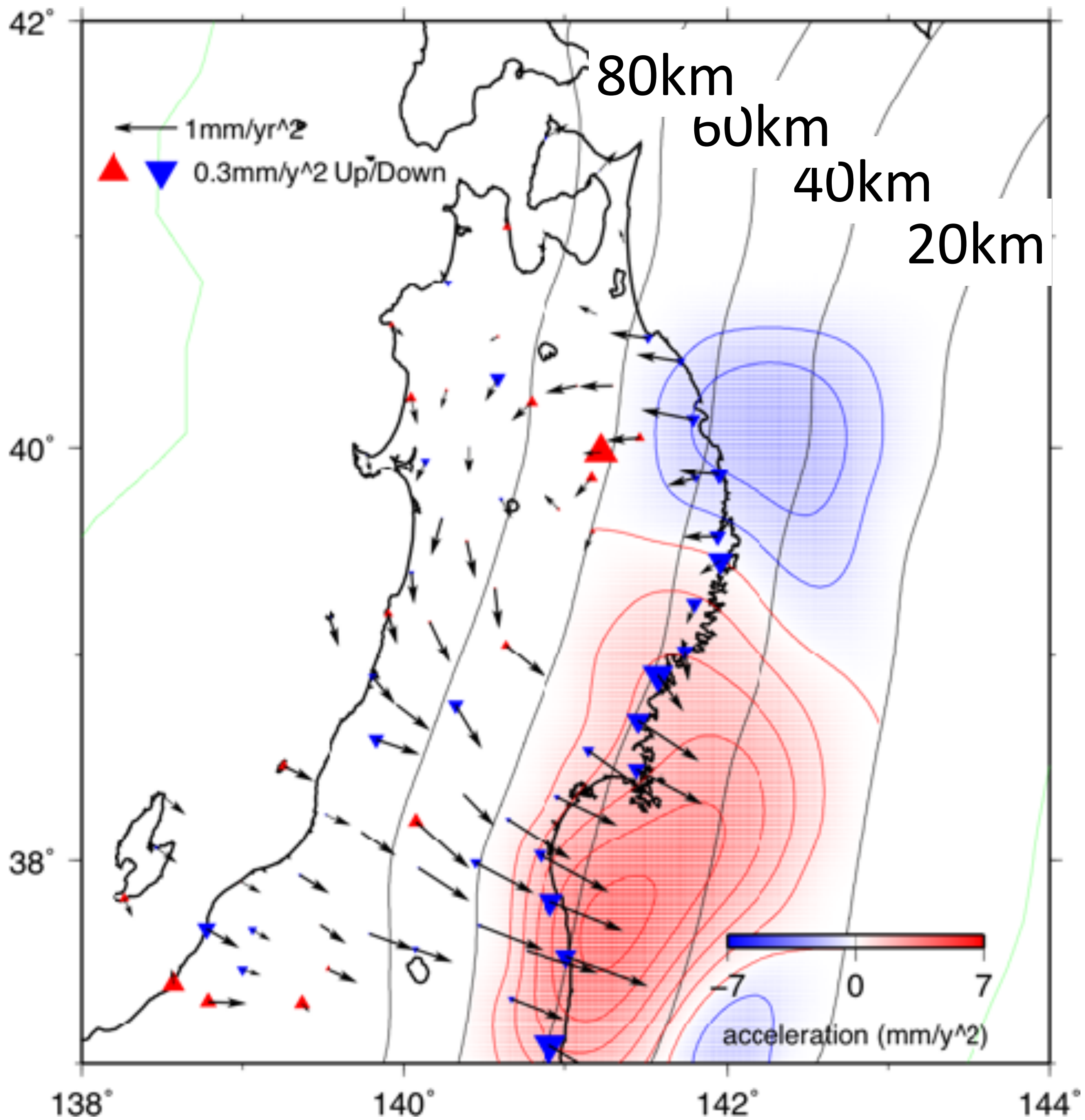
Accelerated Slip on the Plate Interface (preliminary)



- Geodetic inversion with a priori constraint (Yabuki and Matsu'ura, 1992)
  - Slip acceleration in the NA-PA relative plate motion (DeMets et al., 2010)
  - Depth range: 20-80km (Slab 1.0)
- **Accelerated slip at the deeper part of the locked zone**
- Consistent with Mavrommatis et al. (2014, 2015) based on horizontal GPS data

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Conclusion

- There is no confirmed aseismic pre-slip preceding a big earthquake
  - 1944 M7.9 Tonankai: not strong enough
  - 2003 M8.3 Tokachi-oki: no significant change
  - 2011 M9.0 Tohoku-oki: There may be a precursory slip with seismic swarm, but difficult to distinguish from foreshock afterslip. There may be a decadal accelerated slip or lose of interplate coupling.
- Time constant of pre-slip is still not well constrained.
  - a few days ~ a decade

- Precursory phenomena of large earthquakes are a highly interesting scientific target.
- But their use for practical prediction is totally another issue.
- Rigorous testing is indispensable before applying such hypothesis for a practical disaster mitigation countermeasure.
- We should focus on state-of-the-art observation. Re-interpretation of legacy data should be supplementary.

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