

EARLY-EST

Earthquake Rapid Location sYstem

with

Estimation of Tsunamigenesis

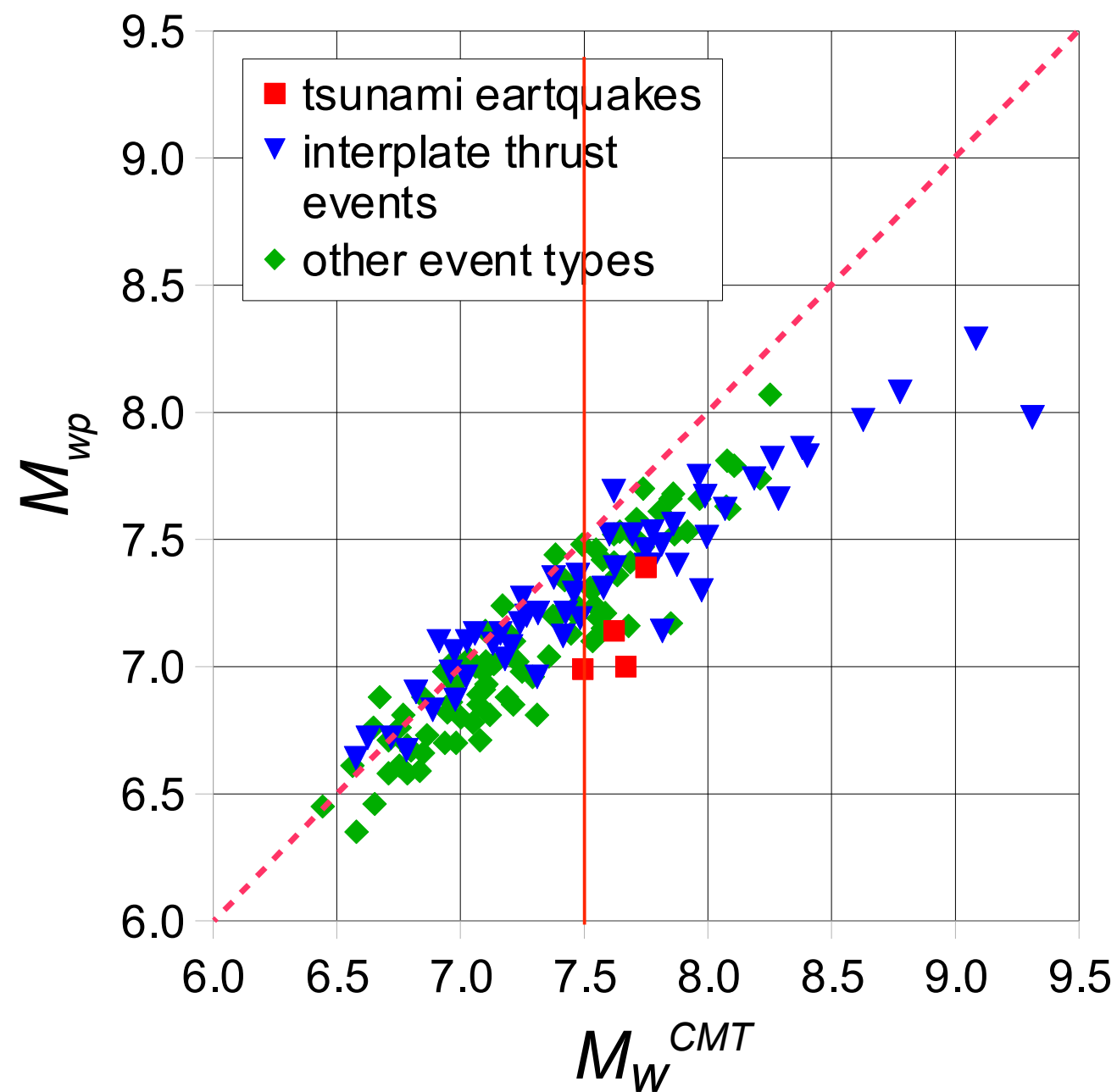
Alberto Michelini and Anthony Lomax



How did this all start ?

- After Sumatra M9.2 2004 earthquake:
 - ➔ necessary to develop techniques for rapid size quantification of large and mega earthquakes (i.e., the existing saturate and the GCMT is too slow)
- After the Java M7.7 2006 tsunami earthquake:
 - ➔ rapid quantification of tsunami potential

P-wave methods saturate for events larger than $M_w \approx 7.5$



M_{wp} magnitudes (Tsuboi *et al.*, 1995, 1999) compared to CMT magnitude M_w^{CMT} for 79 recent, large earthquakes.

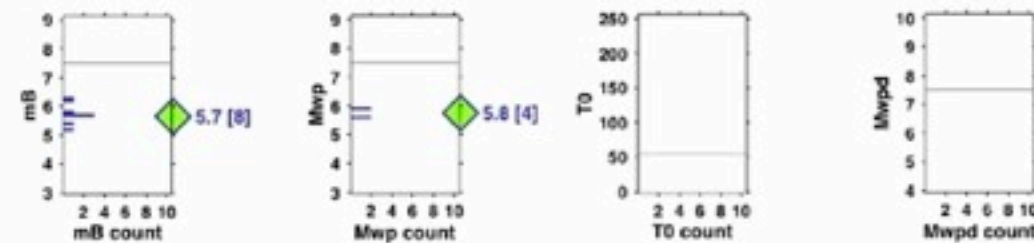
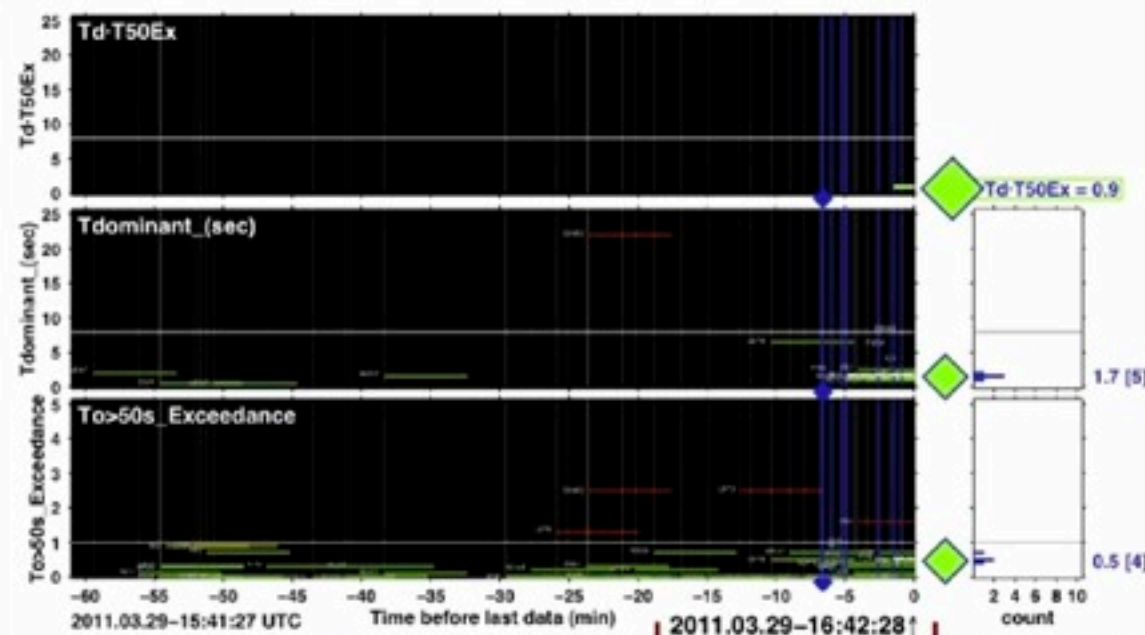
Ingredients

- **Location**
- **Mw_{pd}** (extension of Mw_p with duration)
- **T₀** (rupture duration from band-passed 1-5 Hz broadband seismograms on P-wave train)
- **T_{50Ex}** (proxy of T₀ determined at 55s from P-onset)
- **T_d** (dominant period on P-wave)
- **T_d x T_{50Ex}**

EARLY-EST [infos (I)]

Picks and Tsunamigenic Assessment

Earthquake Magnitude

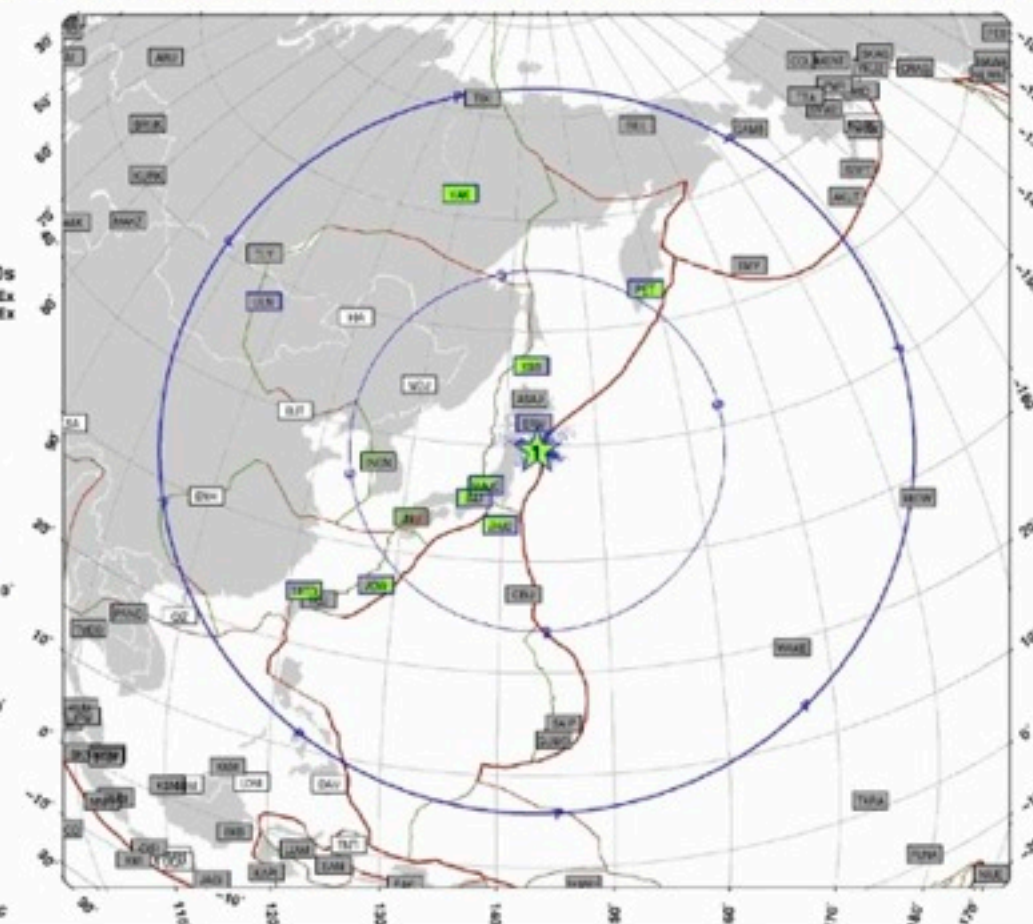
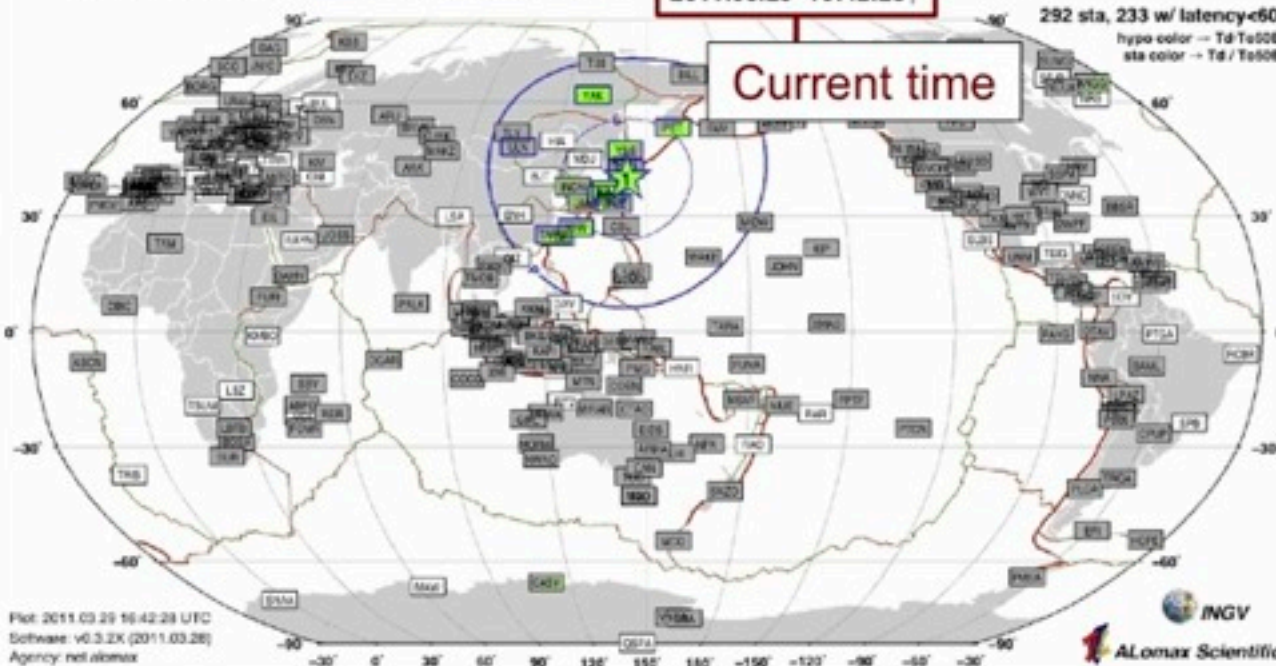


Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin	col	origin-time-UTC	lat°	lon°	err	depth	ex	T50Ex	pe	Td	pe	Td-T50 WL	mB	pe	Mwp	pe	T0	pe	Mwpd	pe
1	8	2.4	1.8	2011.03.29-16:35:50	39.6	143.4	su	17	10	0.5	1.7	0.9	0.9	0.9	5.7	8	5.8	4	n/a	n/a	n/a	n/a

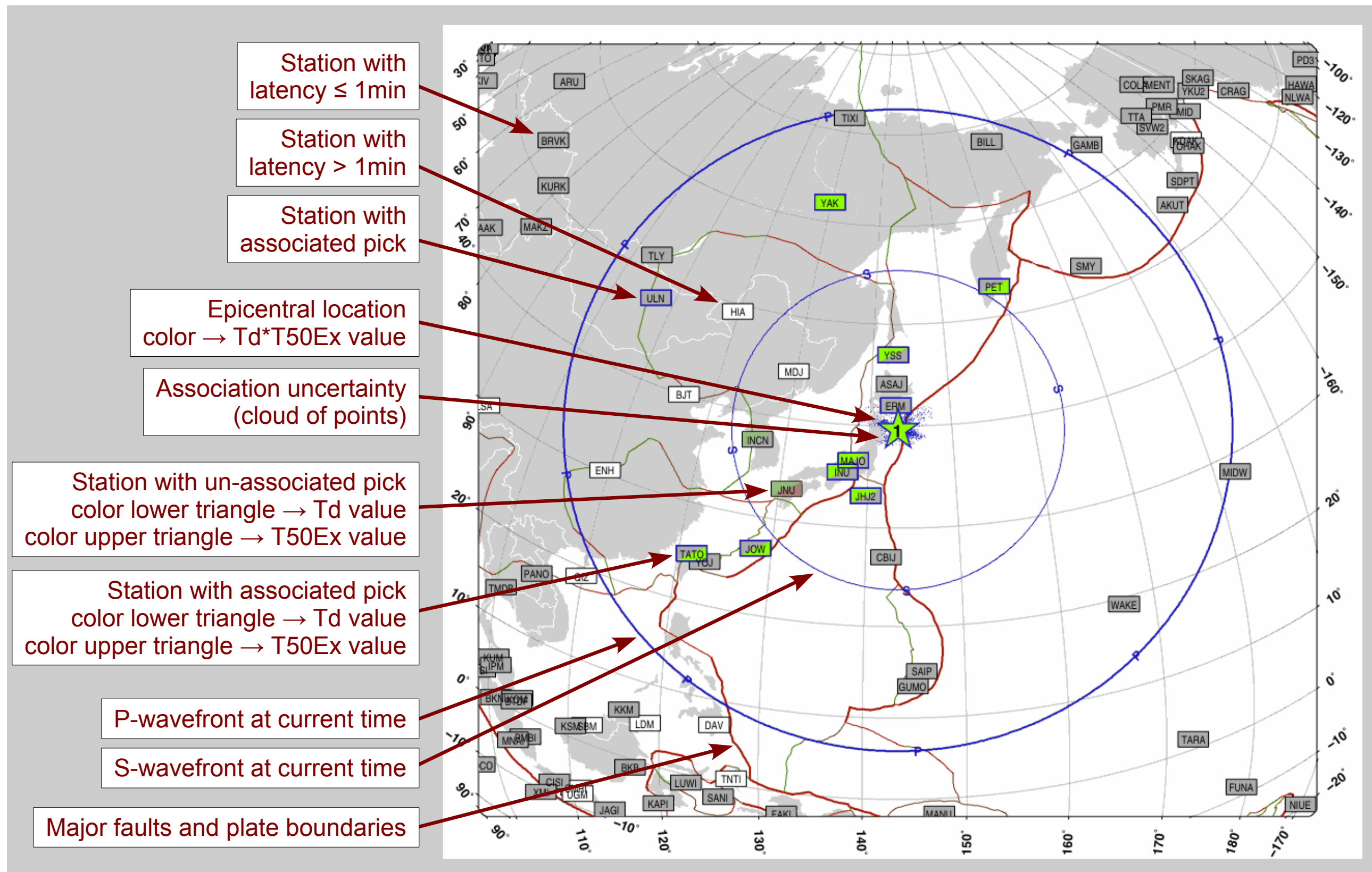
Earthquake Parameters



Earthquake Location

Earthquake Location (zoom)

EARLY-EST [infos (2)]



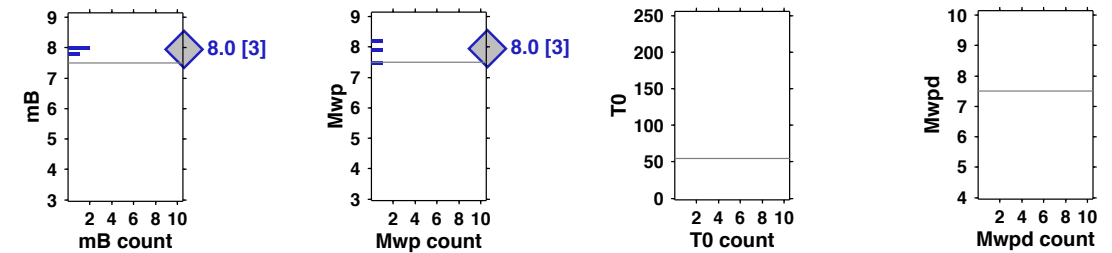
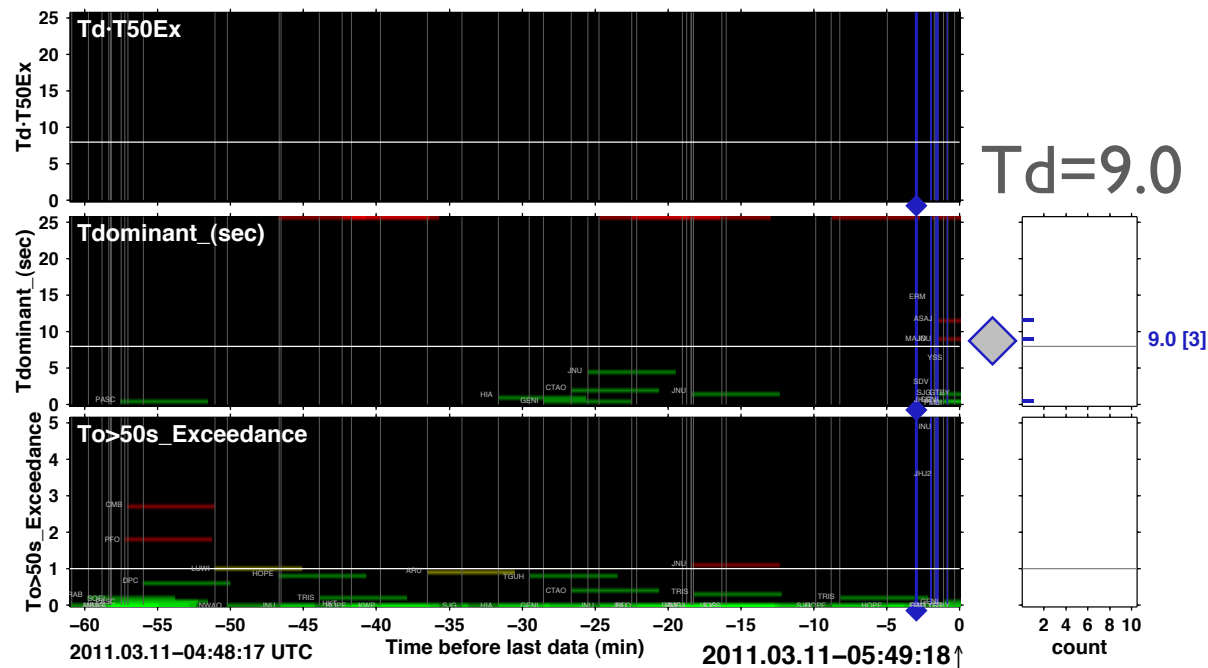
05:49:18 GMT

Tohoku Earthquake M9.0,

~ 3' from OT

11 March 2011, 05:46:20 GMT

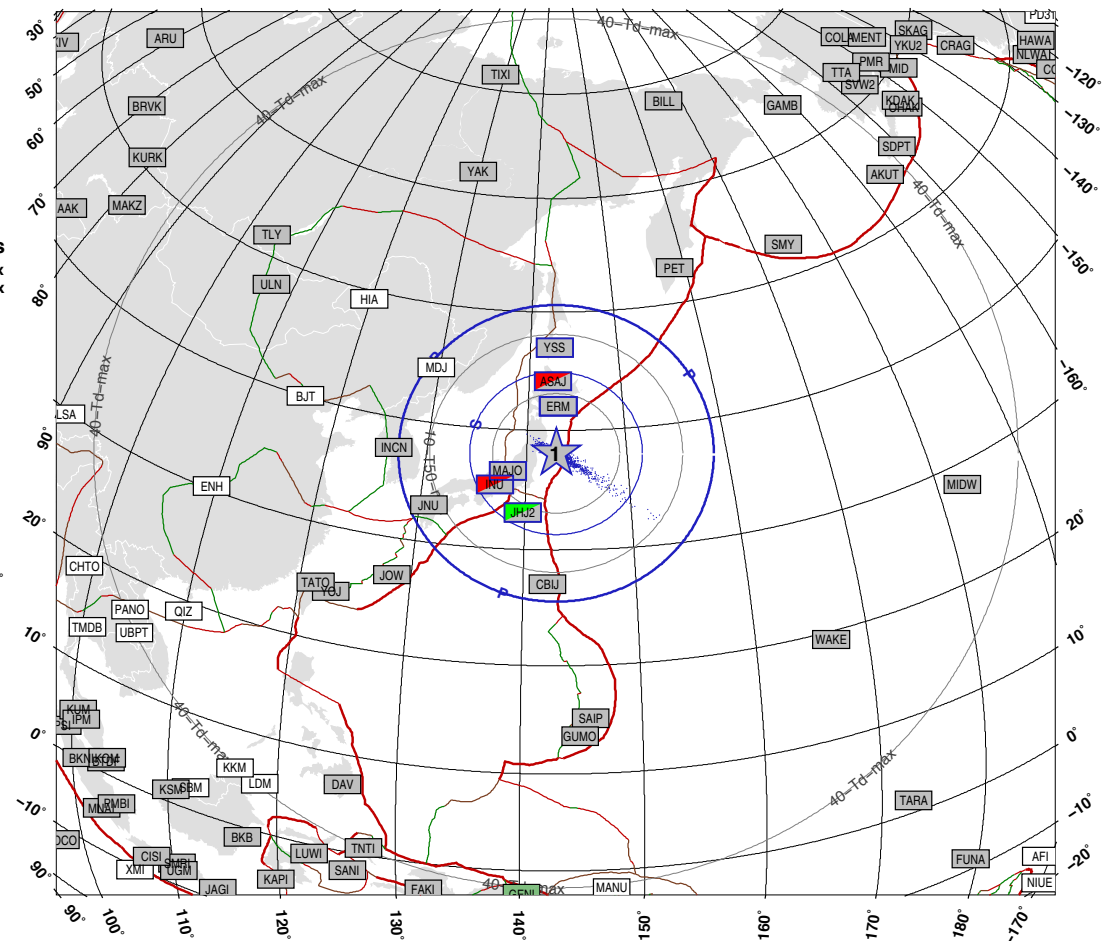
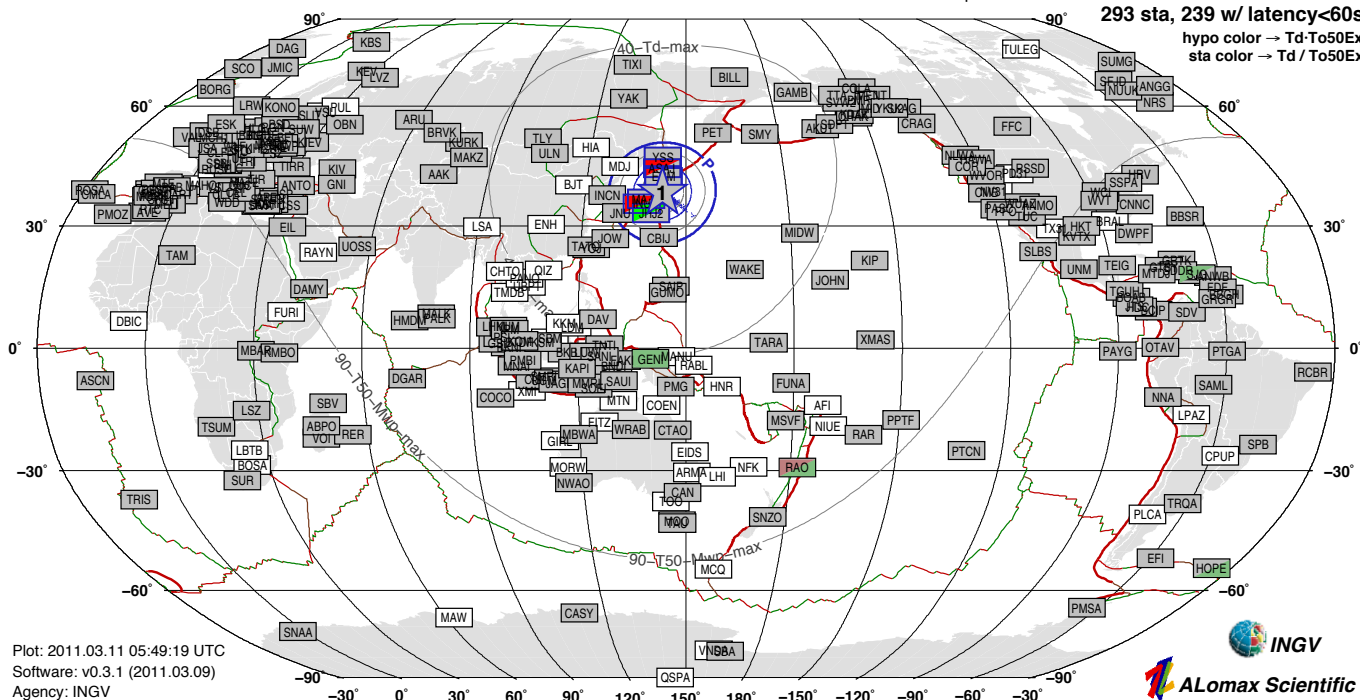
mB=8.0 Mwp=8.0



Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	TdT50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]
1	6	3.9	0.5	2011.03.11-05:46:20	38.1	142.9	28	14	40	0.0	9.0	0.0	n/a	3	n/a	0



see details at http://alomax.free.fr/posters/Japan_2011/Japan_2011_INGV_WarningMonitor.html

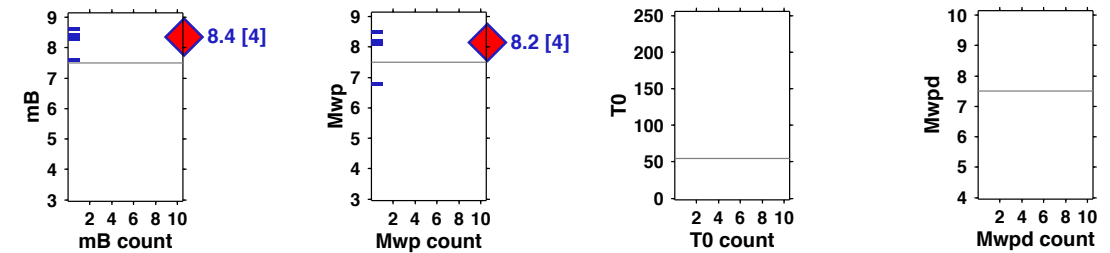
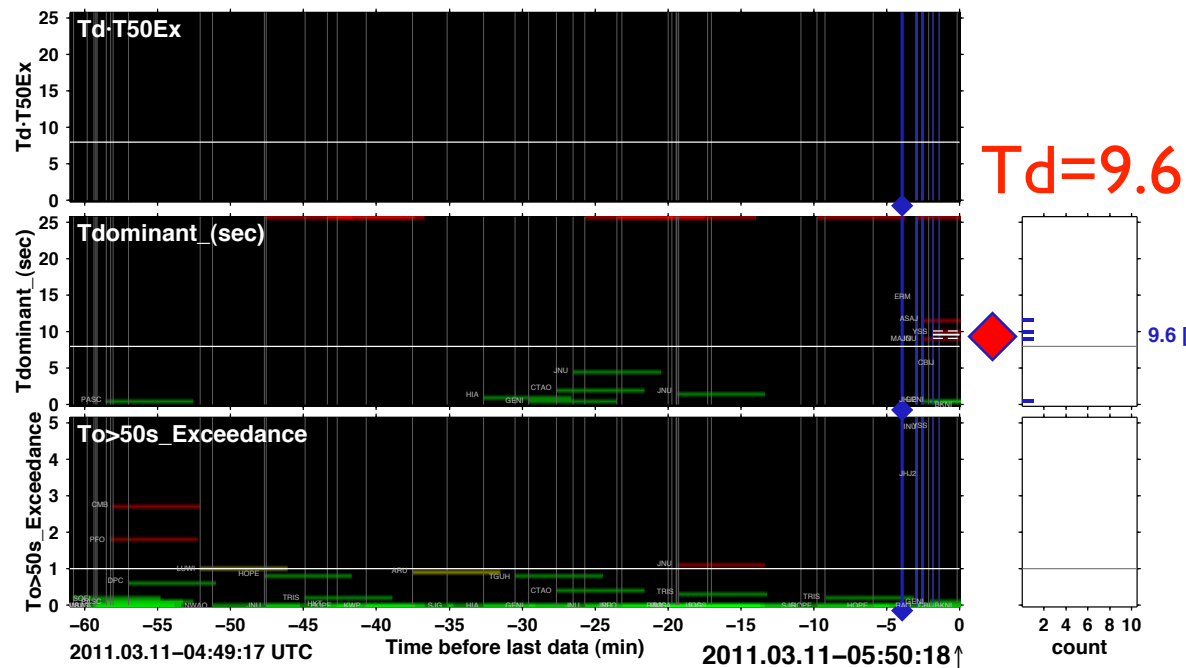
05:50:18 GMT

Tohoku Earthquake M9.0,

~ 4' from OT

11 March 2011, 05:46:20 GMT

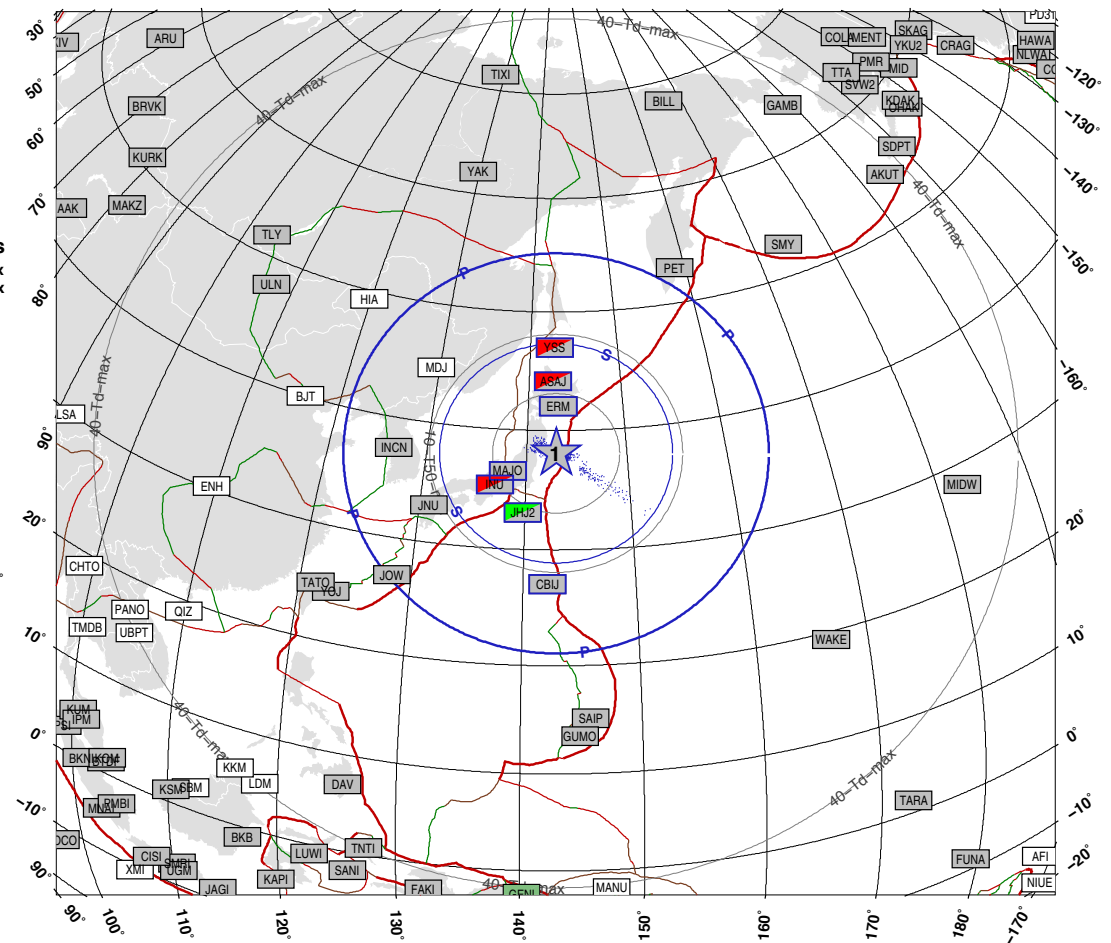
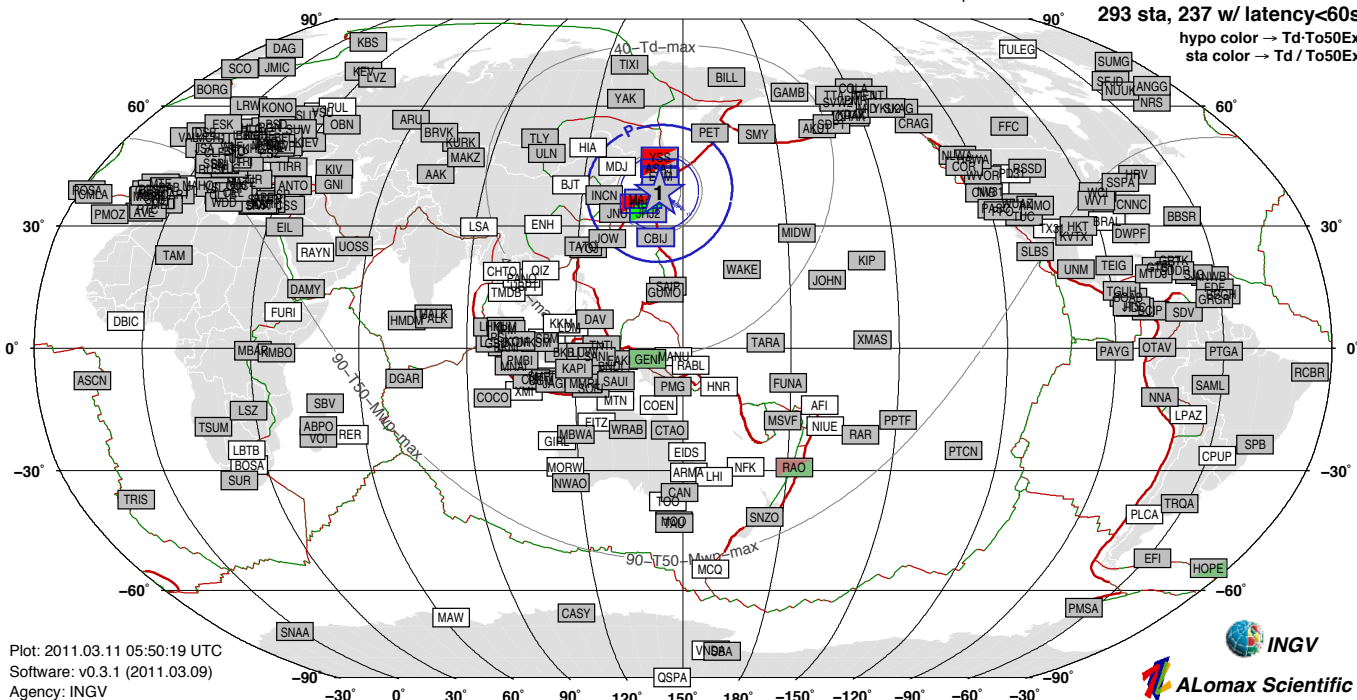
mB=8.4 Mwp=8.2



Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	TdT50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]			
1	7	3.9	0.8	2011.03.11-05:46:20	38.1	142.9	19	14	52	0.0	9.6	4	0.0	8.4	8.2	n/a	0	n/a	0



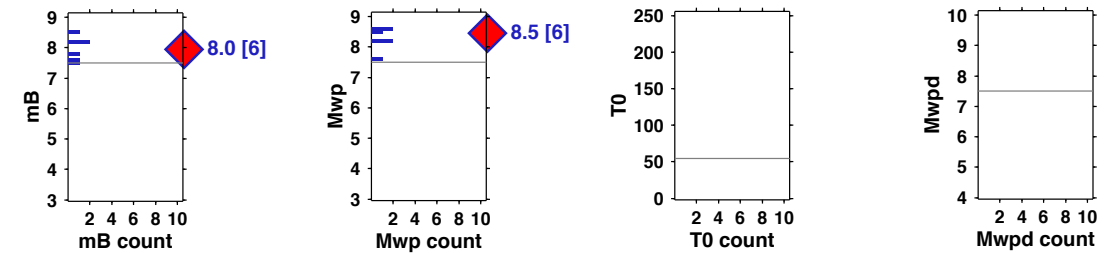
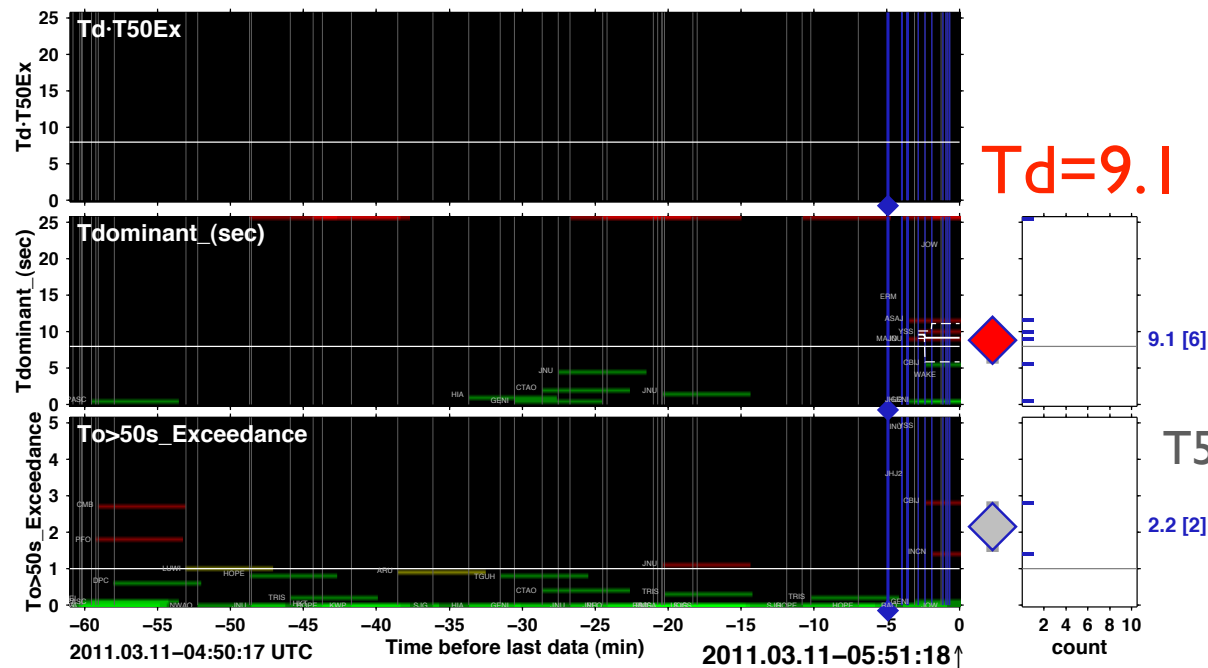
05:51:18 GMT

Tohoku Earthquake M9.0,

~ 5' from OT

11 March 2011, 05:46:20 GMT

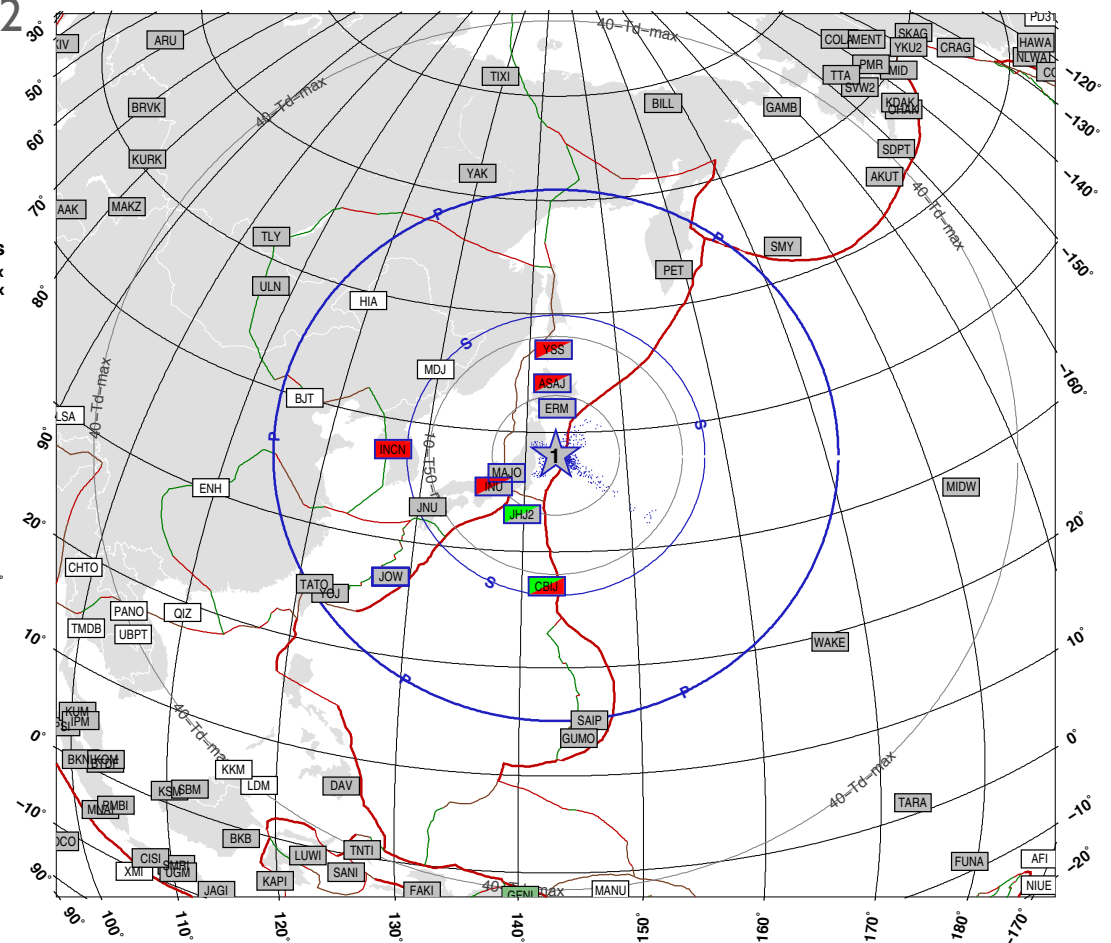
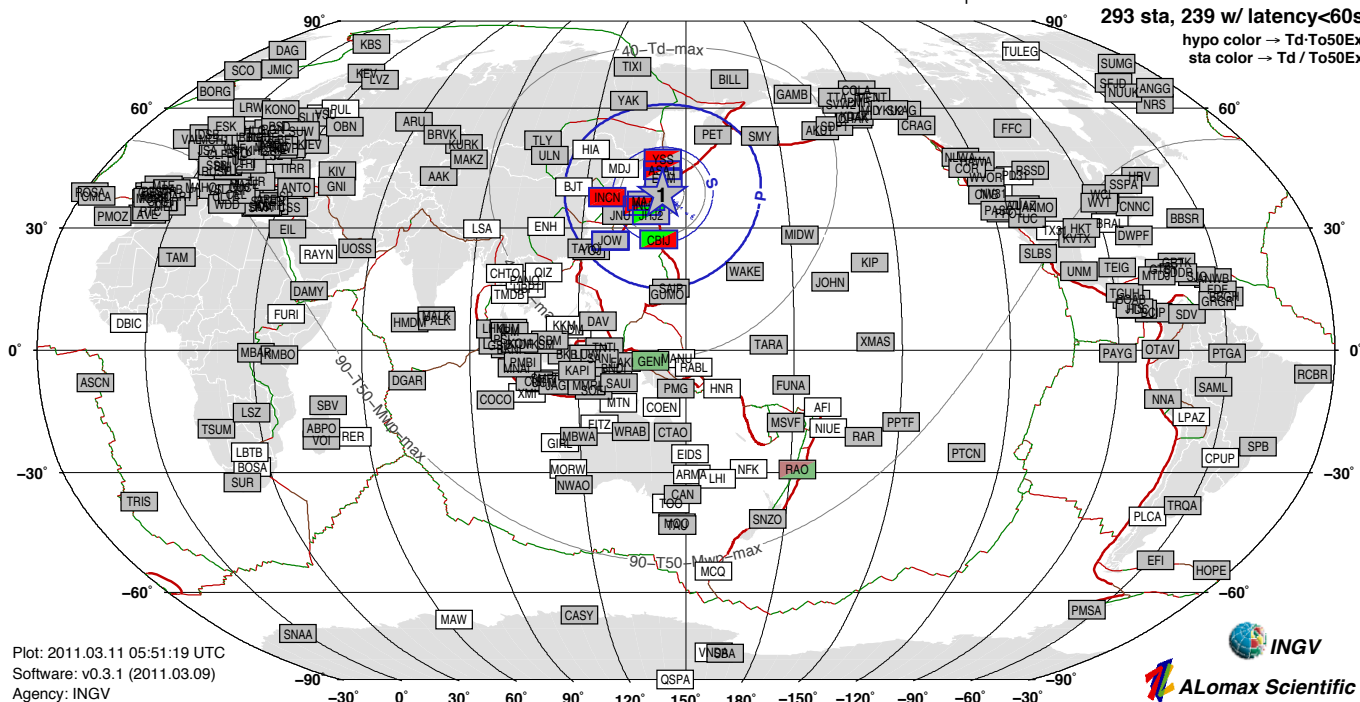
mB=8.0 Mwp=8.5



Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	TdT50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]
1	9	3.9	0.7	2011.03.11-05:46:22	38.1	143.0	17	95	49	2.2 2	9.1 6	0.0	8.0 6	8.5 6	n/a 0	n/a 0



Plot: 2011.03.11 05:51:19 UTC
Software: v0.3.1 (2011.03.09)
Agency: INGV

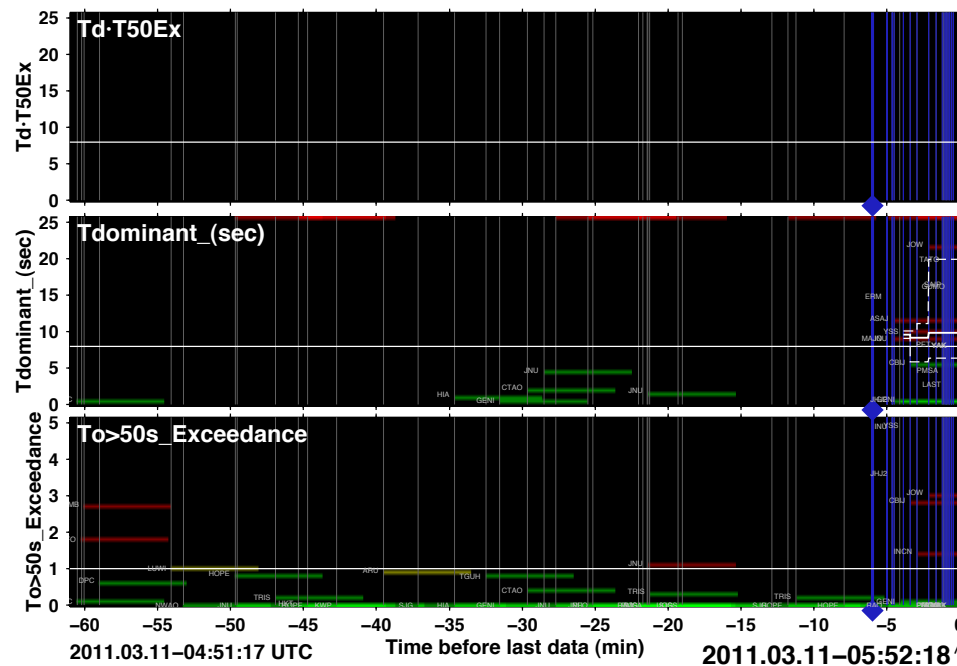
05:52:18 GMT

Tohoku Earthquake M9.0,

~ 6' from OT

11 March 2011, 05:46:20 GMT

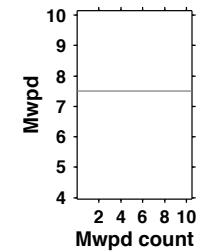
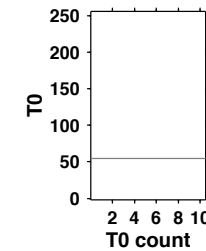
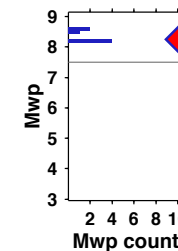
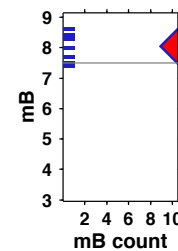
mB=8.1 Mwp=8.3



Td=9.8

9.8 [7]

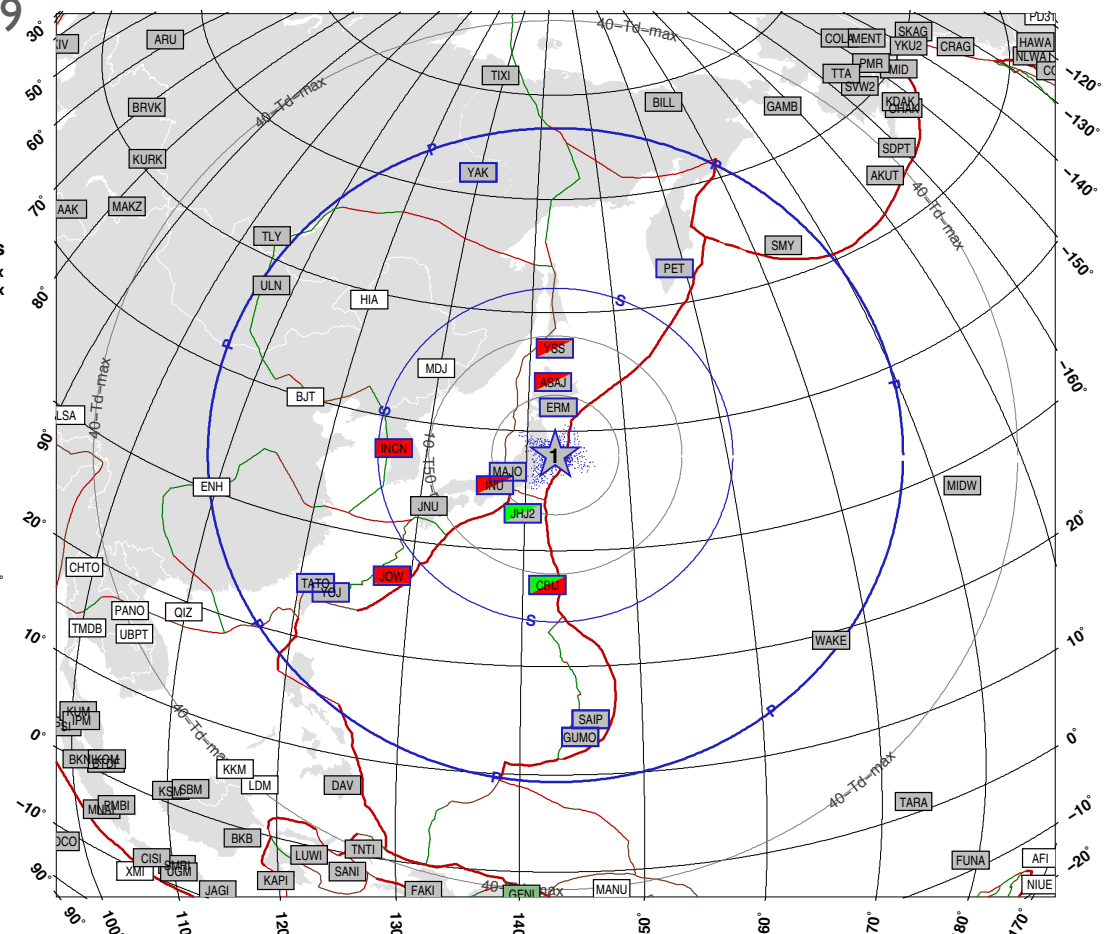
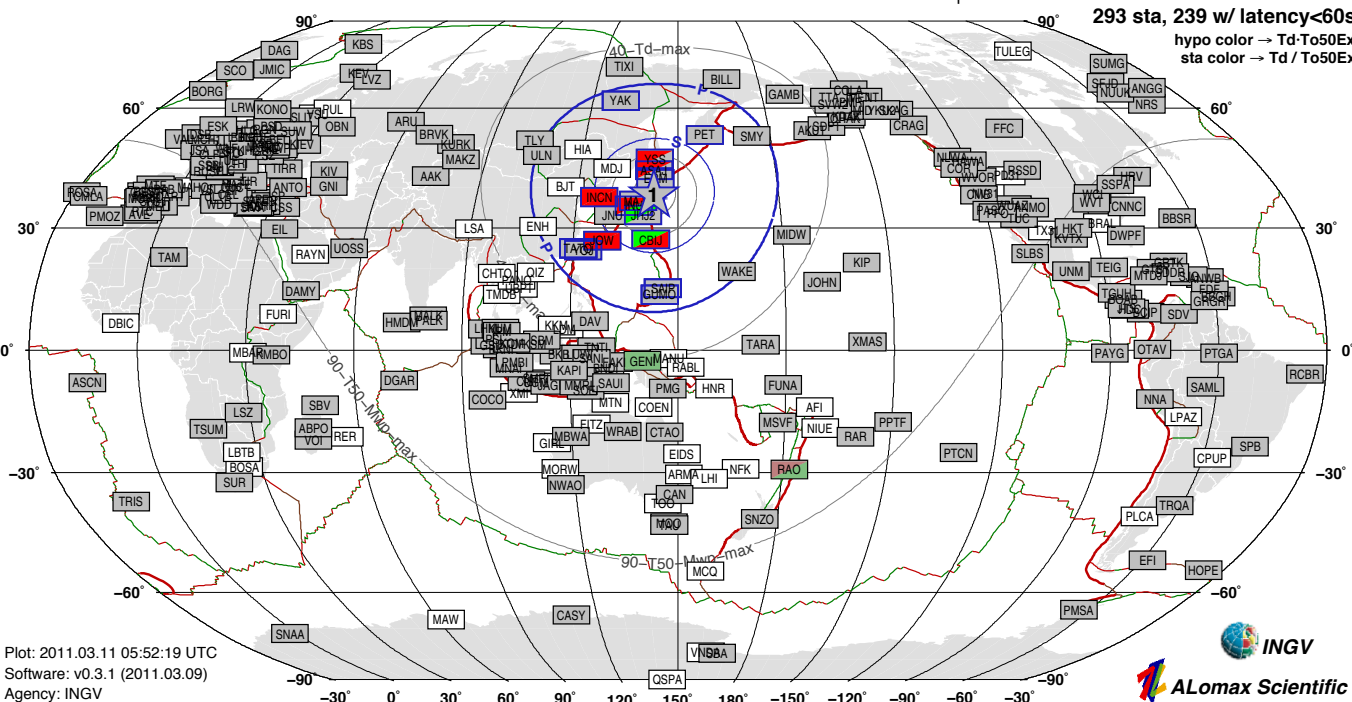
T50Ex=2.9
2.9 [3]



Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	TdT50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]
1	15	4.0	2.0	2011.03.11-05:46:20	38.0	142.9	25	14	19	2.9 3	9.8 7	0.0	8.1 7	8.3 7	n/a 0	n/a 0



Plot: 2011.03.11 05:52:19 UTC
Software: v0.3.1 (2011.03.09)
Agency: INGV

INGV
ALomax Scientific

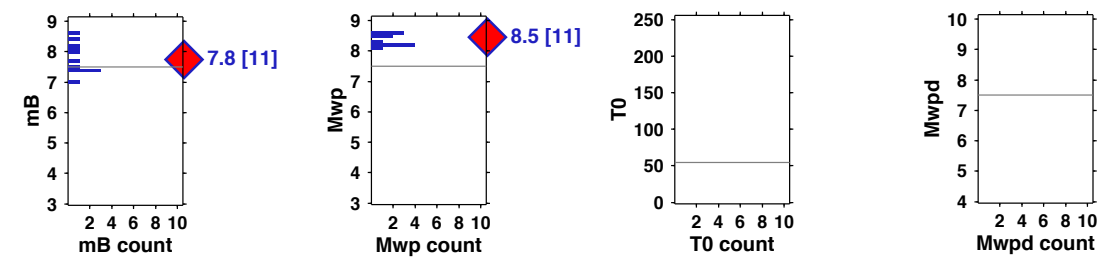
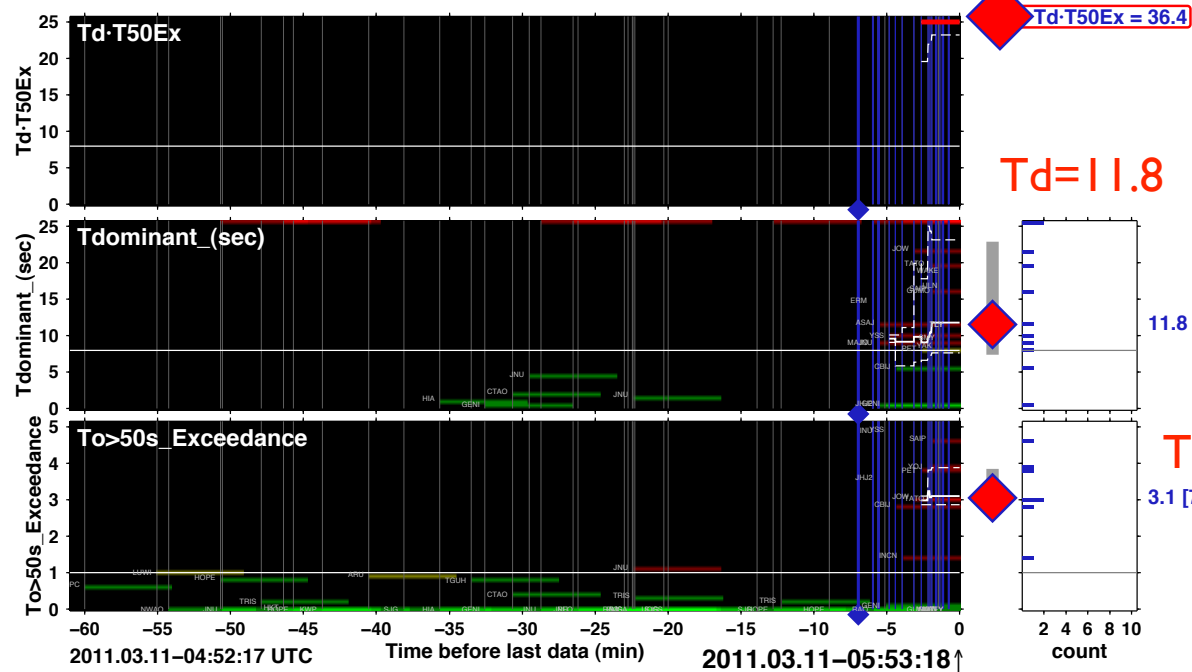
05:53:18 GMT

Tohoku Earthquake M9.0, ~ 7' from OT

11 March 2011, 05:46:20 GMT

Td T50Ex=36.4

mB=7.8 Mwp=8.5



Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

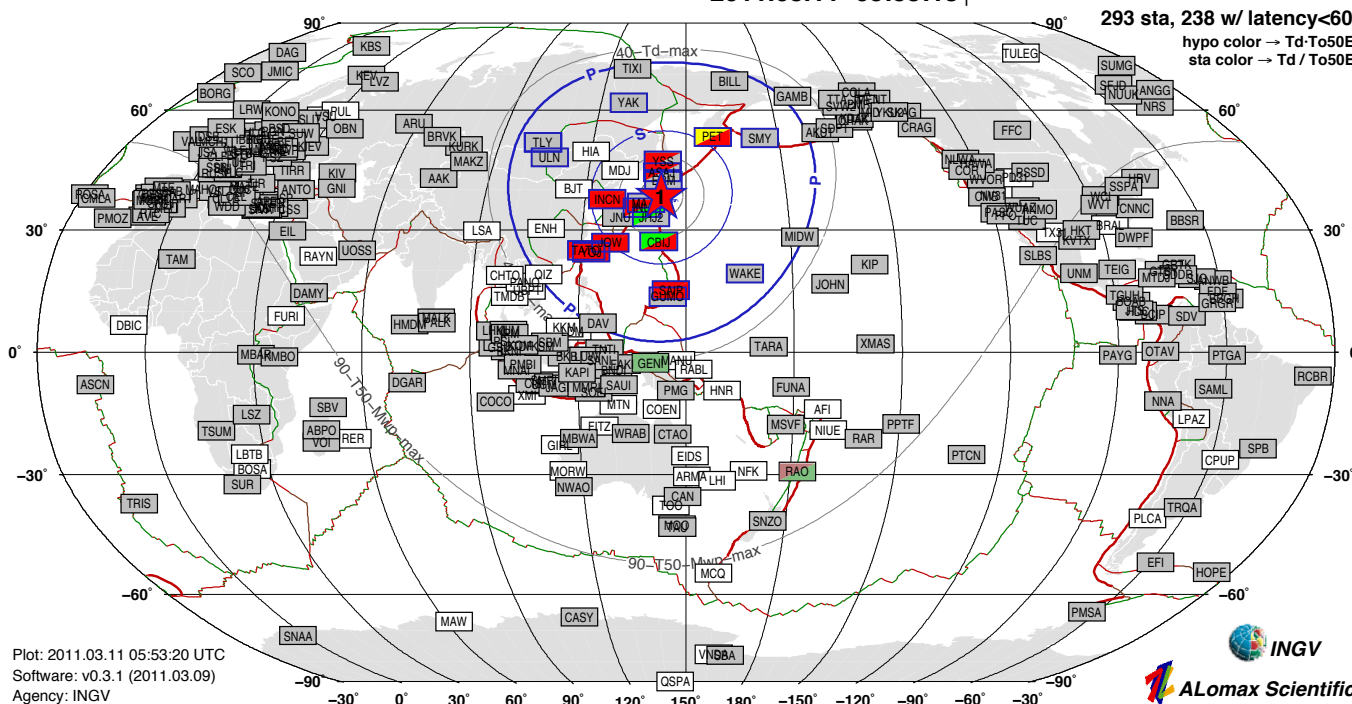
Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	Td-T50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]						
1	19	3.9	2.1	2011.03.11-05:46:21	38.1	142.7	24	14	15	3.1	7	11.8	11	36.4	7.8	11	8.5	11	n/a	0	n/a	0

T50Ex=3.1

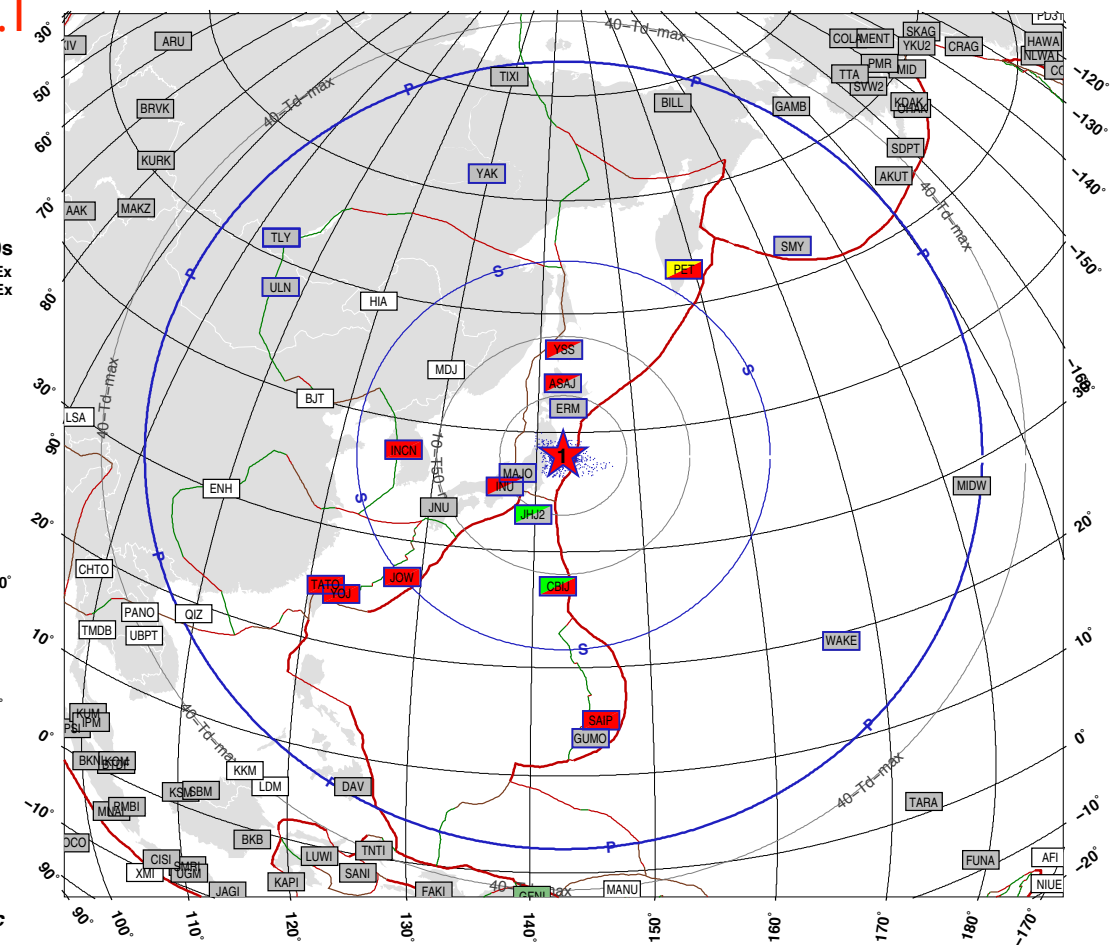
3.1 [7]

293 sta, 238 w/ latency<60s
hypo color → Td-To50Ex
sta color → Td / To50Ex



Plot: 2011.03.11 05:53:20 UTC
Software: v0.3.1 (2011.03.09)
Agency: ING

INGV
ALomax Scientific

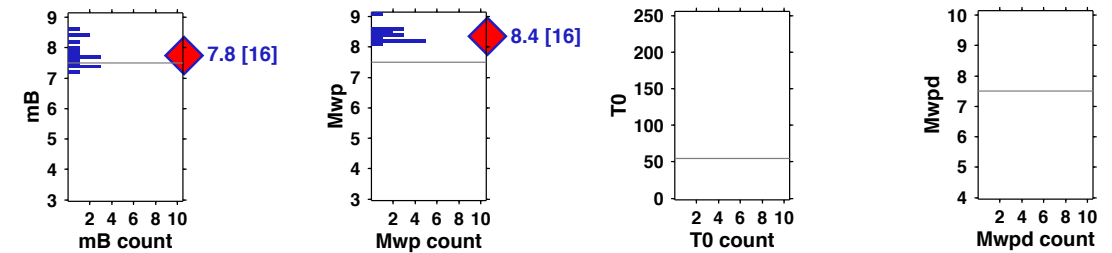
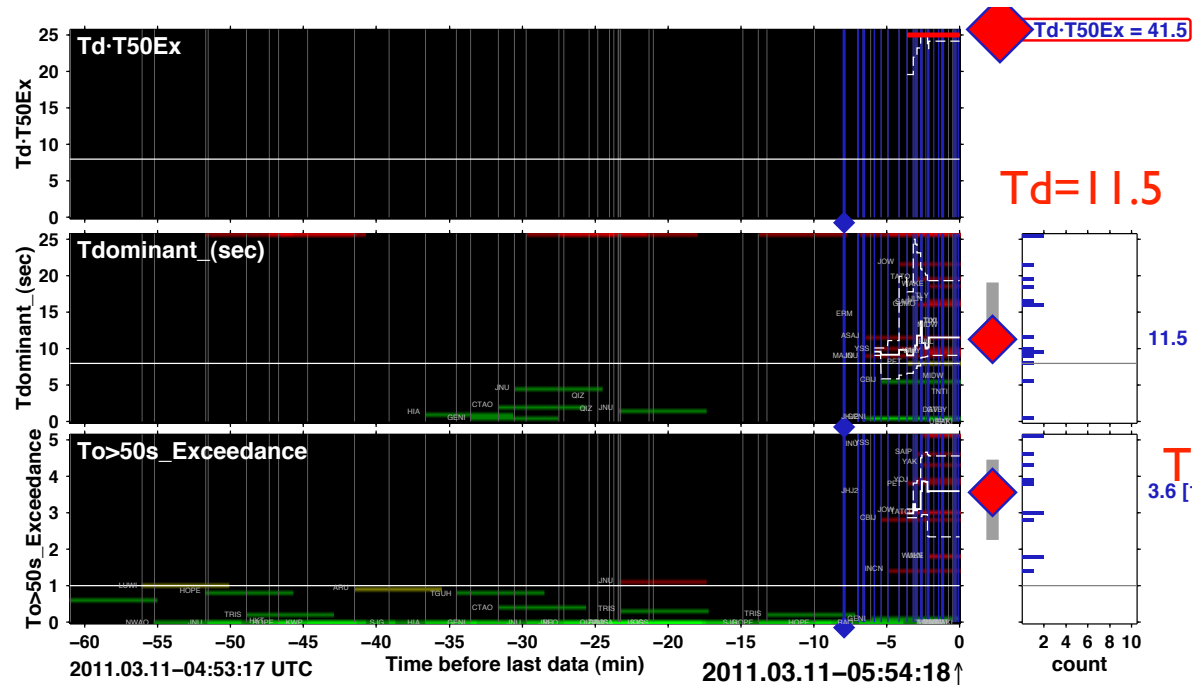


05:54:18 GMT Tohoku Earthquake M9.0, ~ 8' from OT

11 March 2011, 05:46:20 GMT

Td T50Ex=41.5

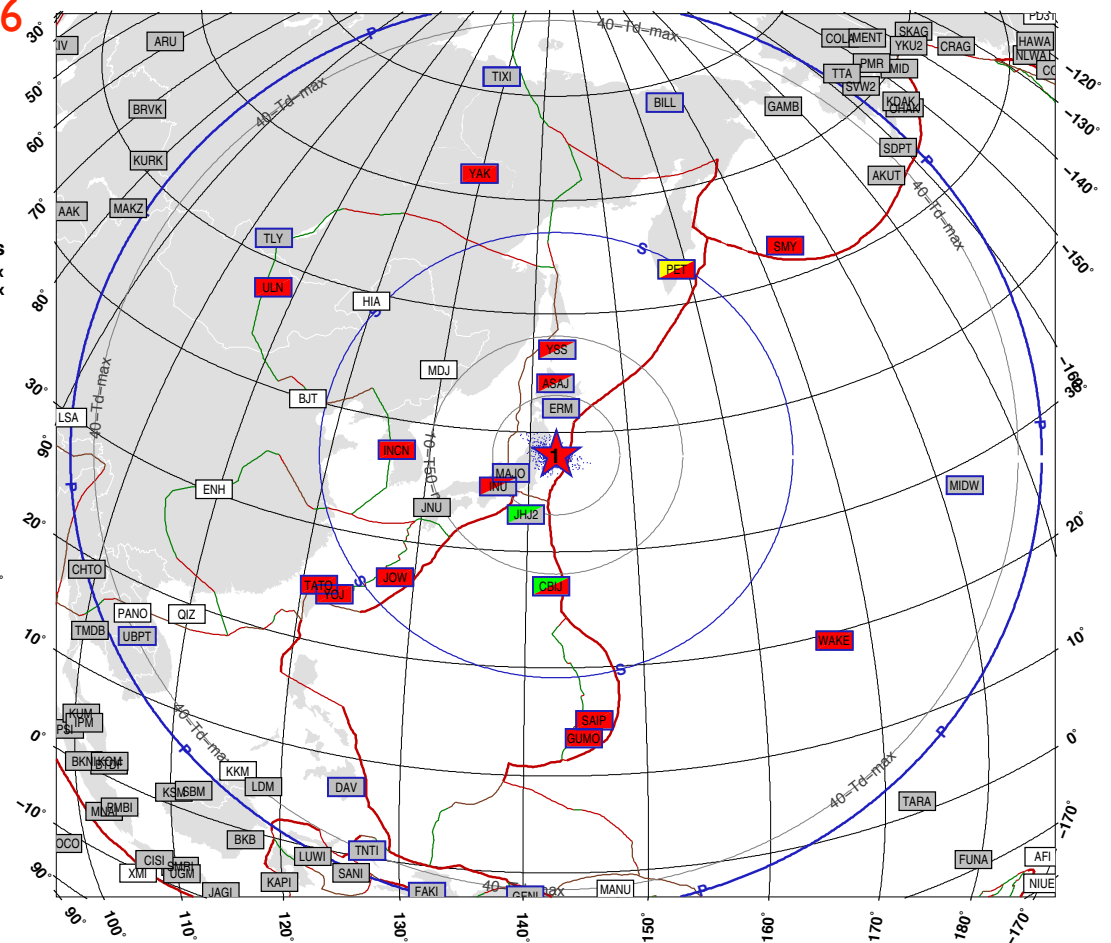
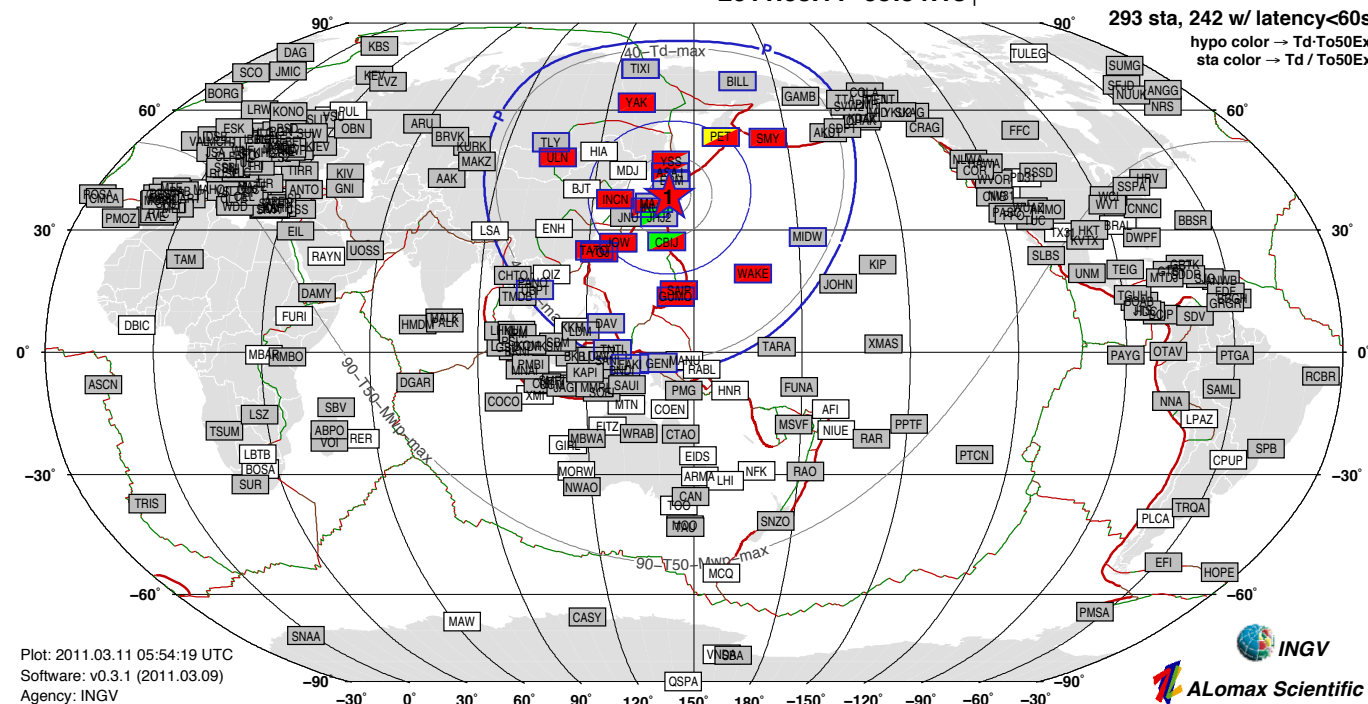
mB=7.8 Mwp=8.4



Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	Td-T50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]						
1	22	3.9	2.0	2011.03.11-05:46:21	38.1	142.6	22	14	16	3.6	12	11.5	16	41.5	7.8	16	8.4	16	n/a	0	n/a	0



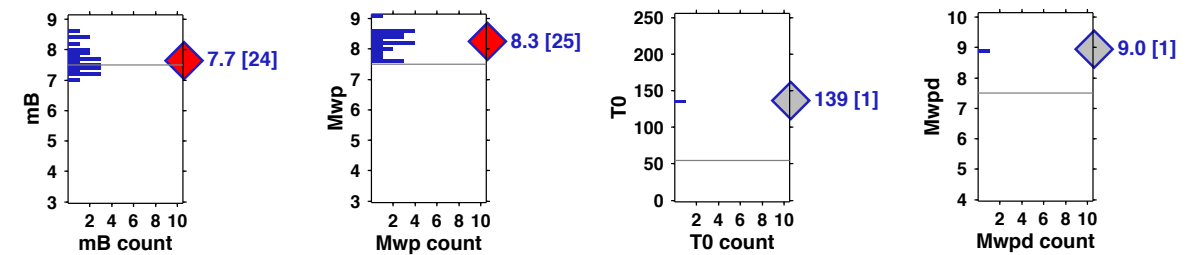
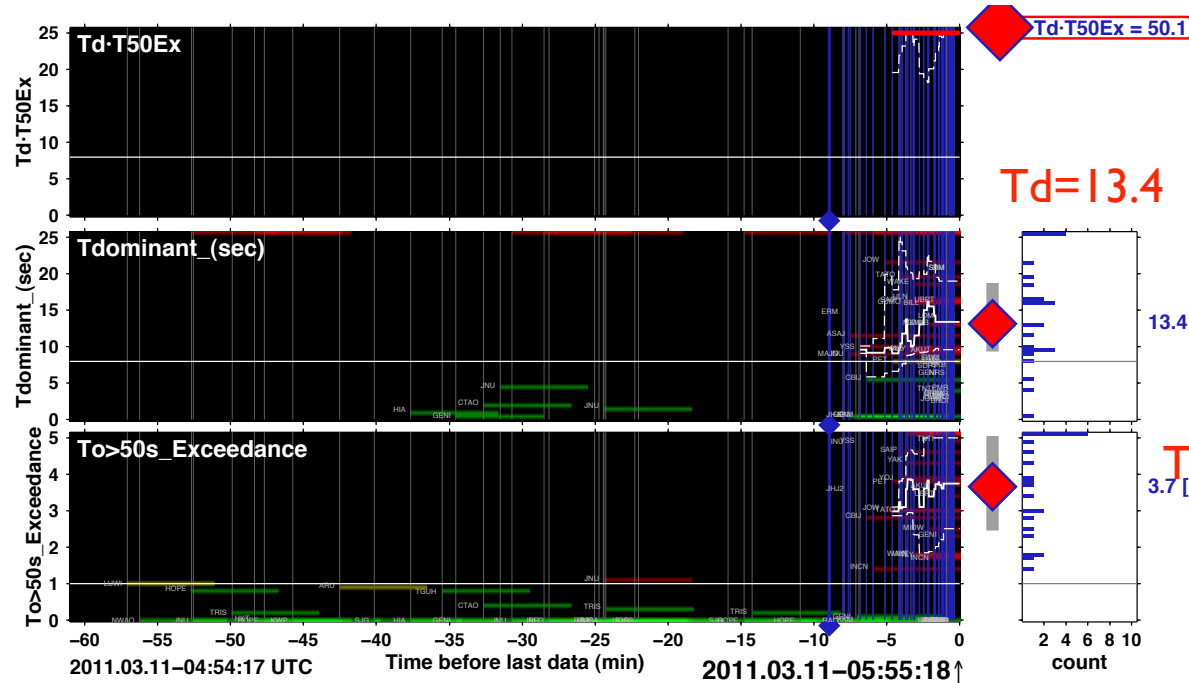
05:55:18 GMT Tohoku Earthquake M9.0, ~ 9' from OT

11 March 2011, 05:46:20 GMT

Td T50Ex=50.1

mB=7.7 Mwp=8.3

T0=139 Mwpd=9.0



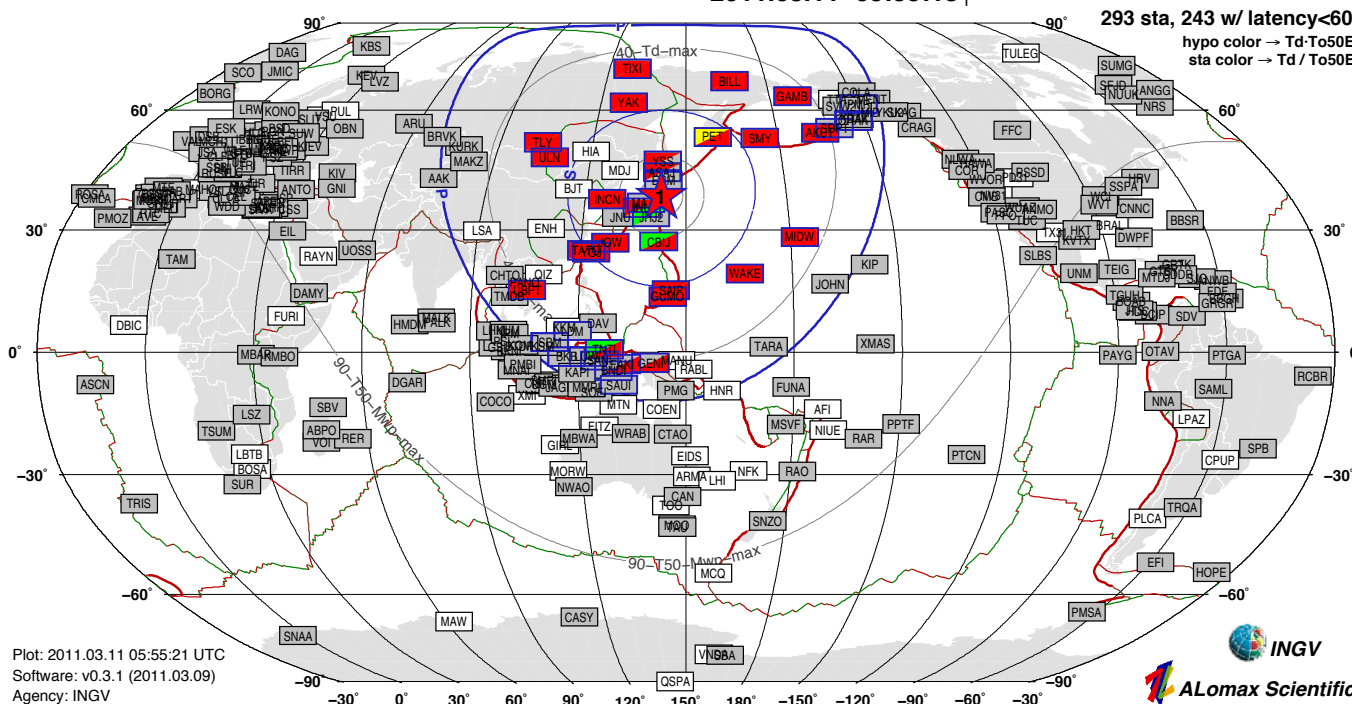
Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	Td-T50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]
1	36	3.9	1.8	2011.03.11-05:46:22	38.1	142.6	25	14	14	3.7 22	13.4 24	50.1	7.7 24	8.3 25	n/a 1	n/a 1

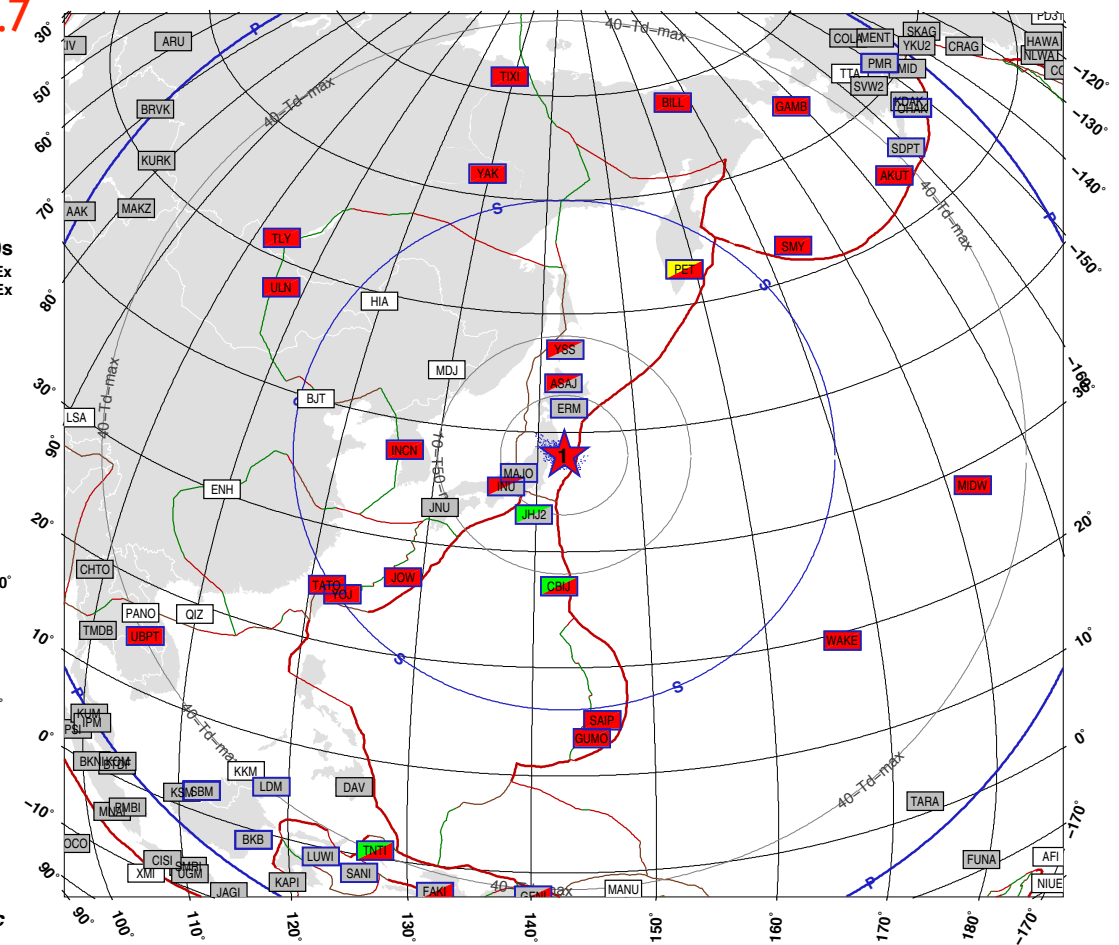
T50Ex=3.7
3.7 [22]

293 sta, 243 w/ latency<60s
hypo color → Td-To50Ex
sta color → Td / To50Ex



Plot: 2011.03.11 05:55:21 UTC
Software: v0.3.1 (2011.03.09)
Agency: ING

INGV
ALomax Scientific



05:56:18 GMT

Tohoku Earthquake M9.0,

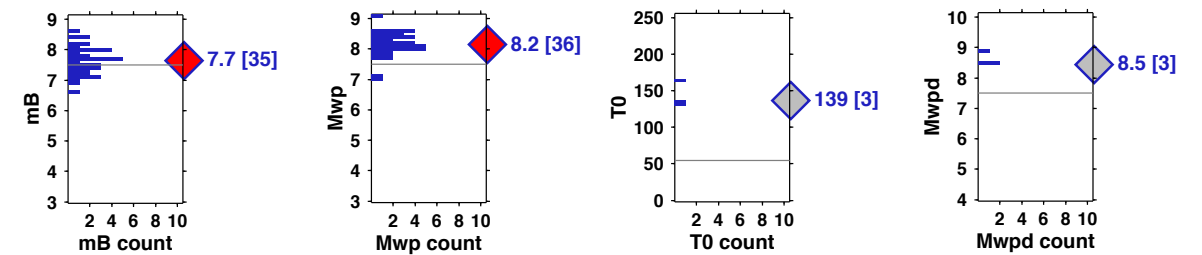
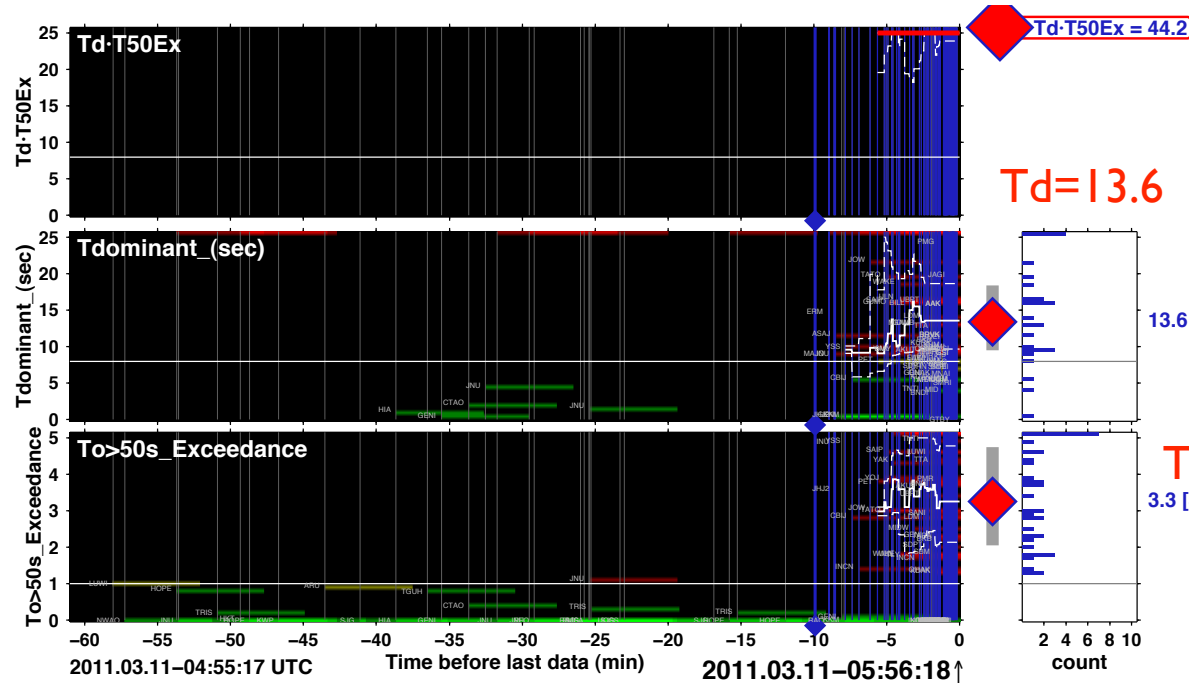
~ 10' from OT

11 March 2011, 05:46:20 GMT

Td T50Ex=44.2

mB=7.7 Mwp=8.2

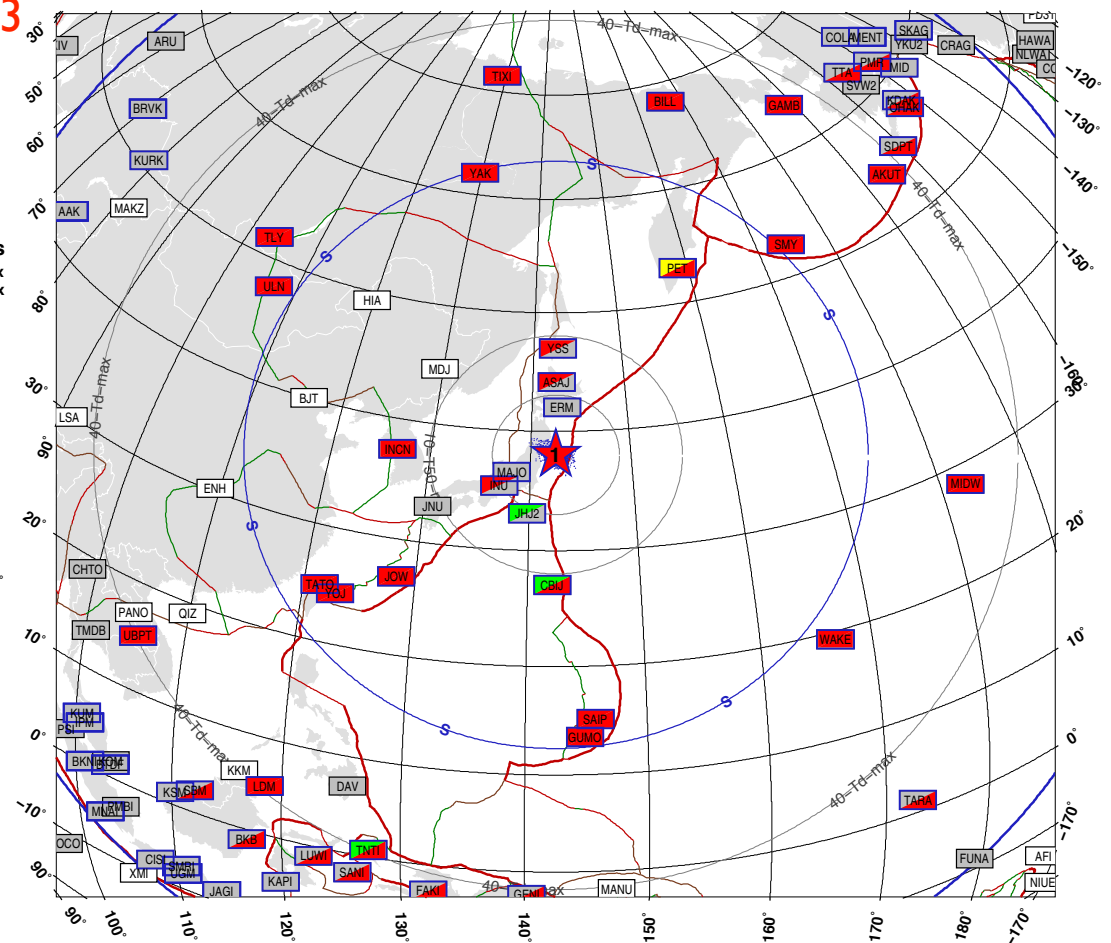
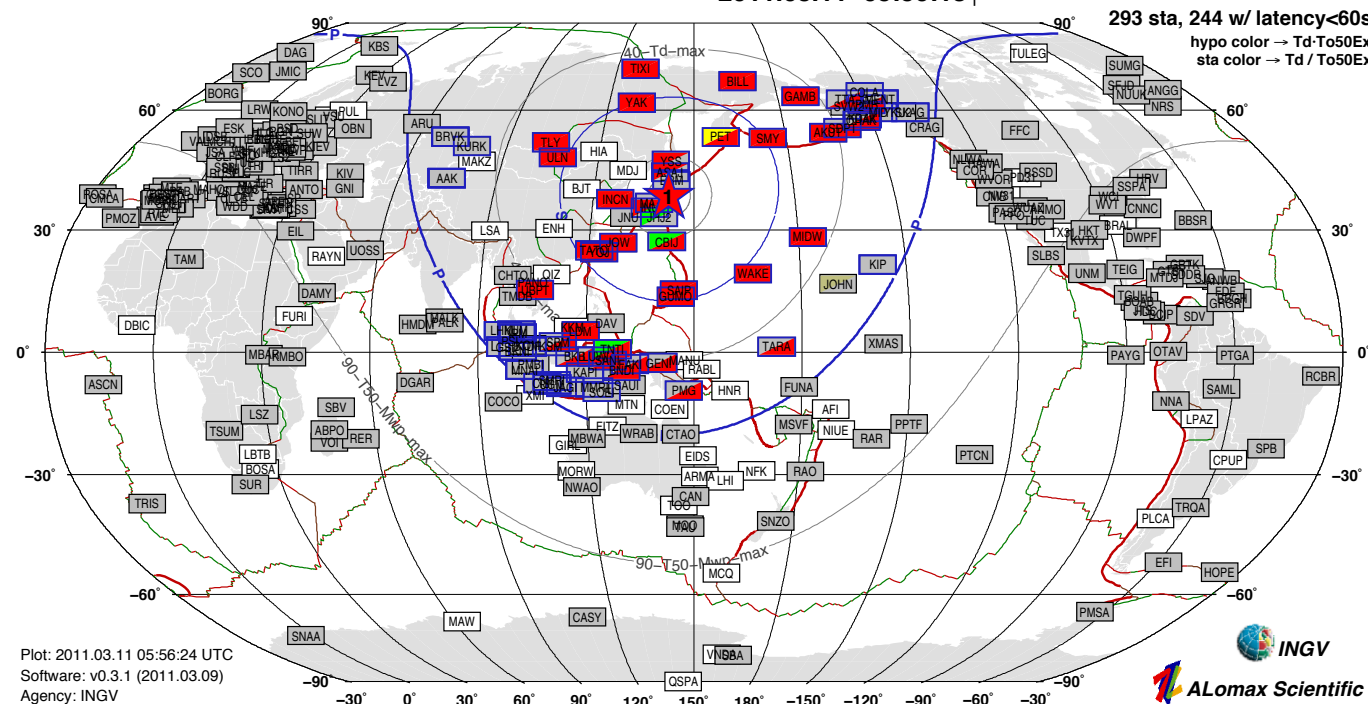
T0=139 Mwpd=8.5



Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	Td-T50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]
1	63	3.7	2.0	2011.03.11-05:46:22	38.0	142.5	26	14	12	3.3 35	13.6 25	44.2	7.7 35	8.2 36	n/a 3	n/a 3



Plot: 2011.03.11 05:56:24 UTC
Software: v0.3.1 (2011.03.09)
Agency: INGV

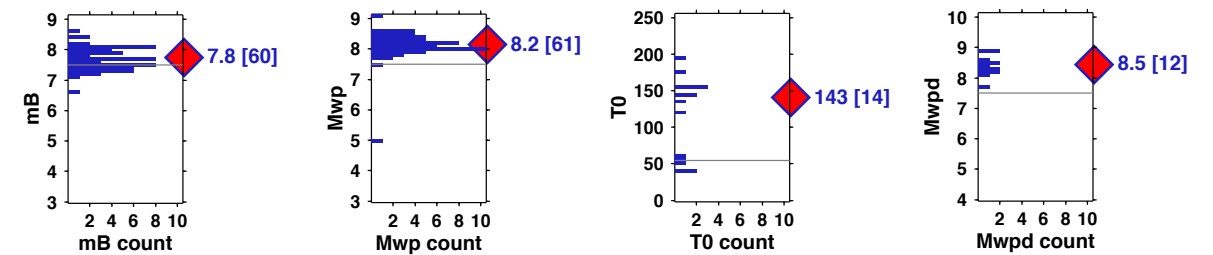
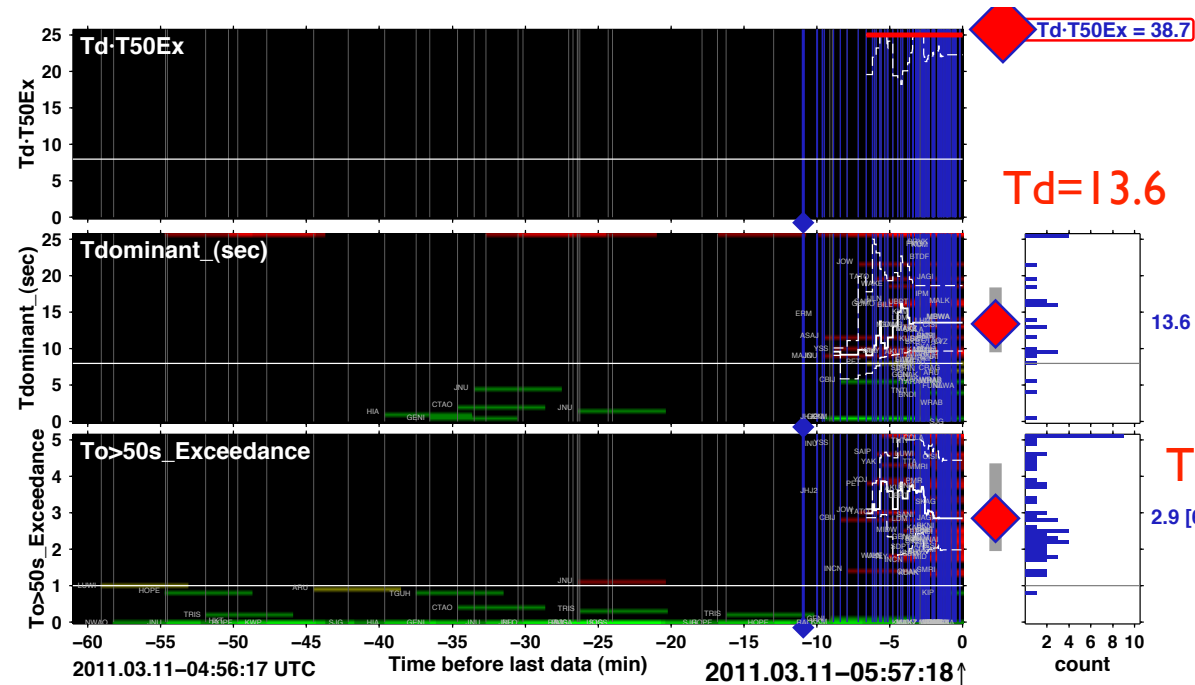
05:57:18 GMT

Tohoku Earthquake M9.0,

~ ||' from OT

Td T50Ex=38.7

mB=7.8 Mwp=8.2 T0=139 Mwpd=8.5



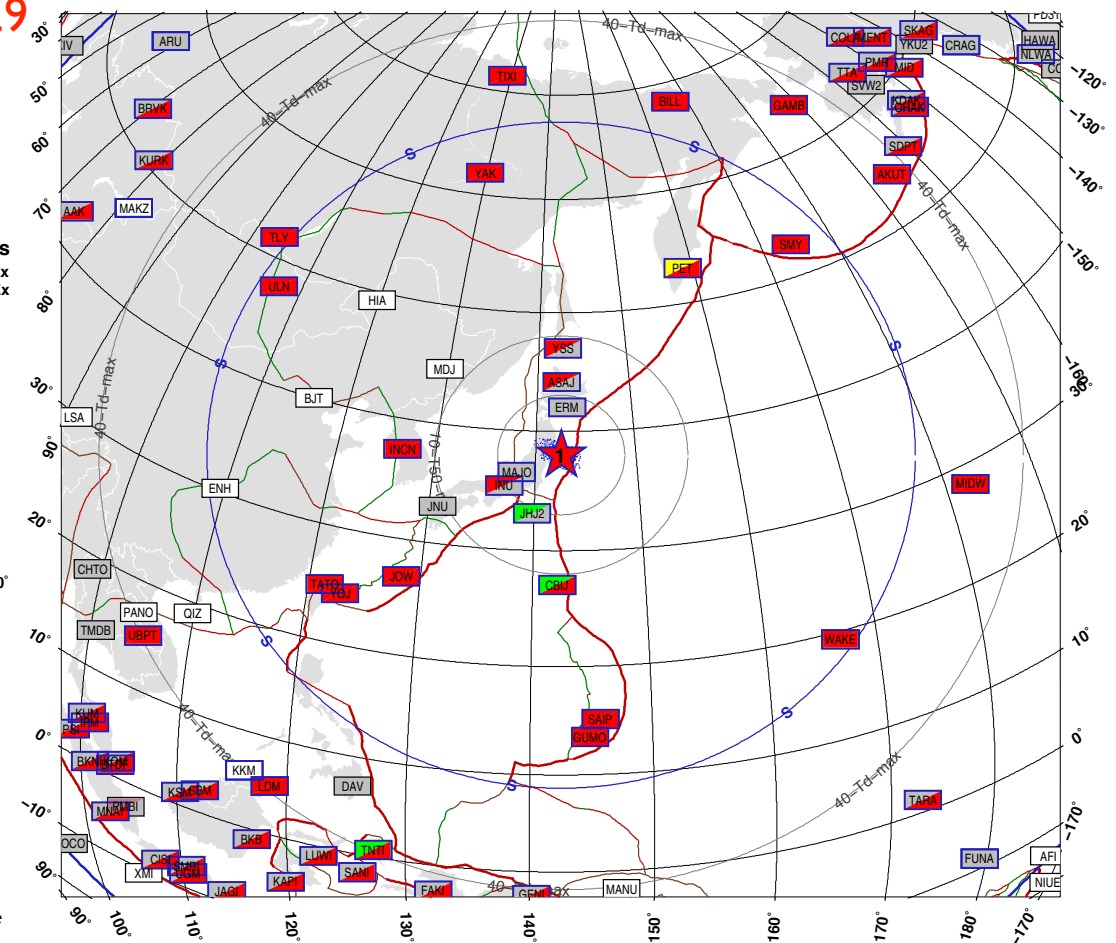
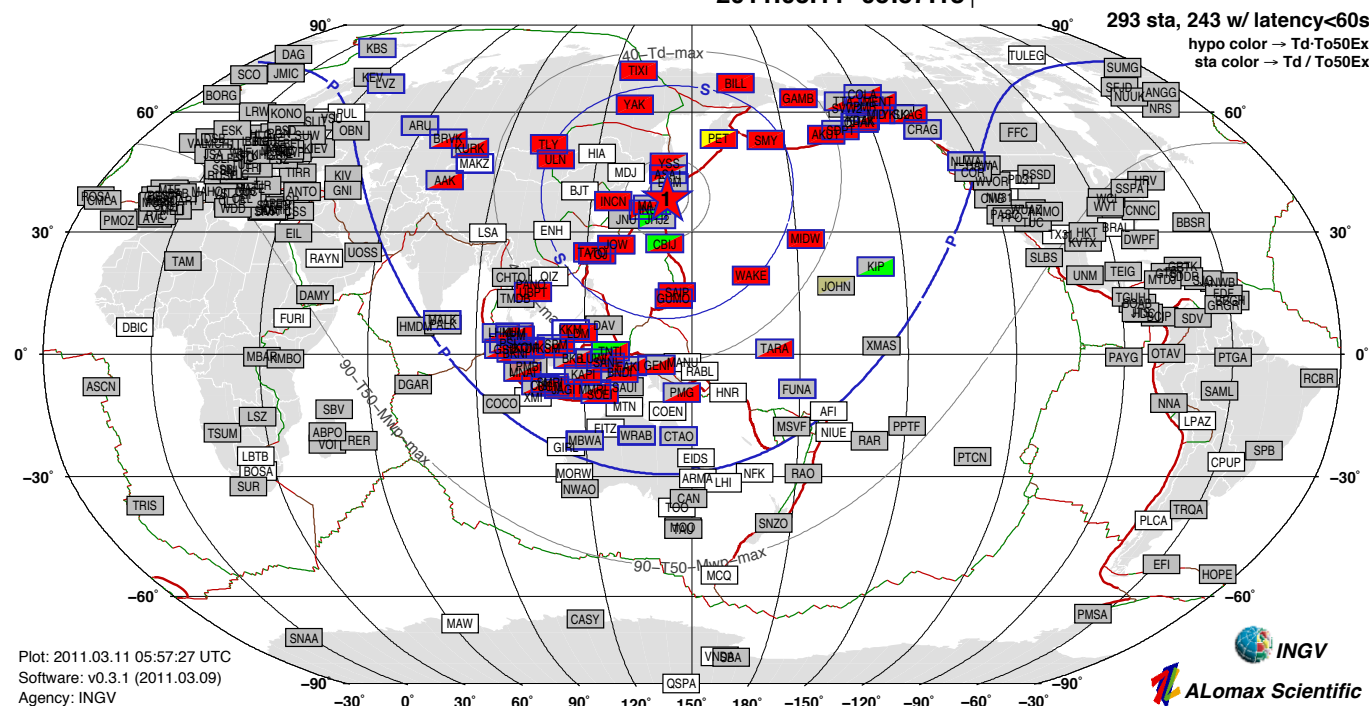
13.6 [25] Earthquake Location · Td·T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Amin°	oort	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex	[n]	Td	[n]	TdT50	WL	mB	[n]	Mwp	[n]	T0	[n]	Mwpd	[n]
1	77	3.8	2.1	2011.03.11-05:46:22	38.0	142.5	27	14	11	2.9	60	13.6	25	38.7		7.8	60	8.2	61	143	14	8.5	12

T50Ex=2.9

2.9 [60]

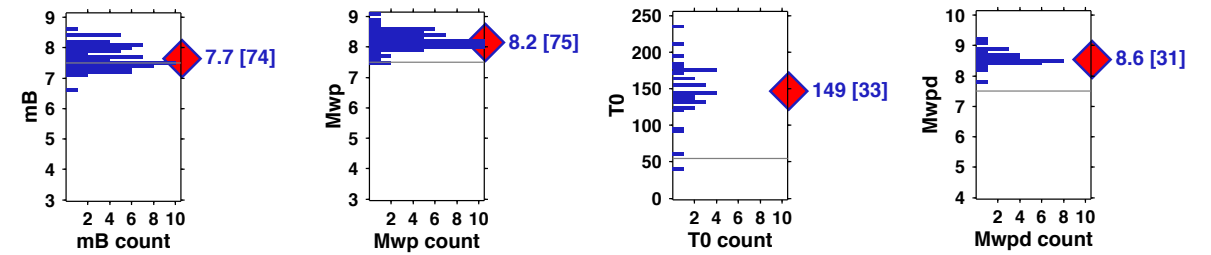
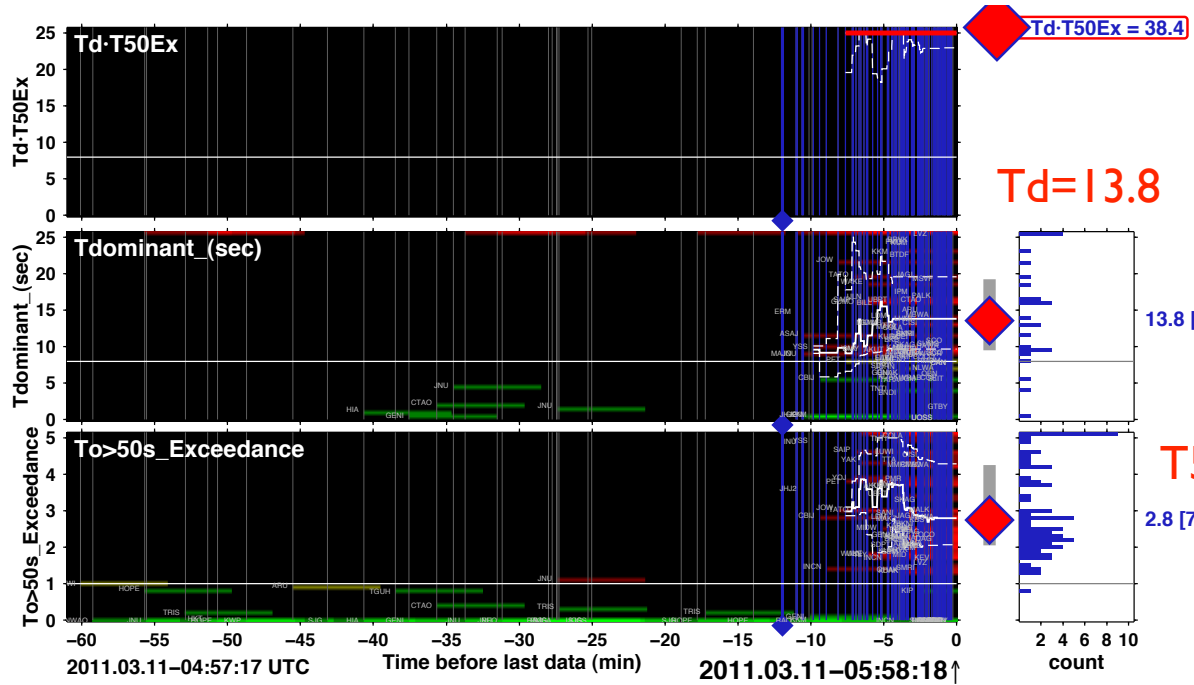


05:58:18 GMT Tohoku Earthquake M9.0, ~ 12' from OT

11 March 2011, 05:46:20 GMT

Td T50Ex=38.4

mB=7.7 Mwp=8.2 T0=149 Mwpd=8.6

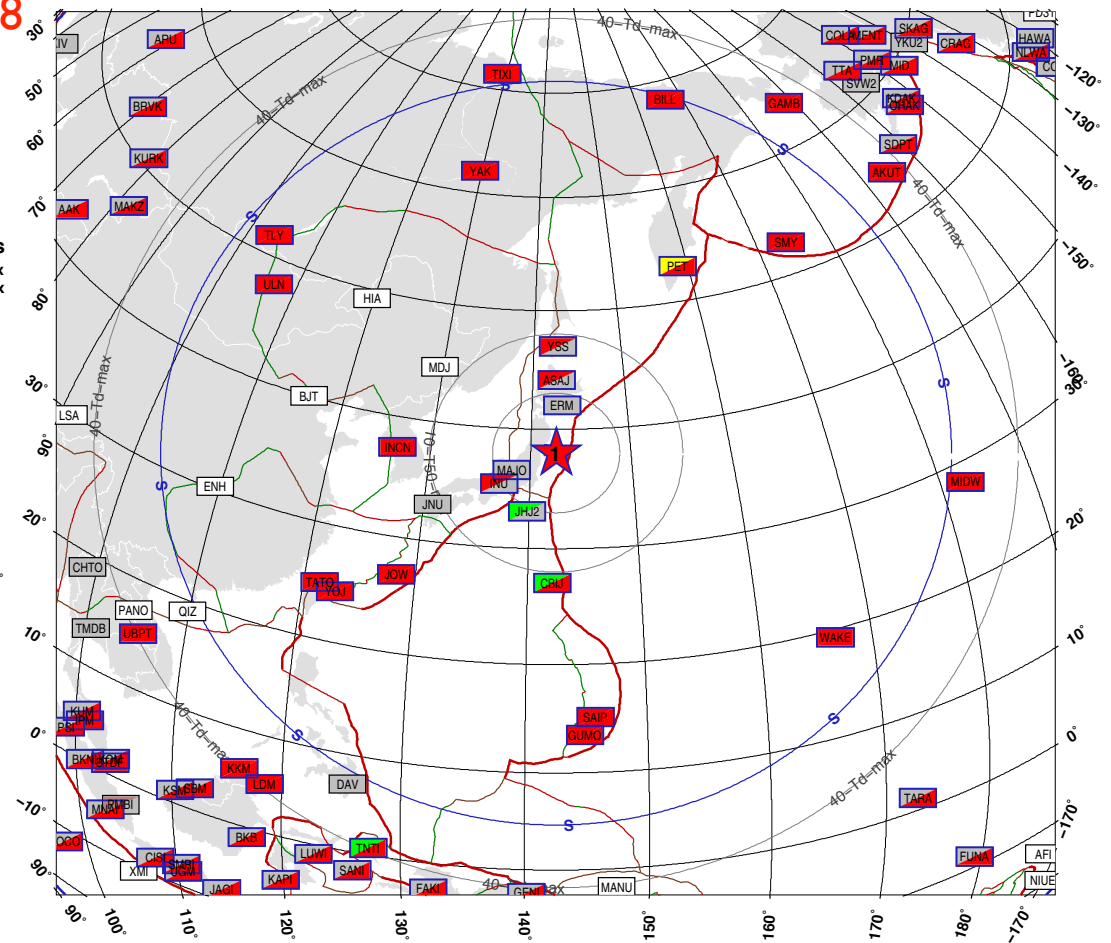
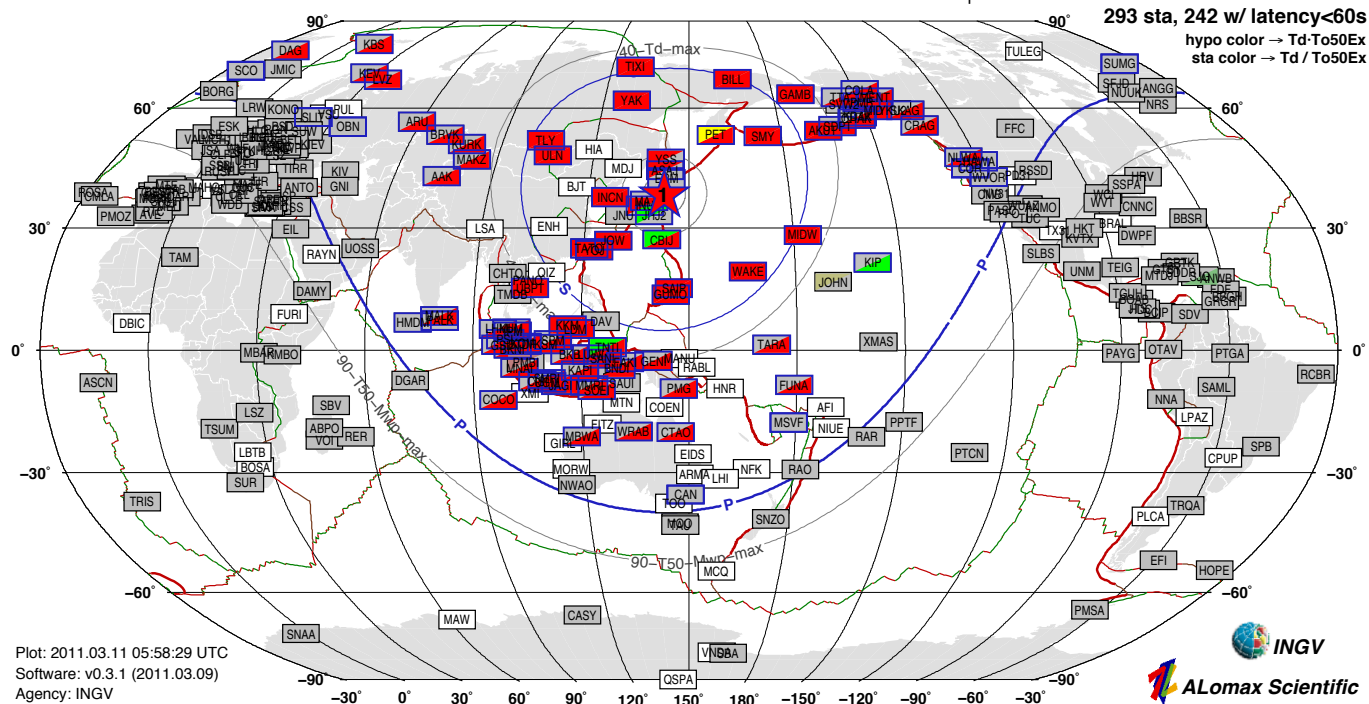


Earthquake Location · Td·T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	$\cot$	origin-time-UTC	lat $^\circ$	lon $^\circ$	errH	depth	errZ	T50Ex [n]	Td [n]	TdT50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]
1	89	3.8	2.1	2011.03.11-05:46:21	38.0	142.5	25	14	13	2.8 ₇₅	13.8 ₂₆	38.4	7.7 ₇₄	8.2 ₇₅	149 ₃₃	8.6 ₃₁

T50Ex=2.8

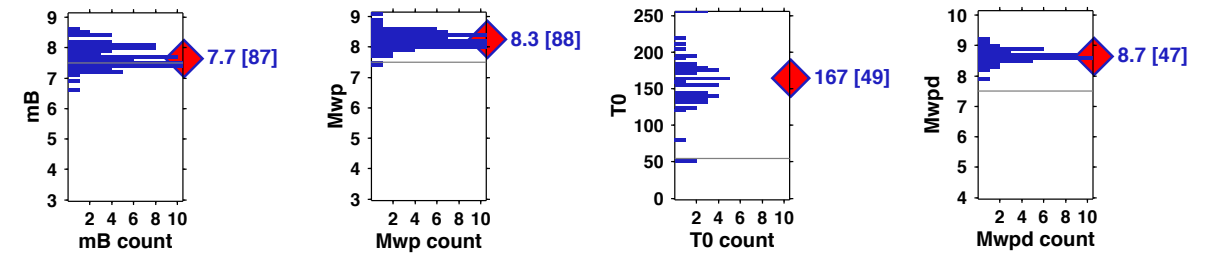
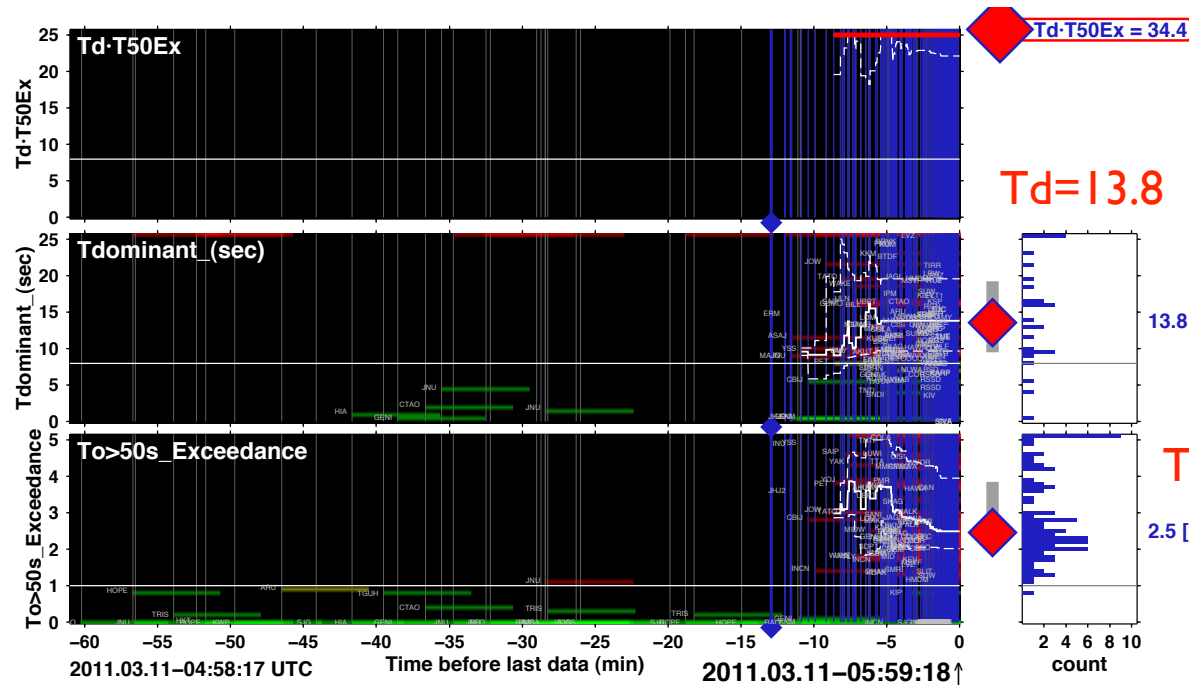


05:59:18 GMT Tohoku Earthquake M9.0, ~ 13' from OT

11 March 2011, 05:46:20 GMT

Td T50Ex=34.4

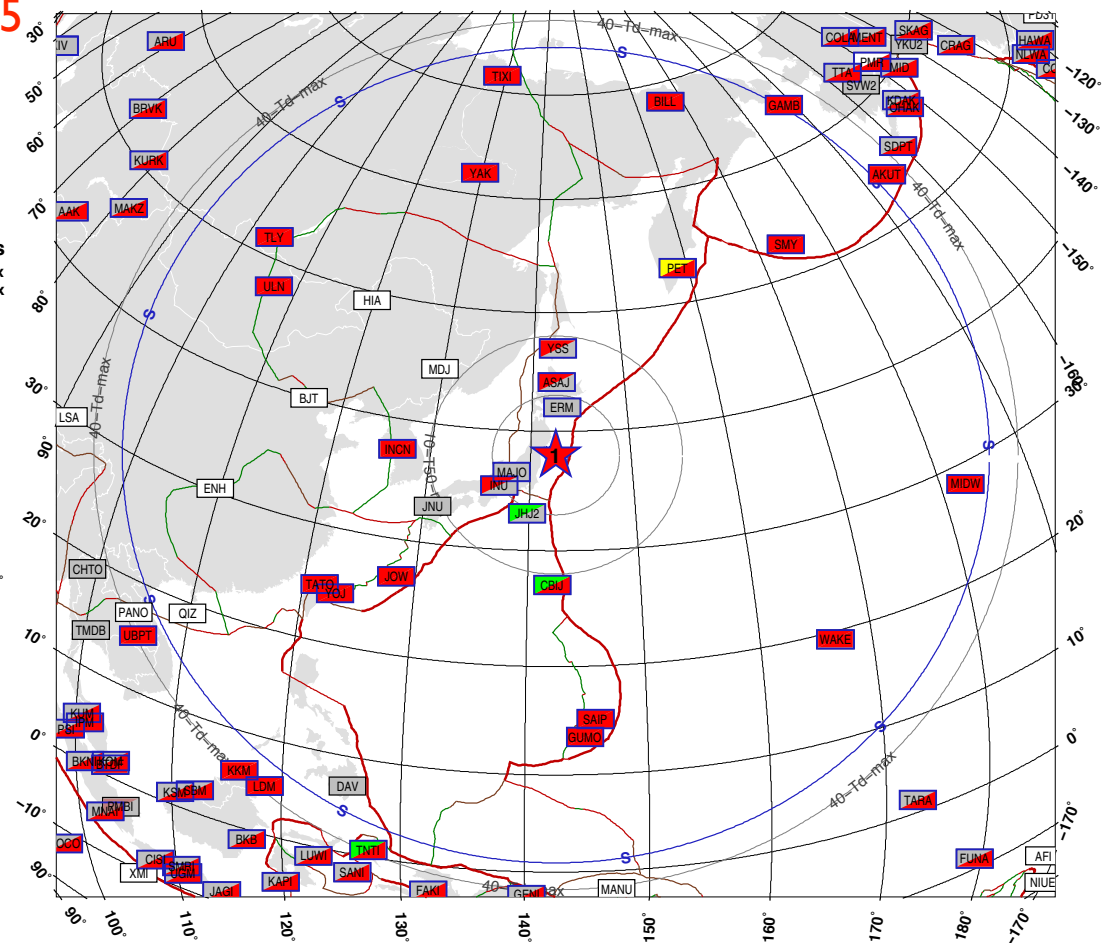
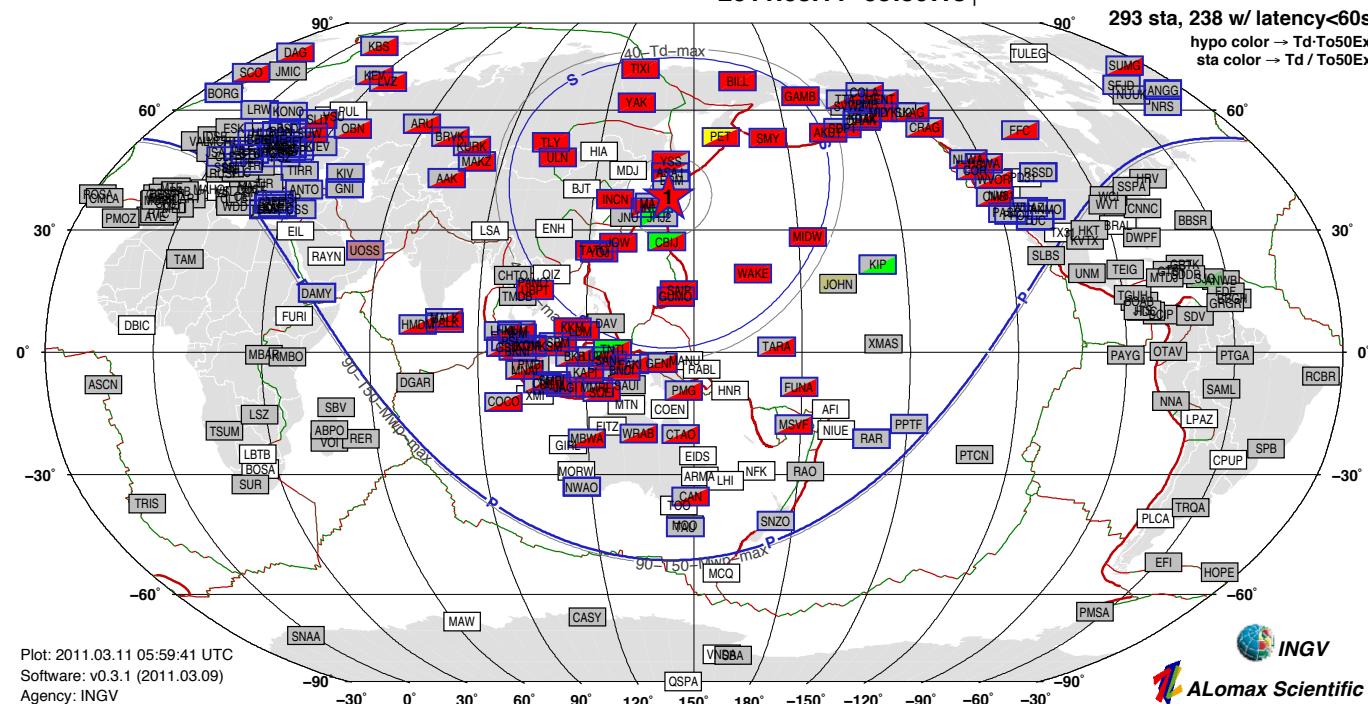
mB=7.7 Mwp=8.3 T0=167 Mwpd=8.7



Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	Td-T50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]
1	139	3.7	2.0	2011.03.11-05:46:22	38.0	142.5	23	14	14	2.5 89	13.8 26	34.4	7.7 87	8.3 88	167 49	8.7 47

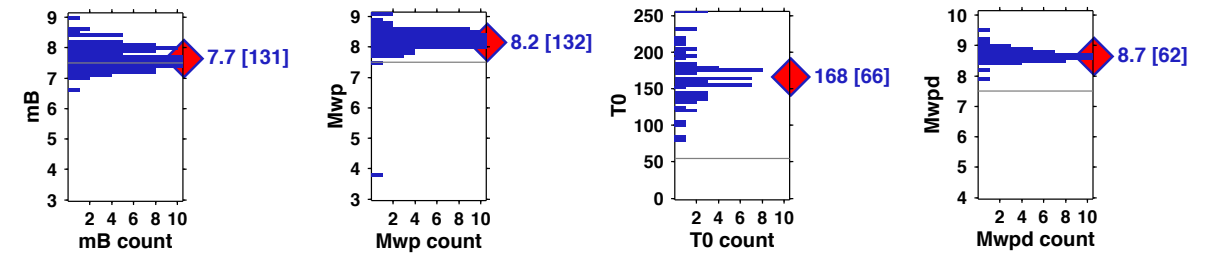
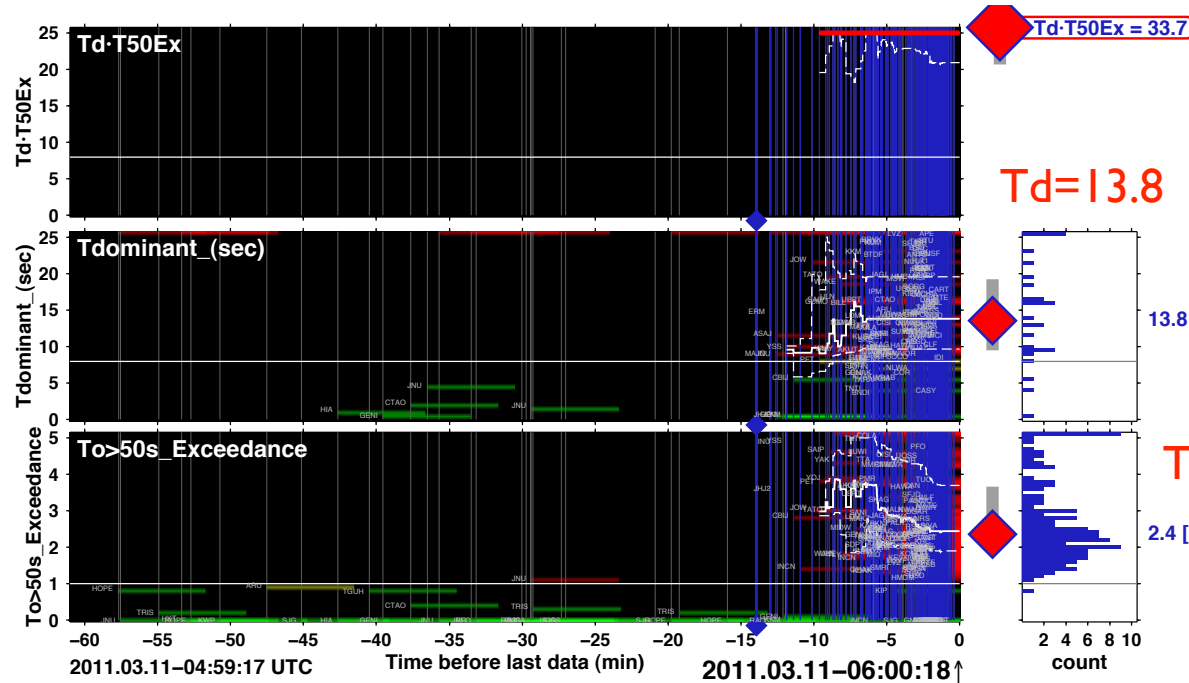


06:00:18 GMT Tohoku Earthquake M9.0, ~ 14' from OT

11 March 2011, 05:46:20 GMT

Td T50Ex=33.7

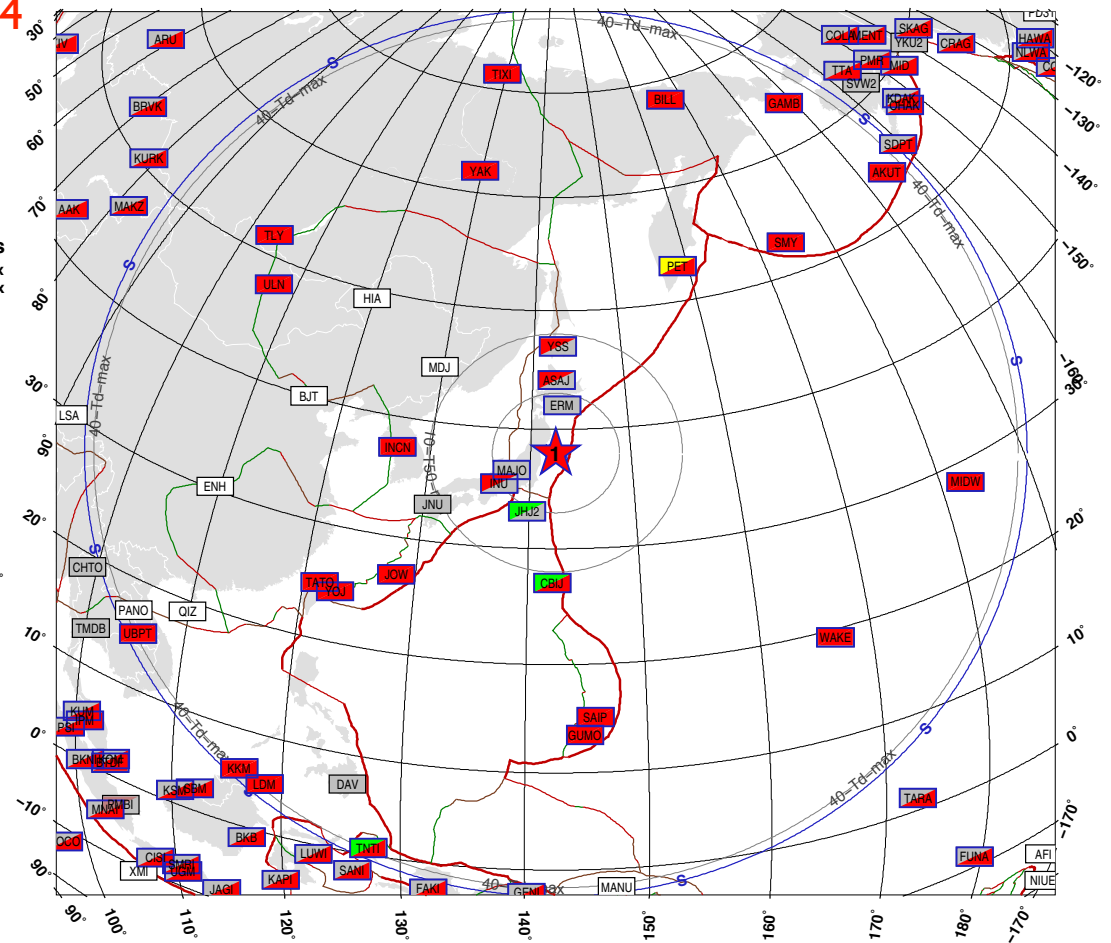
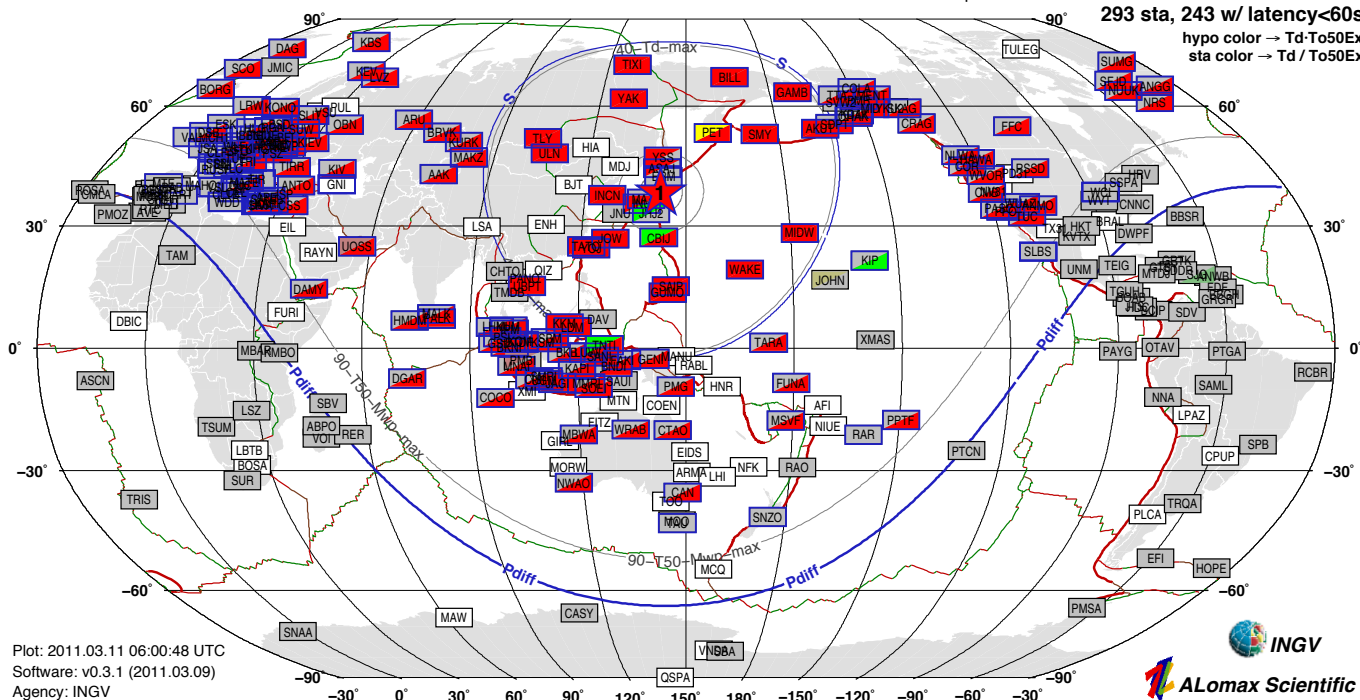
mB=7.7 Mwp=8.2 T0=168 Mwpd=8.7



Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	Td-T50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]			
1	157	3.7	1.9	2011.03.11-05:46:22	38.0	142.5	24	14	14	2.4136	13.8	26	33.7	7.7131	8.2132	168	66	8.7	62



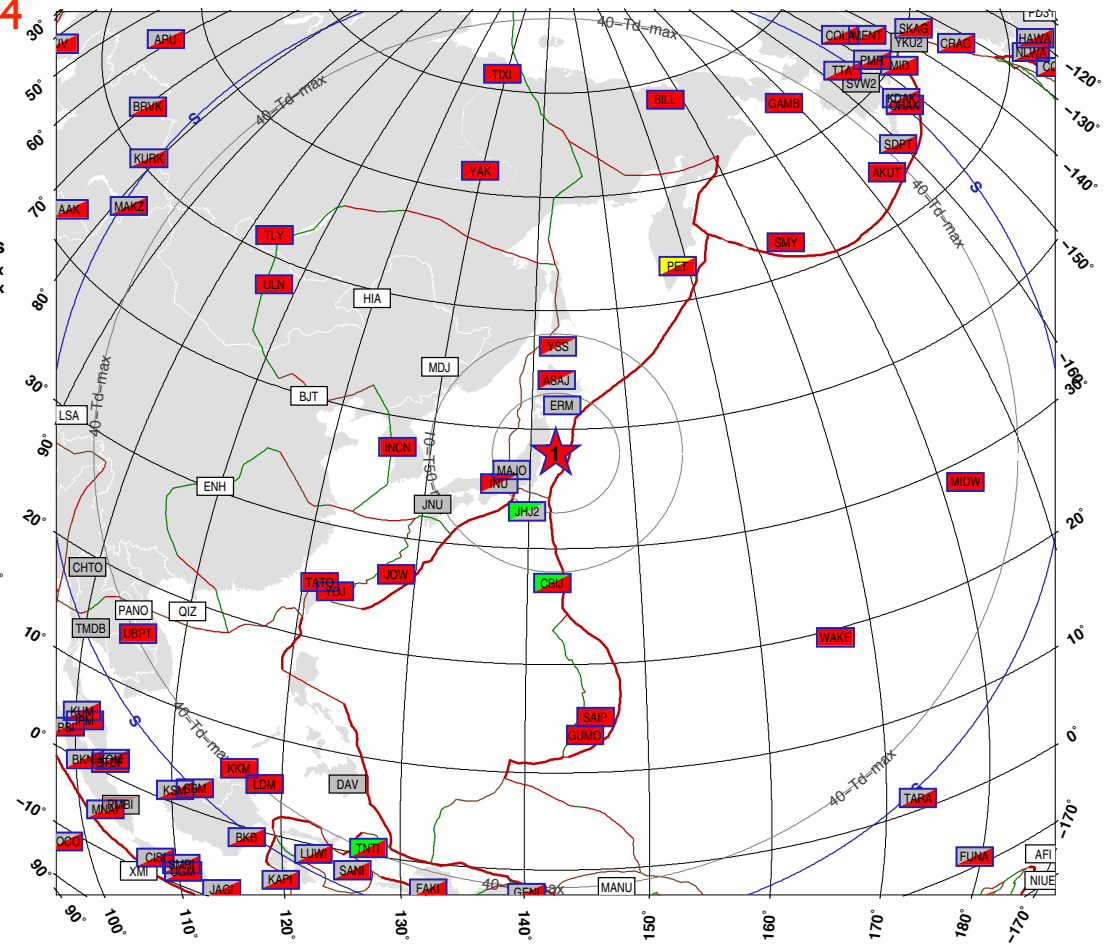
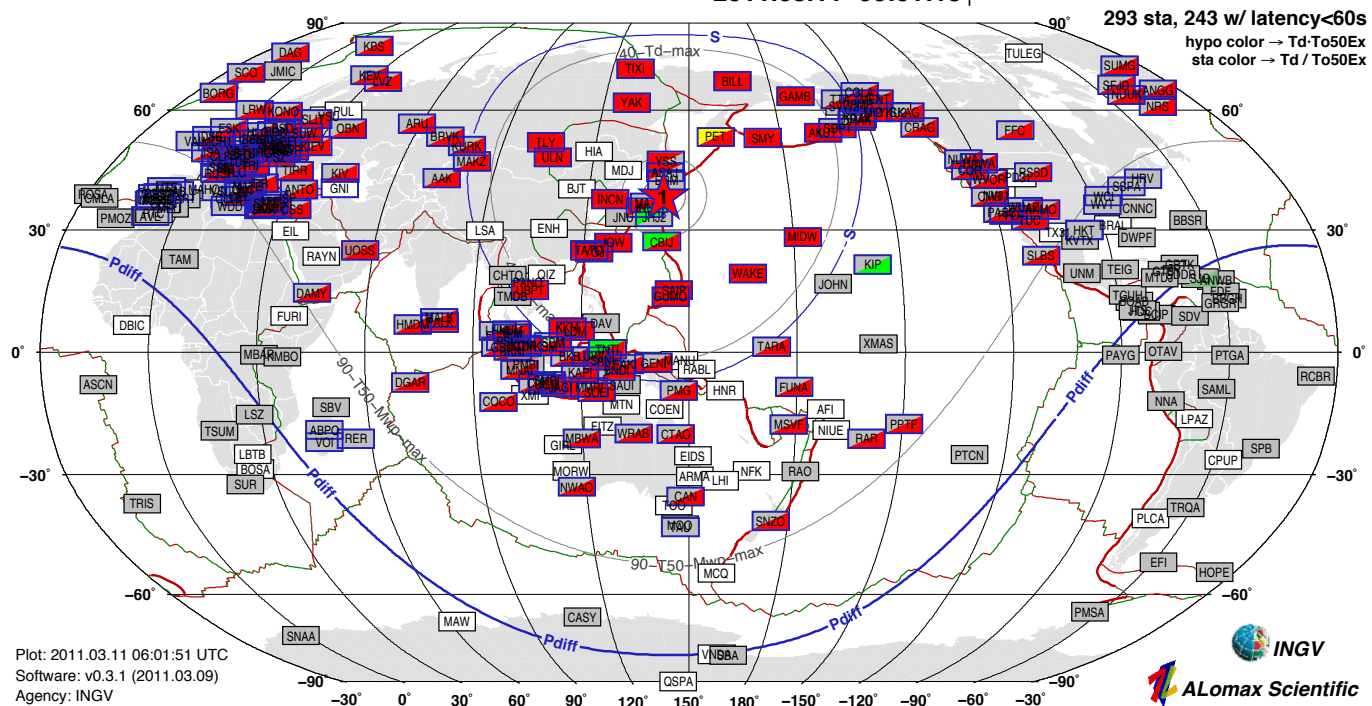
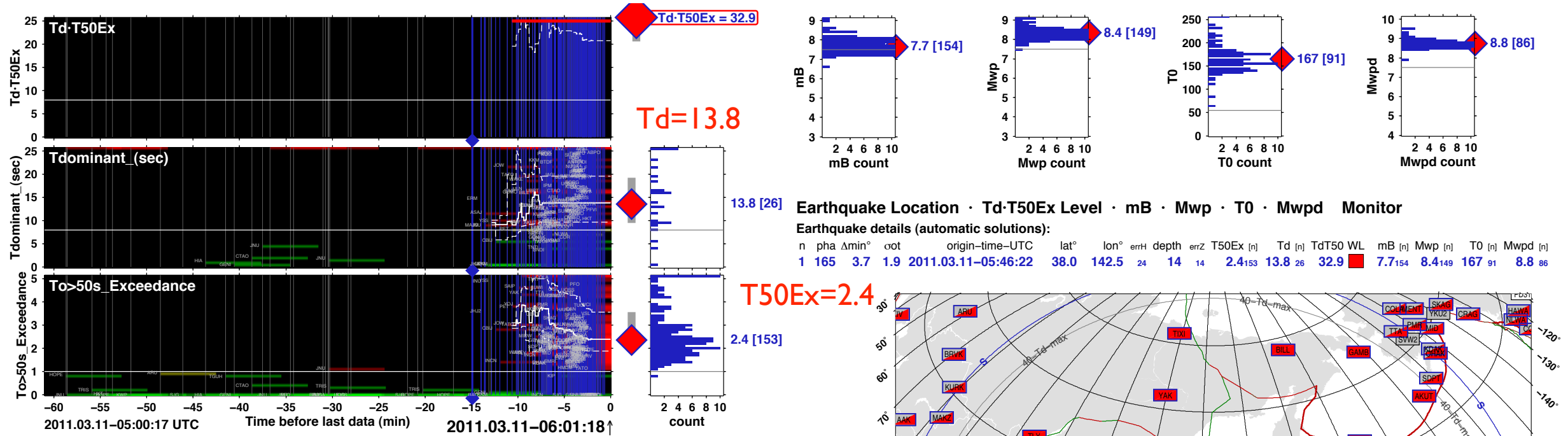
Plot: 2011.03.11 06:00:48 UTC
Software: v0.3.1 (2011.03.09)
Agency: INGV

06:01:18 GMT Tohoku Earthquake M9.0, ~ 15' from OT

11 March 2011, 05:46:20 GMT

Td T50Ex=32.9

mB=7.7 Mw_p=8.4 T₀=167 Mw_{pd}=8.8



06:03:18 GMT

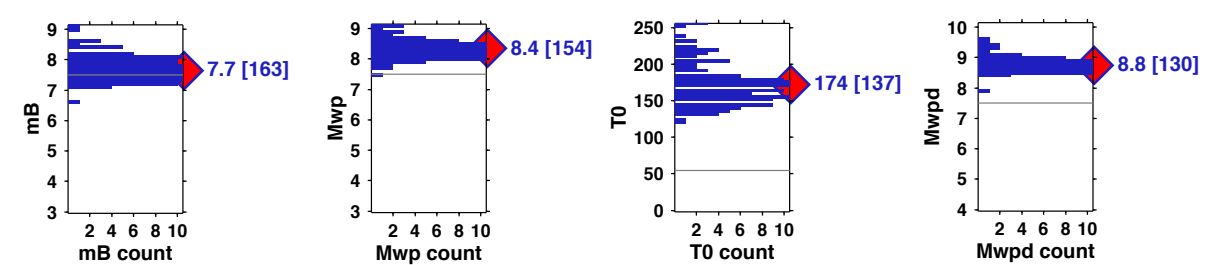
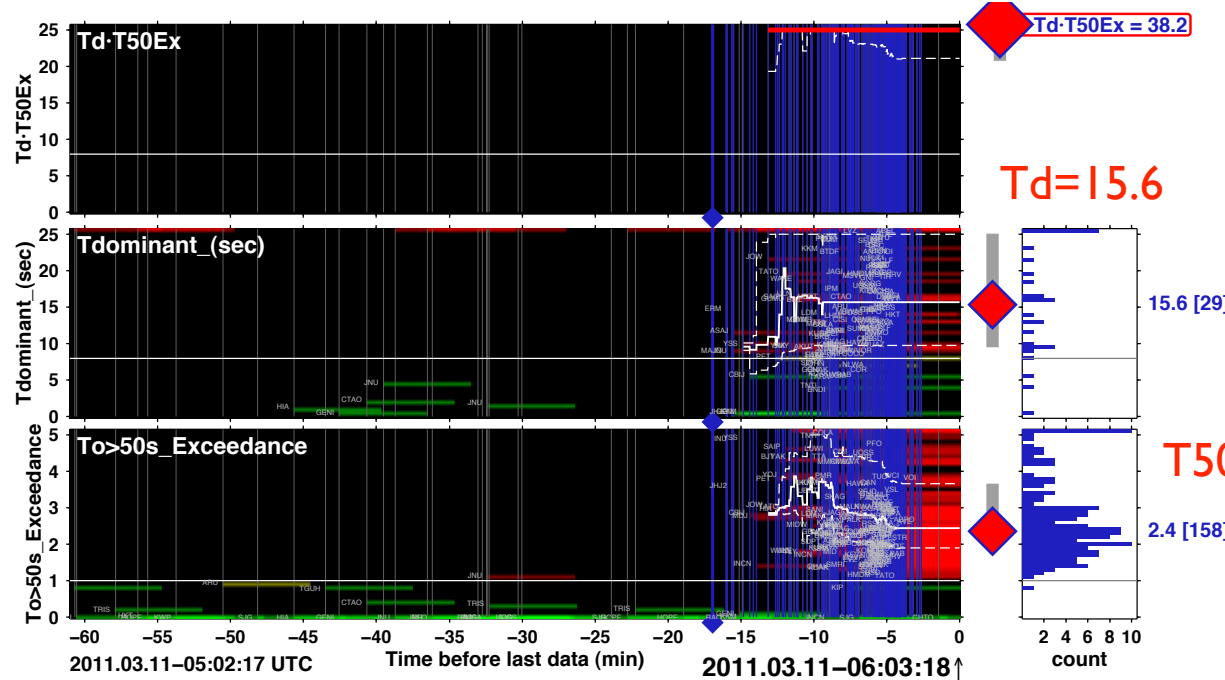
Tohoku Earthquake M9.0,

~ 17' from OT

11 March 2011, 05:46:20 GMT

Td T50Ex=38.2

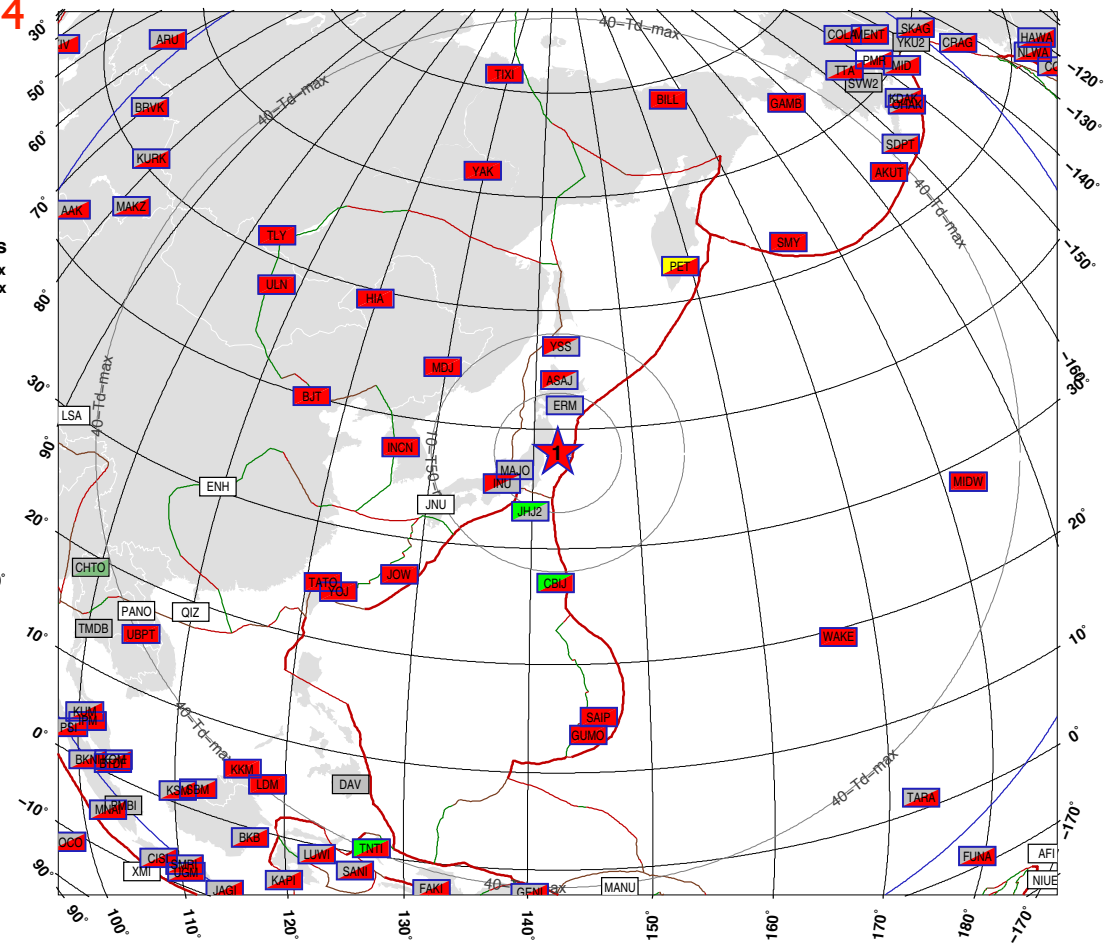
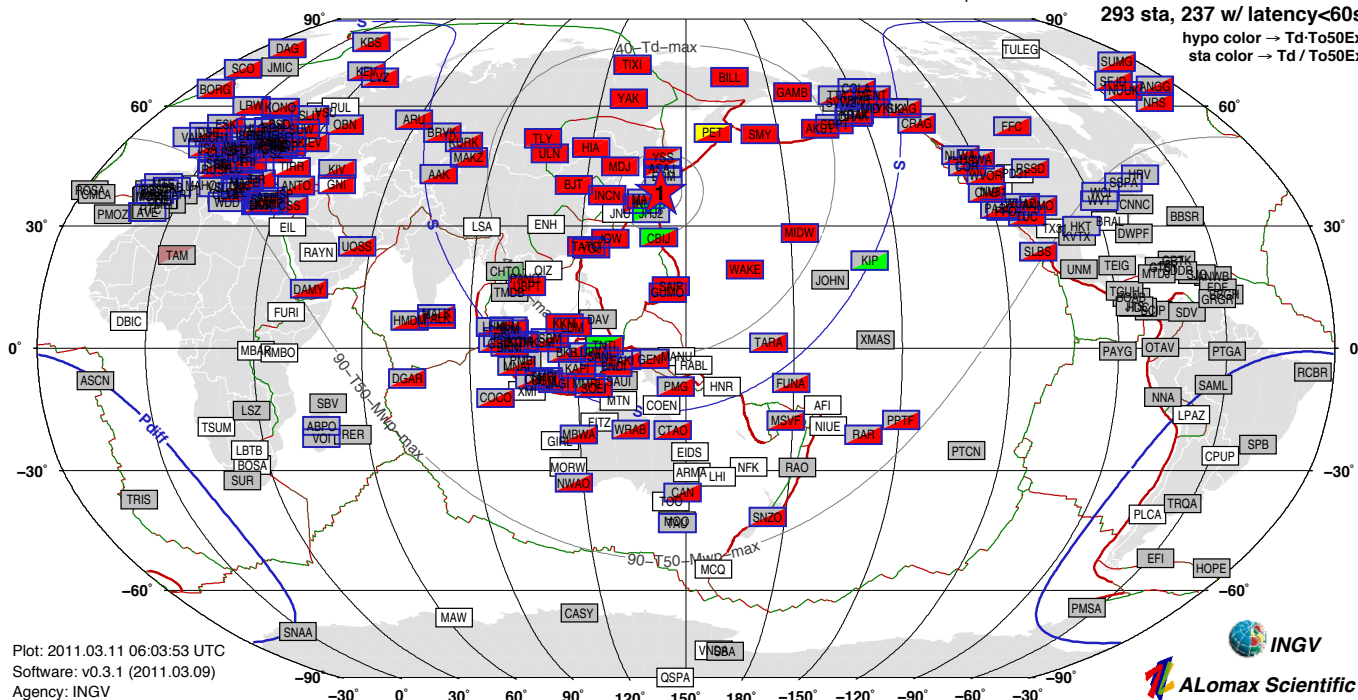
mB=7.7 Mwp=8.4 T0=174 Mwpd=8.8



Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	Td50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]	
1	169	3.7	1.9	2011.03.11-05:46:22	38.0	142.4	23	14	14	2.4158	15.6	29	38.2	7.7163	8.4154	174137	8.8130



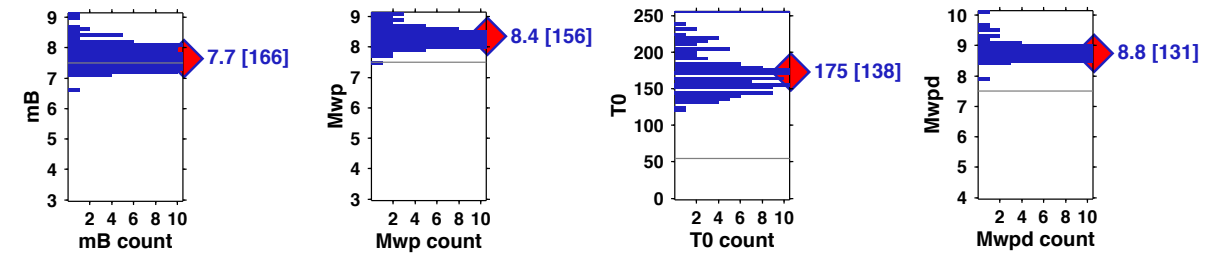
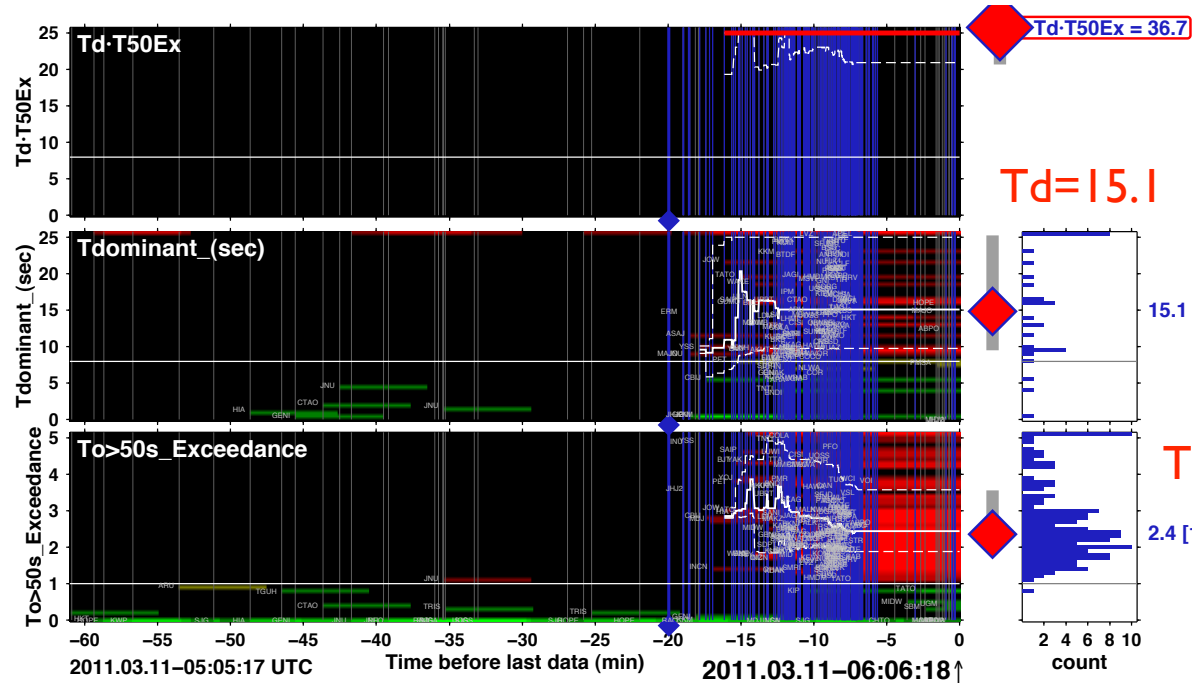
Plot: 2011.03.11 06:03:53 UTC
Software: v0.3.1 (2011.03.09)
Agency: INGV

06:06:18 GMT Tohoku Earthquake M9.0, ~ 20' from OT

11 March 2011, 05:46:20 GMT

Td T50Ex=36.7

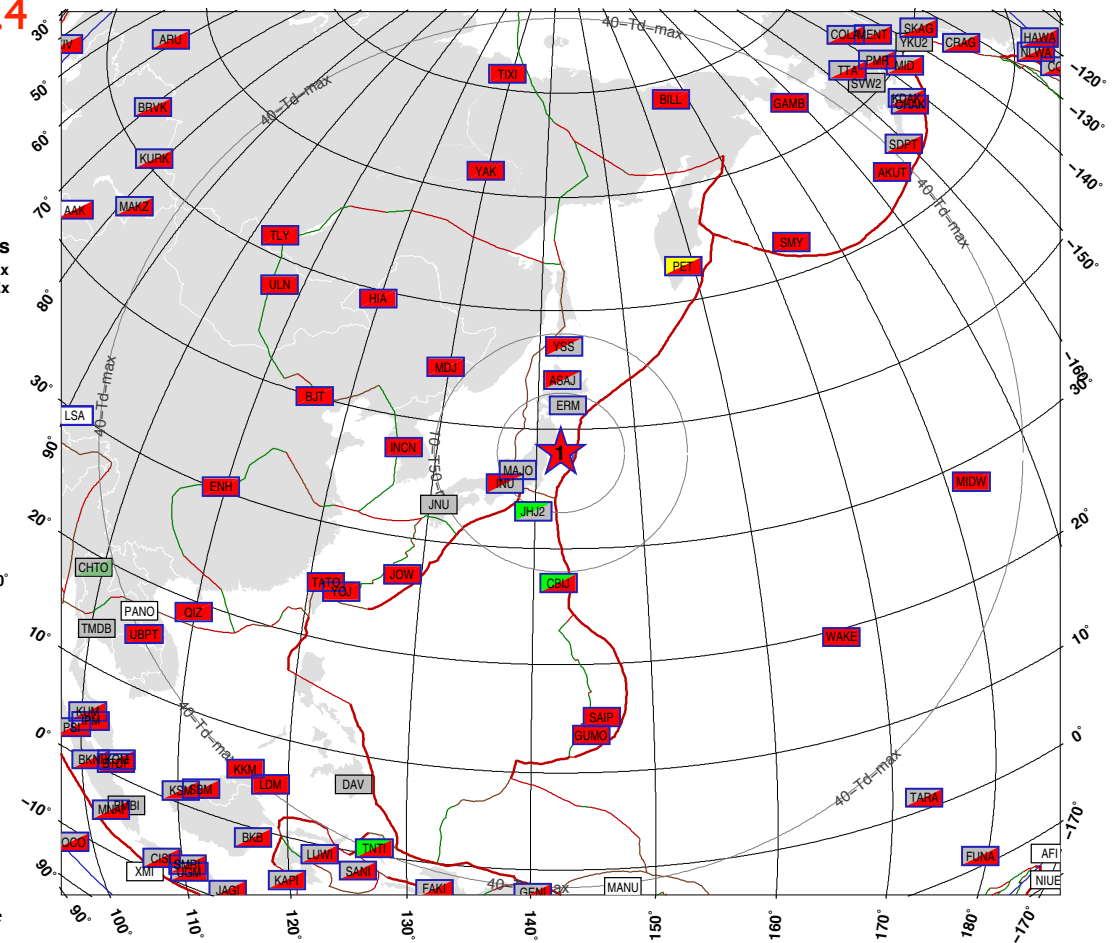
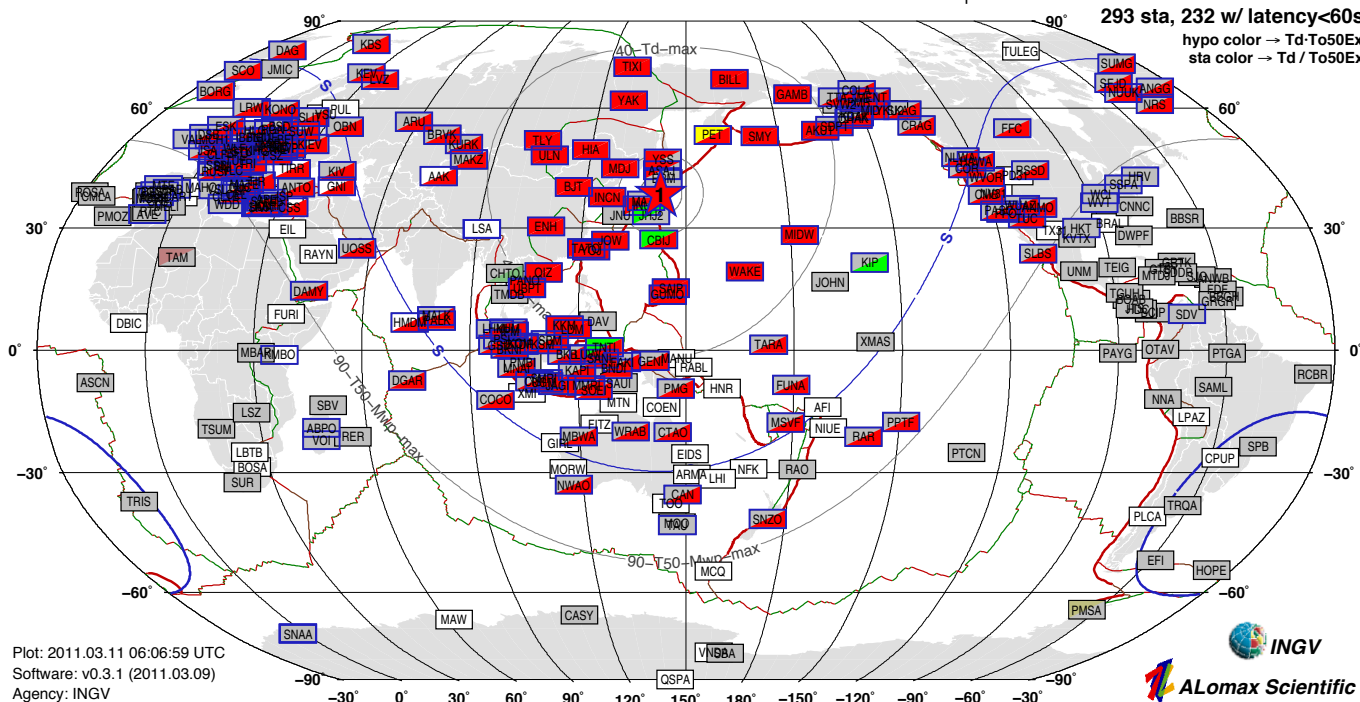
mB=7.7 Mwp=8.4 T0=175 Mwpd=8.8



Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	Td-T50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]
1	177	3.7	1.9	2011.03.11-05:46:22	38.0	142.4	23	14	15	2.4160	15.1	36.7	7.7166	8.4156	175138	8.8131



Plot: 2011.03.11 06:06:59 UTC
Software: v0.3.1 (2011.03.09)
Agency: INGV

Summary

- Location and initial evidence of **M~8**: ~3'
- First magnitude **> 8** (mB & Mwp): ~4'
- First indication of large tsunami potential ($T_d > 9$): ~5'
- Strong indication of **very large tsunami** potential (T_d
 $T_{50Ex} = 36.4 \gg 9$): ~7'
- First indication of very large magnitude (**M~9**) and long
rupture duration ($T_0 > 130s$): ~9'
- First $M_{wpd}=8.5$: **11'**
- Evidence of large magnitude ($M_{wpd}=8.7$) and great rupture
extension ($T_0 \sim 170s$): **13'**
- First robust estimations of magnitude (**Mwpd=8.8**) and
rupture duration (170-175s): **15'**

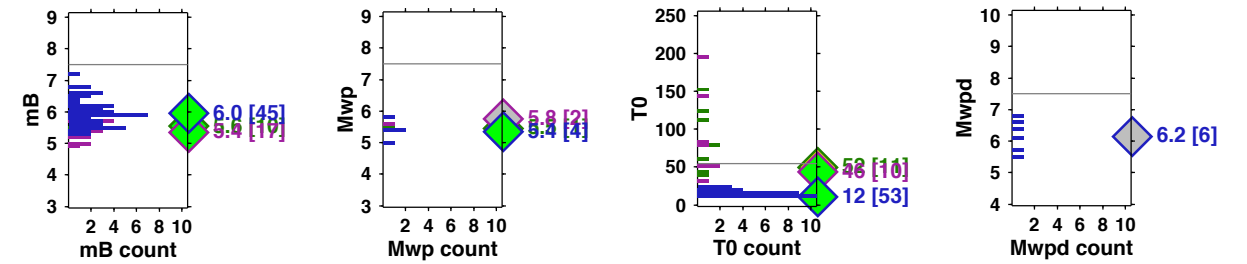
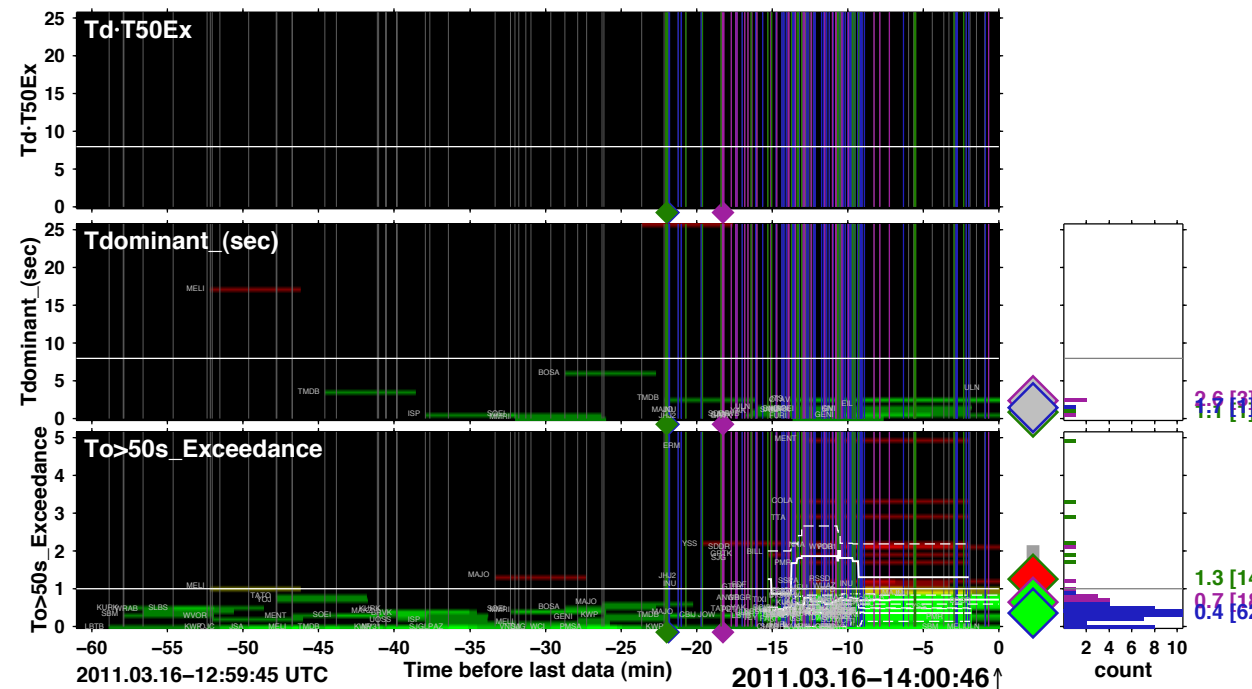
Ingredients

- **Location**
- **Mw_{pd}** (extension of Mw_p with duration)
- **T₀** (rupture duration from band-passed 1-5 Hz broadband seismograms on P-wave train)
- **T_{50Ex}** (proxy of T₀ determined at 55s from P-onset)
- **T_d** (dominant period on P-wave)
- **T_d x T_{50Ex}**

Location

- from continuous streams obtained from many seedlink servers in real-time
- association and location are done simultaneously and continuously by stacking the predicted origin time for each detected phase on a variable grid of potential earthquake location points (i.e, very much alike WaveLoc)
- Avails of a fully probabilistic approach and it is a direct search methodology derived from NonLinLoc
- EARLY-EST is viewable in real-time at <http://s3.rm.ingv.it/warning/warning.html>

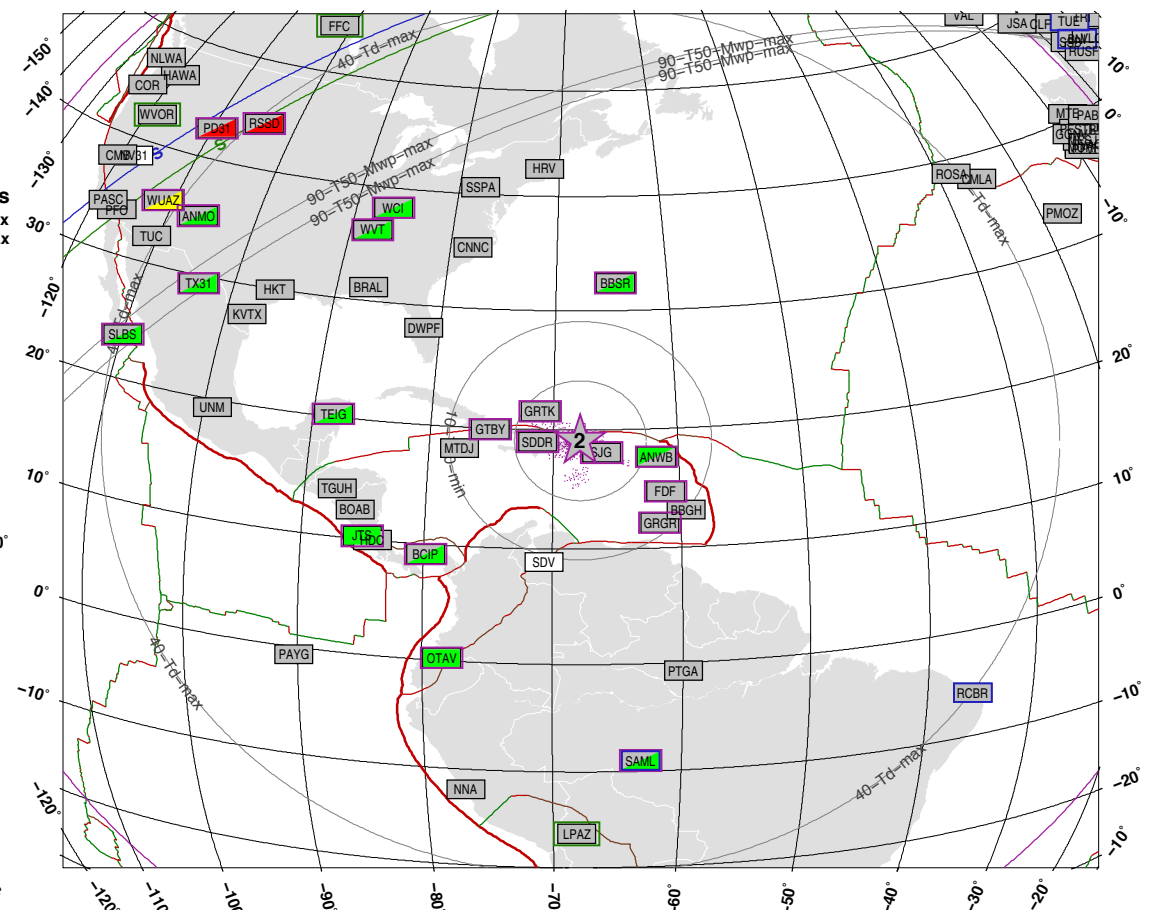
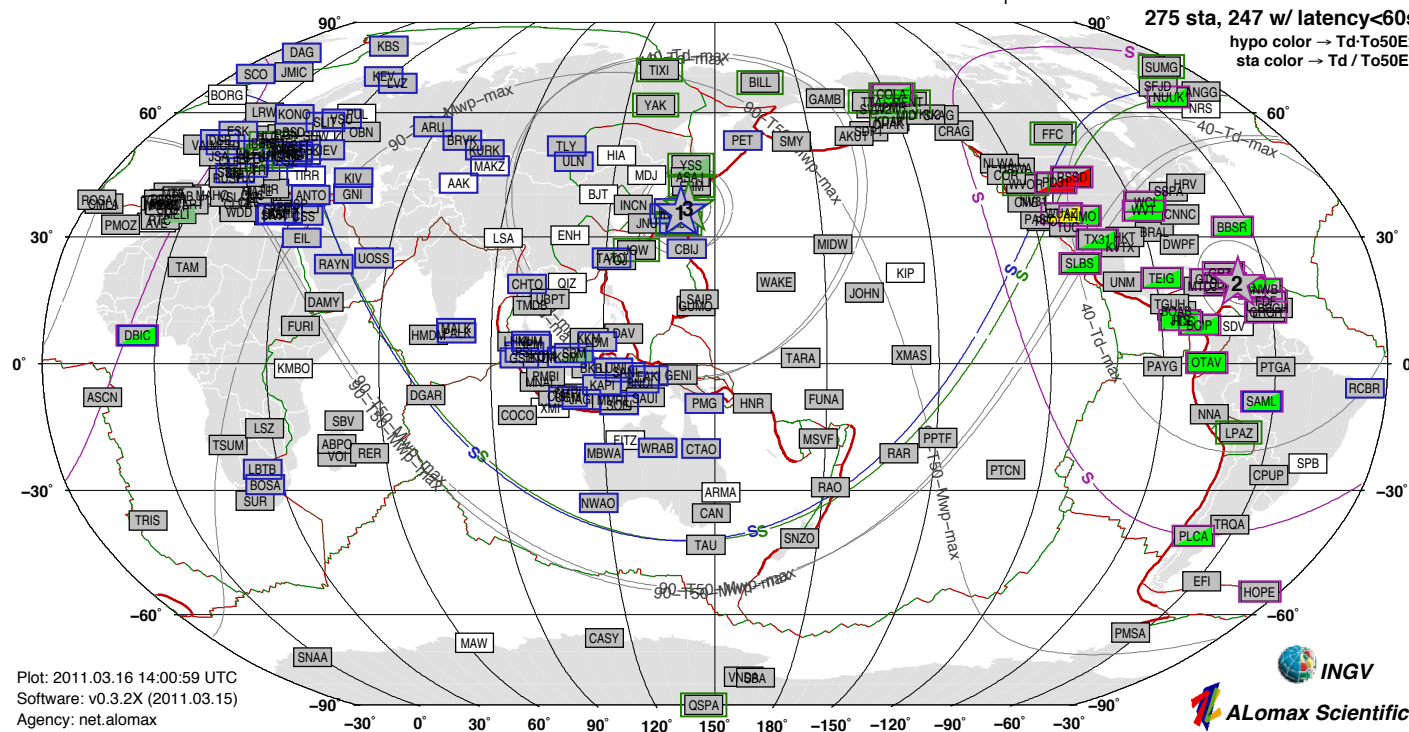
Example of nearly simultaneous earthquakes



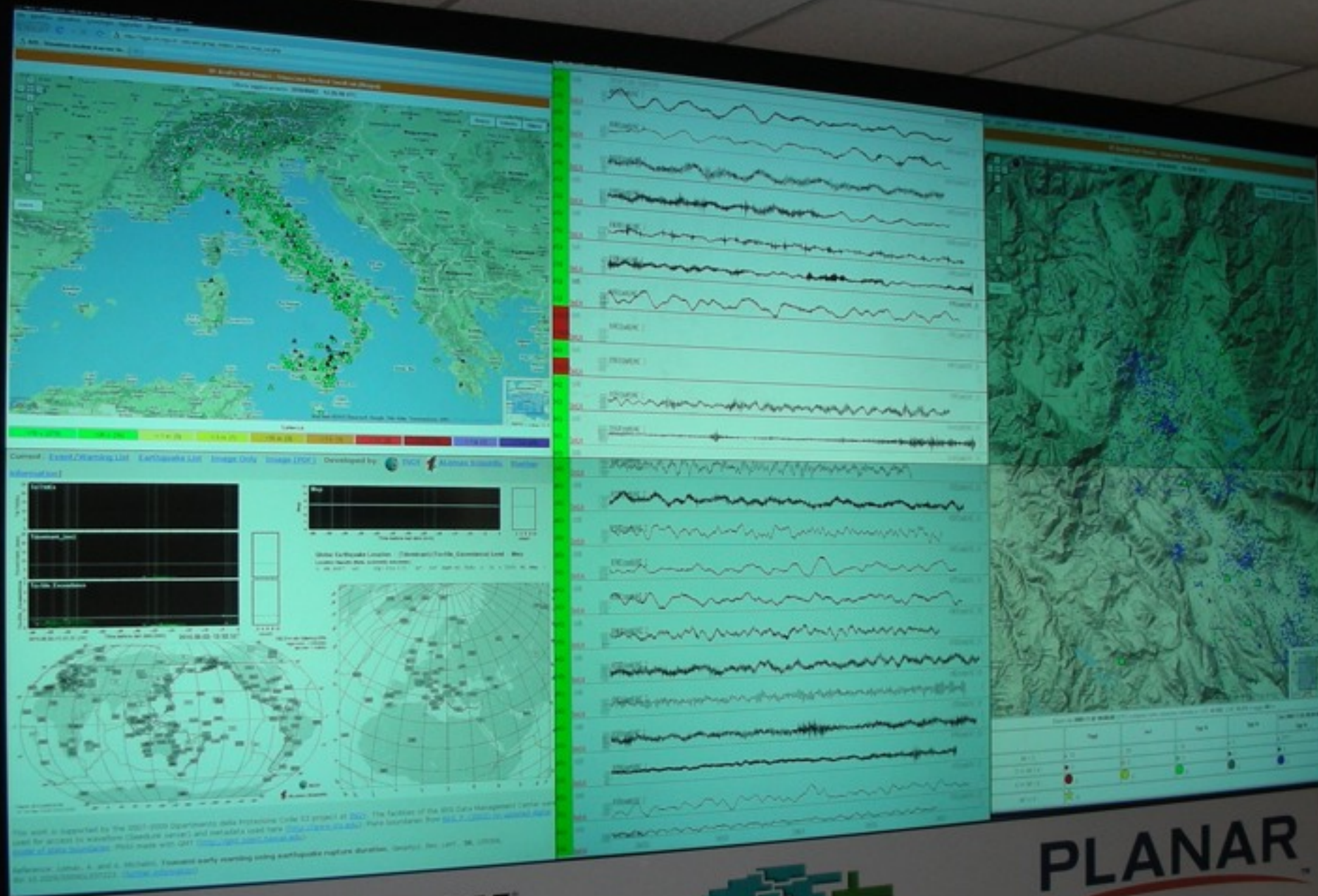
Earthquake Location · Td-T50Ex Level · mB · Mwp · T0 · Mwpd Monitor

Earthquake details (automatic solutions):

n	pha	Δmin°	σot	origin-time-UTC	lat°	lon°	errH	depth	errZ	T50Ex [n]	Td [n]	Td-T50 WL	mB [n]	Mwp [n]	T0 [n]	Mwpd [n]
2	23	1.9	2.2	2011.03.16-13:42:31	19.1	-67.8	22	14	14	0.7 18	2.6 3	0.0	5.4 17	n/a 2	46 10	n/a 0
1	70	1.9	1.8	2011.03.16-13:38:55	35.7	140.3	23	5	54	0.4 62	1.7 1	0.0	6.0 45	5.4 4	12 53	inv 6
3	17	5.3	1.9	2011.03.16-13:38:46	36.7	142.5	64	14	20	1.3 14	1.1 1	0.0	5.6 10	n/a 1	52 11	n/a 0



Plot: 2011.03.16 14:00:59 UTC
Software: v0.3.2X (2011.03.15)
Agency: net.alomax



 **BLACK BOX**
NETWORK SERVICES

PLANAR

T0

- The duration T0 calculated from 1-5 Hz BB records can be interpreted as the duration of the rupture on the fault

Mw_{pd}

- essentially an extension of Mw_p in which the duration of the rupture is accounted for (i.e., the displacement seismograms are integrated by considering all signal within the rupture duration T_0)

Duration-Amplitude Equations

$$M_0 = C_M \int_{t_P}^{t_P+T_0} u(t) dt$$

Moment M_0 From far-field, P-displacement $u(t)$, for an earthquake source of rupture duration, T_0 ,

$$\hat{M}_0 = kC_M \text{Max} \left[\int_{t_P}^{t_P+T_0} u^+(t) dt, \int_{t_P}^{t_P+T_0} |u^-(t)| dt \right]$$

Estimate of Moment M_0

$$M_w = (\log_{10} M_0 - 9.1) / 1.5$$

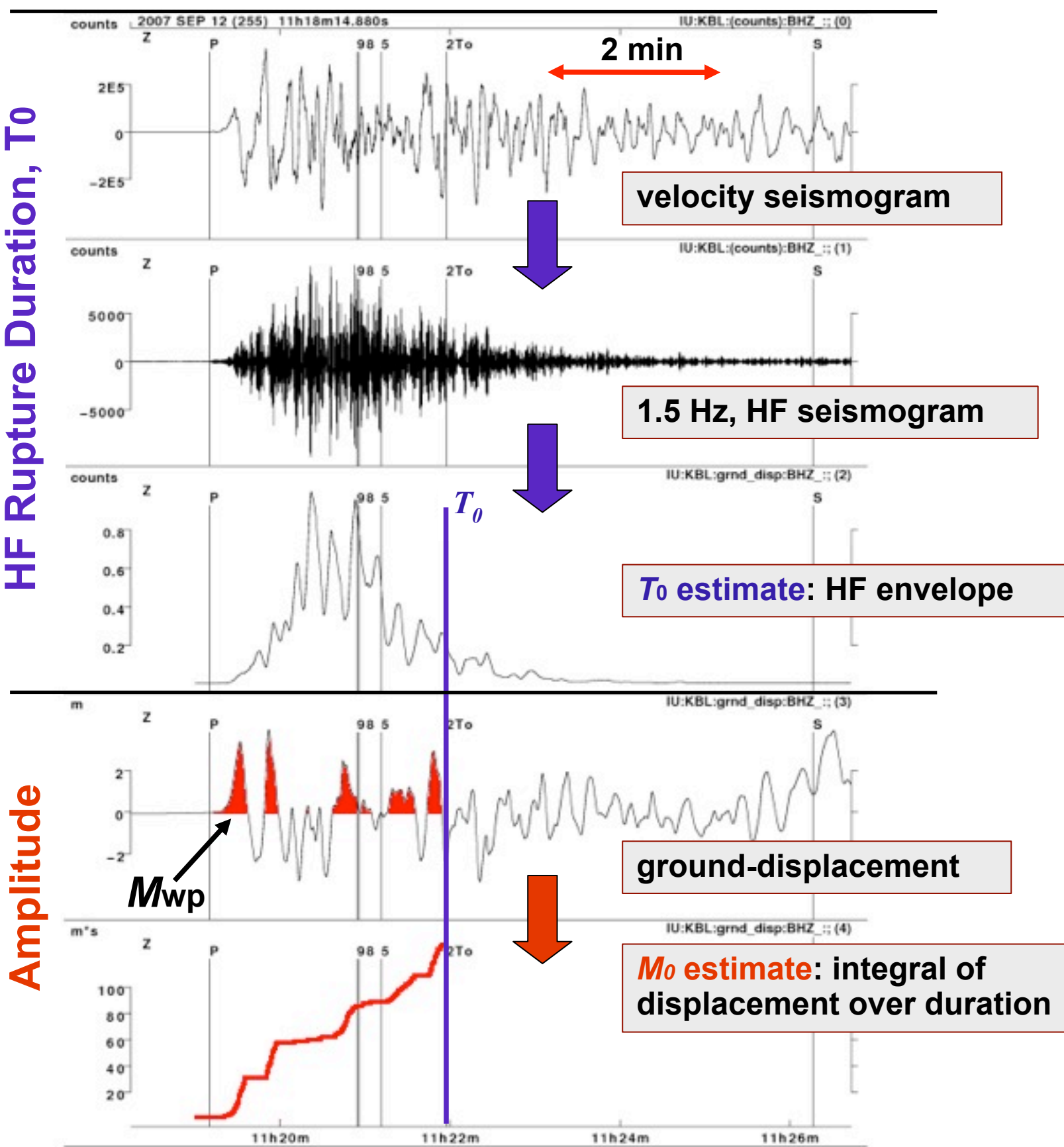
Estimate of Magnitude M_w
(Hanks and Kanamori, 1979;
Bormann, 2002)



M_{wpd} and high-frequency, apparent rupture duration T_0

HF Rupture Duration, T_0

Amplitude

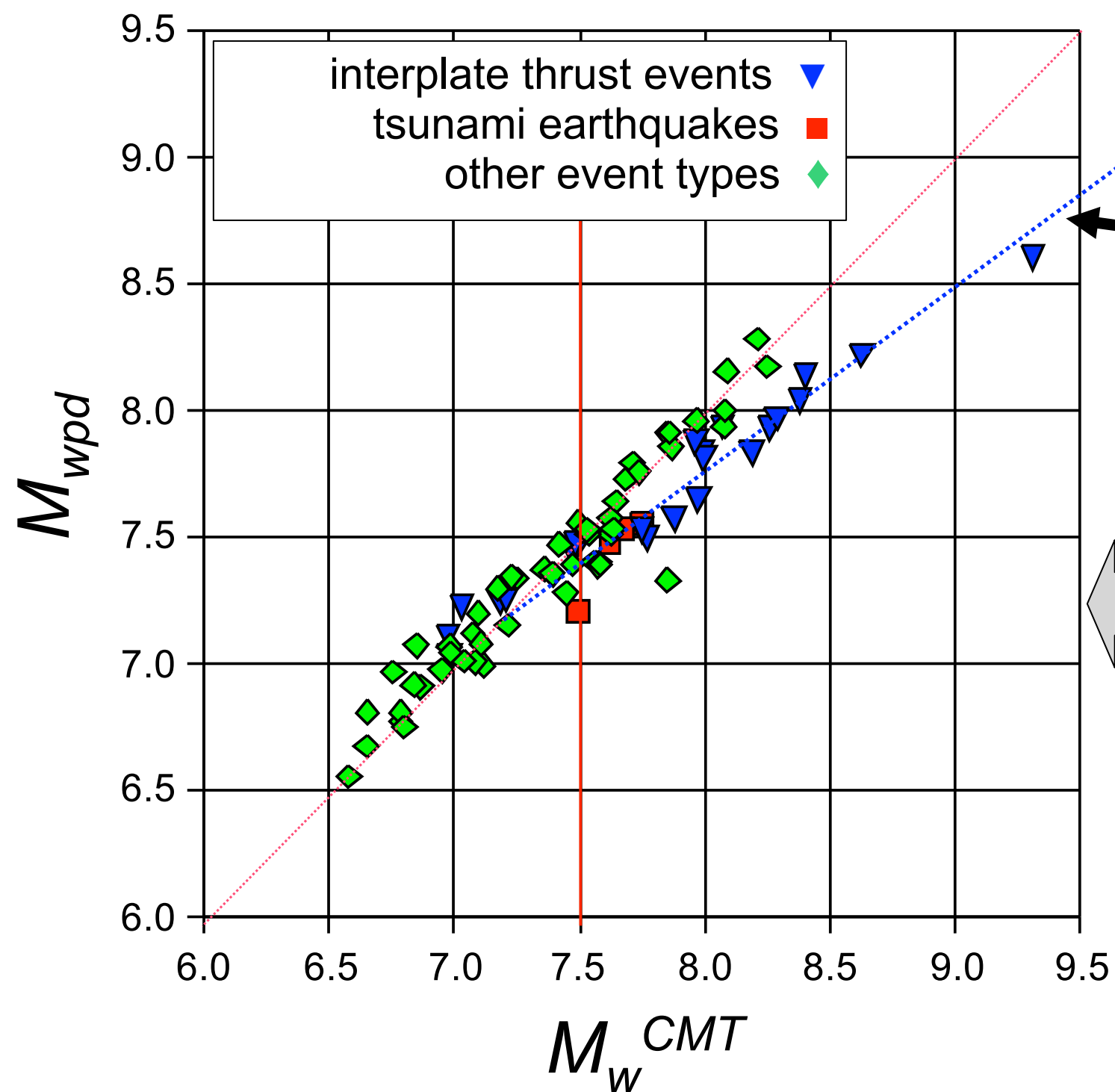


M_{wpd} processing steps:
12 September 2007,
M8.4 Sumatra
(Lomax & Michelini 2009A)

M_{wpd} (8.5)
OT+8-15min



Duration-amplitude magnitude M_{wpd}

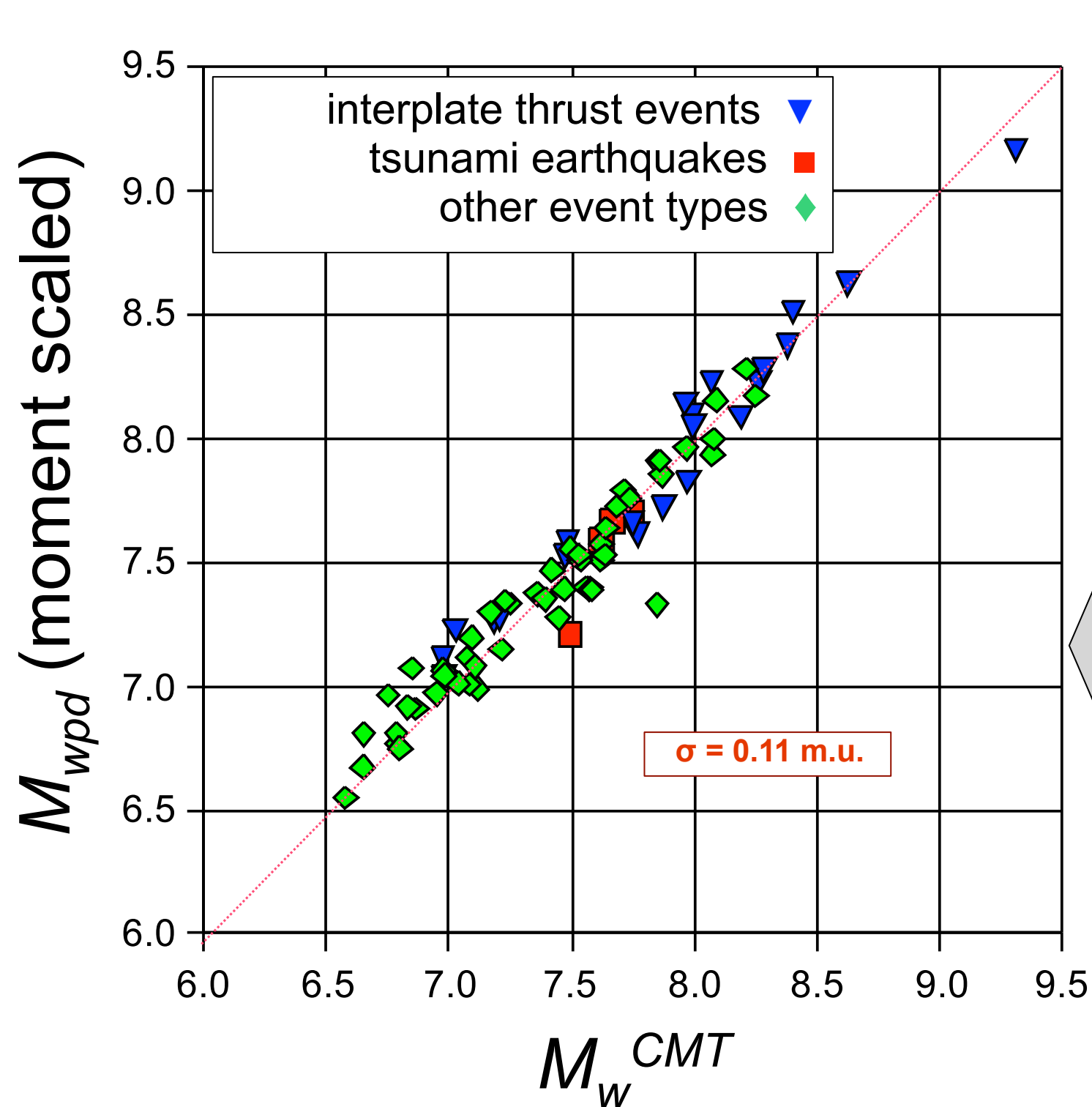


Raw M_{wpd} underestimates M_w^{CMT} for largest interplate thrust and tsunami earthquakes

Raw M_{wpd} compared to M_w^{CMT} for 79 recent, large earthquakes.



Duration-amplitude magnitude M_{wpd} with moment scaling



$$M_0^{pd} = \hat{M}_0 \left(\frac{\hat{M}_0}{M_0^{cutoff}} \right)^{0.45}$$

$$M_0^{cutoff} \approx 7.5 \times 10^{19} \text{ N-m}$$

(equivalent to $M_w \approx 7.2$)

Comparison of M_w^{CMT} with M_{wpd} corrected with moment scaling for interplate thrust and tsunami earthquakes.



Implications of moment scaling: large earthquake rupture

Moment scaling

→ deficiency in down-going (teleseismic) amplitude and energy

trapped energy...
re-absorbed at rupture front?
helps to drive rupture?

less mass
in upper plate

destructive interference
of pP or sP waves with
down-going P waves

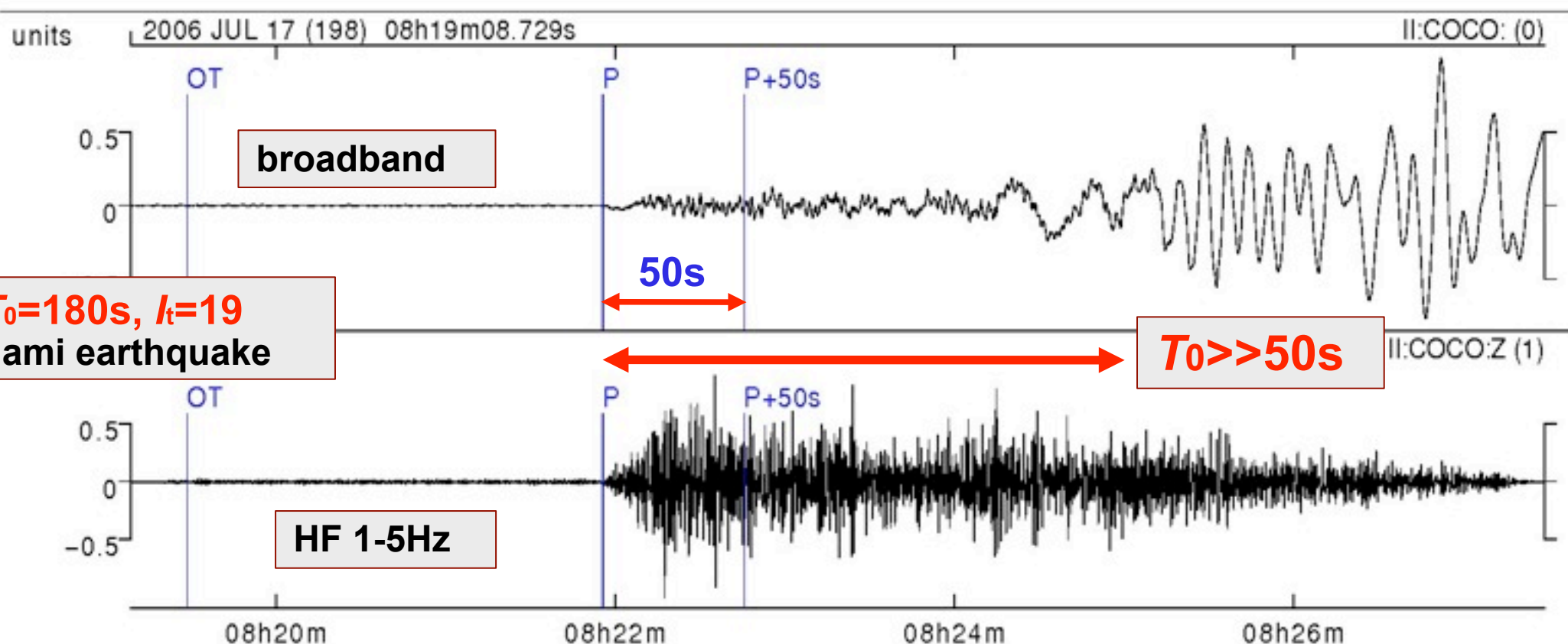
T50Ex

- Rapid estimation on whether T_0 exceeds 50 s

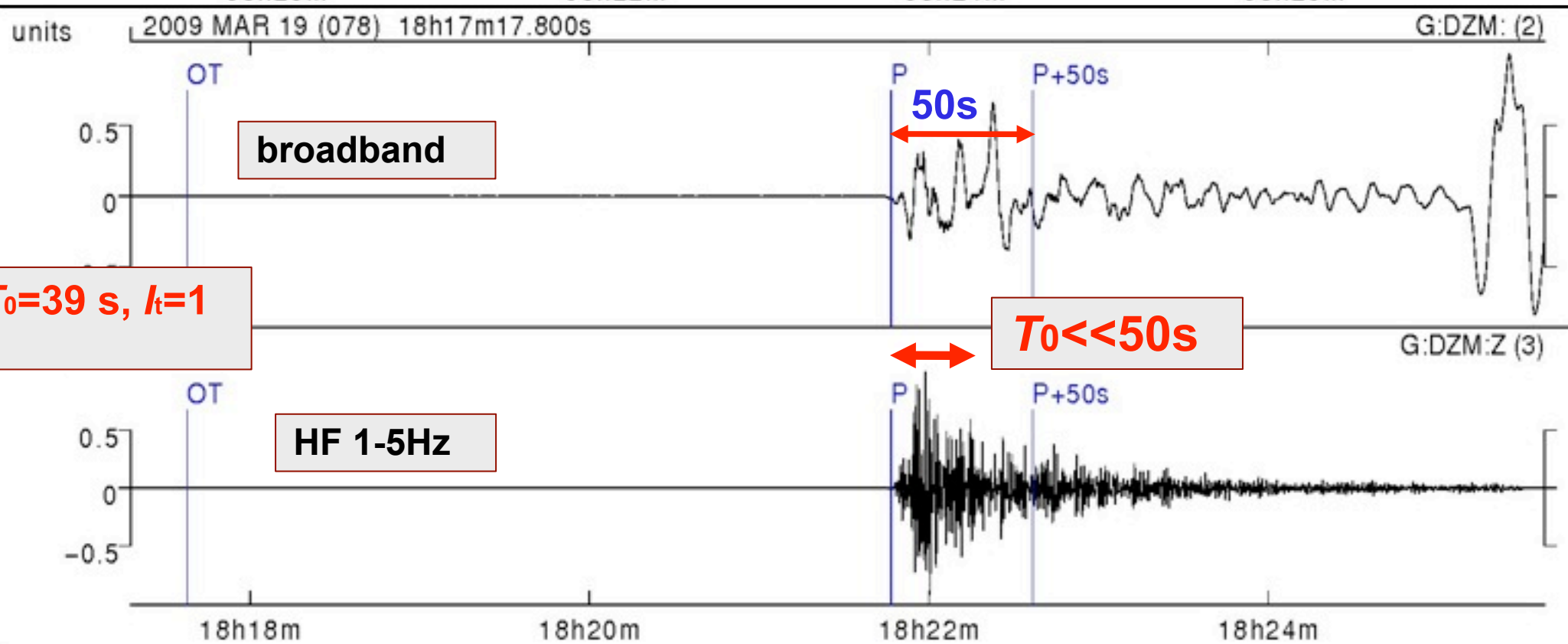


Discriminating Tsunamigenic earthquakes: $T_0 > 50s$

2006, $M_w 7.7$, $T_0 = 180s$, $I_t = 19$
Indonesia tsunami earthquake

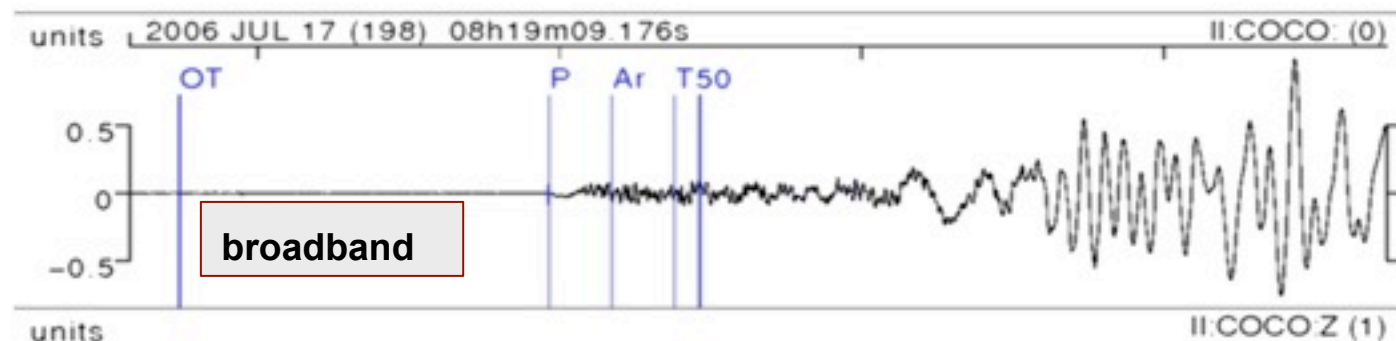


2009, $M_w 7.6$, $T_0 = 39s$, $I_t = 1$
Tonga Islands

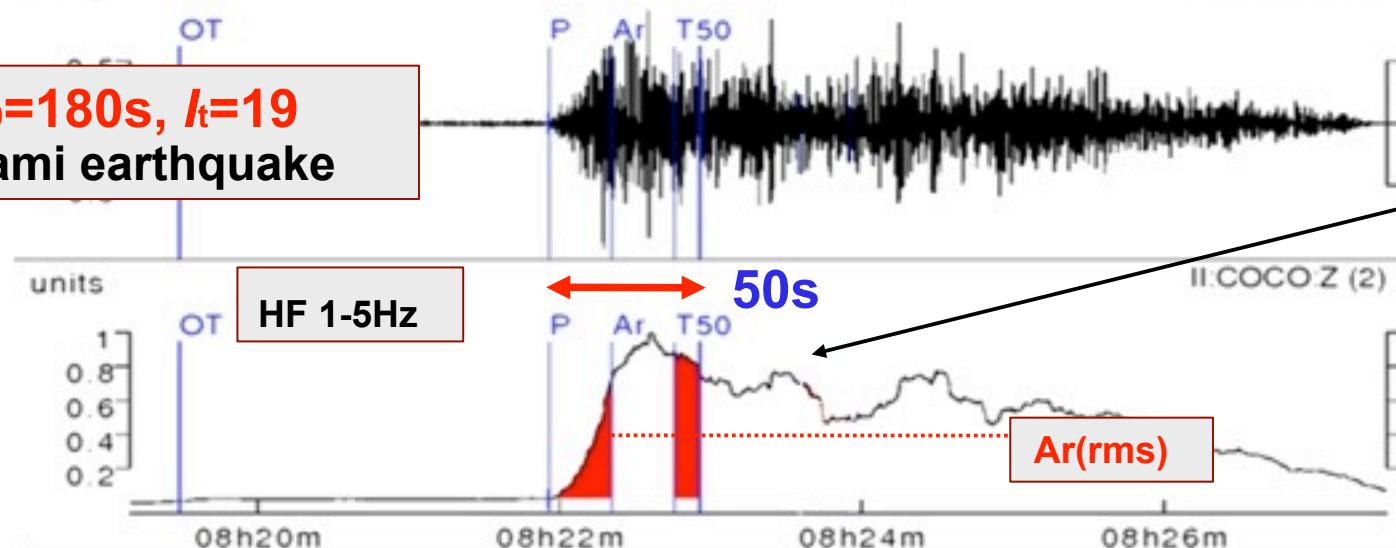




Near real-time, direct assessment of tsunami potential



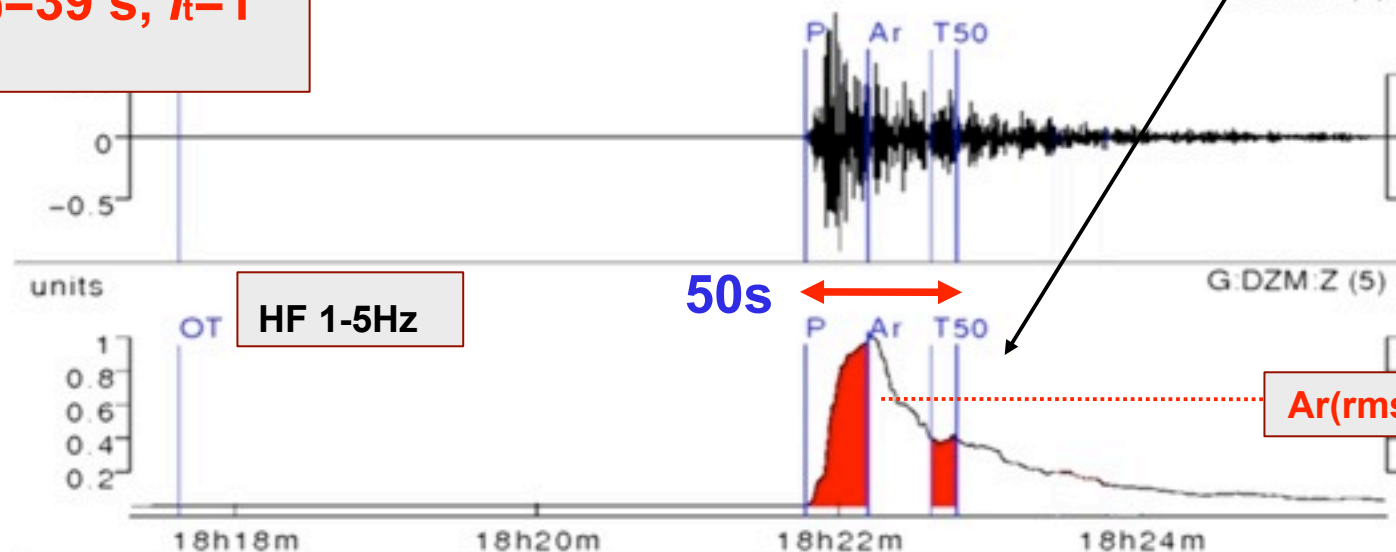
2006, $M_w 7.7$, $T_0=180s$, $I_t=19$
Indonesia tsunami earthquake



Exceedance level $T_0 > 55s$
 $T50Ex \equiv T50/Ar(rms)$



2009, $M_w 7.6$, $T_0=39s$, $I_t=1$
Tonga Islands



$T_d \cdot T_0$ discriminant
→ $T_d \cdot T50Ex$ discriminant
→ event completed
at OT+6-10m

Td

- Dominant period of the P-wave train

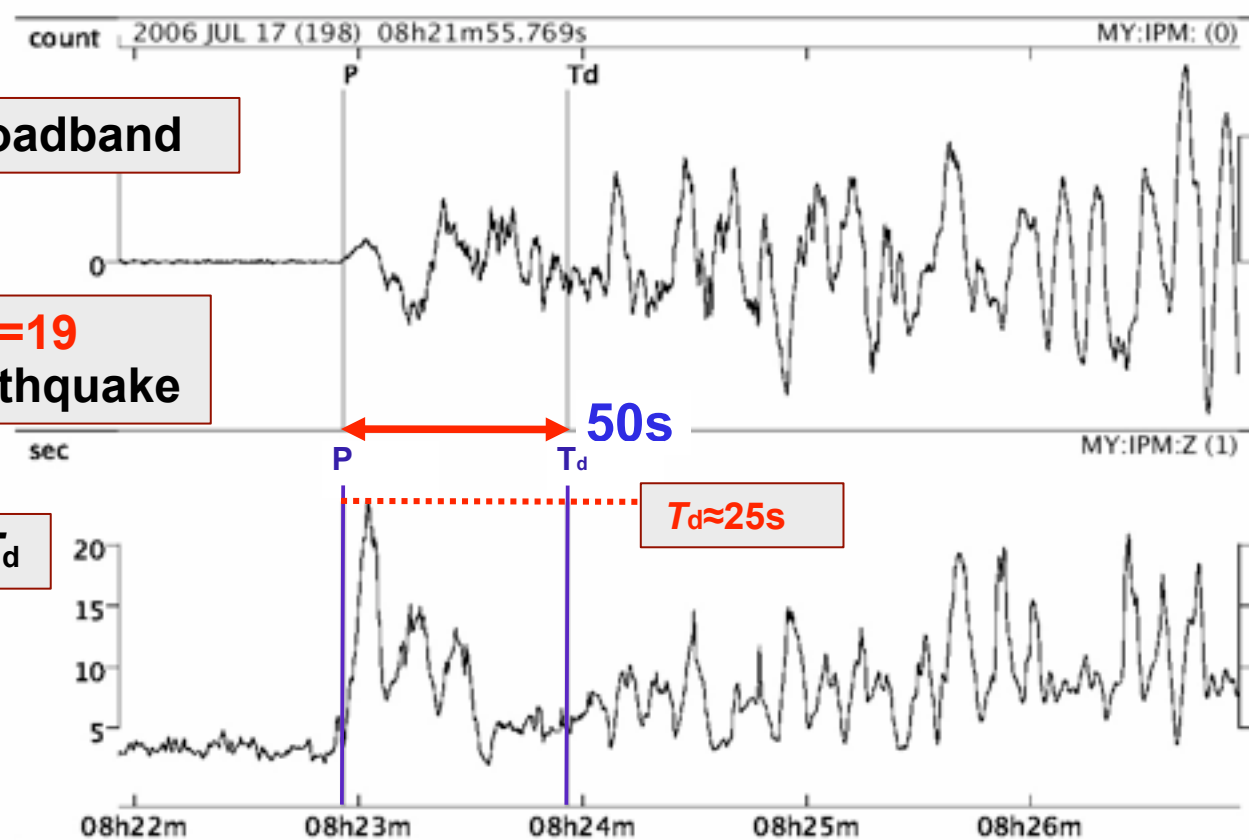


P-wave dominant period calculation

broadband

2006, $M_w 7.7$, $T_0=180s$, $I_t=19$
Indonesia tsunami earthquake

dominant period T_d



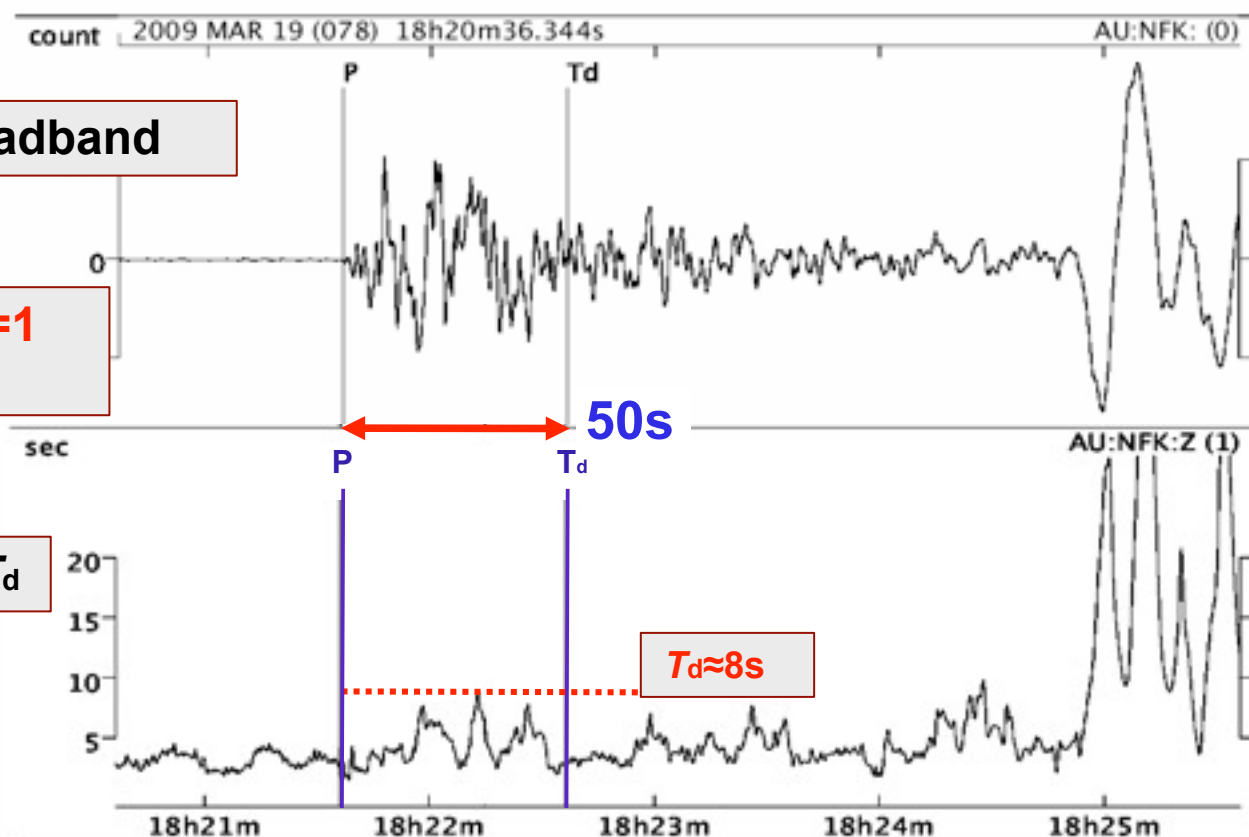
Use TauC:
time-domain,
instantaneous-period
methodology (Nakamura
1988;
Wu and Kanamori 2005)

T_d event completed
at OT+6-10m

broadband

2009, $M_w 7.6$, $T_0=39s$, $I_t=1$
Tonga Islands

dominant period T_d



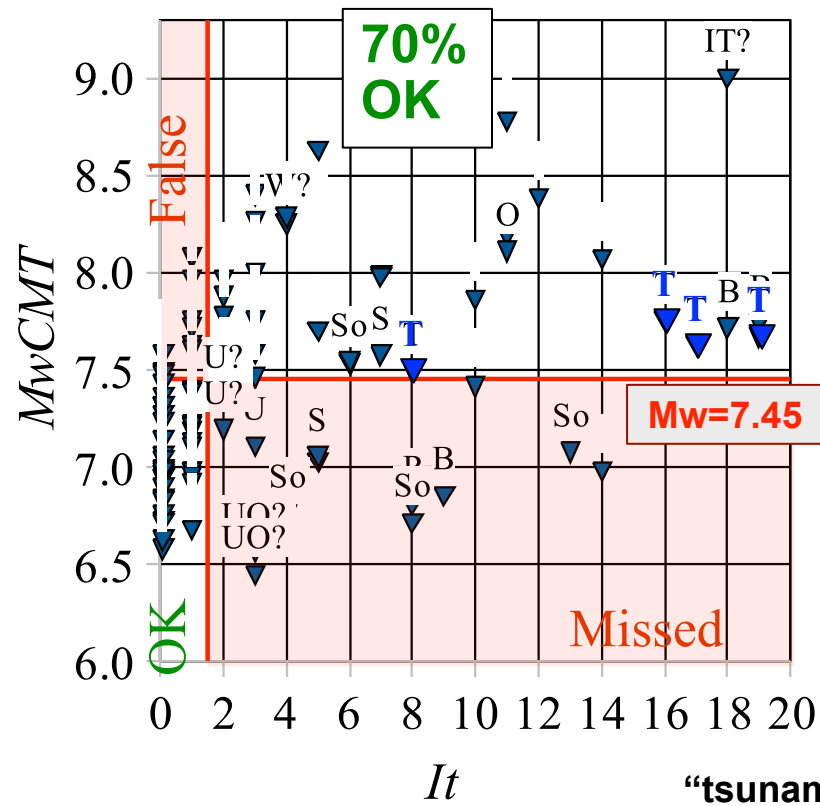
Td T0

- Product between dominant period of the P-wave train and high-frequency duration
- in the real-time system Td T50Ex is used
- Both Td and T0 are direct measures
 - ▶ no inversion
 - ▶ carry direct infos on source extent and depth

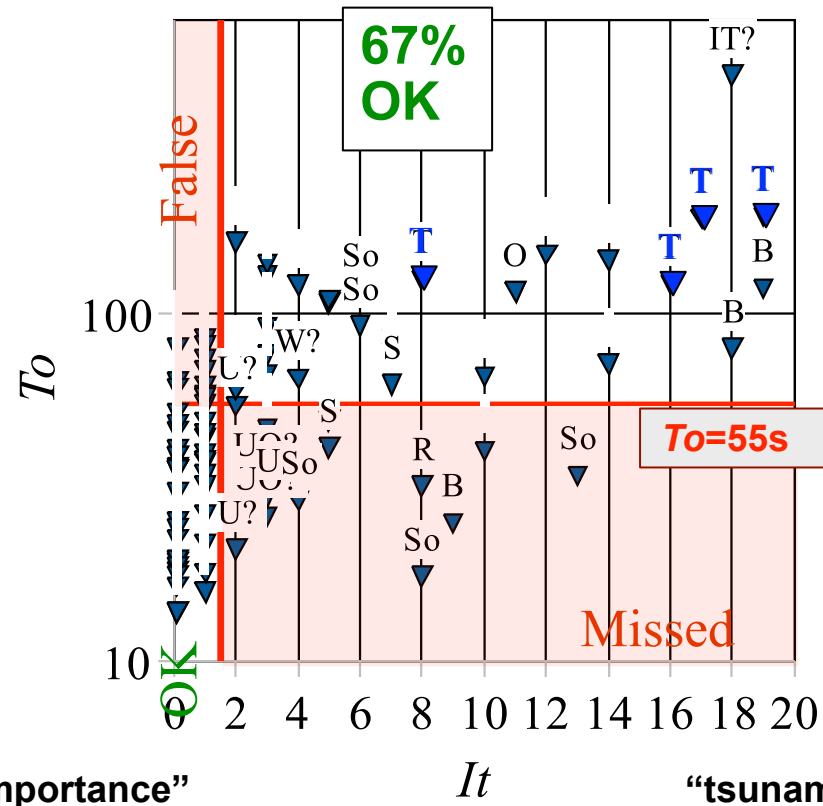


Tsunamigenic earthquakes: the T_d - T_0 discriminant

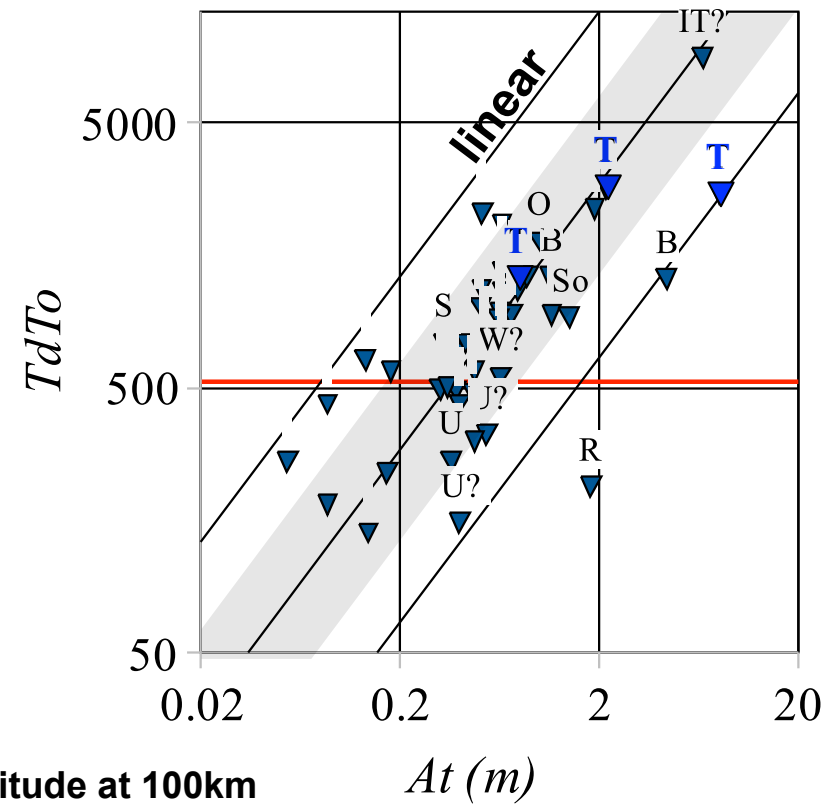
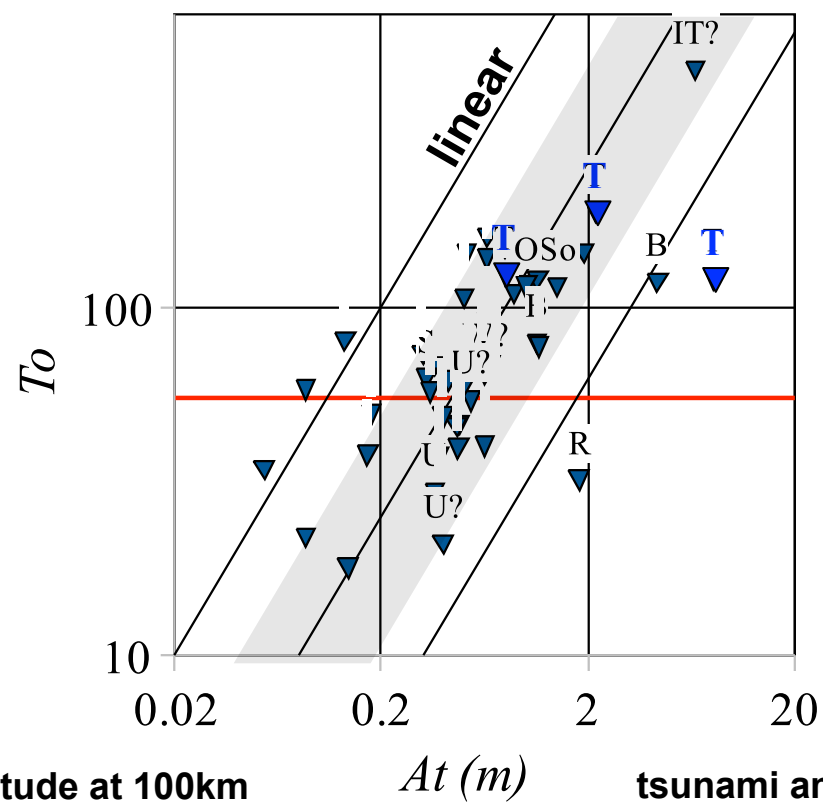
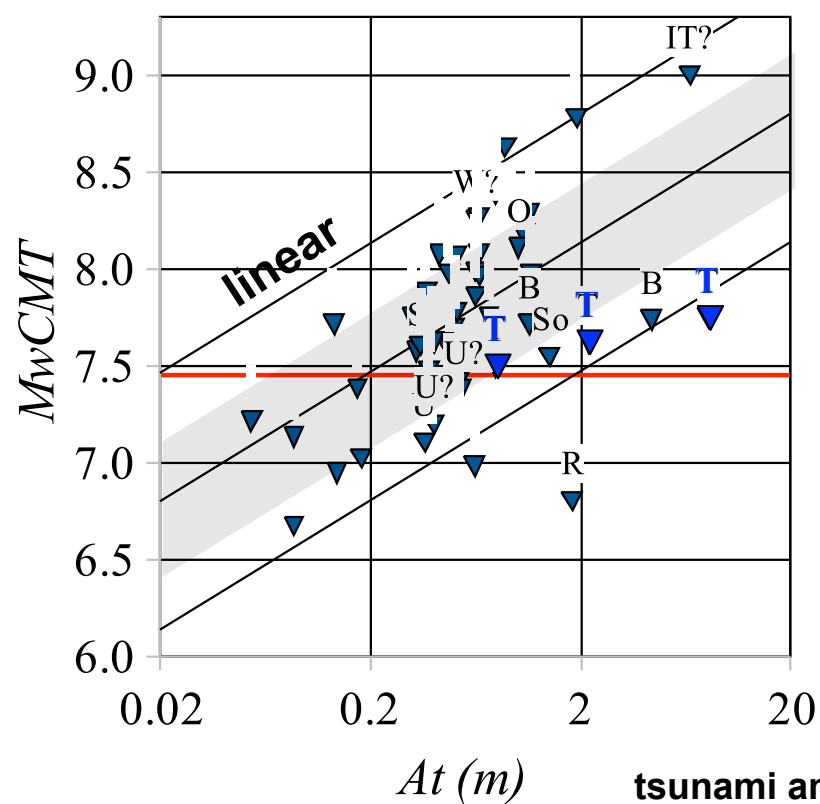
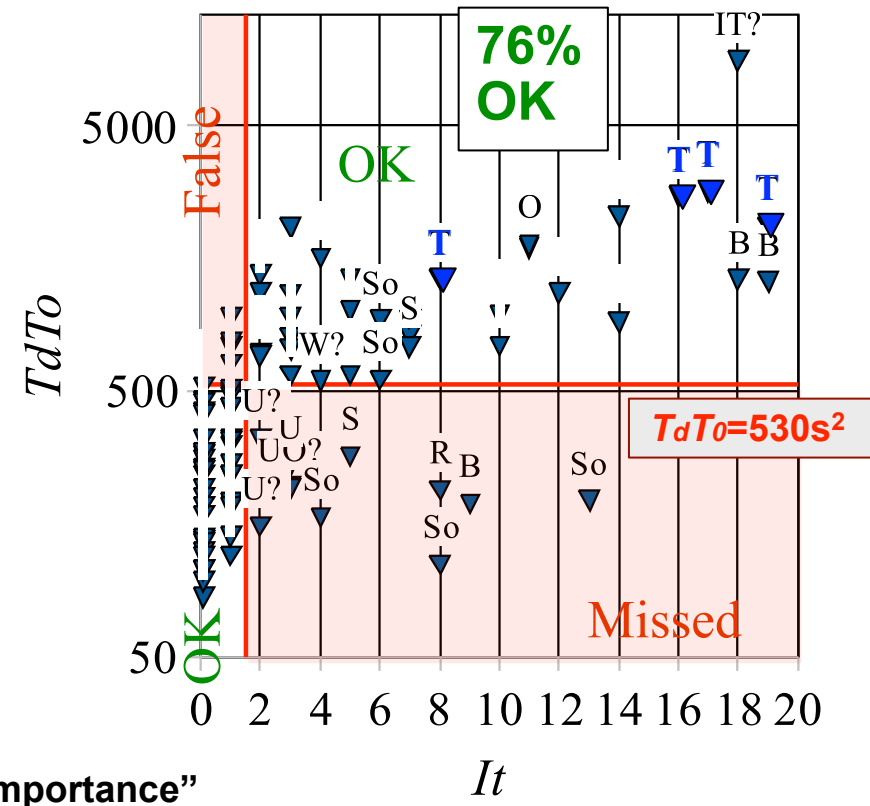
M_w CMT $\rightarrow$ OT+30m+



T_0 - teleseismic HF $\rightarrow$ OT+15m



T_d - T_0 discriminant $\rightarrow$ OT+15m



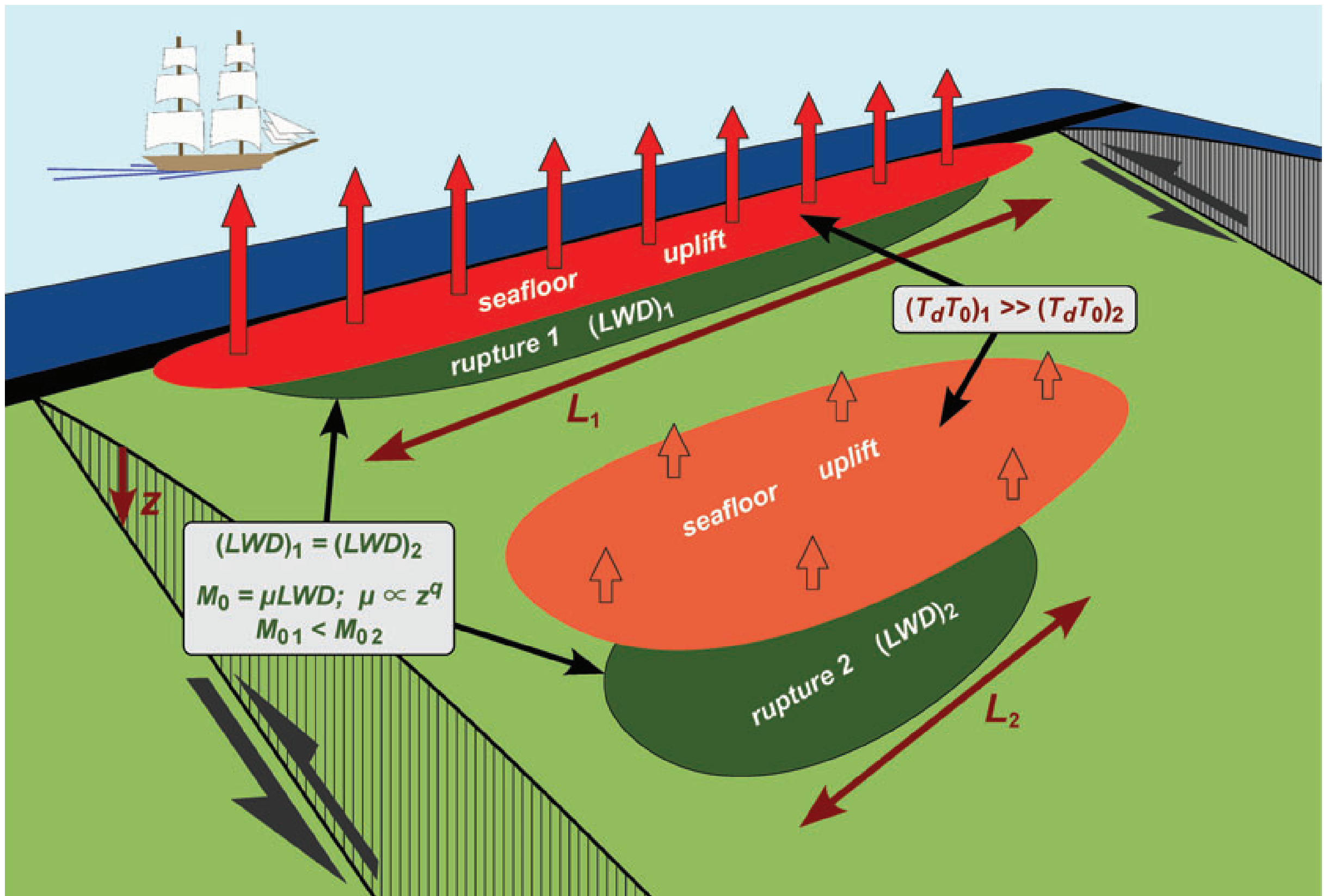


Figure 4. Simplified diagram of a subduction zone mega-thrust (pale green surface) showing two interplate thrust ruptures 1 and 2 with the same seismic potency LWD (dark green patches), but different vertical seafloor displacement (uplift areas shown in red and orange). The long, shallow rupture 1 produces greater total seafloor uplift than the deeper rupture 2. Since $M_0 = \mu LWD$ and μ increases with depth (e.g. $\mu \propto z^q$, q positive), M_0 will be smaller for rupture 1 than for rupture 2. In contrast, since $L_1 > L_2$, and v_r is lower at shallow depths, $T_0 \propto L/v_r$ will be larger for rupture 1 than for rupture 2. Since T_d may give additional information on z , W or D , the quantity $T_d T_0$ for rupture 1 can be larger or much larger than for rupture 2, correctly identifying the greater seafloor uplift and tsunami potential of the long, shallow rupture 1.

Possible source physics for a fault of fixed potency LWD

- As rupture depth decreases:
 - ▶ the rupture velocity, v_r , also decreases, so $T0$ and Td , when interpreted as related to L/v_r , W/v_r or D/v_r , must increase.
 - ✓ Thus the quantity $Td T0$ increases with decreasing rupture depth, more or less correctly reflecting the increased tsunami potential of the shallowest, underwater earthquakes

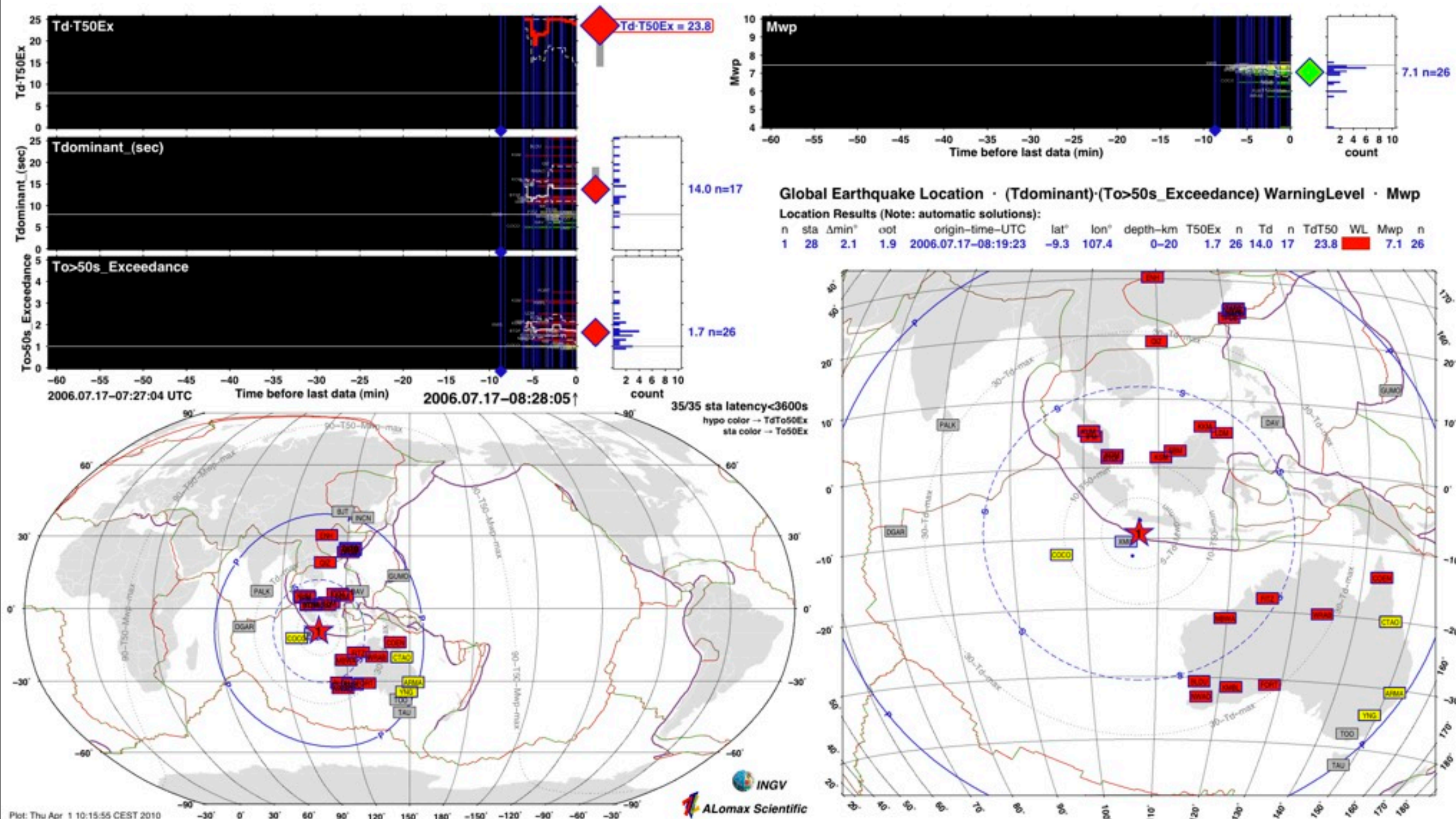
A few more examples

- Same magnitude but different tsunamigenic potential
 - ➡ Java, Indonesia 2006 M7.7
 - ➡ Tonga, M7.6 2009
- The M8.8, 2010 Chile earthquake
- The M7.8, 2010 Mentawai Earthquake



Real-time monitor: Indonesia 2006, $M_w 7.7$, $T_0=180s$, $t_t=19$

INGV monitor simulation, IRIS realtime data, OT+9min

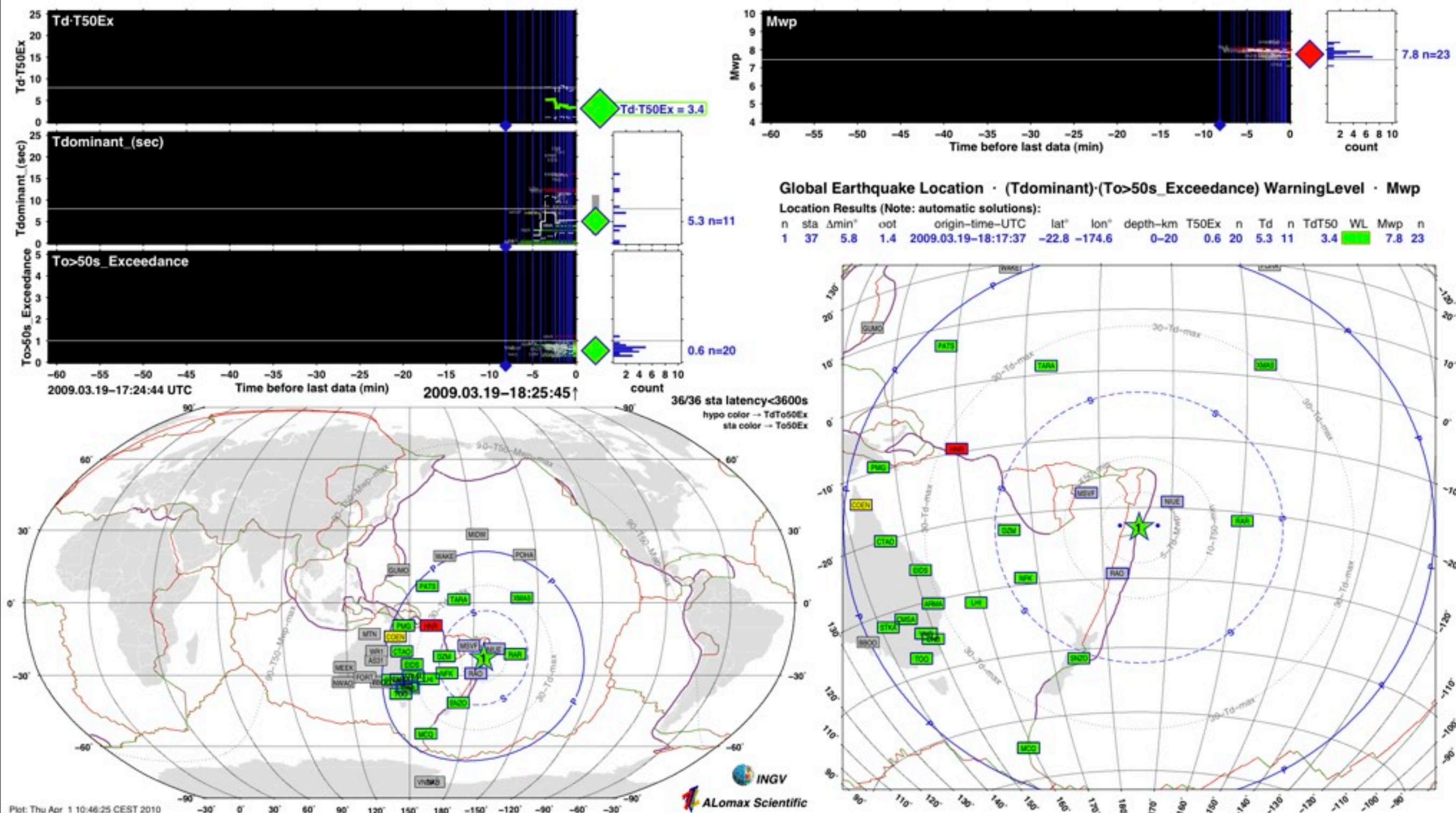


<http://s3.rm.ingv.it/>



Real-time monitor: Tonga Islands 2009, $M_w 7.6$, $T_0=39s$, $t_t=1$

INGV monitor simulation, IRIS realtime data, OT+9min

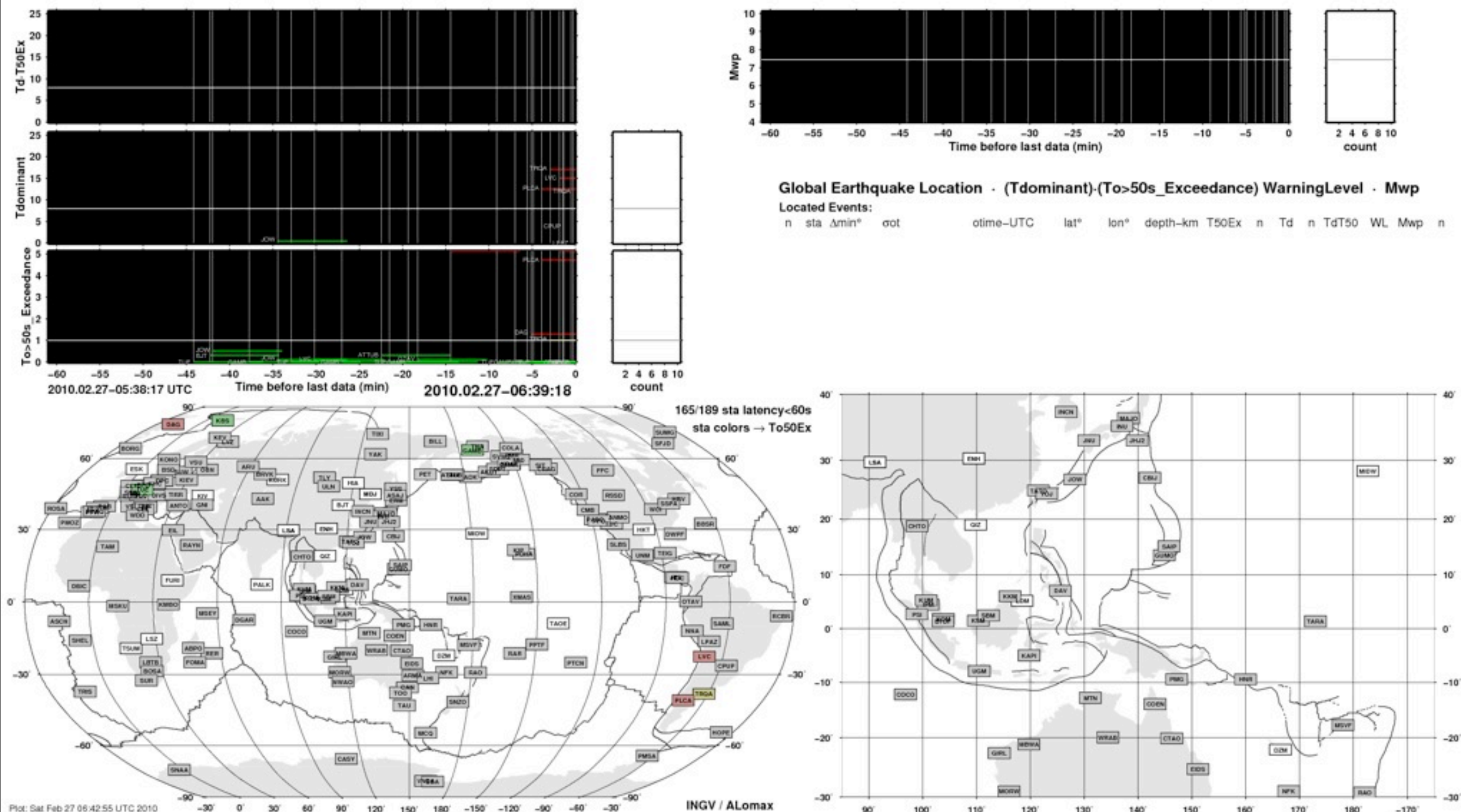


<http://s3.rm.ingv.it/>



Real-time monitor: Chile 2010, $M_w 8.8$ $T_0=144s$ $t=11$

INGV real-time screen-shot, IRIS SeedLink realtime data, OT+6min

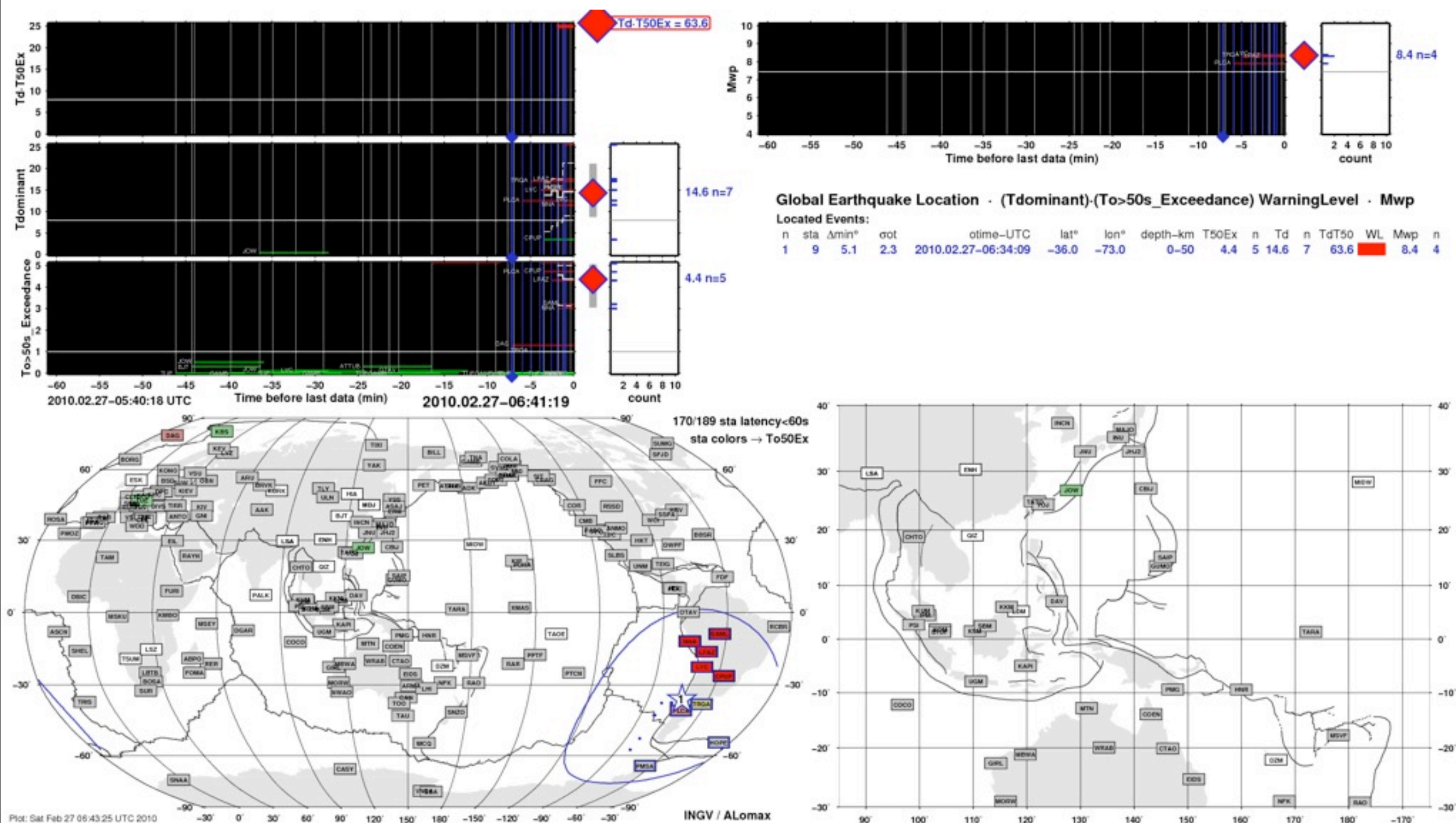


<http://s3.rm.ingv.it/>



Real-time monitor: Chile 2010, $M_w 8.8$ $T_0=144s$ $t=11$

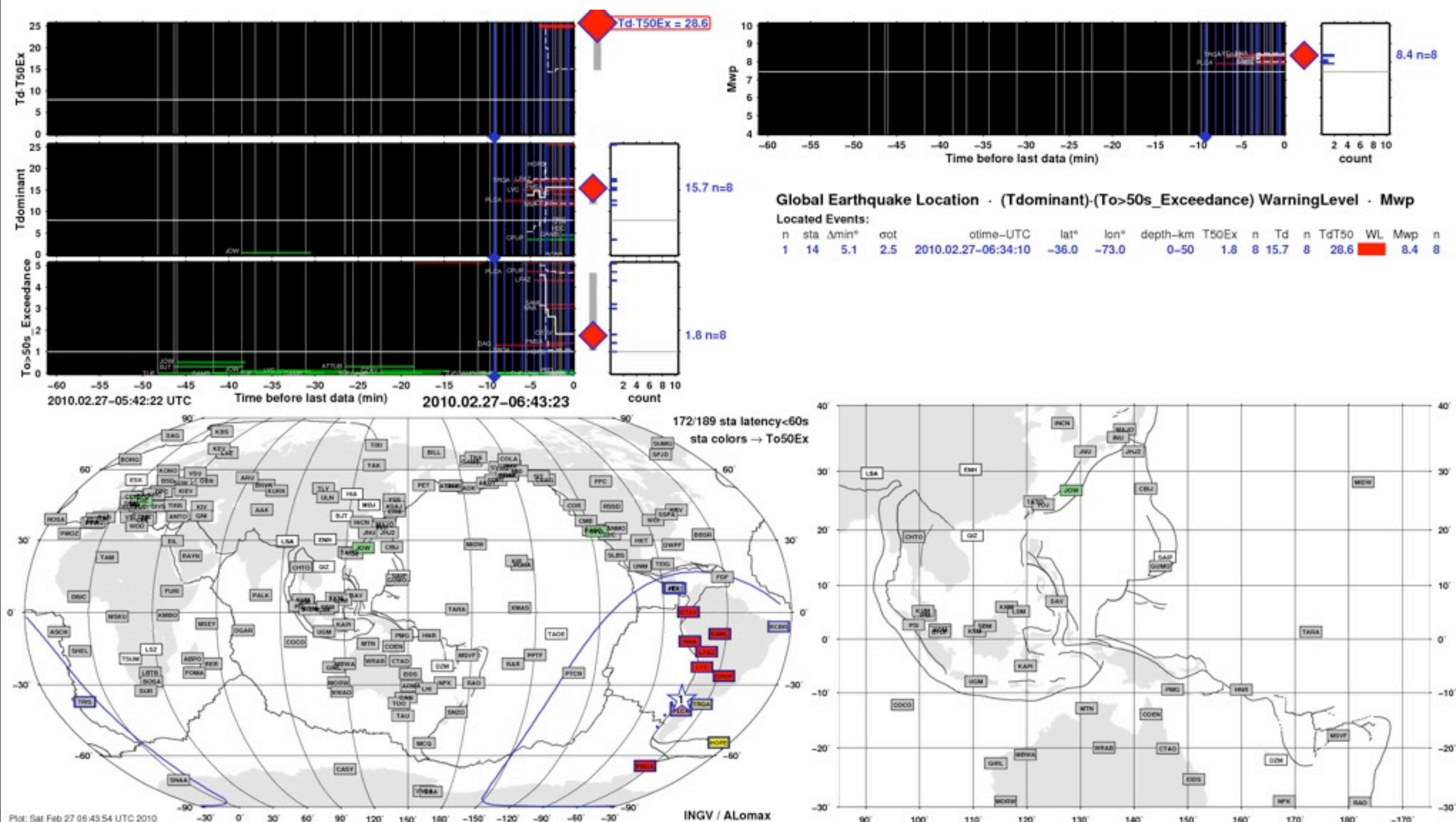
INGV real-time screen-shot, IRIS SeedLink realtime data, OT+8min





Real-time monitor: Chile 2010, $M_w 8.8$ $T_0=144s$ $t=11$

INGV real-time screen-shot, IRIS SeedLink realtime data, OT+10min

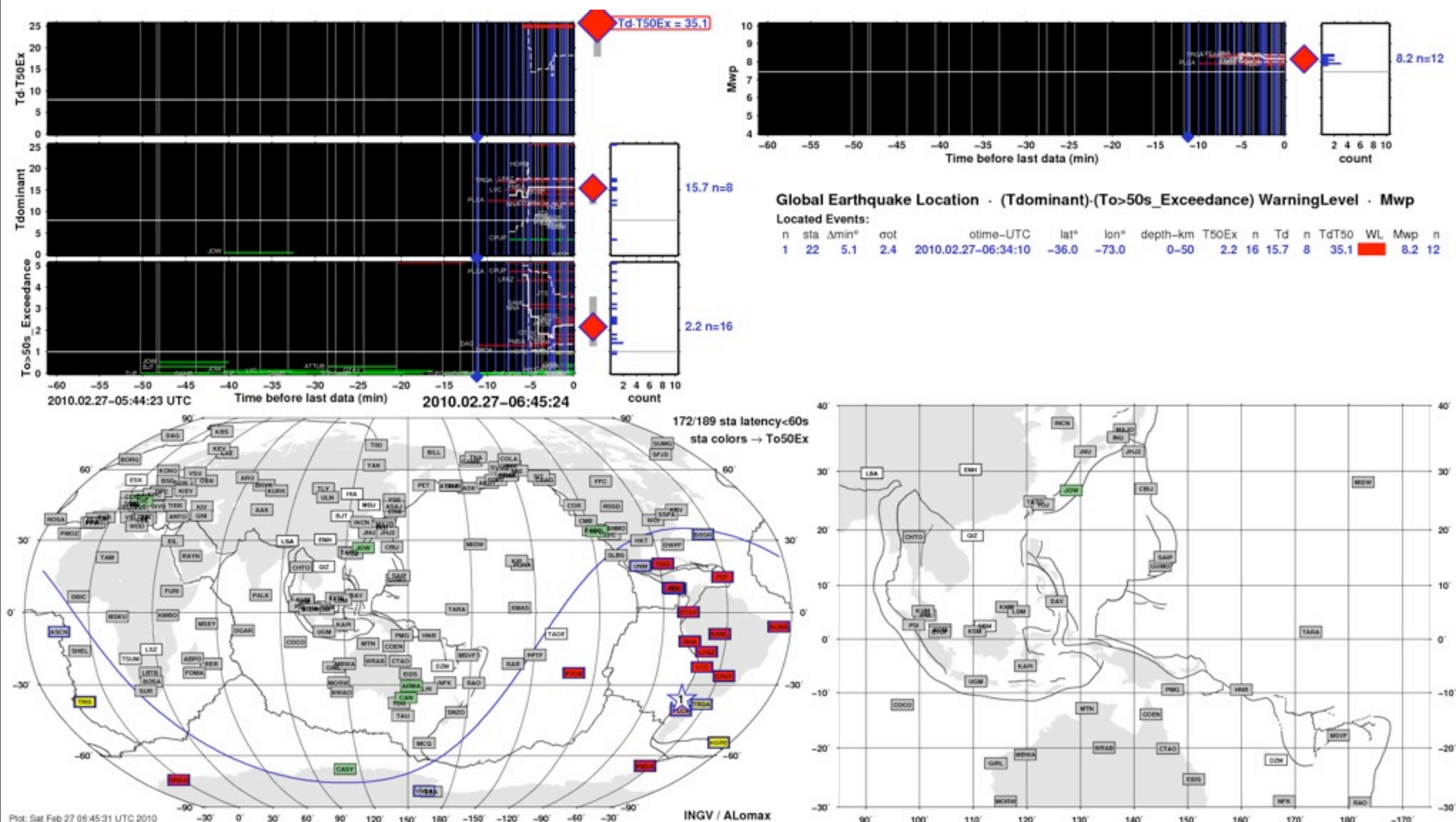


<http://s3.rm.ingv.it/>



Real-time monitor: Chile 2010, $M_w 8.8$ $T_0=144s$ $t=11$

INGV real-time screen-shot, IRIS SeedLink realtime data, OT+12min

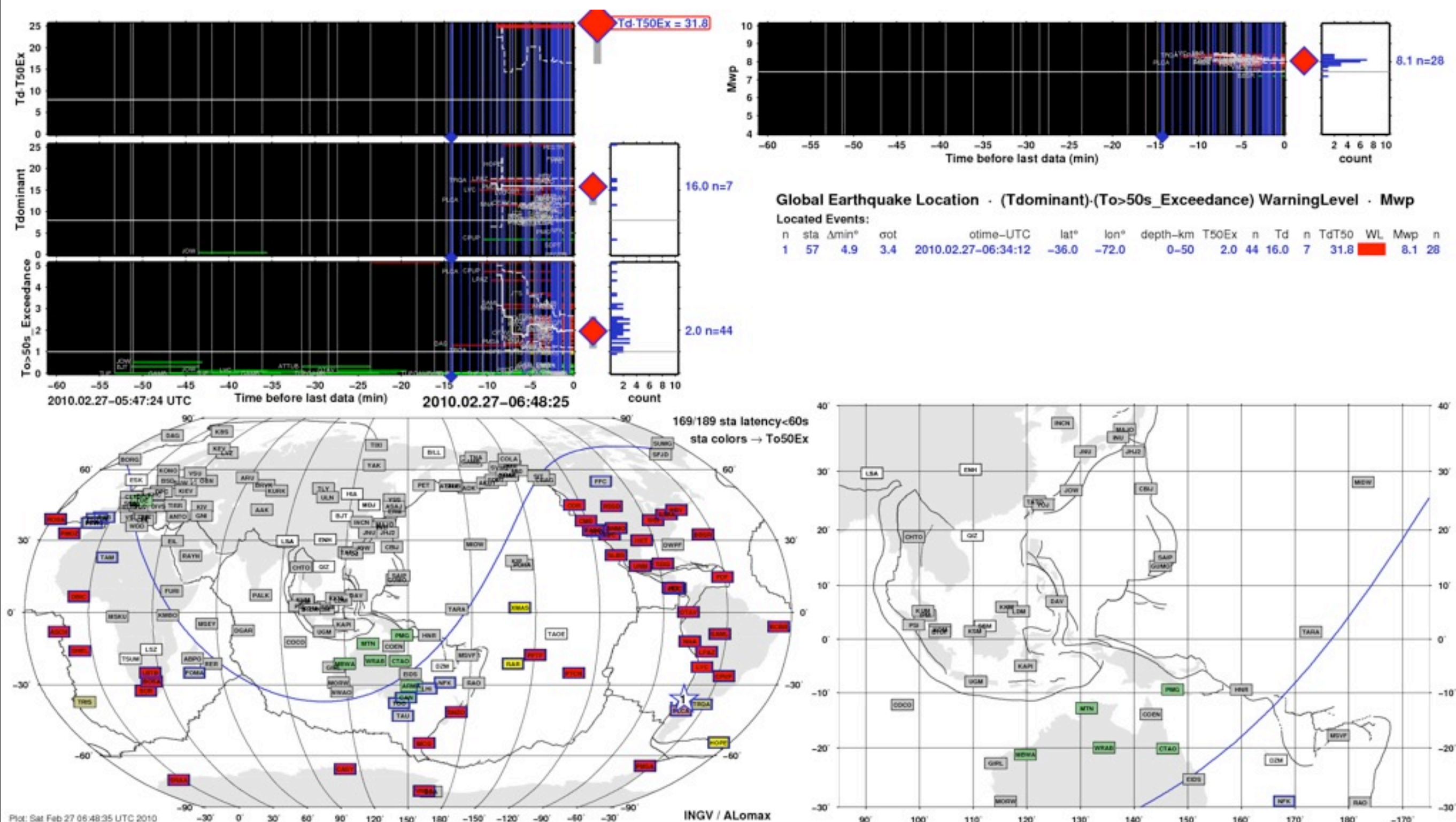


<http://s3.rm.ingv.it/>



Real-time monitor: Chile 2010, $M_w 8.8$ $T_0=144s$ $t=11$

INGV real-time screen-shot, IRIS SeedLink realtime data, OT+15min

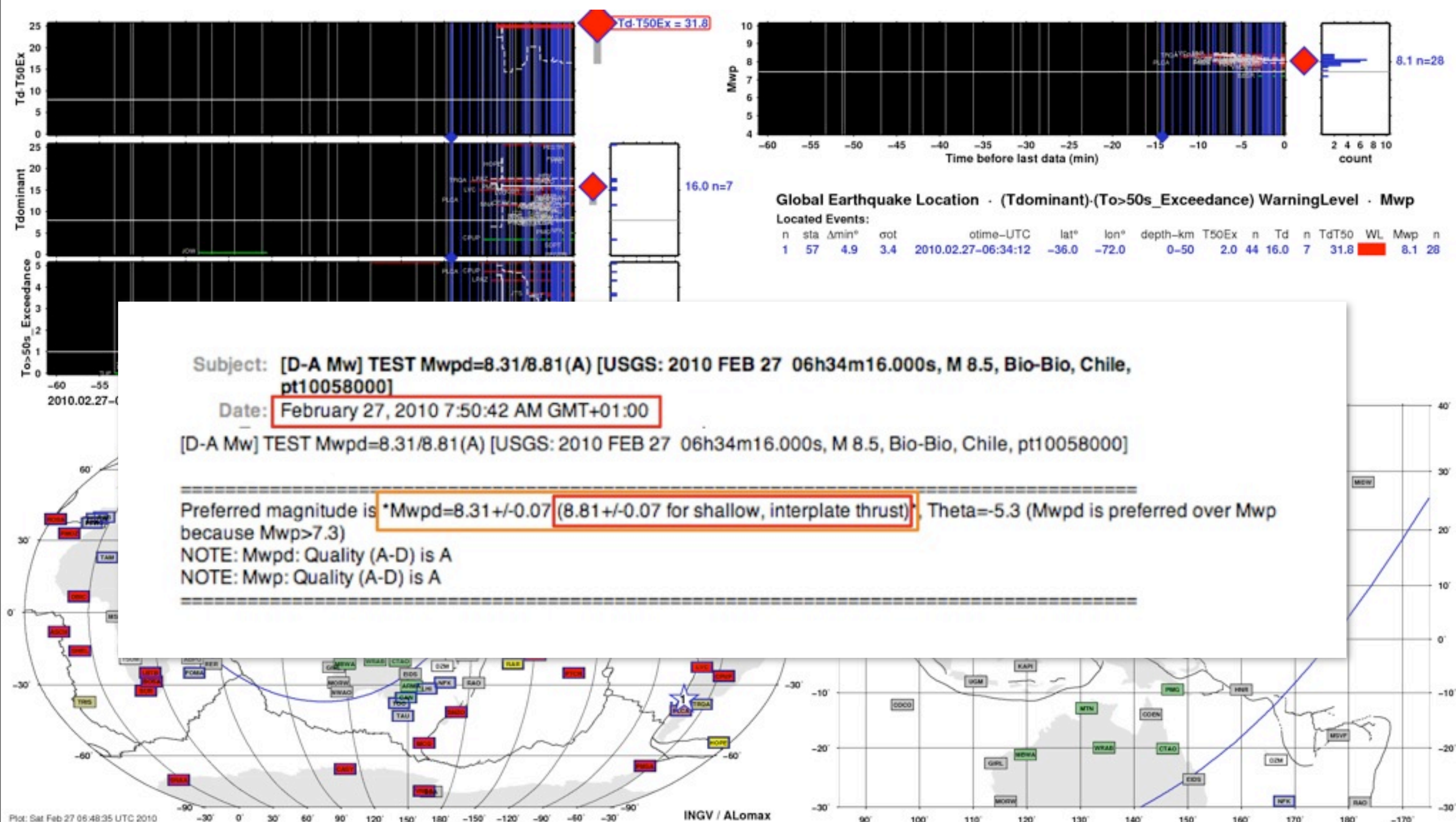


<http://s3.rm.ingv.it/>



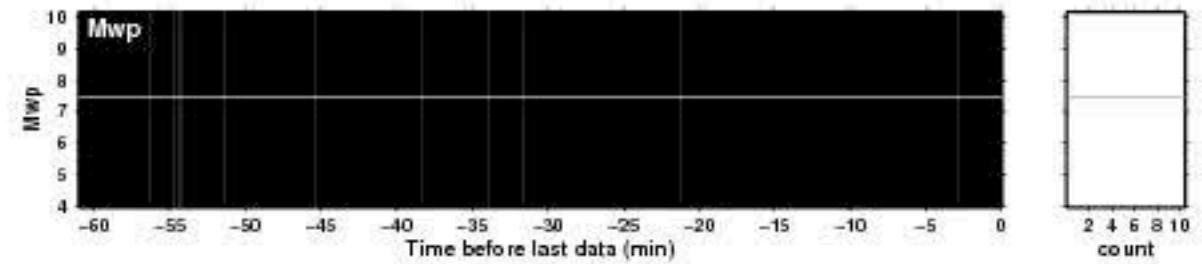
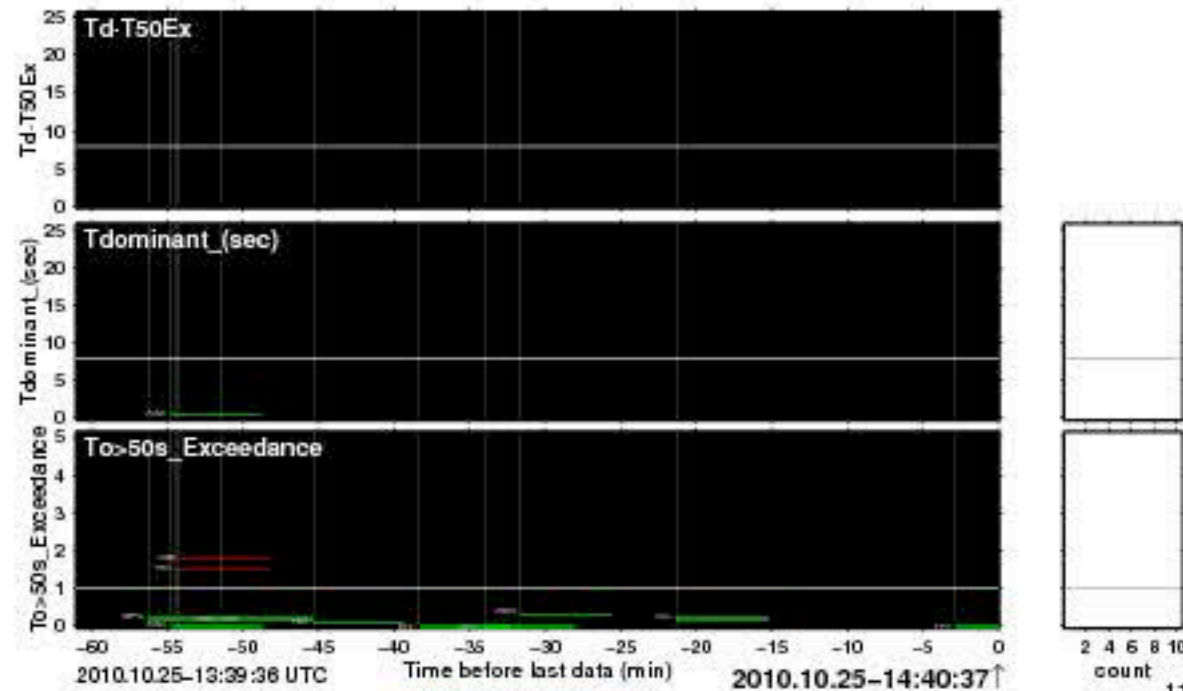
Real-time monitor: Chile 2010, $M_w 8.8$ $T_0=144s$ $t=11$

INGV real-time screen-shot, IRIS SeedLink realtime data, OT+15min



<http://s3.rm.ingv.it/>

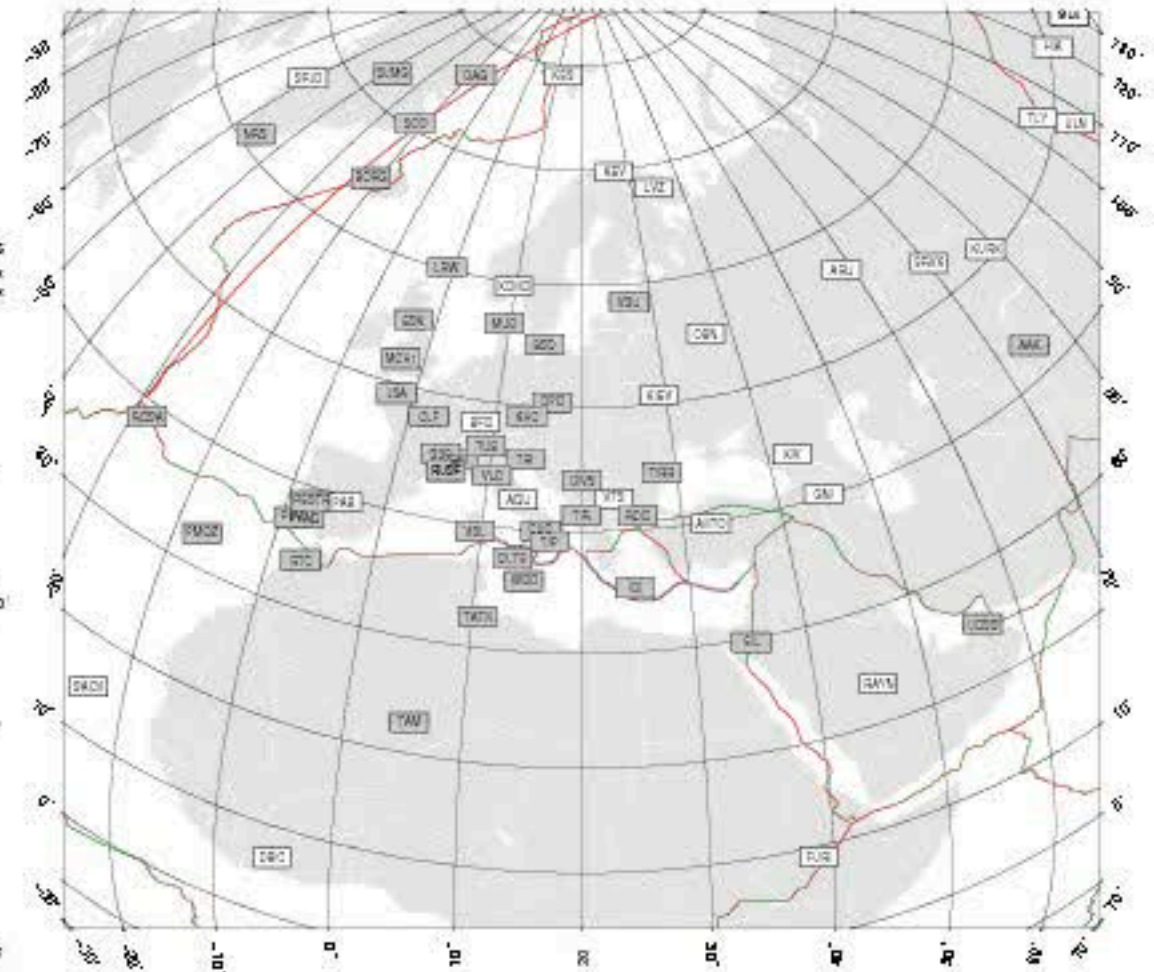
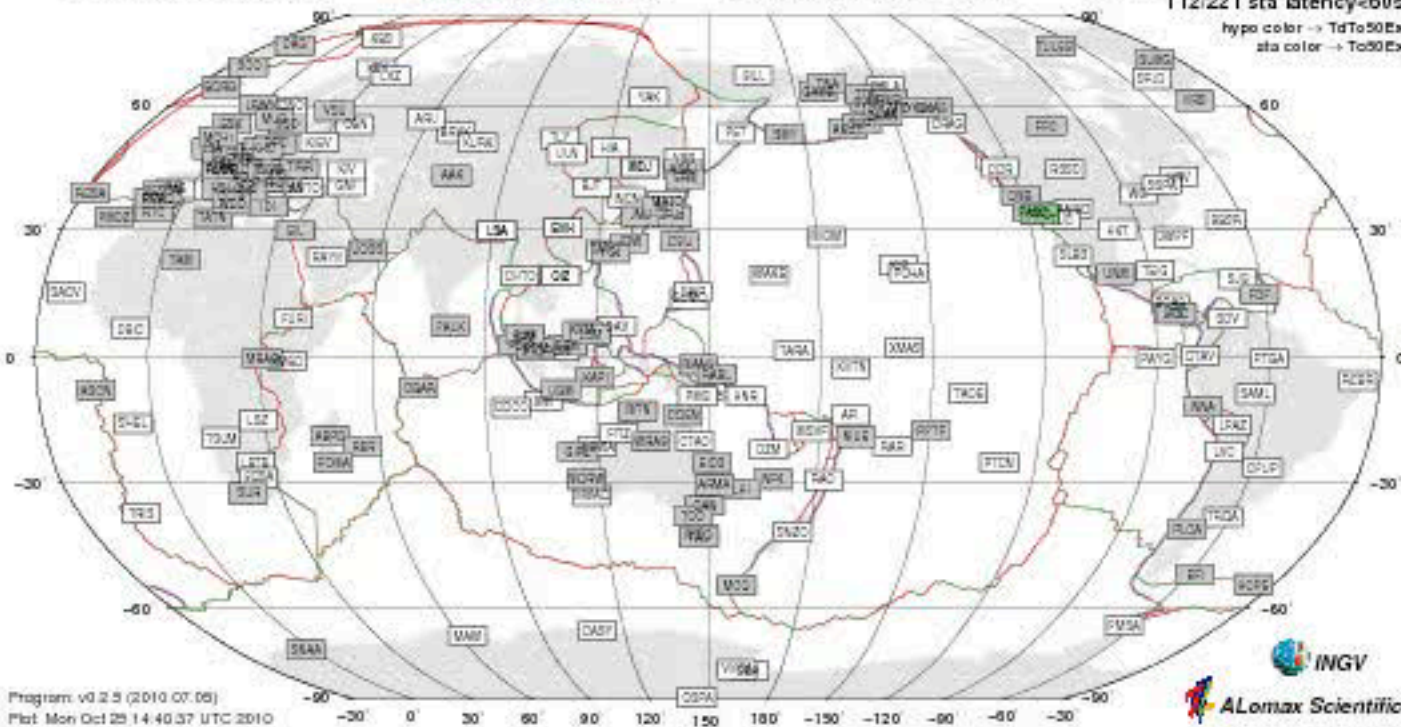
Mentawai, Mw=7.8 10/25/2010



Global Earthquake Location - (Tdominant)-(To>50s_ Exceedance) Level - Mw

Location Results (Note: automatic solutions):

n sta Δmin° cot origin-time-UTC lat° lon° depth-km T50Ex n Td n TdT50 WL Mw n



Program: v0.2.3 (2010.07.08)
Plot: Mon Oct 25 14:40:37 UTC 2010

INGV
ALomax Scientific



Tsunami early warning → within 5-15min after OT ∴ *adopt discriminants* ?

Blood test Example

Descrizione		Risultato	Unita'	Int. di Riferimento	
Creatininemia	→	* 0,89	mg/dL	0,90	1,30
GOT	✓	23	U/L	0	34
GPT	✓	38	U/L	10	49
Gamma GT	✓	36	U/L	0	73
Colesterolemia	→	* 232	mg/dL	<200	
Trigliceridi	✓	134	mg/dL	<250	
Colesterolo HDL	✓	51	mg/dL	>40	



Tsunami early warning → within 5-15min after OT ∴ *adopt discriminants ?*

<i>Description</i>	<i>Reference values</i>	<i>Timing</i>
Location	underwater	< 4'÷5'
Magnitude (e.g., Mwp, Mwpd)	> 7.5 (WW), >6.5 ÷ 7.0 (in Med)	OT + 8'÷15'
Source Depth	< 10-20 km	< 4'÷5'
Mechanism	Interplate thrust, Reverse slip, Normal, Strike-slip ?	OT+ 15'÷30'
P-wave duration (T0)	> 50 s	OT + 6'÷12'
Dominant period (Td)	> 8 s (?)	OT + 6'÷12'
Tectonics	Interplate thrust, Reverse slip, Normal, Strike-slip ?	
Historical info	Previous tsunamis ?	
Combinations (e.g., T0 Td)	(> 500 s ²)	OT + 6'÷12'

Conclusions

- EARLY-EST has proven very effective for global earthquake monitoring and tsunami potential assessment
- For tsunami assessment it appears that the concept of discriminants should be applicable
- Magnitude not necessarily is a good indicator of tsunamigenesis
- The duration-amplitude magnitude M_{wpd} :
 - ▶ Available <15 after OT
 - ▶ Extremely useful for $M > 7.5$ earthquakes
- The T_o, T_d & $T_o T_d$ period-duration discriminant:
 - ▶ Available <10 min after OT
 - ▶ Provide prompt discrimination of tsunamigenic potential
- Real-time monitoring at <http://s3.rm.ingv.it/warning/warning.html/>

Further information

- Lomax, A. and A. Michelini, 2010. Tsunami early warning using earthquake rupture duration and P-wave dominant-period: the importance of length and depth of faulting, Geophys. J. Int., submitted.
- Lomax, A. and A. Michelini, 2009B. Tsunami early warning using earthquake rupture duration, Geophys. Res. Lett., 36, L09306, doi:10.1029/2009GL037223
- Lomax, A. and A. Michelini, 2009A. Mwprd: A duration-amplitude procedure for rapid determination of earthquake magnitude and tsunamigenic potential from P waveforms, Geophys. J. Int., 176, 200–214, doi:10.1111/j.1365-246X.2008.03974.x
- Michelini, A., Lauciani, V., Selvaggi, G., and A. Lomax. The 2010 Chile Earthquake: Rapidly Assessing Magnitude and Tsunami Threat (EOS, 2010 vol. 91 (35) pp. 305-306)

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The IRIS DMC (<http://www.iris.edu>) and USGS NEIC provided access to waveforms used in this study; we thank all those who install, operate and maintain seismic stations worldwide.

Valentino Lauciani is greatly thanked for maintaining it at INGV



*Placca del Colosseo
Augusto Flavio, oggi detto Colosseo - Arco di Costantino - Rovine antiche che fino nell'Orto di S. Maria la Nuova & Chiesa Convento di S. Benigno.*

Faulting size, rupture duration and dominant period

moment: $M_0 \leftarrow \mu LWD$ (“seismic” faulting model)

rupture duration: $T_0 \leftarrow L / V_r$

P -wave velocity dominant period:

$T_d \leftarrow 1/f_c \propto W? \propto D?$

$T_d \leftarrow 1/z?$ (e.g. tsunami earthquake)

moment: $M_0 \leftarrow \mu LWD$ (“seismic” faulting model)

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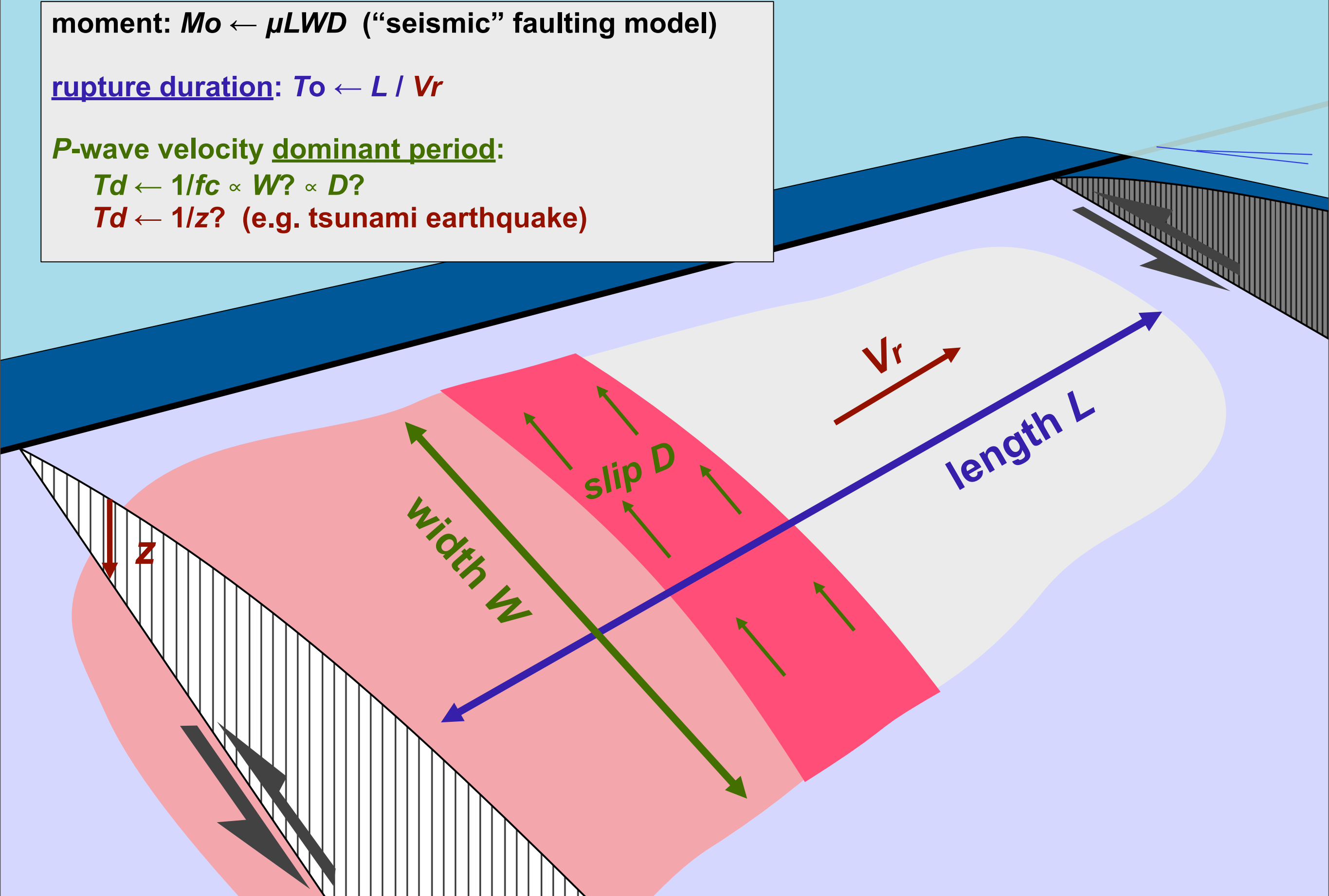
moment: $M_0 \leftarrow \mu LWD$ (“seismic” faulting model)

rupture duration: $T_0 \leftarrow L / V_r$

P -wave velocity dominant period:

$T_d \leftarrow 1/f_c \propto W? \propto D?$

$T_d \leftarrow 1/z?$ (e.g. tsunami earthquake)



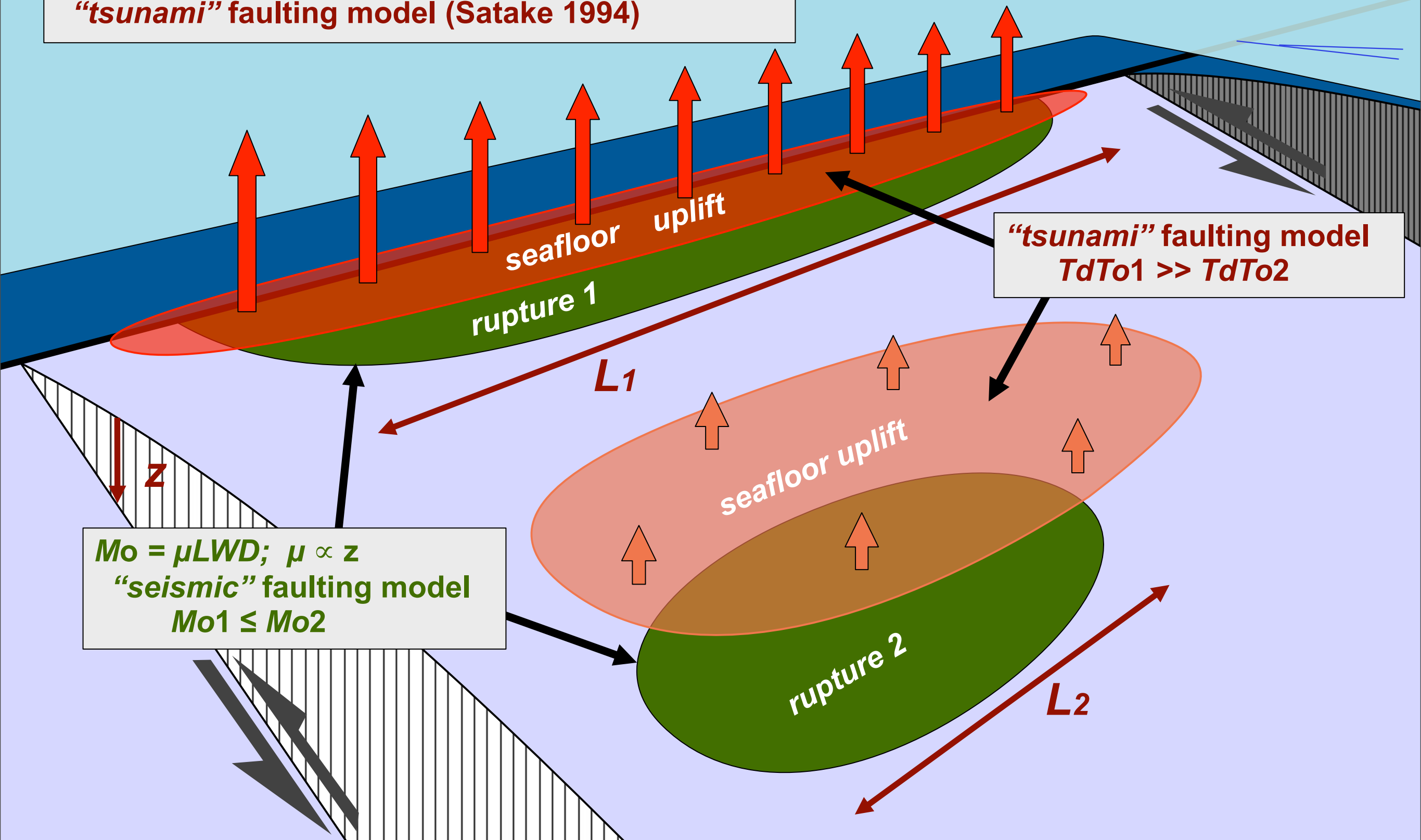


Importance of identifying length and depth of faulting

rupture duration: $T_o \leftarrow L / V_r$; $V_r \propto z$

→ T_o grows with increasing L and decreasing z

→ $T_d T_o$ discriminant identifies seafloor uplift:
“tsunami” faulting model (Satake 1994)



Example of nearly simultaneous earthquakes

