Constraining the overall source process of large earthquakes with long period data: the case of W phase

Luis Rivera[1)]
Main collaborators: Hiroo Kanamori[2)] y Zacharie Duputel[1)]
1) Institut de Physique du Globe de Strasbourg; Université de Strasbourg
2)Seismological Laboratory, Caltech

ICTP, Trieste
August 29th - September 3rd, 2016

School on Seismology beyond Textbooks

Overview
Morning session

1. Motivation and Introduction
2. W phase: waveform examples
3. W phase source inversion algorithm
4. Global application
   - Global seismicity, 1990-2010 - $M_w \geq 6.5$
5. Regional application
   - Japan 2003-2010 - $M_{jma} \geq 6.5$
6. Real time Implementations
7. Uncertainty analysis for source inversion
8. Conclusions

Overview
Afternoon session

1. Requirements
2. Download and installation
3. The Green's function database
4. Input files
5. Run several examples:
   2016 Ecuador, 2010 Maule, 2011 Tohoku, etc
6. Output files
7. Examining some scripts
8. Some useful URL's

Objectives

Provide a general overview of the concepts
Present a few specific technical details
Show how to install and run the codes
Work several pre-prepared examples
Work some examples from scratch

Questions are more than welcome at any time !

Sumatra-Andaman earthquake 2004 (Mw=9.2)

Source: National Oceanic and Atmospheric Administration

O.T. : ***Origin time (00:58 UTC)***

15min : PTWC announce M8.0; “No Tsunami threat around the Pacifique”

25min : ***Tsunami hits Indonesia***

1h05min : PTWC updates to M8.5 and mention the possibility of a tsunami near the epicenter

1h35min : ***Tsunami hits Thailandia***

1h45min : ***Tsunami hits Sri Lanka***

2h00min : ***Tsunami hits India***

4h30min : Global CMT solution, Mw=8.9

6h30min : ***Tsunami hits Somalia***

1 day : Global CMT update to Mw=9.0

(PTWC: Pacific Tsunami Warning Center)

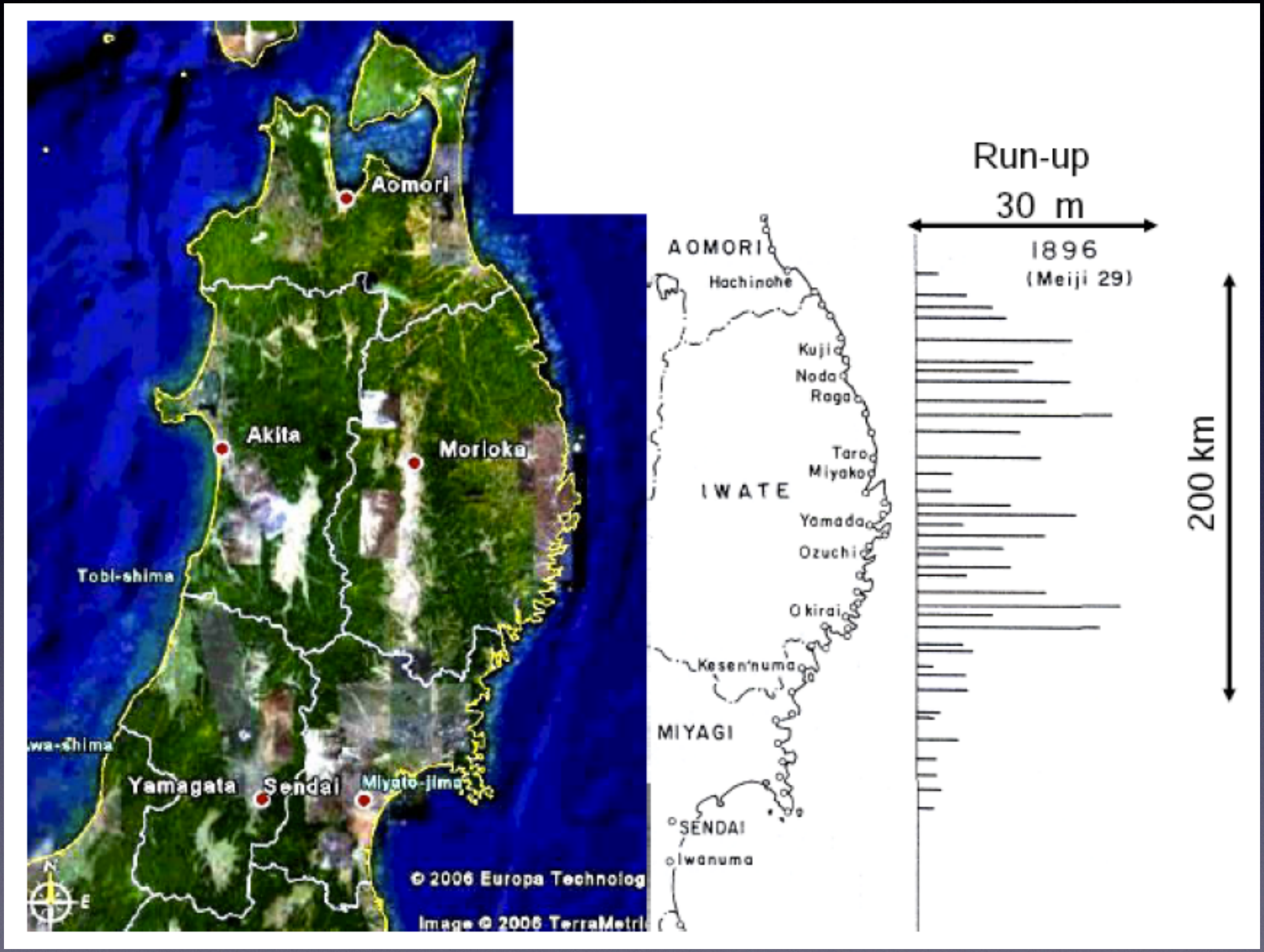
Java "tsunami" earthquake 2006 (Mw=7.7)

Source: Jim Mori, Kyoto University

O.T.	: ***Origin time (08:19 UTC)***
11min	: BMG: "No tsunami risk" (M6.8)
17min	: PTWC: local warning for Indonesia and Australia (M7.2)
27min	: JMA: warning for the Indian ocean (M7.2, coord. PTWC)
56min	: ***Tsunami hits Pangandaran***
6h15min	: Global CMT solution Mw=7.7

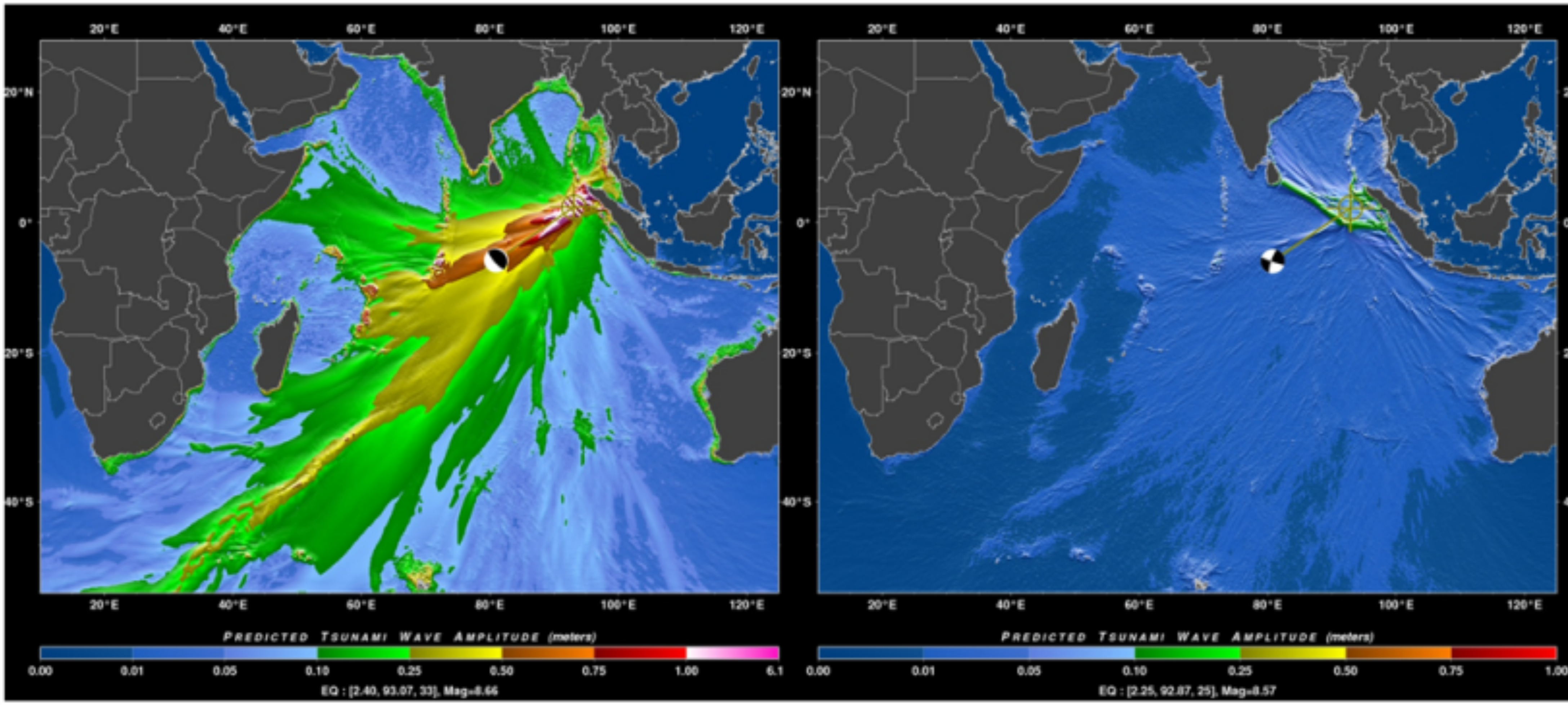
PTWC: Pacific Tsunami Warning Center
BMG : Bandan Meterologi dan Geofisika

1896, Sanriku earthquake, M ~7.2
first tsunami arrival ~ 30 min



11th April 2012, offshore Sumatra Tsunami Forecast, (Dailin Wang, PTWC)

PTWC Real Time Forecast of Tsunamis (RIFT)



Based on shallow thrust assumption
Mwp=8.66 (initial PTWC Magnitude)

USGS (Gavin Hayes)
Wphase CMT: Mw=8.57 (Strike-slip)

The initial PTWC magnitude is larger than that of the USGS CMT magnitude, but the major difference between the two runs are focal mechanisms: thrust vs. strike-slip.

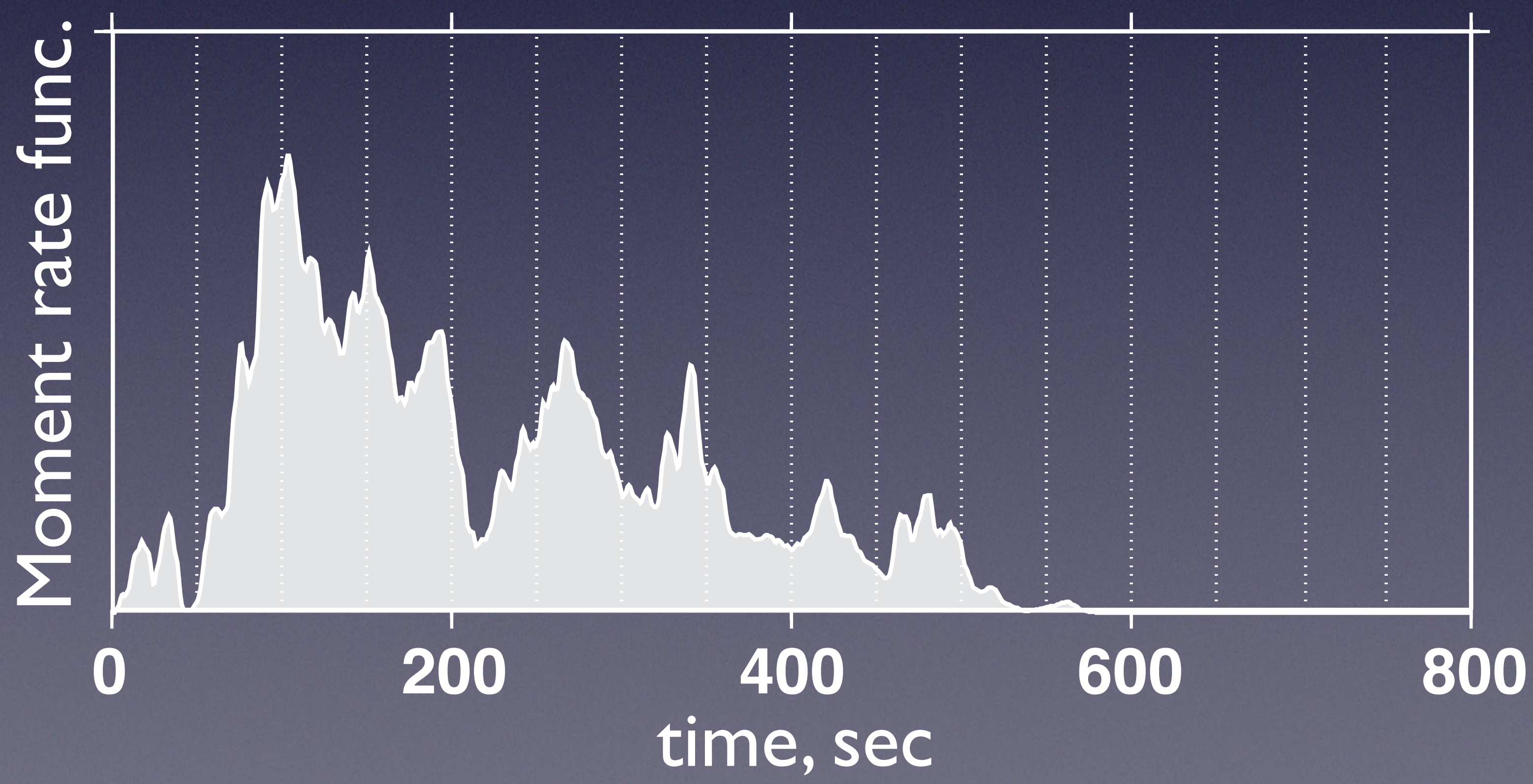
Major earthquakes ($M_w > 7.5$)

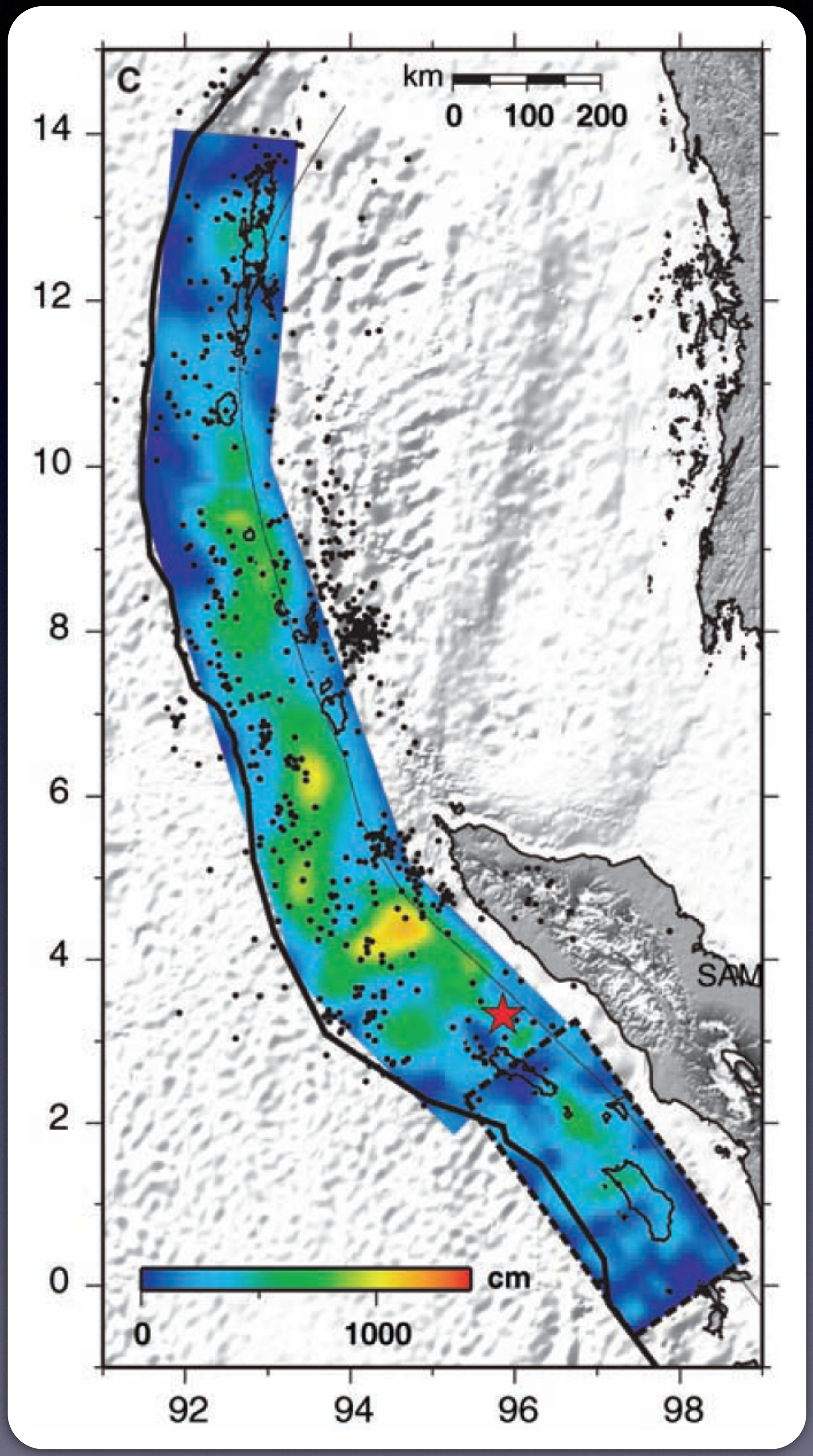
Large ruptures

↓

point-source approximation?

Example: Sumatra-Andaman 2004





Ammon et al., 2005

JOURNAL OF GEOPHYSICAL RESEARCH VOL. 72, NO. 4 FEBRUARY 15, 1967

Scaling Law of Seismic Spectrum

KEIITI AKI

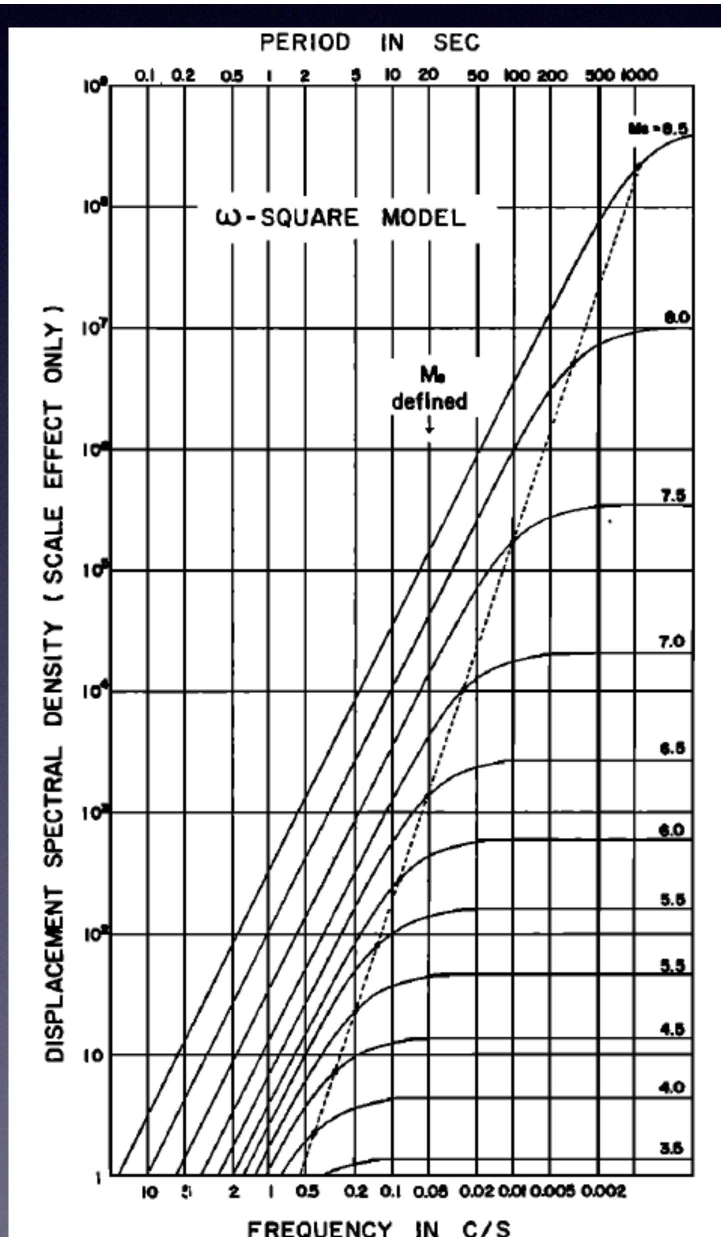


Fig. 3. Dependence of amplitude spectral density of earthquake magnitude *M*, for the ω-square model.

Scaling law

K. Aki, 1967

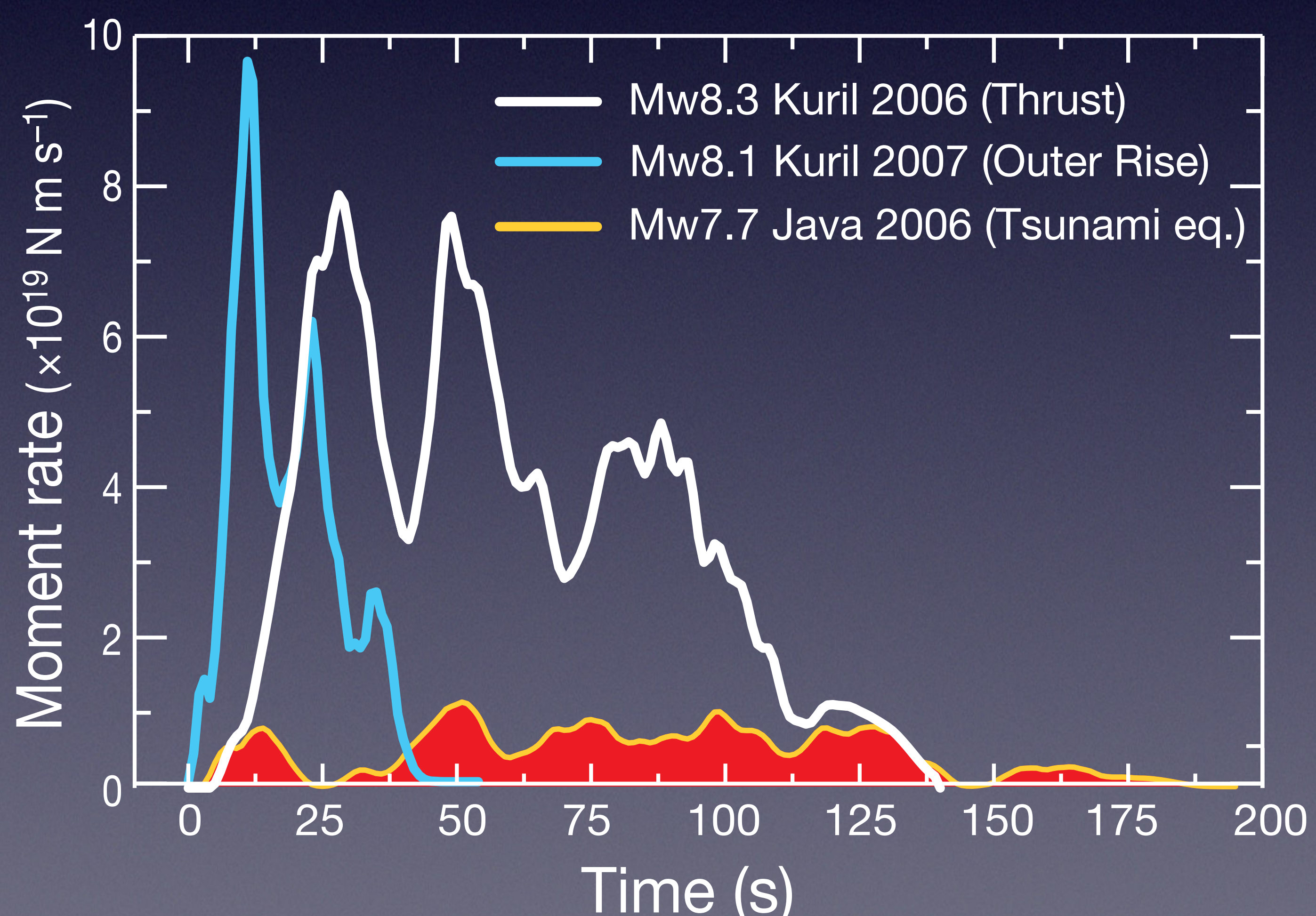
Source duration ~ $Mo^{1/3}$

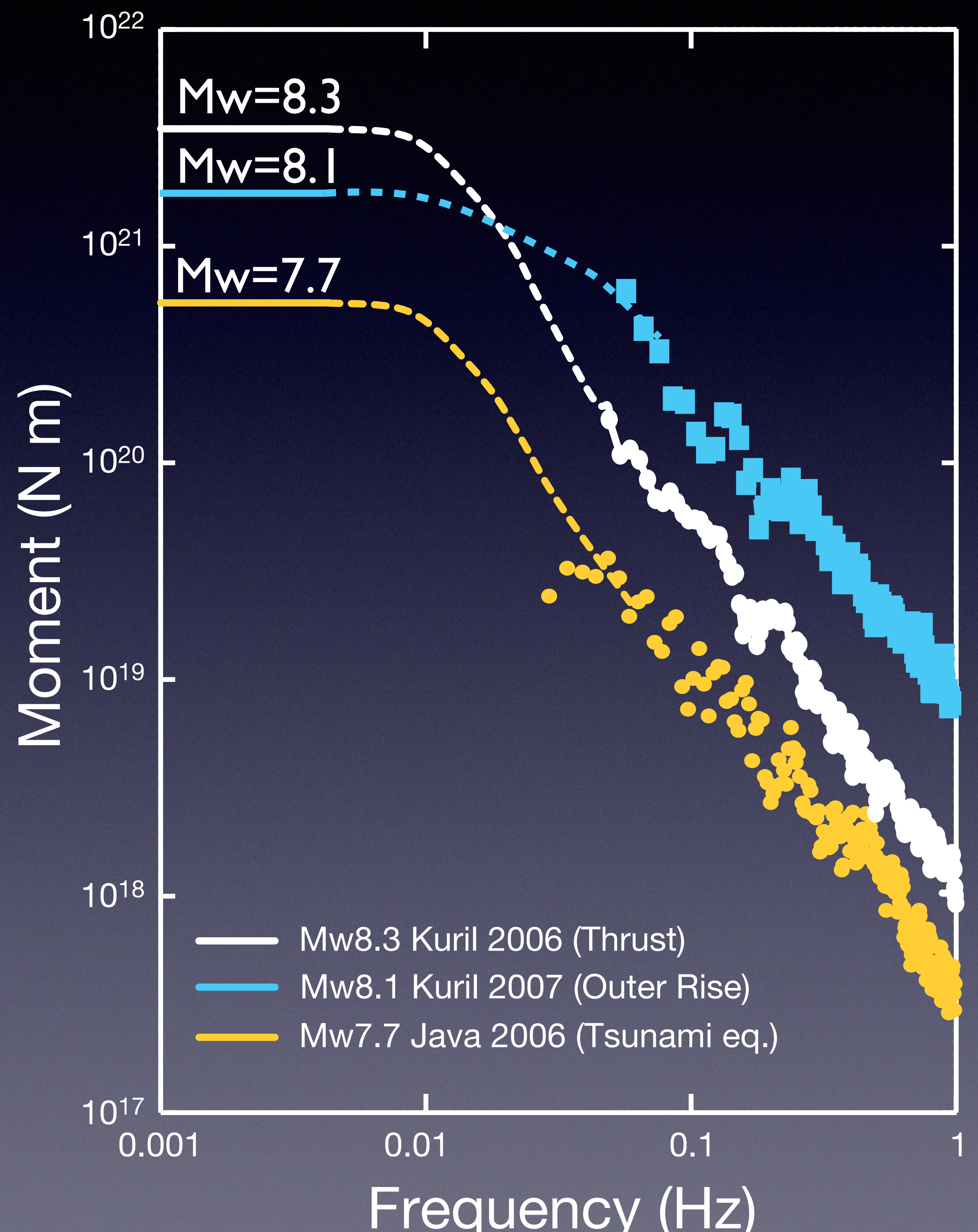
e.g. half duration = 1.2e-8 $Mo^{1/3}$ s/(dyn cm)$^{1/3}$

Major earthquakes ($M_w > 7.5$)

Complexity/Diversity

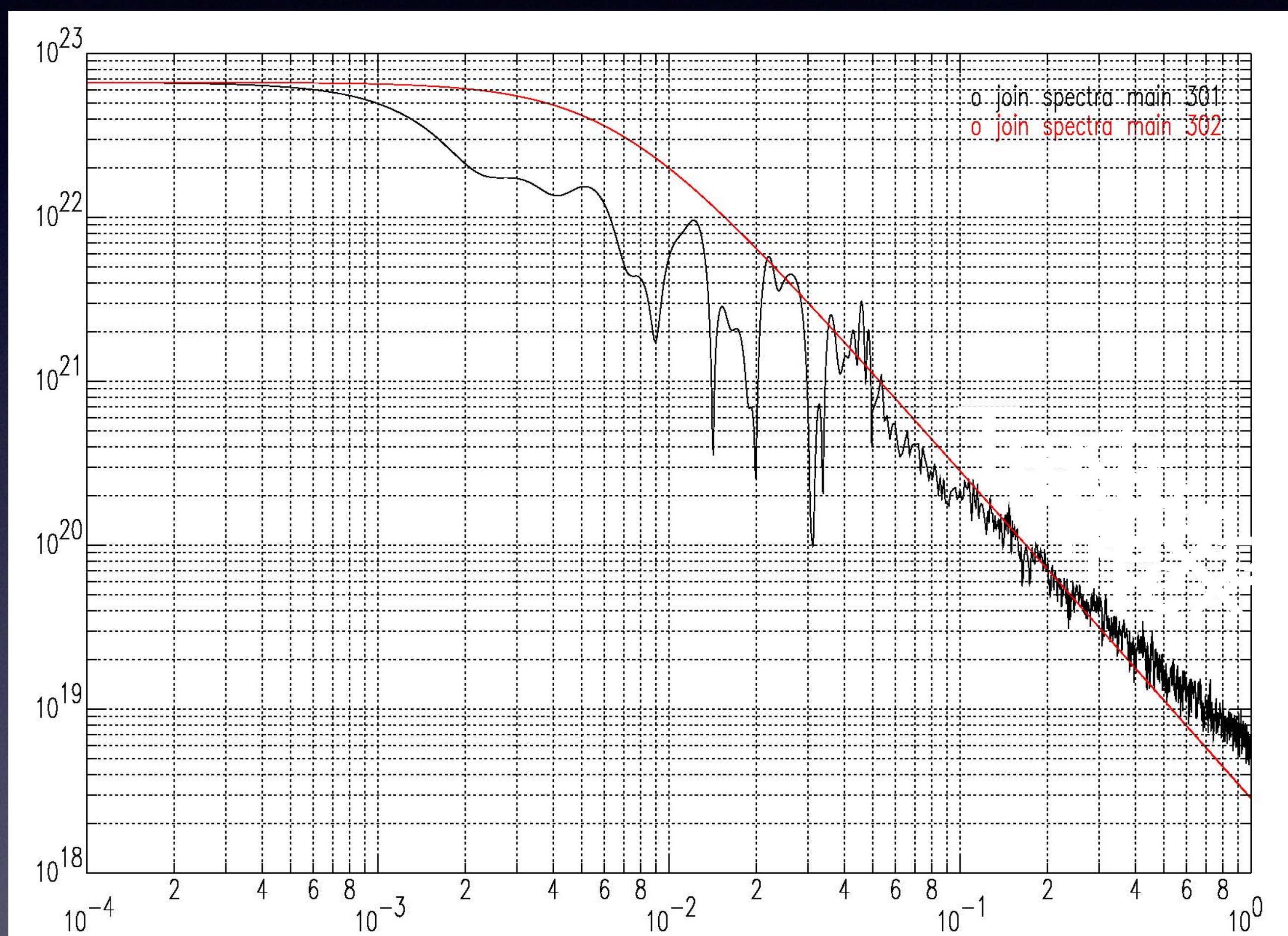
- Tsunami earthquakes
- Outer-rise earthquakes

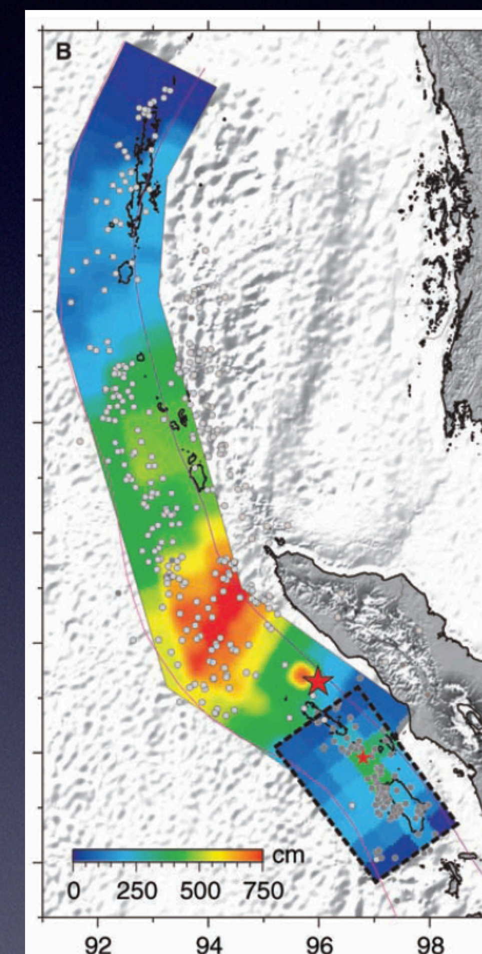




Ammon et al., 2006, 2008

Sumatra 2004 Moment rate spectrum





Frequency Hz

Amon et al., 2005

Need for a method providing a *fast* and *robust* estimation of the *first order* source parameters for *very large* earthquakes

Large earthquakes:

- Source complexity and diversity

- Data clipping

e.g. for Sumatra 2004, most of the broad band records within 40° of distance were clipped at the surface waves arrival

- Minimizing sensitivity to the Earth model

Two previous examples

Use of long-period surface waves for rapid determination of earthquake-source parameters

Hiroo Kanamori and Jeffrey W. Given

Physics of the Earth and Planetary Interiors, 27 (1981) 8–31

AN EXPERIMENT IN SYSTEMATIC STUDY OF GLOBAL SEISMICITY: CENTROID-MOMENT TENSOR SOLUTIONS FOR 201 MODERATE AND LARGE EARTHQUAKES OF 1981

Adam M. Dziewonski and John H. Woodhouse

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, NO. B4, PAGES 3247-3271, APRIL 10, 1983

> Global cmt (Ekstrom, et al.)

Kanamori & Given, 1981

$$u_r(\mathbf{r},t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \hat{C}_{\mathrm{R}}(\omega)\exp(\mathrm{i}\omega t)\,\mathrm{d}\omega$$

where

$$\hat{C}_{\mathrm{R}}(\omega) = \frac{1}{(\sin\theta)^{1/2}}\exp\left(\frac{1}{4}\pi\mathrm{i}\right)$$

$$\exp\left(-\frac{\mathrm{i}\omega a\theta'}{C}\right)\exp\left(\frac{1}{2}m\pi\mathrm{i}\right)$$

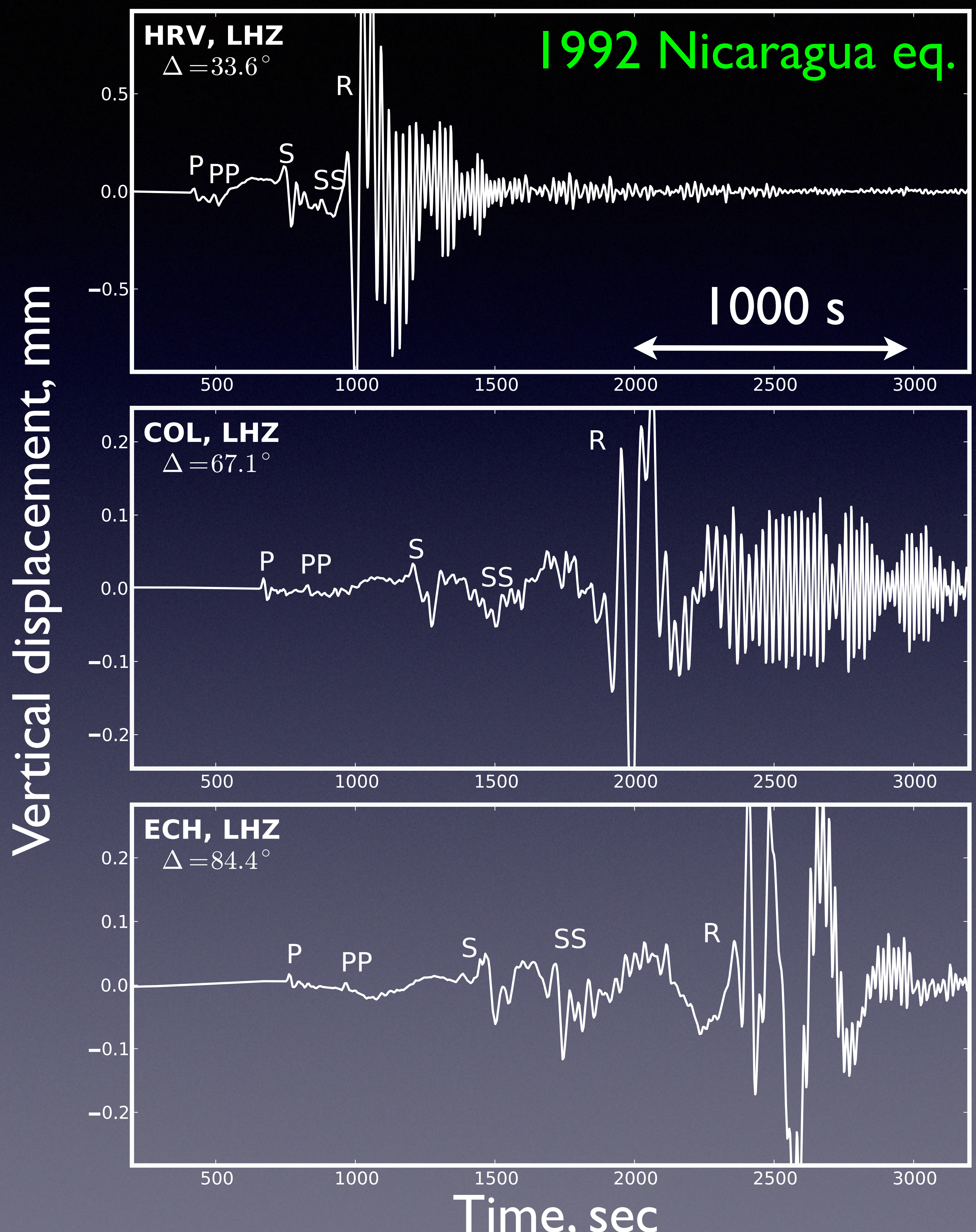
$$\left\{-P_{\mathrm{R}}^{(1)}\left[M_{xy}\sin 2\phi - \frac{1}{2}(M_{yy}-M_{xx})\cos 2\phi\right]\right.$$

$$+\frac{1}{3}\left(S_{\mathrm{R}}^{(1)}+N_{\mathrm{R}}^{(1)}\right)M_{zz}$$

$$+\frac{1}{6}\left(2N_{\mathrm{R}}^{(1)}-S_{\mathrm{R}}^{(1)}\right)(M_{xx}+M_{yy})$$

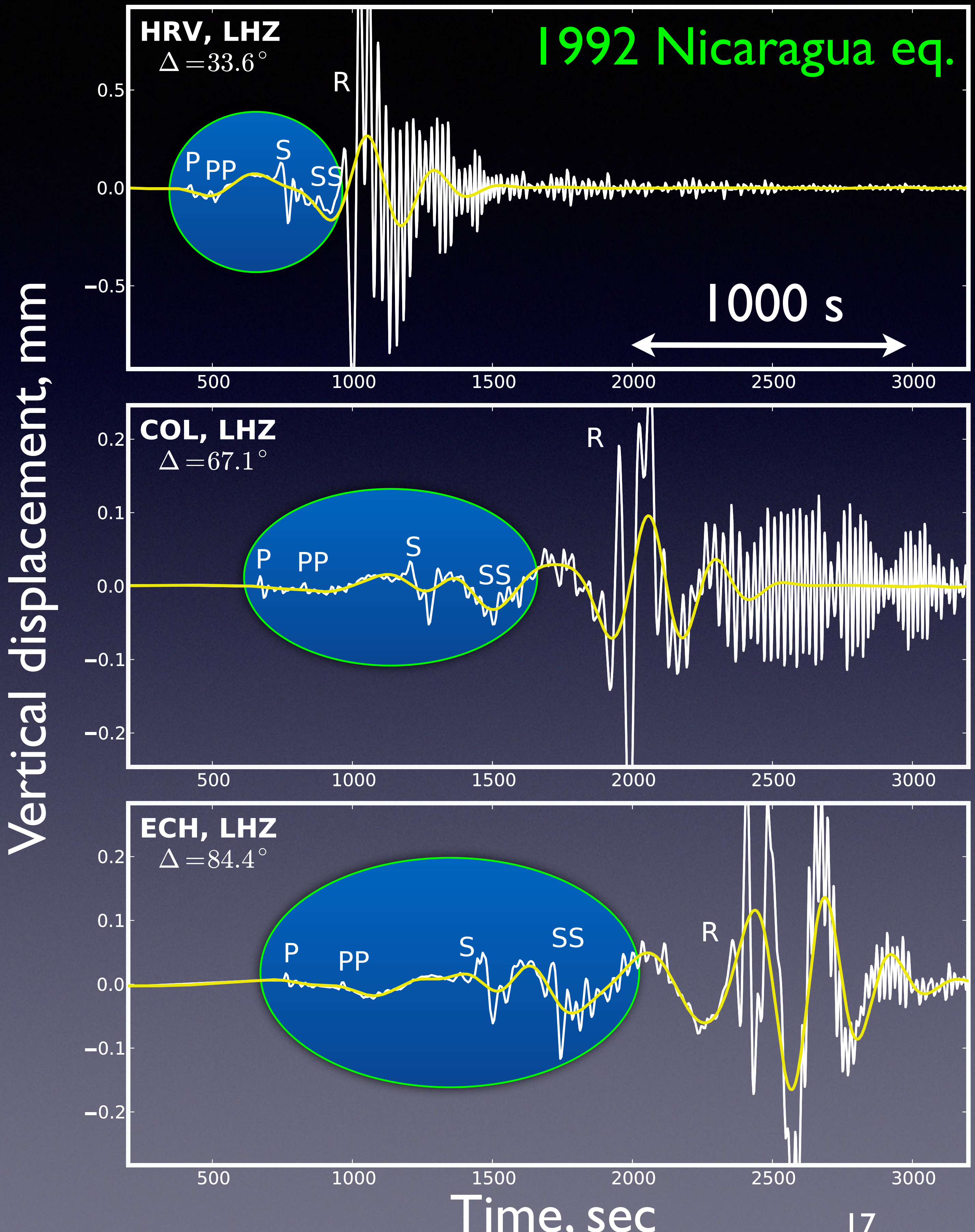
$$\left.+\mathrm{i}Q_{\mathrm{R}}^{(1)}(M_{yz}\sin\phi + M_{xz}\cos\phi)\right\} \qquad (2)$$

Phase W



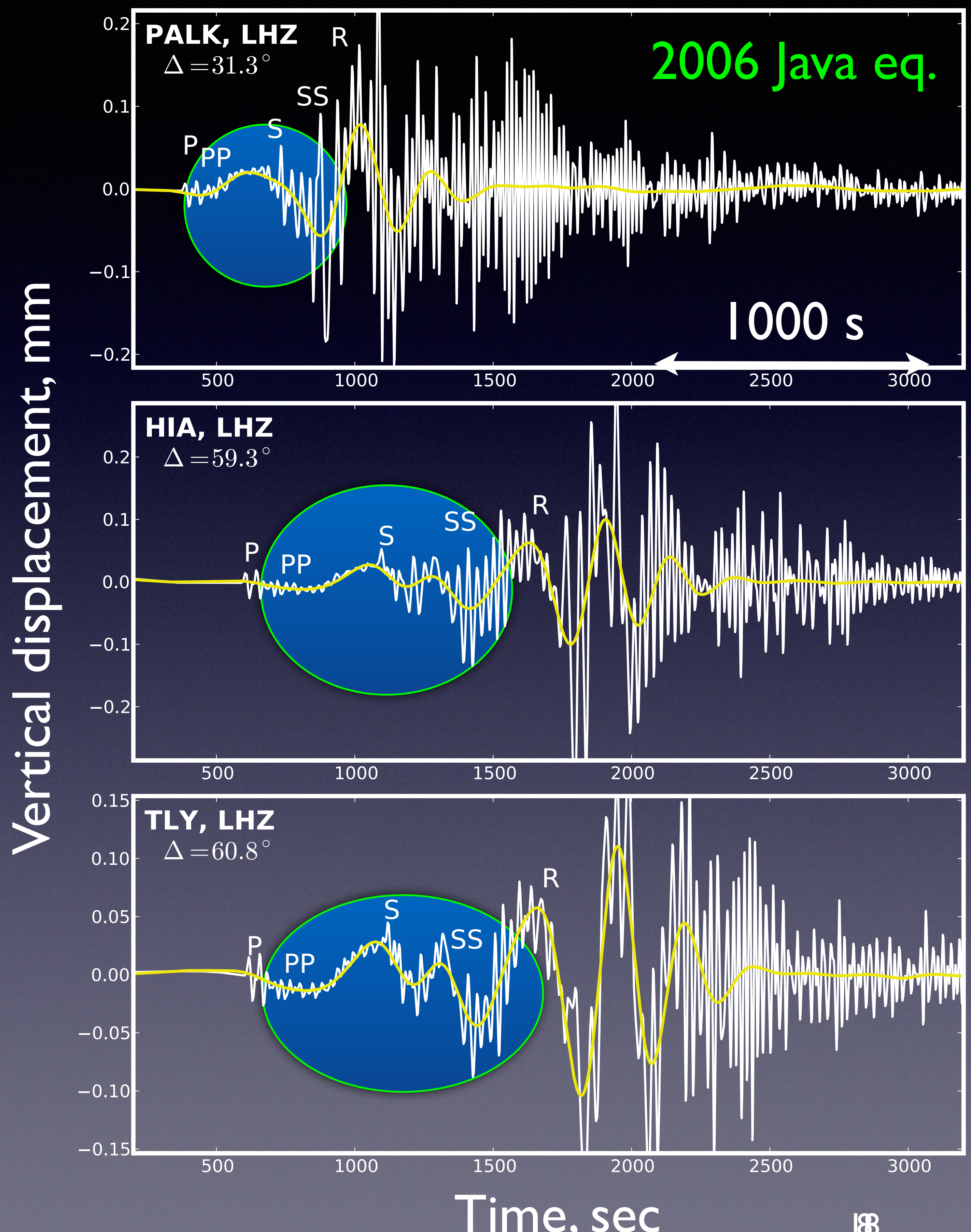
- Full elastic field
  - Near field + Far field
  - "Higher modes"
- Group velocity: 4.5-9km/s
- Very long period:
  - 100 s - 1000 s
- Kanamori (1993)
  - Tsunami earthquakes: Nicaragua 1992
- Modeling W phase:
  - Point source
  - Structure (ex: PREM)
  - Normal mode summation

Phase W



- Full elastic field
  - Near field + Far field
  - "Higher modes"
- Group velocity: 4.5-9km/s
- Very long period:
  - 100 s - 1000 s
- Kanamori (1993)
  - Tsunami earthquakes: Nicaragua 1992
- Modeling W phase:
  - Point source
  - Structure (ex: PREM)
  - Normal mode summation

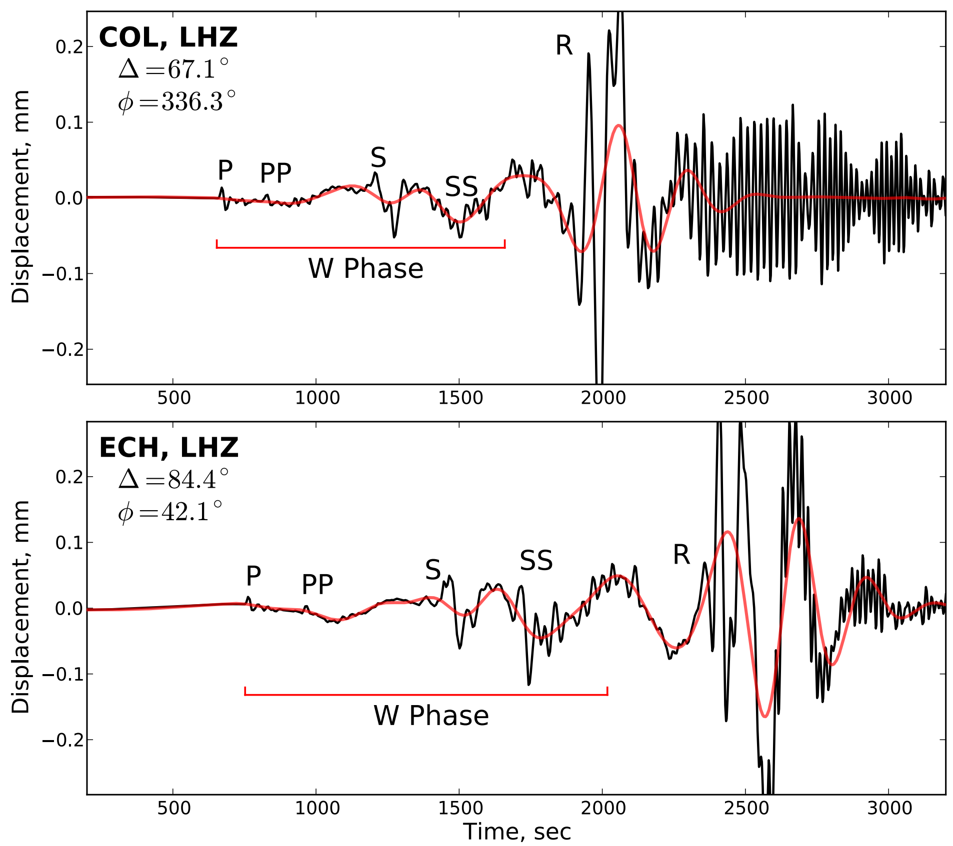
Phase W



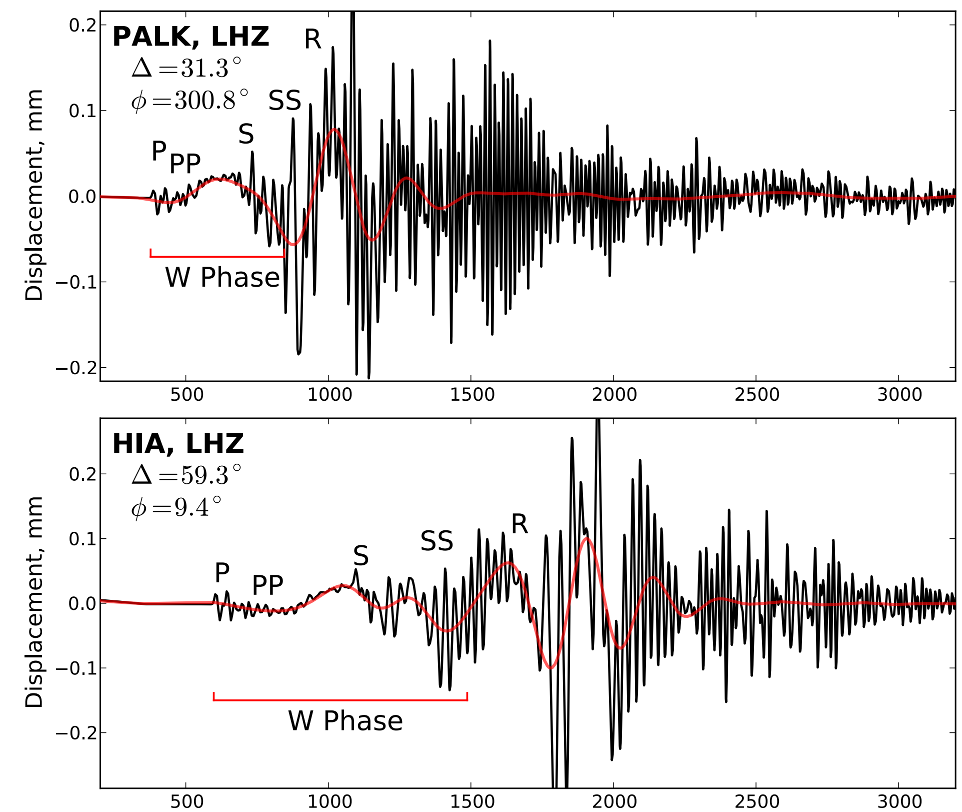
- Full elastic field
  - Near field + Far field
  - "Higher modes"
- Group velocity: 4.5-9km/s
- Very long period:
  - 100 s - 1000 s
- Kanamori (1993)
  - Tsunami earthquakes: Nicaragua 1992
- Modeling W phase:
  - Point source
  - Structure (ex: PREM)
  - Normal mode summation

Phase W : Whispering gallery

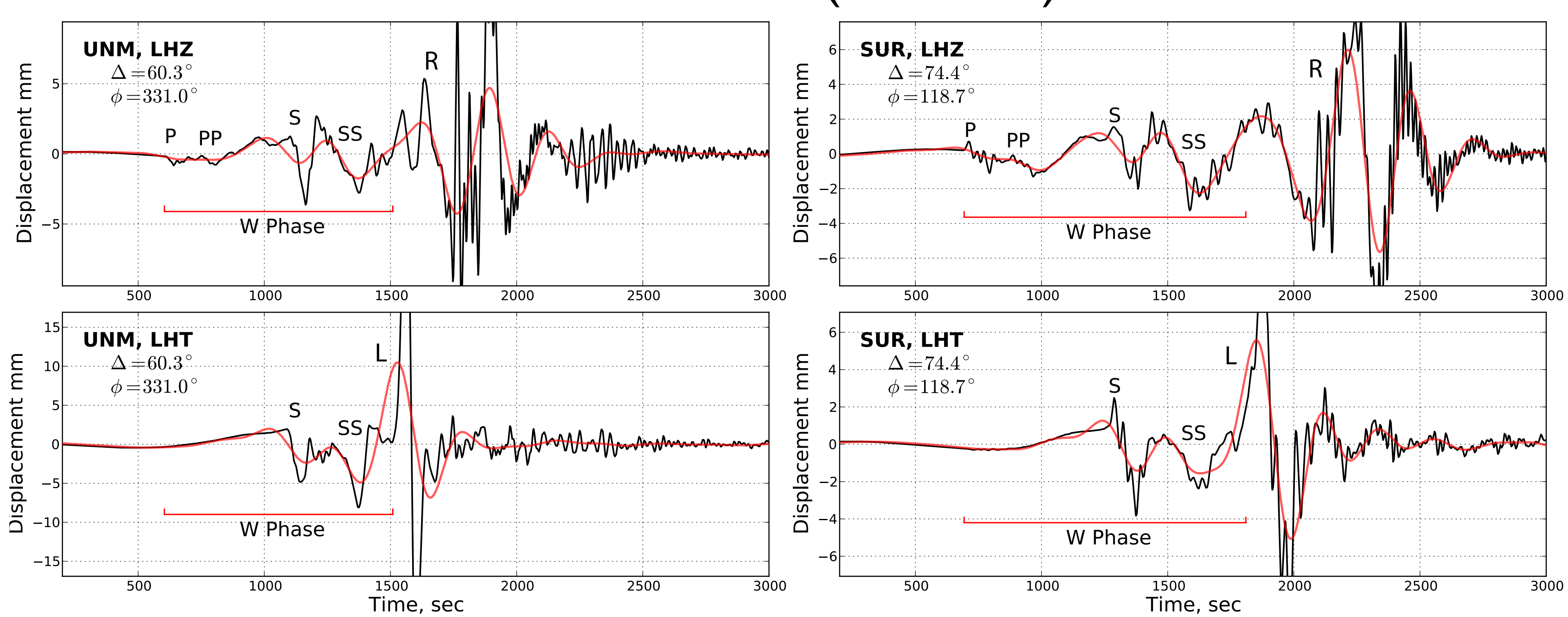
Nicaragua 1992 (Mw=7.6)



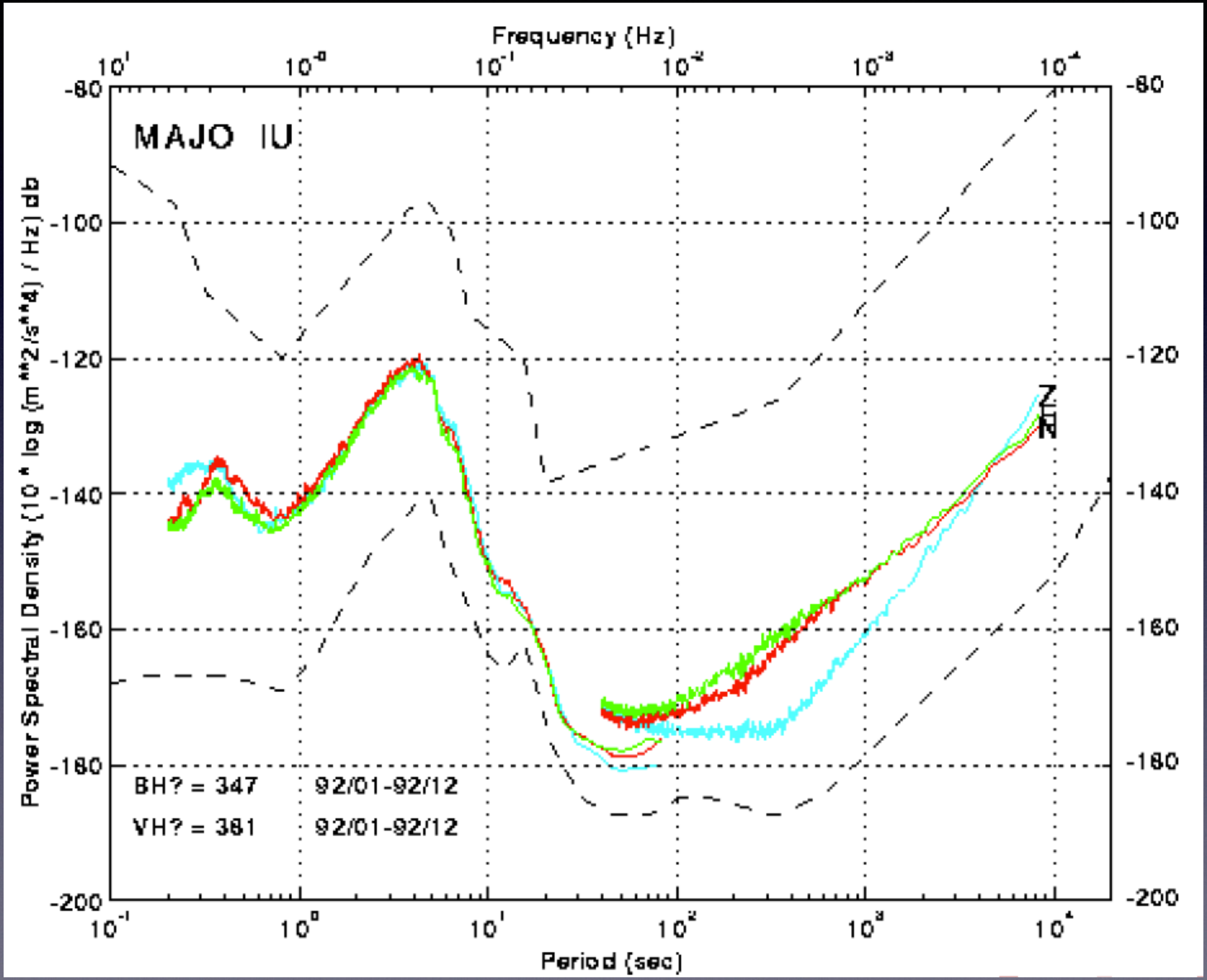
Java 2006 (Mw=7.7)



Maule 2010 (Mw=8.8)

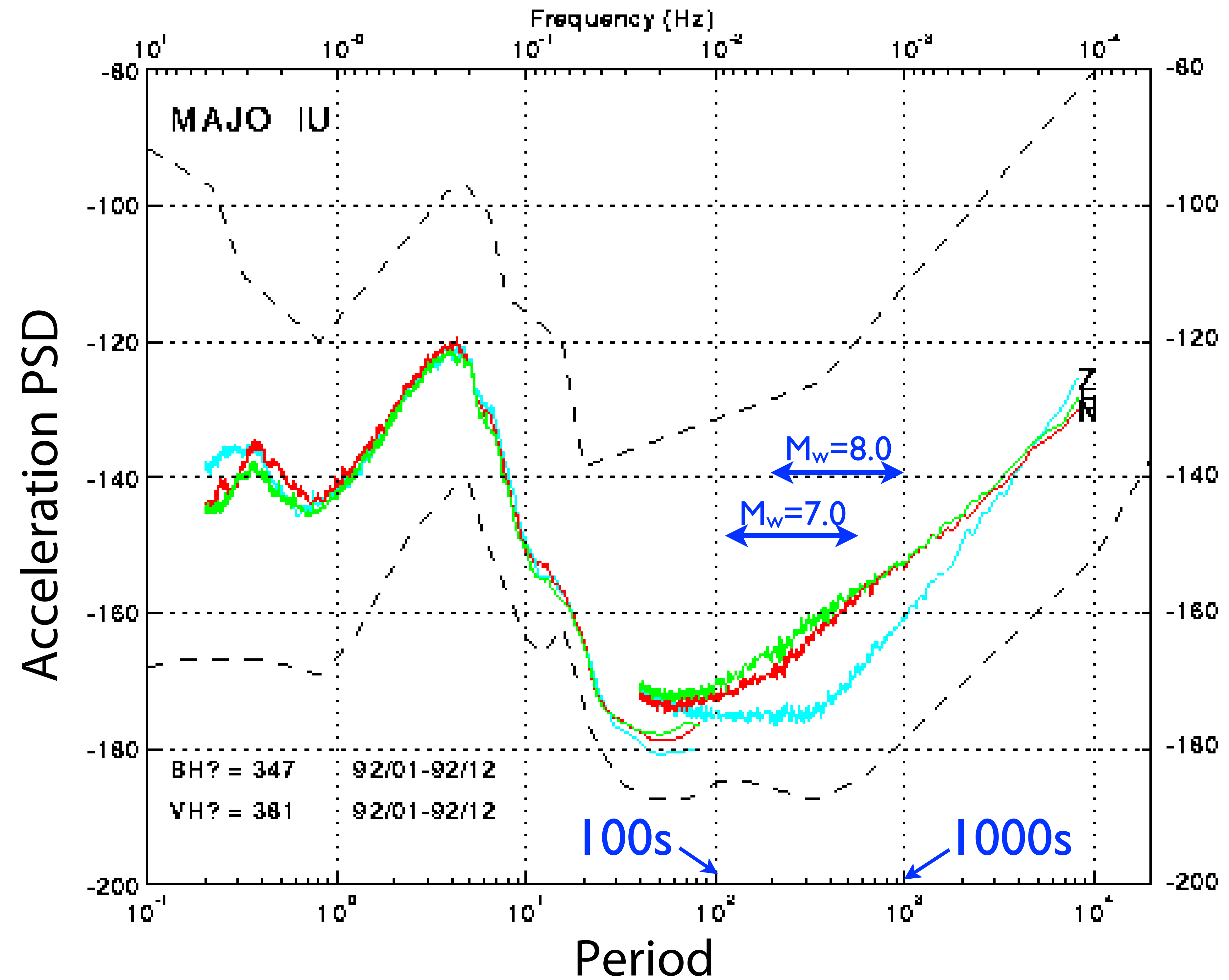


Typical Noise spectrum



Moderate earthquakes ($M_W \leq 7.5$)

Noise spectrum



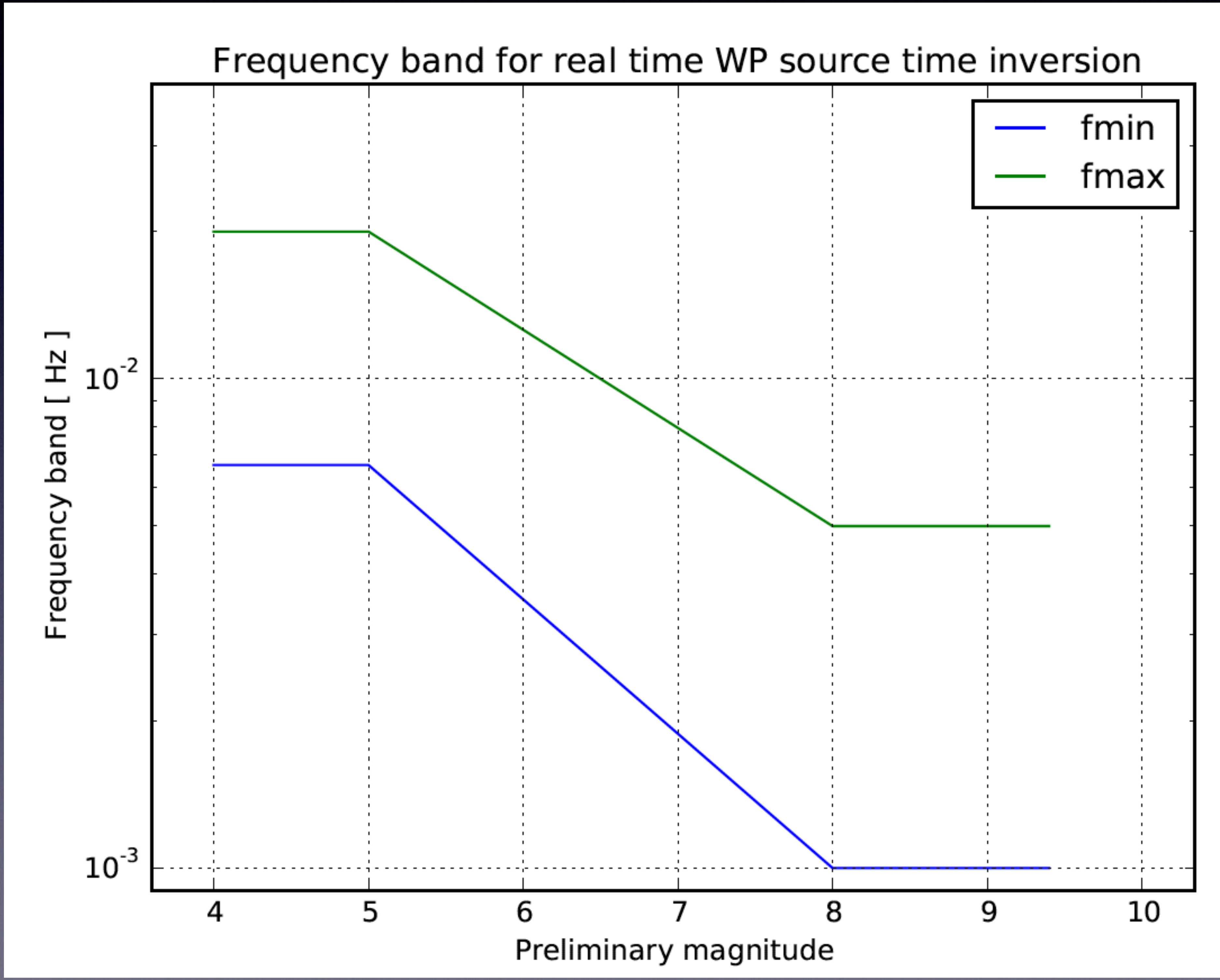
Wphase band pass filter

Table 2. Corner frequencies used for butterworth bandpass filtering (fourth order, causal) in W phase inversion when using three components. The frequency passbands used by Hayes *et al.* (2009) were defined for W phase inversion using only vertical components.

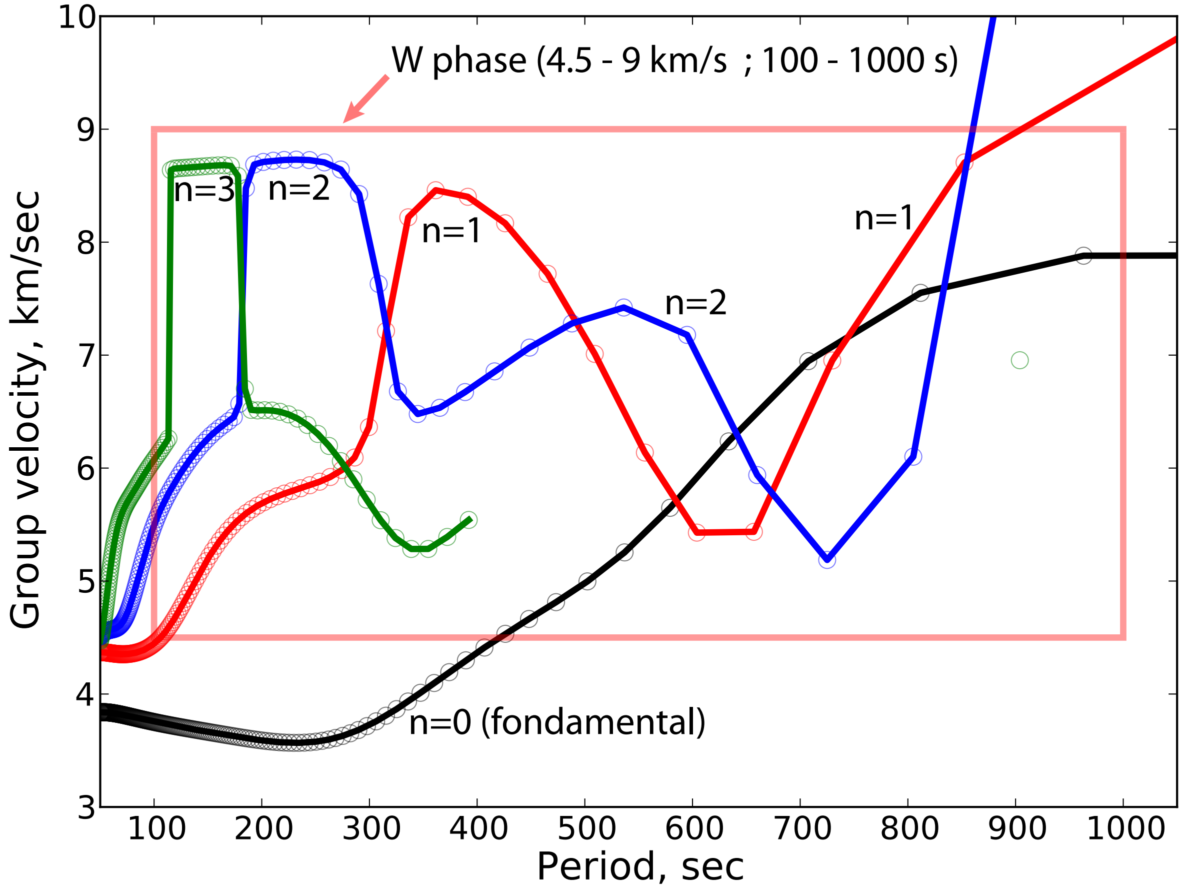
Magnitude range	Passband filter, mHz (s)
$M_{\text{w-wprel}} \geq 8.0$	1.0–5.0 (200–1000)
$8.0 > M_{\text{w-wprel}} \geq 7.5$	1.7–6.7 (150–500)
$7.5 > M_{\text{w-wprel}} \geq 7.0$	2.0–8.3 (120–500)
$7.0 > M_{\text{w-wprel}} \geq 6.5$	4.0–10.0 (100–250)

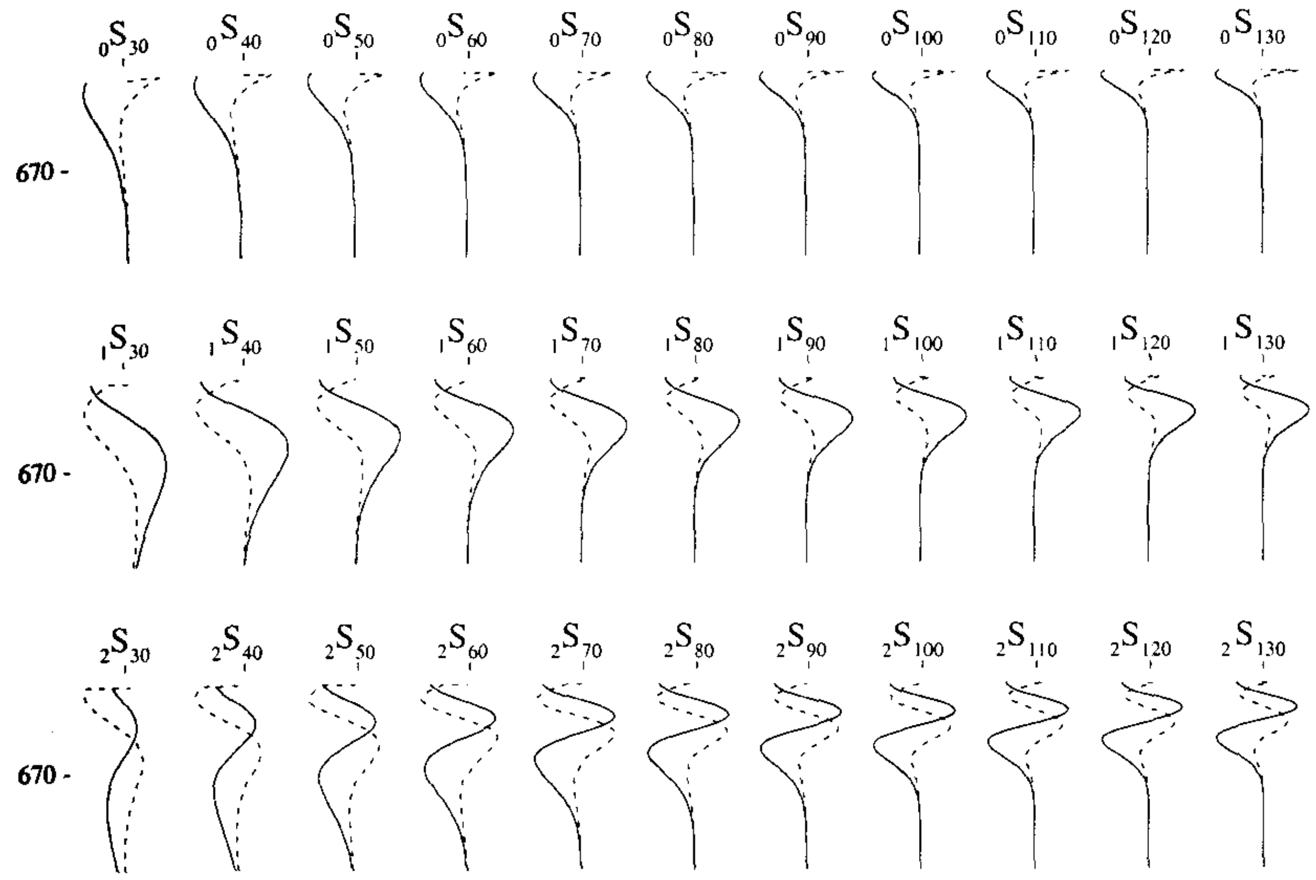
Duputel et al., 2012

Wphase band pass filter

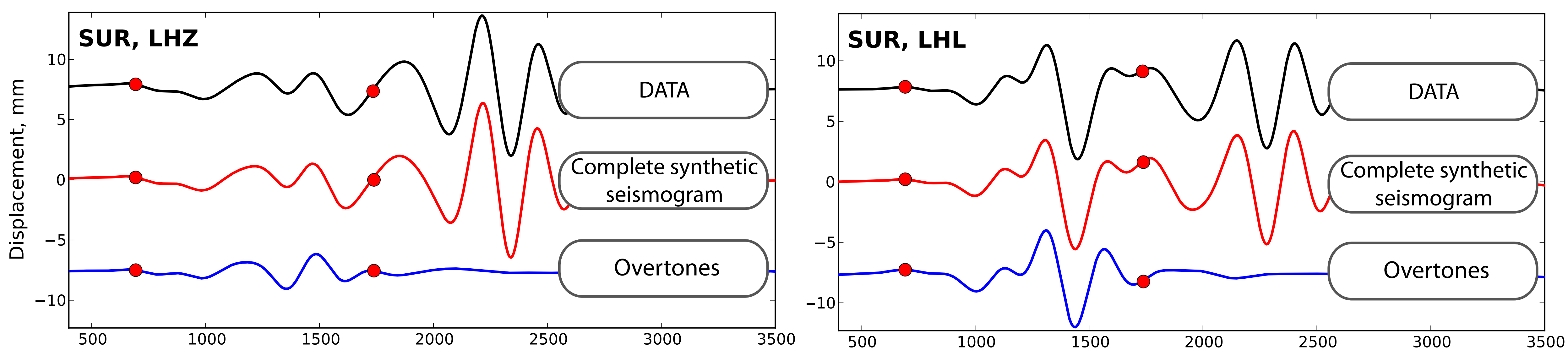


W phase and Earth free oscillations





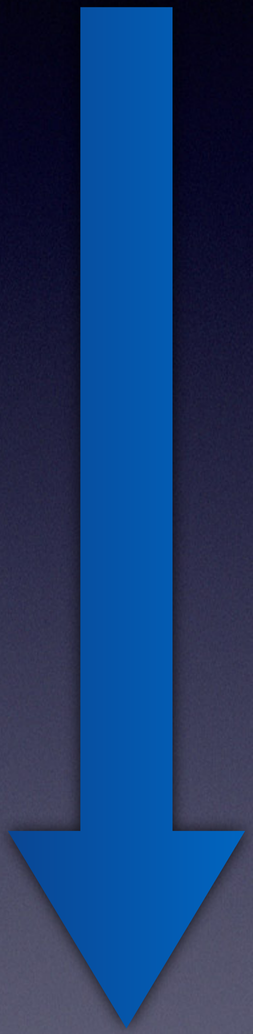
Maule 2010 (Mw=8.8), Station SUR(Δ = 74°, φ = 119°), 1-5mHz

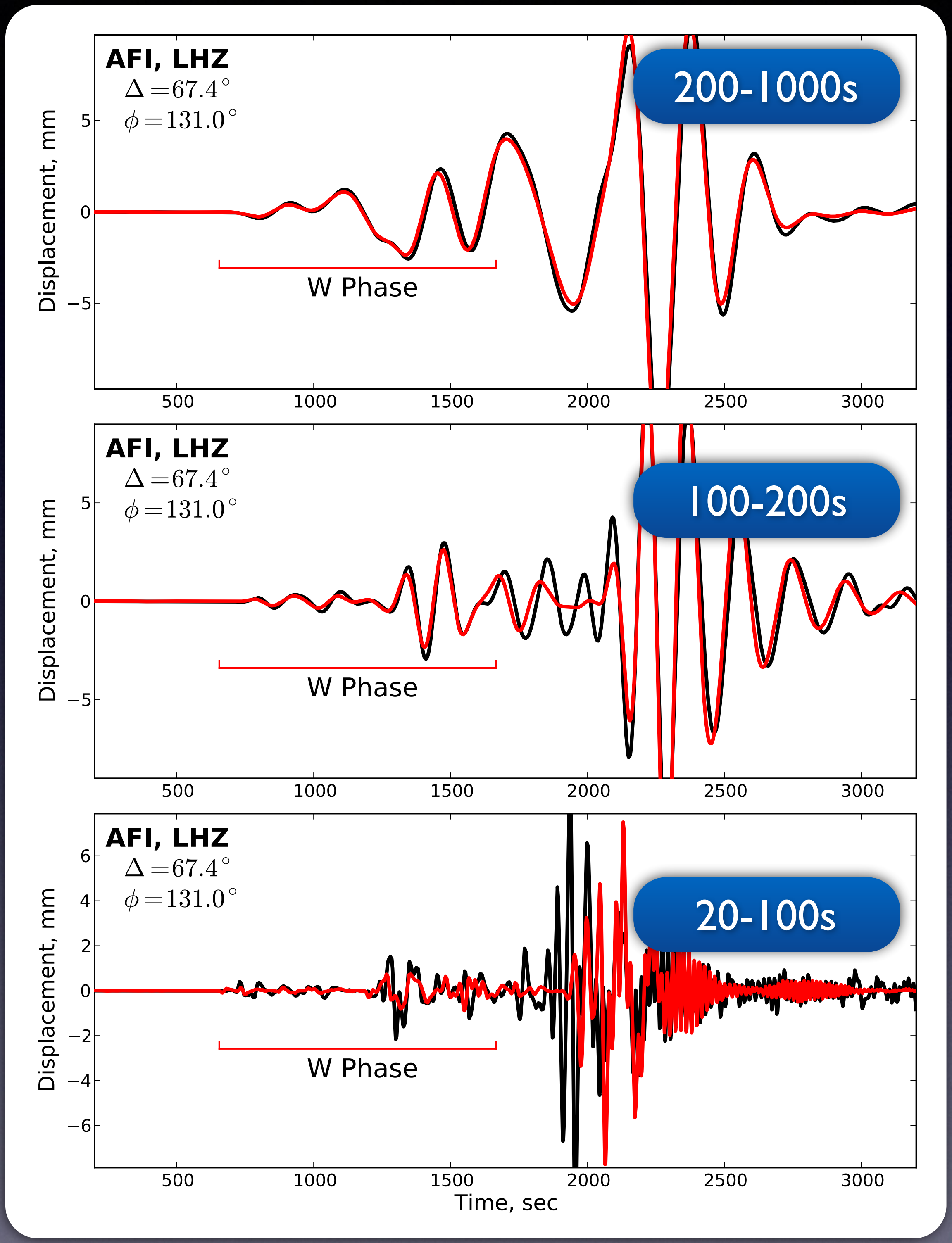


Spherical modeling vs real Earth

ex: Tohoku-oki 2011 (Mw=9.0)

Short period

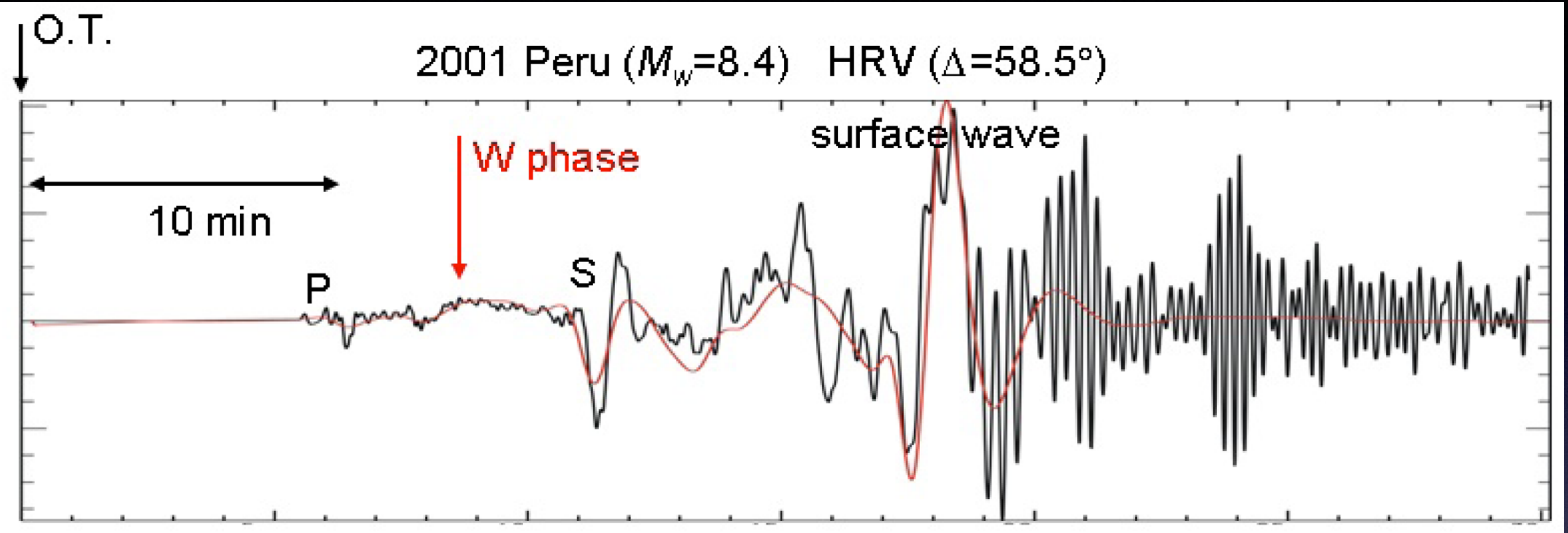




black: data

red: PREM synthetics

Modeling W-Phase



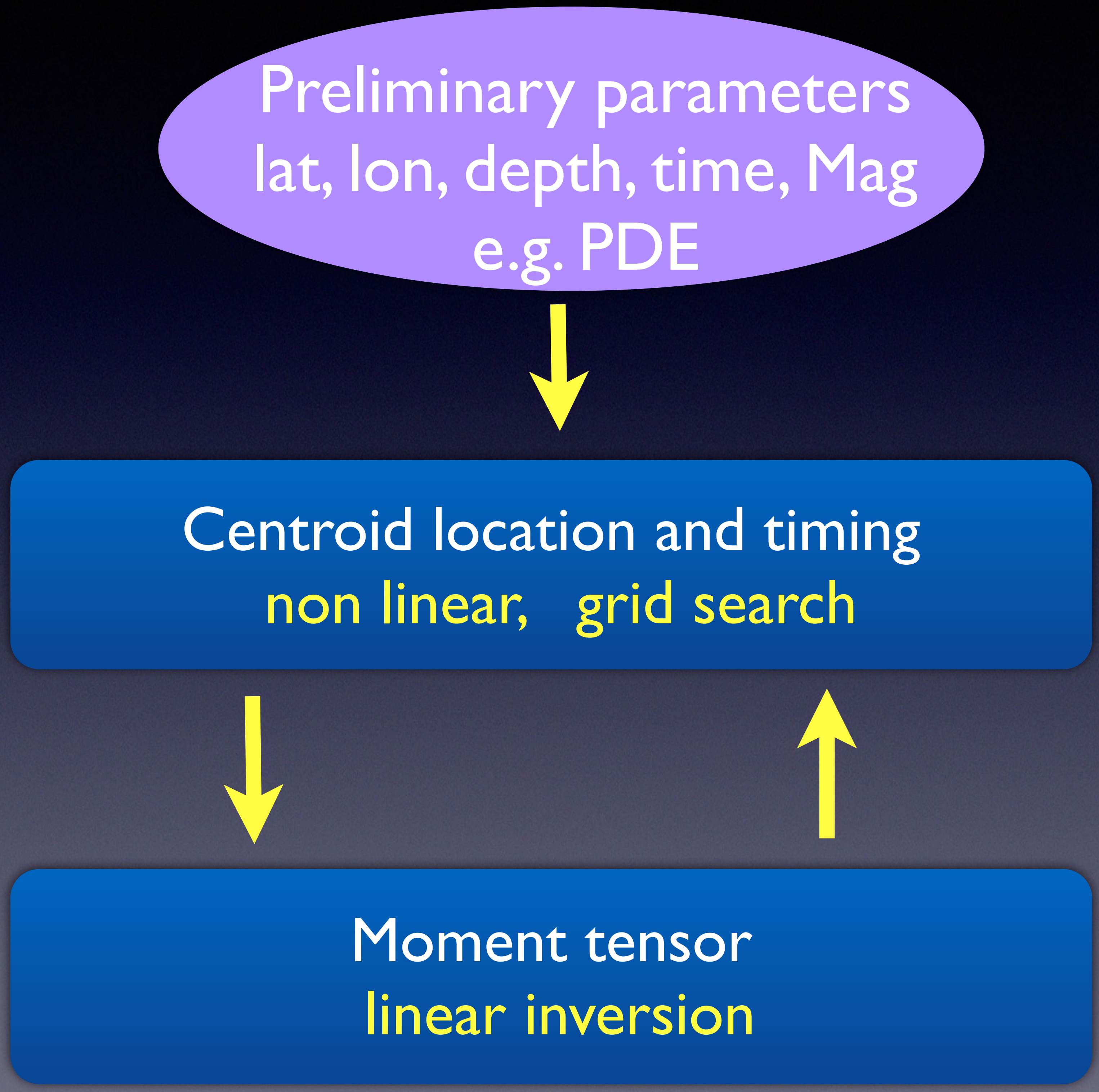
$$\boldsymbol{u}(\boldsymbol{r},t) = \sum_k [(\boldsymbol{M} : \varepsilon_k(\boldsymbol{r}_s))\boldsymbol{y}_k(\boldsymbol{r})] \frac{1 - e^{-\gamma_k t}\cos(\omega_k t)}{c_k \omega_k^2}$$

- Point source: Moment Tensor, location and timing
- Spherical model (e.g. PREM)
- Modal summation

The Green's functions DB

Definition
Moment Tensor components
Symmetries
Regional vs Global GFs
Frequency contents
Spatial sampling
Computing them

W phase Source Inversion Algorithm (WCMT)



(CMT: Centroid Moment Tensor)

W-Phase Source Inversion Algorithm

Example: Java 2006
(Mw=7.7)

Inputs

↓

Inversion with PDE

↓

t

↓

xyz grid-search

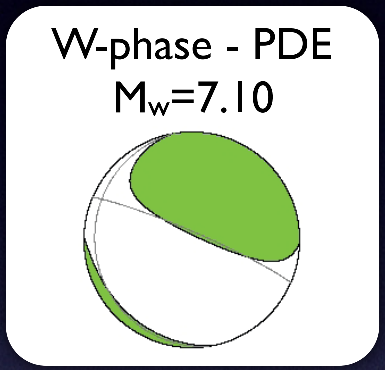
```
WCMT: W-phase CMT
PDE : Preliminary
      Determined
      Epicenter
```

W-Phase Source Inversion Algorithm

Example: Java 2006
(Mw=7.7)

Inputs

Inversion with PDE



t

xyz grid-search

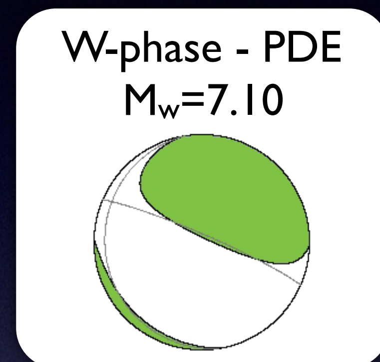
WCMT: W-phase CMT
PDE : Preliminary Determined Epicenter

W-Phase Source Inversion Algorithm

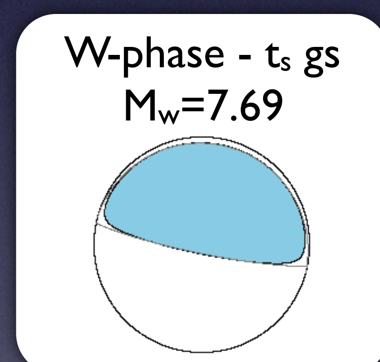
Example: Java 2006
(Mw=7.7)

Inputs

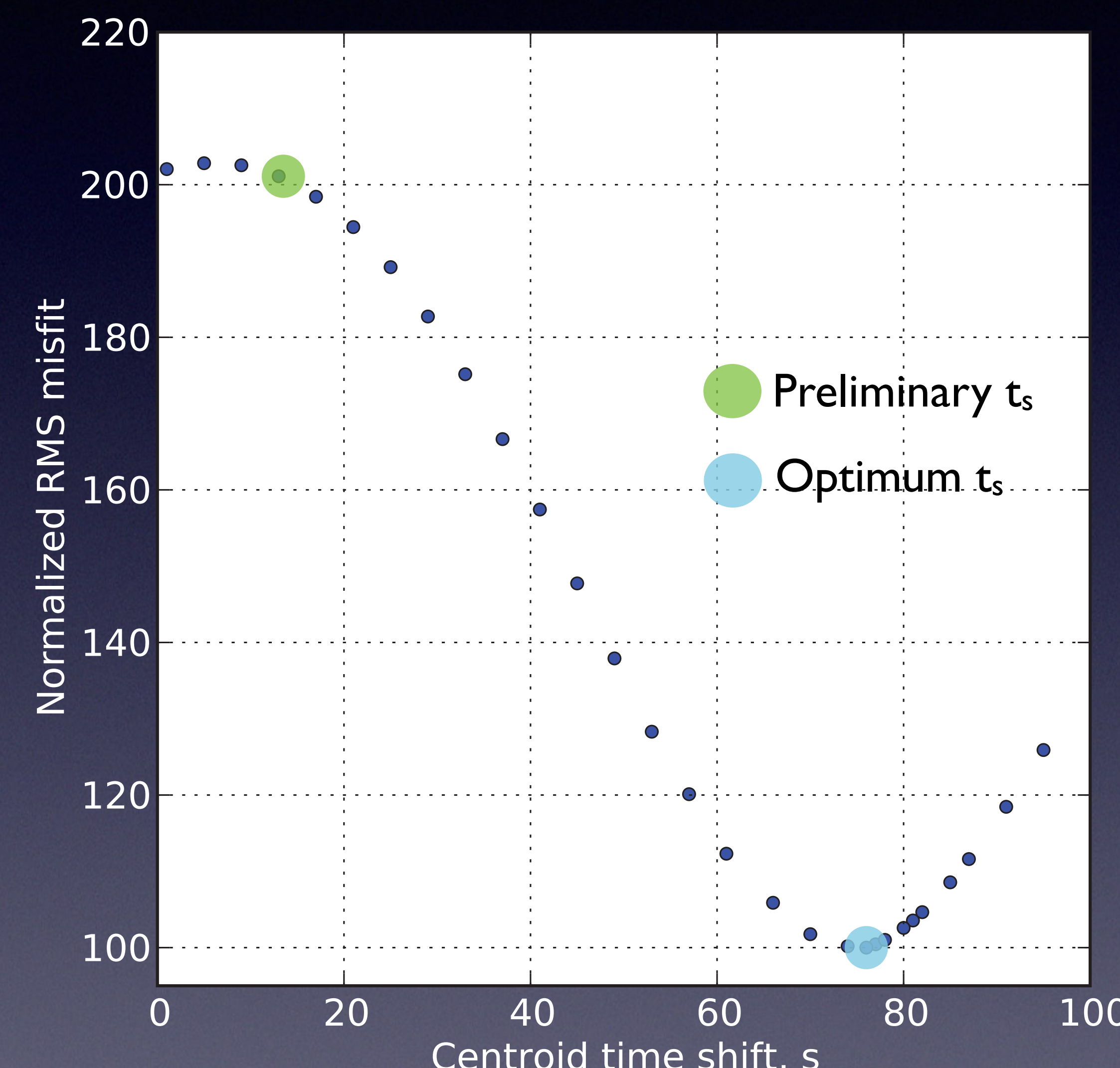
Inversion with PDE



t



xyz grid-search



WCMT: W-phase CMT
PDE : Preliminary Determined Epicenter

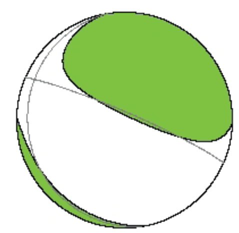
W-Phase Source Inversion Algorithm

Example: Java 2006
(Mw=7.7)

Inputs

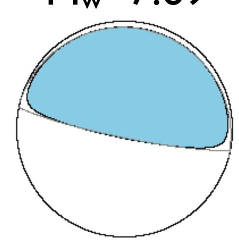
↓

Inversion with PDE → W-phase - PDE
M_w=7.10



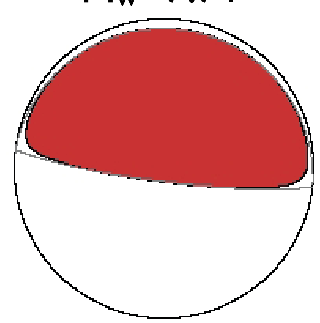
↓

t → W-phase - t_s gs
M_w=7.69

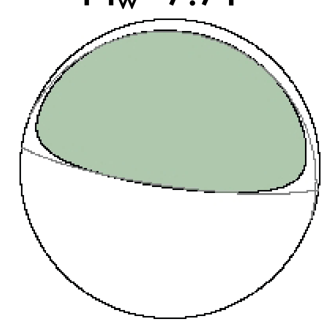


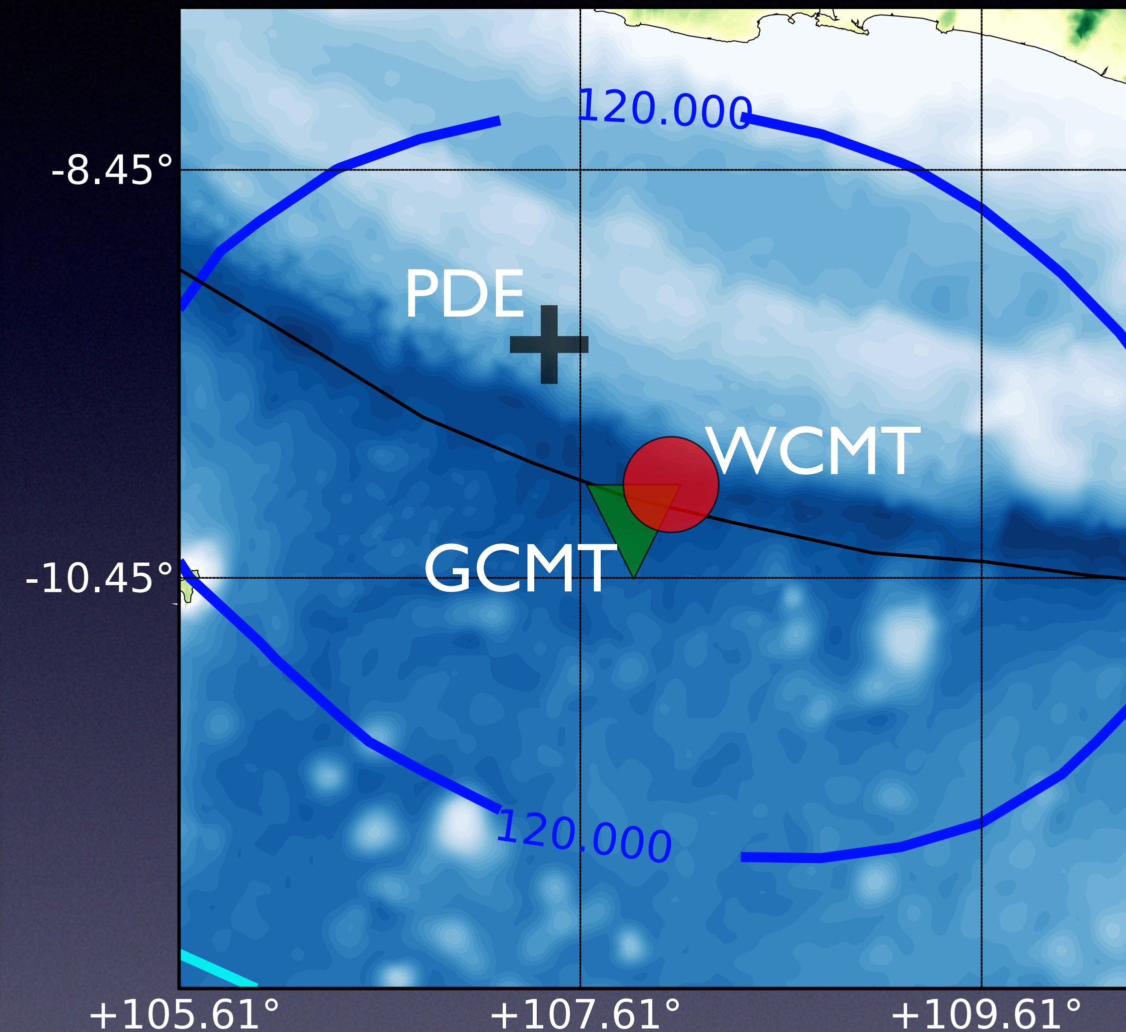
↓

xyz grid-search → WCMT - final solution
M_w=7.71



GCMT
M_w=7.71

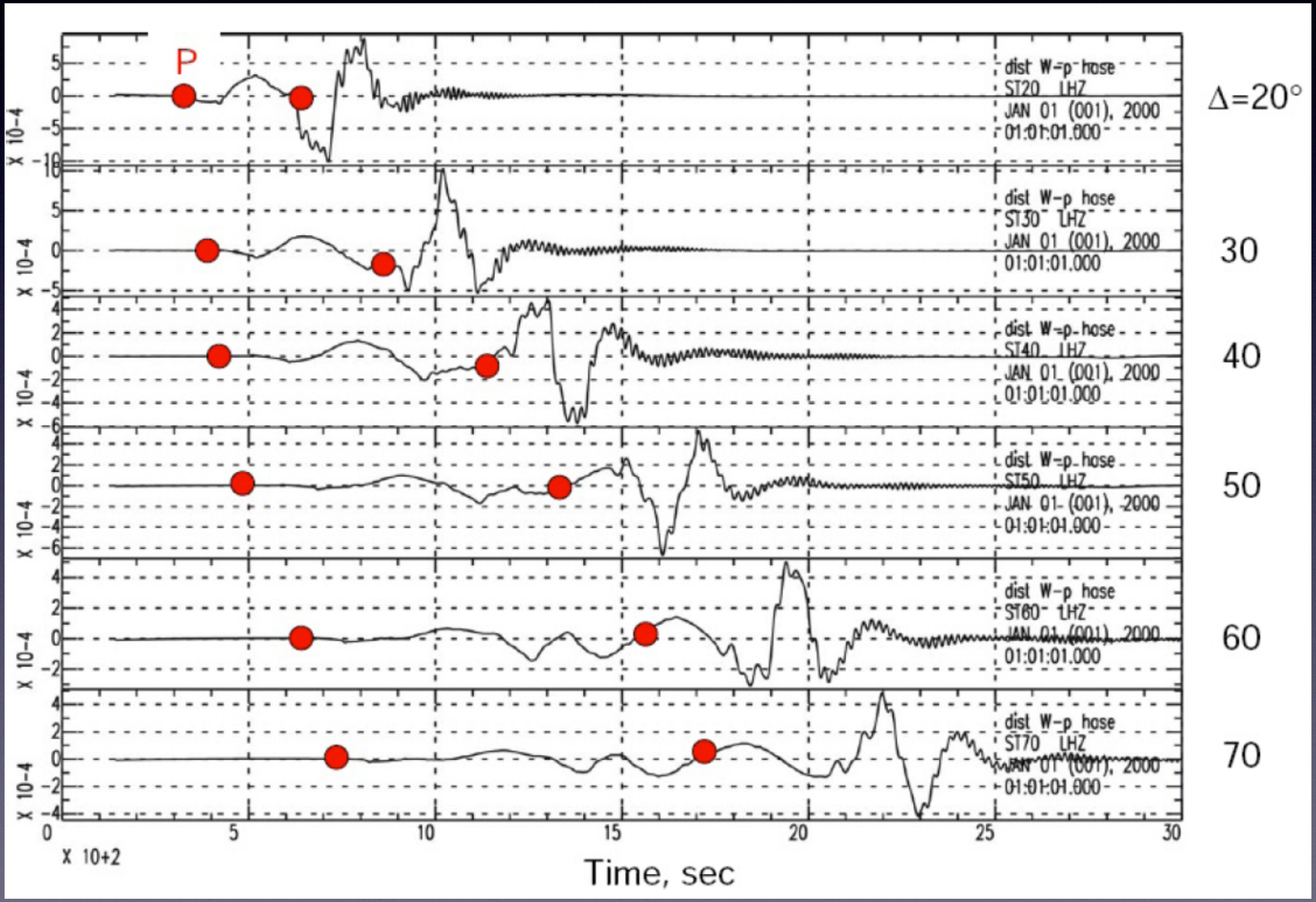




GCMT: Global CMT
WCMT: W-phase CMT
PDE : Preliminary Determined Epicenter

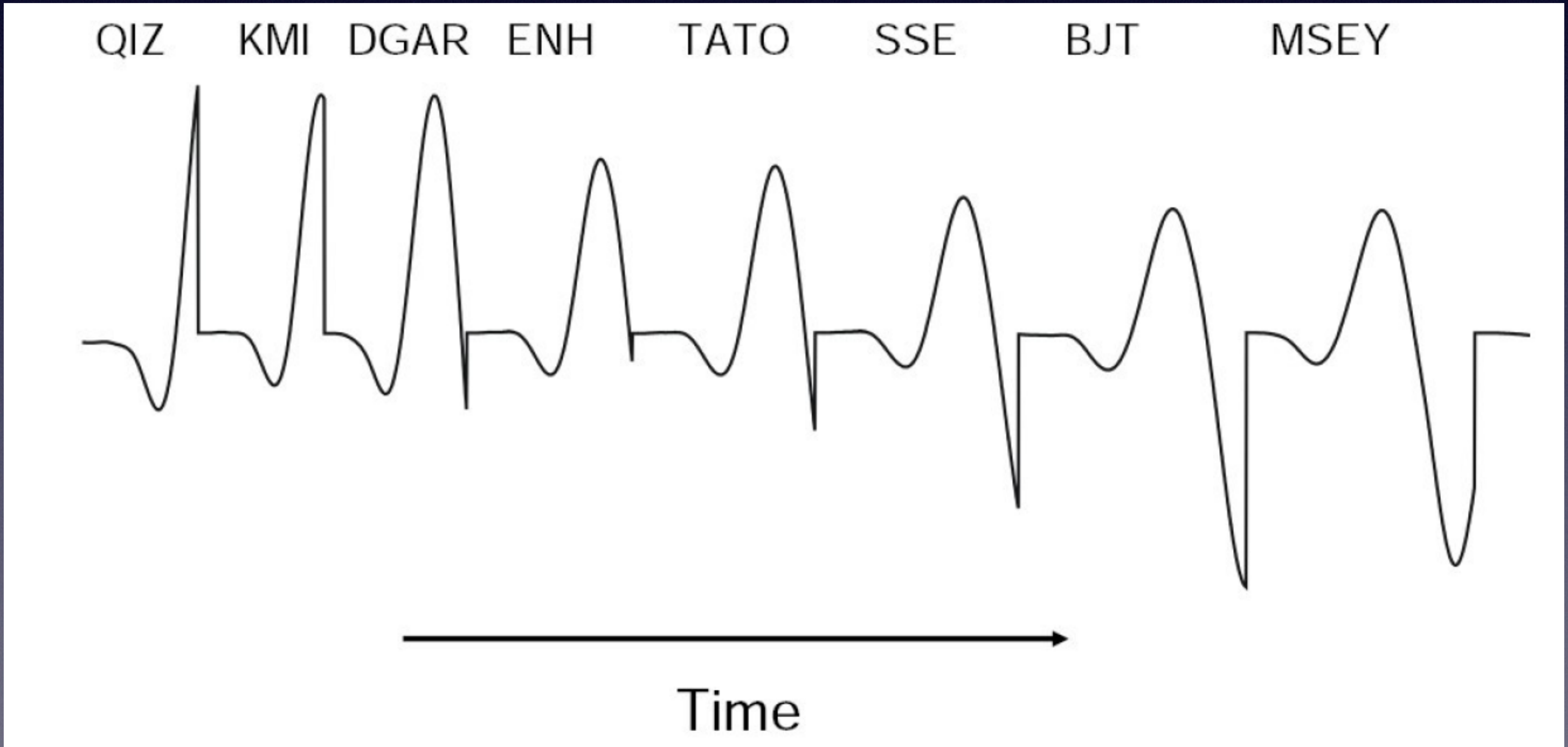
Data:

W phase time window:
P, P+ 15 Δ s/°



Data:

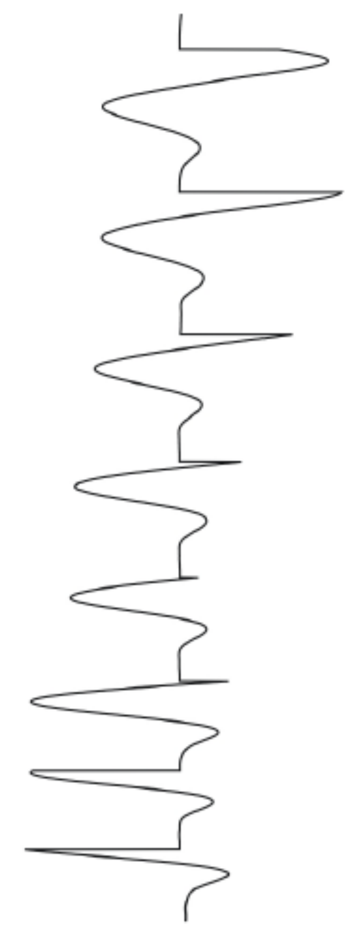
Concatenation of W phase data
bandwidth: 0.001 hz - 0.005 hz
time window: (P, P + 15Δ s/°)



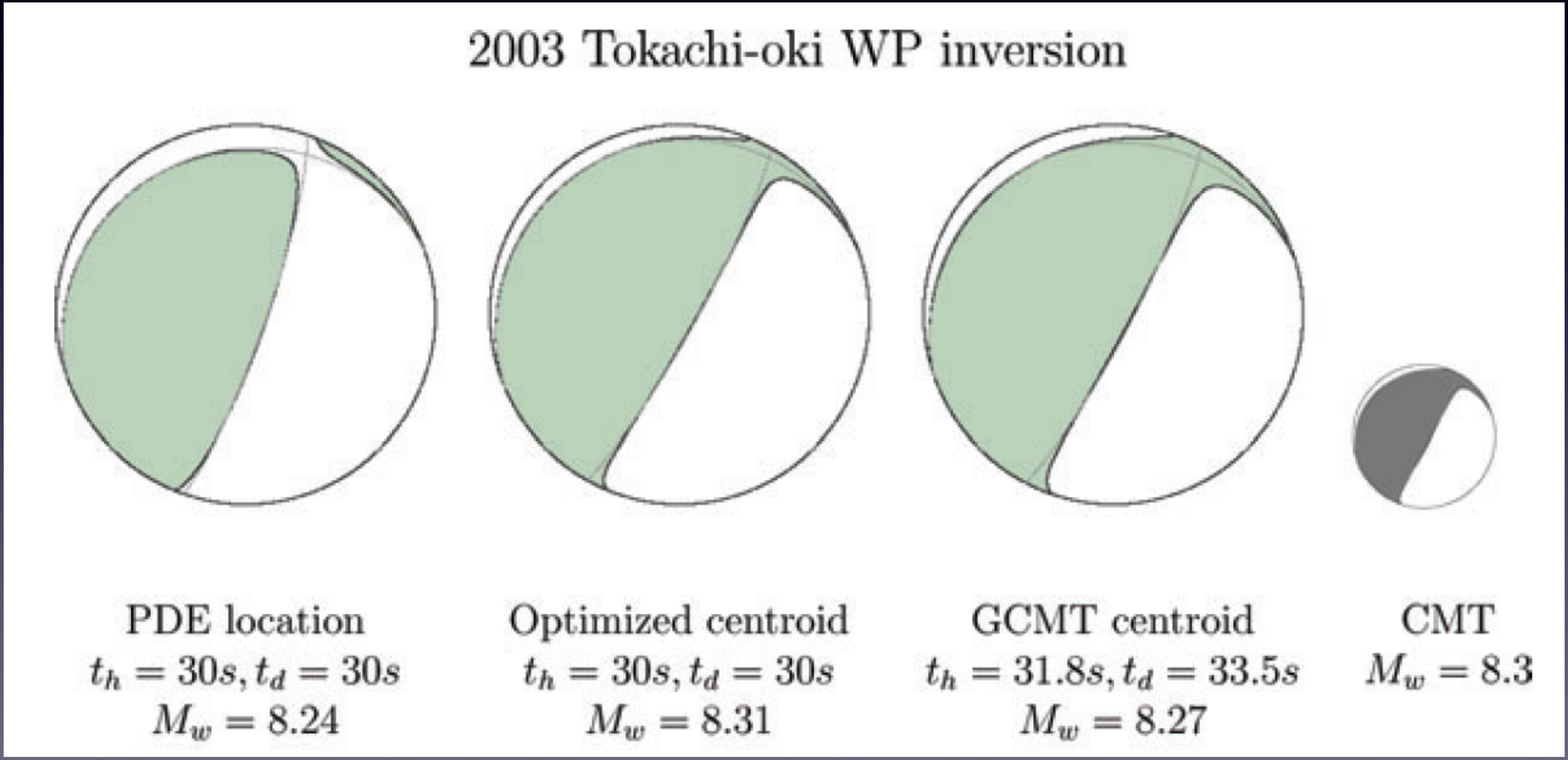
Linear inverse problem

u_{wj}: W phase trace at station j

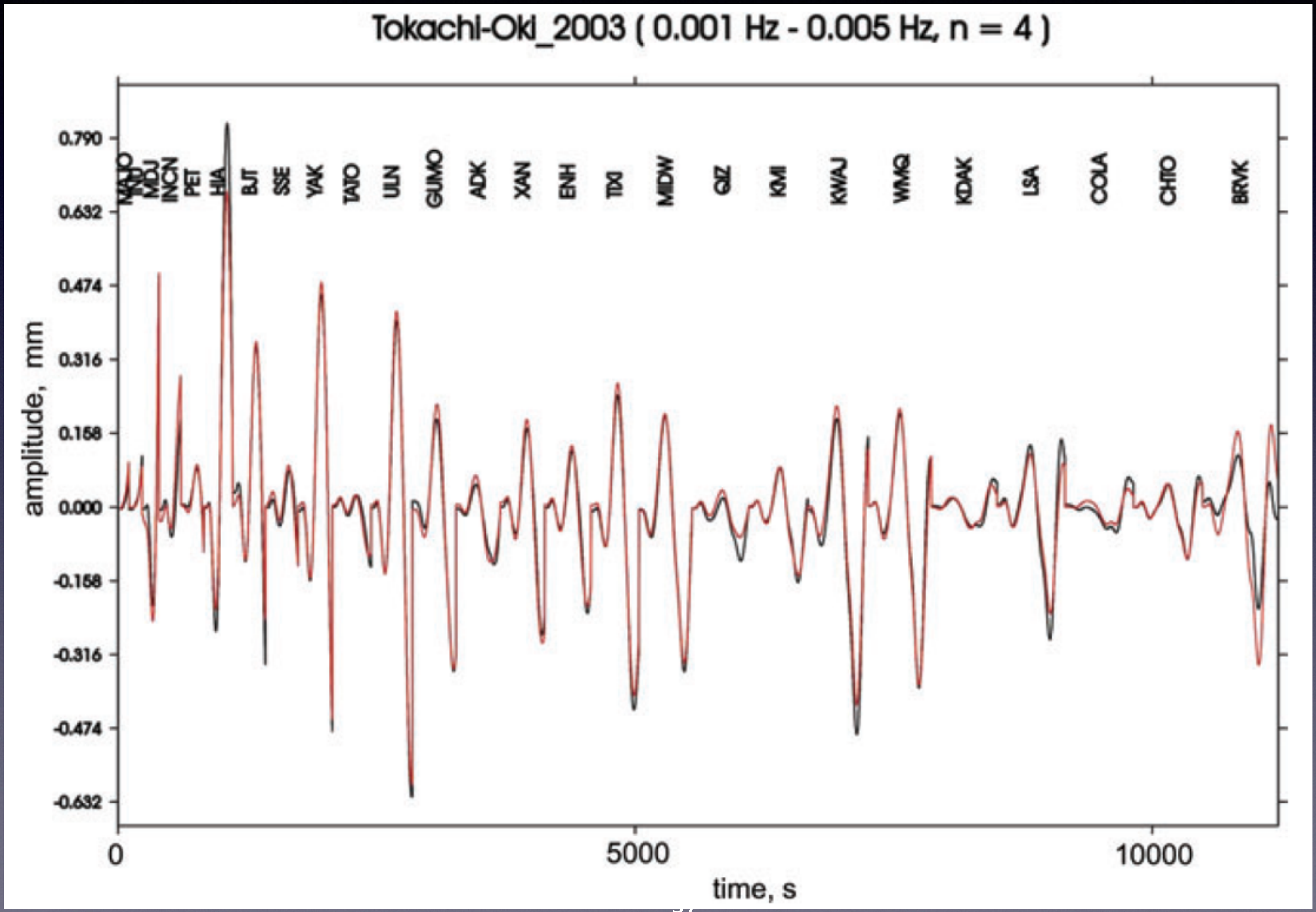
$$\begin{bmatrix} g_{w1}^{1,1} & g_{w1}^{22} & \cdots & \cdots & g_{w1}^{23} \\ g_{w2}^{1,1} & g_{w2}^{22} & \cdots & \cdots & g_{w2}^{23} \\ g_{w3}^{1,1} & g_{w3}^{22} & \cdots & \cdots & g_{w3}^{23} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ g_{wn}^{1,1} & g_{wn}^{22} & \cdots & \cdots & g_{wn}^{23} \end{bmatrix} \begin{bmatrix} M_{11} \\ M_{22} \\ M_{33} \\ M_{12} \\ M_{13} \\ M_{23} \end{bmatrix} = \begin{bmatrix} u_{w1} \\ u_{w2} \\ u_{w3} \\ \vdots \\ \vdots \\ u_{wn} \end{bmatrix}$$



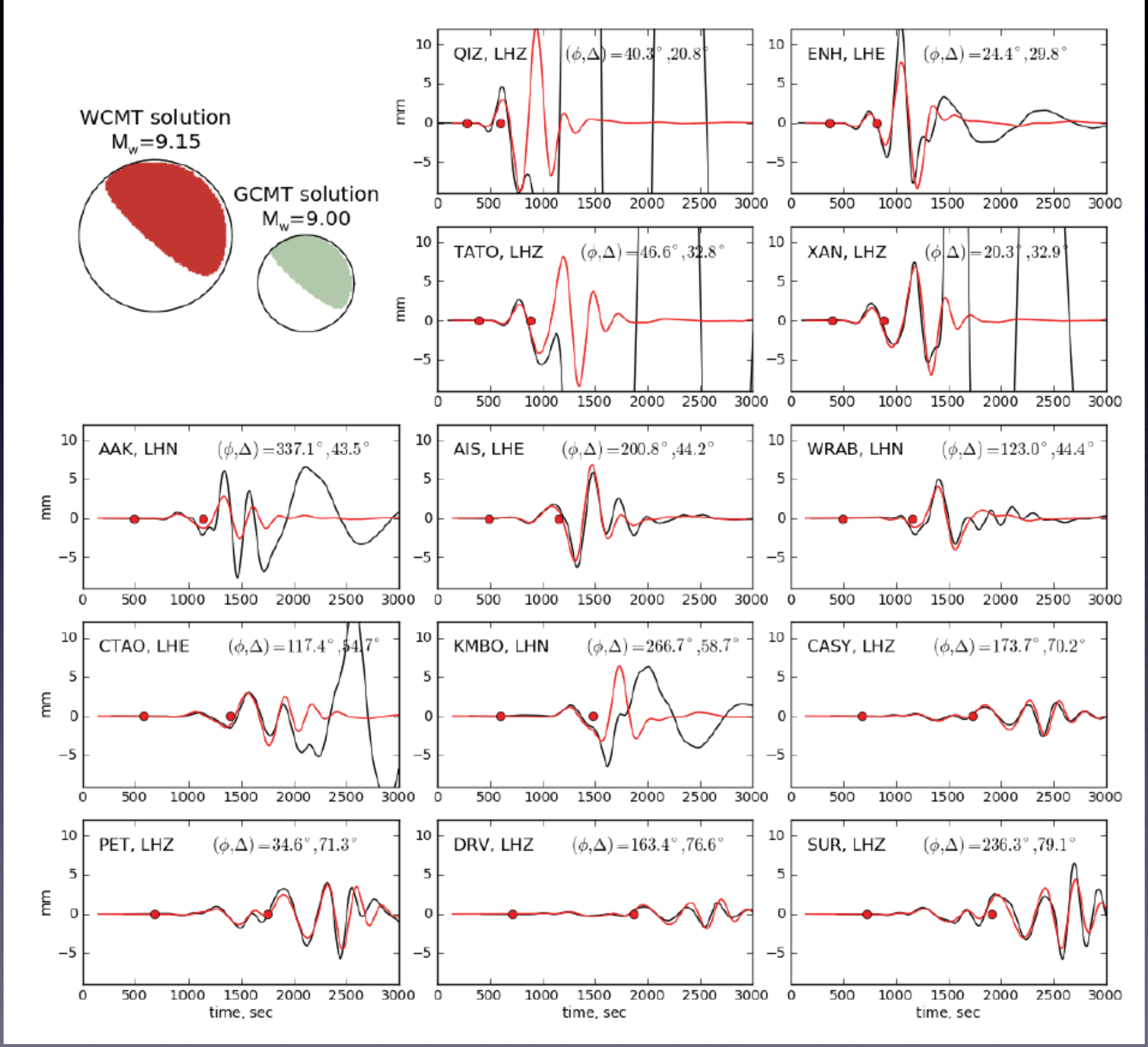
2003 Tokachi-oki
W phase source inversion



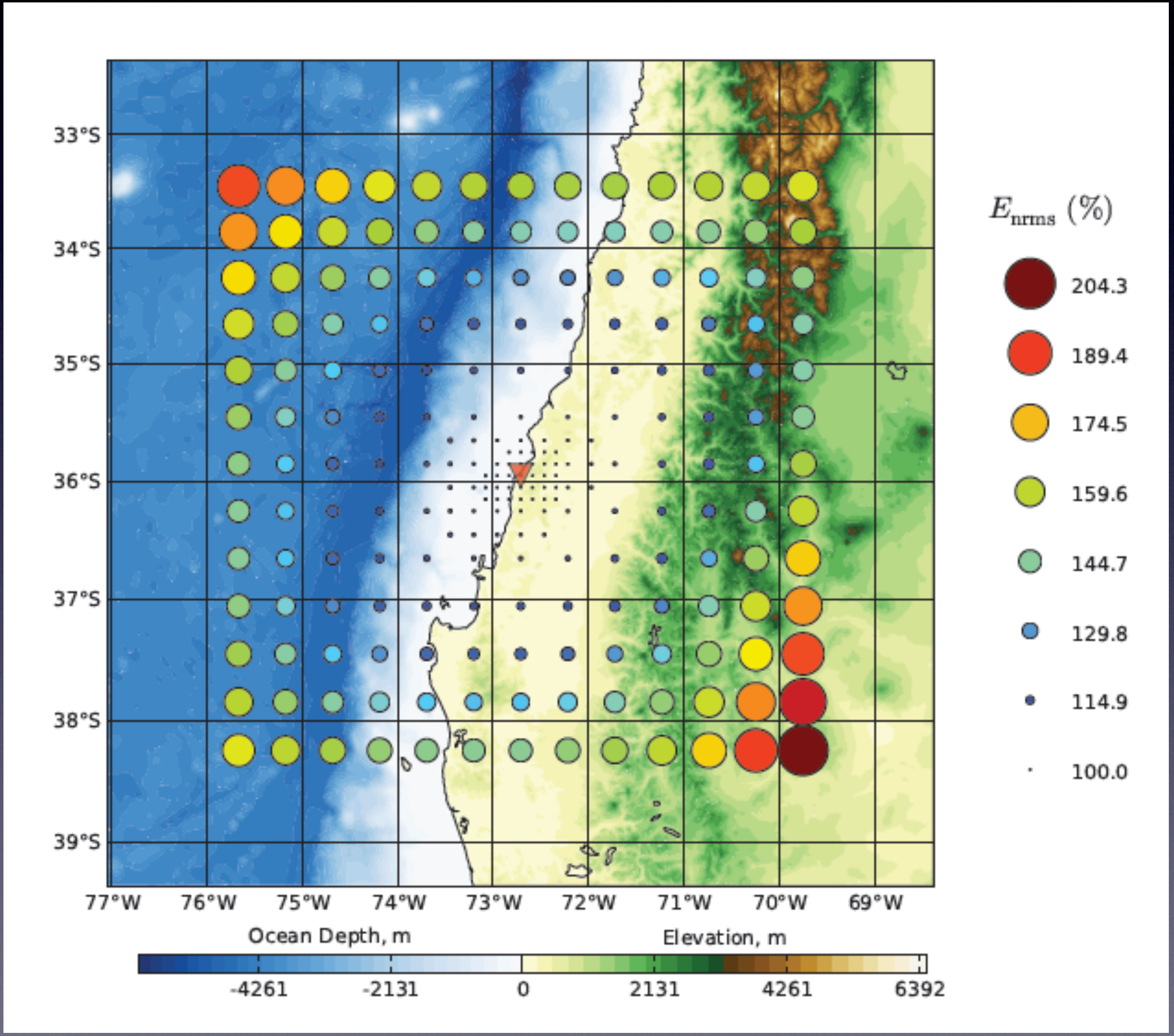
2003 Tokachi-oki
W phase source inversion: misfit



Sumatra, 2004



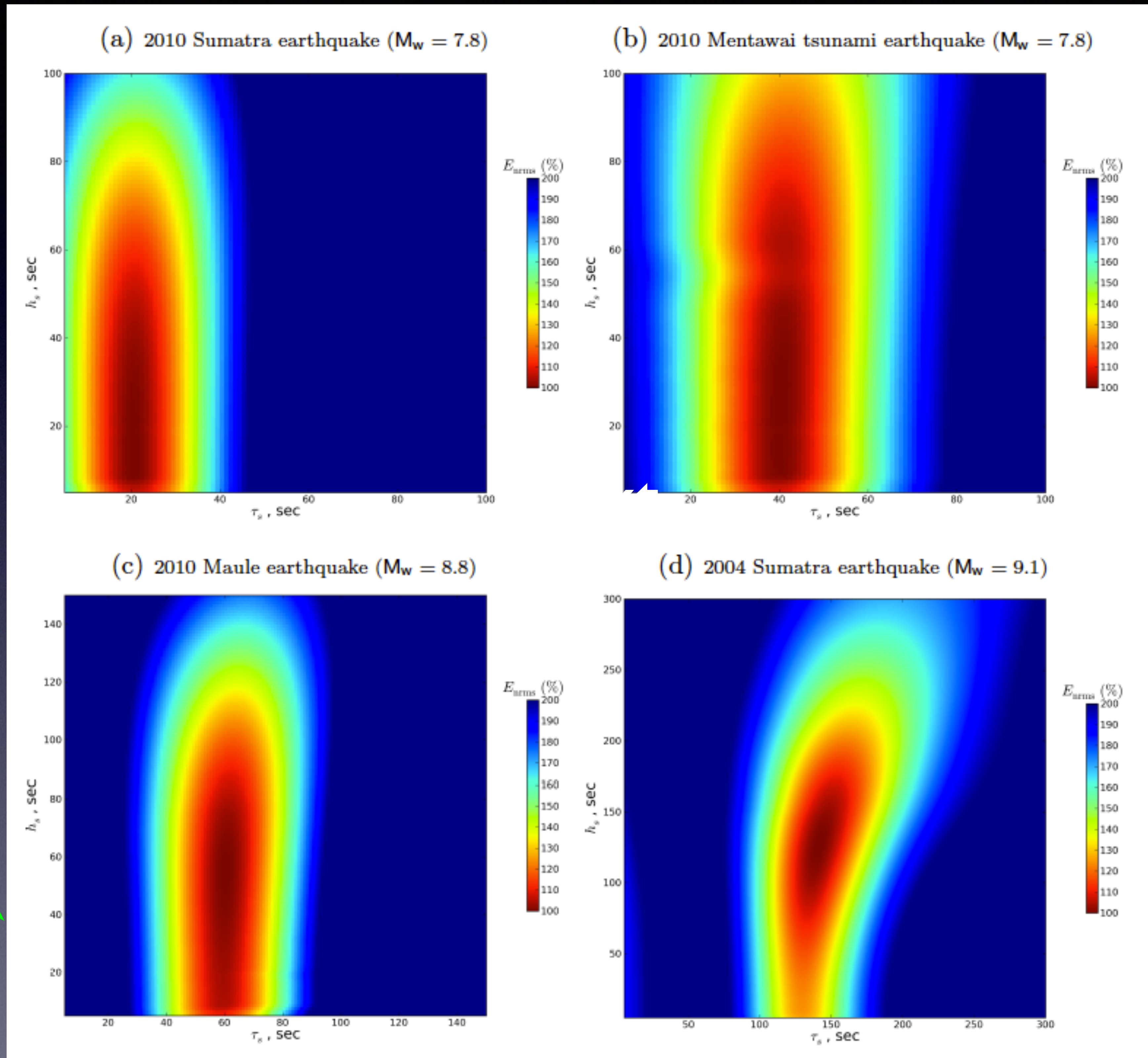
Spatiale grid search



Constraining the CMT timing

Sumatra 2010

Mentawai 2010



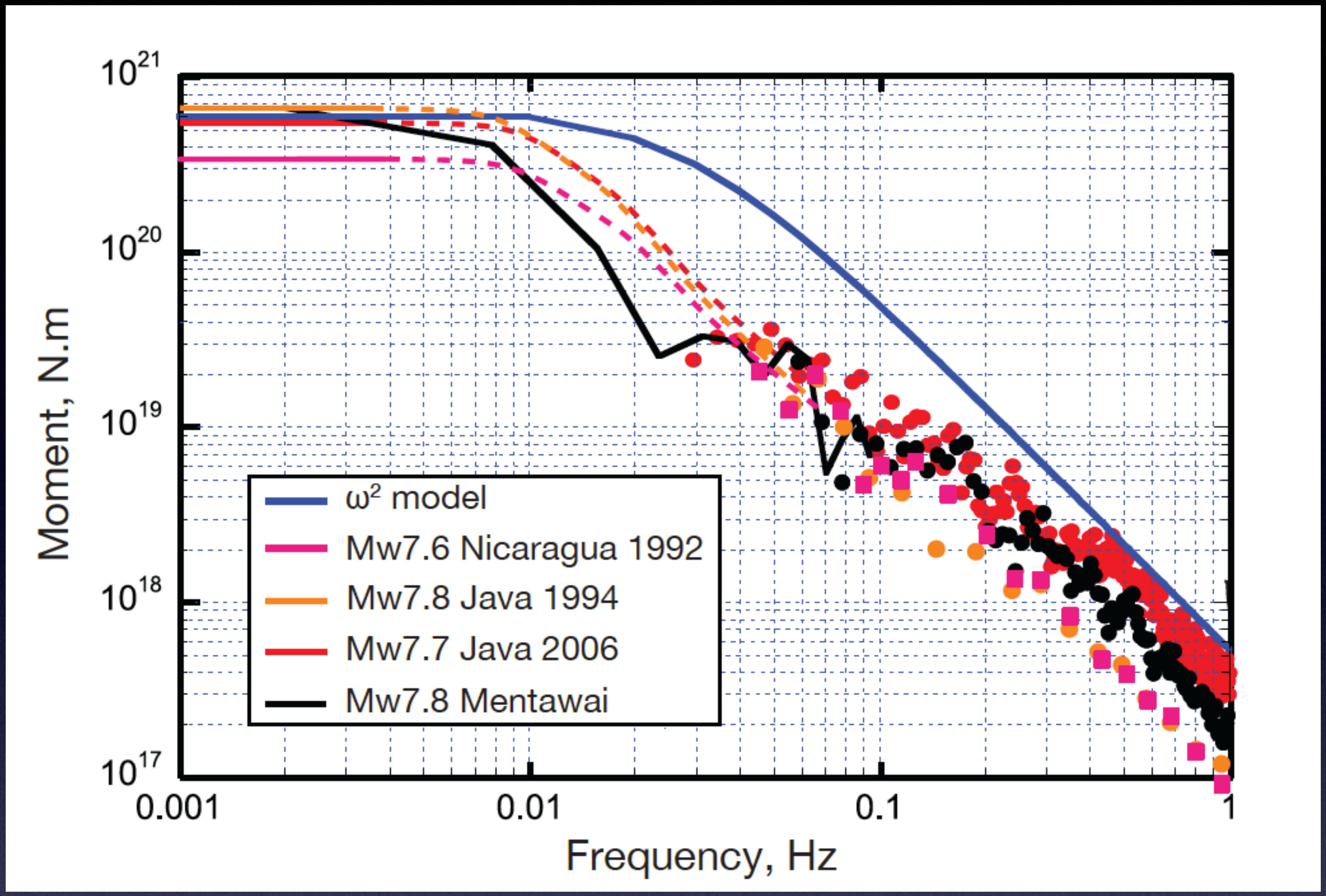
Maule 2010

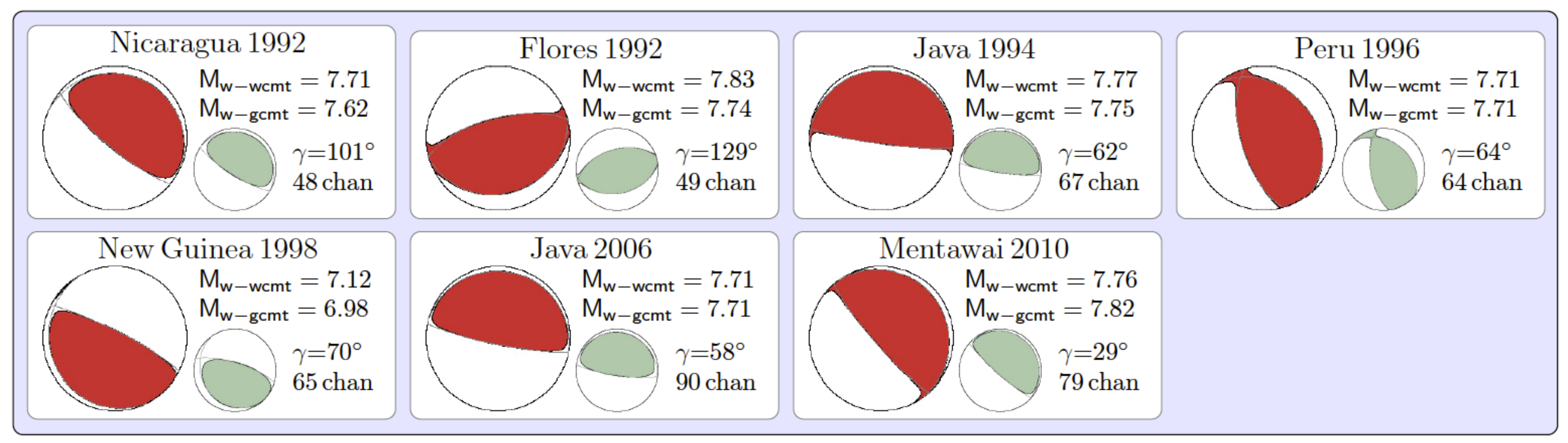
Sumatra 2004

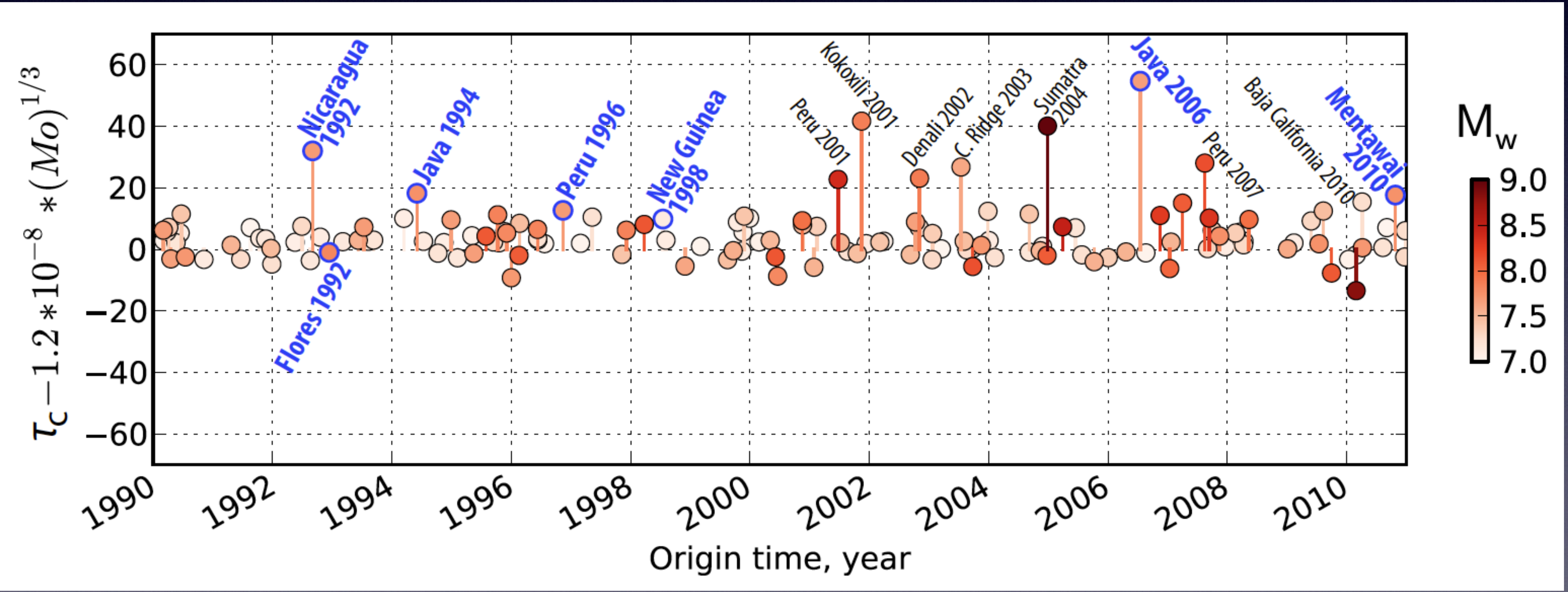
half duration

centroid time

"Tsunami earthquakes"
W phase
source inversion

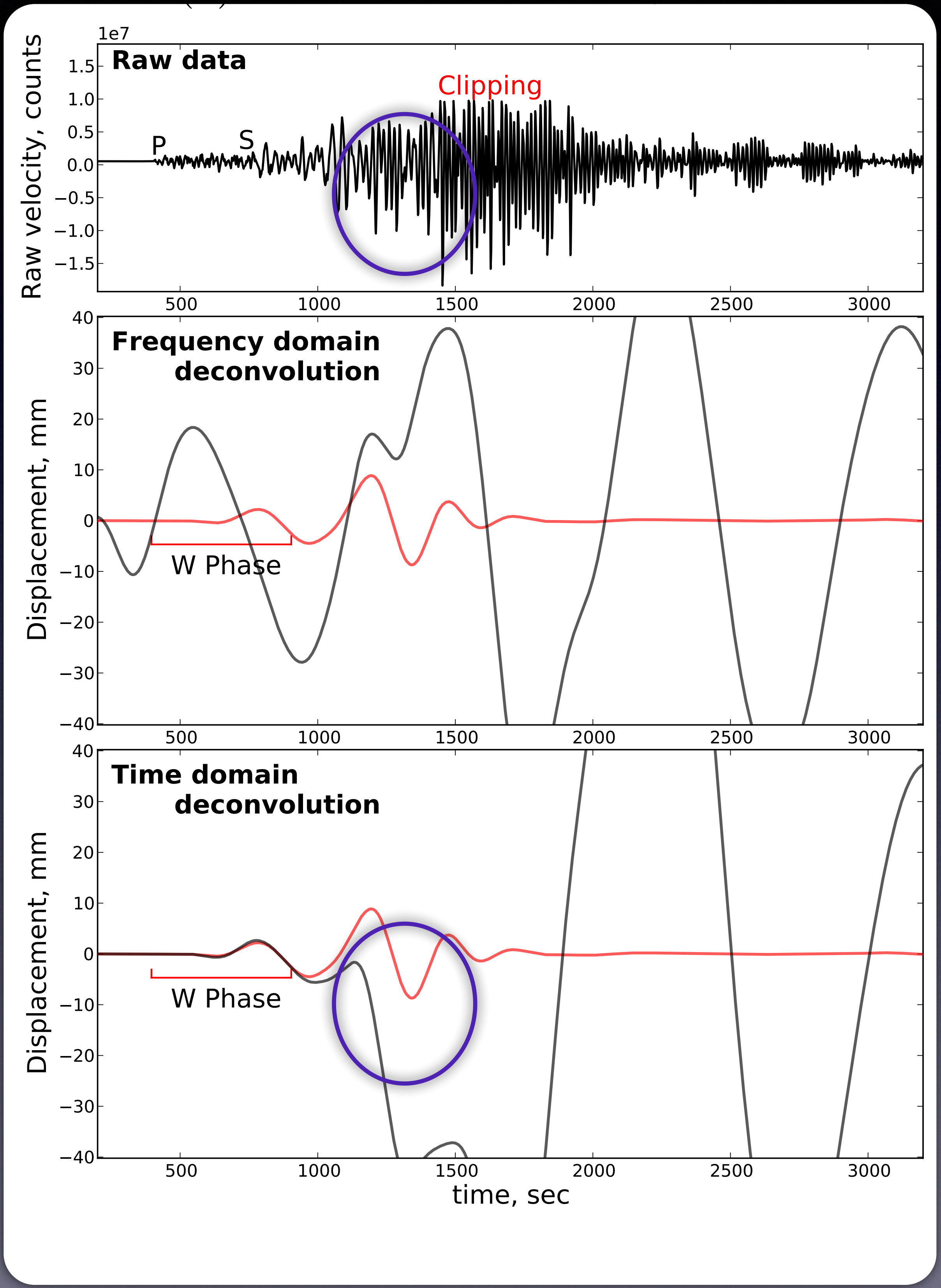


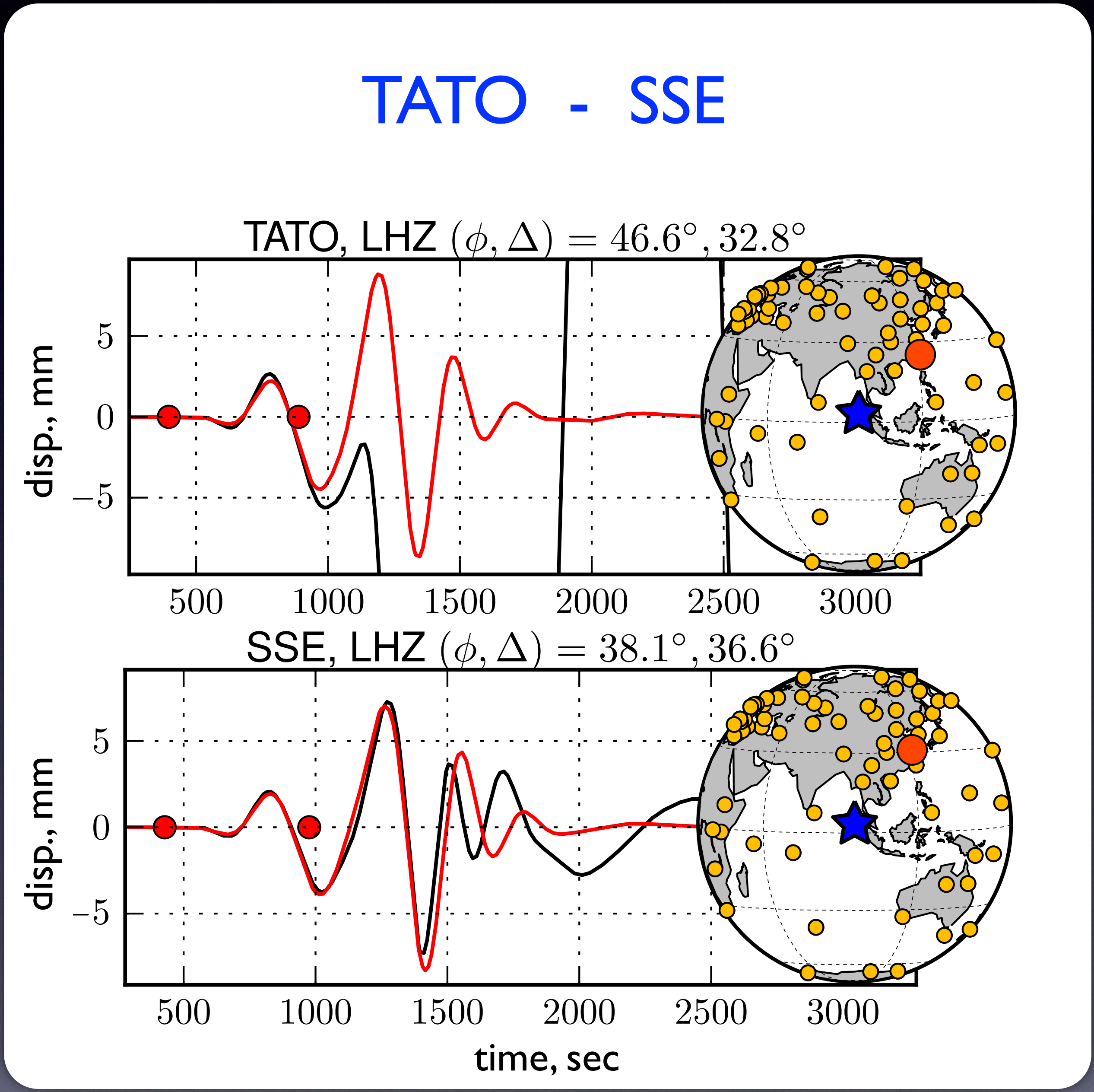




$\tau_c - 1.2*10^{-8}*(Mo)^{1/3}$
Origin time, year
M_w
Nicaragua 1992
Flores 1992
Java 1994
Peru 1996
New Guinea 1998
Peru 2001
Kokoxili 2001
Denali 2002
C. Ridge 2003
Sumatra 2004
Java 2006
Peru 2007
Baja California 2010
Mentawai 2010

Frequency vs Time-domain deconvolution





Sumatra-Andaman 2004

Time domain instrument deconvolution

Equation of motion

$$\ddot{y}(t) + 2h\omega_0\dot{y}(t) + \omega_0^2 y(t) = G\dddot{x}(t)$$

$$\ddot{y}(t) + 2h\omega_0\dot{y}(t) + \omega_0^2 y(t) = G\dot{a}(t)$$

Finite difference:

$$\frac{y_{i+2} - 2y_{i+1} + y_i}{\Delta t^2} + 2h\omega_0\frac{y_{i+2} - y_{i+1}}{\Delta t} + \omega_0^2 y_{i+2} = G\frac{a_{i+2} - a_{i+1}}{\Delta t}$$

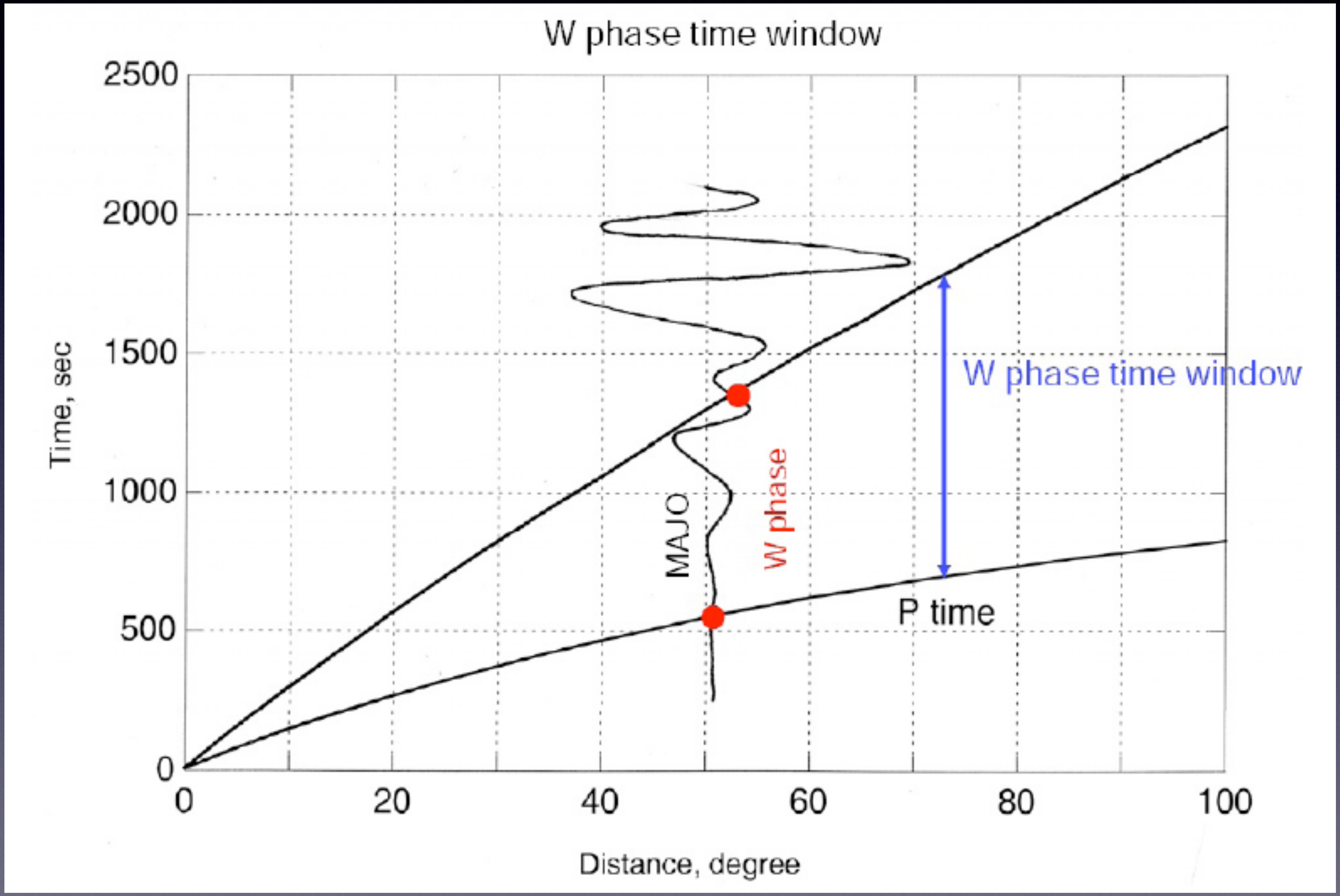
Recurrence relation for the ground motion:

$$a_{i+2} = a_{i+1} + c_2 y_{i+2} + c_1 y_{i+1} + c_0 y_i$$

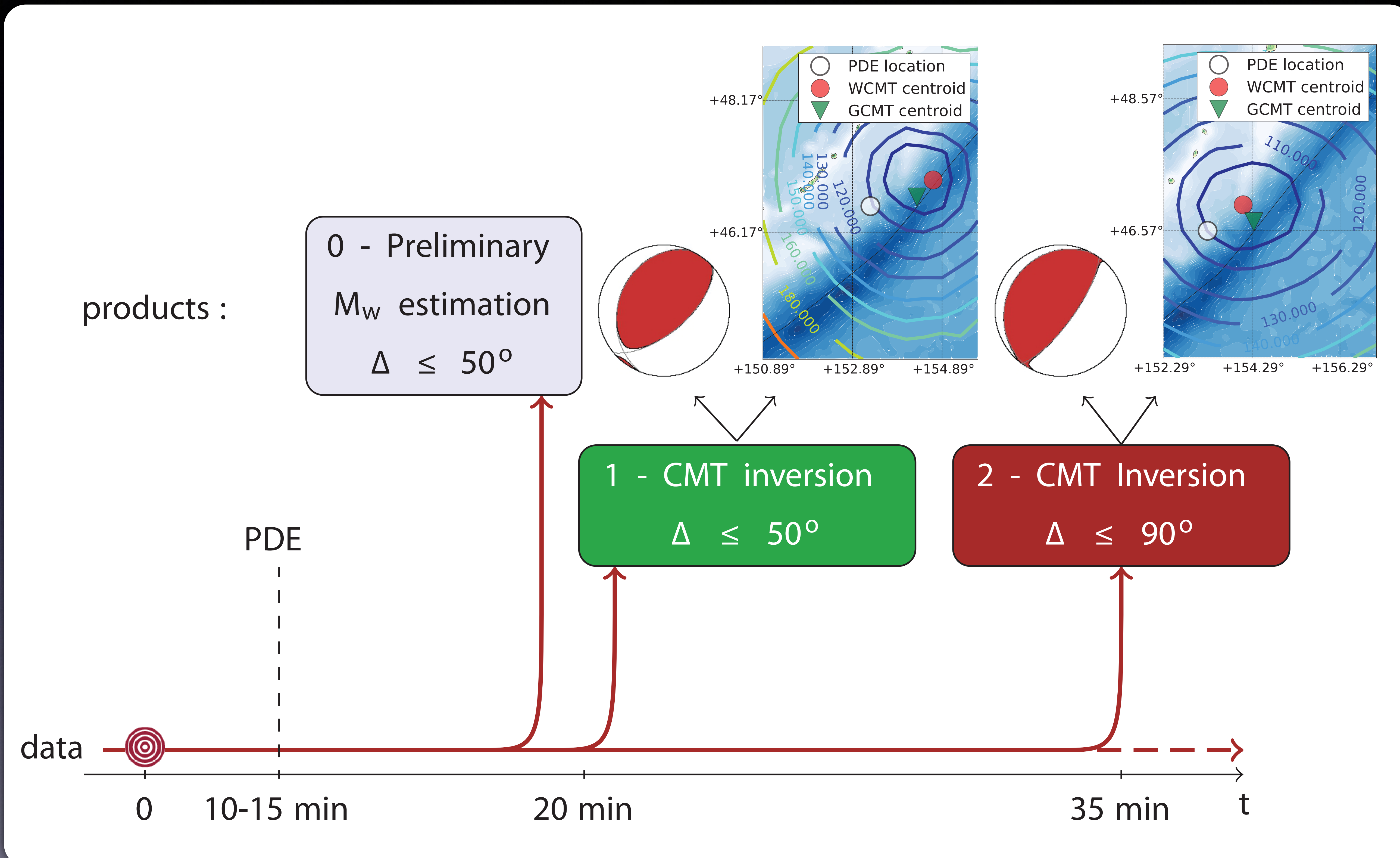
$$c_0 = \frac{1}{G\Delta t} \qquad c_1 = -2\frac{1 + h\omega_0\Delta t}{G\Delta t} \qquad c_2 = \frac{1 + 2h\omega_0\Delta t + \Delta t^2\omega_0^2}{G\Delta t}$$

How fast (global application)

W phase time window: (tp, tp + 15* Δ)



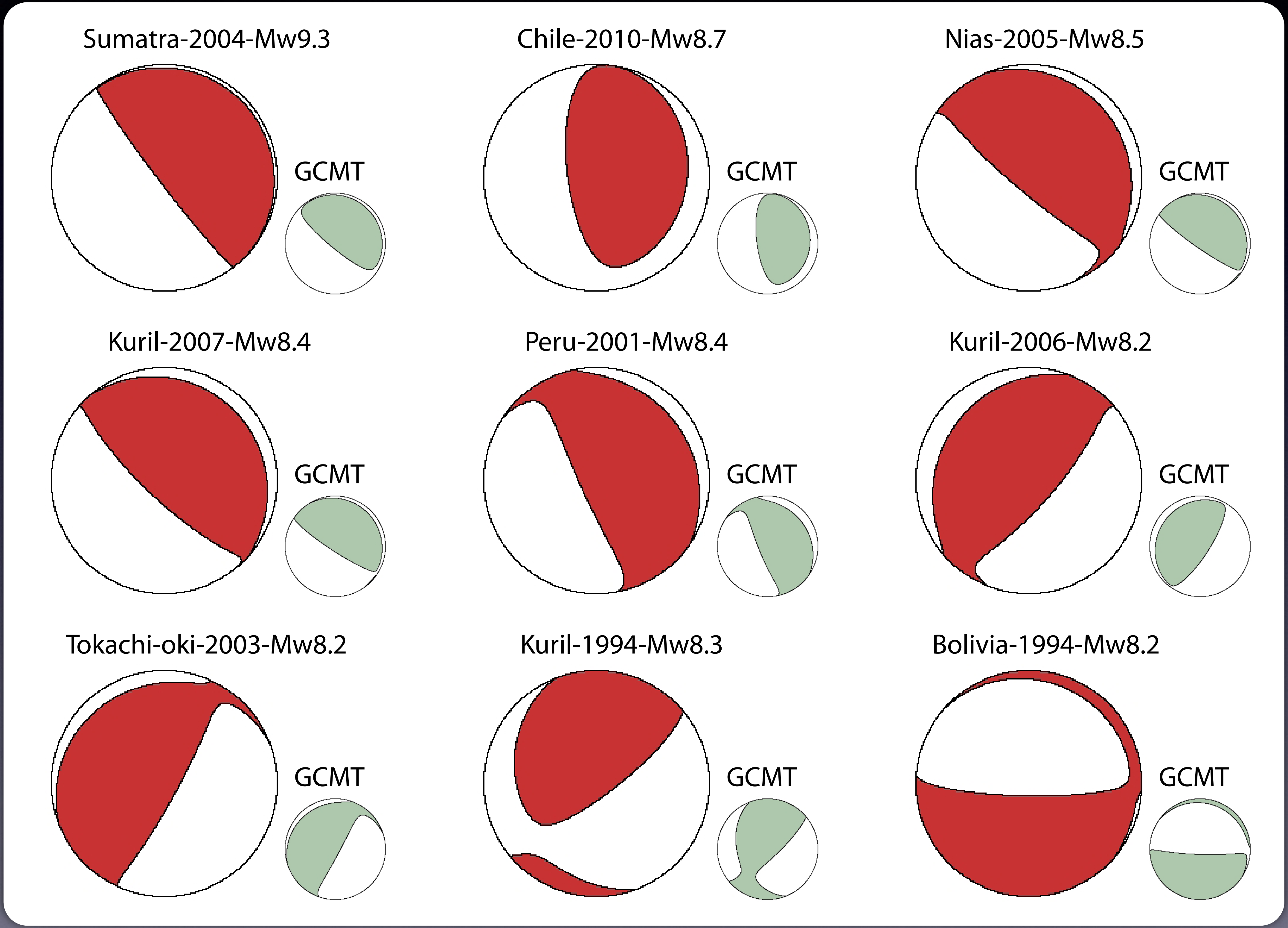
Real time operation (global application)



World seismicity 1990-2010 - Mw≥6.5

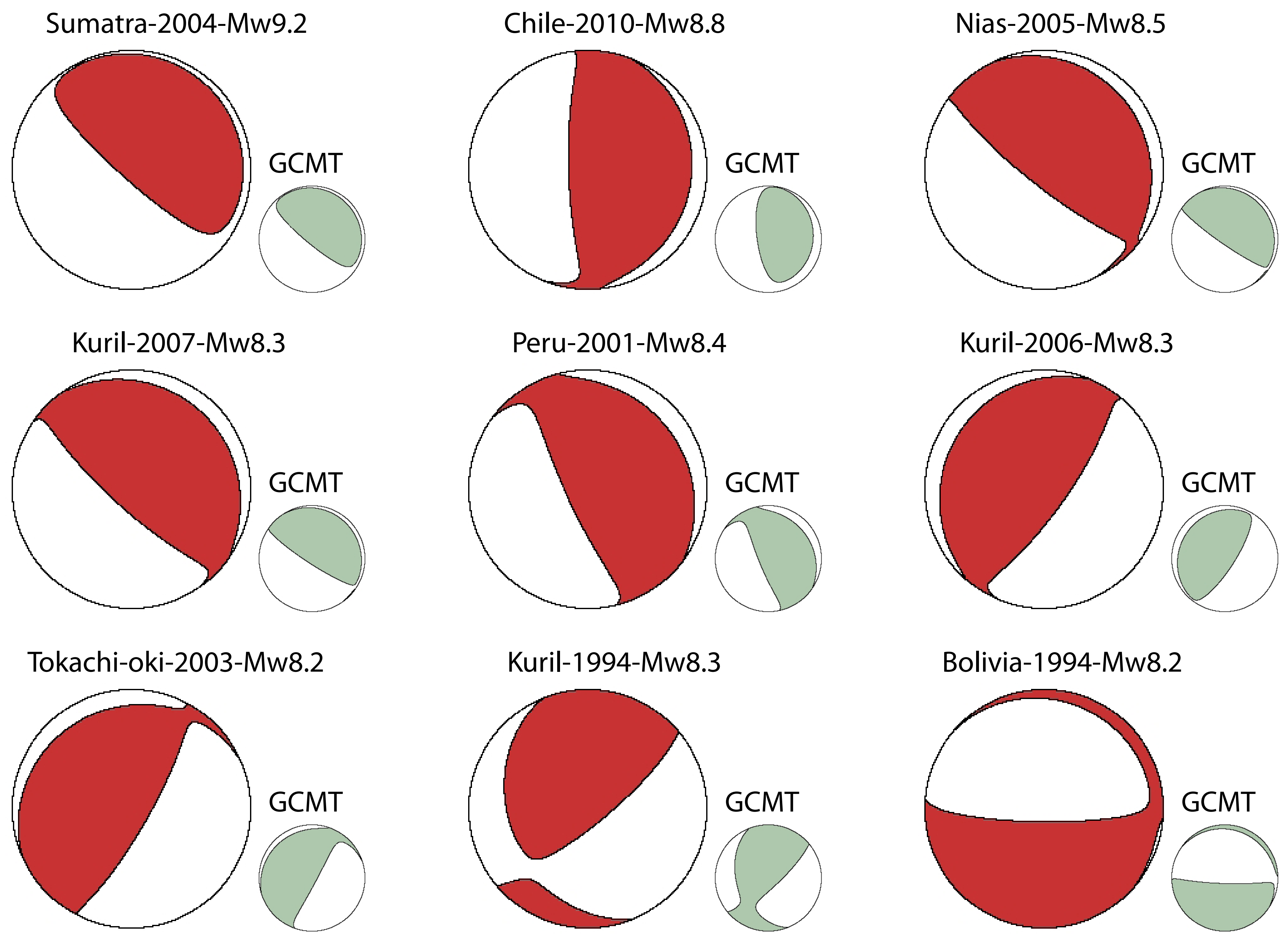
- Parameters: MT, lat., lon., depth., centroid time
  - T ~ 20 min - $\Delta \leq 50^\circ$
  - T ~ 35 min - $\Delta \leq 90^\circ$
- Data: broad-band velocimetric, 3 components:
  - networks II, IU, G, GE, etc.
  - priority to longer period sensors
- Frequency band = f(M_w). between 100 s et 1000 s
  e.g.:
  - Mw = 7.0 → 120 s - 500 s
  - Mw = 8.0 → 200 s - 1000 s
- In case of large events close in time: rejection of events showing a significant contamination by a previous event
  - For example: $M_w \geq 7$ with $\Delta T < 10$h;
  - 44/815, mainly aftershocks.

Focal Mechanisms - W phase (I) - 1990-2010
T ~ 20 min - $\Delta \leq 50^\circ$



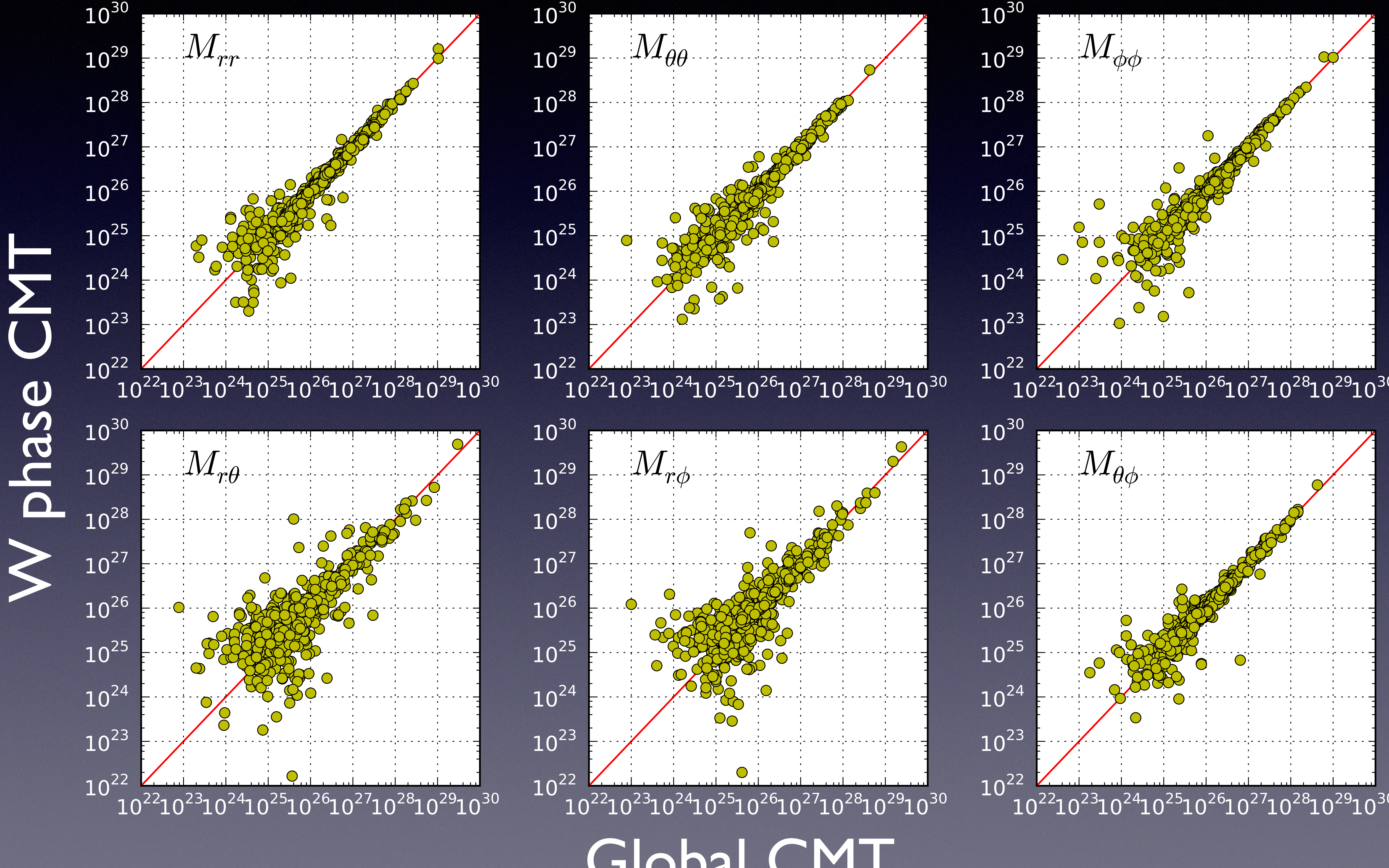
(GCMT: Global CMT)

Seismic moment tensor - W phase (2) - 1990-2010
T ~ 35 min - $\Delta \leq 90^{\circ}$

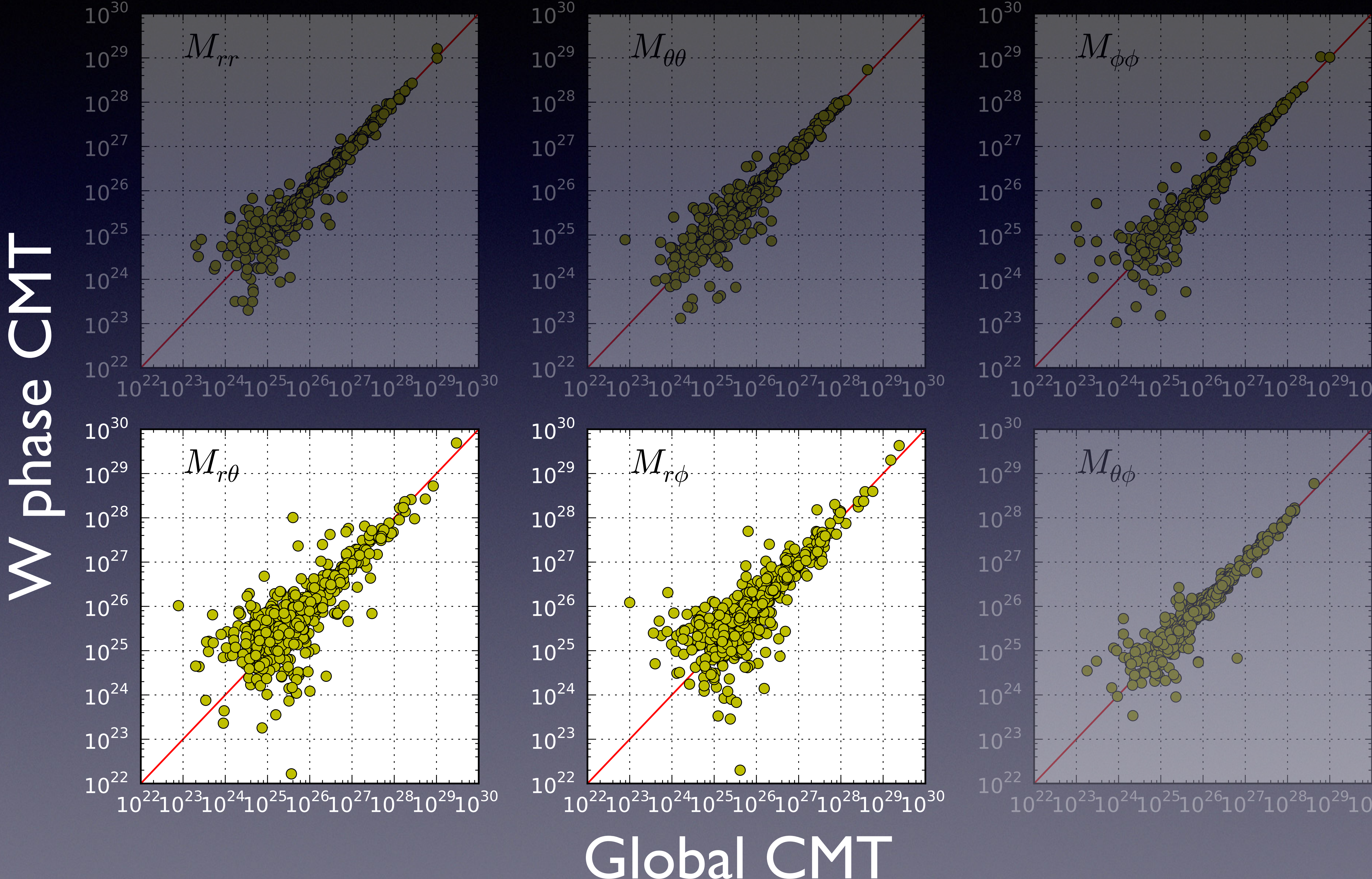


(GCMT: Global CMT)

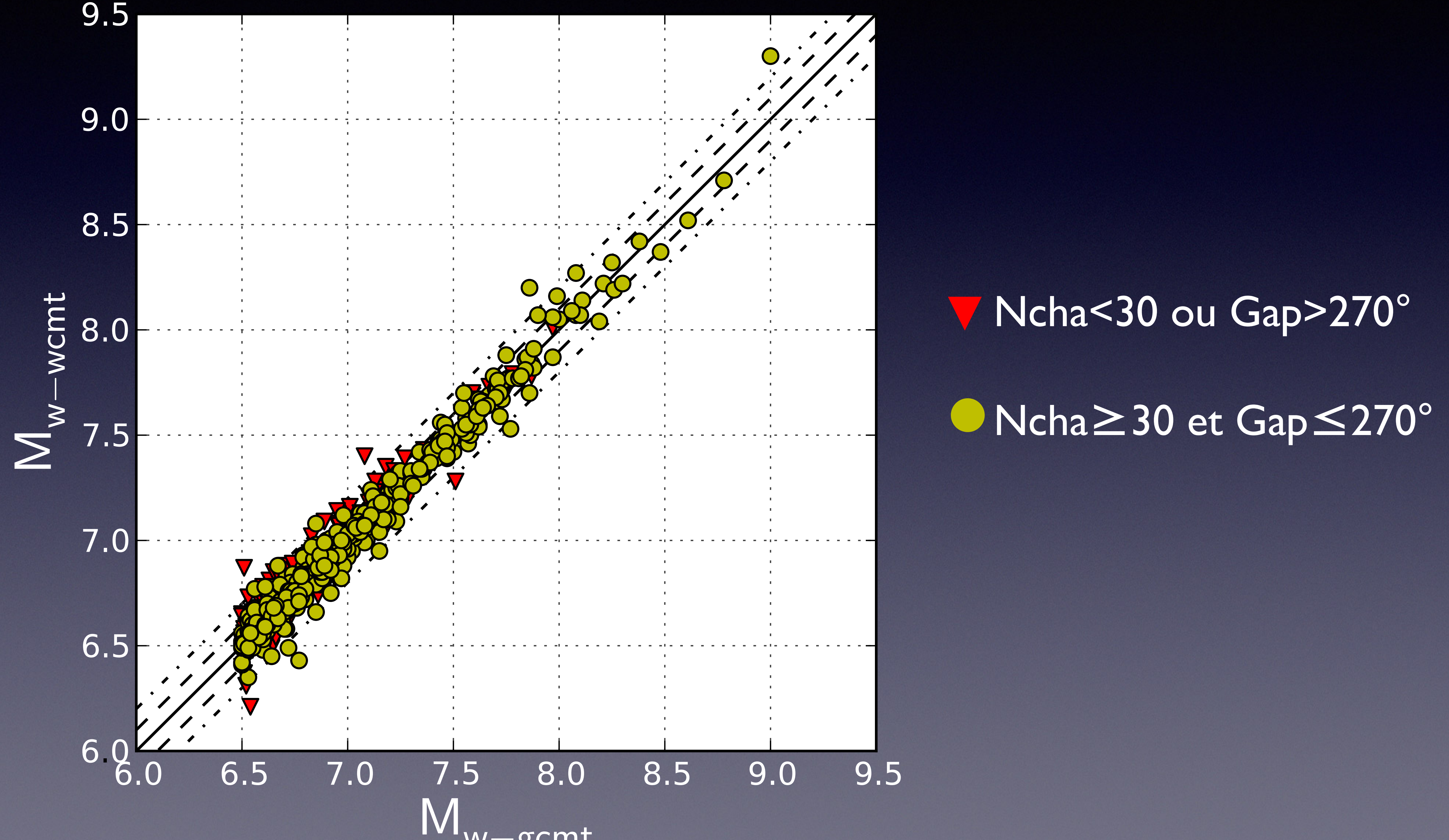
Seismic moment tensor - W phase (2) - 1990-2010
T ~ 35 min - $\Delta \leq 90^\circ$



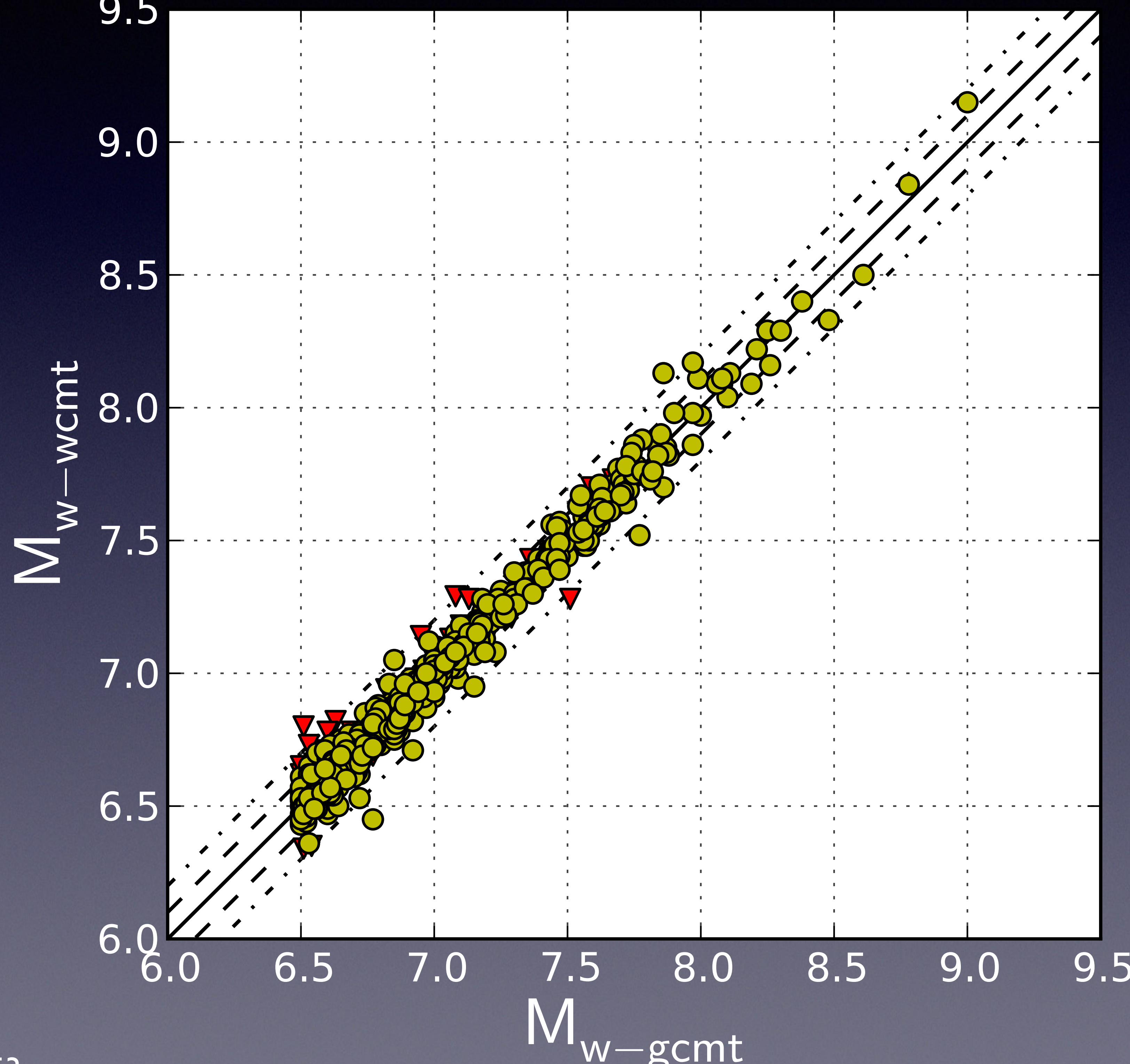
Seismic moment tensor - W phase (2) - 1990-2010
T ~ 35 min - $\Delta \leq 90^\circ$



Moment magnitude M_w - W phase (1) - 1990-2010
T ~ 20 min - $\Delta \leq 50^\circ$



Moment magnitude M_w - W phase (2) - 1990-2010
T ~ 35 min - $\Delta \leq 90^\circ$

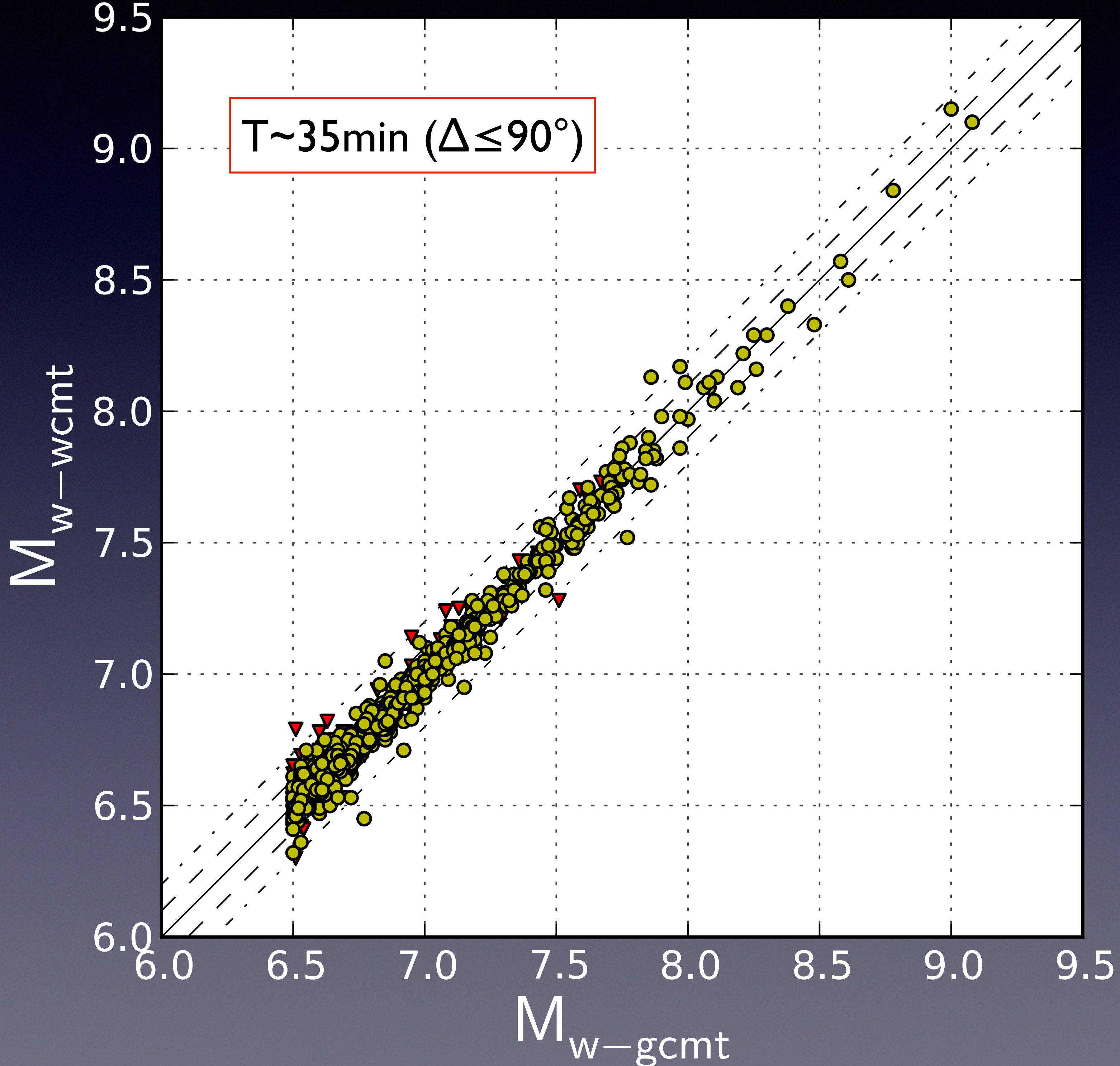


σ_{Mw}=0.04

ΔMw < 0.2 (99% ev.)

GCMT: Global CMT
WCMT: W-phase CMT

Global scale - 1990-2012 - Mw≥6.5
Solution after 20-35 min



▼ Ncha<30 or Gap>270°

● Ncha≥30 and Gap≤270°

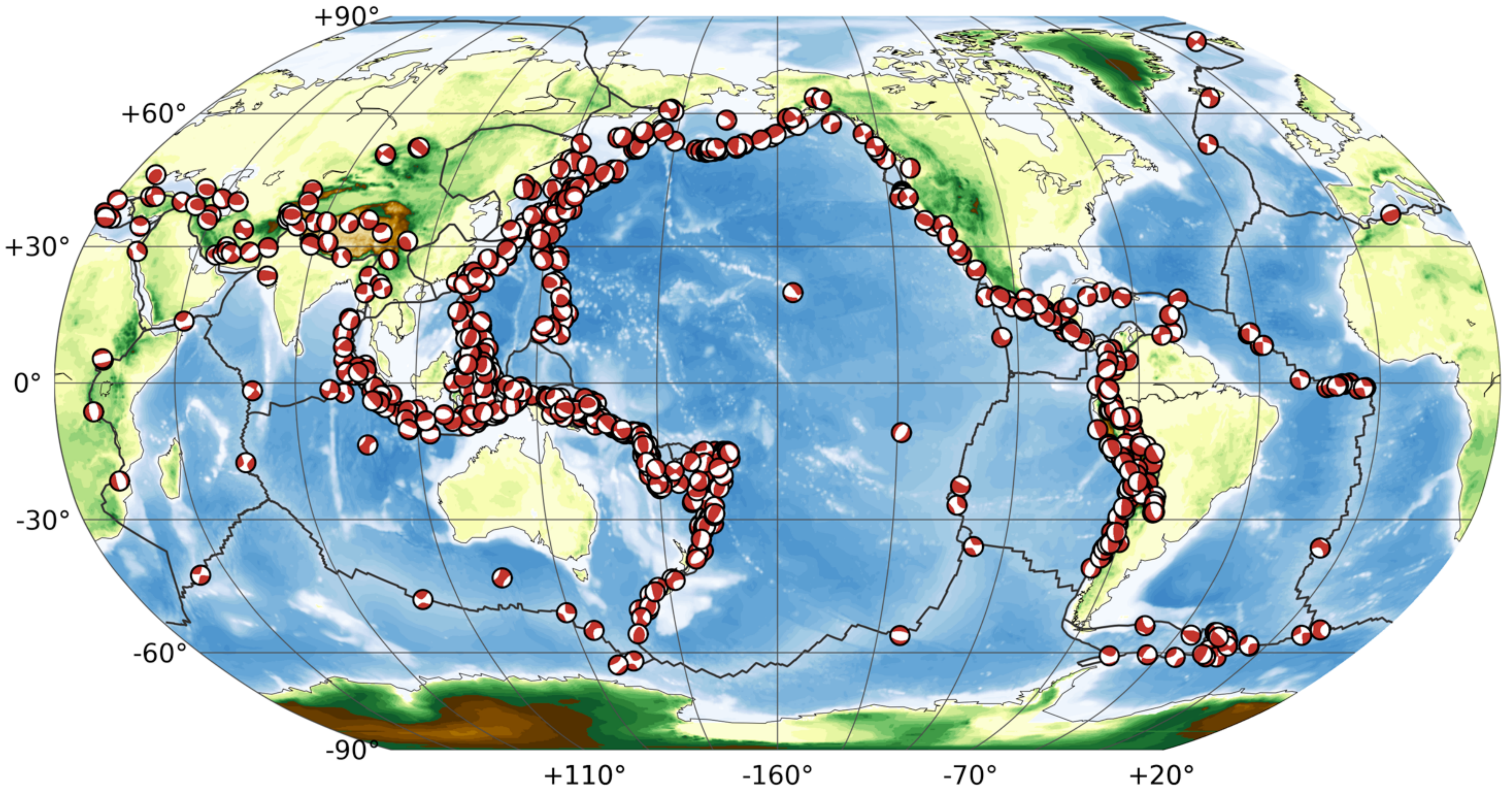
σ_{Mw}=0.04

ΔMw < 0.2 (99% ev.)

Duputel et al. (GJI, 2012)

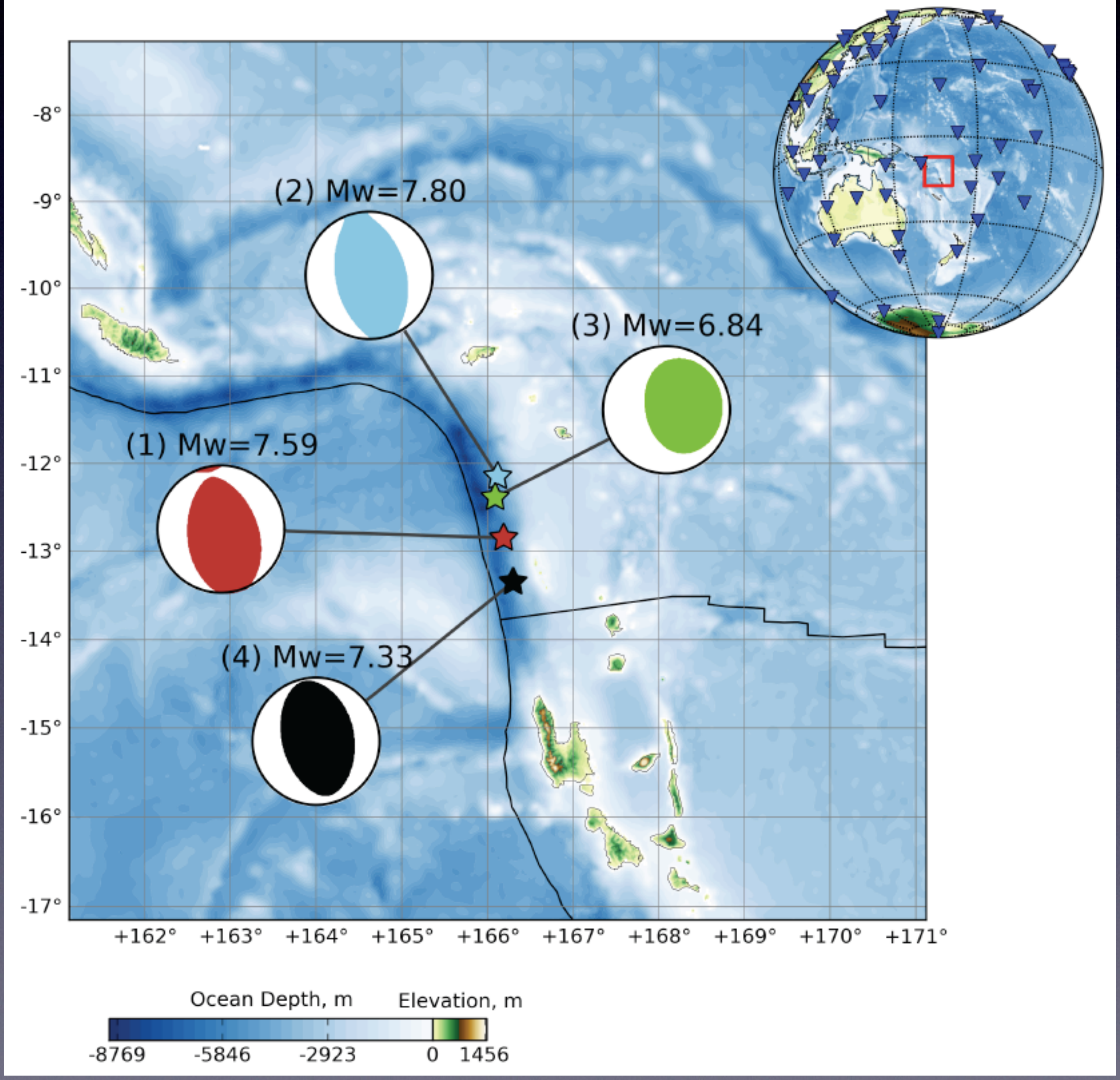
Collaboration: G.P. Hayes

I.I. Global scale - 1990-2012 - Mw≥6.5
Solution after 20-35 min

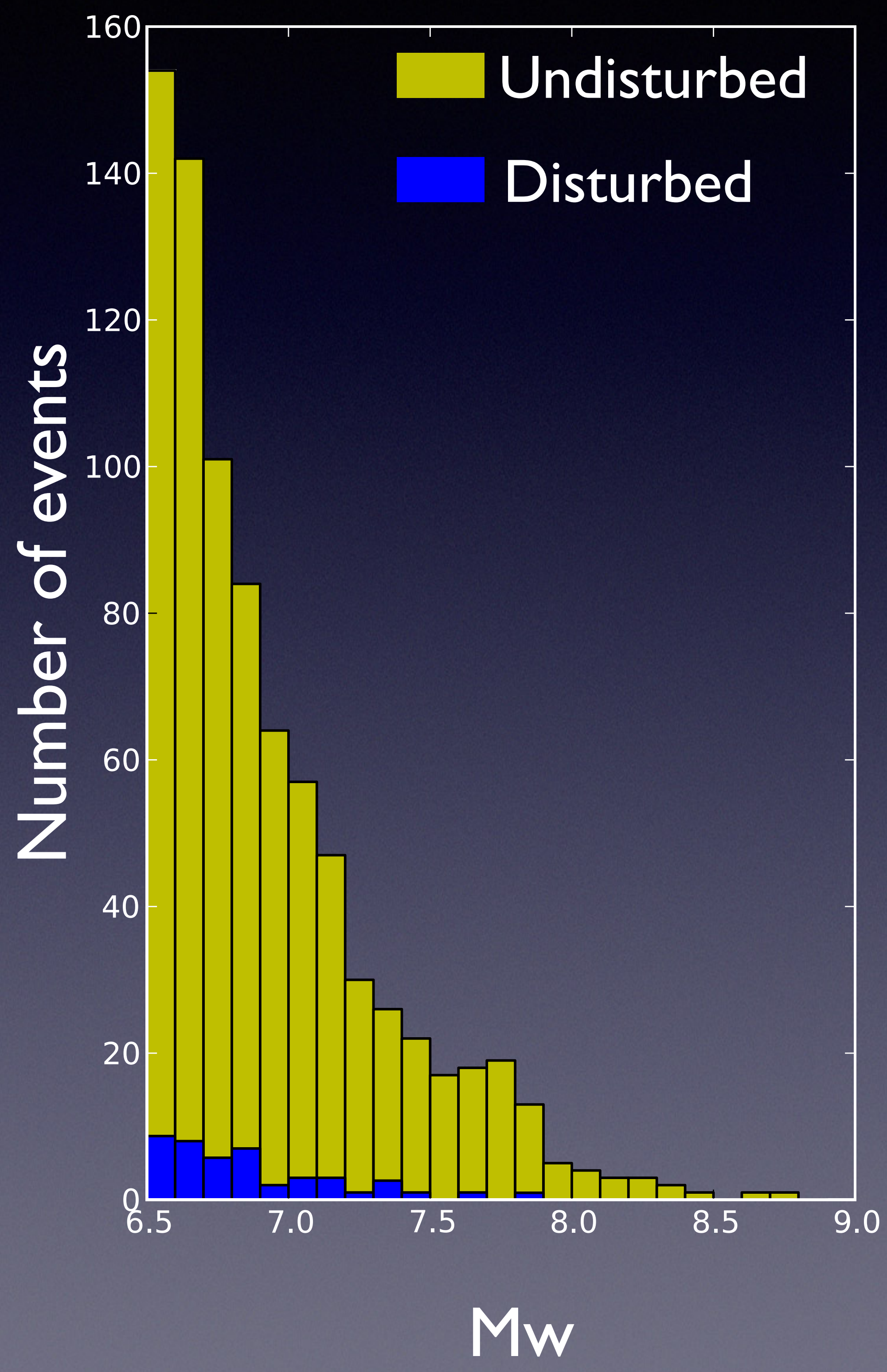


W phase solutions available at: http://eost.u-strasbg.fr/wphase/MGE65

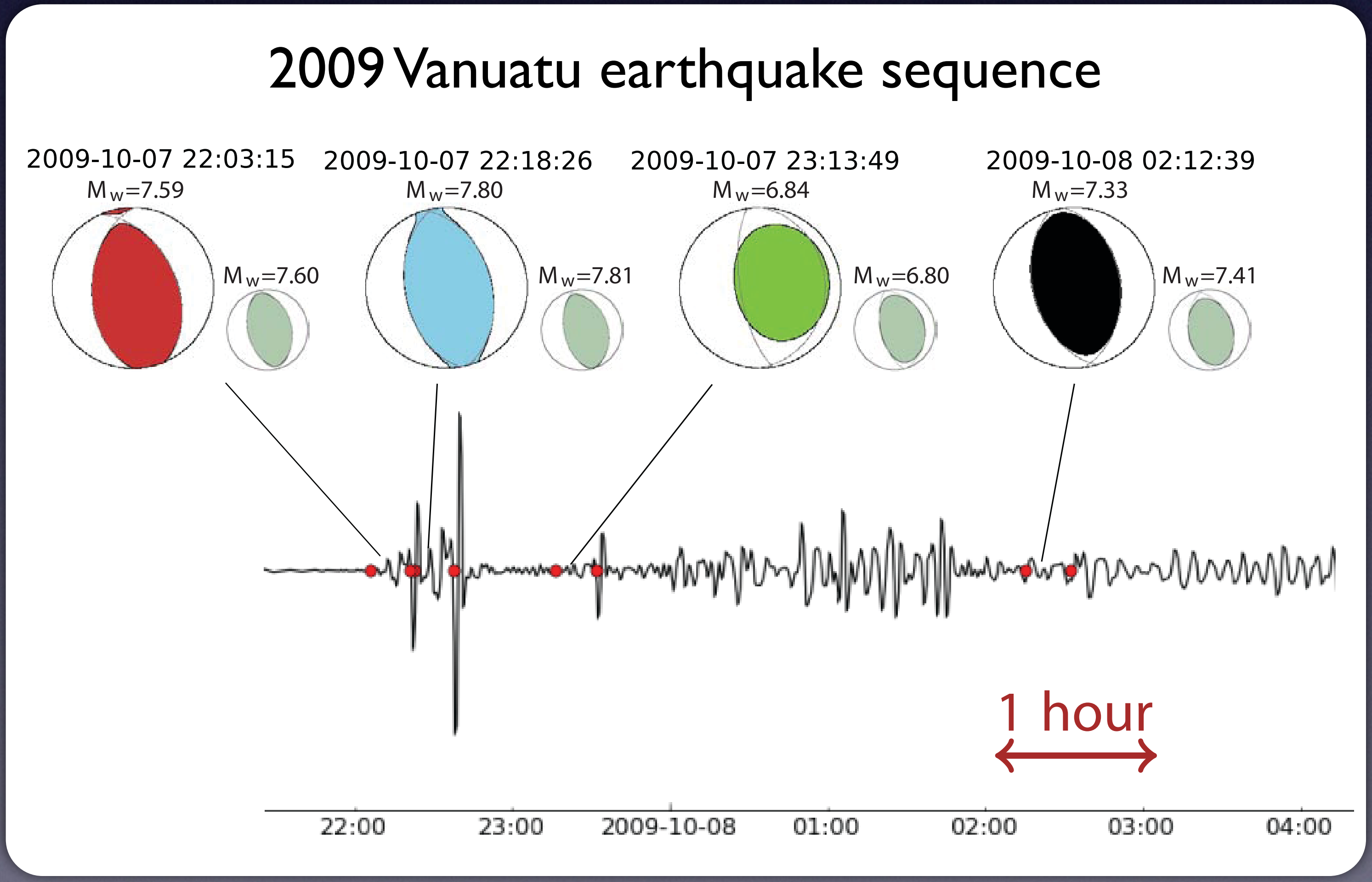
Vanuatu sequence
7 Octobre 2010
4 events Mw > 6.8 within 4h



Perturbed events



- Superposition of waveforms generated by several events occurring close in time.
- Possible solution: successively stripping the synthetic waveforms corresponding to previous events.

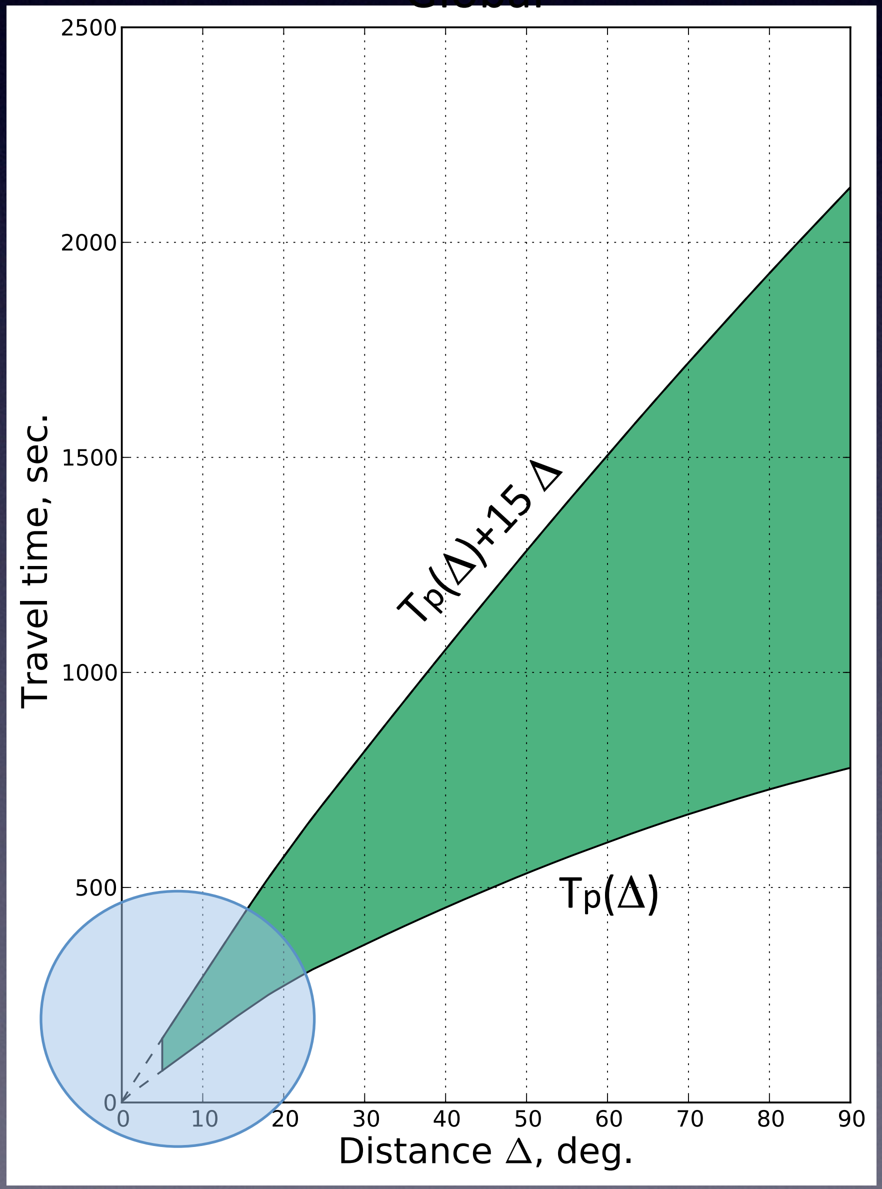


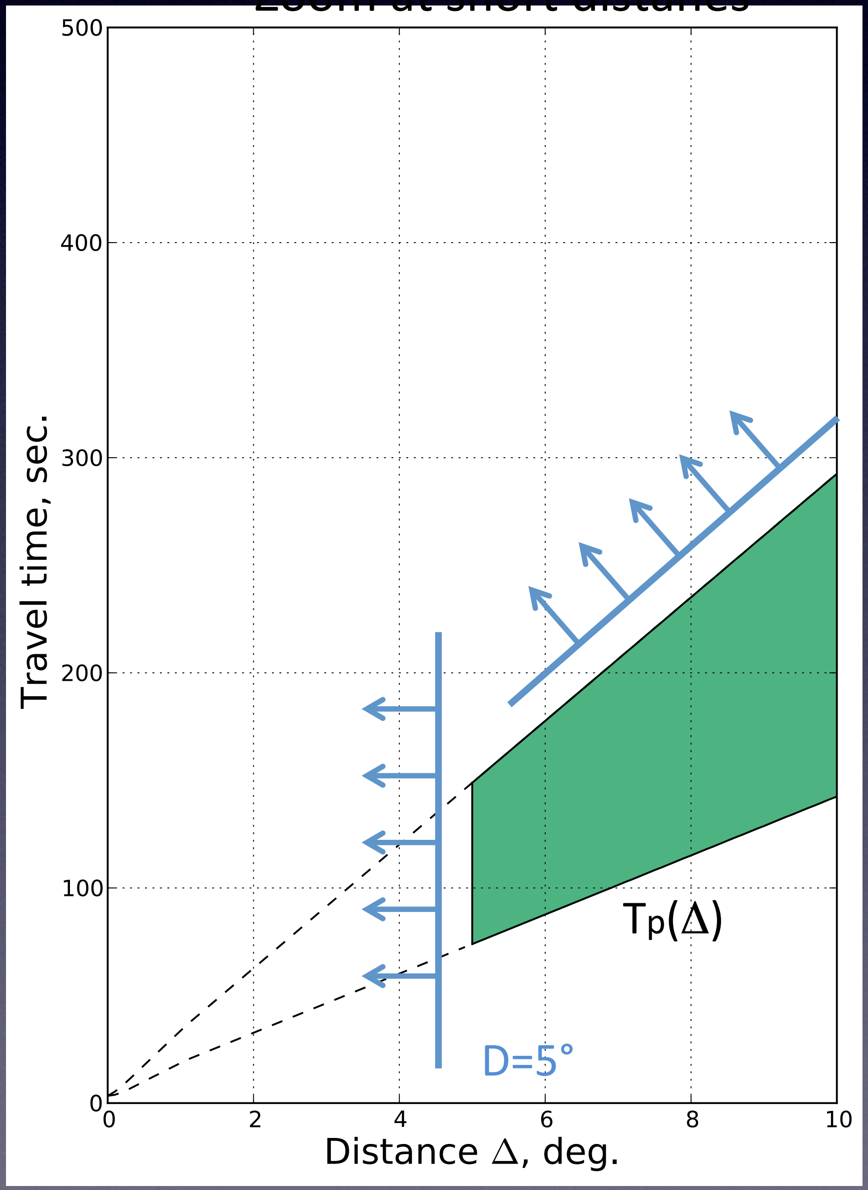
Regional vs Global applications

Not much difference
Exactly same code
Green's functions
Band pass
Time window
Magnitudes ….

Regional application

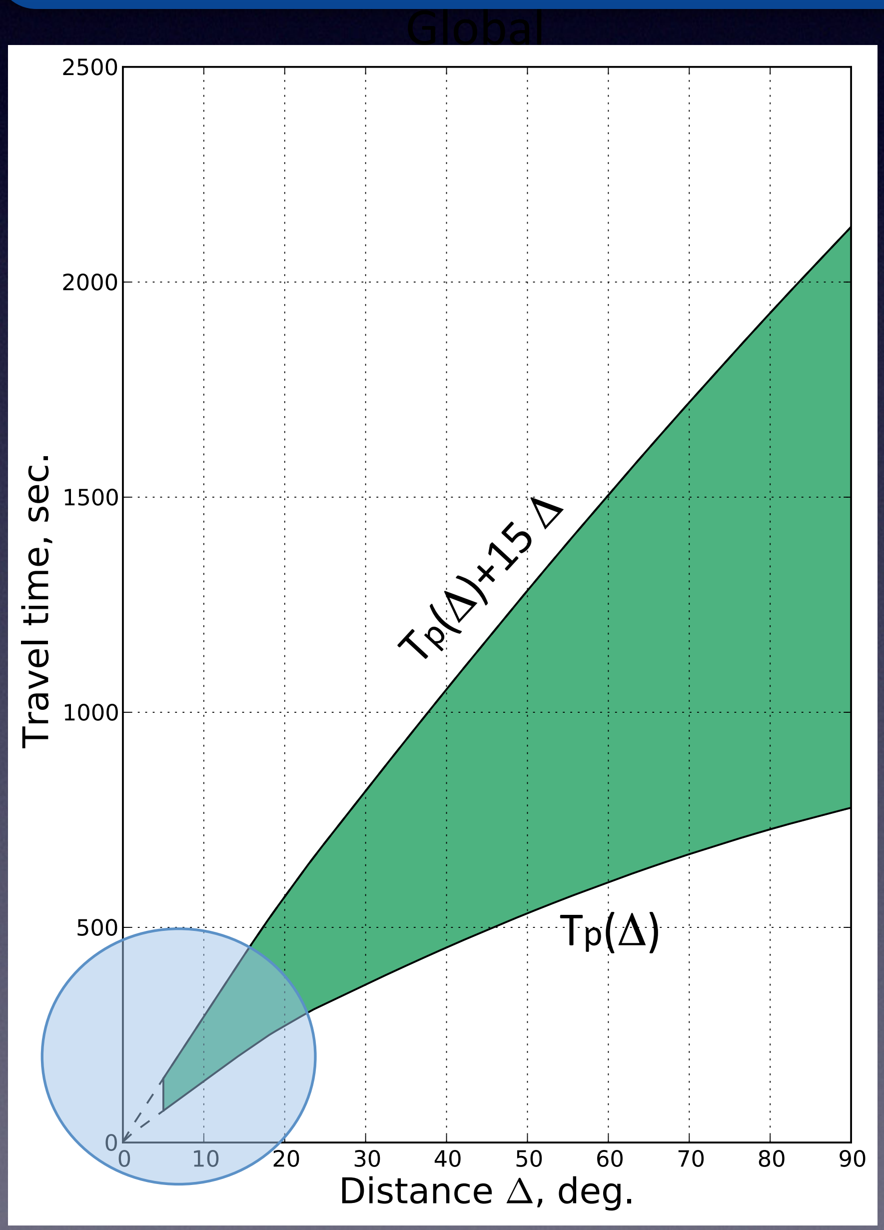
W phase time window
adapting for regional distances

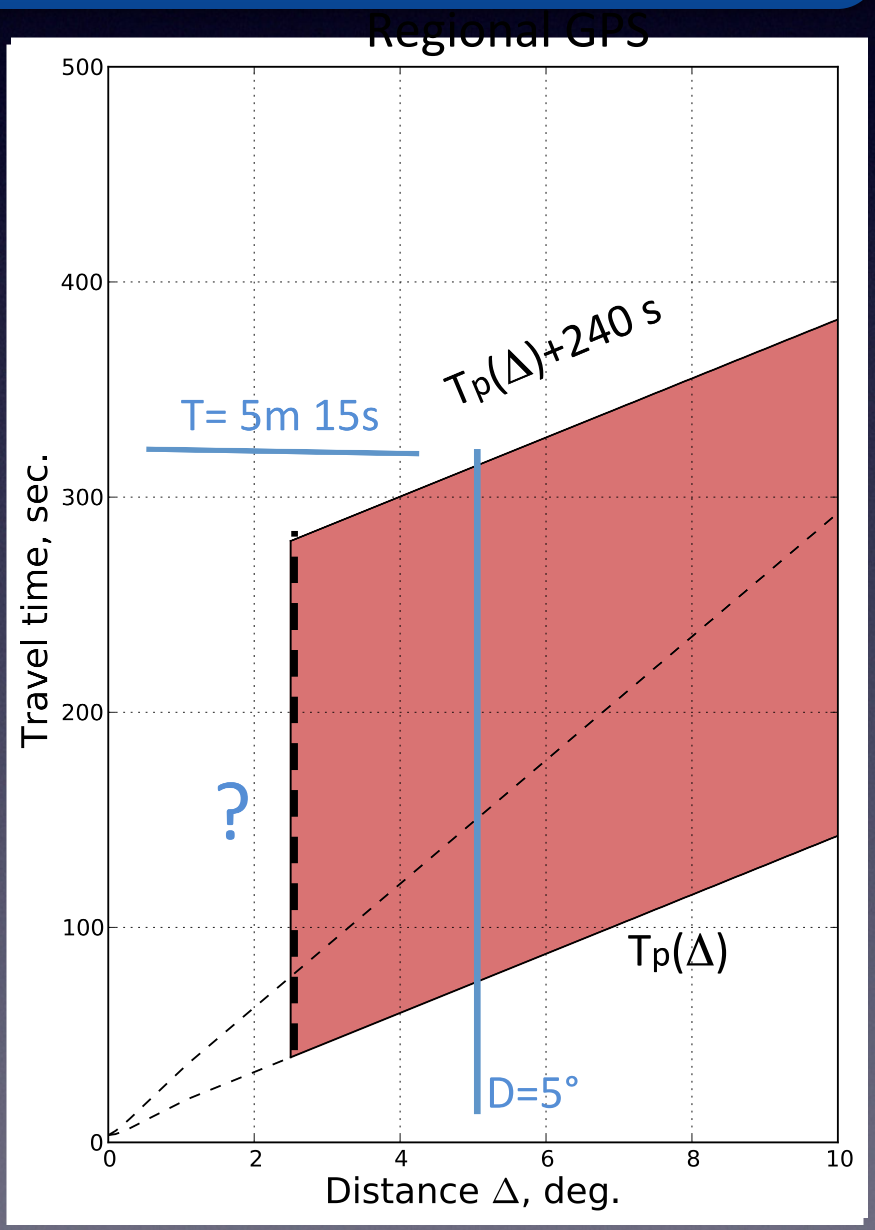




Regional application

W phase time window adapting for regional distances





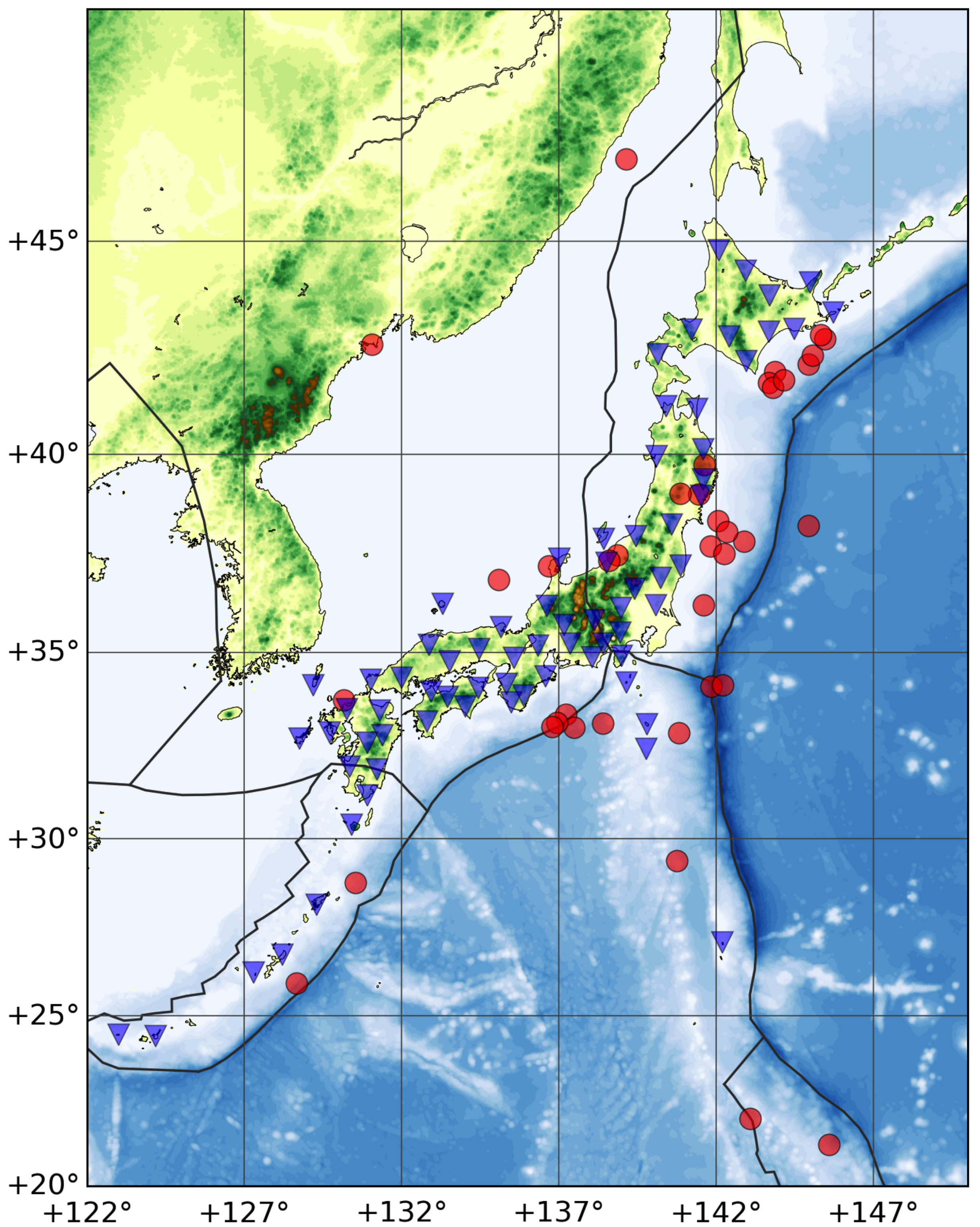
Real time implementations by 2015

1. Global scale:
   - IPGS, EOST; France (dev. site)
   - NEIC, USGS; Colorado
   - PTWC, NOAA; Hawai
   - ERI, JMA; Japan
   - CPPT ; Tahiti

2. Regional scale:
   - UNAM; Mexico.
   - ERI, JMA; Japan
   - SSUCH; Chile
   - SGC, Colombia
   - CENALT; France
   - In progress: California, etc.

IPGS: Institut de Physique du Globe de Strasbourg
EOST: Ecole et Observatoire des Sciences de la Terre
USGS: United States Geological Survey
NEIC: National Earthquake Information Center
PTWC: Pacific Tsunami Warning Center
NOAA: Nat. Oceanic and Atmospheric Administration
UNAM: Universidad Nacional Autónoma de México
CPPT: Centre Polynesien de Prevention des Tsunamis
CENALT: Centre National d'Alert aux Tsunamis

Regional application
2003-2010 - $M_{jma} \geq 6.5$

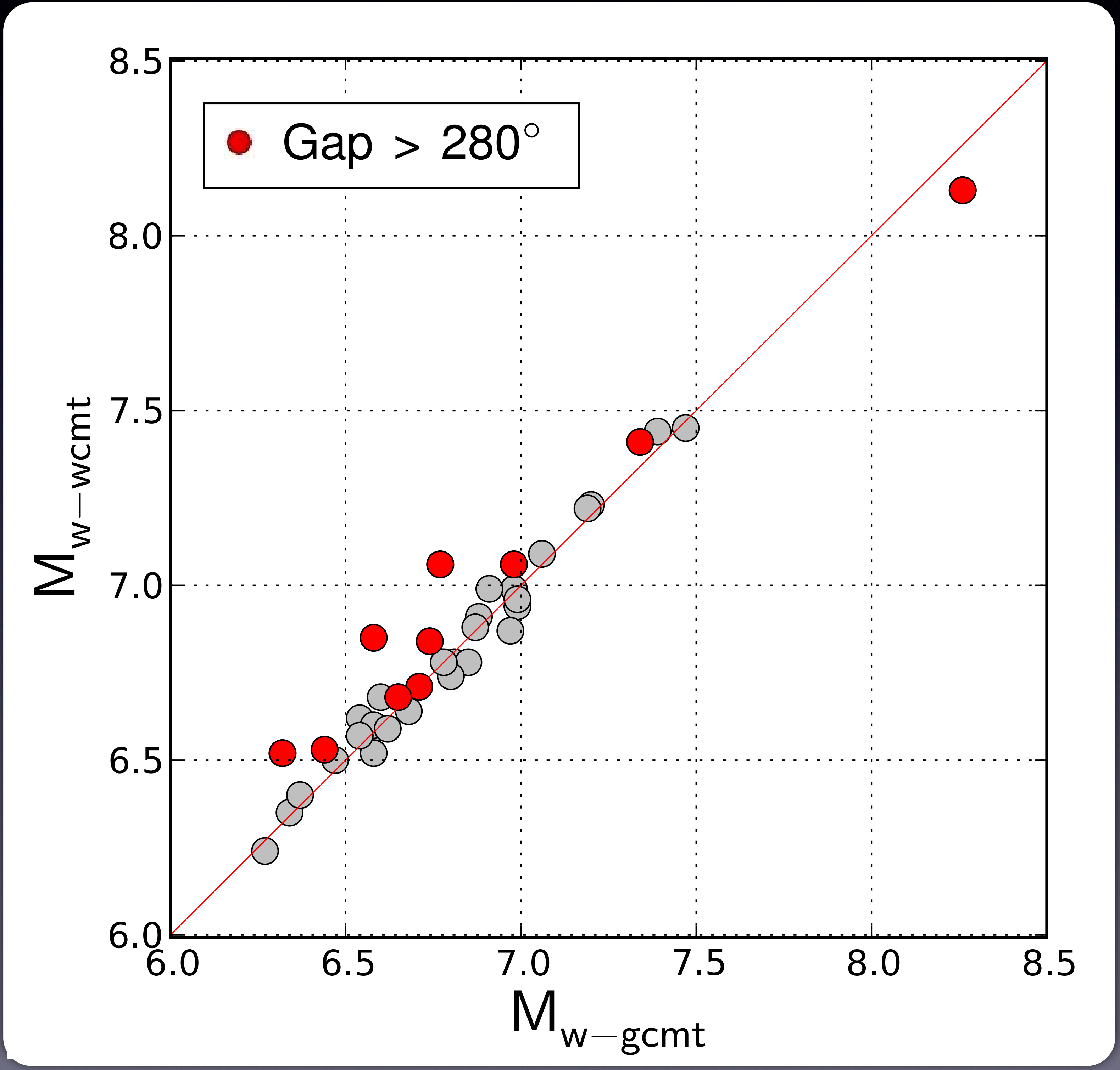


Adapting the W phase source inversion algorithm to the regional scale:

- Data: broad band F-net (NIED)
- Inversion at $T \sim 12$min ($5° \leq \Delta \leq 25°$)
- Time window
  - $[t_P ; t_P+180 \text{ s}]$ for $\Delta \leq 12°$
  - $[t_P ; t_P+15 \times \Delta \text{ s/°}]$ for $\Delta > 12°$
- band pass = f(prelim. mag.)
- (regional green's functions DB)

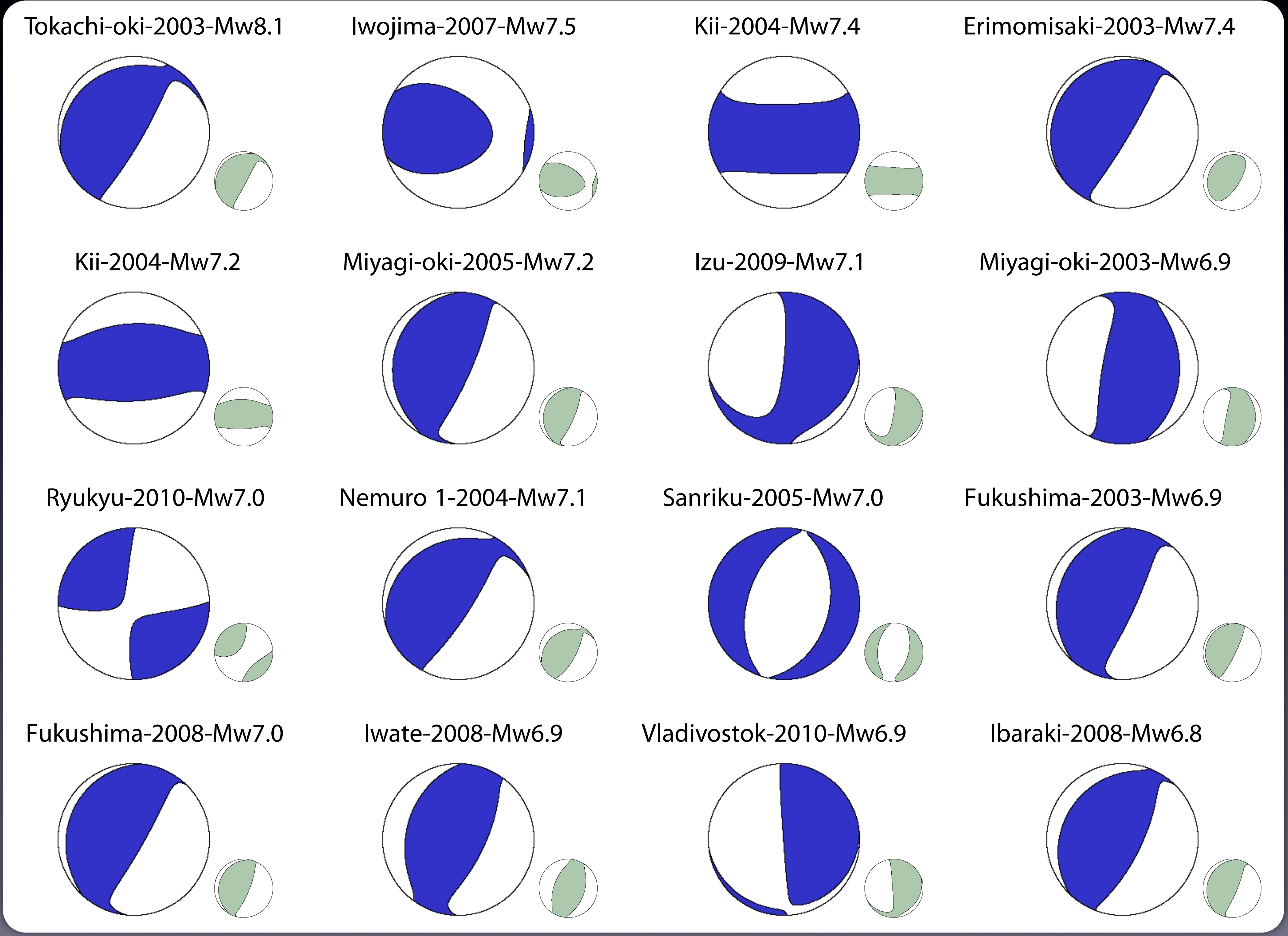
(JMA: Japan Meteorological Agency)

Moment magnitude M_w - regional W Phase
Japan - T ~ 12 min - $\Delta \leq 25^\circ$

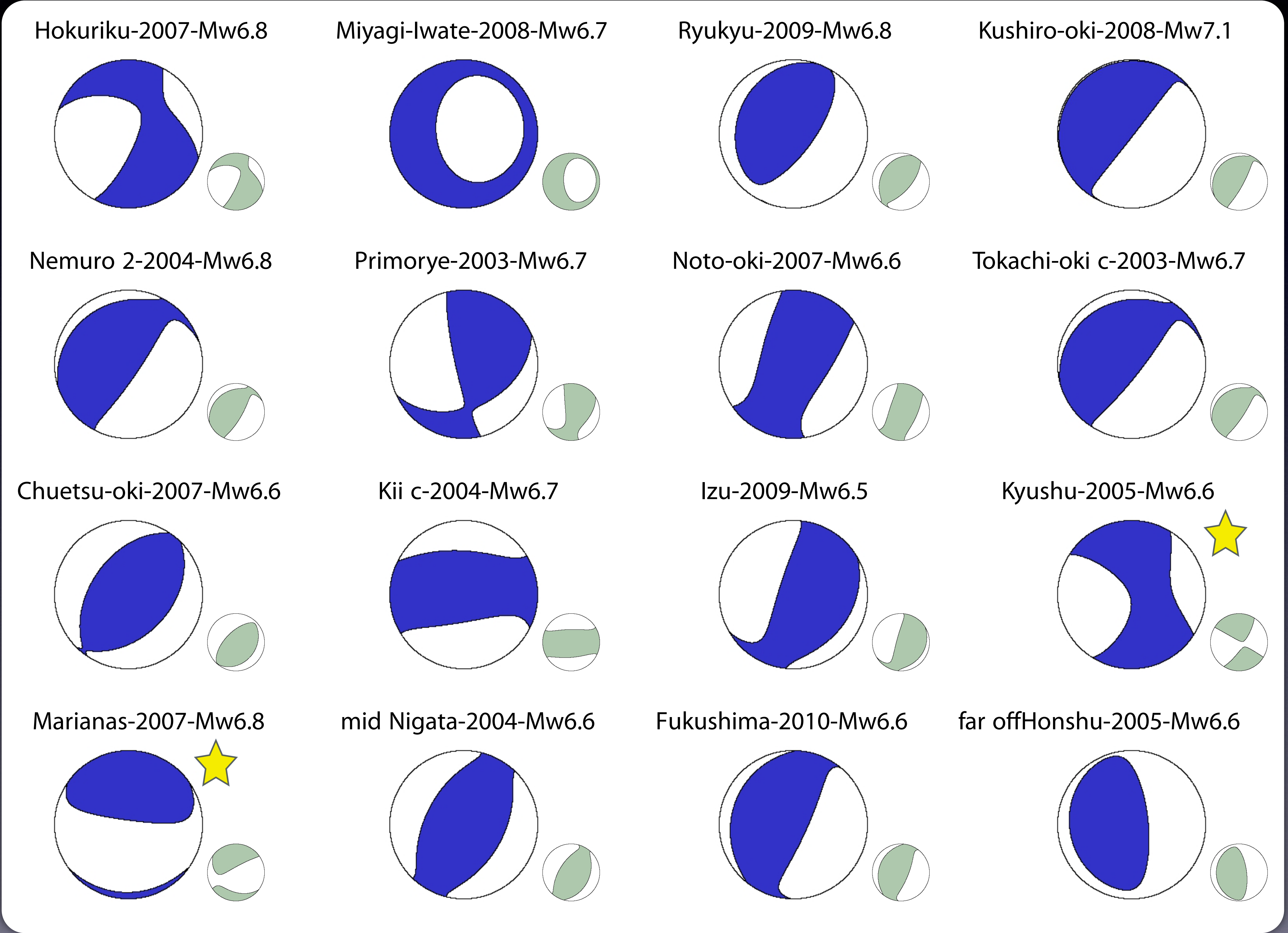


GCMT: Global CMT
WCMT: W-phase CMT

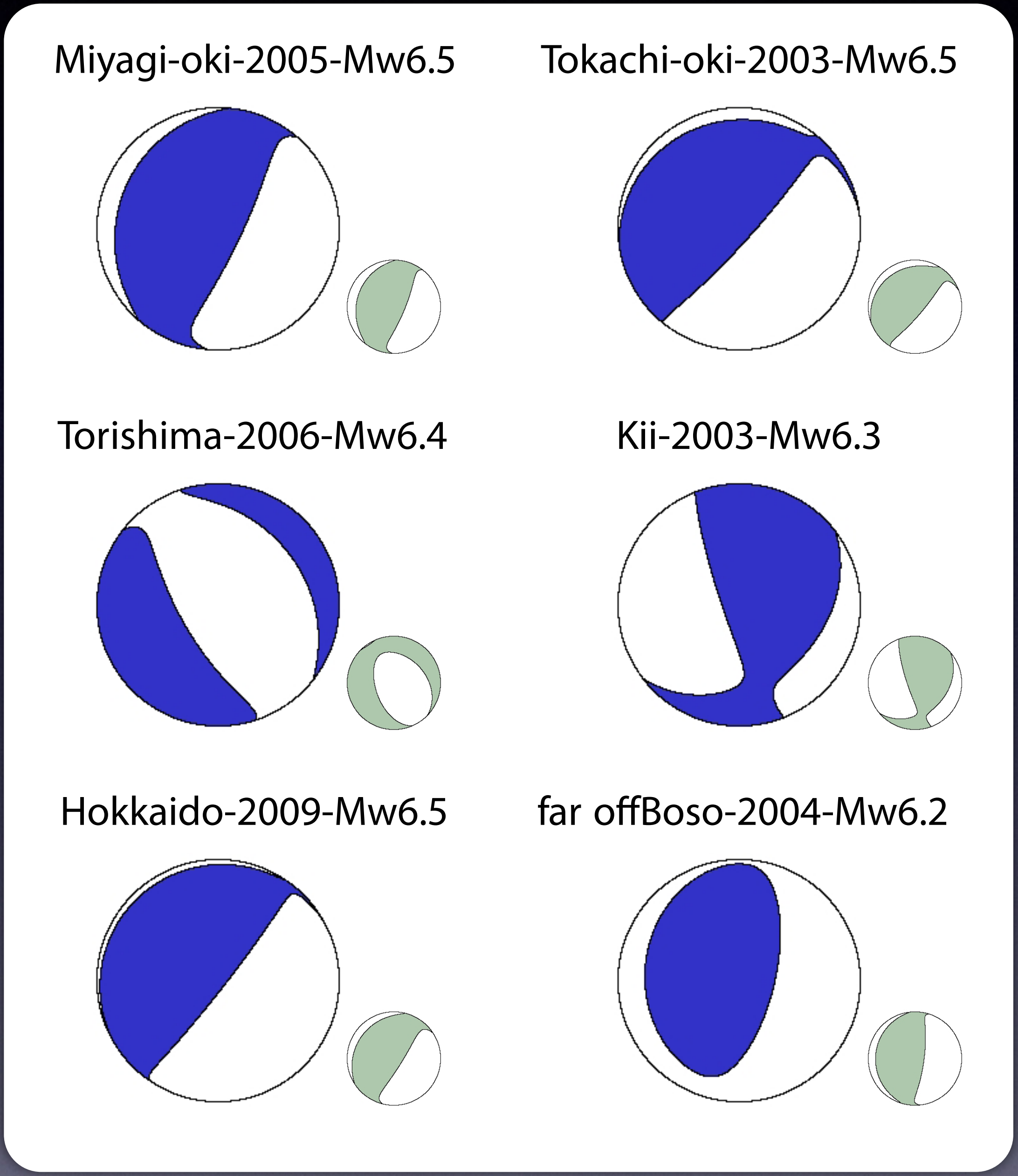
Focal Mechanisms- regional W Phase - 1/3
Japan - T ~ 12 min - $\Delta \leq 25^\circ$

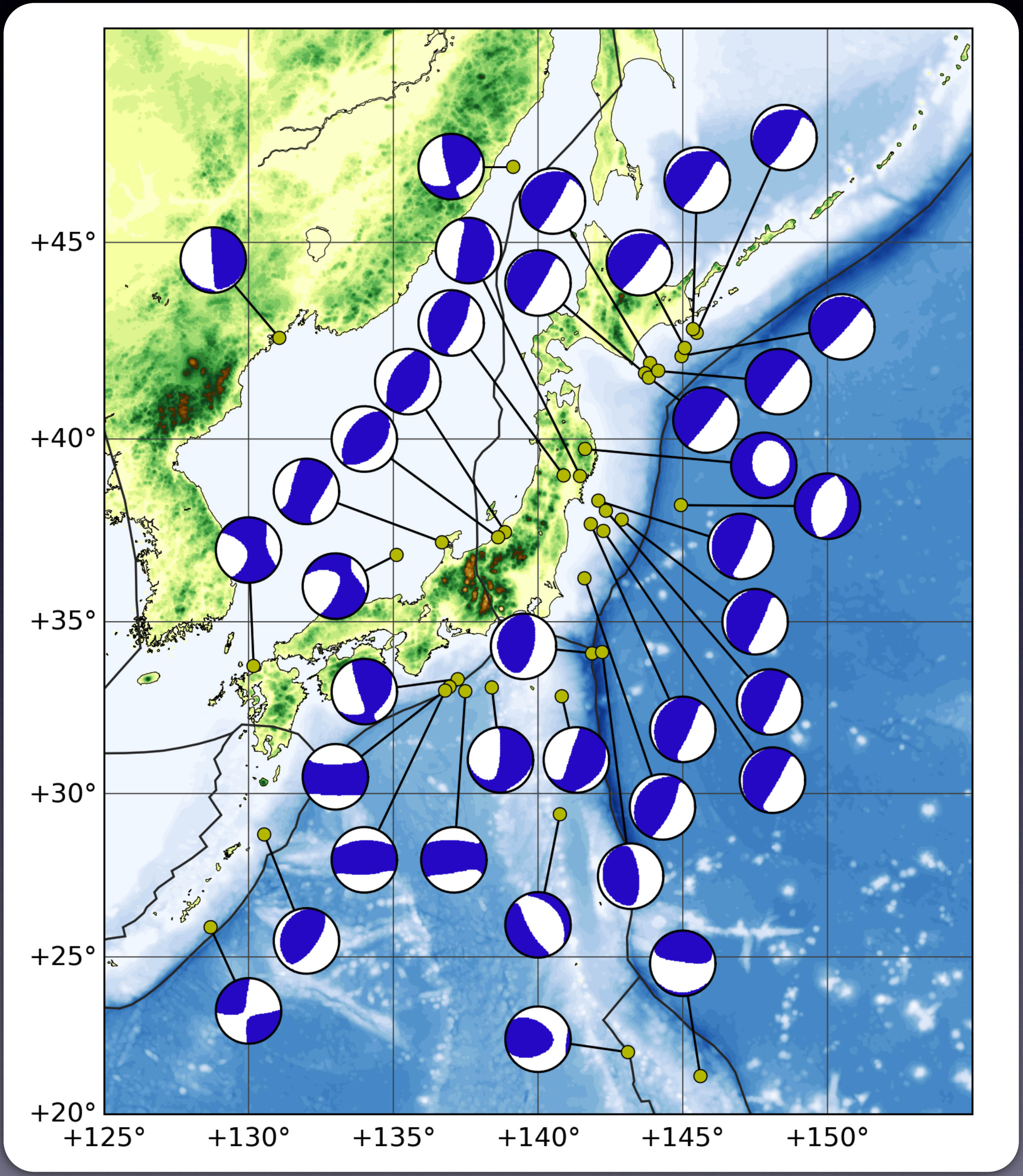


Focal Mechanisms- regional W Phase - 2/3
Japan - T ~ 12 min - Δ ≤ 25°



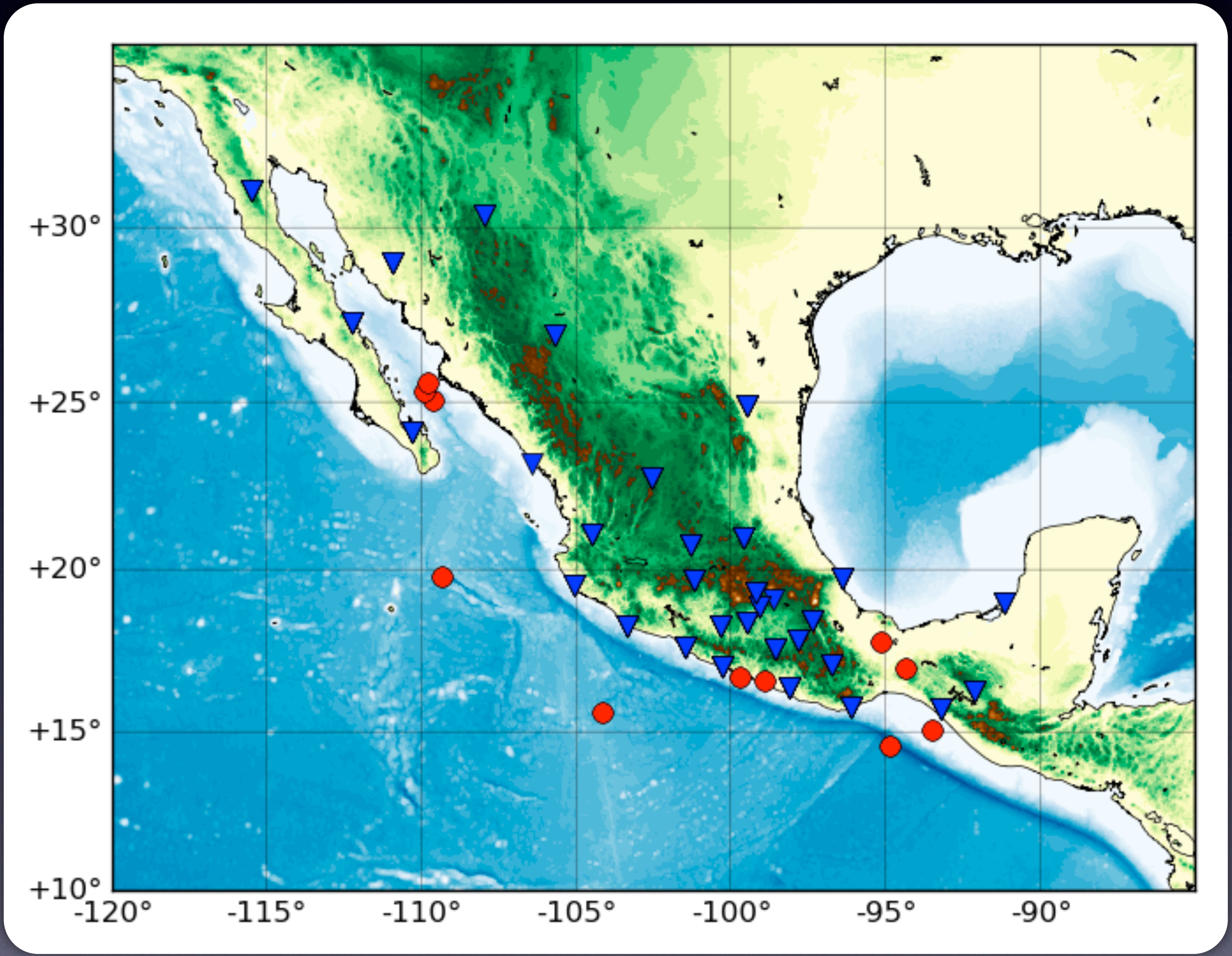
Focal Mechanisms- regional W Phase - 3/3
Japan - T ~ 12 min - $\Delta \leq 25^\circ$





Regional Scale - Mexico (UNAM)

Real time results - M_{SSN}>5.0



Mexican seismological network

- Broad band stations (STS2)

Preliminary location provided by the Nationa Seism. Service (SSN)

Wphase source inversion: $\Delta \leq 25°$ (T ~ 12min)

Implemented since October 2010

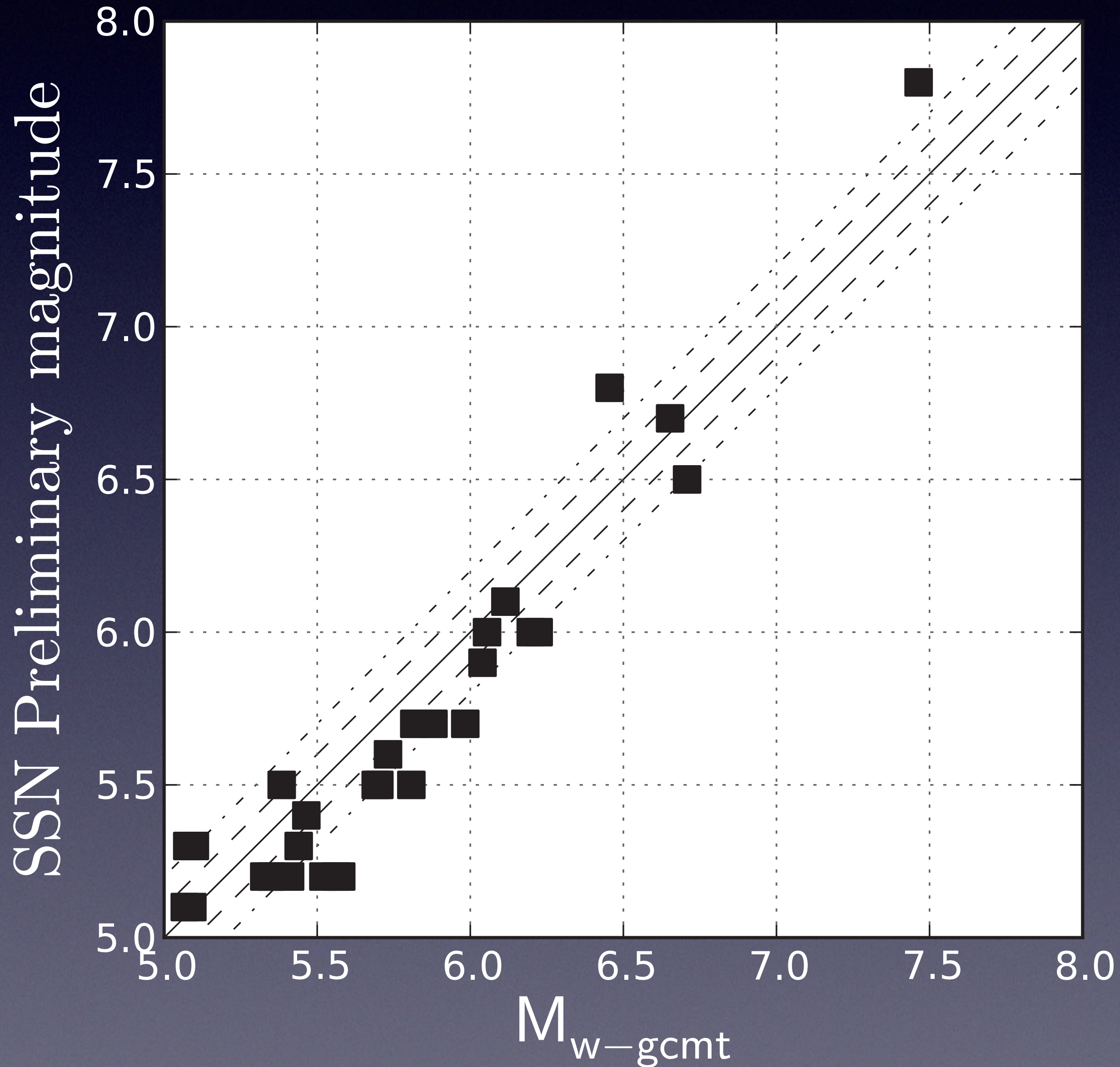
Collaborations: A. Iglesias Mendoza, X. Pérez Campos

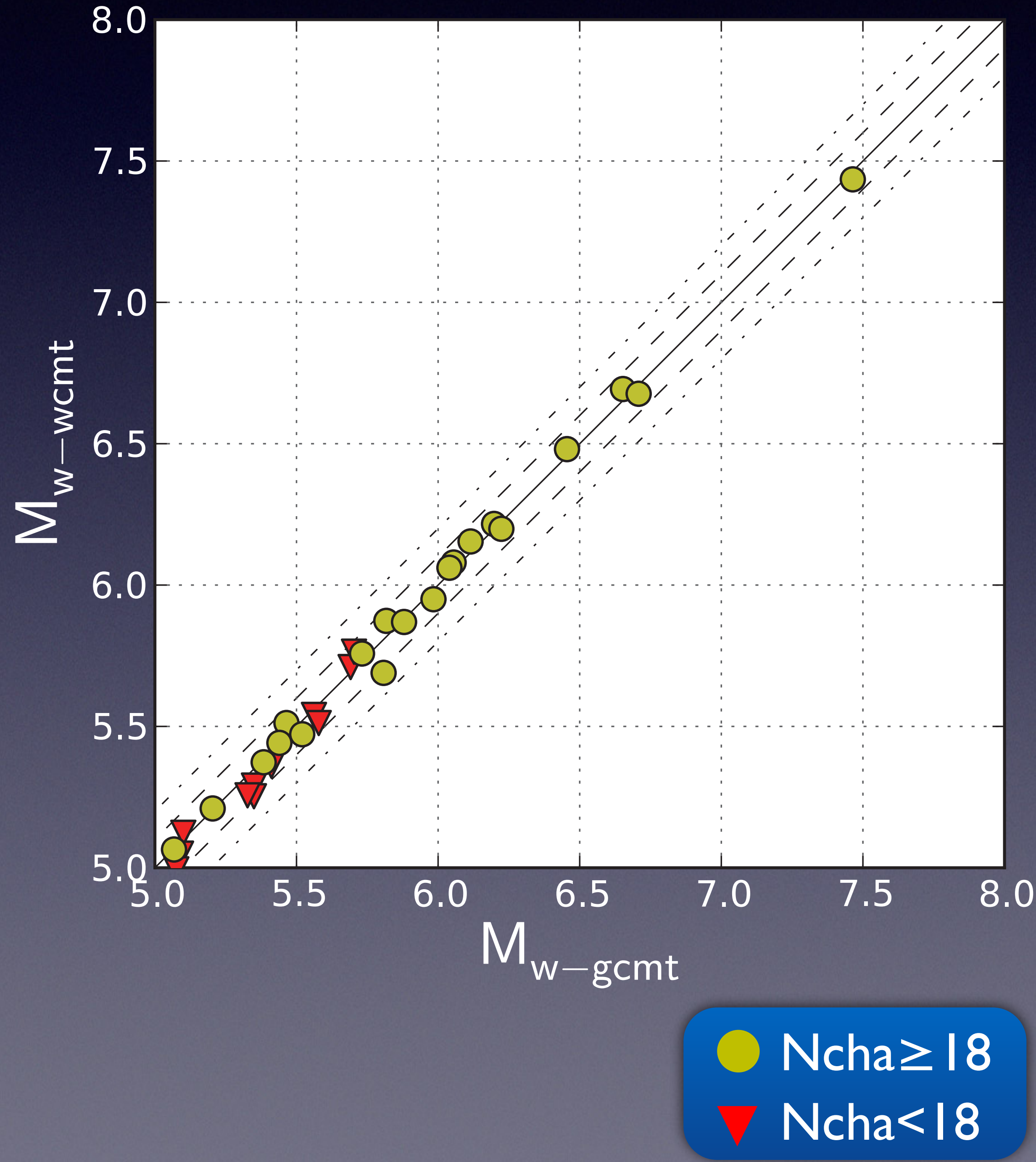
UNAM: Universidad Nacional Autónoma de México
SSN : Servicio Sismológico Nacional

Regional scale - Real-time results
Mexico - M_{SSN}>5.0

Moment magnitude

Earthquakes: 10/2010 - 08/2012

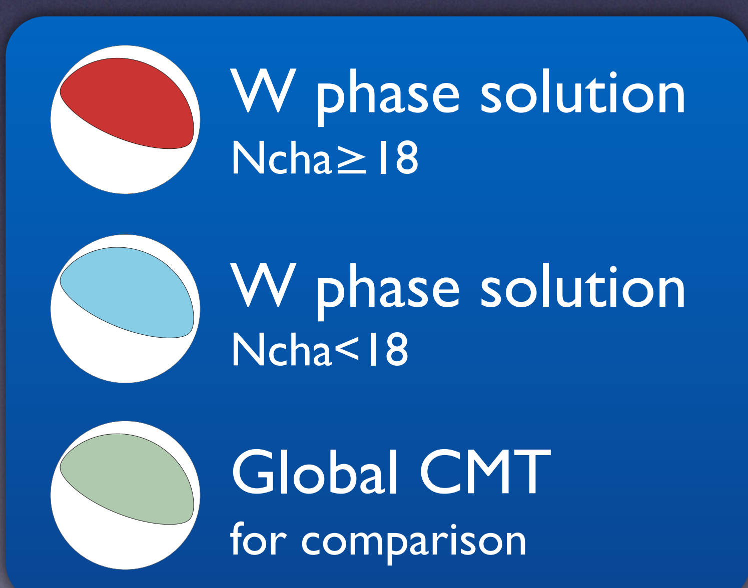


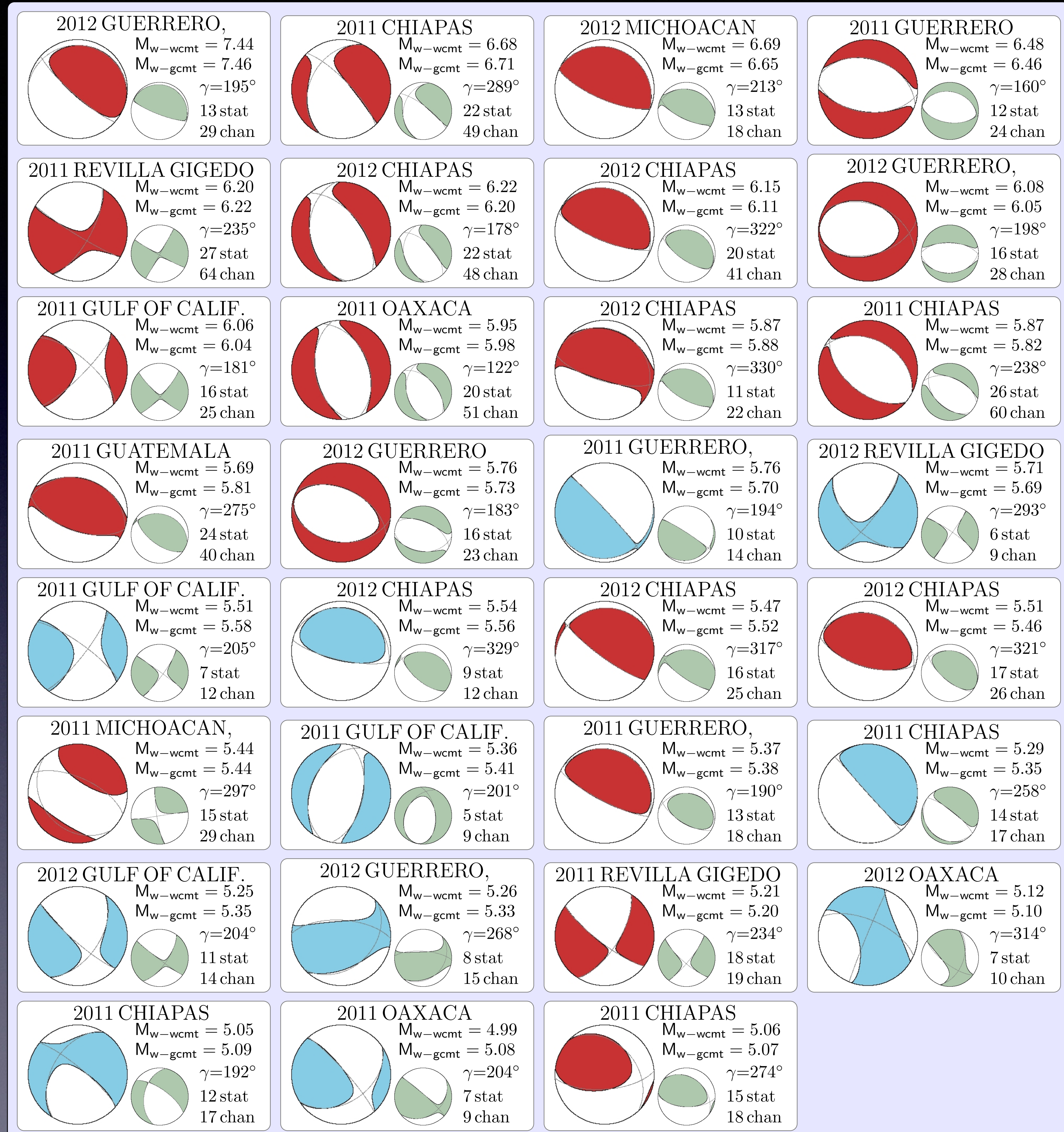


Real-time results
Mexico - M_{SSN}>5.0

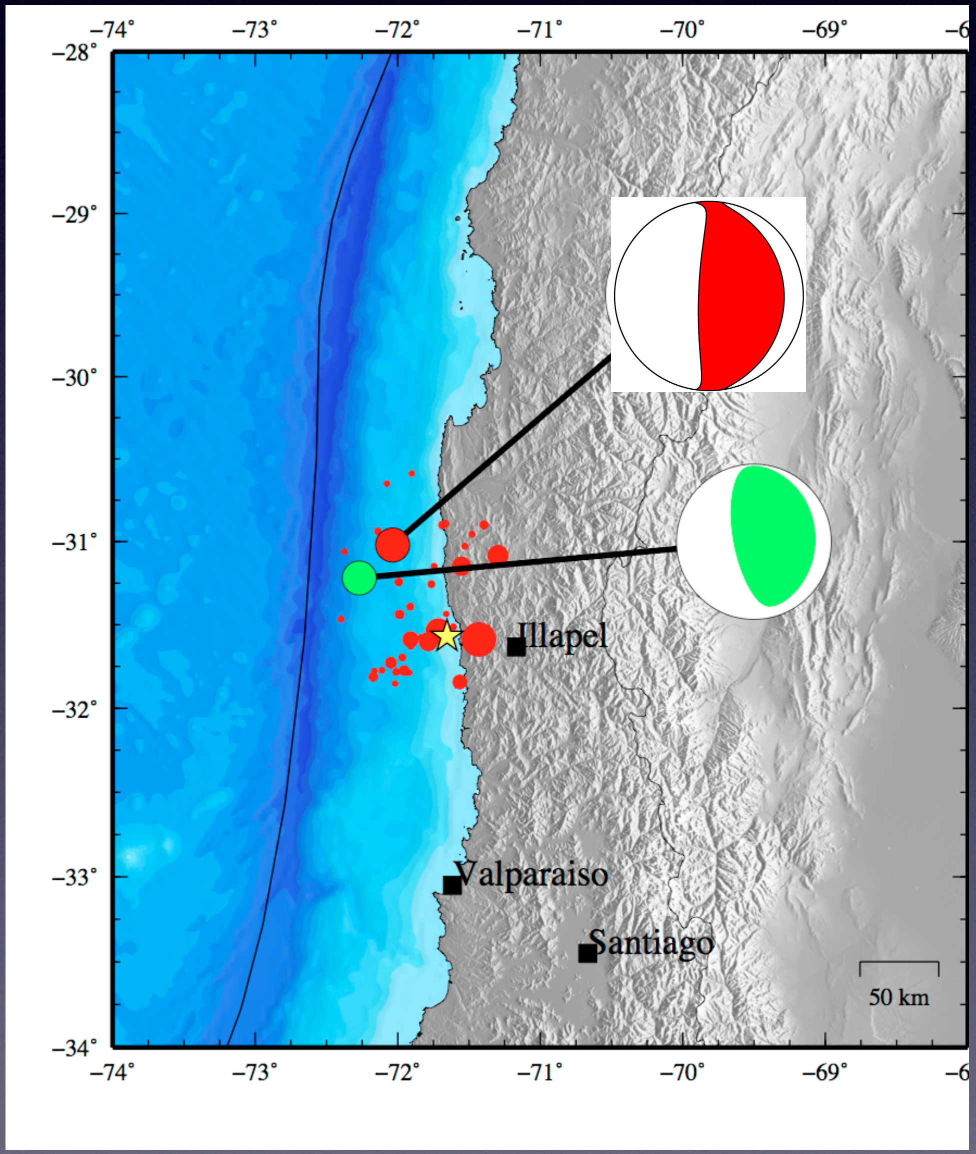
Focal Mechanisms

Earthquakes: 10/2010 - 08/2012





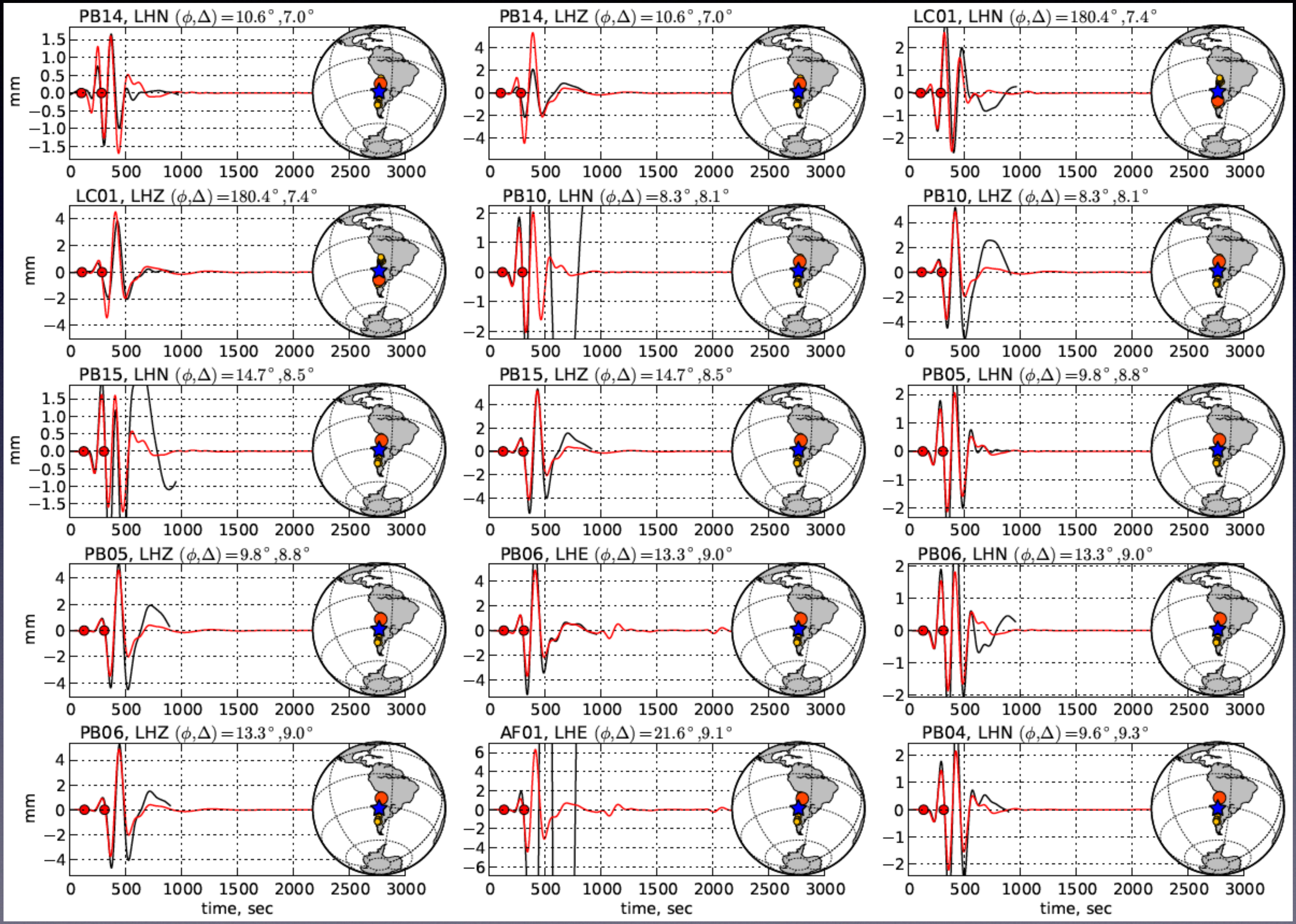
Norte de Chile, septiembre 2015
Solución a T.O. + 5 min



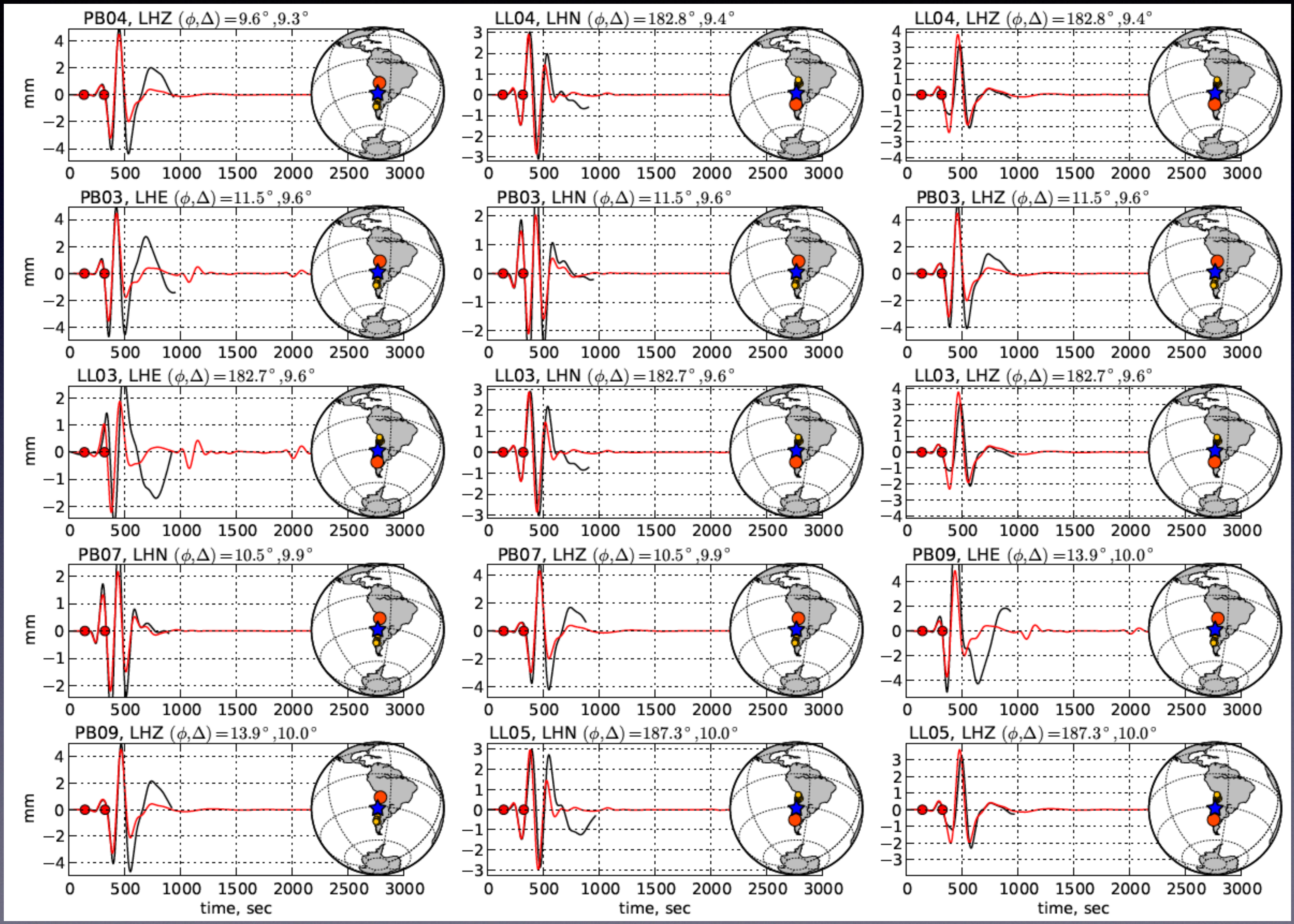
WCMT (Mw 8.4)

GCMT (Mw 8.2)

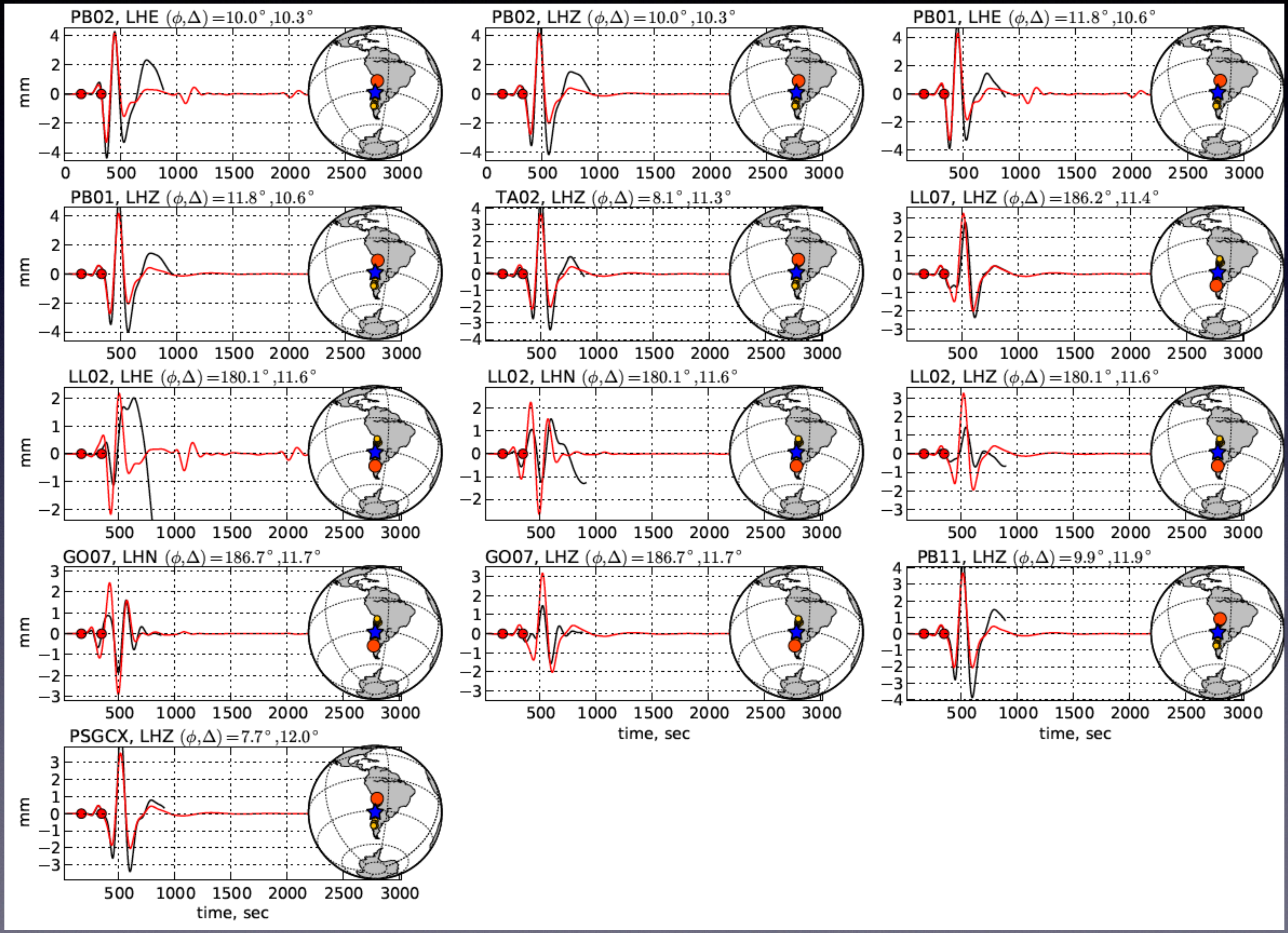
Norte de Chile, septiembre 2015
Solución a T.O. + 5 min



Norte de Chile, septiembre 2015
Solución a T.O. + 5 min



Norte de Chile, septiembre 2015
Solución a T.O. + 5 min



Global scale - Real time implementation

Tohoku-oki 11-03-2011 (Mw=9.0)

Delay, min	Origin	Magnitudes
5	PTWC Mwp Magnitude	7,5
10	PTWC Public Release	7,9
13	ATWC Public Release	7,9
19	USGS Public Release	7,9
20	USGS W Phase (internal)	9
22	PTWC W Phase (internal)	8,8
38	Coordinated Magnitude Update USGS+PTWC+JMA (from W Phase at PTWC)	8,8
65	Magnitude Update, USGS public release (from W Phase at USGS)	8,9

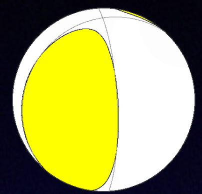
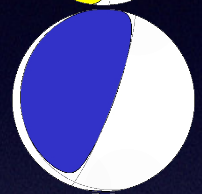
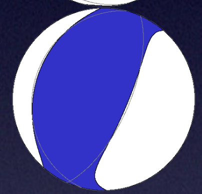
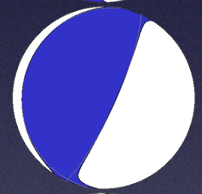
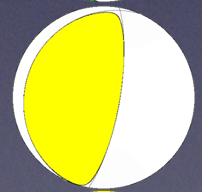
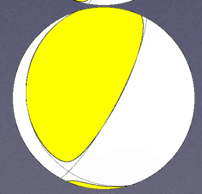
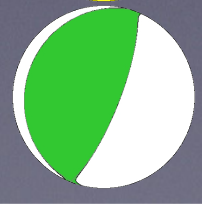
Preliminary magnitudes (Mwp, ...)

W phase magnitudes

PTWC: Pacific Tsunami Warning Center
ATWC: Alaska Tsunami Warning Center
USGS: United States Geological Survey
JMA: Japan Meteorological Agency

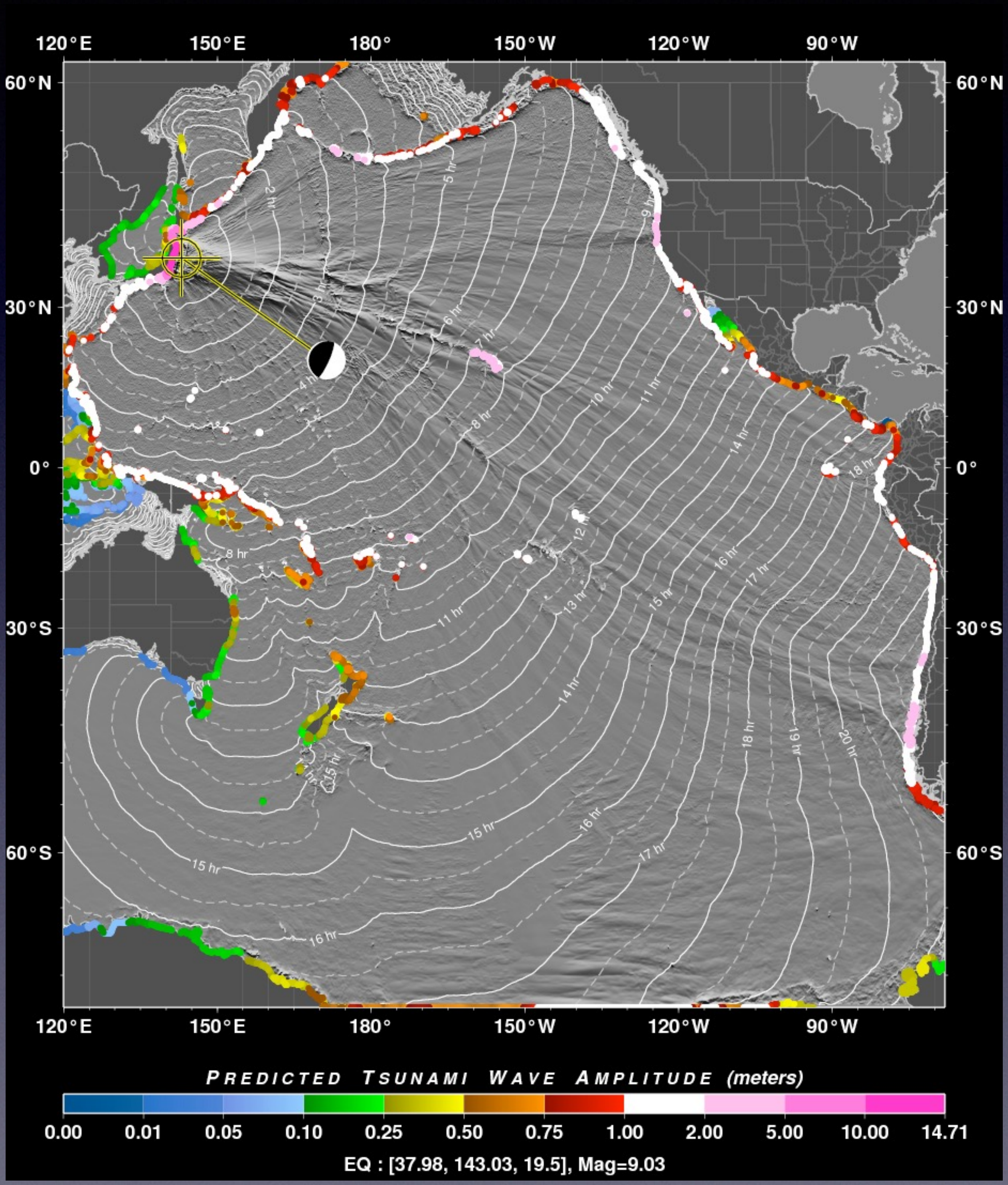
Global scale - Real time results

Tohoku-oki 11-03-2011 (Mw=9.0)

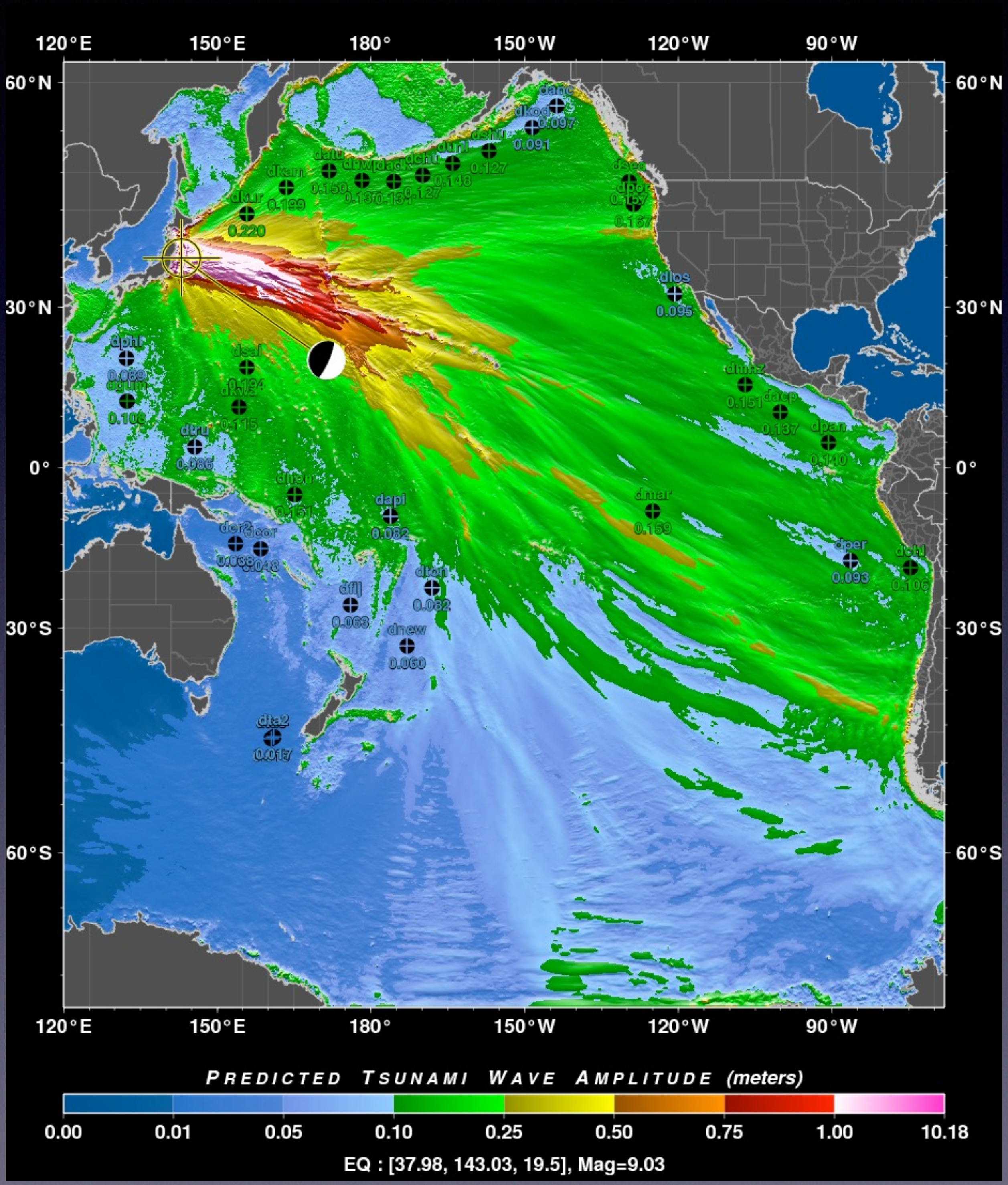
Delay	Origin	M_w	Dip, deg	Depth, km	# chan.	Mech.
20min	USGS	9	16,8	24,4	6	
22min	PTWC	8,8	10,3	83,5	29	
30min	PTWC	8,8	22,8	83,5	74	
40min	PTWC	9	11,1	24,4	105	
45min	IPGS	9	10,8	24,4	31	
48min	USGS	8,9	14,8	24,4	74	
1h02min	USGS	8,9	16,9	24,4	89	
1h30min	IPGS	9	14,4	24,4	146	

Tsunami modelisation from W-Phase CMT

(Dailin Wang, PTWC)



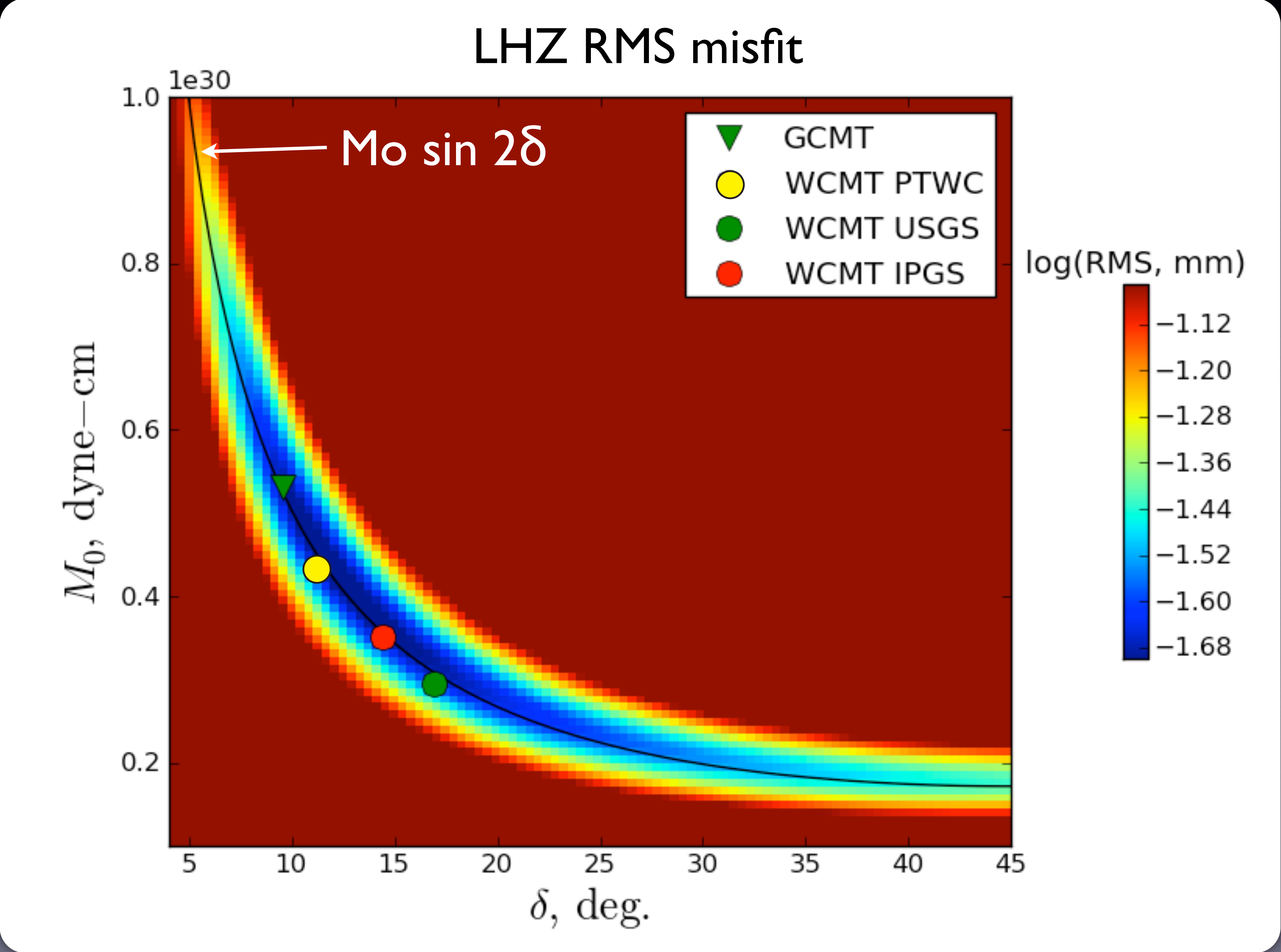
Coastal Maximum amplitudes



Maximum Wave amplitudes

Global scale - Real time results

Tohoku-oki 11-03-2011 (Mw=9.0)



GCMT: Global CMT
WCMT: W-phase CMT

Tohoku-oki 11-03-2011 (Mw=9.0)
Post-Mortem results - Dip-Mo trade-off

Two approaches for reducing the dip-Mo:

I

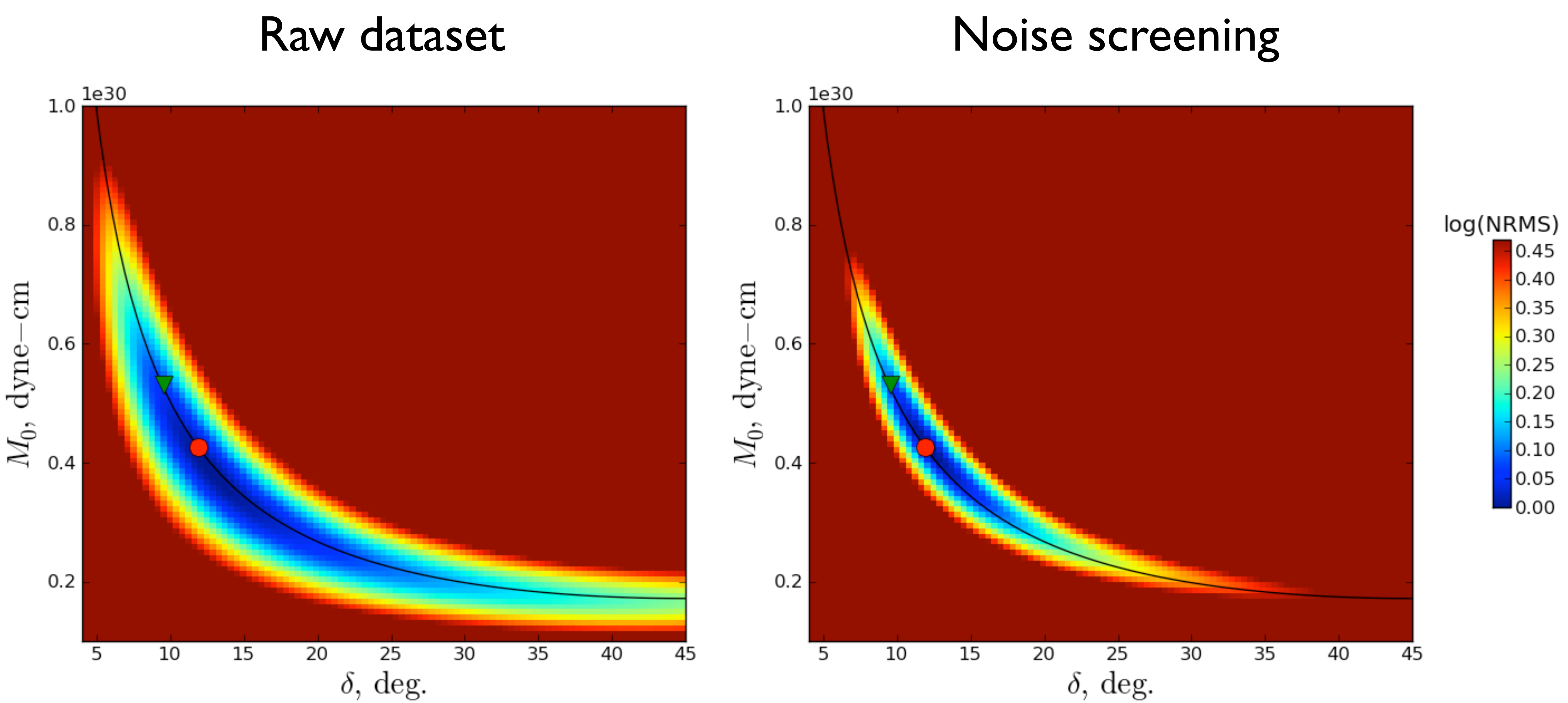
Improving the S/N ratio
Importance of 3 components of displacement

II

Using the a available prior information on the interface geometry.
cf: Gavin Hayes et al., G^3 (2009)
Tsai et al., GRL (2011)

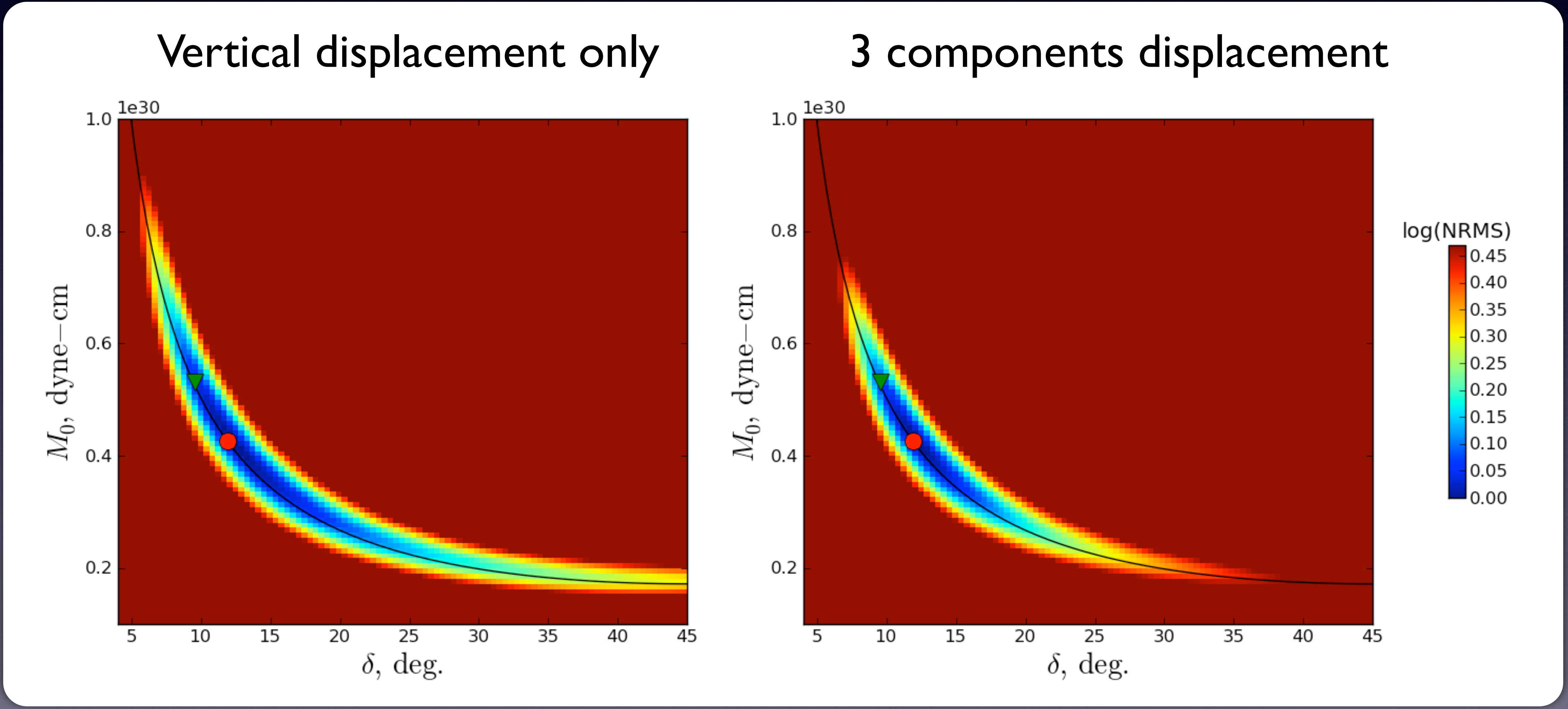
Post-mortem results
I. Improving the S/N ratio

Pre-event (3h) nois level data selection



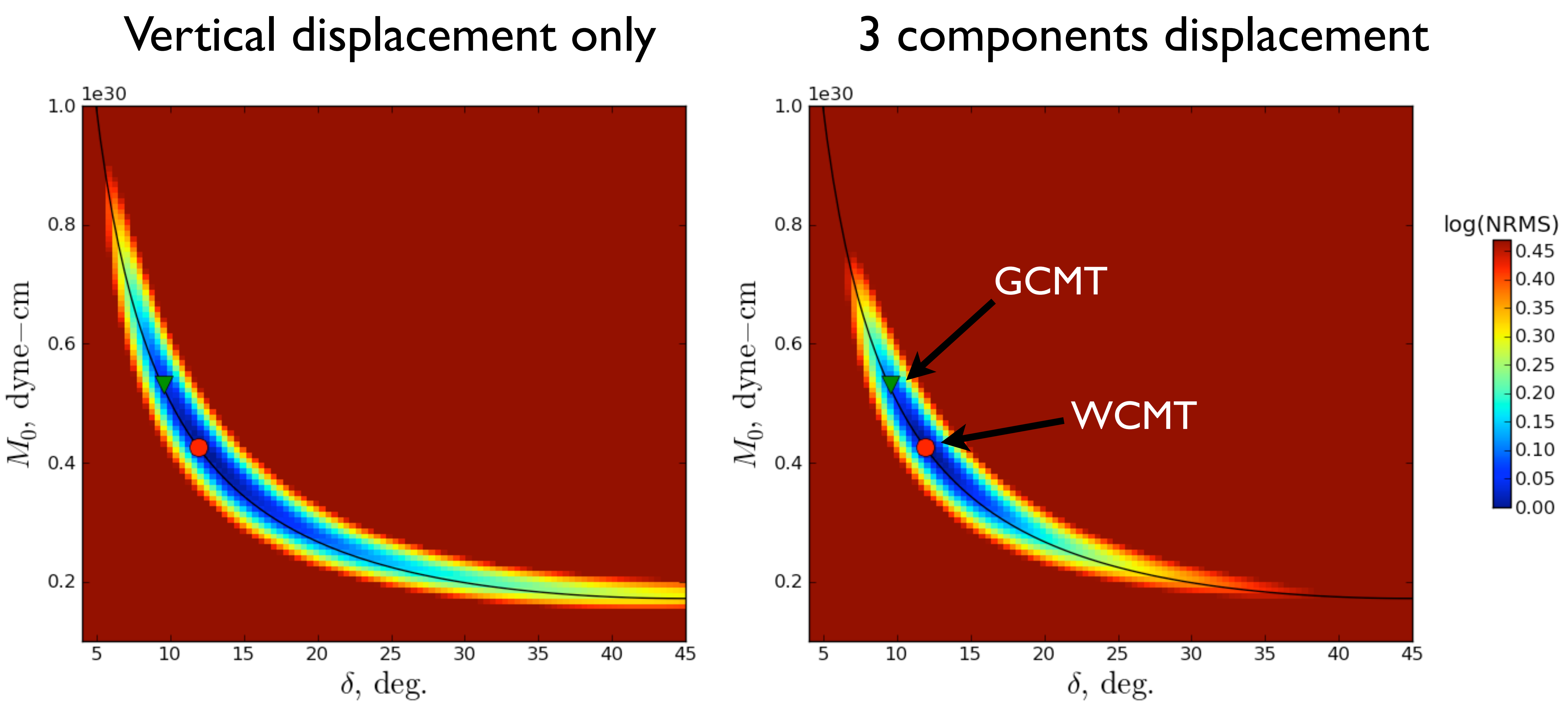
Post-mortem results
I. Improving the S/N ratio

Using 3 components of displacement



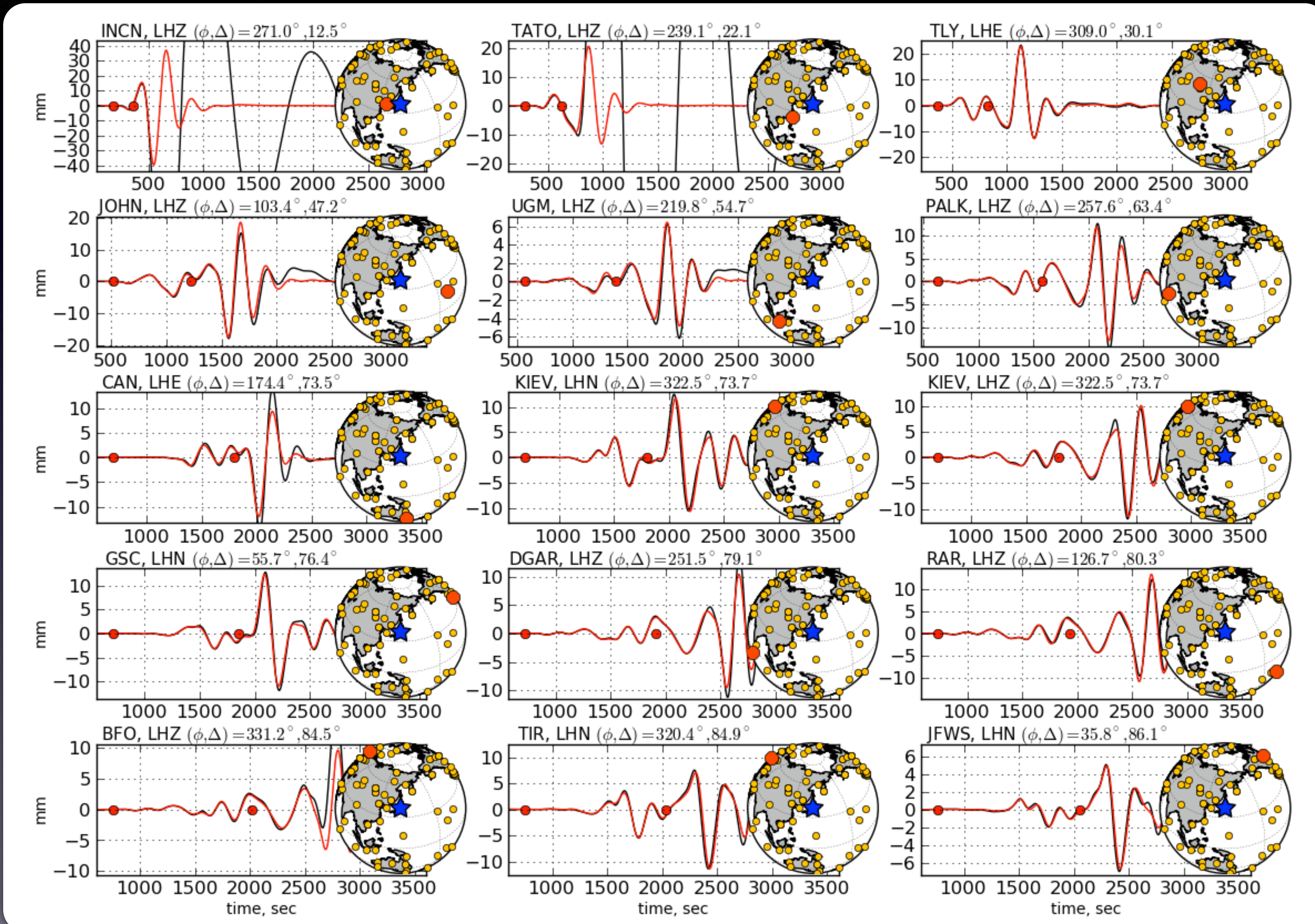
Post-mortem results
I. Improving the S/N ratio

Using 3 components of displacement



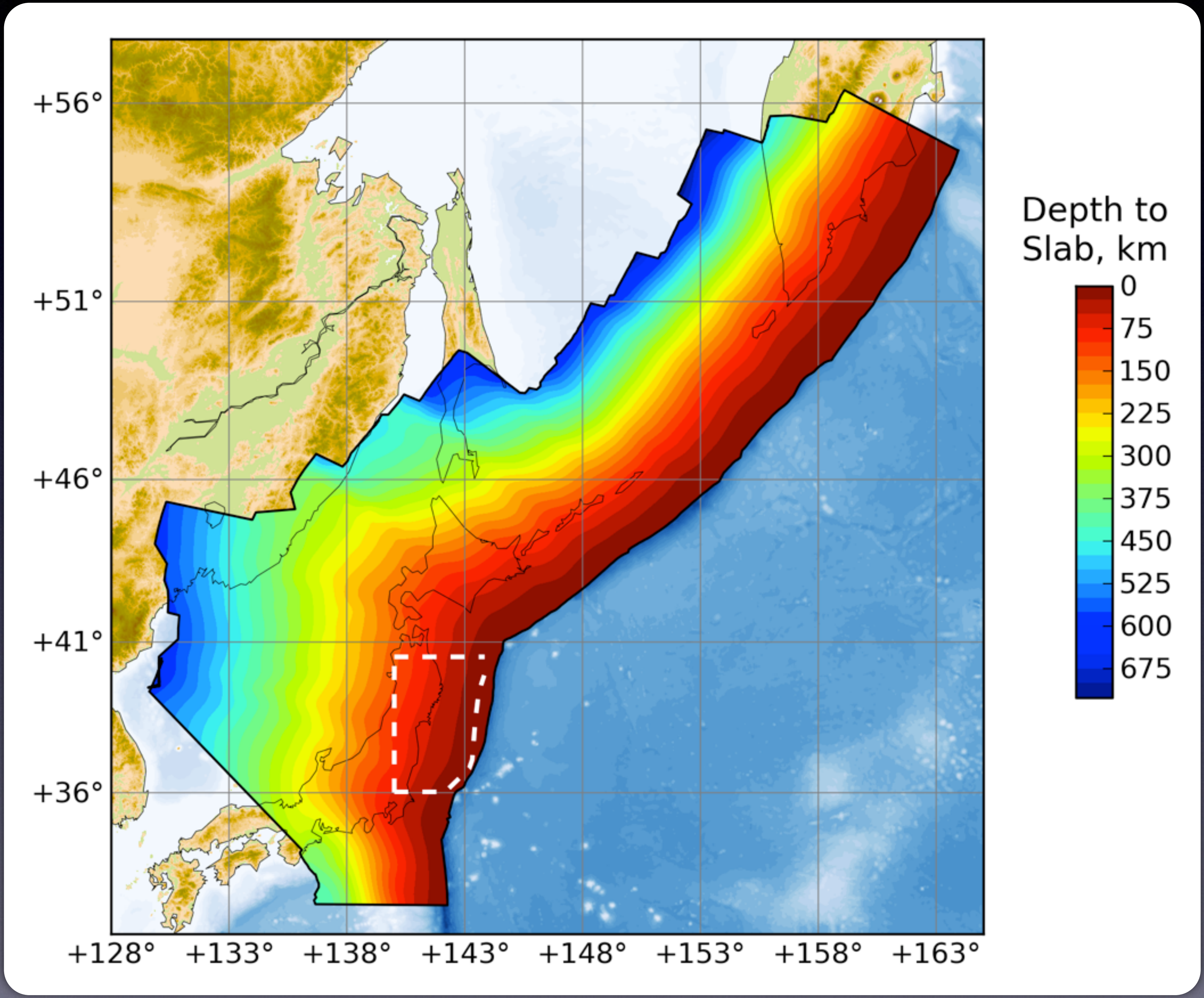
Post-mortem results

I. Improving the S/N ratio



Post-mortem results

II. Using prior information on the interface geometry



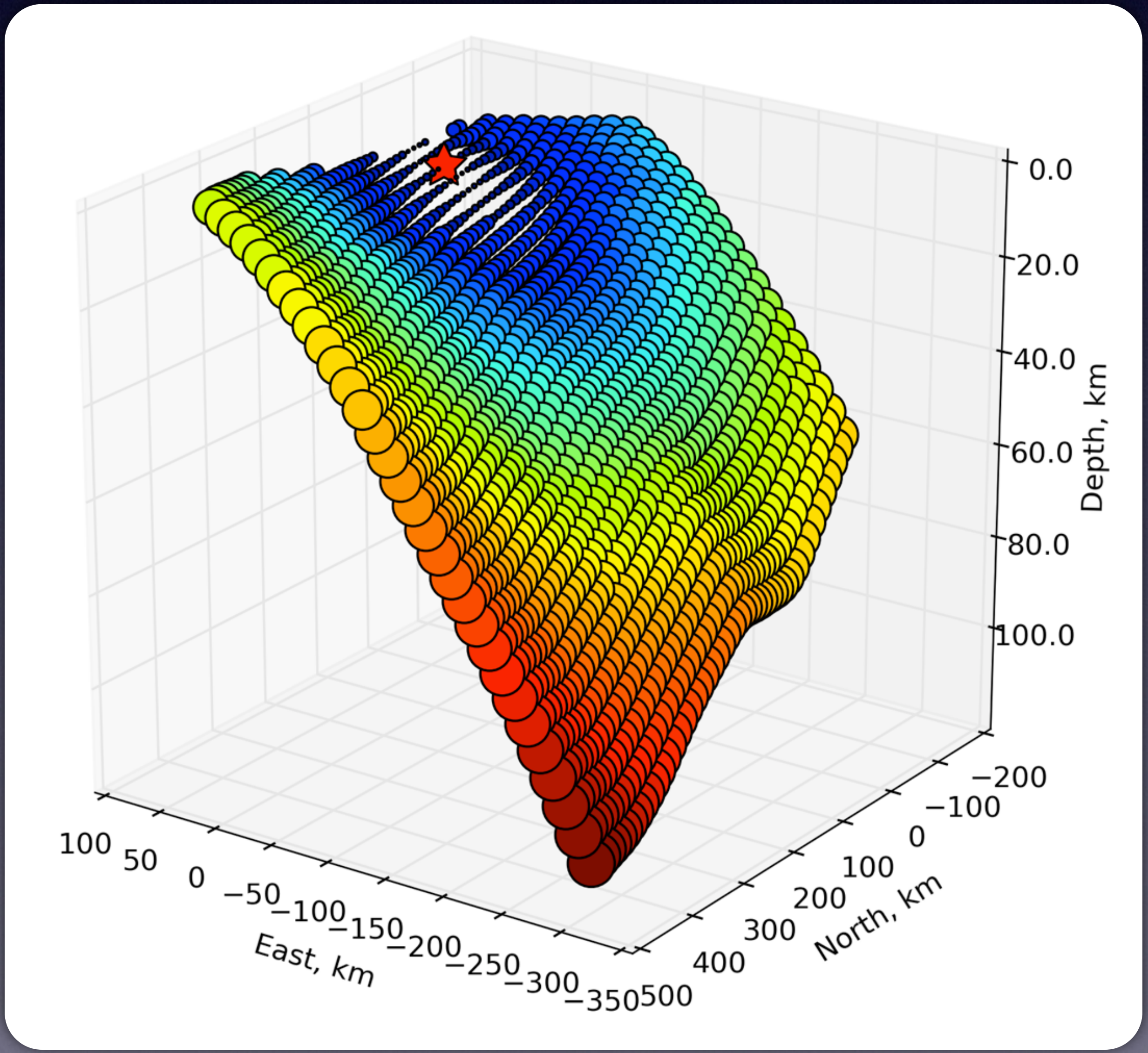
Hayes et al., 2009

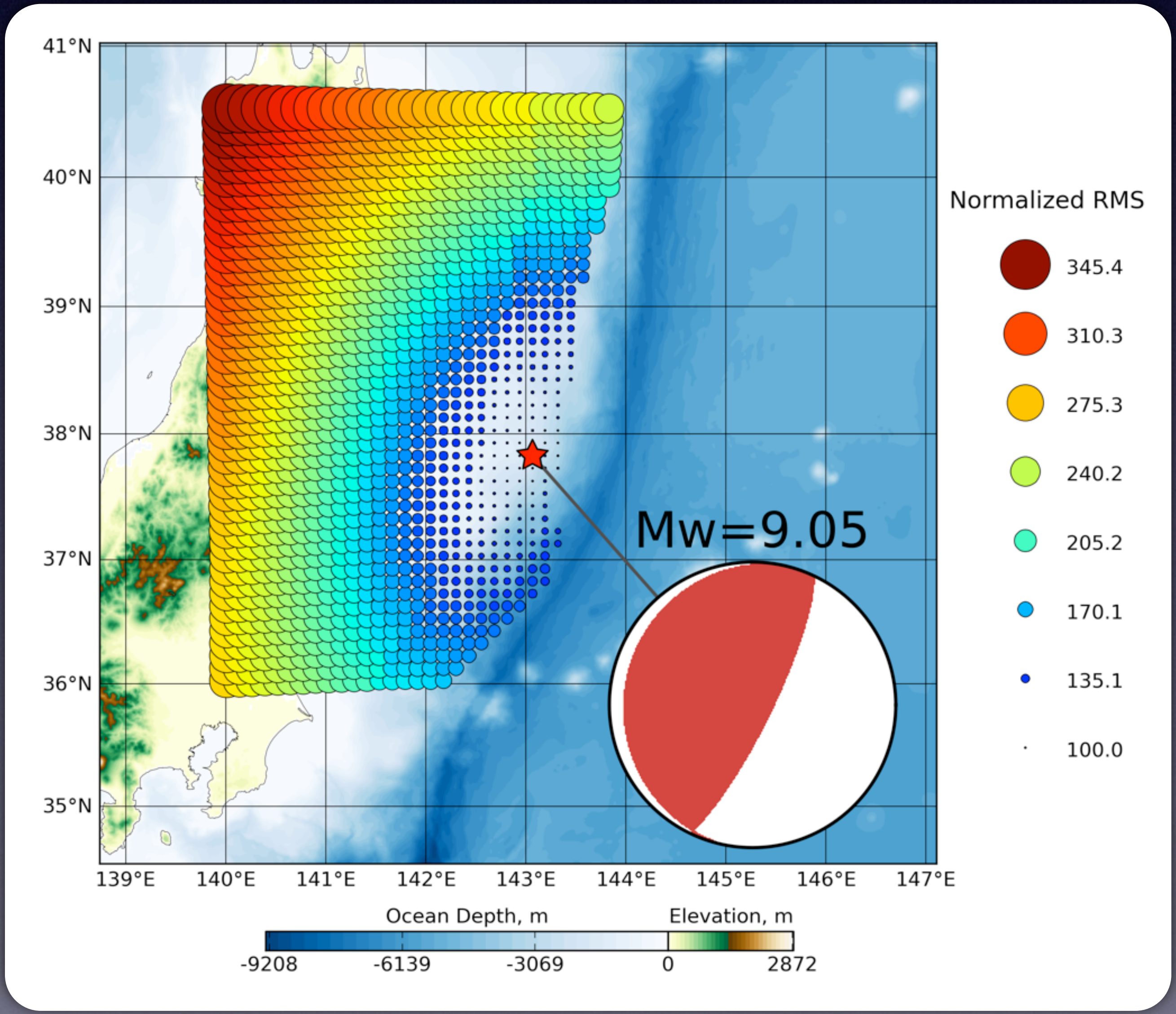
Post-mortem results

II. Using prior information on the interface geometry

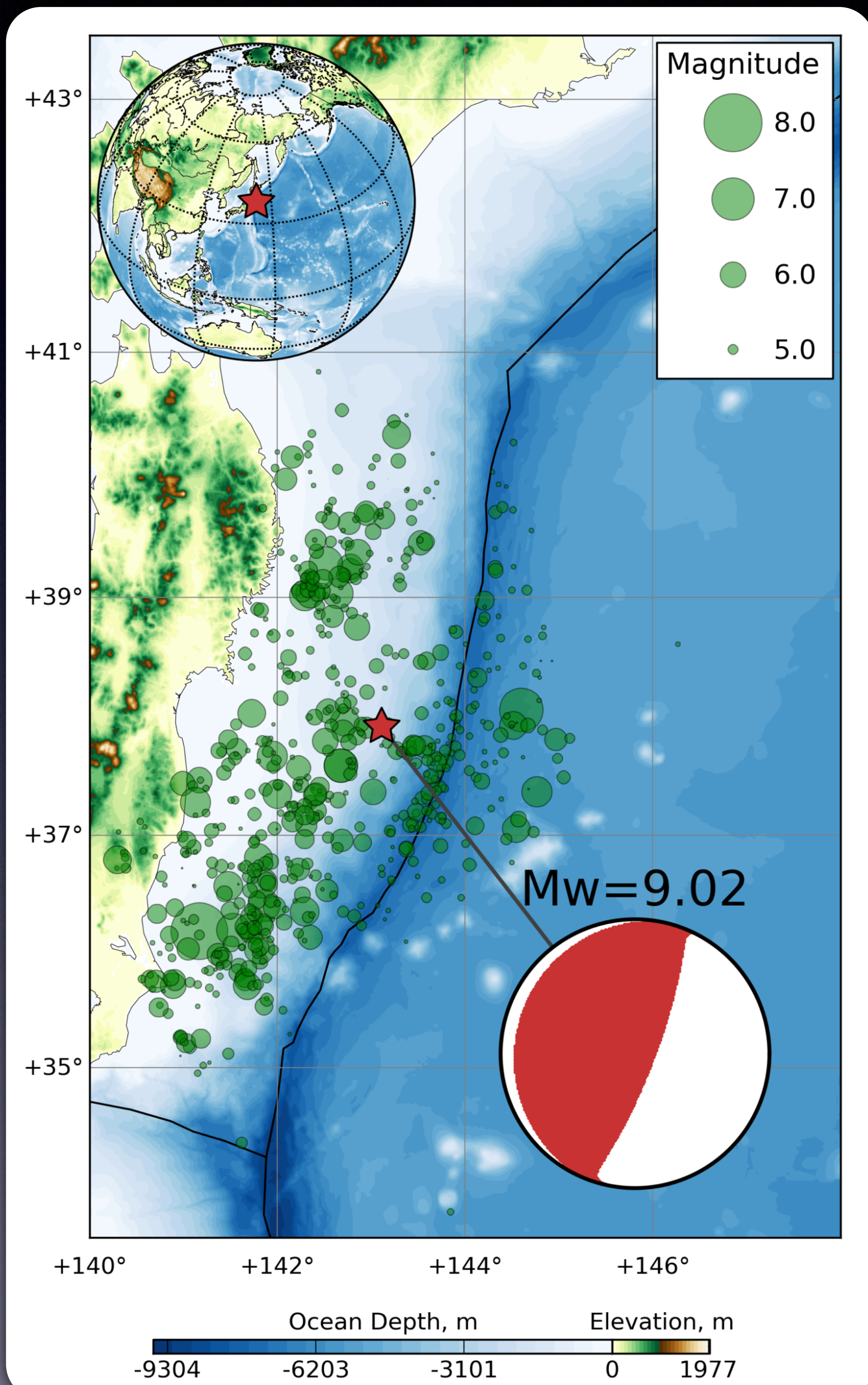
- At any point on the interface we perform a constraint inversion by fixing the dip (Non linéar problem: strike, rake et Mo).

- We search an optimal centroid location on the interface by 2D-grid-search.





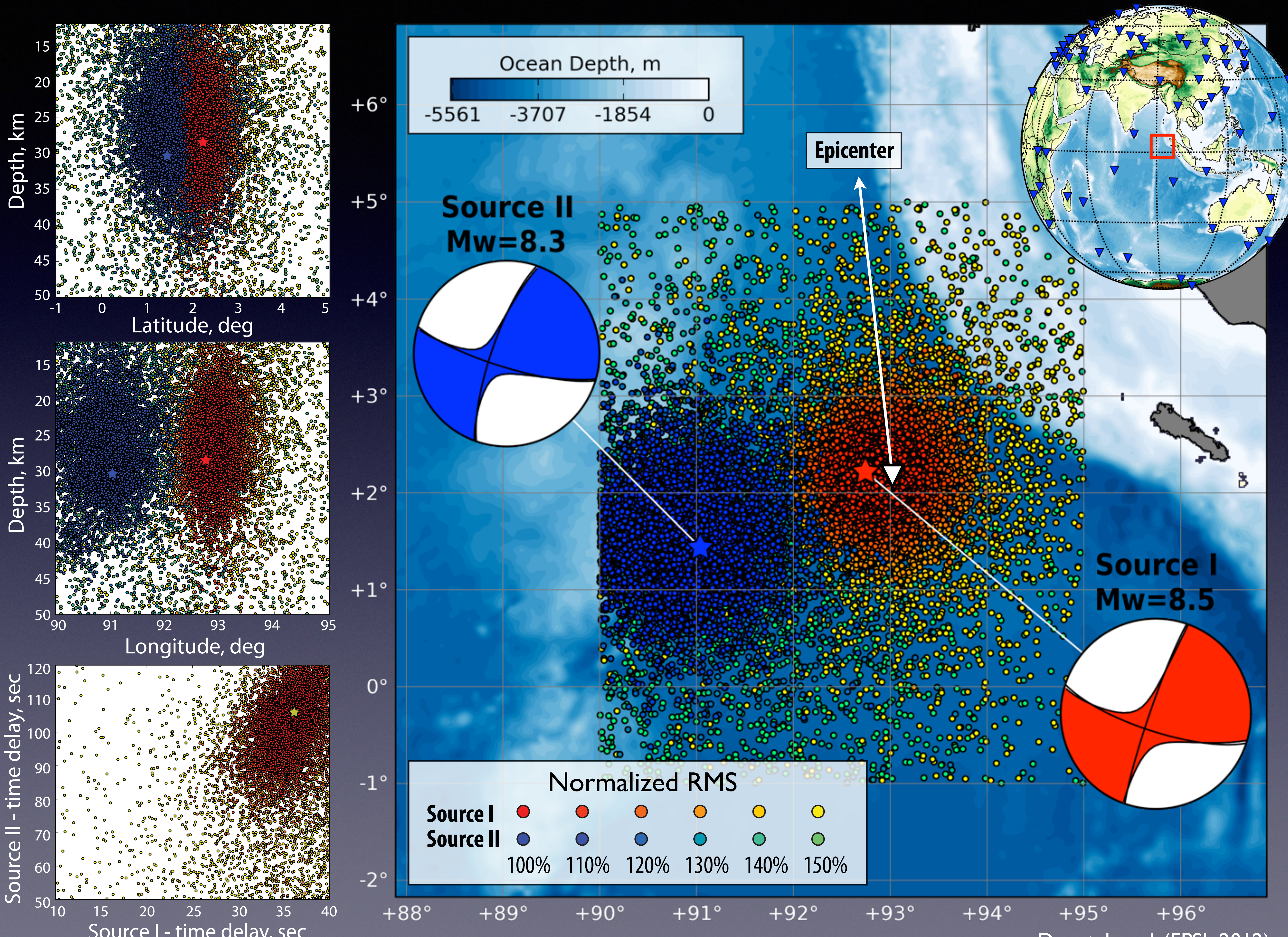
Post-mortem results
I. Improving the S/N ratio




```
Mw:  9.02
Centroid Location:
             latitude  = 37.92°N
             longitude = 143.11°E
             depth     = 19.5 km

Centroid Timing:
             Time delay    = 68.0 sec
             Half duration = 68.0 sec

Moment tensor: scale= 1.0E+29 dyn.cm
rr= 1.695 ; tt=-0.147 ; pp=-1.548
rt= 1.403 ; rp= 3.637 ; tp=-0.534

Principal Axes:
1.(T) Val= 4.242 ; Plg= 57° ; Azm=292°
2.(N)      0.031 ;       1° ;     201°
3.(P)     -4.273 ;      33° ;     110°

Best Double Couple: M0=4.26E+29 dyn.cm
NP1: Strike=196° ; Dip=12° ; Slip= 85°
NP2: Strike= 21° ; Dip=78° ; Slip= 91°

Fit Quality: 96 channels (69 stations)
             RMS  = 0.195 mm
             NRMS = 0.164
             GAP  = 31.6°
             C#   = 117
```

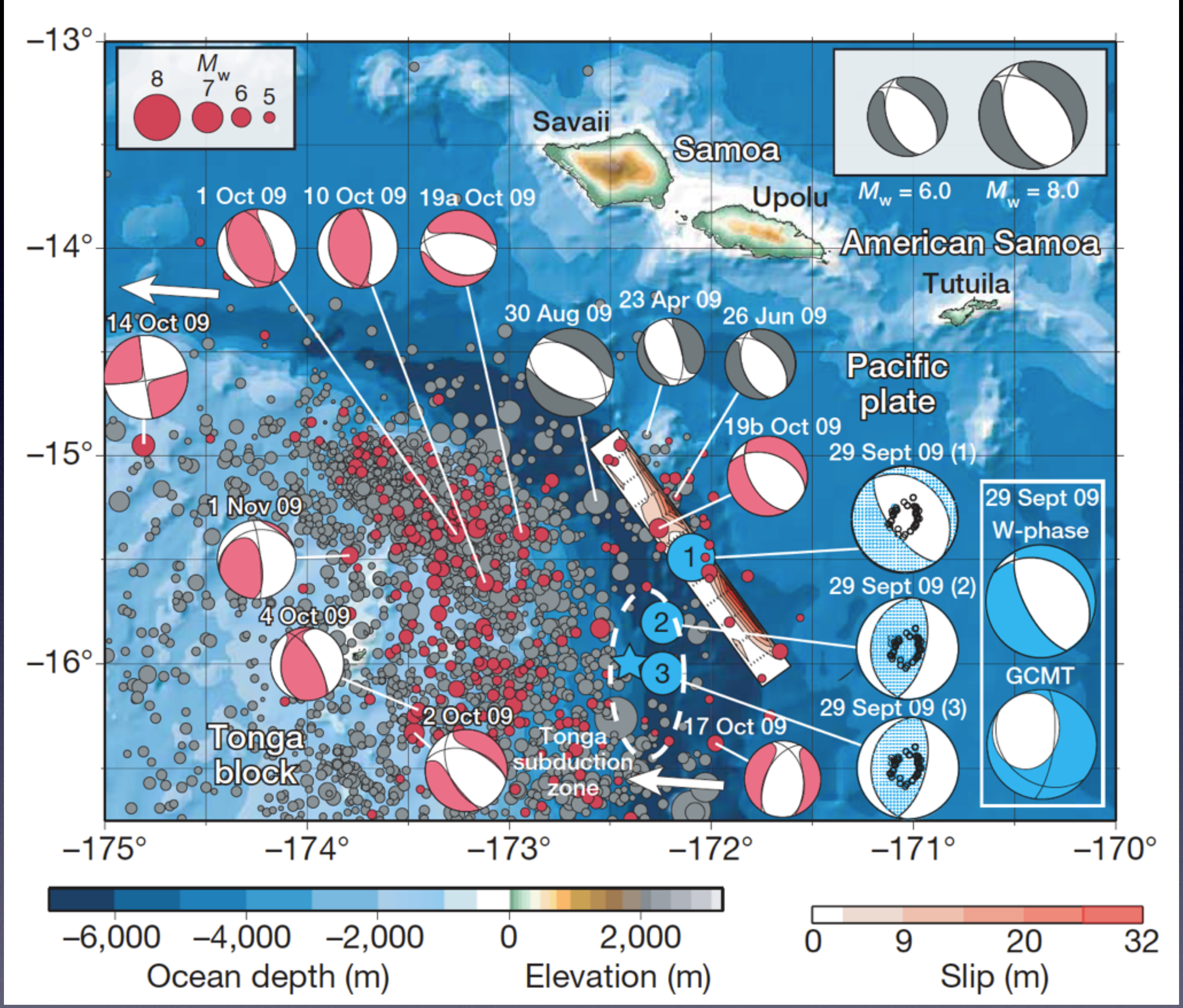
Some special events

Multiple-point-source analysis: 2012 off-Sumatra mainshock



Duputel et al. (EPSL 2012)

The Samoa 2009 doublet

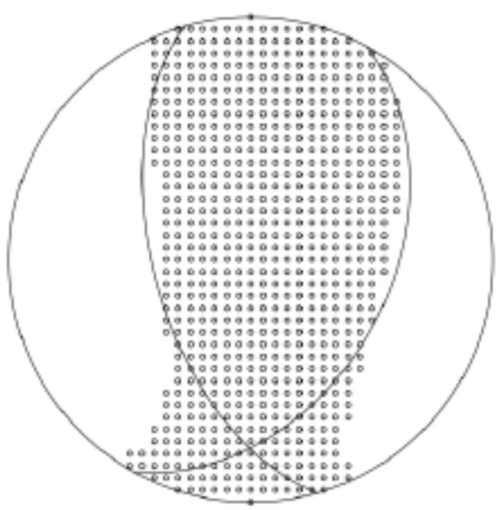


Lay et al., Science, 2010

Honshu-December 7, 2012 doublet (dt = 12 s)
W phase double source inversion

Inversion using F-NET+GSN

Honshu 2012 - Source I

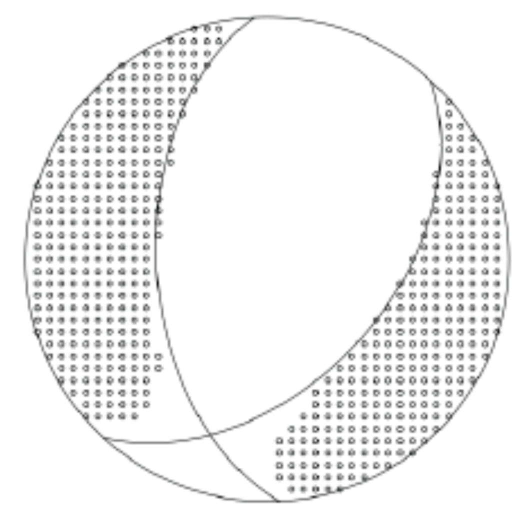


WCMT, Mw= 7.15

Moment Tensor: 0.04892 0.02566 -0.07458 0.01209 -0.01858 -0.00856
Scalar moment: 6.75e+26 dyn cm (Mo_12 = 1.65e+27 dyn cm)
Best Nodal planes (strike/dip/rake): NP1: 28.6/ 42.2/ 126.0
NP2: 164.2/ 57.0/ 61.9
Eigenvalues: 0.05724 0.02052 -0.07775 (Mw = 7.15)
Fit Quality: RMS: 0.00690 mm (0.308)
GAP: 38.1°, C# 635

h = 60 km

Honshu 2012 - Source II



WCMT, Mw= 7.10

Moment Tensor: -0.04421 -0.00660 0.05081 -0.01501 0.00942 0.02342
Scalar moment: 5.58e+26 dyn cm (Mo_12 = 1.36e+27 dyn cm)
Best Nodal planes (strike/dip/rake): NP1: 42.6/ 48.0/ -55.7
NP2: 177.0/ 52.1/ -122.1
Eigenvalues: 0.05930 -0.00695 -0.05235 (Mw = 7.10)
Fit Quality: RMS: 0.00690 mm (0.308)
GAP: 38.1°, C# 635

h = 20 km

Central Italy, August 24 2016

M6.2 - 10km SE of Norcia, Italy

2016-08-24 01:36:33 UTC | 42.714°N 13.172°E | 10.0 km depth

Moment Tensor

View alternative moment tensors (4 total)

Contributed by US[2] last updated 2016-08-24 02:03:13 (UTC)

✓ The data below are the most preferred data available
✓ The data below have been reviewed by a scientist

NEIC, USGS
Wphase solution

W-phase Moment Tensor (Mww)

Moment	2.450e+18 N-m
Magnitude	6.2 Mww
Depth	11.5 km
Percent DC	86 %
Half Duration	6 s
Catalog	US
Data Source	US[2]
Contributor	US[2]

Nodal Planes

Plane	Strike	Dip	Rake
NP1	328°	43°	-103°
NP2	165°	49°	-78°

Principal Axes

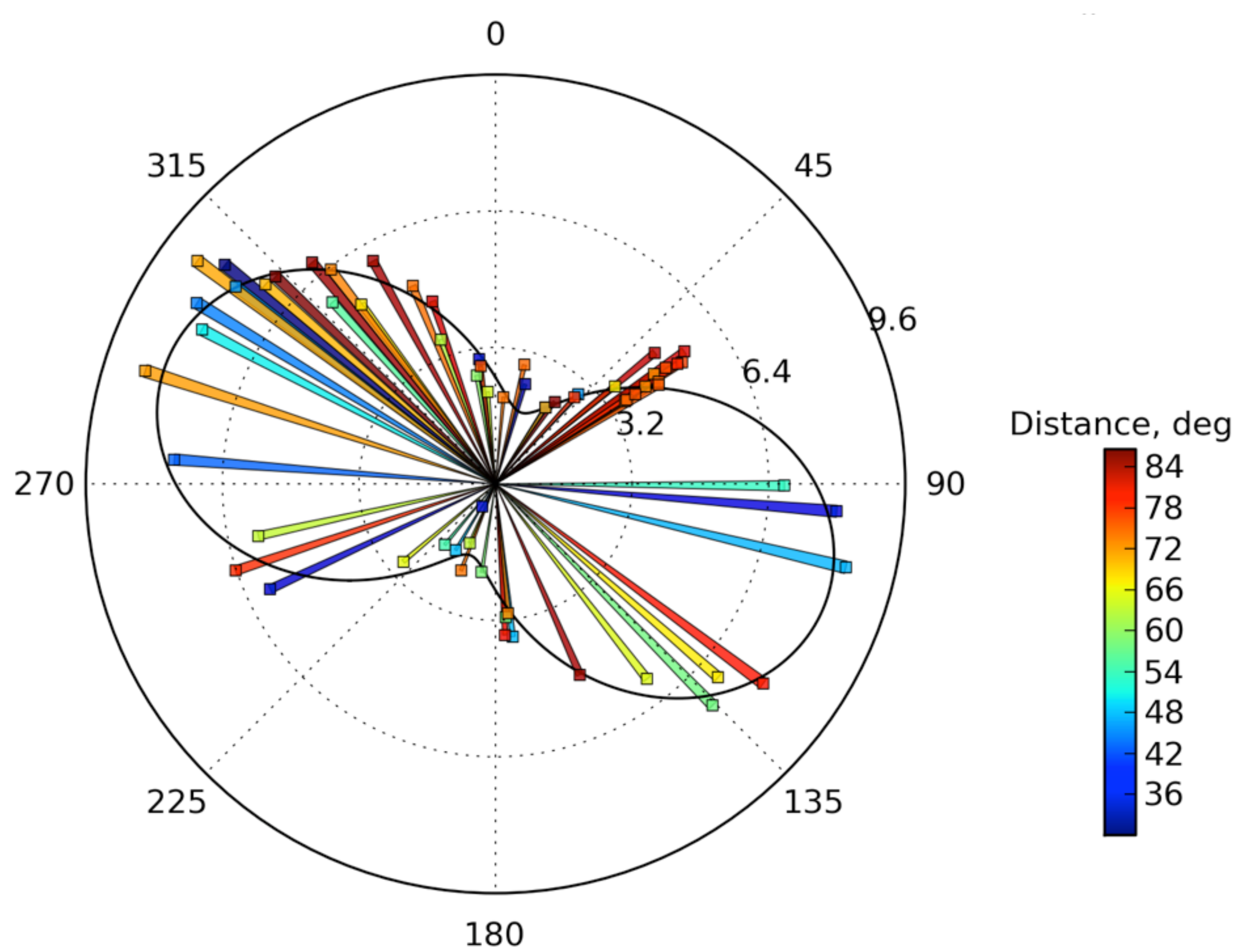
Axis	Value	Plunge	Azimuth
T	2.359e+18 N-m	3°	247°
N	0.172e+18 N-m	9°	337°
P	-2.531e+18 N-m	81°	140°

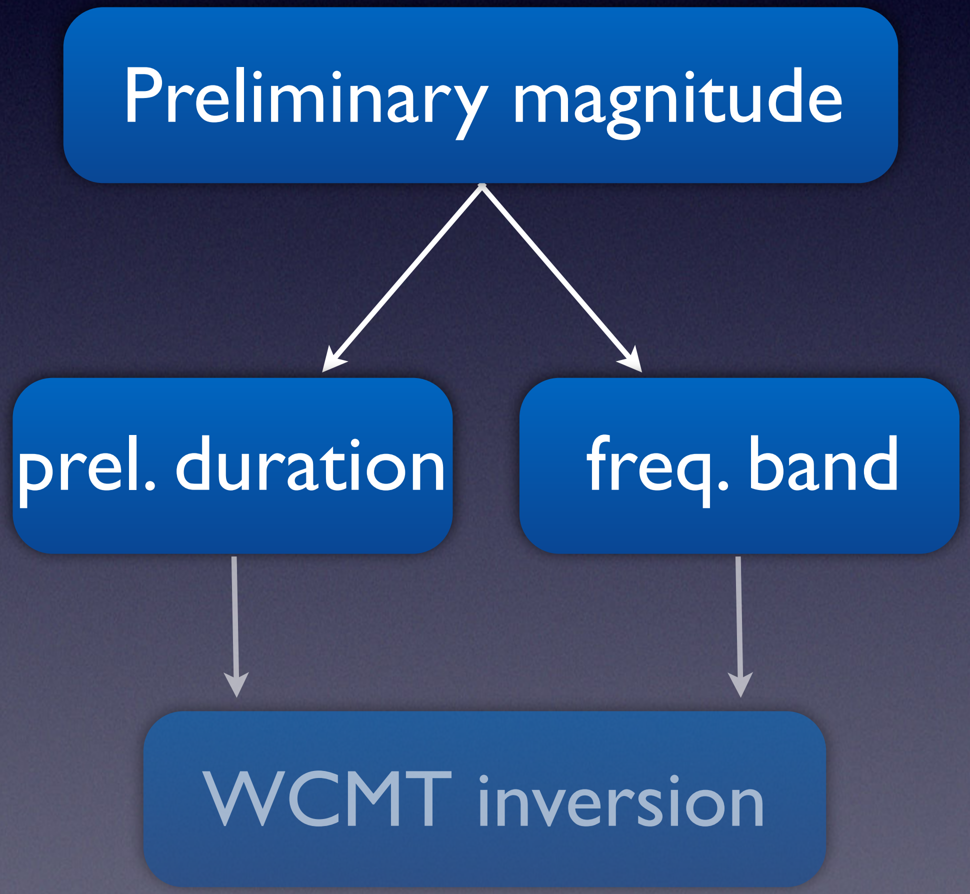
http://earthquake.usgs.gov/earthquakes/eventpage/us10006g7d#moment-tensor

Real-time preliminary magintude estimation

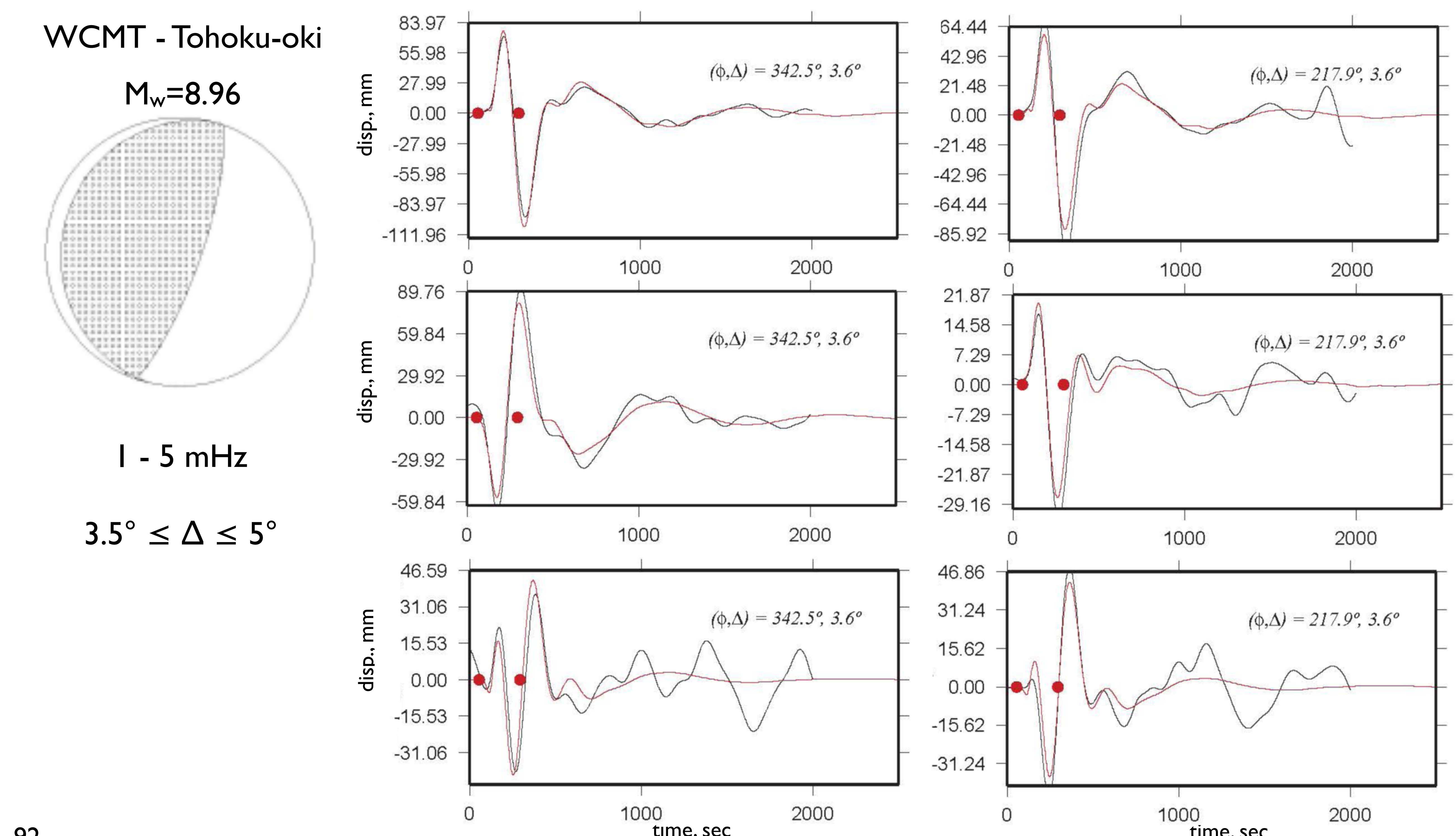
- Measuring the average W phase amplitude
- Allowing for some simple azimuthal variability (e.g. 2 lobes, pure thrust)

Example: Tohoku-oki 2011 : prel. Mw = 9.1





Regional W phase W: using continuous GPS
(T ~ 5 min if real time available data)



Uncertainty analysis for source inversions

- Simple case: linear - gaussian

  Problème direct: $\mathbf{d} = \mathbf{G}\mathbf{m}$

  Solution: $\widetilde{\mathbf{m}} = \left(\mathbf{G}^t\mathbf{C}_\mathrm{D}^{-1}\mathbf{G} + \mathbf{C}_\mathrm{m}^{-1}\right)^{-1}\left(\mathbf{G}^t\mathbf{C}_\mathrm{D}^{-1}\mathbf{d}_\mathrm{obs} + \mathbf{C}_\mathrm{m}^{-1}\mathbf{m}_\mathrm{prior}\right)$

- No prior information: $(\mathbf{C}_\mathrm{m}^{-1} = \mathbf{0})$

$$\widetilde{\mathbf{m}} = \left(\mathbf{G}^t\mathbf{C}_\mathrm{D}^{-1}\mathbf{G}\right)^{-1}\mathbf{G}^t\mathbf{C}_\mathrm{D}^{-1}\mathbf{d}_\mathrm{obs}$$

$$\widetilde{\mathbf{C}}_\mathrm{m} = \left(\mathbf{G}^t\mathbf{C}_\mathrm{D}^{-1}\mathbf{G}\right)^{-1}$$

$$\mathrm{C_D} = \sigma^2\mathrm{I} \longrightarrow \mathrm{C_D} = \mathrm{C_d} + \mathrm{C_T}$$

$\mathrm{C_d}$: observational error

$\mathrm{C_T}$: modelisation error

$$S(m) = ||d_{obs} - Gm||$$

Uncertainty analysis for source inversions

- Simple case: linear - gaussian

  Problème direct: $\mathbf{d} = \mathbf{G}\mathbf{m}$

  Solution: $\widetilde{\mathbf{m}} = \left(\mathbf{G}^t\mathbf{C}_\mathrm{D}^{-1}\mathbf{G} + \mathbf{C}_\mathrm{m}^{-1}\right)^{-1}\left(\mathbf{G}^t\mathbf{C}_\mathrm{D}^{-1}\mathbf{d}_\mathrm{obs} + \mathbf{C}_\mathrm{m}^{-1}\mathbf{m}_\mathrm{prior}\right)$

- No prior information: $(\mathbf{C}_\mathrm{m}^{-1} = \mathbf{0})$

$$\widetilde{\mathbf{m}} = \left(\mathbf{G}^t\mathbf{C}_\mathrm{D}^{-1}\mathbf{G}\right)^{-1}\mathbf{G}^t\mathbf{C}_\mathrm{D}^{-1}\mathbf{d}_\mathrm{obs}$$

$$\widetilde{\mathbf{C}}_\mathrm{m} = \left(\mathbf{G}^t\mathbf{C}_\mathrm{D}^{-1}\mathbf{G}\right)^{-1}$$

~~$\mathbf{C}_\mathrm{D} = \sigma^2\mathbf{I}$~~ $\longrightarrow$ $\mathbf{C}_\mathrm{D} = \mathbf{C}_\mathrm{d} + \mathbf{C}_\mathrm{T}$

observational error

modelisation error

Uncertainty analysis for source inversions

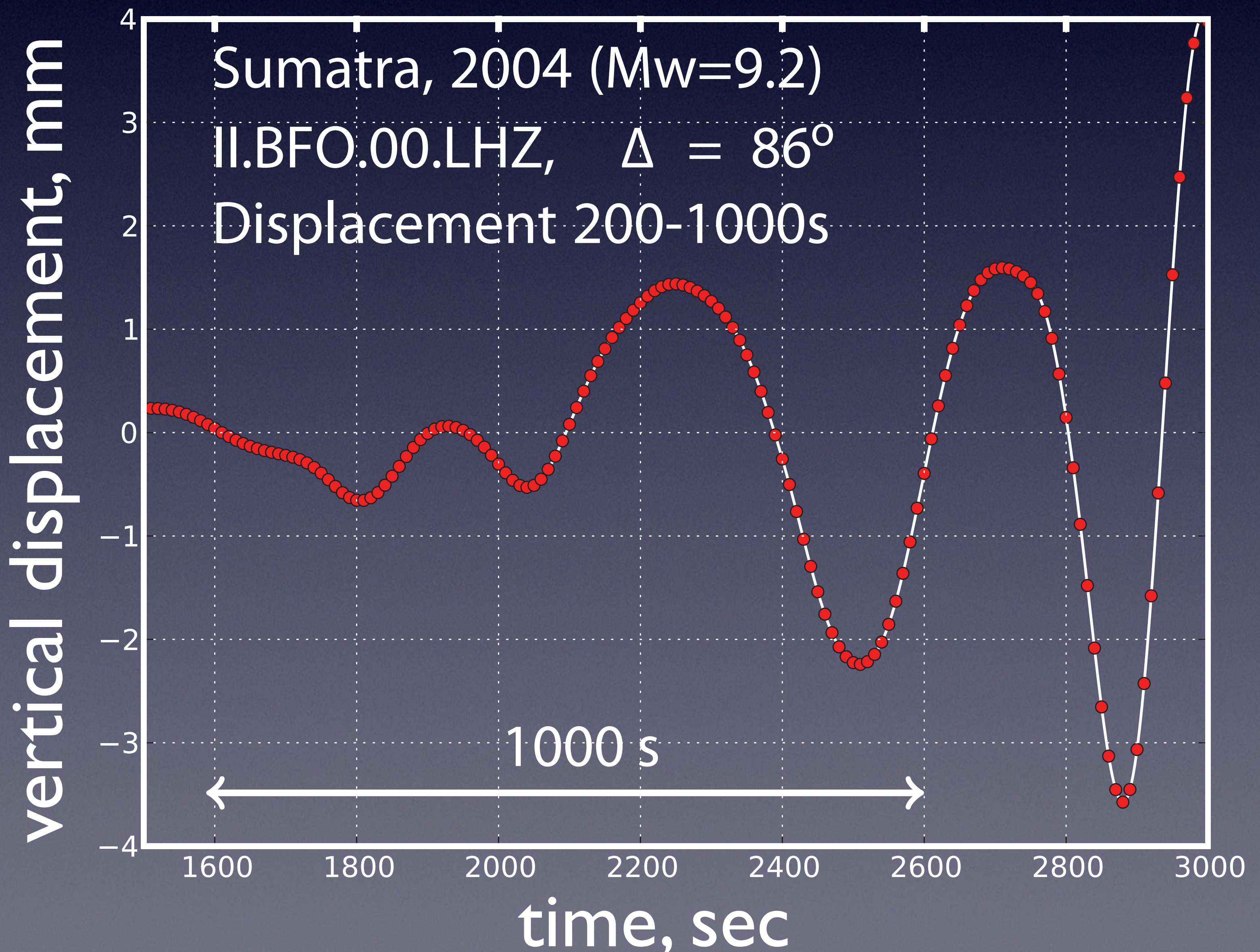
- Observations - error:

$$(\mathbf{C}_{\mathrm{d}}^{n})^{ij} = (\sigma^n)^2 \exp(-|\Delta t_{ij}|/t_0)$$

Noise level at station *n*

Time interval between samples i and j

shortest period to be modeled



Uncertainty analysis for source inversions

- Modelisation uncertainty:

$$\mathbf{C}_\mathrm{T}$$

- We know that our modelisation is often incomplete :

  e.g.: Elastic structure, source location, finiteness, etc.

- How to introduce this information into the solution ?
- We can use a "non-deterministic theory" allowing for some fuzziness in the predictions.
- As an example we consider here some uncertainty on the centroid location (x)
- The associated covariance matrix for the prediction is :

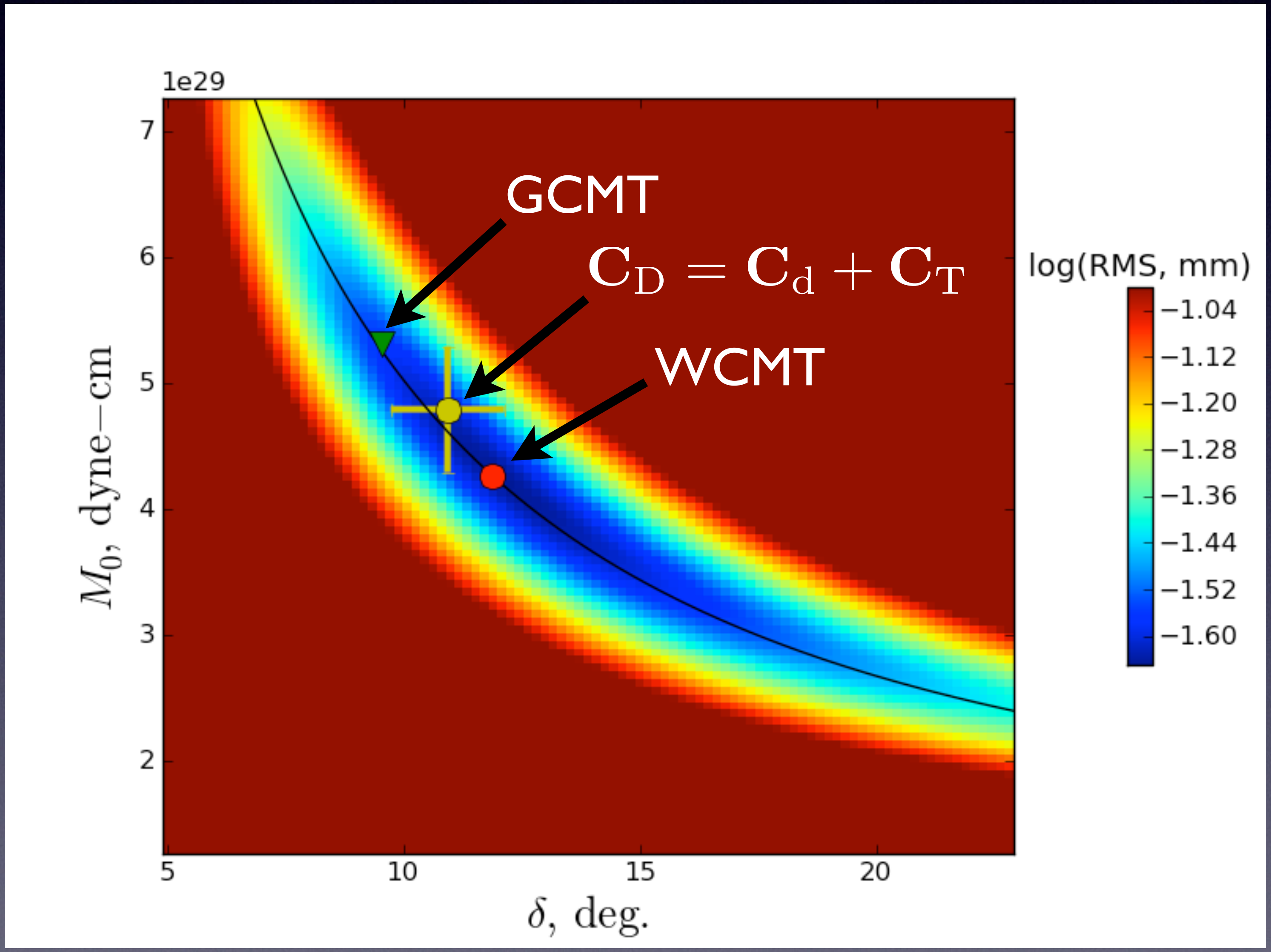
$$\mathbf{C}_\mathrm{T} = \nabla\mathbf{d}\,\mathbf{C}_\mathrm{x}\,\nabla\mathbf{d}^t$$

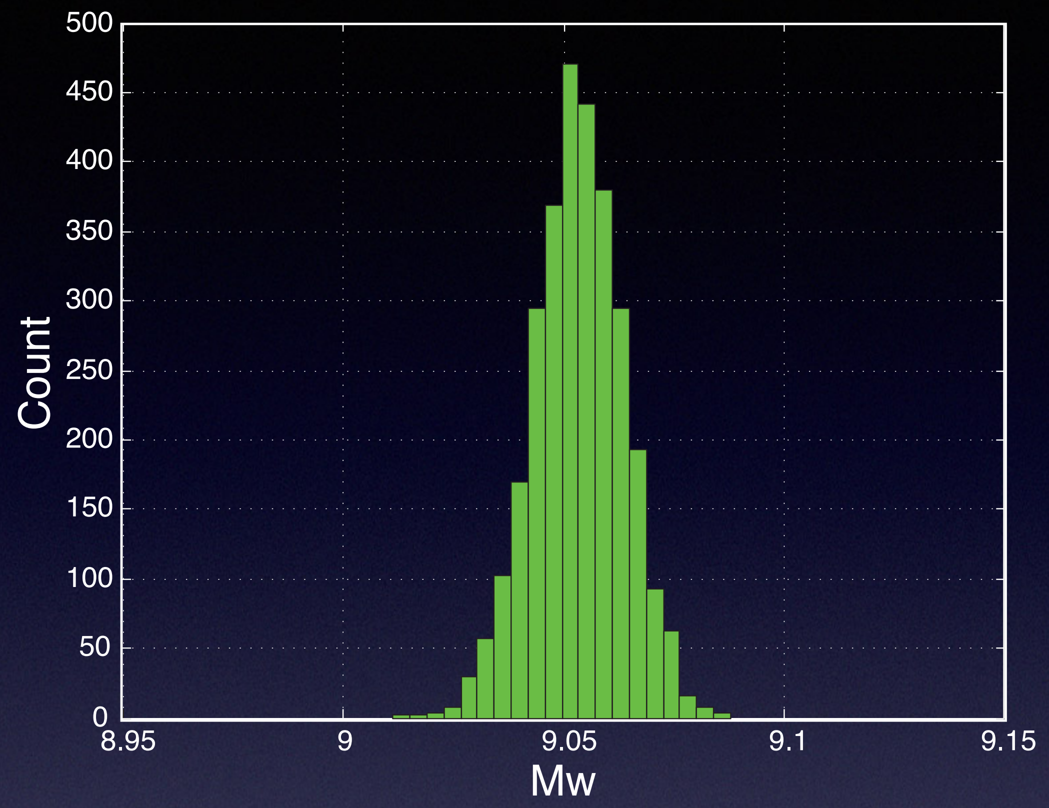
Partials with respect to the centroid location

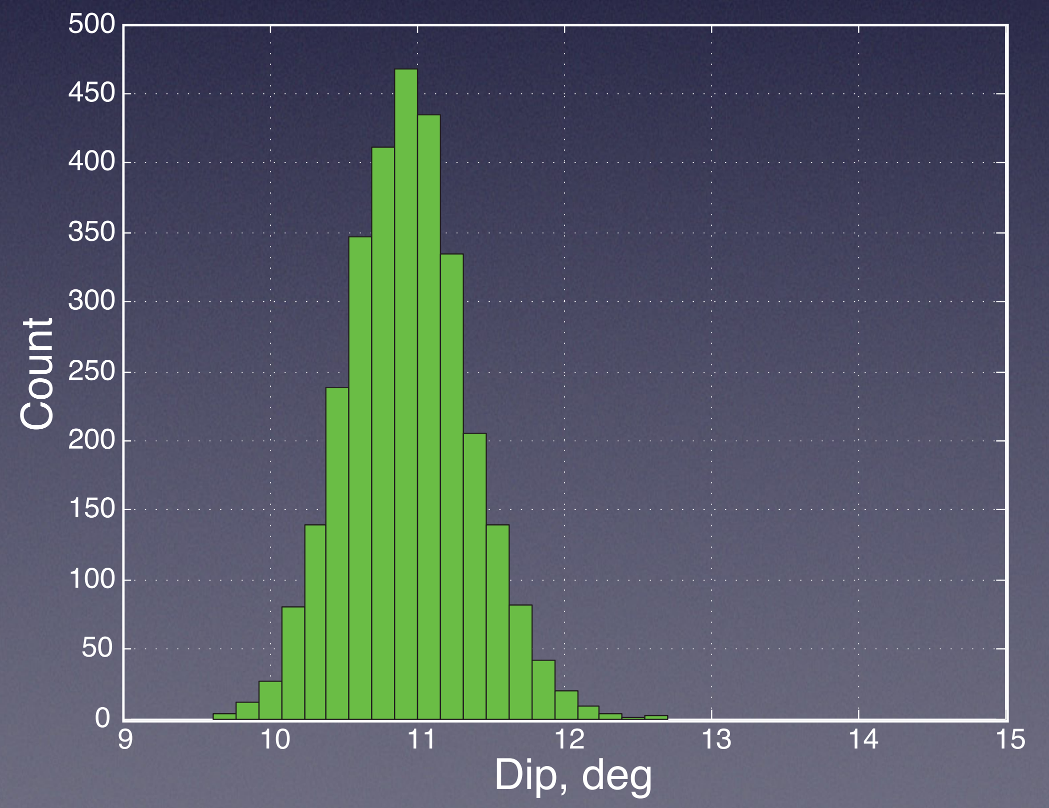
Covariance matrix carrying the uncertainty on the cent. location

Uncertainty analysis for source inversions

Tohoku-oki 2011 earthquake:
Mo-dip: incertainty and trade-off

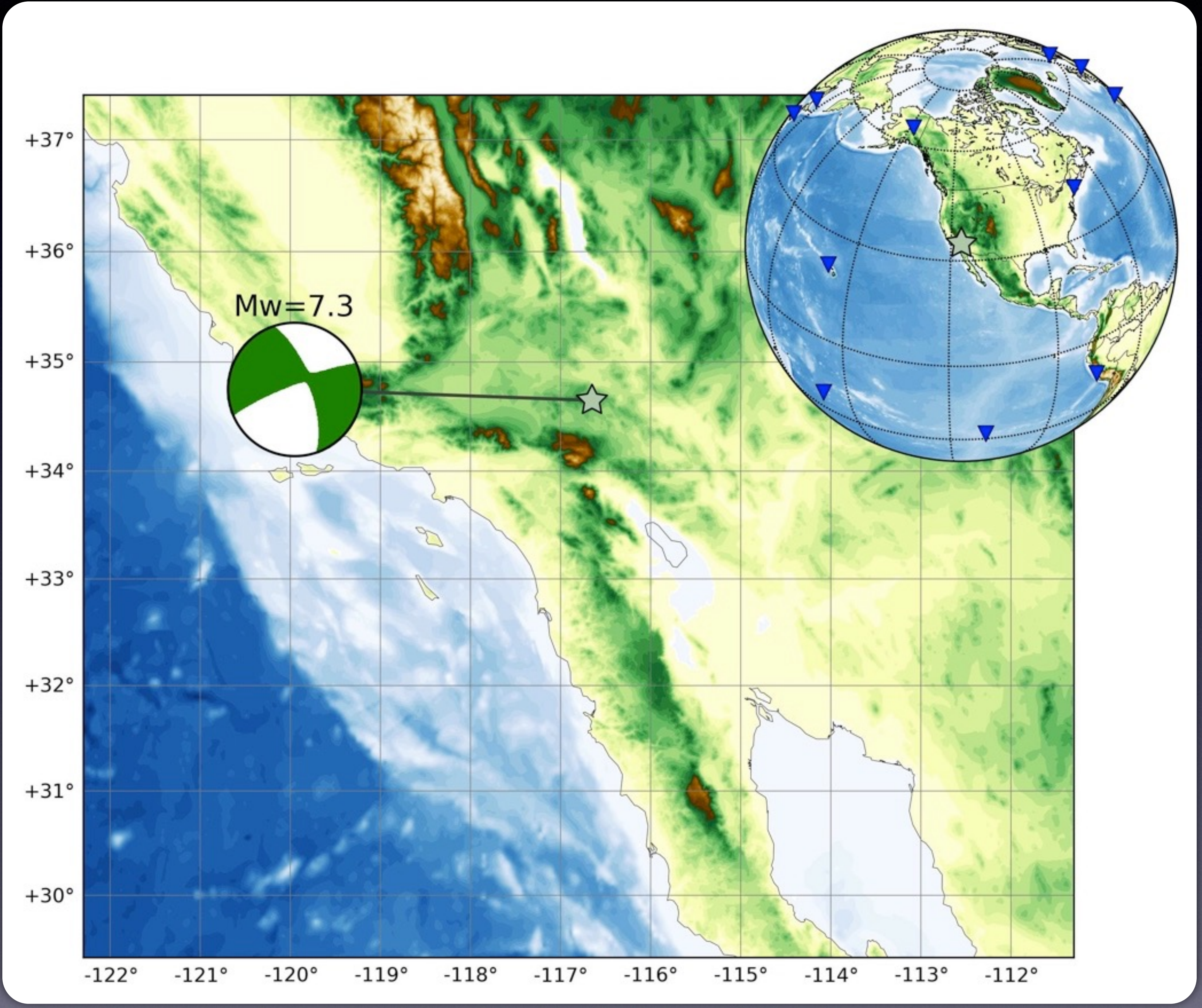






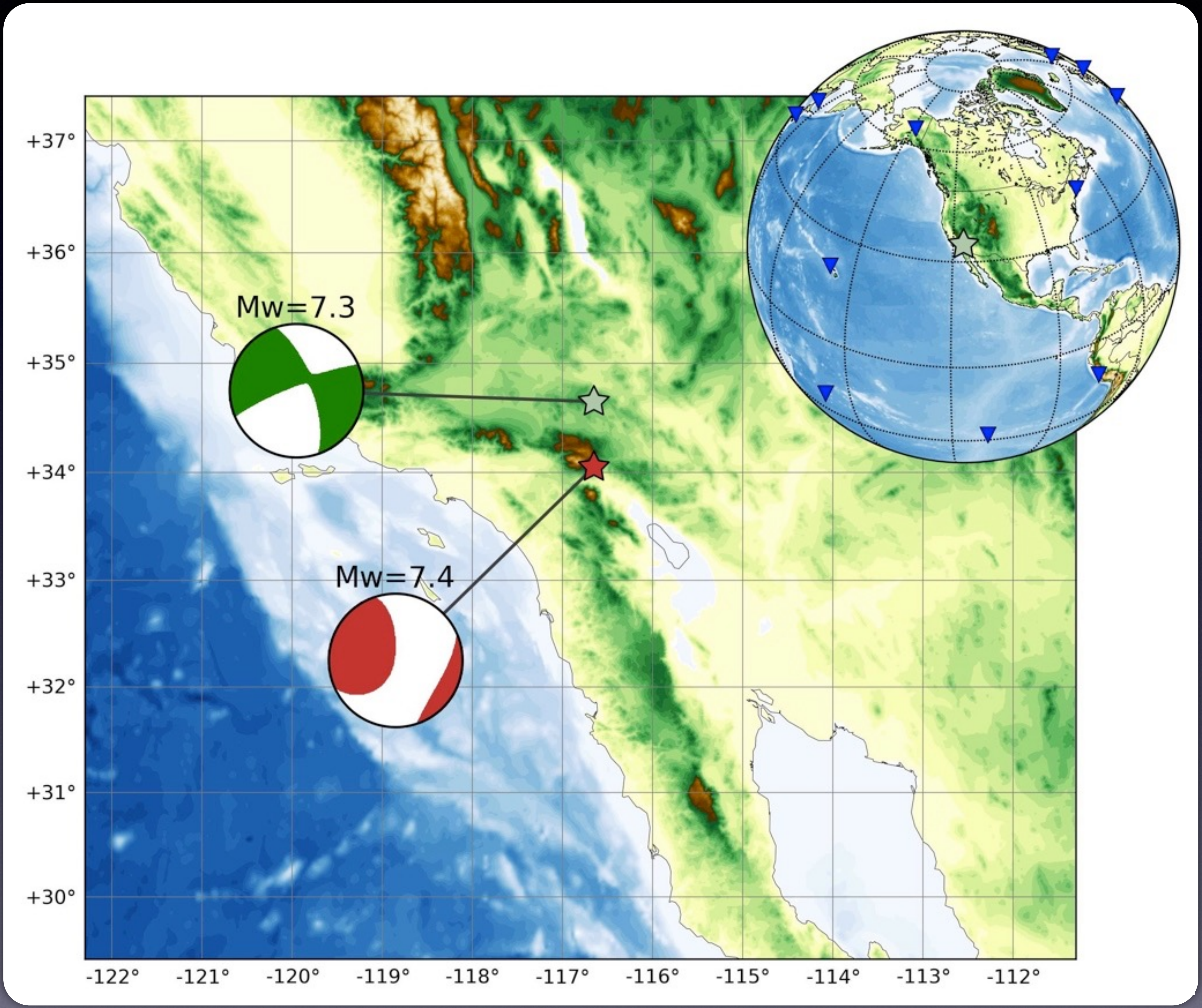
Uncertainty analysis for source inversions

Uncertainty in the centroid location - synthetic test



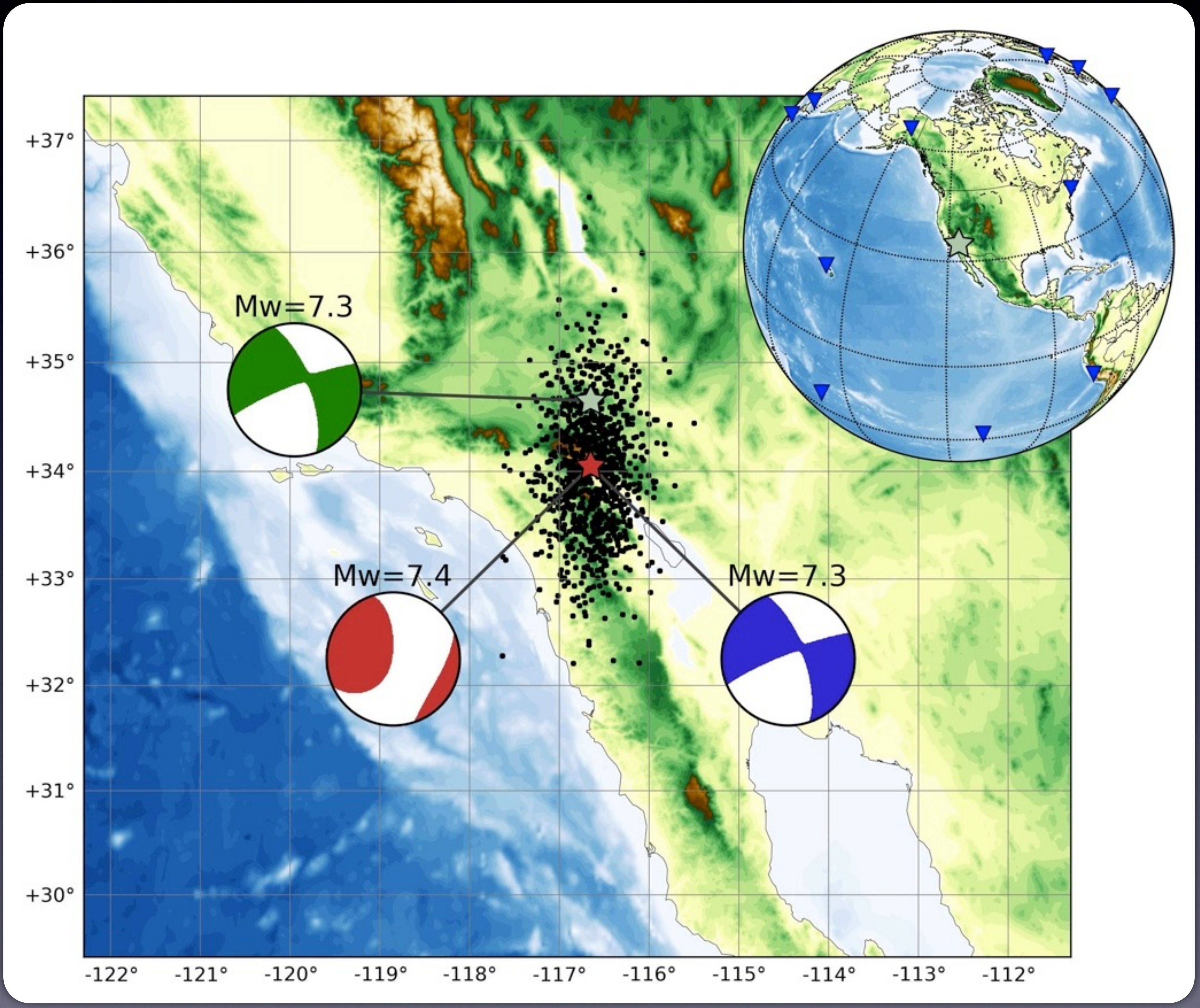
Uncertainty analysis for source inversions

Uncertainty in the centroid location - synthetic test



Uncertainty analysis for source inversions

Uncertainty in the centroid location - synthetic test

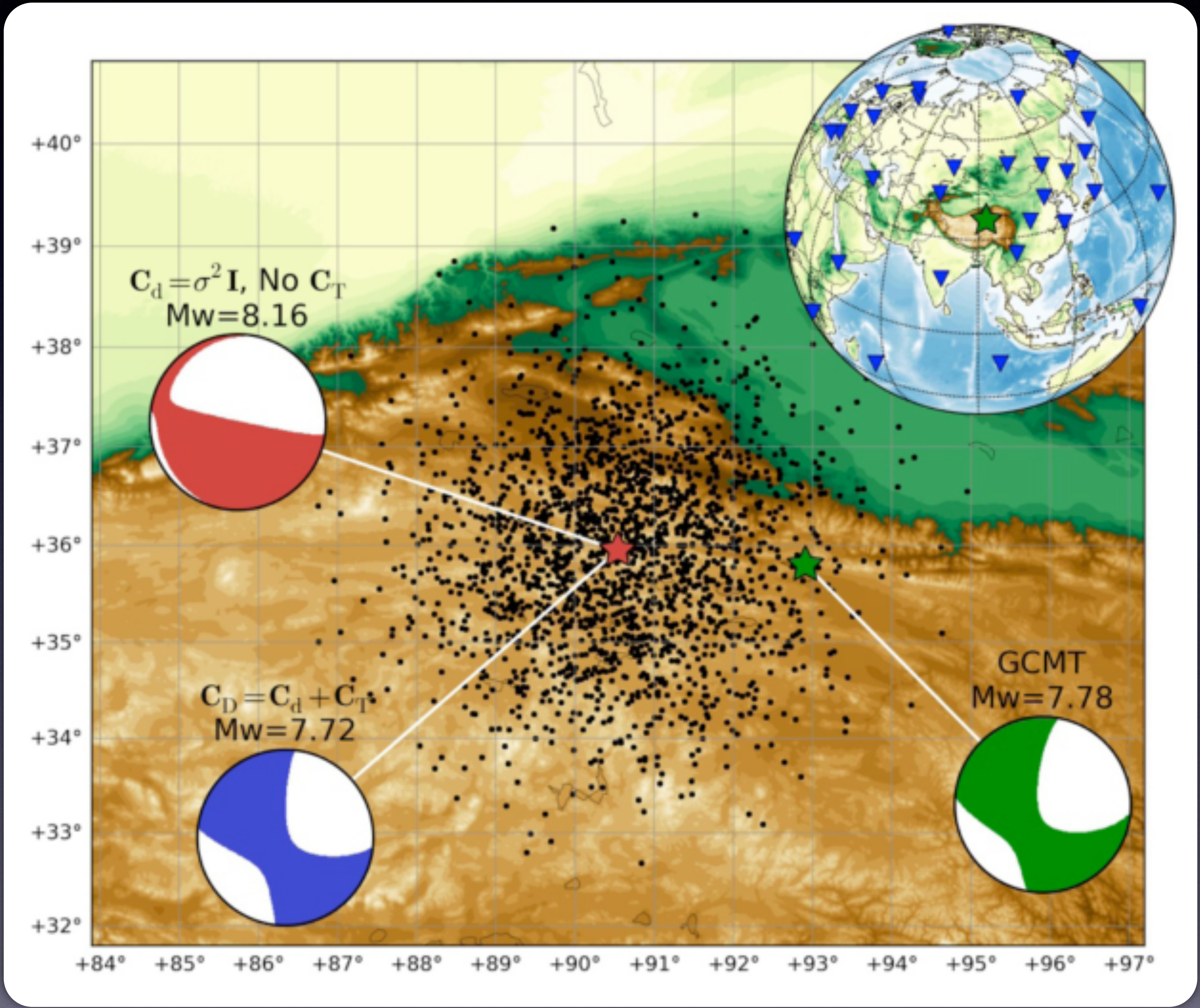


Points noirs: incertitude dans la localisation du centroid (Cx)

Uncertainty analysis for source inversions

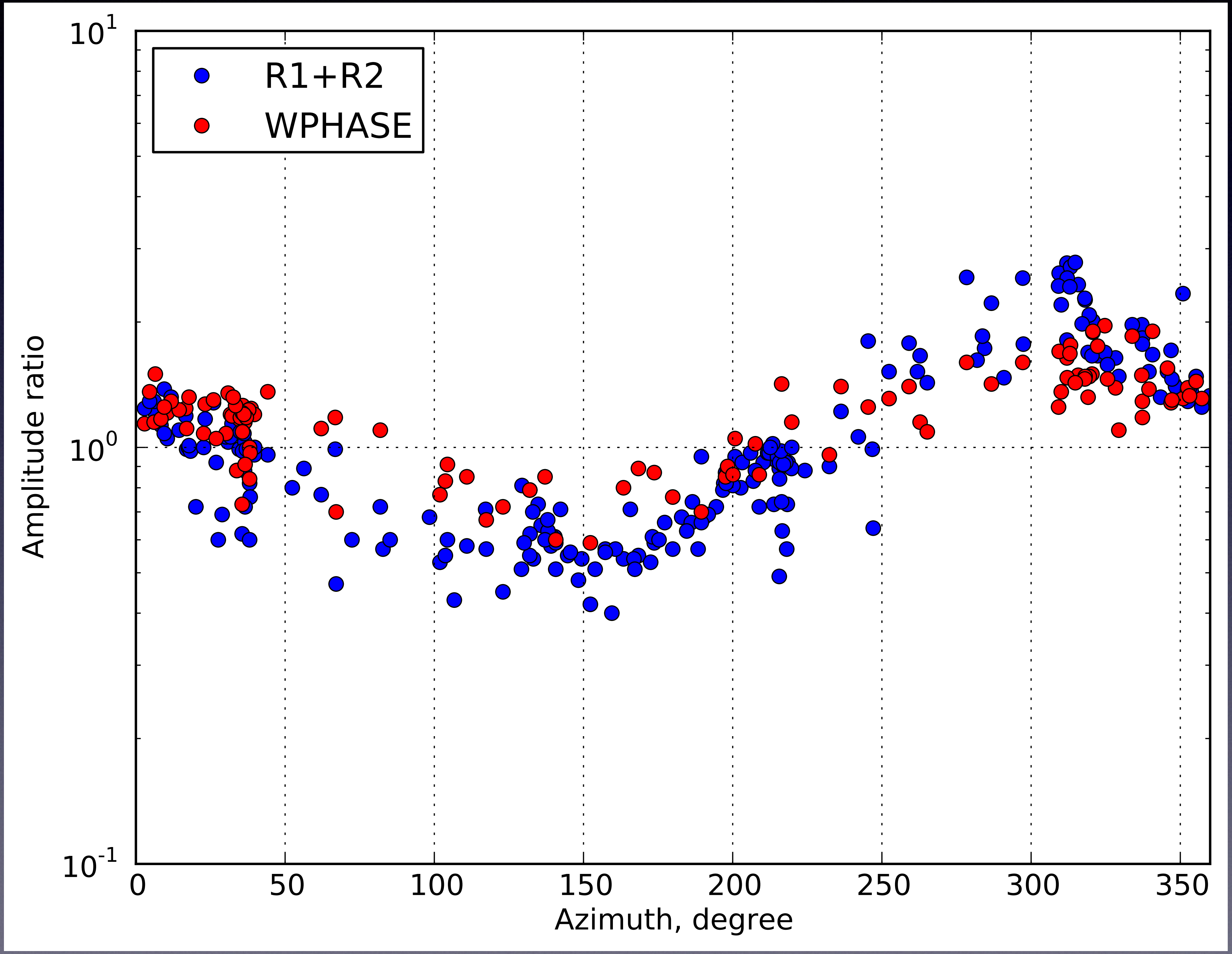
Incertainty in the centroid location - Kokoxili 2001 (Mw=7.8)

Centroid fixed at PDE location

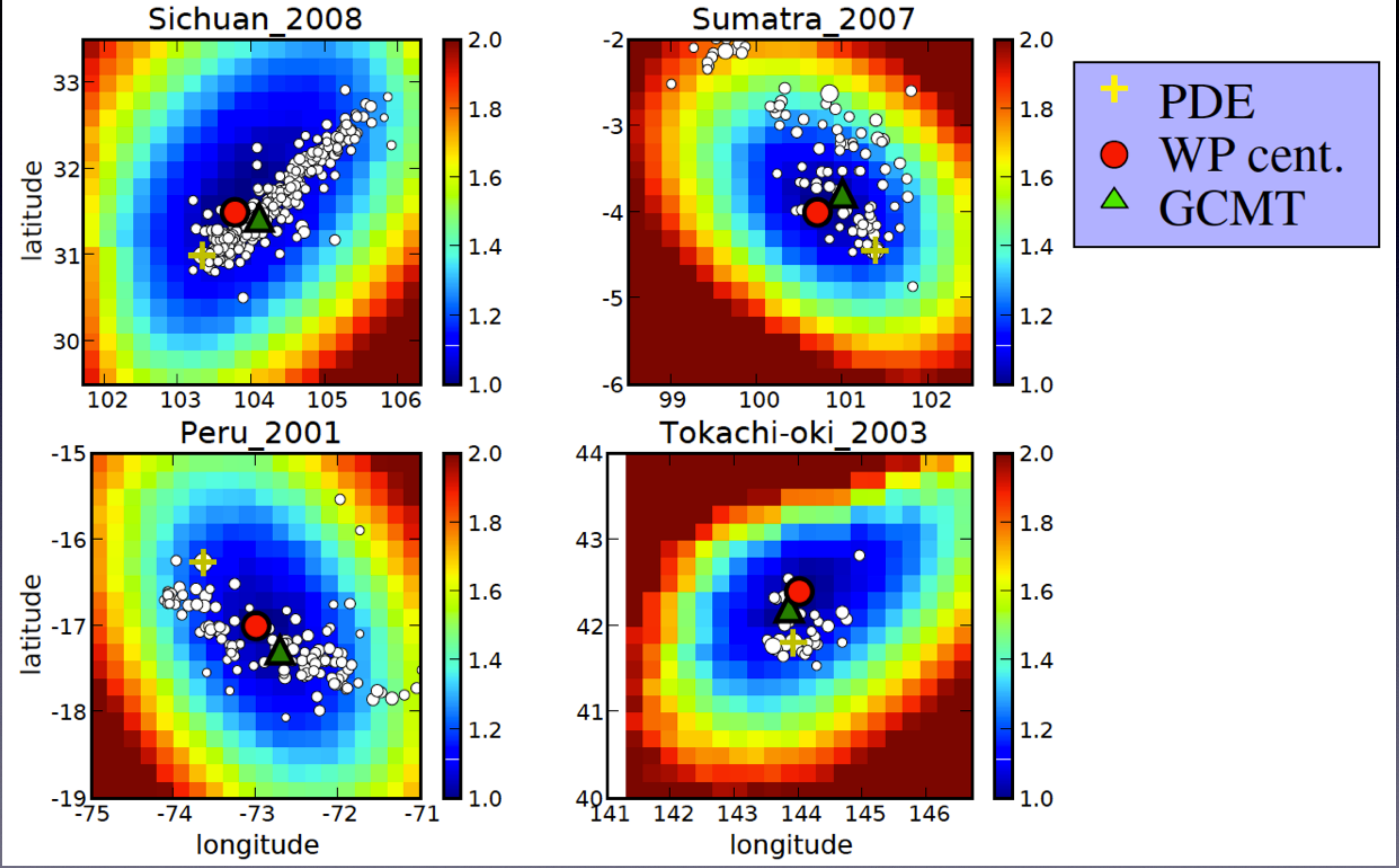


Black dots cloud indicate the uncertainty on the centroid location (Cx)

Perspectives: Directivity (finiteness)



Perspectives
Grid search byproduct: Finiteness ?



Conclusions

- W phase source inversion provides fast and robust overall source information for large earthquakes both at global and regional scale:
  - Mw, focal mechanism, centroid location and time
- This can be used as a safe constraint for more detailed source studies.
- Real time operation:
  - Global scale ~ 20 - 35 min
  - Regional scale ~12 min ($\Delta < 25°$)
  - Local scale, real time continuous GPS
- W phase can be used for early detection of sources complexity
- Large events close in time require special handling

Thanks for your attention