Source inversion in seismology

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Outline

Source inversion in seismology

- Goals and inversion structure
- Source model and inversion method, a multi-step inversion approach
- Source inversion using the Kiwi tools
- Inversion tips: frequency vs. time domain, bodywaves vs. full waveforms, ...

Example of applications

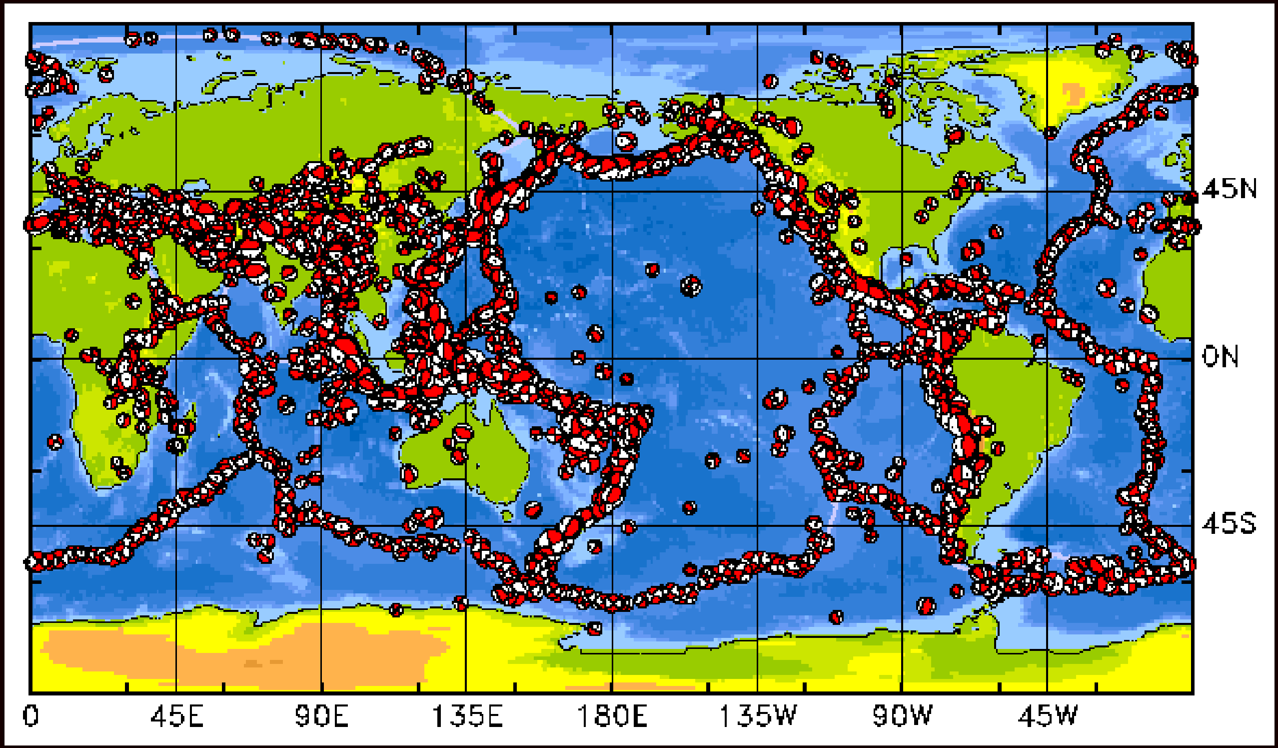
- Point source inversion using full waveforms, regional applications
- Extended source inversion, an overview on different approaches
- Point source inversion using bodywaves, a deep earthquake case
- Microseismicity application, source inversion in mining environments

Source inversion in seismology

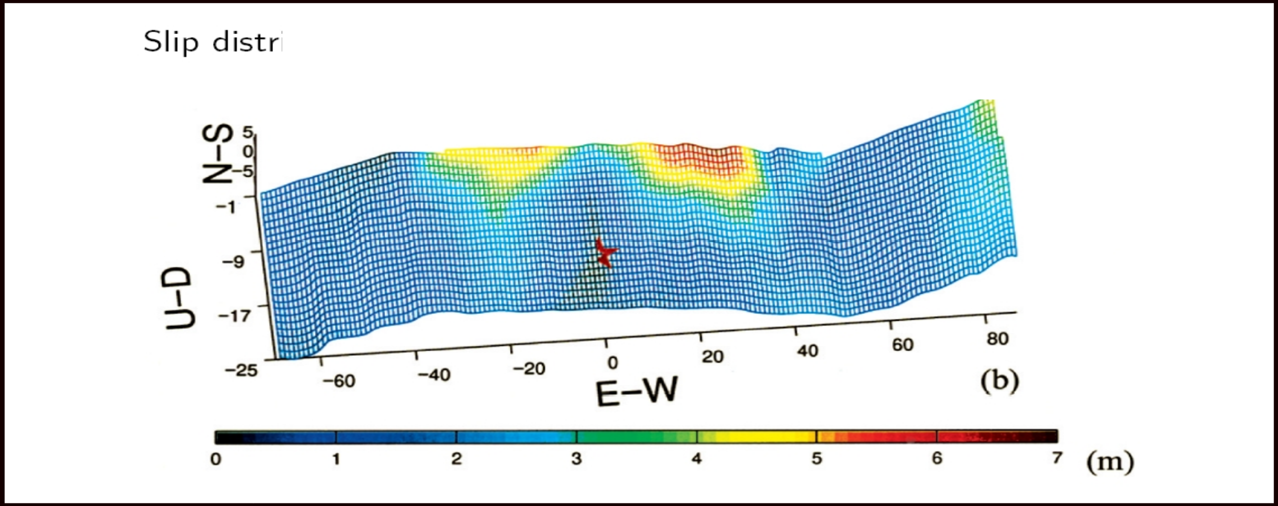
Source inversion in seismology, overview

Global CMT catalogue,

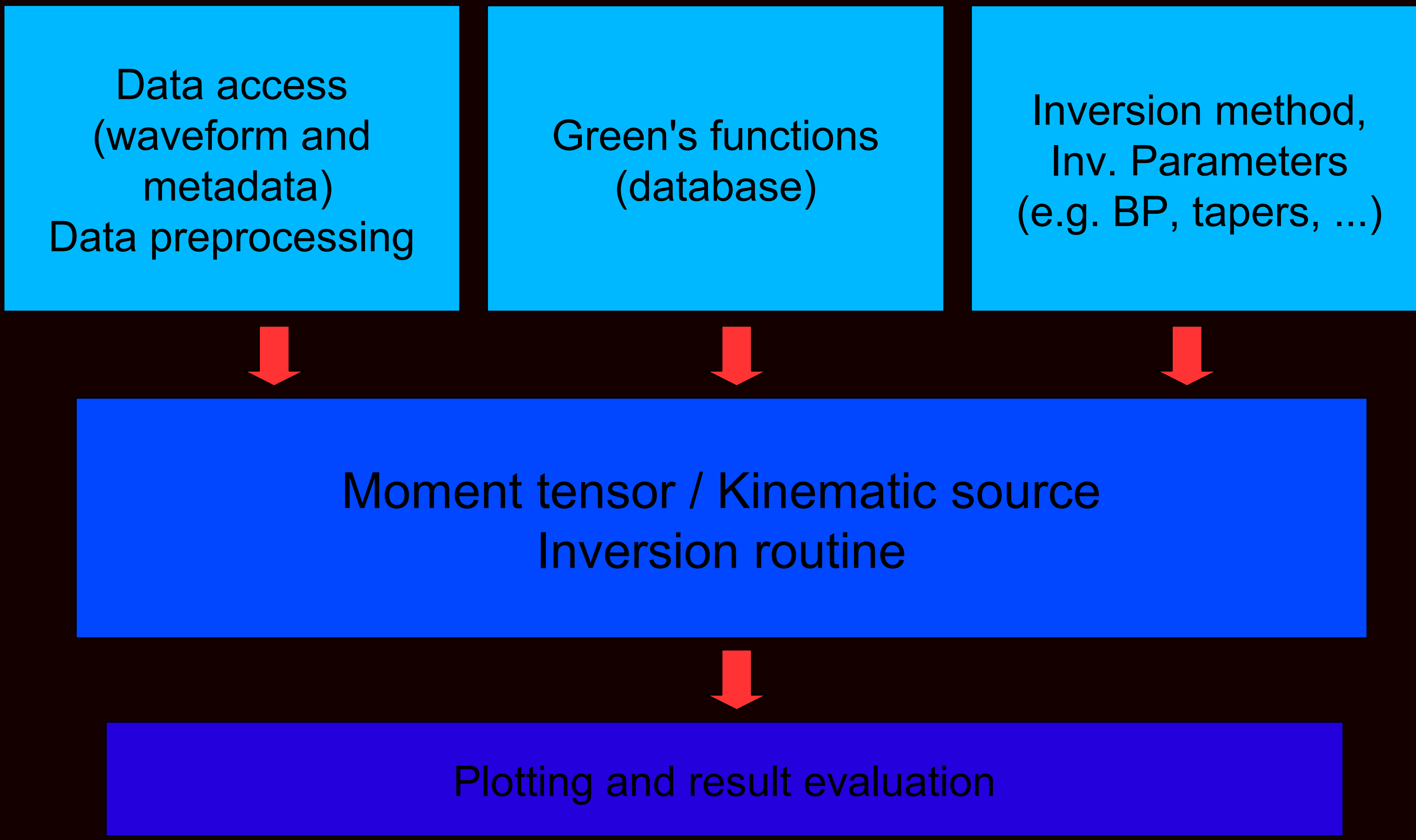
1976-2005



Slip map
kinematic model
(Li et al. 2002)



Source inversion in seismology, what do we need?



Source inversion in seismology, what do we need?

Data access (waveform and metadata)
Data preprocessing

Data access/preprocessing

Waveforms (here displacements)

Station information (location, instrument, sampling)

Instrumental responses

Processing tools
(filtering, mean/trend removal, tapering, resampling…)

Acceleration/Velocities/Displacements

Data quality evaluation (gaps, spikes, seismic noise)

Source inversion in seismology, what do we need?

MESS 2012 Data

- Displacement waveforms (mostly broadband seismometers)
- Preprocessed (instrument response, integration, ...)
- Metadata: Station information (location, instrument, sampling)

A number of different events

- Mw Ca. 4 - 7
- Epic. Distances up to 1000km
- Source Depth down to 30km

Source inversion in seismology, what do we need?

Green's functions database

Green's functions (1D)

Needed to build
synthetic seismograms

Accounting for the earth structure

Precompiled database structures to allow rapid access and less storage requirements

What is needed?

- 1D GFs database access for reference models (e.g. PREM, AK135, …)
- Tools for specific databases for local applications
- Database handlers (generation, access)

We use fast access databases based on HDF5. Kiwi tools handle database access.

The system is independent on the algorithm used to compute GFs.

Source inversion in seismology, what do we need?

MESS 2012 GFDB

- 1D model (physical property = f(depth))
- IASP91 model
- Source depths (0-40km)
- Epic. Distances (0-1000km)
- 10 Gfs

Source inversion in seismology, what do we need?

MESS 2012 Synthetic seismograms

- GFDB (z,d,10GFs)
- Source model
- Source & station locations
- (station azimuth)
- 10 GFs
  - z=source depth
  - d=epicentral distance
- 3-component Synthetics

Source inversion in seismology, what do we need?

Inversion method/parameters

Many different approaches exist.

Often specific methods are more suited for specific events (e.g. depth, magnitude)

Tools which may consider specific selection of:

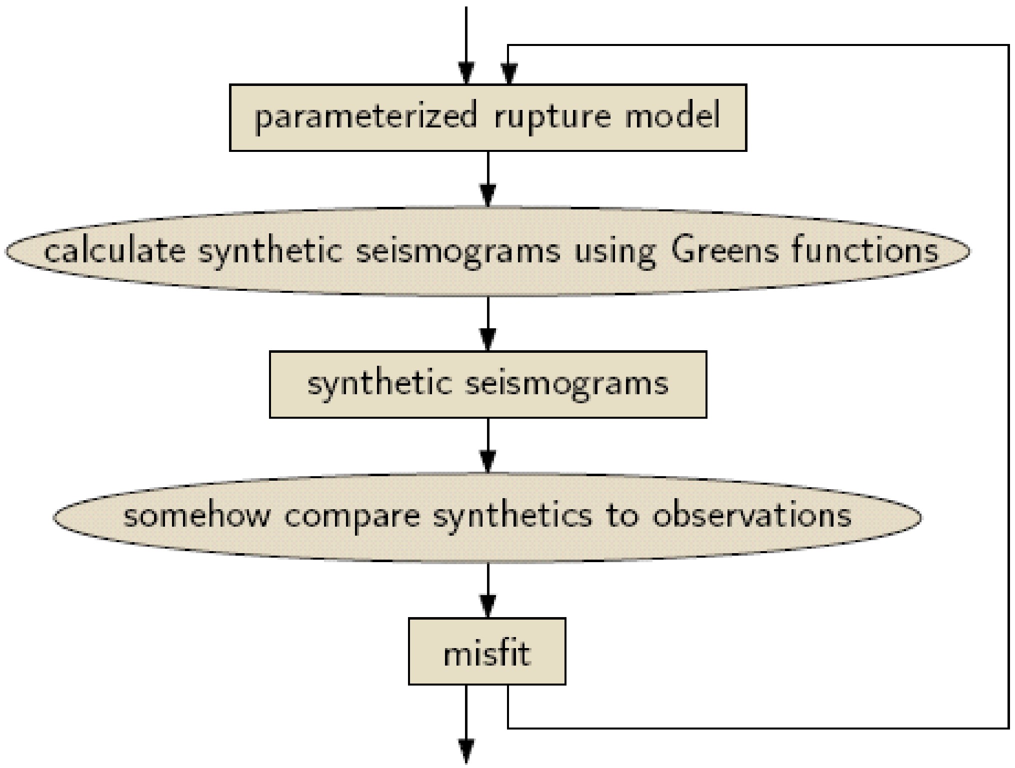
- Fitting approach (time domain, amplitude spectra, others?, norms)
- Inversion approach (e.g. grid walk, gradient methods, …)
- Source constraints (DC, DC+CLVD, DC+CLVD+ISO, extended source models, others?)
- Seismic phases (e.g. full waveforms vs. single phases), tapering
- Frequency range (BP is typically chosen in base of magnitude, phases)
- Selection/removal of stations/components
- Parameters uncertainties

Inversion method,
Inv. Parameters
(e.g. BP, tapers, ...)

Source inversion in seismology, what do we need?

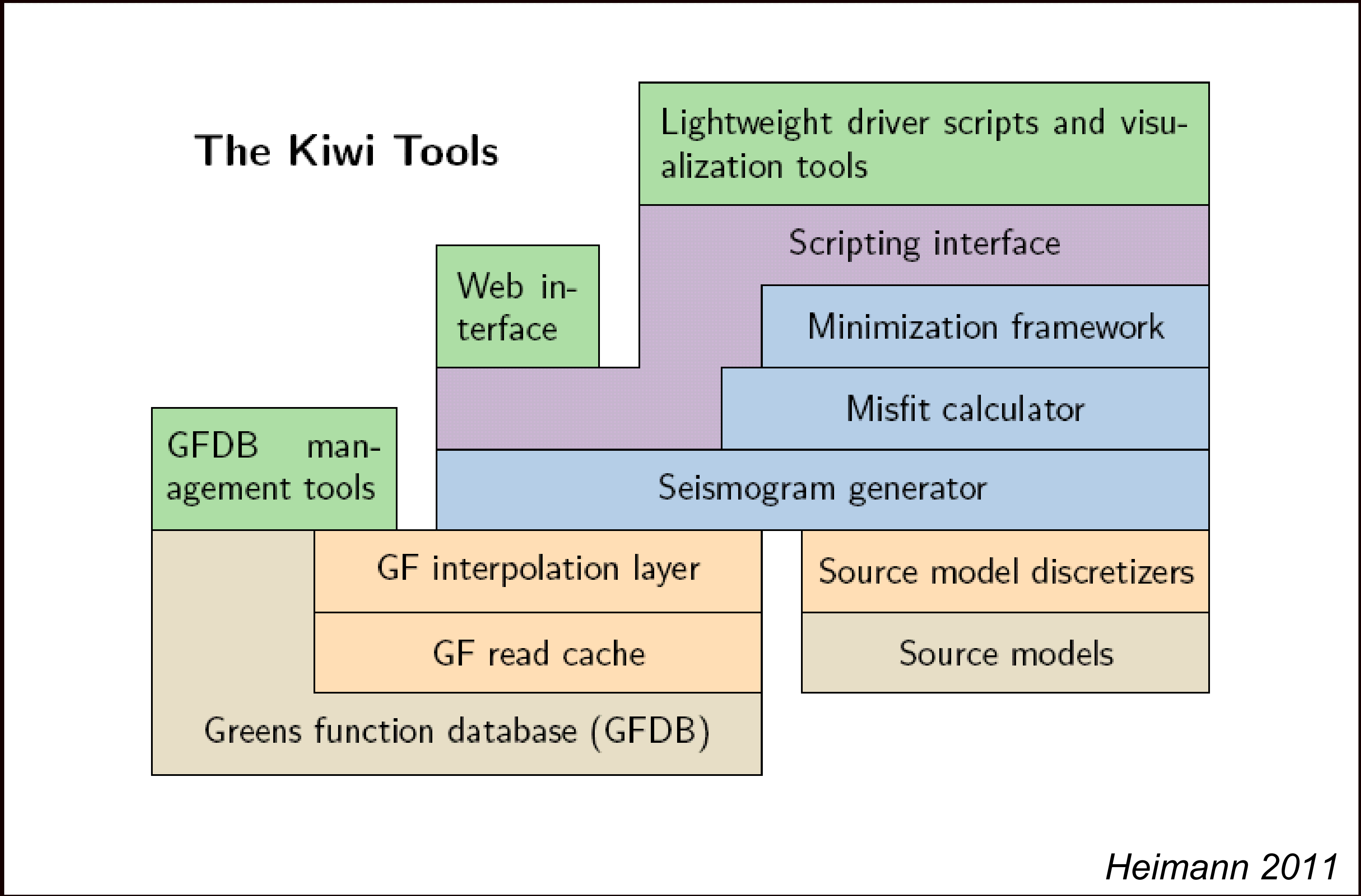
Inversion method/parameters

- Time domain inversion (fitting waveforms)
- Frequency domain inversion (fitting amplitude spectra only)
- Own Bandpass
- Own Taper (P, S, P+S, full waveforms)
- Own Norm (L1, L2)
- Parameters uncertainty by bootstrap



Heimann 2011

Source inversion in seismology using the Kiwi tools



OpenSource

Running under Linux

Python + Fortran implementation

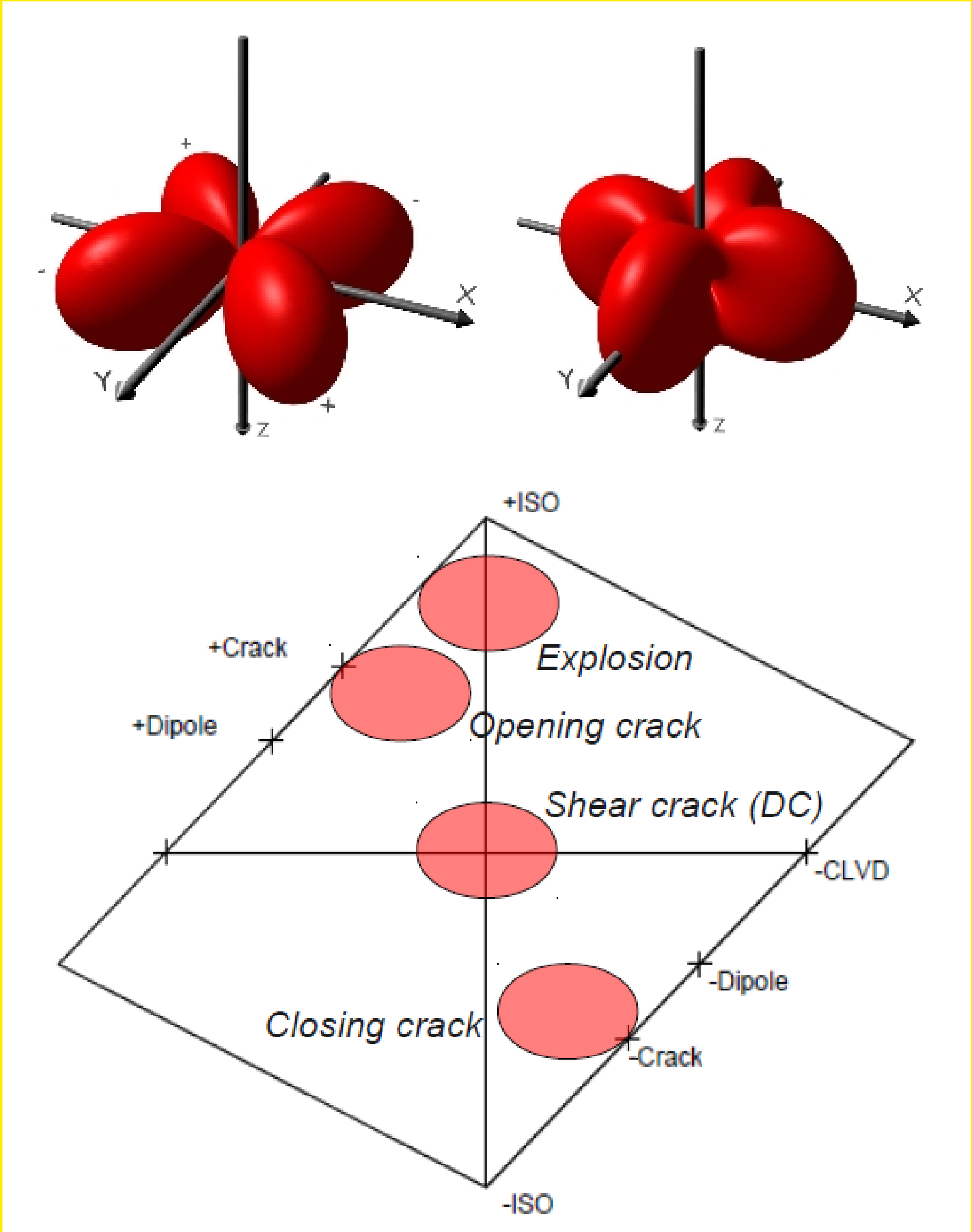
http://kinherd.org

Point source model, double couple & moment tensor

Earthquakes is often well modeled in terms of shear cracks, using a point source representation (DC model).

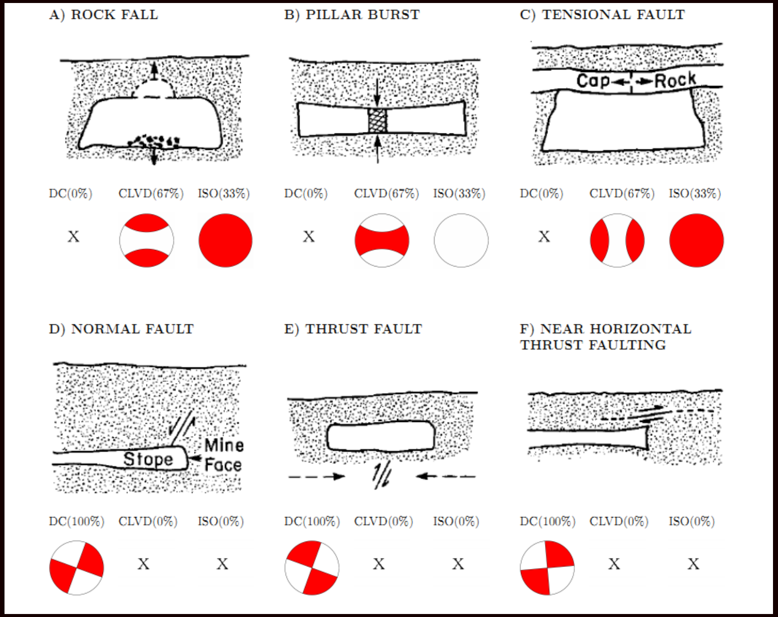
More complete point source model is represented by a moment tensor (MT)

$$MT = MT_{DC} + MT_{CLVD} + MT_{ISO}$$



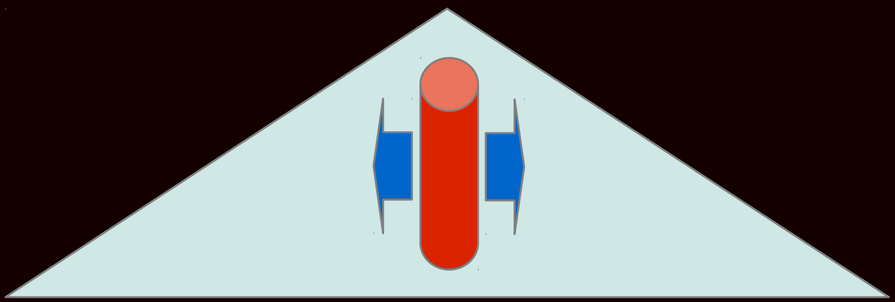
On the adoption of full moment tensor source models

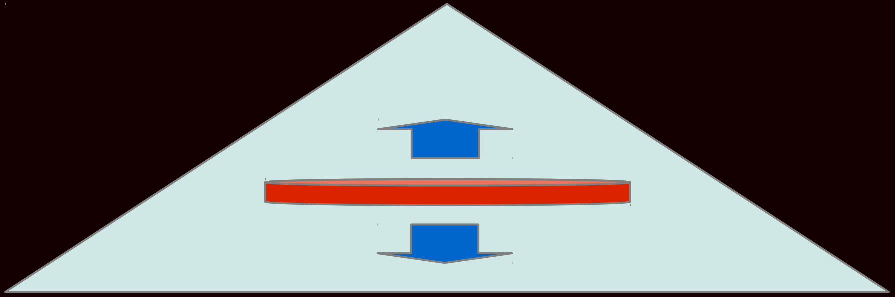
Mining environments



after Hasegawa et al. (1989)

Volcanoes





Non DC source components are relevant

Volume variations, tensile cracks, explosions and collapse sources can be investigated

On the adoption of full moment tensor source models

Common ISO=0 constraint for natural earthquakes (e.g. Global CMT)

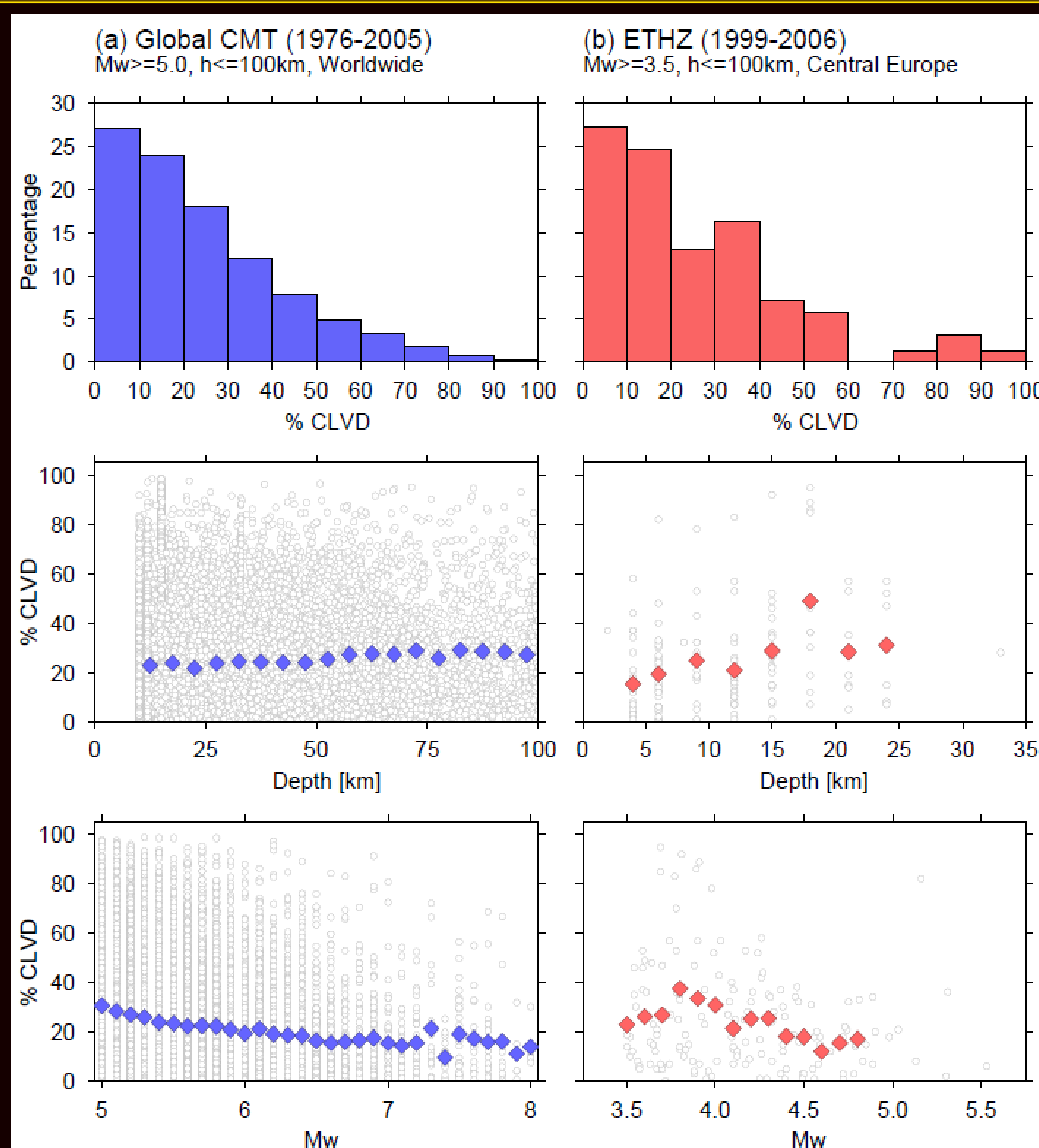
Spurious non-DC terms:

Waveform propagation mismodeling

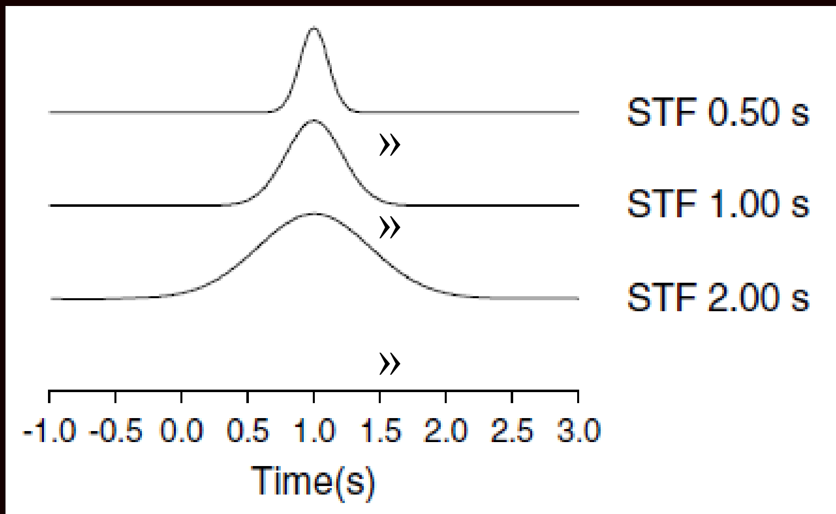
Poor network configurations and data quality

Complex sources

Real non-DC features



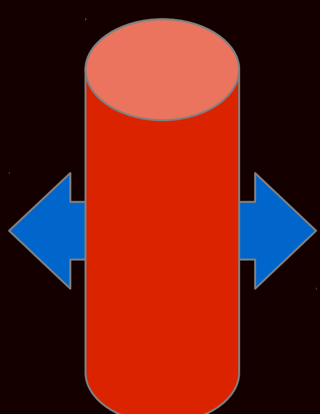
On the source time function

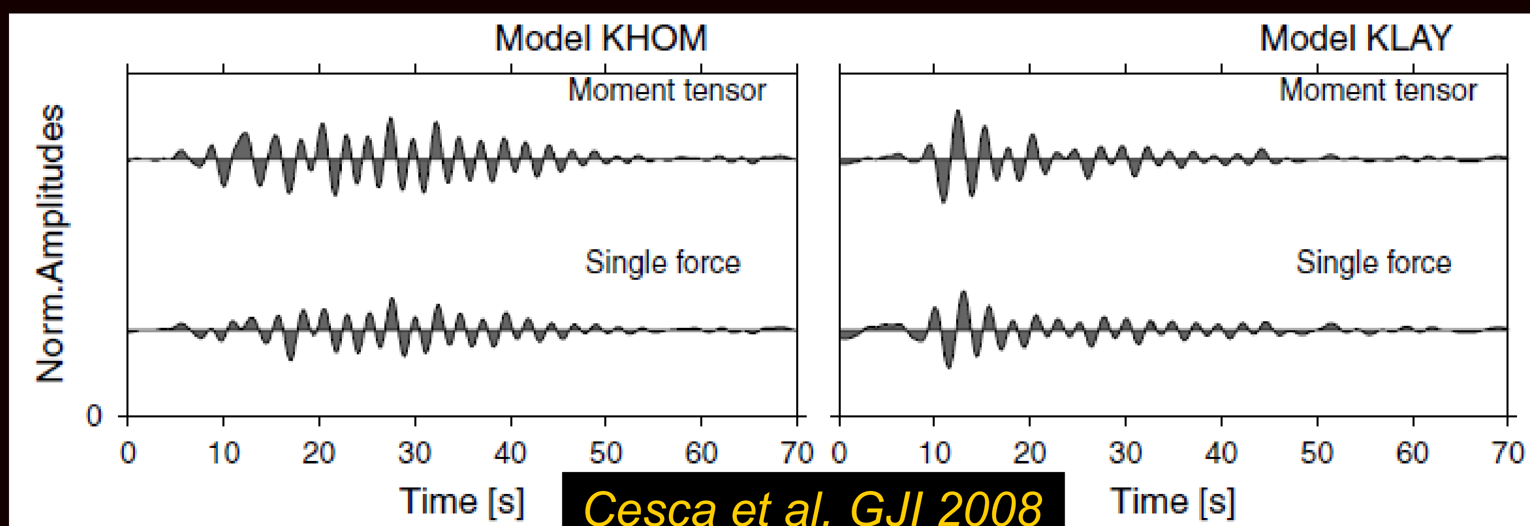


STF (slip rate function)

- Simple aproximation is valid for DC event
- Rise time is the time a point source releases energy
- Note that finite rupture are superposition of point sources with constant rise time

Complex STFs may be needed for other environments, e.g. at volcanoes, to describe resonant sources, tremors, and in general sources excited along a large time.

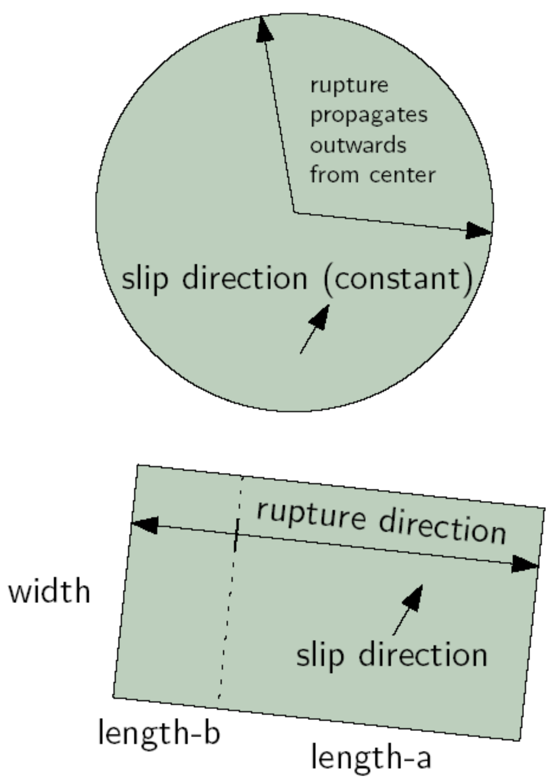


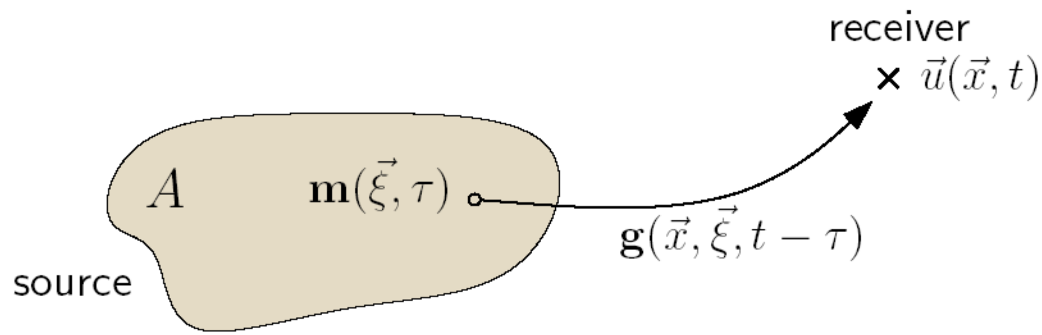


Cesca et al. GJI 2008

Extended source model, definitions

Extended sources may be reproduced by superposition of several point sources distributed along a planar (or bended) rupture surface. Each point source start radiating when reached by the rupture front. Radiation lasts for a given (rise) time.

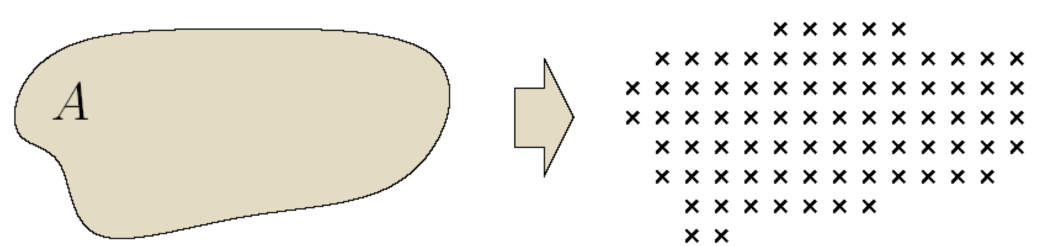




$$\vec{u}(\vec{x},t) = \int_A \int_T \mathbf{F}\left[\, \mathbf{m}(\vec{\xi},\tau),\ \mathbf{g}(\vec{x},\vec{\xi},t-\tau) \,\right] \, d\tau \, dA$$

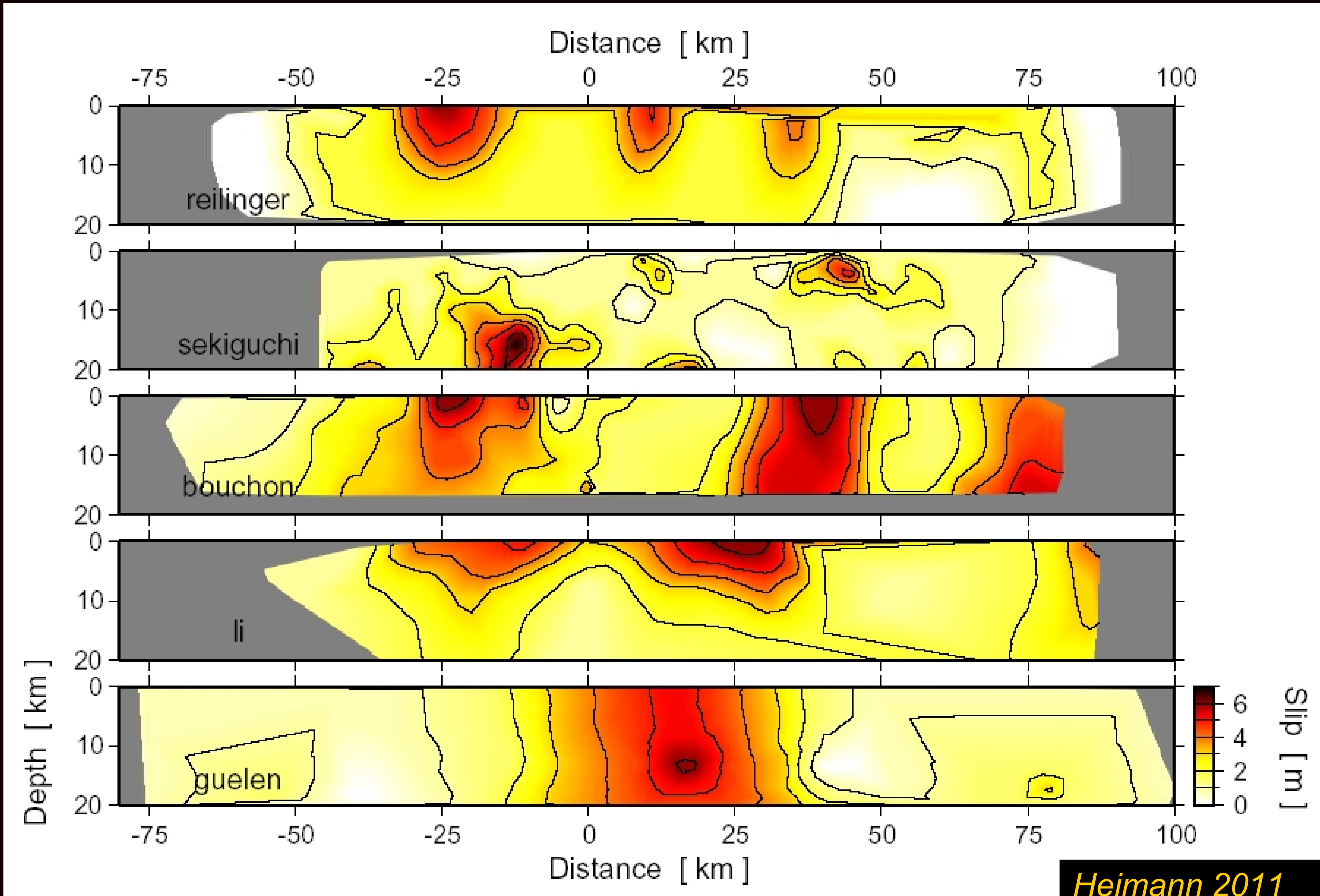
A rupture surface

- Approximate moment tensor density distribution by a number of point sources.



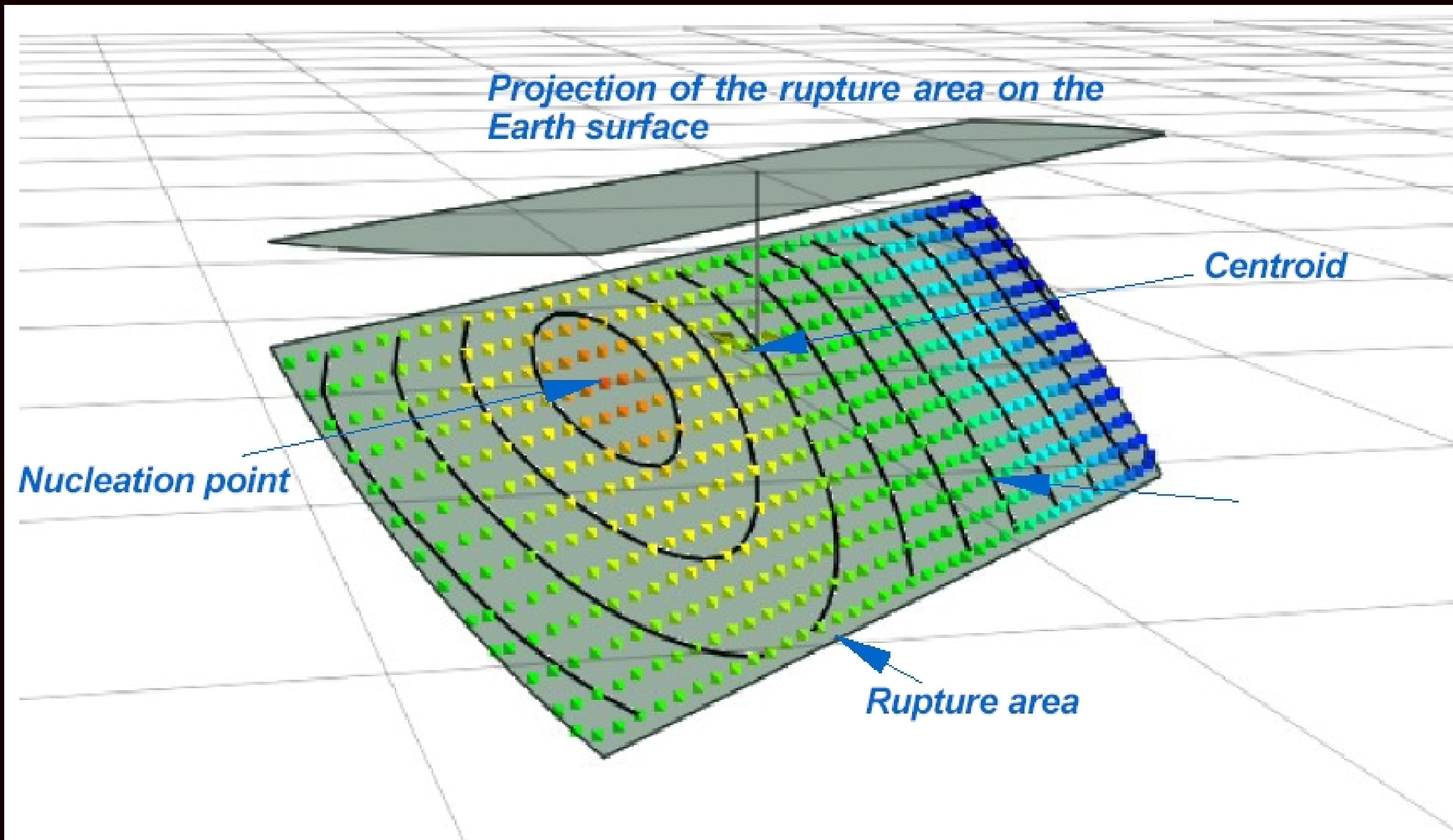
Heimann 2011

One earthquake, five solutions



Heimann 2011

The eikonal source model



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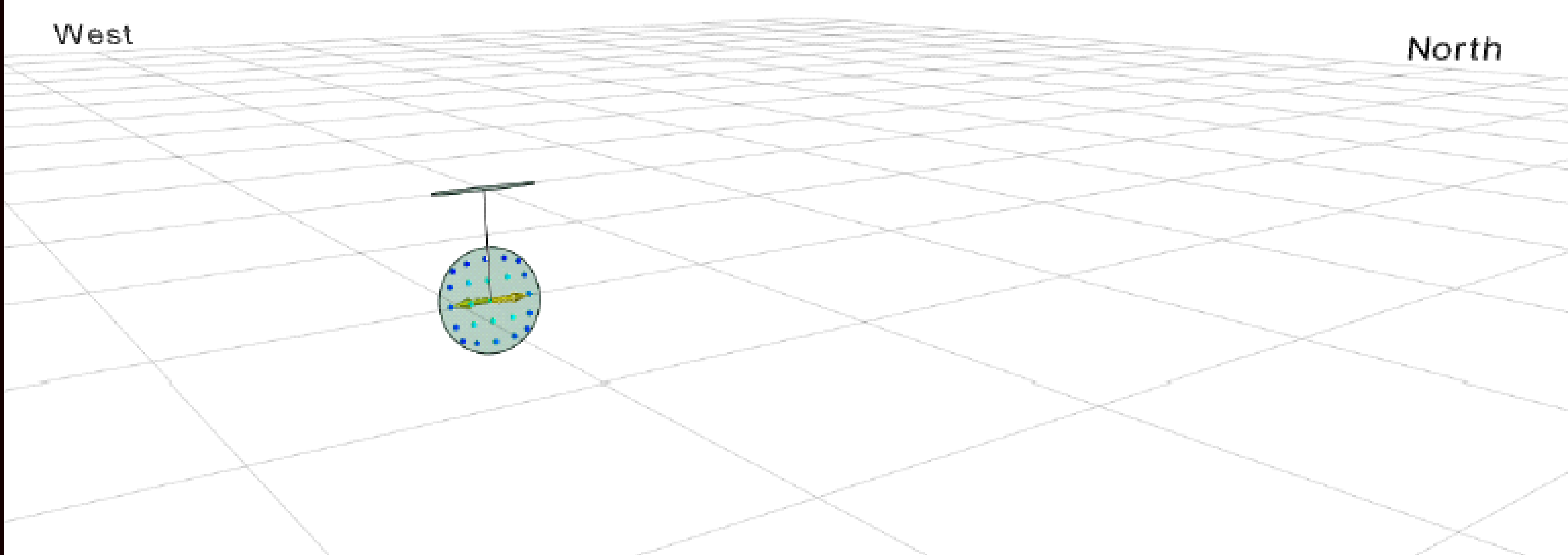
- Clipped at the surface
- Region may be constrained by additional planes
- Variable nucleation point
- Rupture velocity proportional to shear wave velocity profile



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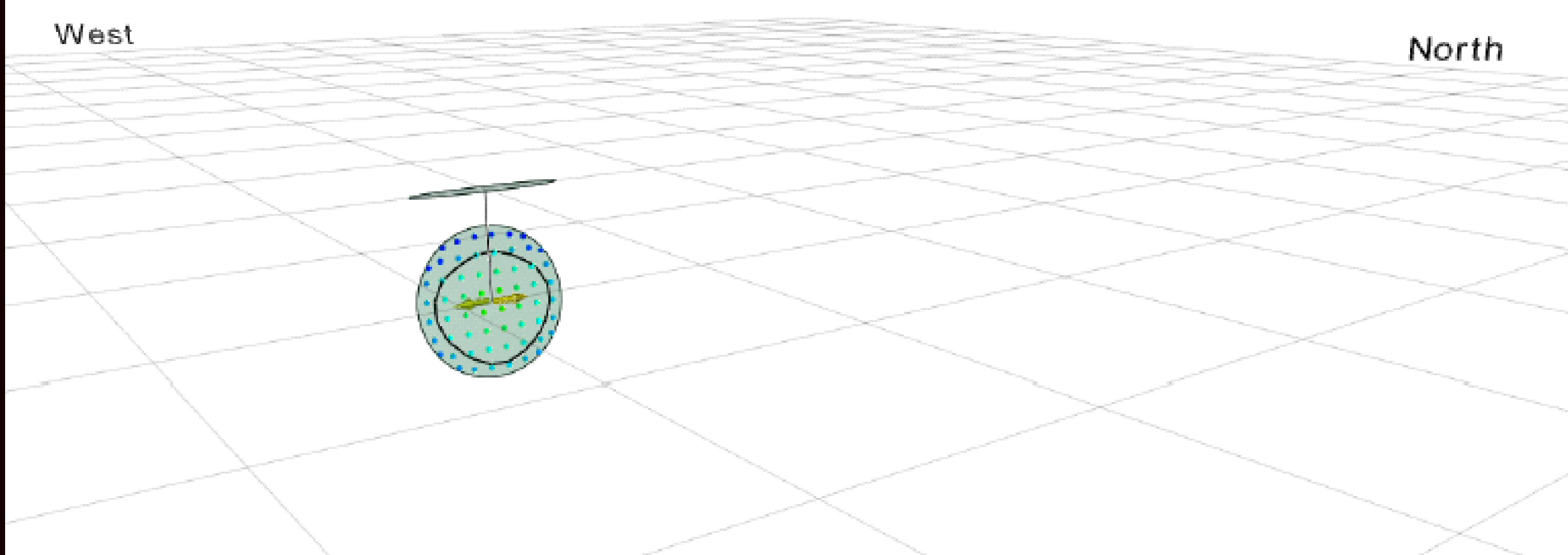

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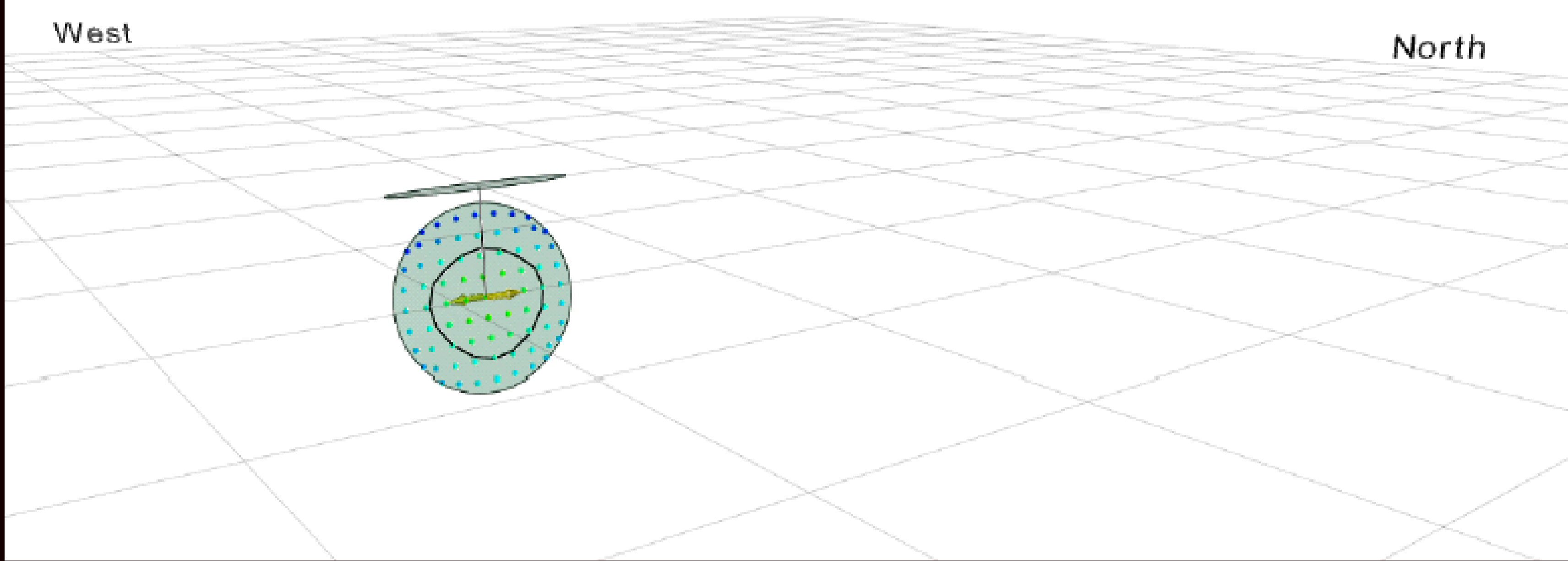

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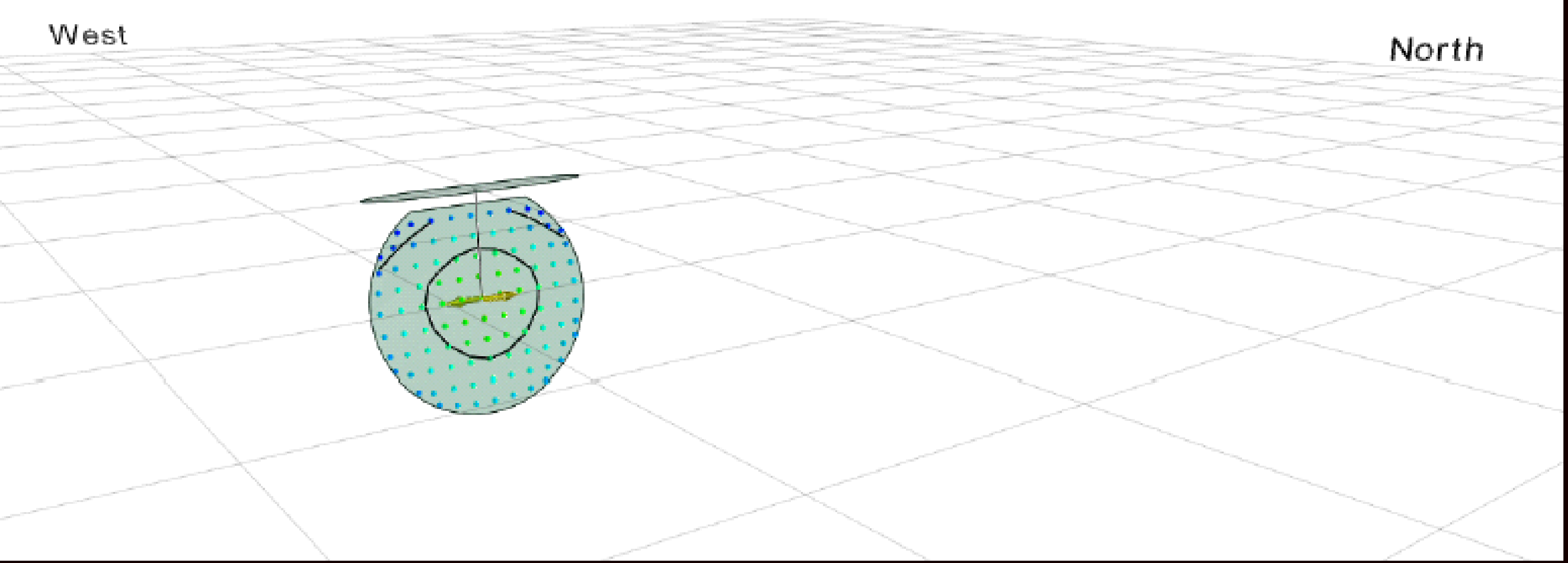

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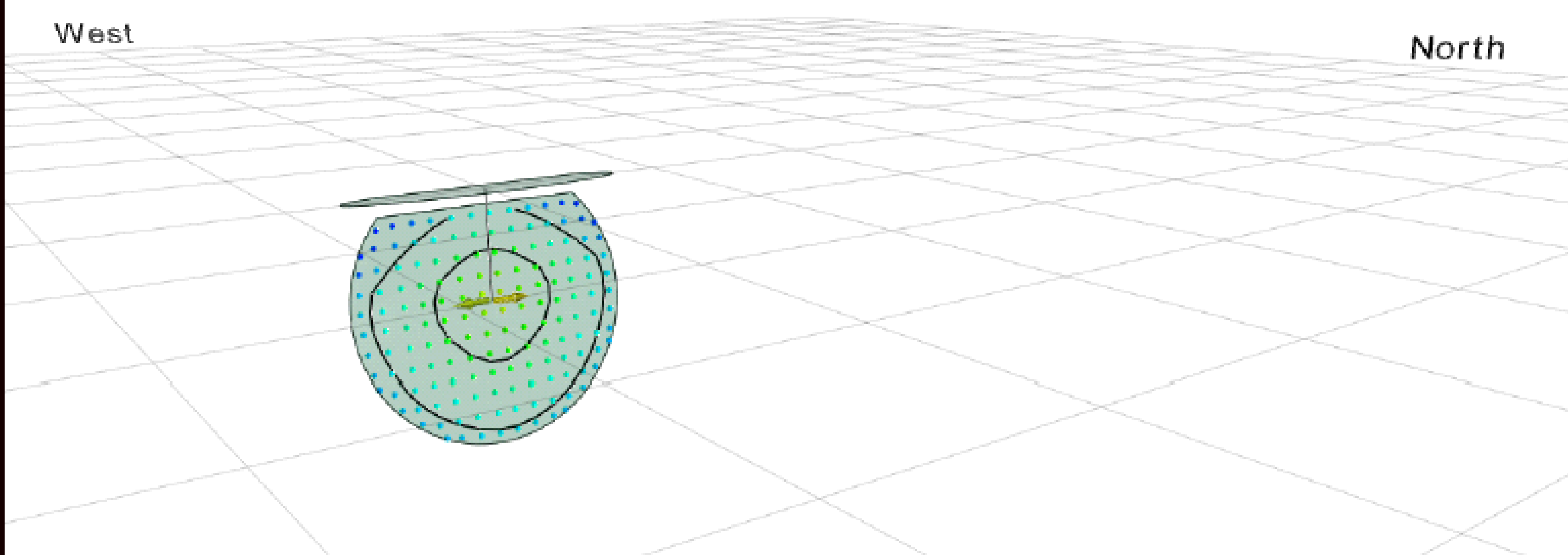

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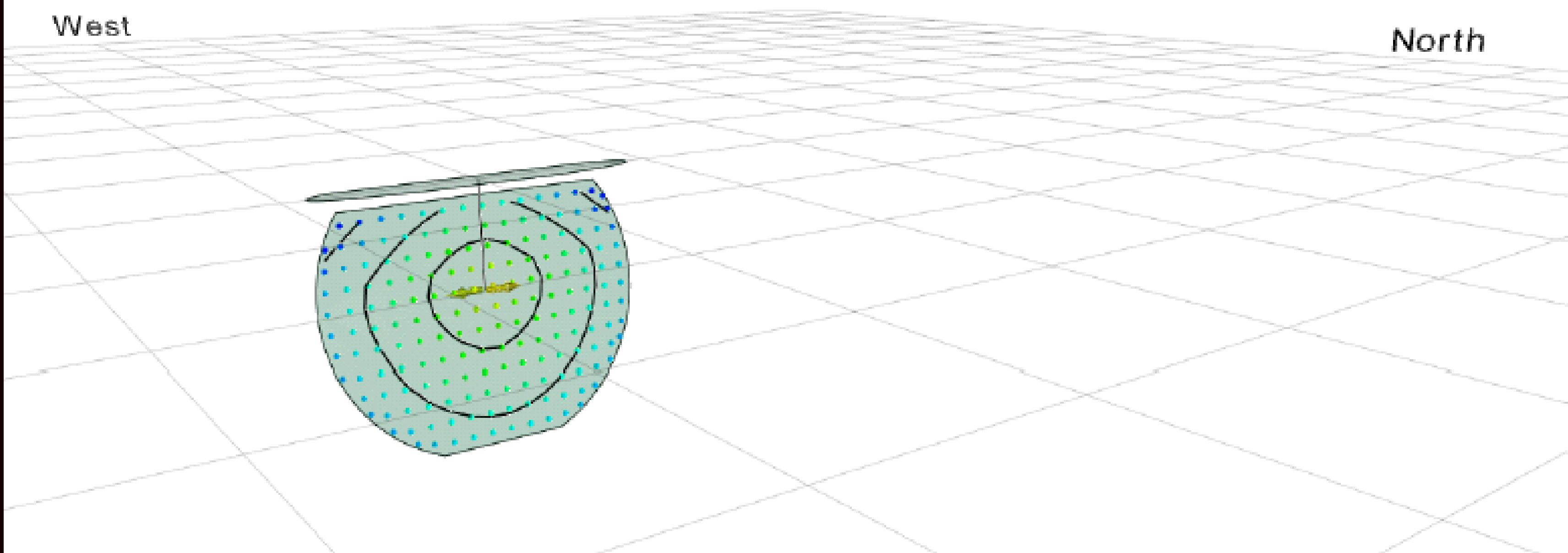

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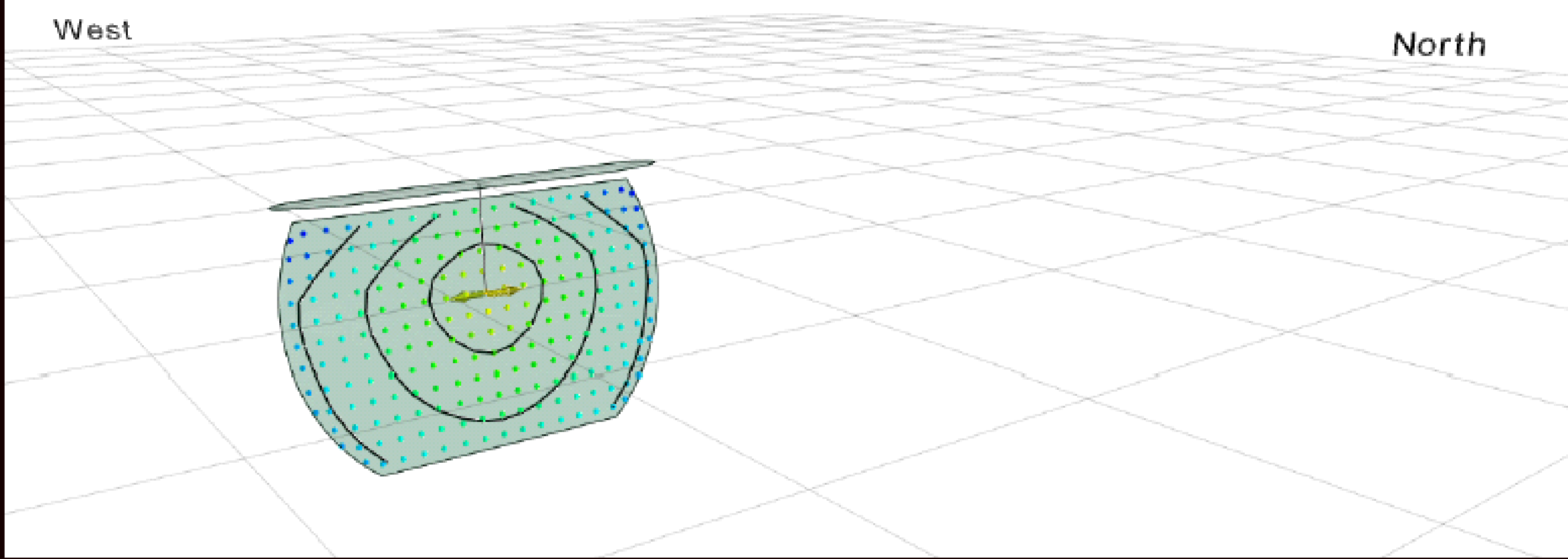

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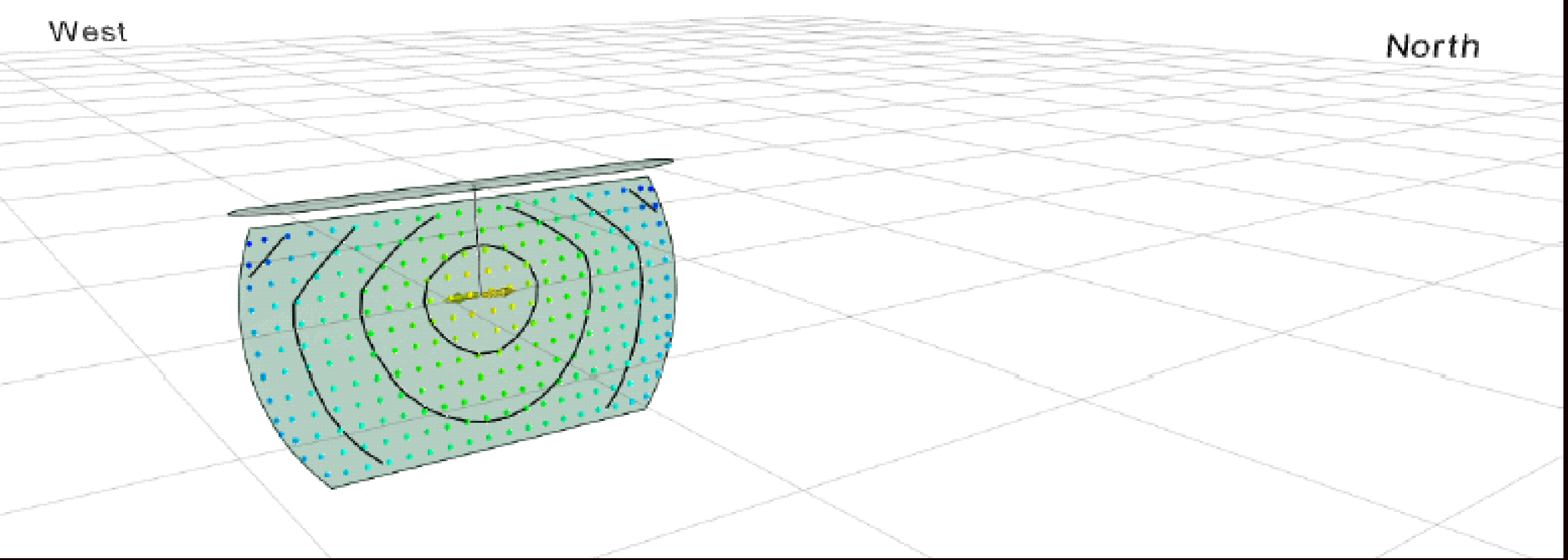

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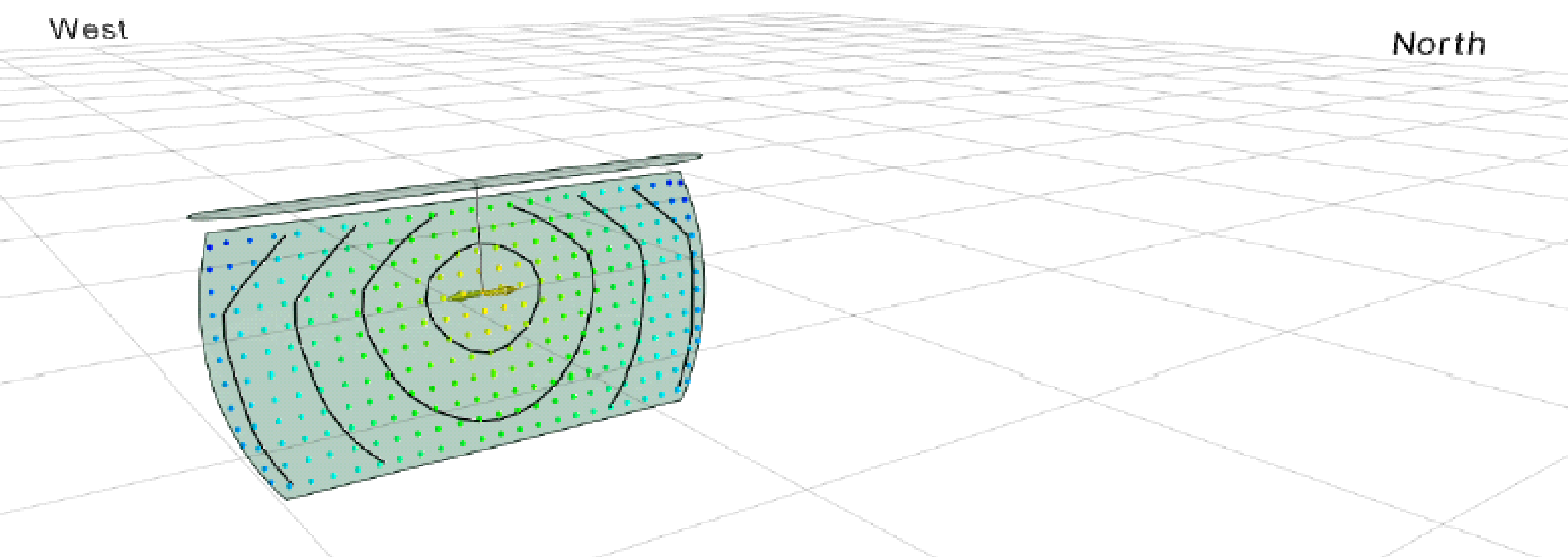

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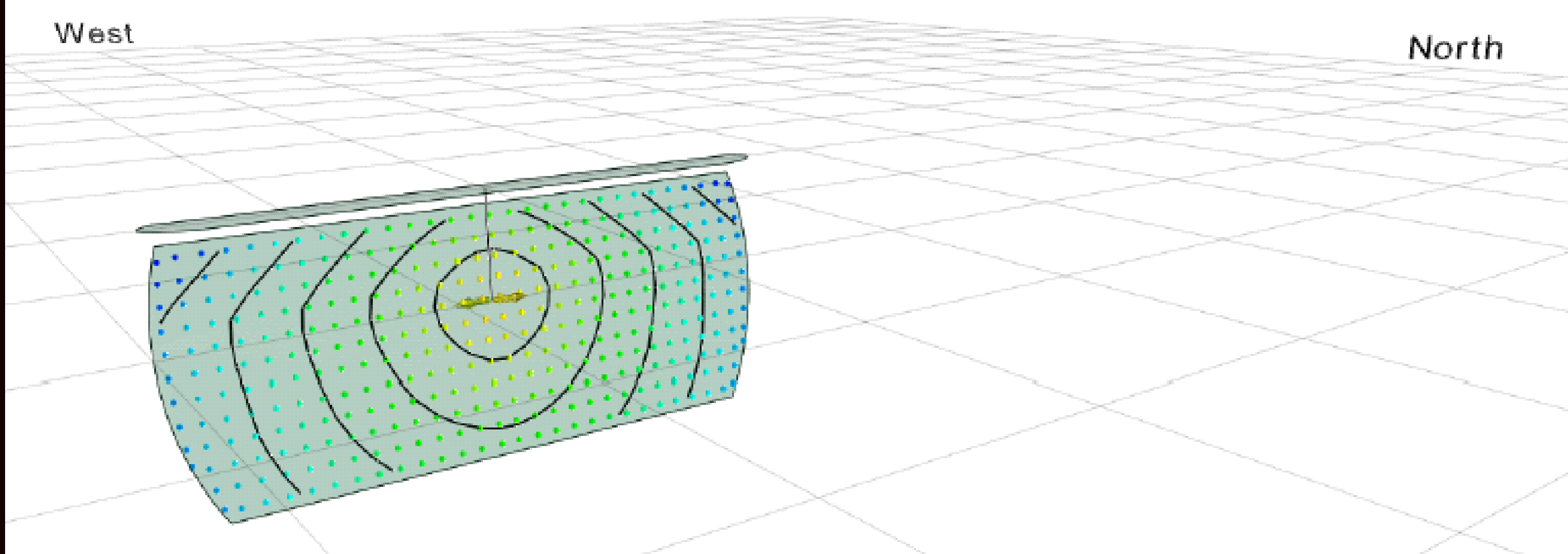

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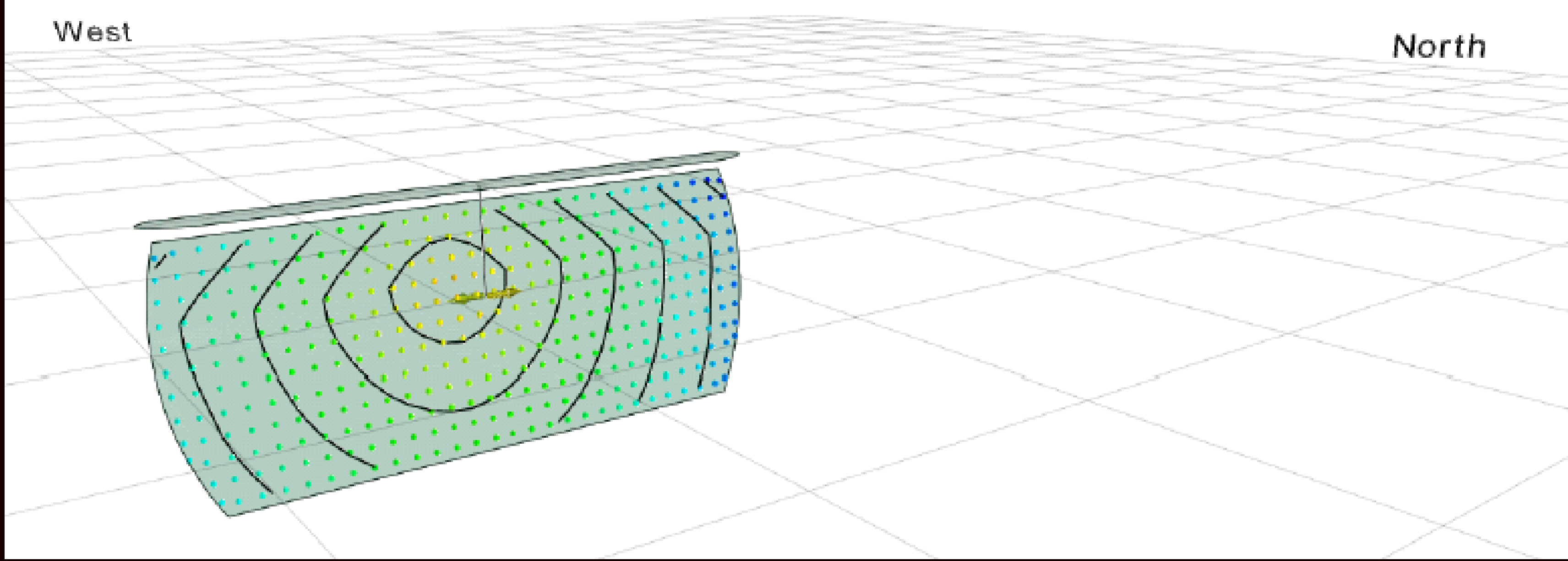

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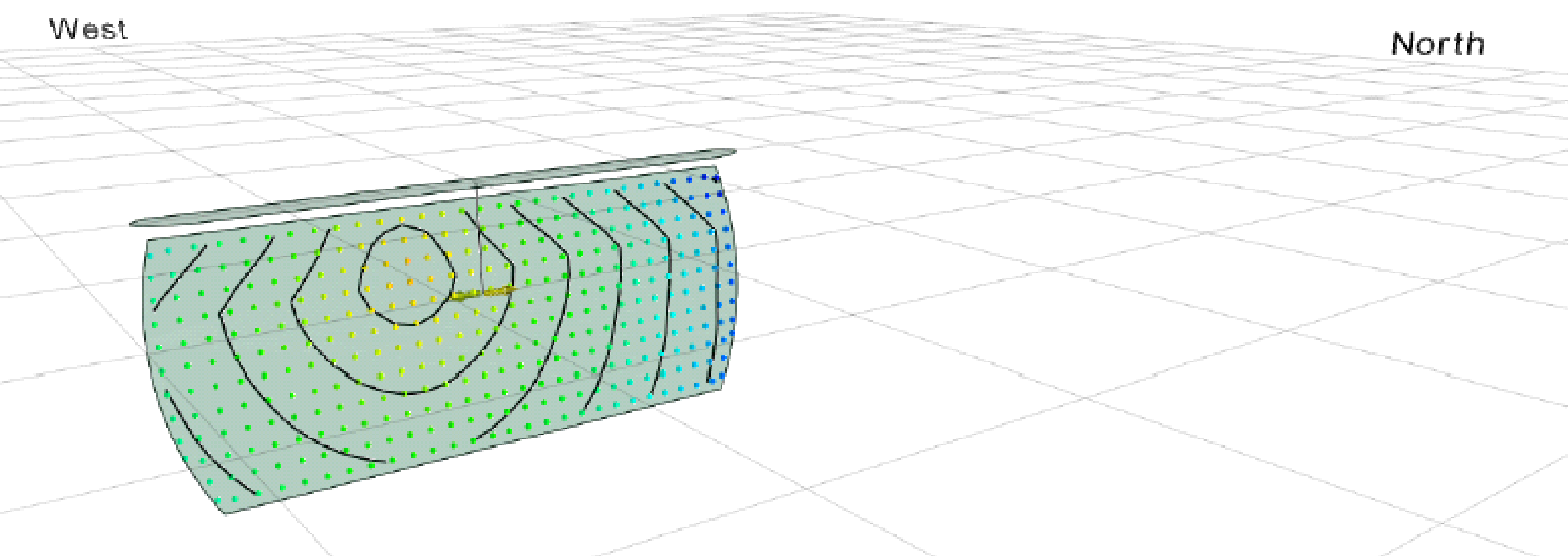

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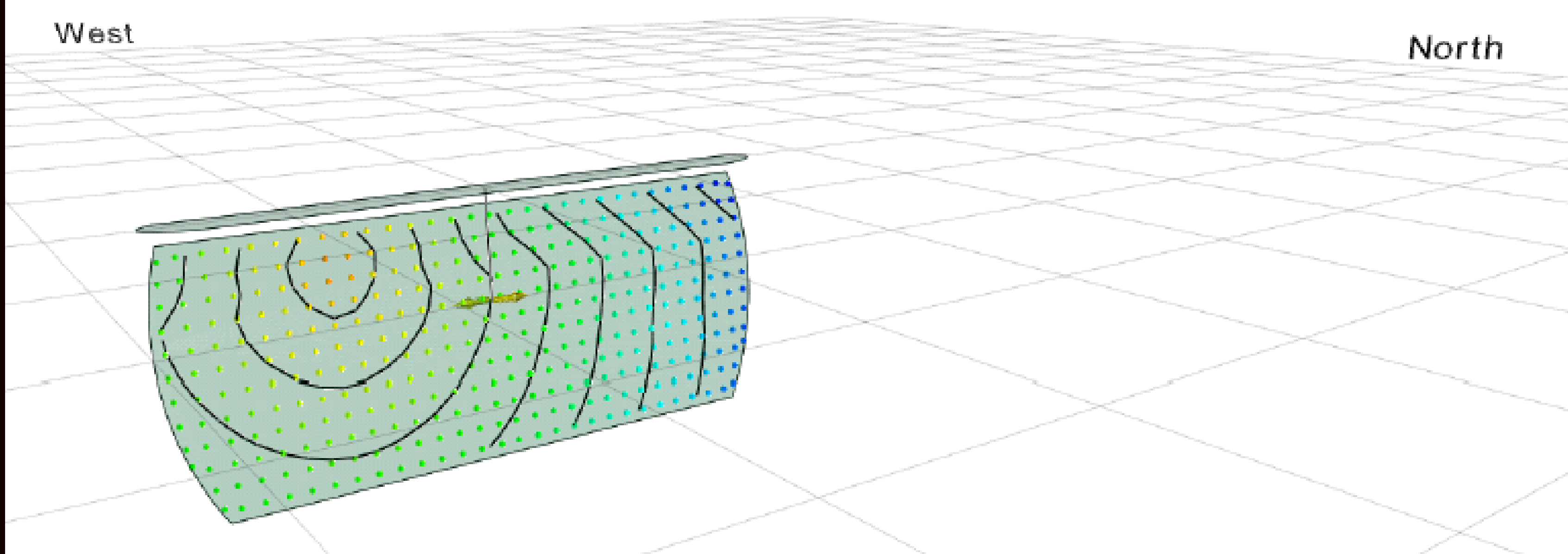

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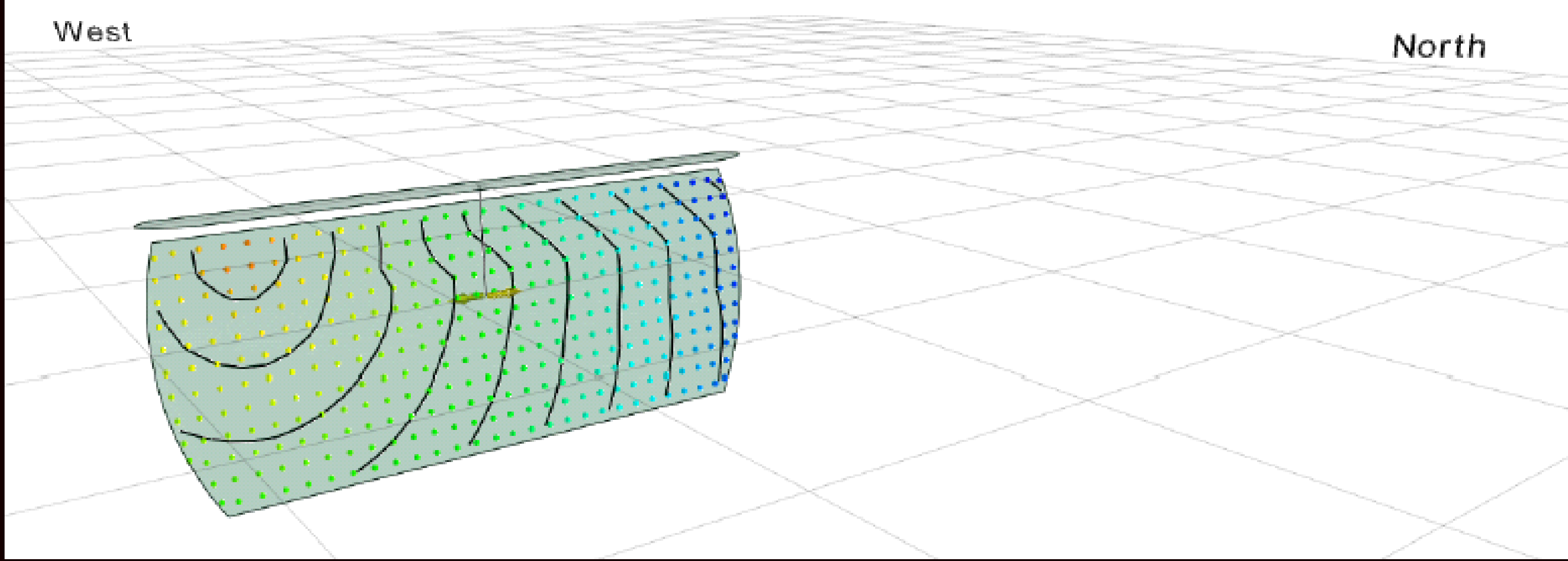

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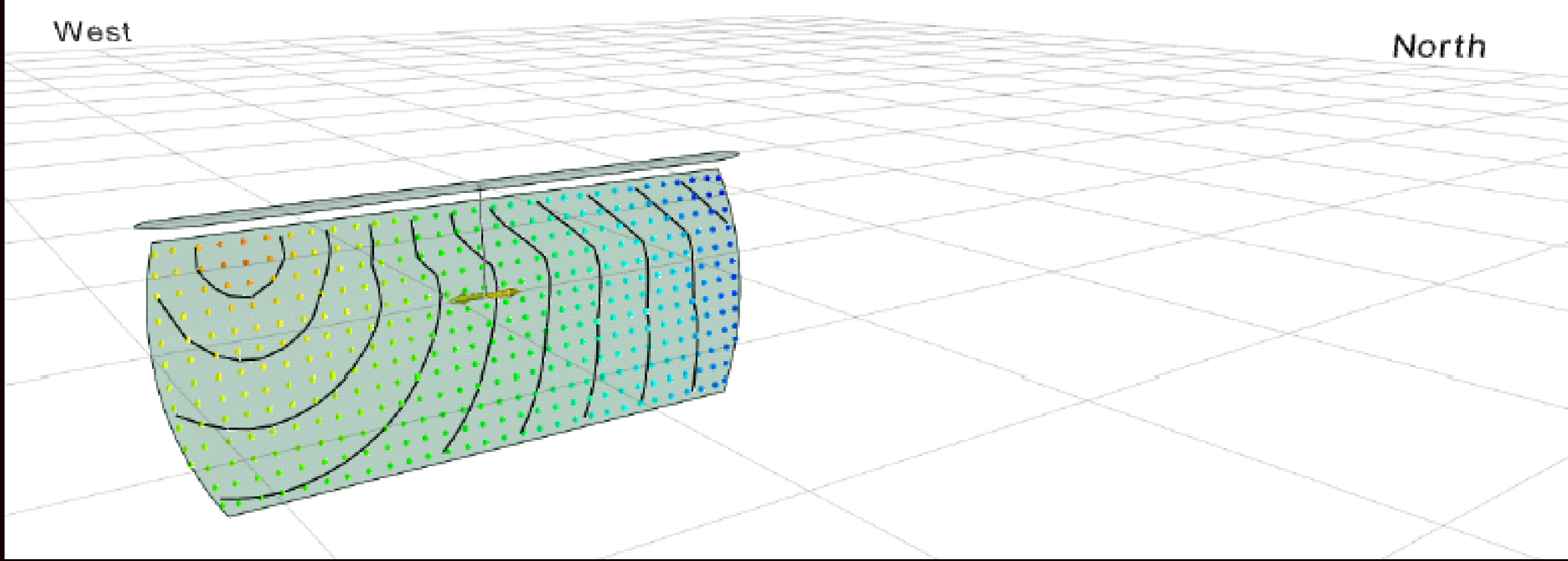

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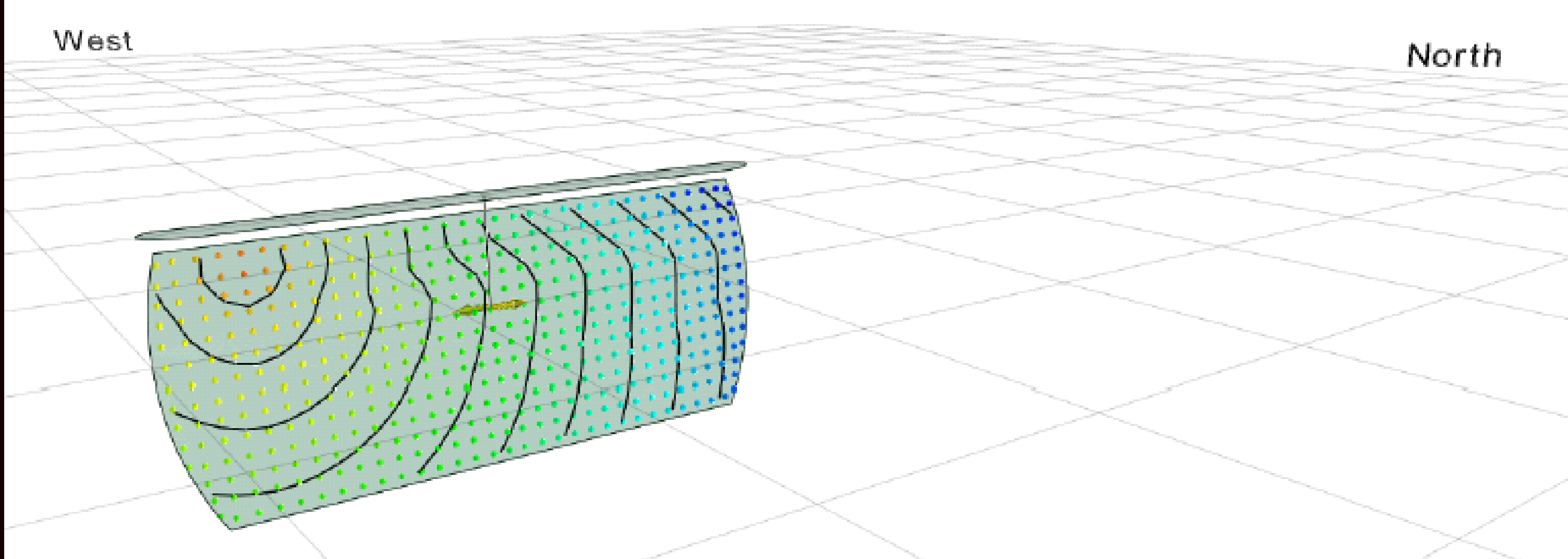

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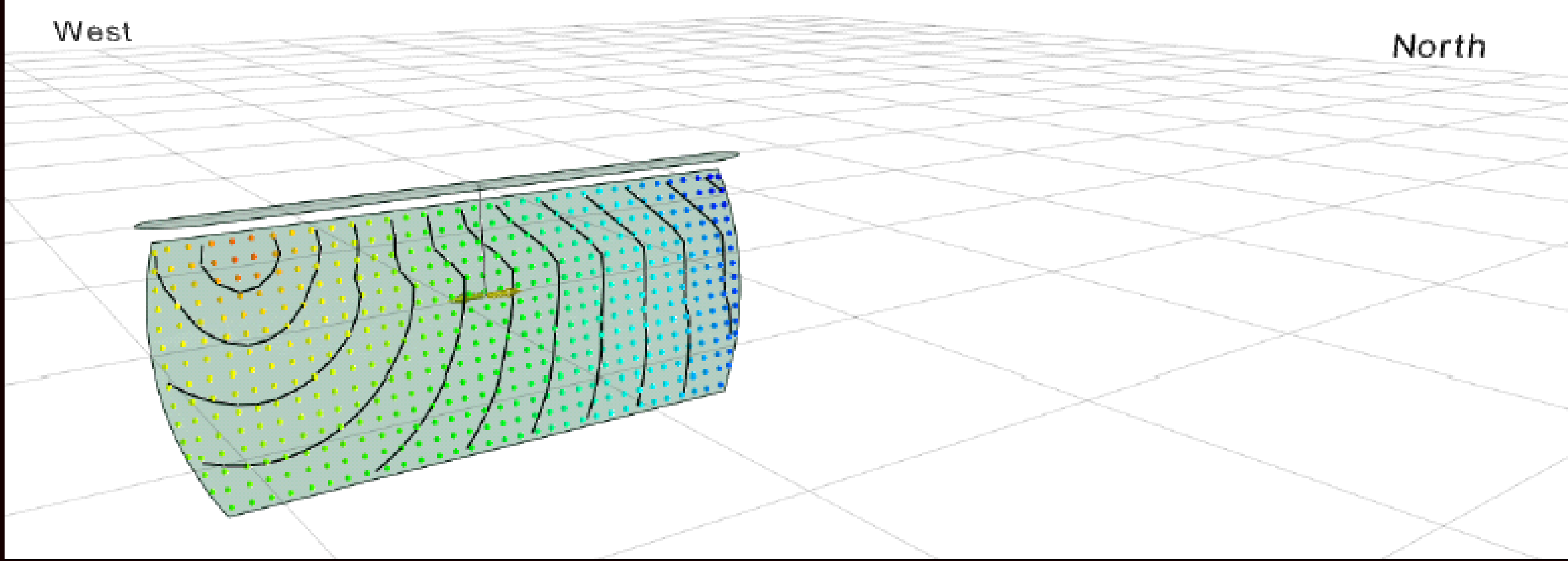

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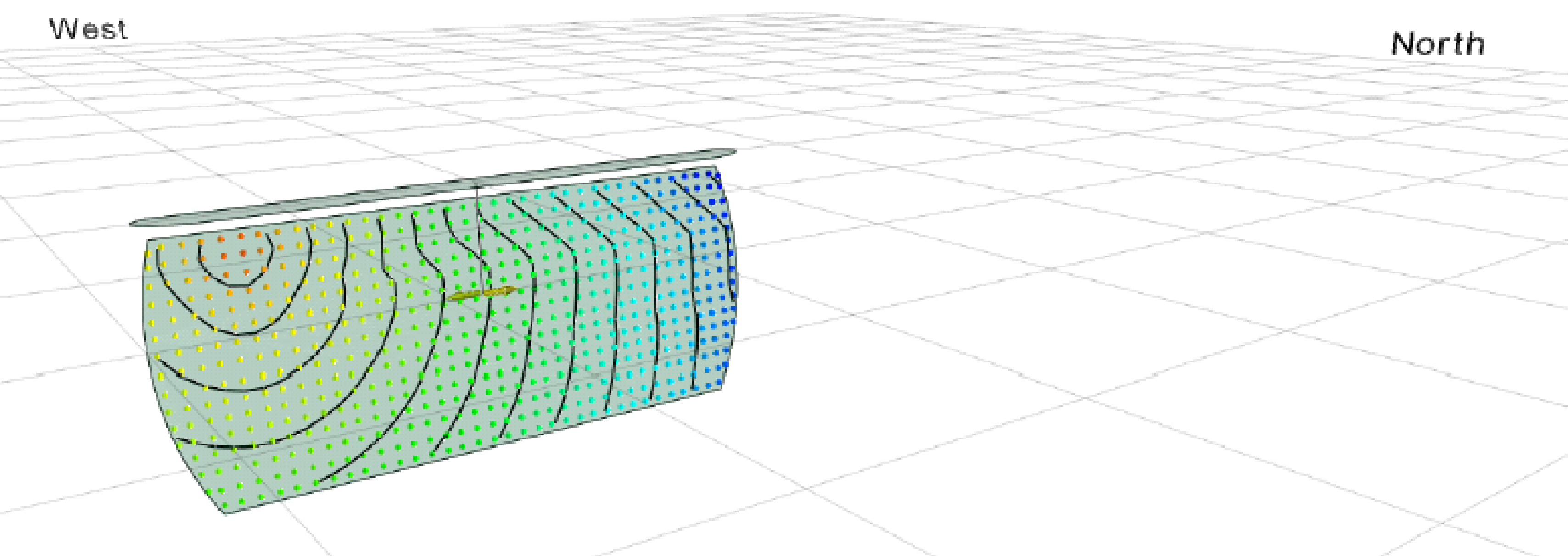

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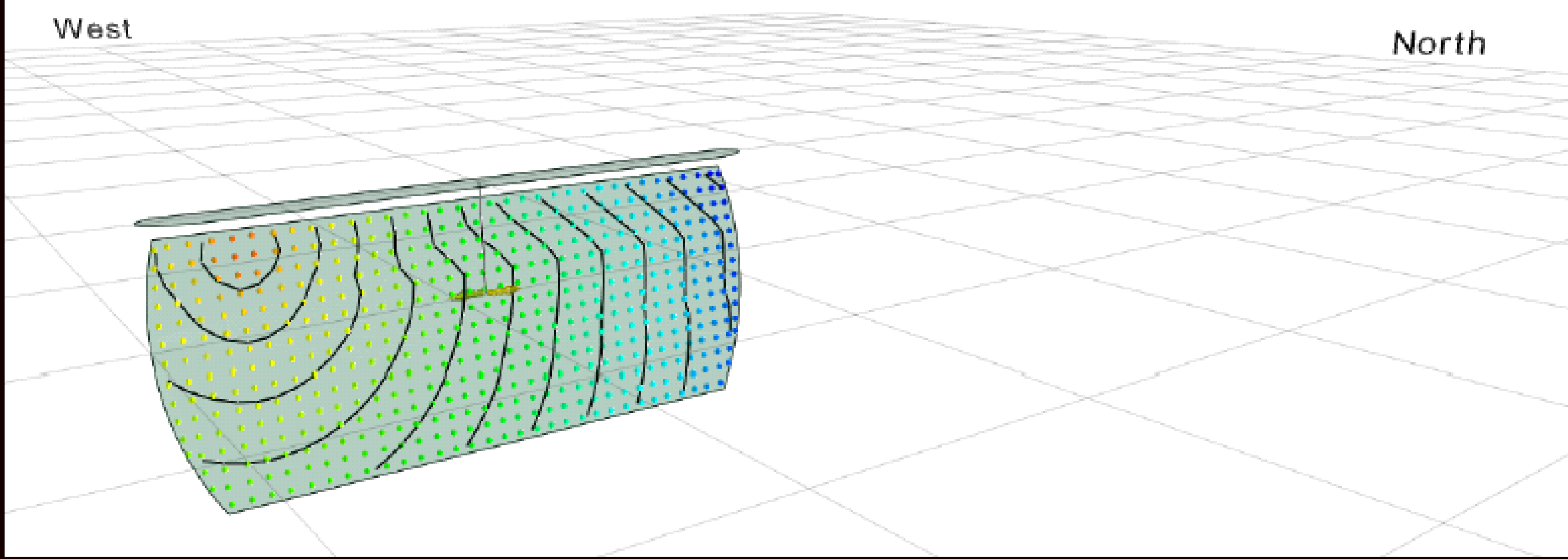

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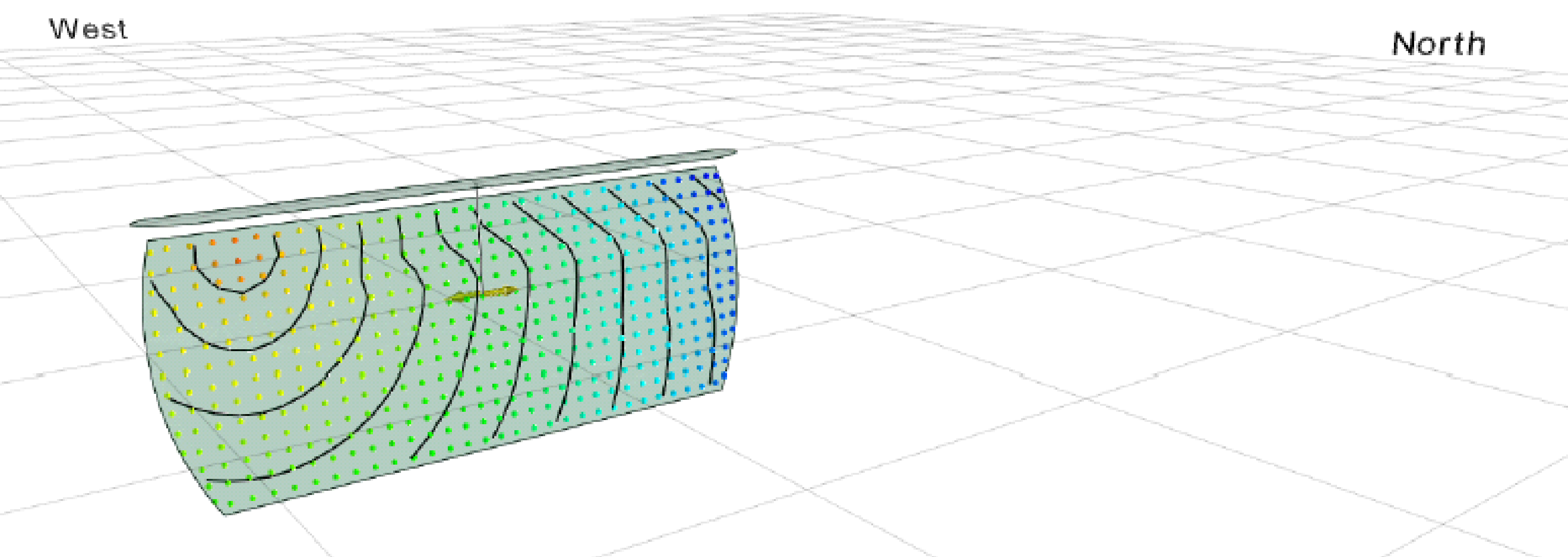

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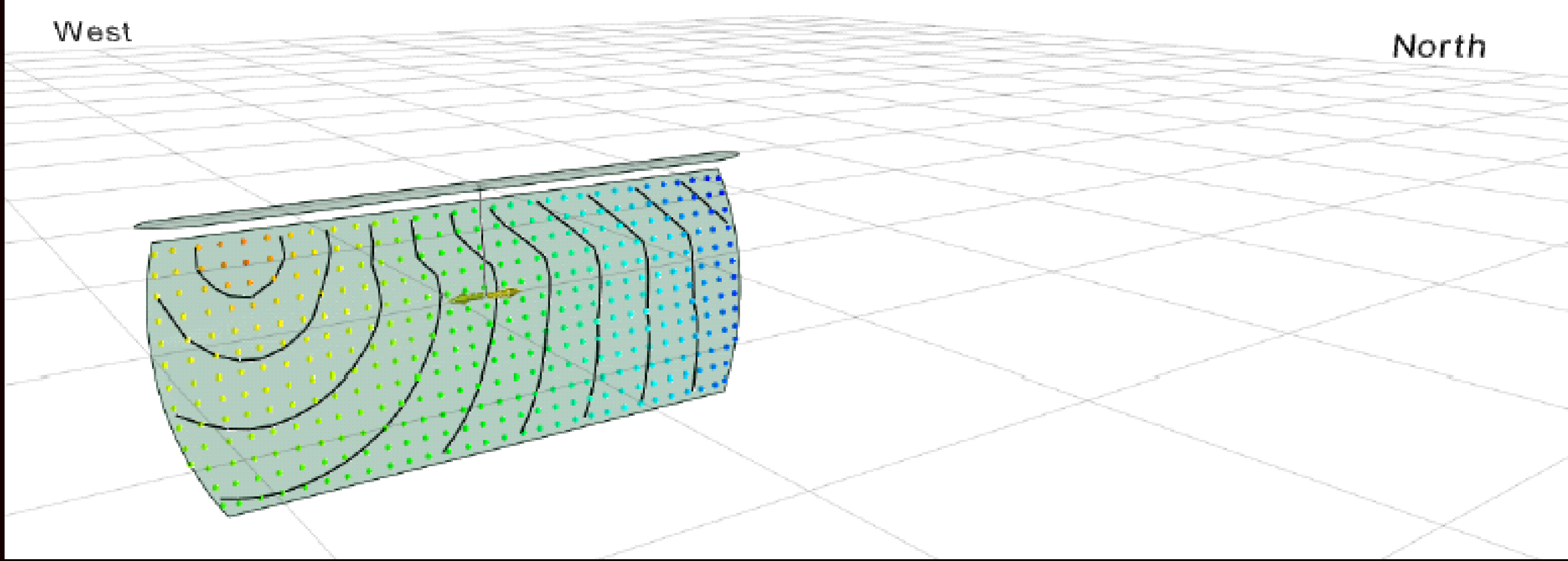

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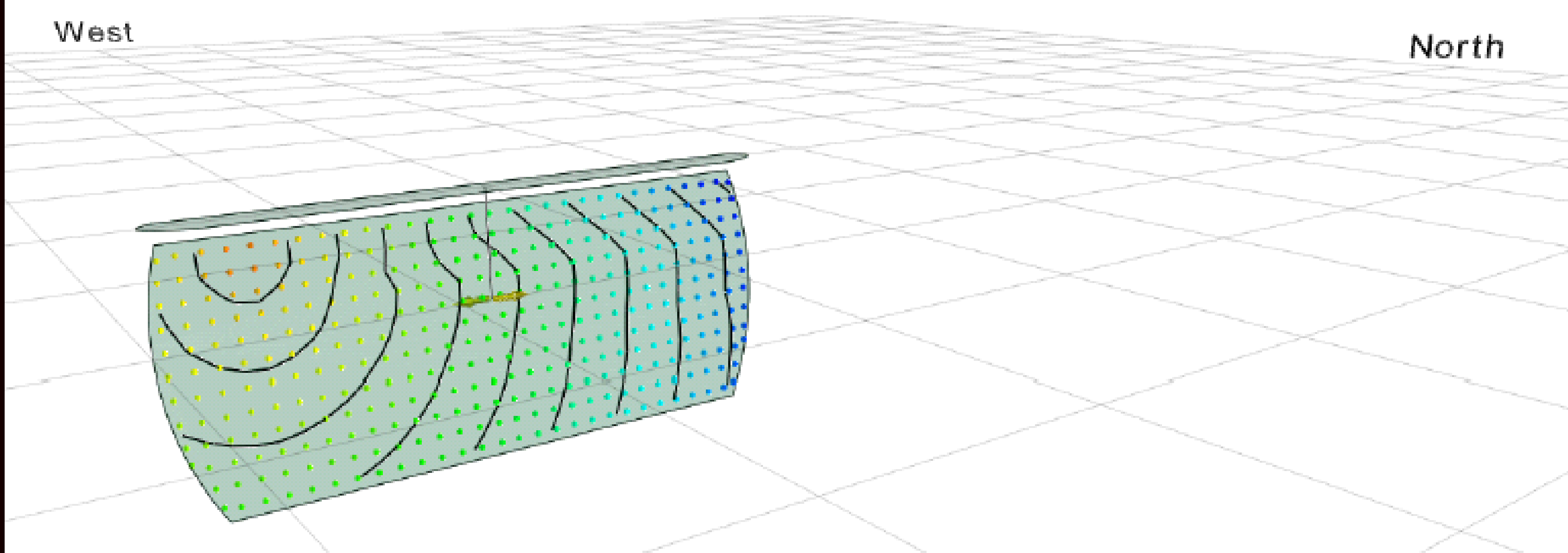
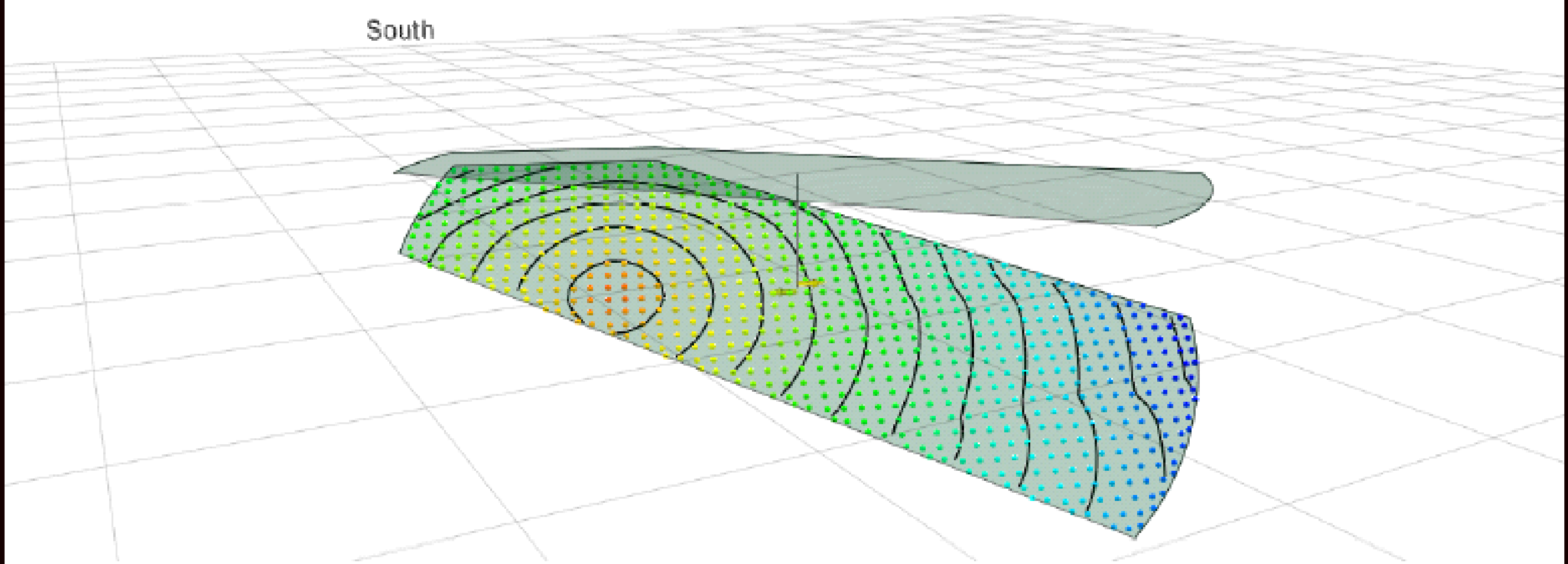


- Constraining planes enable implementation of quite complex geometries.
- E.g. the geometry of a subduction slab could be given.



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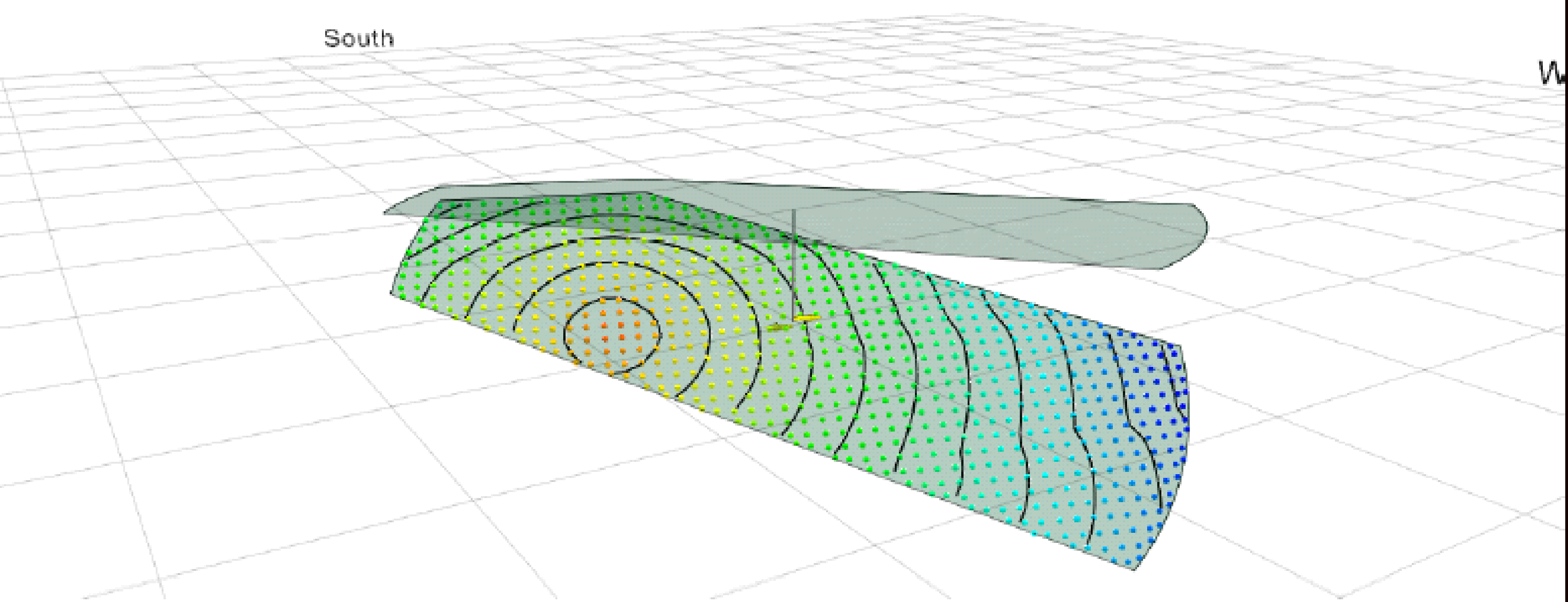

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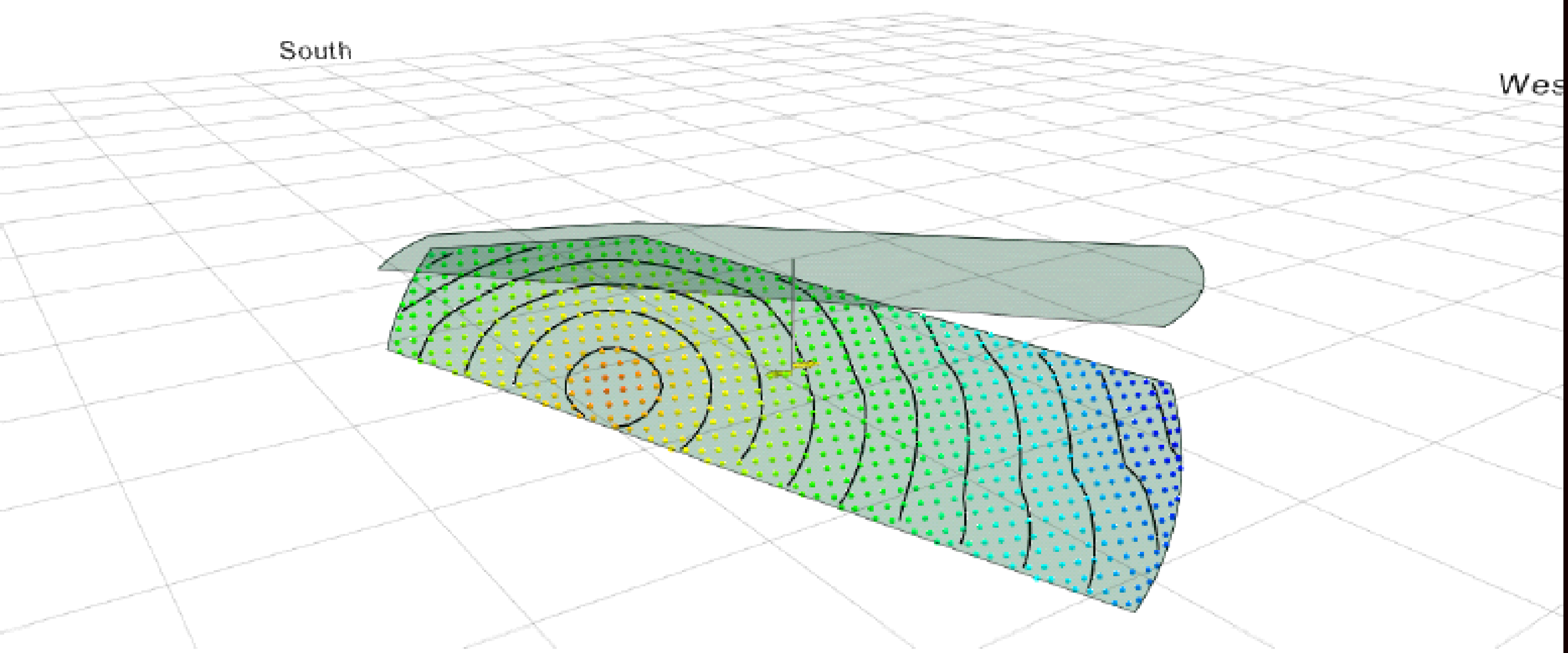

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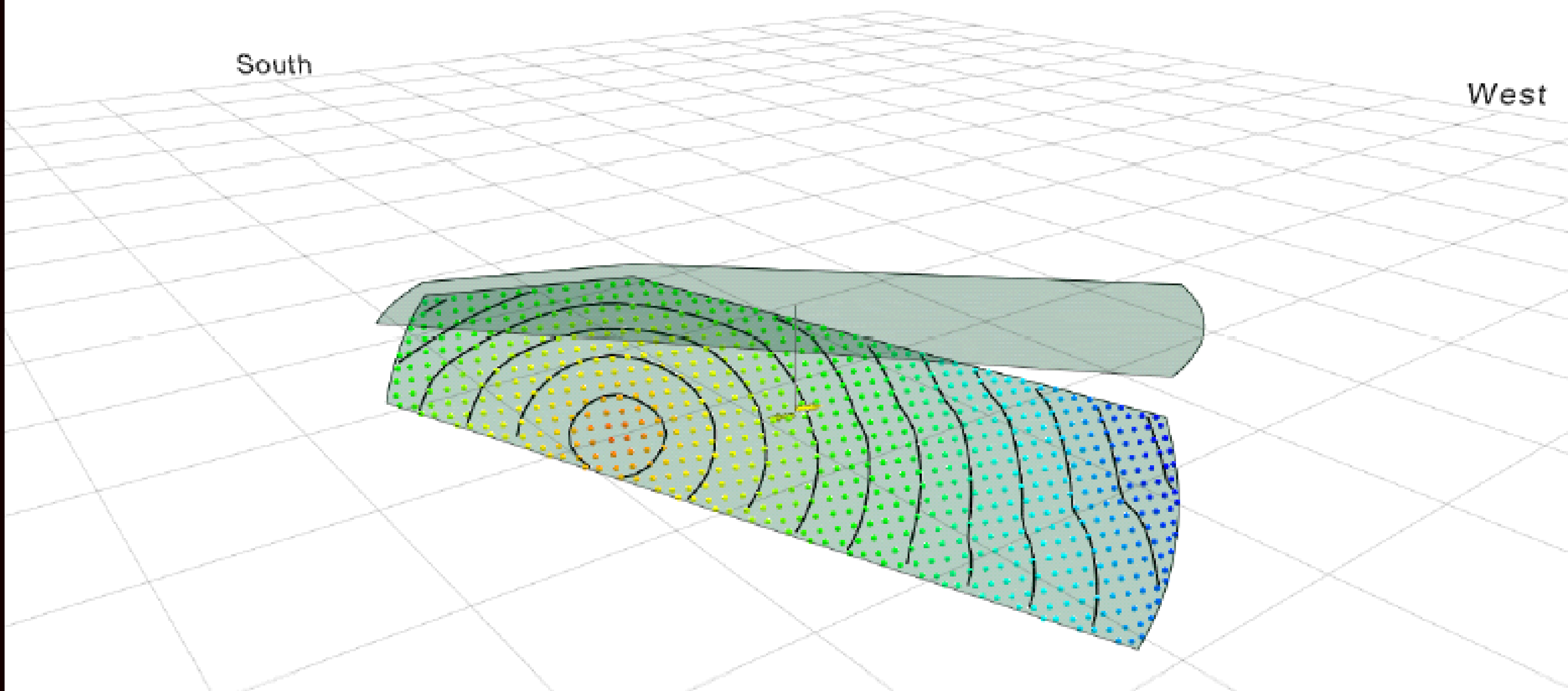

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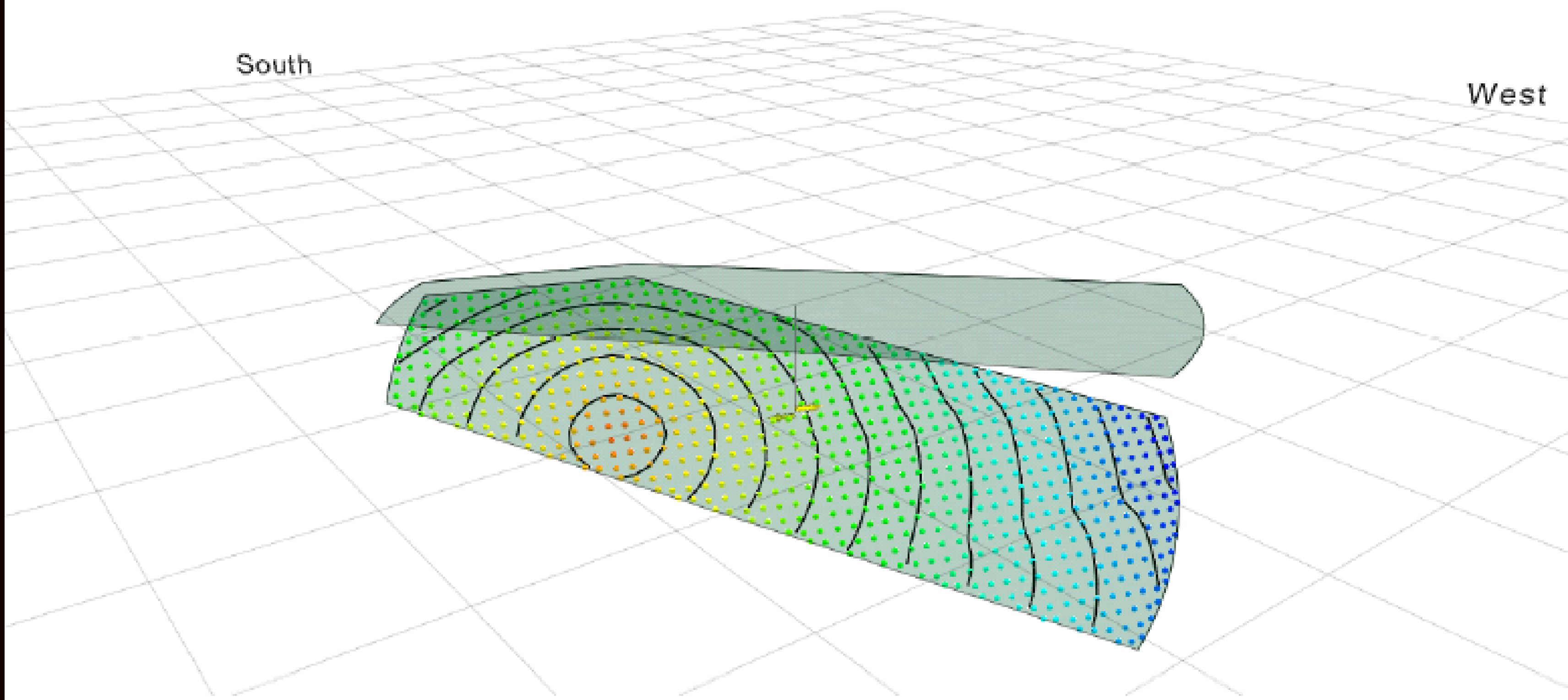
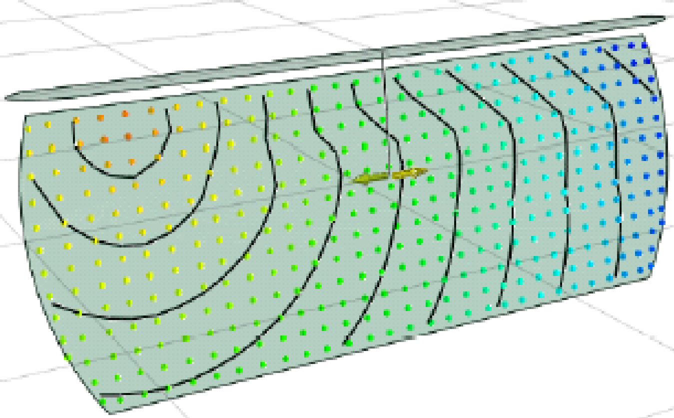


Despite its flexibility the eikonal source model is described by only 13 parameters.

(Considering constraints and earth model as fixed and known. :-)



13 parameters:

time
north-shift
east-shift
depth
moment
strike
dip
slip rake
border radius
nucleation point x-shift
nucleation point y-shift
relative rupture velocity
rise-time

The eikonal source model, only 13 parameters

Circular area, plus constraints

Rupture velocity scales with shear velocity

Despite its flexibility, the eikonal source model is described by only 13 parameters (considering constraints and earth model as fixed and known)

13 parameters:

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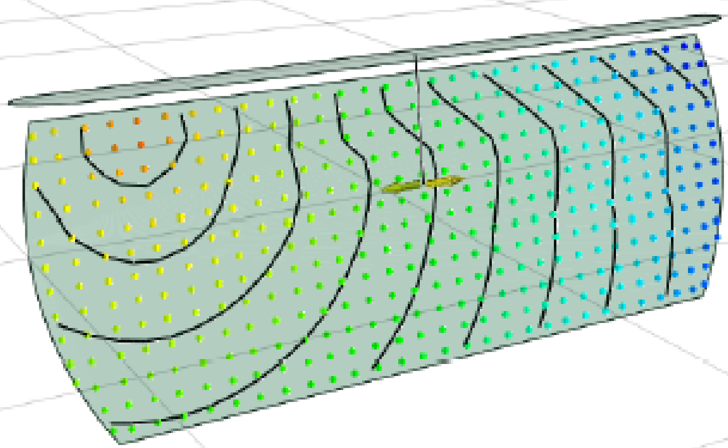


Heimann 2011

Source model parameters and inversion priorities

Source model parameters (13)

Time	Lat	Lon	Depth	M_0	Strike	Dip	Rake	Rad	NucX	NucY	RuptV	RiseT

General source description

Source location	Radiation pattern	Rupture process

Scale of source model

Point source	Finite source

Information from data

Low frequencies	High frequencies

Inversion priority

Step 1, 2	Step 3

Inversion strategy

Time | Lat | Lon | Depth | M_0

Step 1, Focal mechanism (DC and full moment tensor)

amplitude spectra inversion

Depth | M_0 | Strike | Dip | Rake

Inversion strategy

Time	Lat	Lon	Depth	M_0

Step 1b, Full moment tensor

amplitude spectra inversion

Depth	M_0	Strike	Dip	Rake

Depth	M_{xx}	M_{yy}	M_{zz}	M_{xy}	M_{xz}	M_{yz}

Inversion strategy

Time	Lat	Lon	Depth	M_0	Strike	Dip	Rake

Depth	M_0	Strike	Dip	Rake

Step 2, Focal mechanism (DC and full moment tensor)

waveform inversion

Time	Lat	Lon	Depth	M_0	Strike	Dip	Rake

Inversion strategy

Time | Lat | Lon | Depth | M_0 | Strike | Dip | Rake

Depth | M_0 | Strike | Dip | Rake

Step 2b, Full moment tensor

waveform inversion

Time | Lat | Lon | Depth | M_0 | Strike | Dip | Rake

Time | Lat | Lon | Depth | M_{xx} | M_{yy} | M_{zz} | M_{xy} | M_{xz} | M_{yz}

Inversion strategy

Time | Lat | Lon | Depth | M_0

Depth | M_0 | Strike | Dip | Rake

Time | Lat | Lon | Depth | M_0 | Strike | Dip | Rake

Step 3, Kinematic source model

amplitude spectra inversion (incl. higher frequencies)

Time | Lat | Lon | Depth | M_0 | Strike | Dip | Rake | Rad | NucX | NucY | RuptV | RiseT

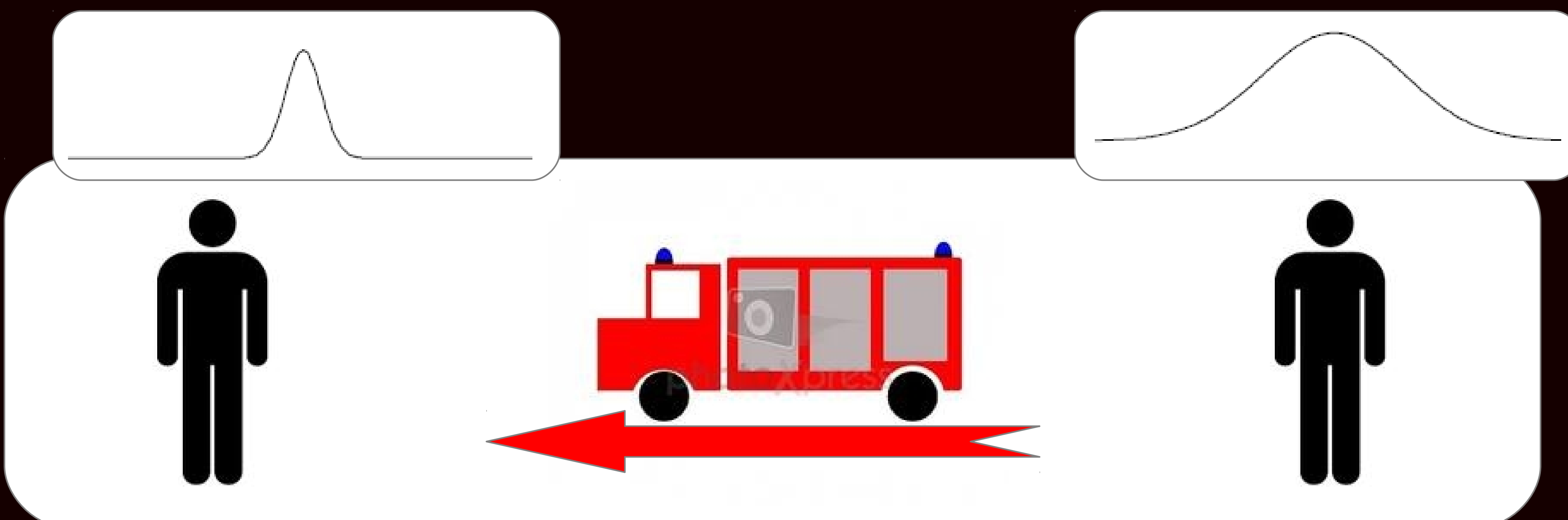
Fast directivity detection

A simplified, but fast, alternative approach

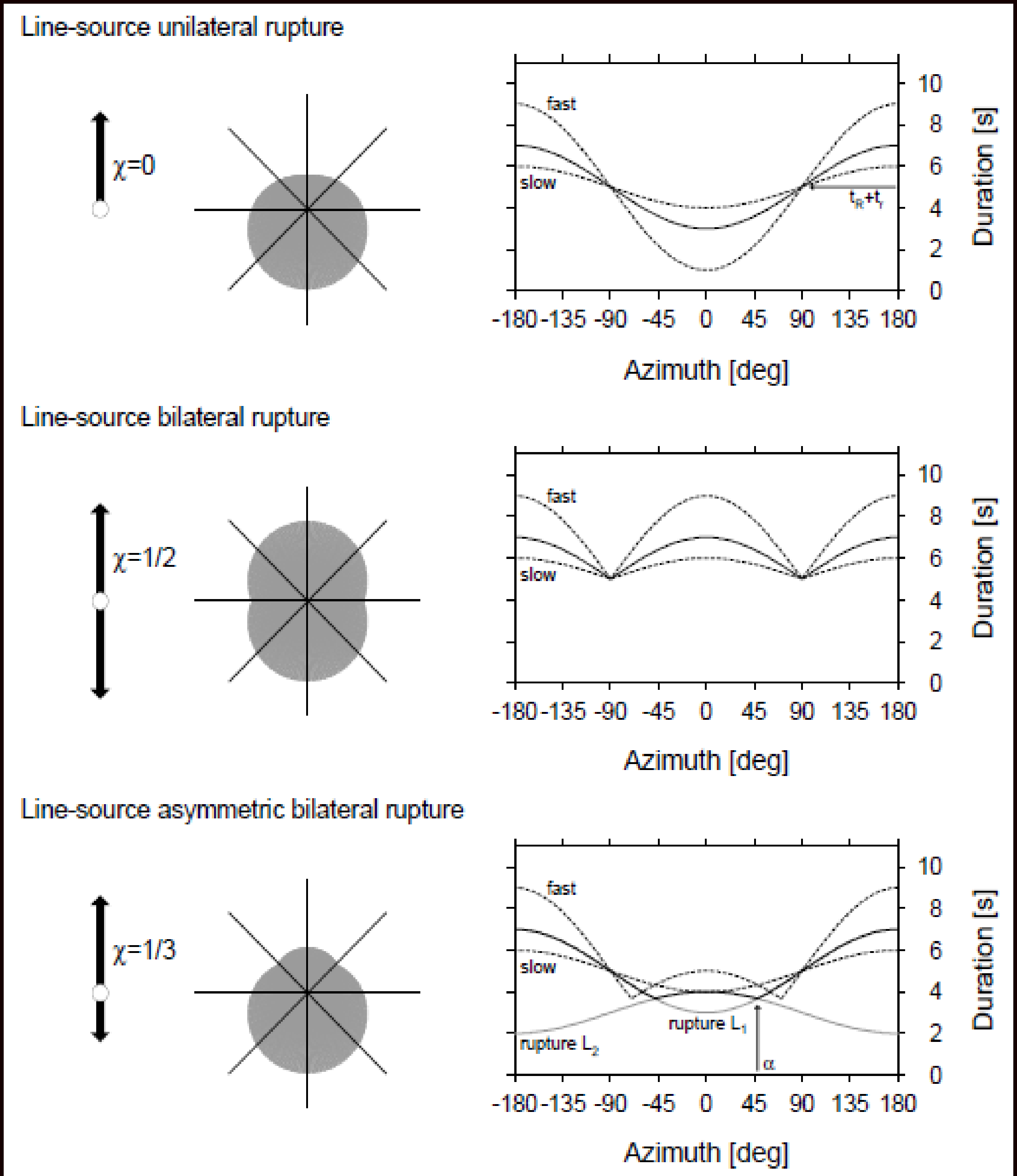
Spatial point source approximation

Apparent STF duration at single station

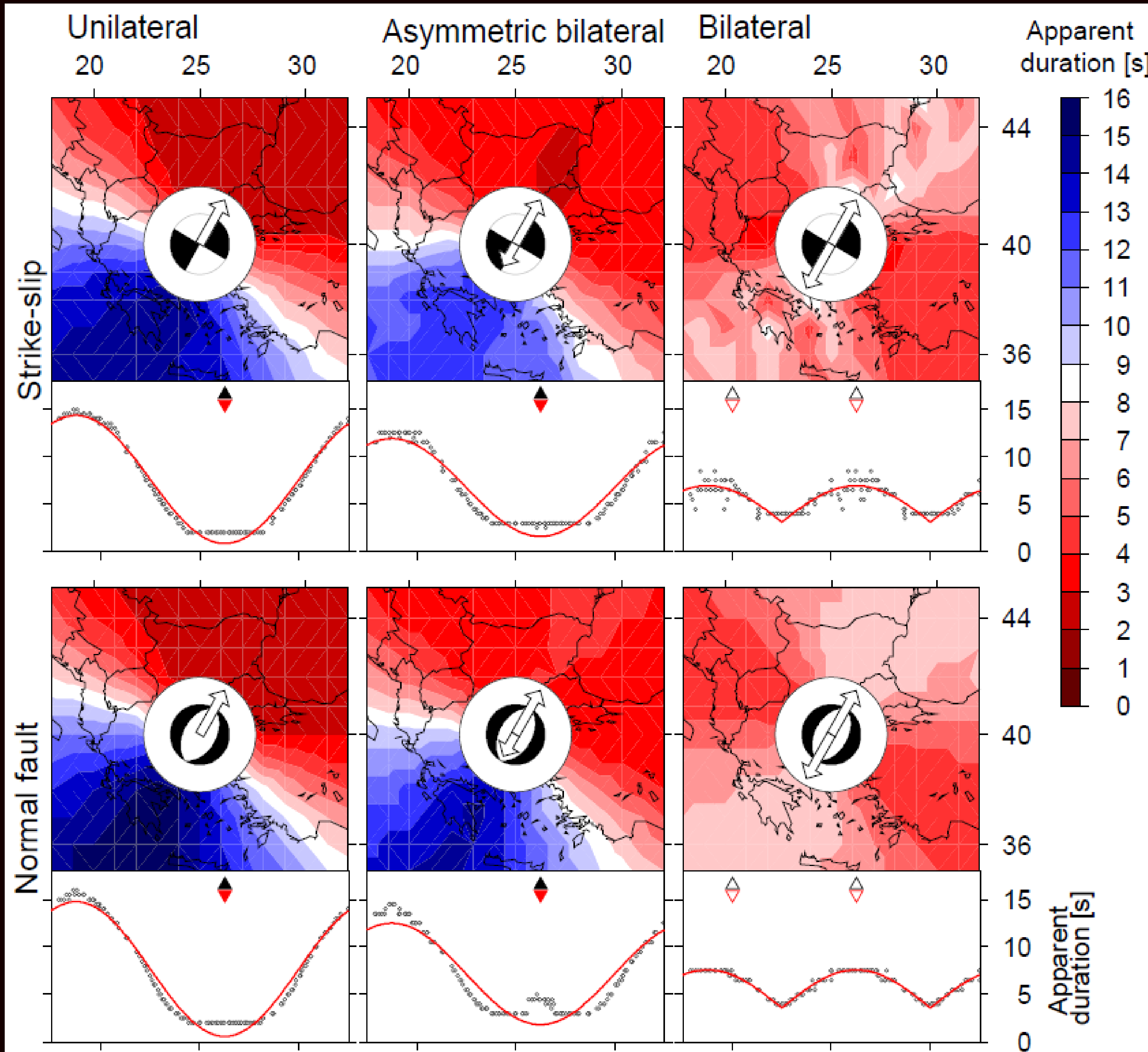
Azimuthal variation of apparent STF



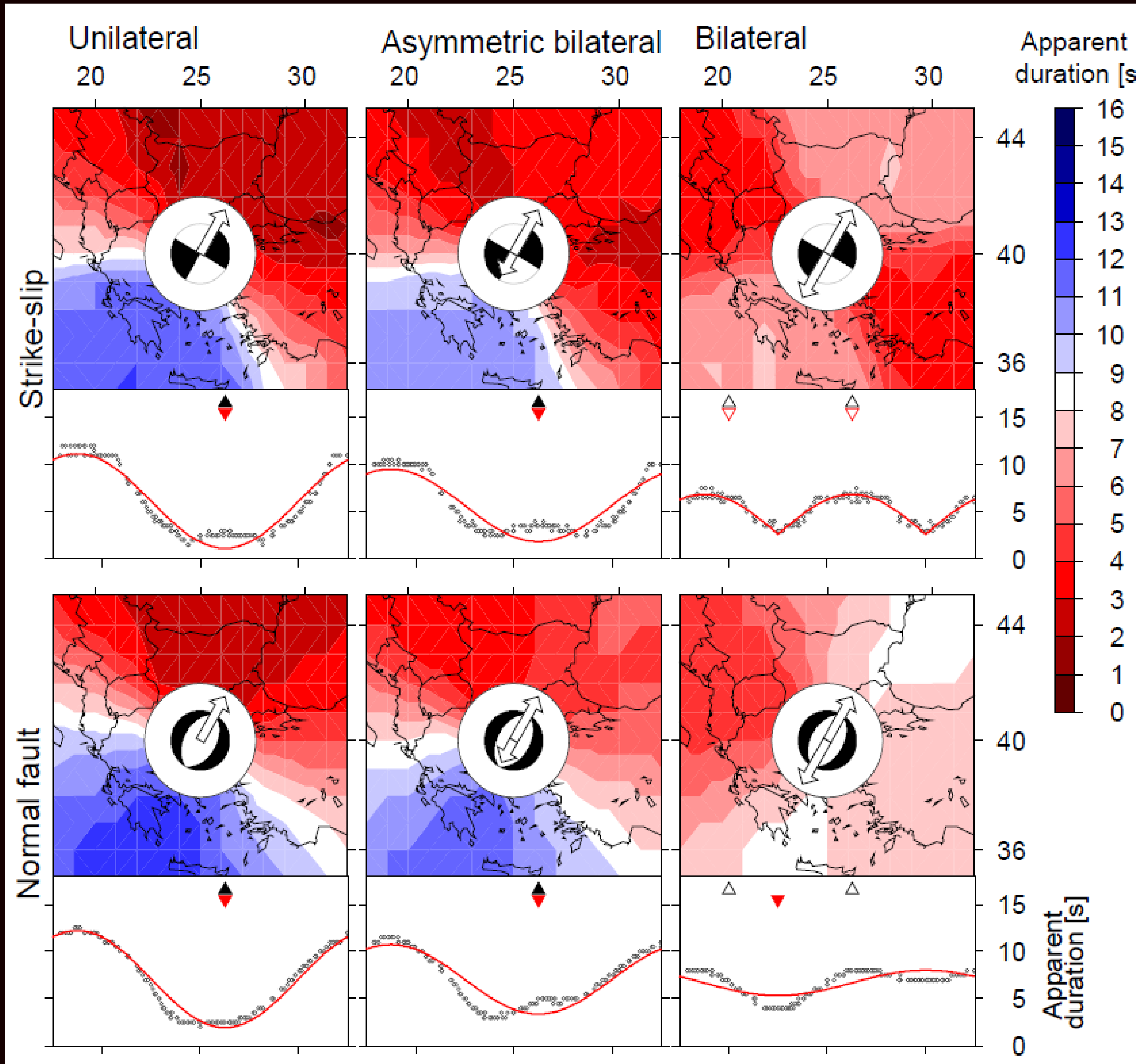
Fast directivity detection



Cesca et al.
J. Seismol. 2011

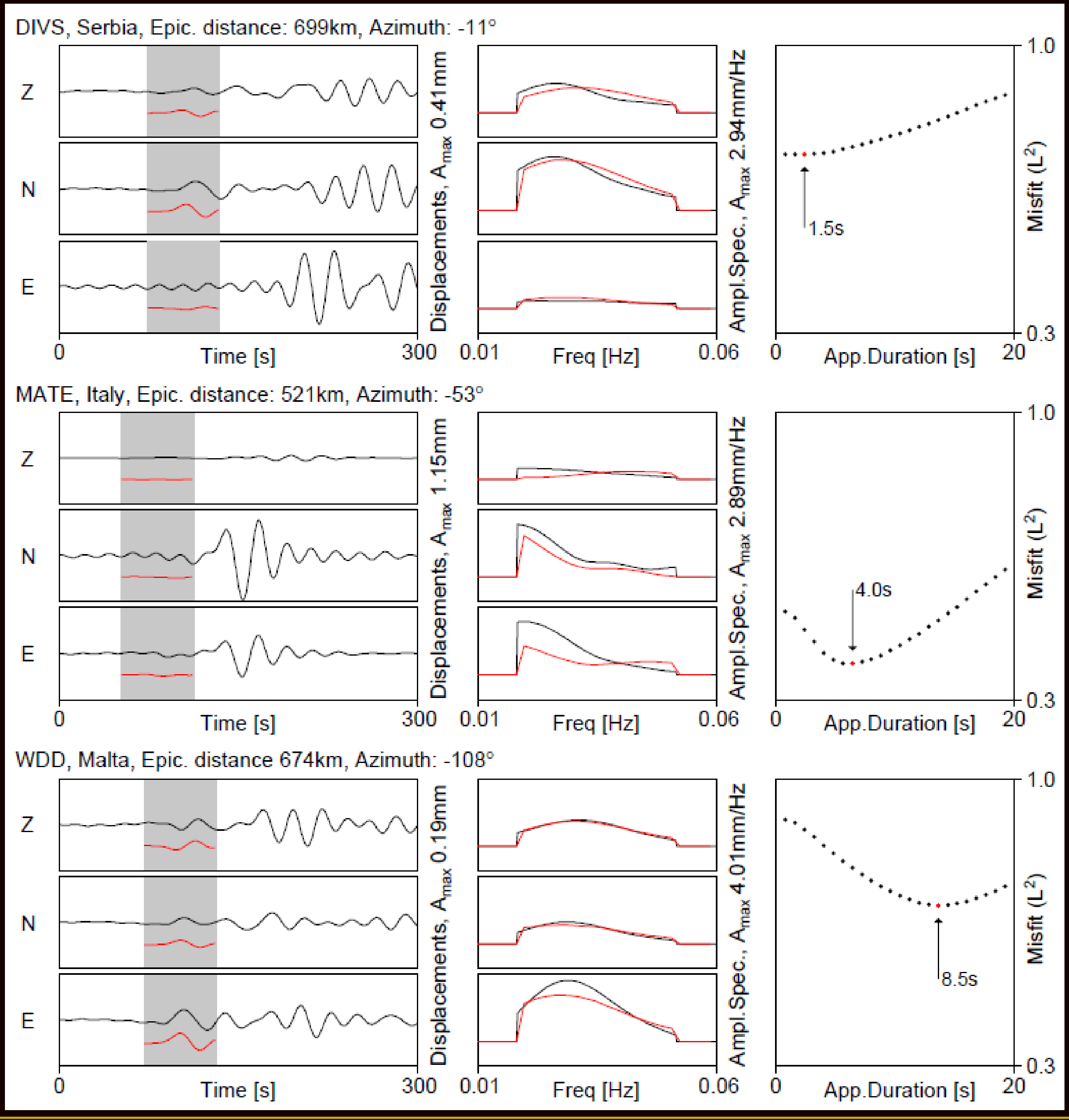


Cesca et al.
J. Seismol. 2011

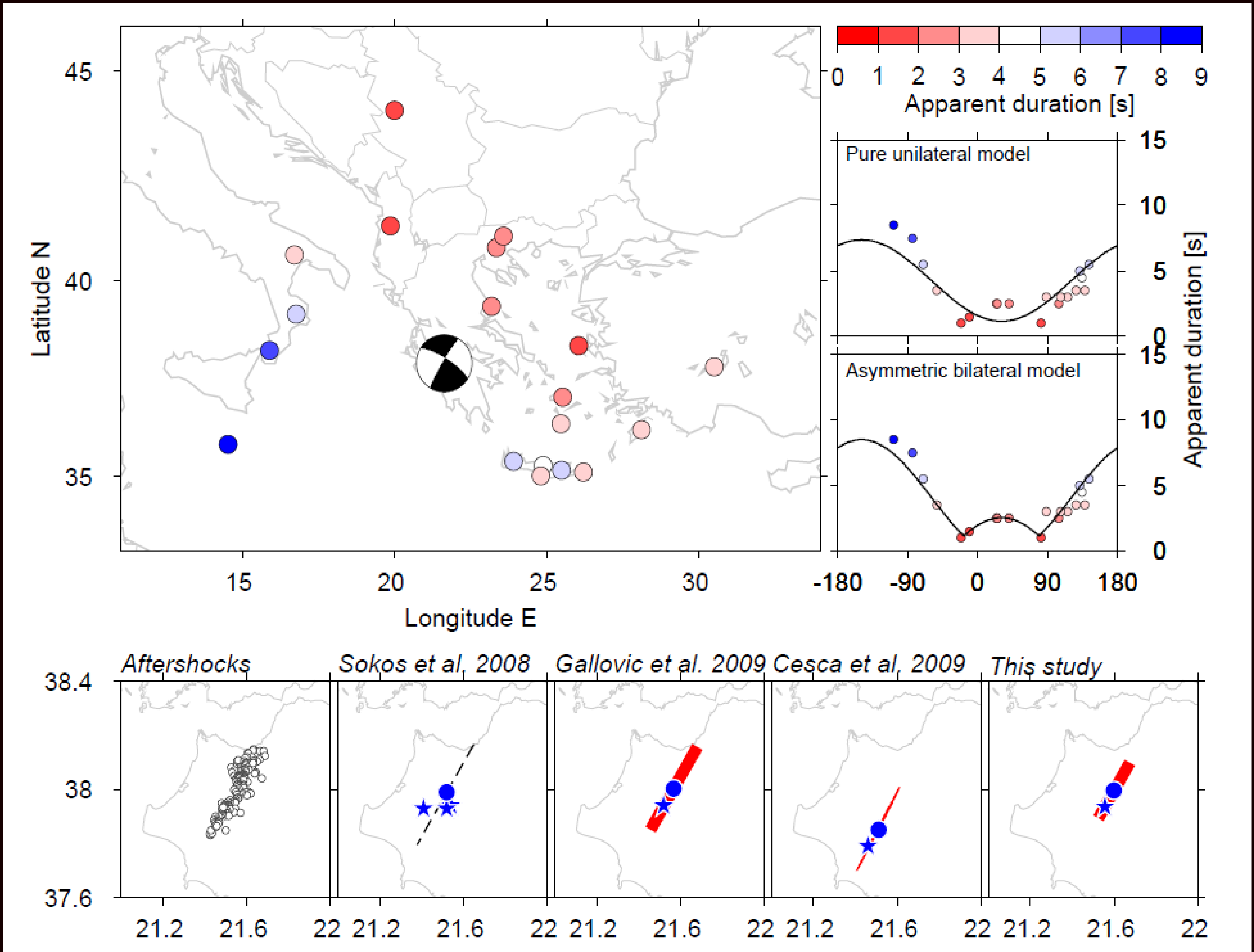


Cesca et al.
J. Seismol. 2011

Fast directivity detection



Cesca et al.
J. Seismol. 2011



0 1 2 3 4 5 6 7 8 9
Apparent duration [s]
45
40
35
Latitude N
15 20 25 30
Longitude E
Pure unilateral model
Asymmetric bilateral model
15
10
5
0
Apparent duration [s]
-180 -90 0 90 180
Aftershocks
Sokos et al, 2008
Gallovic et al. 2009
Cesca et al, 2009
This study
38.4
38
37.6
21.2 21.6 22

Inversion tips

Time vs. Frequency domain

Time domain inversion

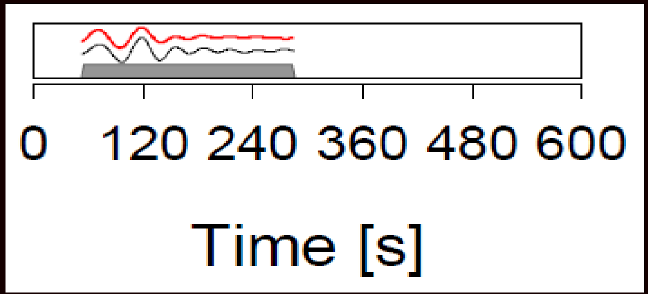
- Widely used at regional and teleseismic distances
- Sensitive to traces alignment
- Unstable at higher frequencies, for simplified velocity models

Frequency domain (amplitude spectra) inversion

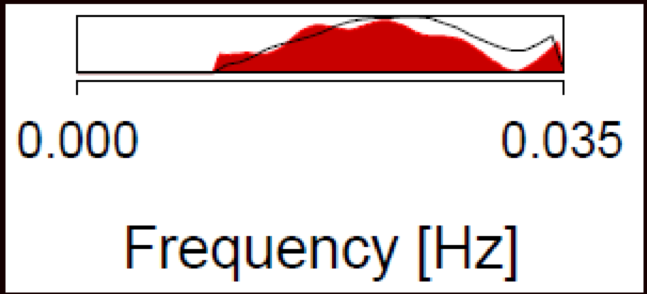
- Less sensitive to traces alignment, wave propagation mismodeling
- Implicit polarity ambiguity

Time vs. Frequency domain

Time domain inversion



Frequency domain



Time domain inversion

- Widely used at regional and teleseismic distances
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Frequency domain (amplitude spectra) inversion

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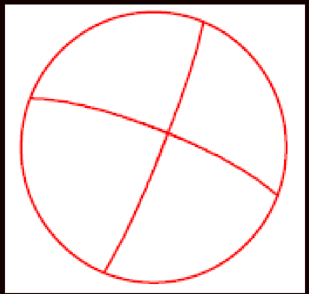
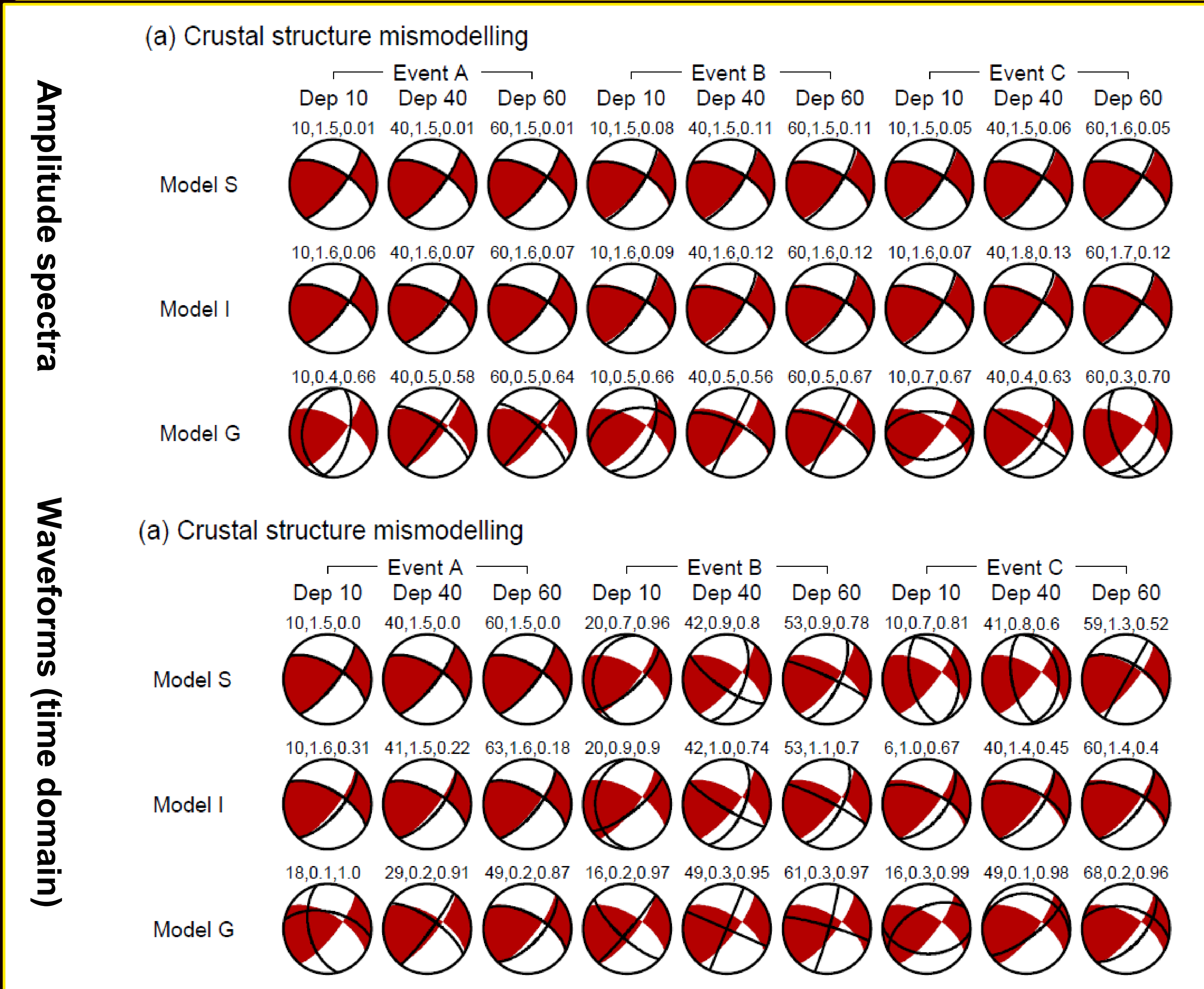
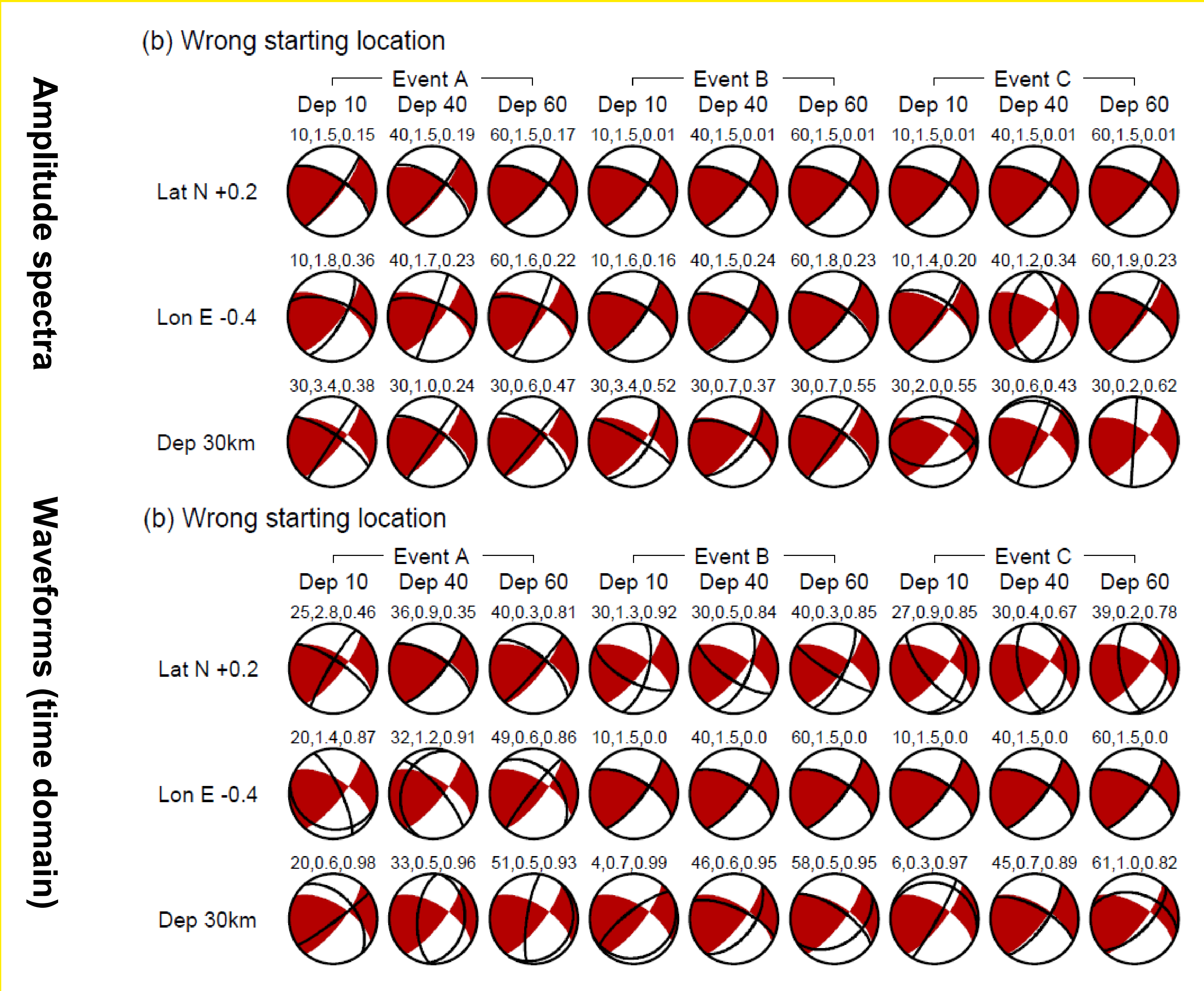



Amplitude spectra
(a) Crustal structure mismodelling
Event A
Event B
Event C
Dep 10
Dep 40
Dep 60
Model S
10,1.5,0.01
40,1.5,0.01
60,1.5,0.01
10,1.5,0.08
40,1.5,0.11
60,1.5,0.11
10,1.5,0.05
40,1.5,0.06
60,1.6,0.05
Model I
10,1.6,0.06
40,1.6,0.07
60,1.6,0.07
10,1.6,0.09
40,1.6,0.12
60,1.6,0.12
10,1.6,0.07
40,1.8,0.13
60,1.7,0.12
Model G
10,0.4,0.66
40,0.5,0.58
60,0.5,0.64
10,0.5,0.66
40,0.5,0.56
60,0.5,0.67
10,0.7,0.67
40,0.4,0.63
60,0.3,0.70
Waveforms (time domain)
(a) Crustal structure mismodelling
Event A
Event B
Event C
Dep 10
Dep 40
Dep 60
Model S
10,1.5,0.0
40,1.5,0.0
60,1.5,0.0
20,0.7,0.96
42,0.9,0.8
53,0.9,0.78
10,0.7,0.81
41,0.8,0.6
59,1.3,0.52
Model I
10,1.6,0.31
41,1.5,0.22
63,1.6,0.18
20,0.9,0.9
42,1.0,0.74
53,1.1,0.7
6,1.0,0.67
40,1.4,0.45
60,1.4,0.4
Model G
18,0.1,1.0
29,0.2,0.91
49,0.2,0.87
16,0.2,0.97
49,0.3,0.95
61,0.3,0.97
16,0.3,0.99
49,0.1,0.98
68,0.2,0.96


Amplitude spectra
(b) Wrong starting location
Event A
Event B
Event C
Dep 10 Dep 40 Dep 60 Dep 10 Dep 40 Dep 60 Dep 10 Dep 40 Dep 60
Lat N +0.2
10,1.5,0.15 40,1.5,0.19 60,1.5,0.17 10,1.5,0.01 40,1.5,0.01 60,1.5,0.01 10,1.5,0.01 40,1.5,0.01 60,1.5,0.01
Lon E -0.4
10,1.8,0.36 40,1.7,0.23 60,1.6,0.22 10,1.6,0.16 40,1.5,0.24 60,1.8,0.23 10,1.4,0.20 40,1.2,0.34 60,1.9,0.23
Dep 30km
30,3.4,0.38 30,1.0,0.24 30,0.6,0.47 30,3.4,0.52 30,0.7,0.37 30,0.7,0.55 30,2.0,0.55 30,0.6,0.43 30,0.2,0.62
Waveforms (time domain)
(b) Wrong starting location
Event A
Event B
Event C
Dep 10 Dep 40 Dep 60 Dep 10 Dep 40 Dep 60 Dep 10 Dep 40 Dep 60
Lat N +0.2
25,2.8,0.46 36,0.9,0.35 40,0.3,0.81 30,1.3,0.92 30,0.5,0.84 40,0.3,0.85 27,0.9,0.85 30,0.4,0.67 39,0.2,0.78
Lon E -0.4
20,1.4,0.87 32,1.2,0.91 49,0.6,0.86 10,1.5,0.0 40,1.5,0.0 60,1.5,0.0 10,1.5,0.0 40,1.5,0.0 60,1.5,0.0
Dep 30km
20,0.6,0.98 33,0.5,0.96 51,0.5,0.93 4,0.7,0.99 46,0.6,0.95 58,0.5,0.95 6,0.3,0.97 45,0.7,0.89 61,1.0,0.82

Surface waves vs. Body waves

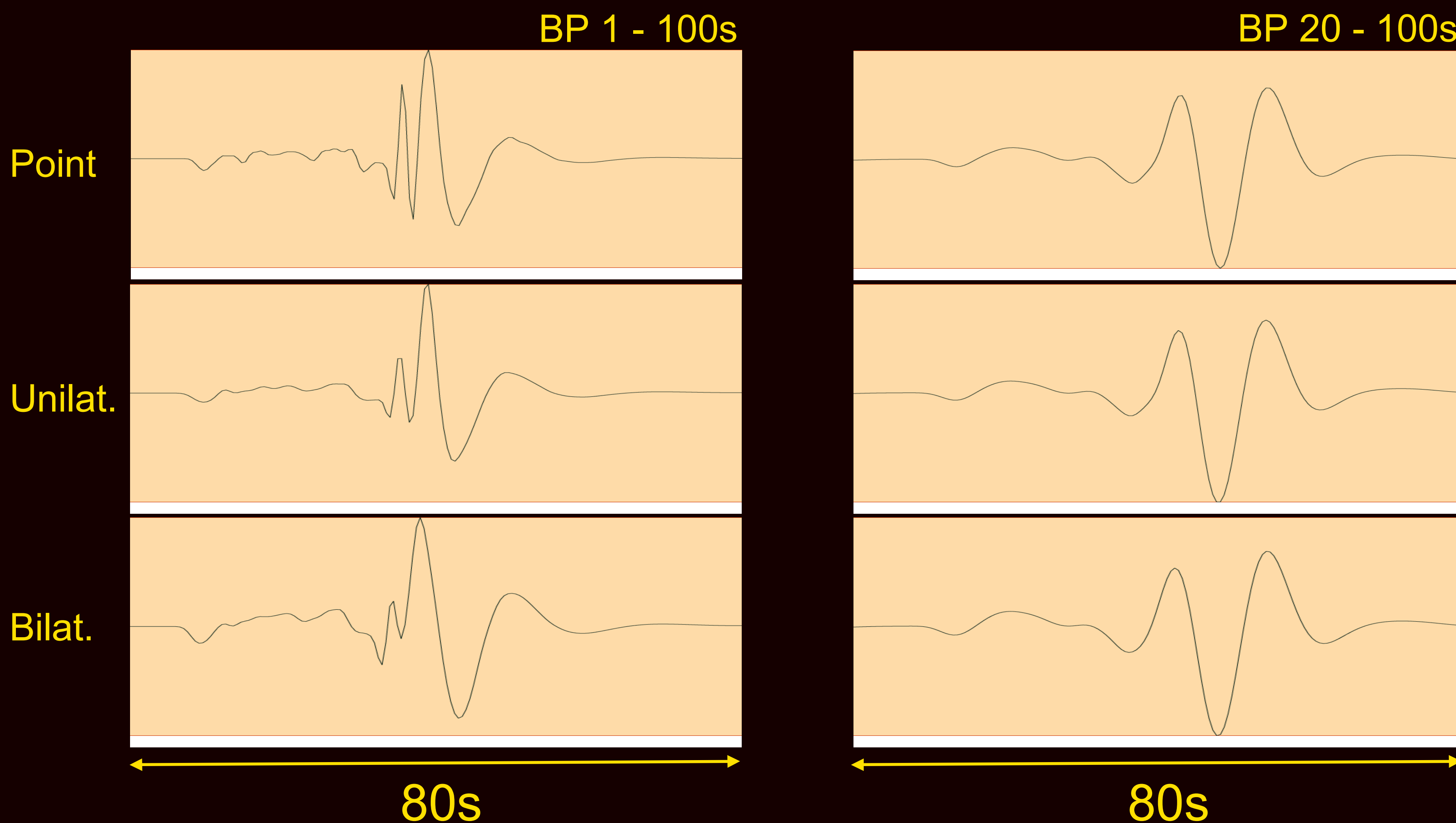
Surface waves (or full waveform)

- Widely used at regional (and teleseismic distances)
- Robust as low frequencies can be used
- Poor resolution (Mxz, Myz) for shallow sources

Bodywaves

- Strong dependency on precise velocity and attenuation models
- Potentially good focal mechanism coverage and MT resolution
- Intermediate/deep seismicity

On the choice of the best frequency range



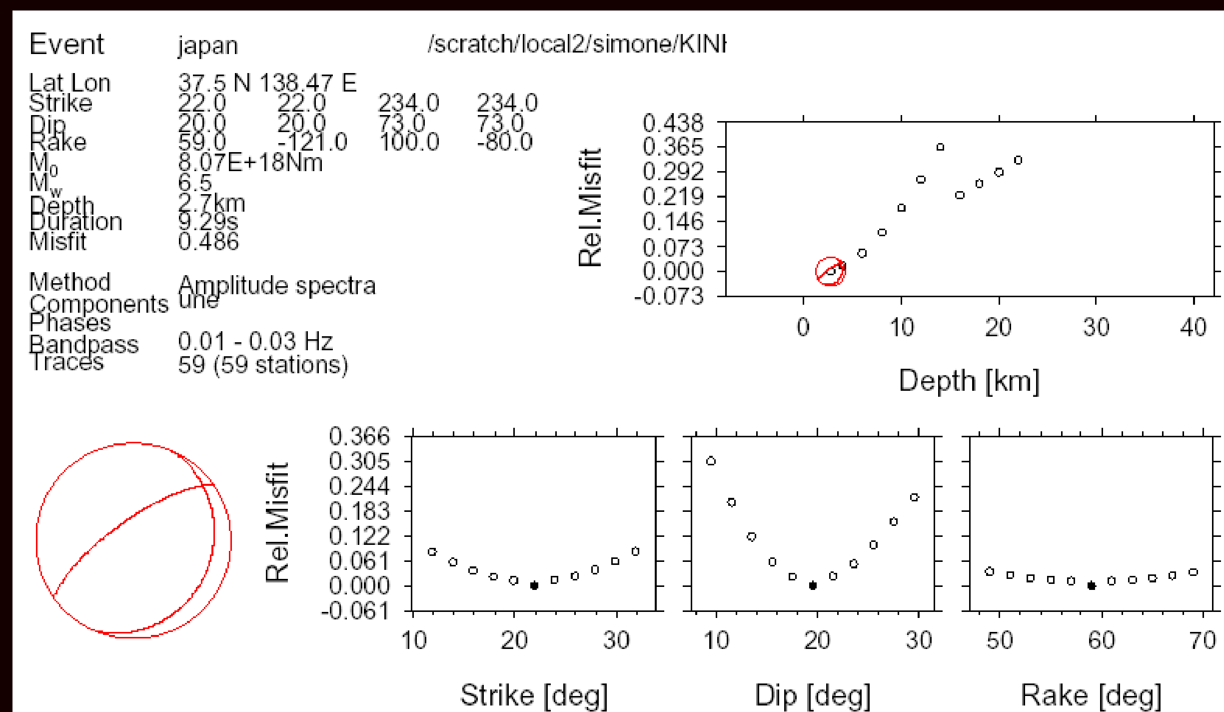
Flat/known instrumental response
Below spectra corner frequency (point source), or above (to resolve finite rupture)
10-50s for local/regional earthquakes Mw<5.5
30-100s for regional/teleseismic distances Mw >5.5

About the bootstrap approach

General estimation of data fit

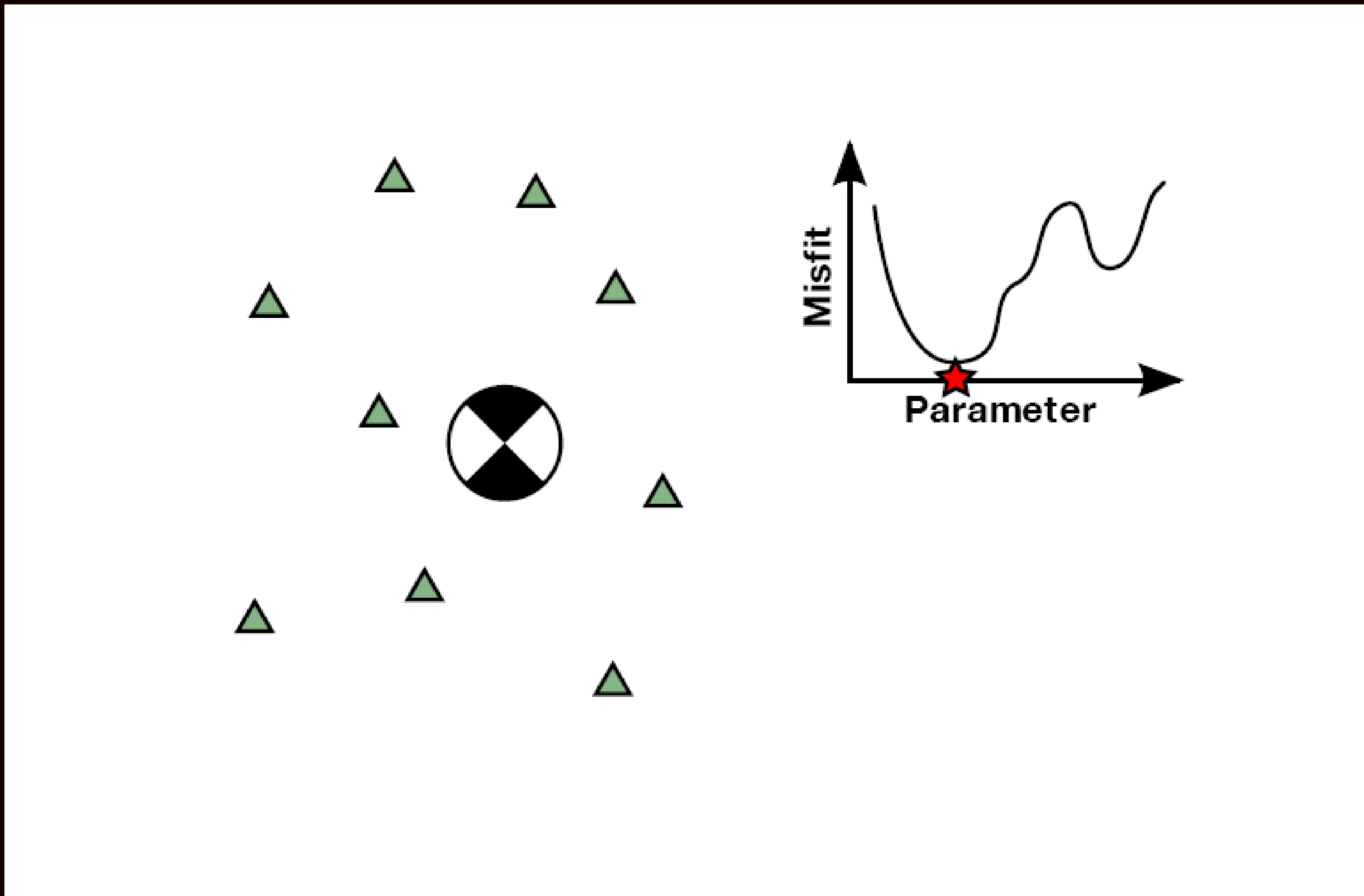
We need additional information on inversion stability

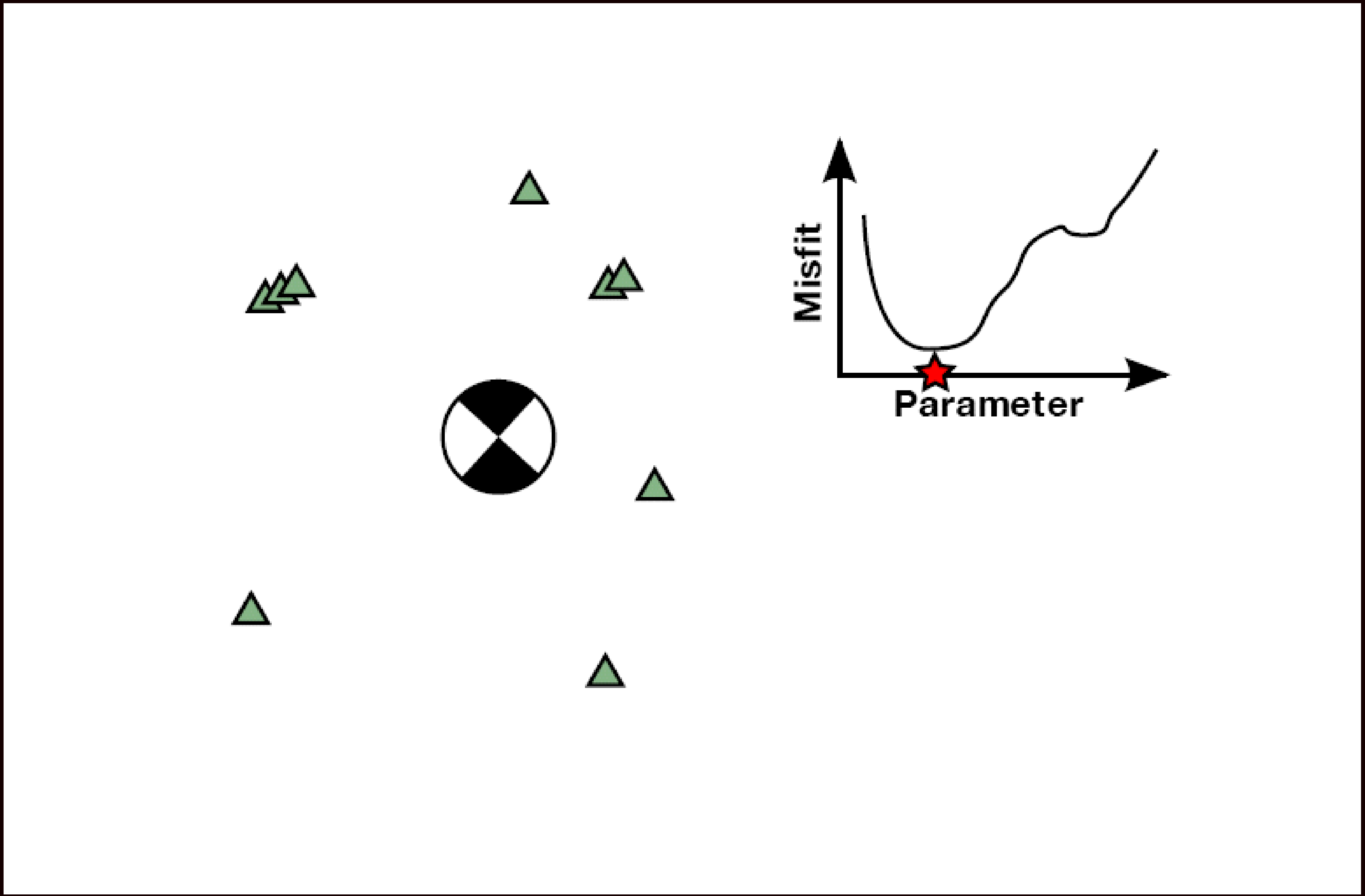
Relative misfit curve (perturbation of single source parameters)

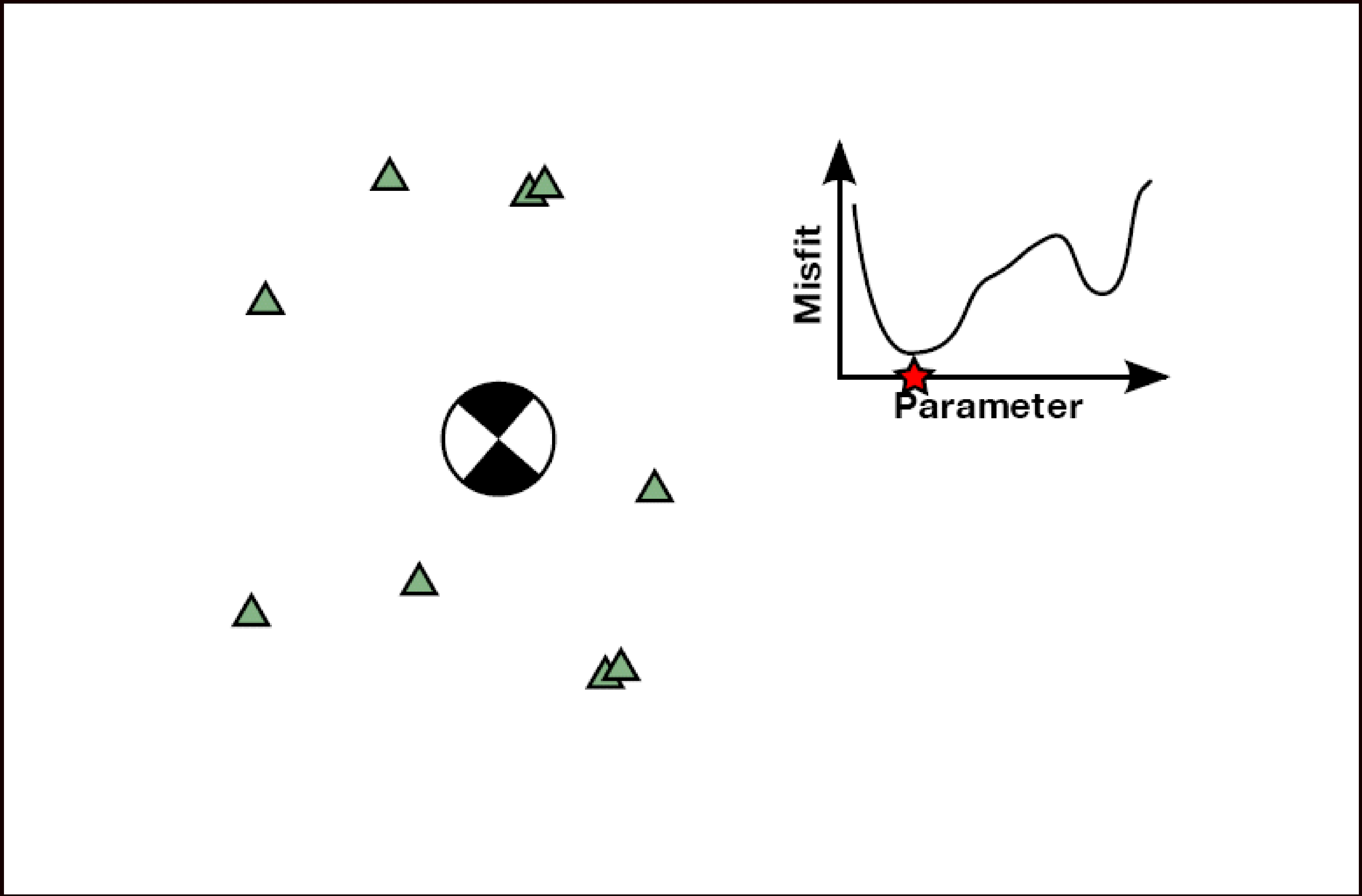


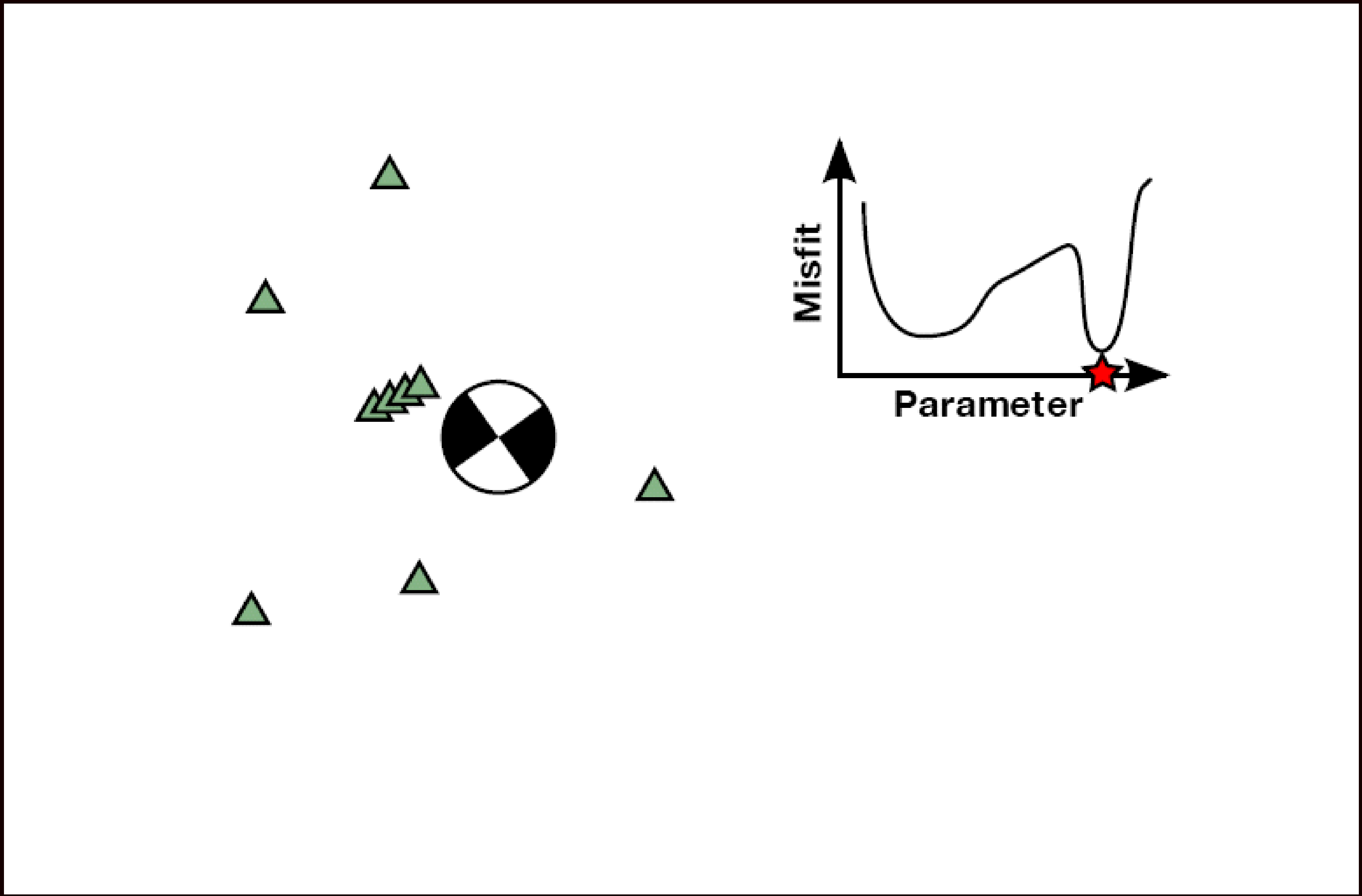
…and a Bootstrap analysis

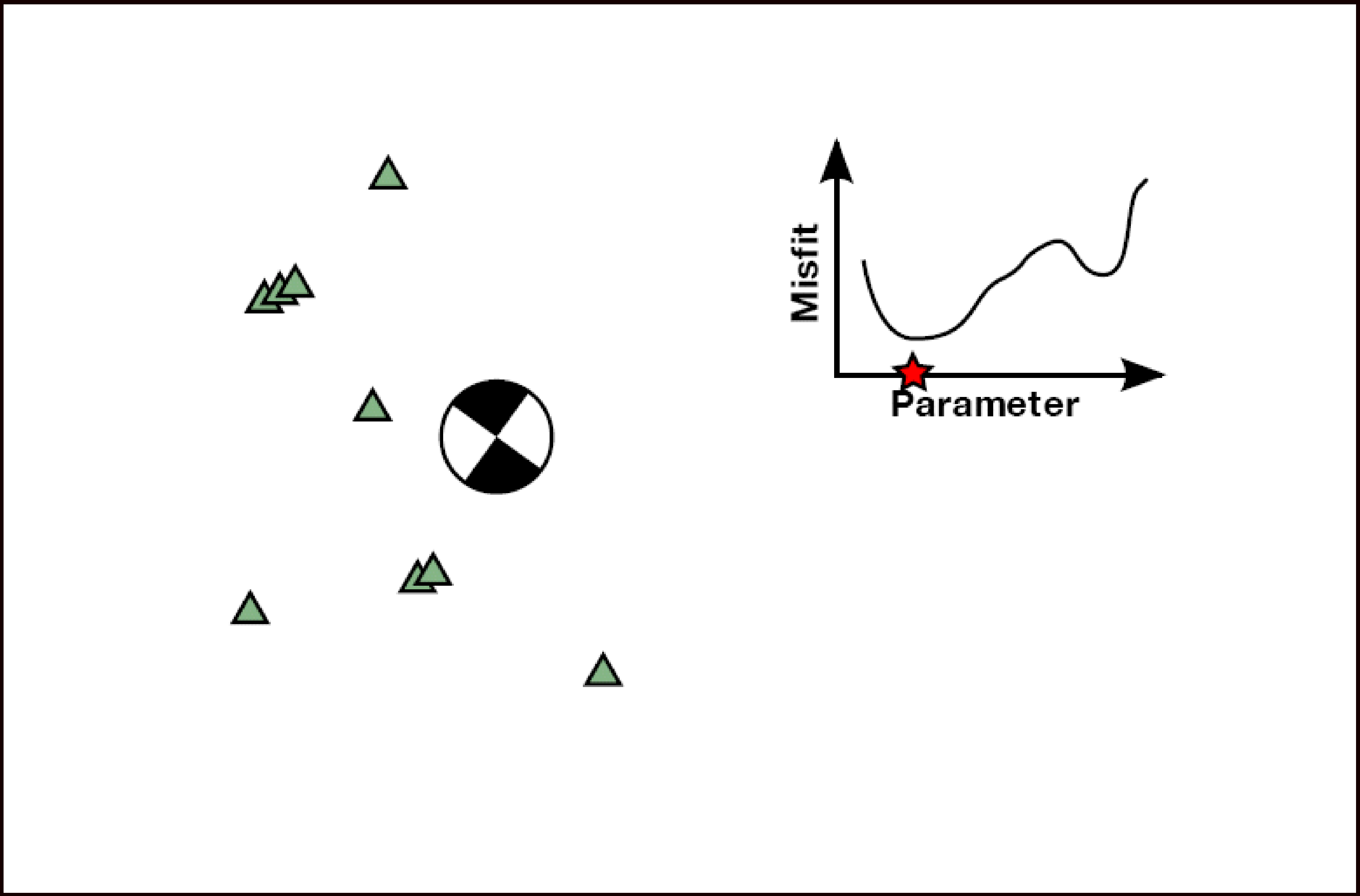
About the bootstrap approach

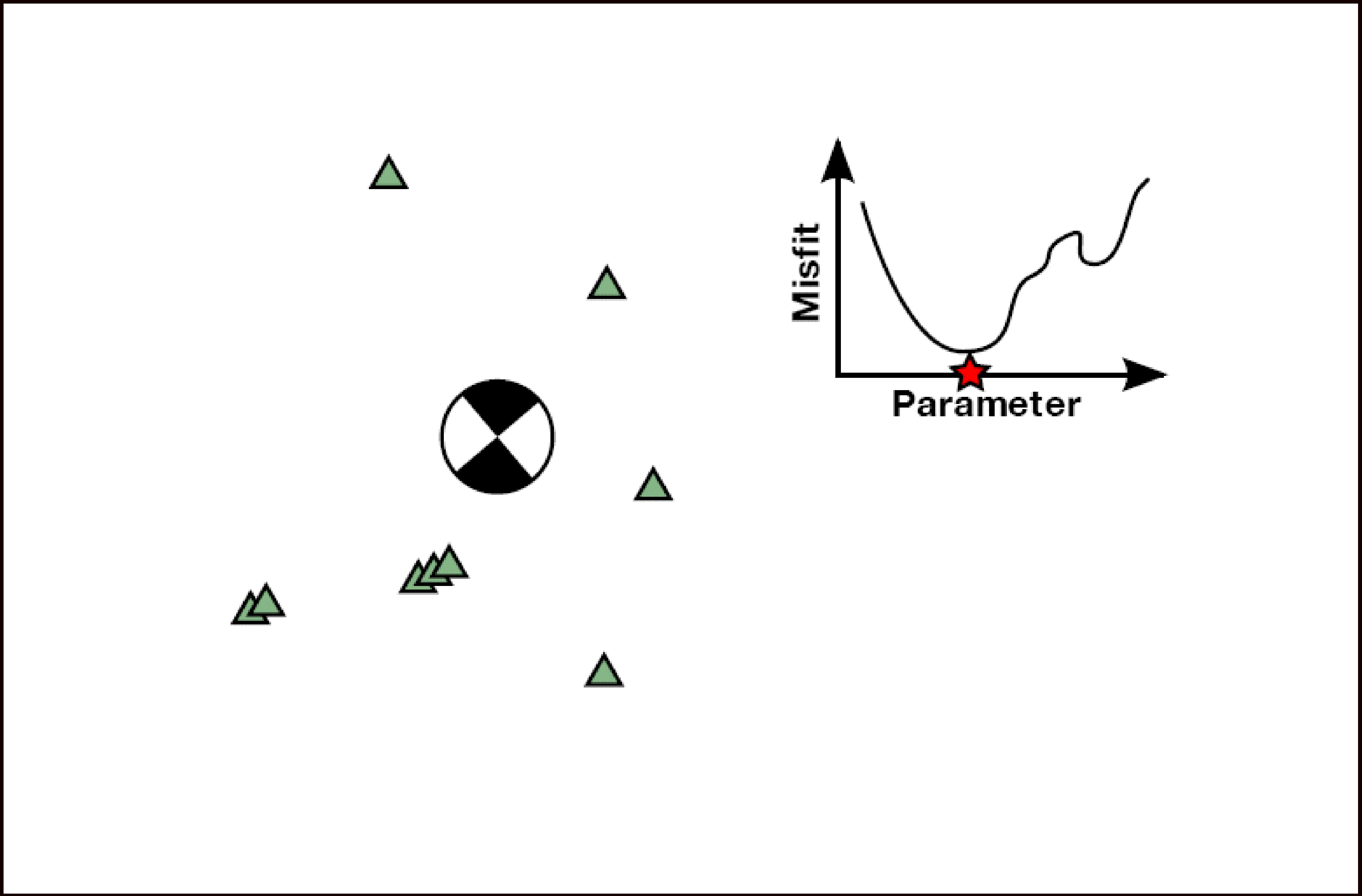


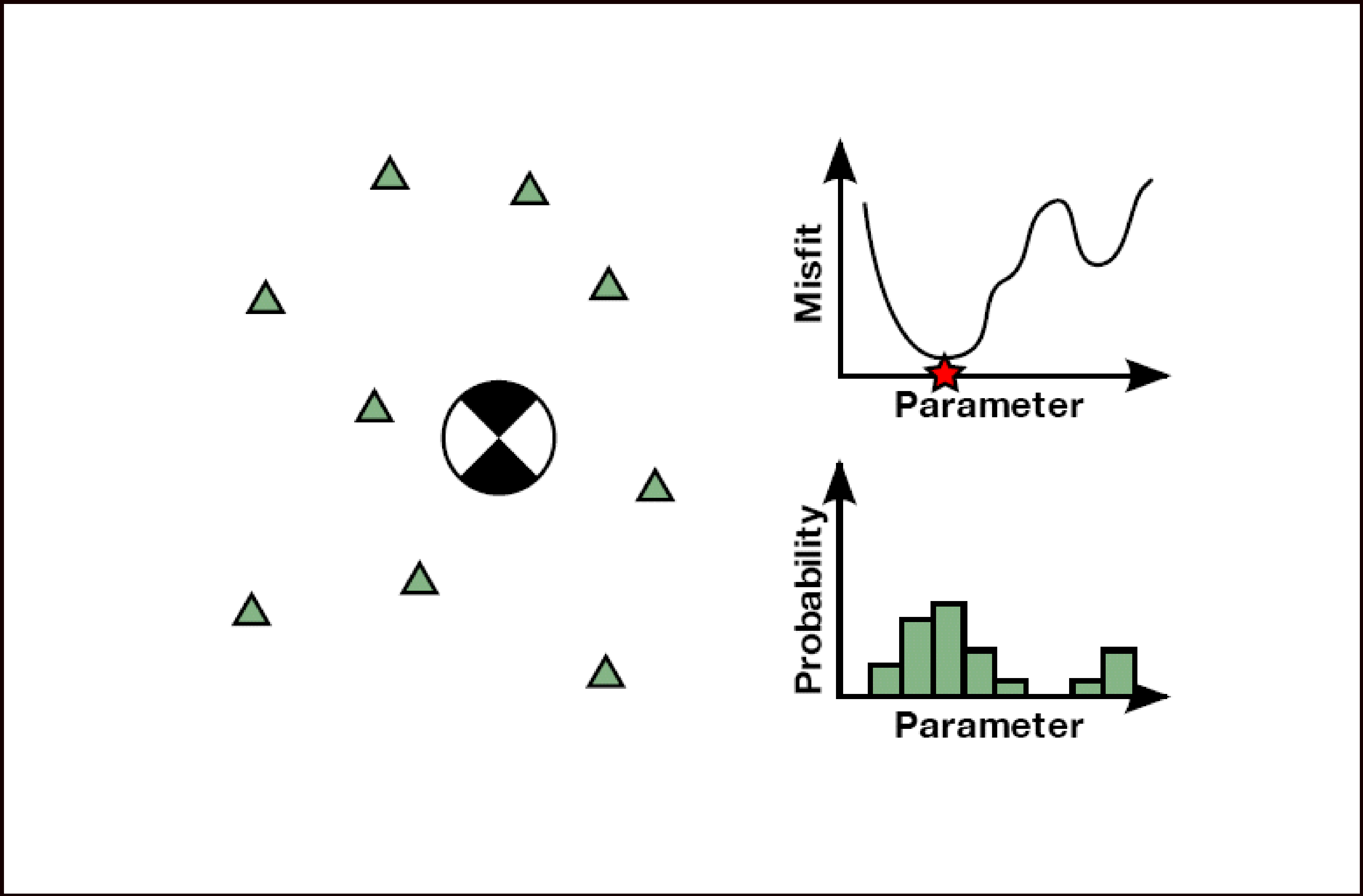

Misfit
Parameter


Misfit
Parameter

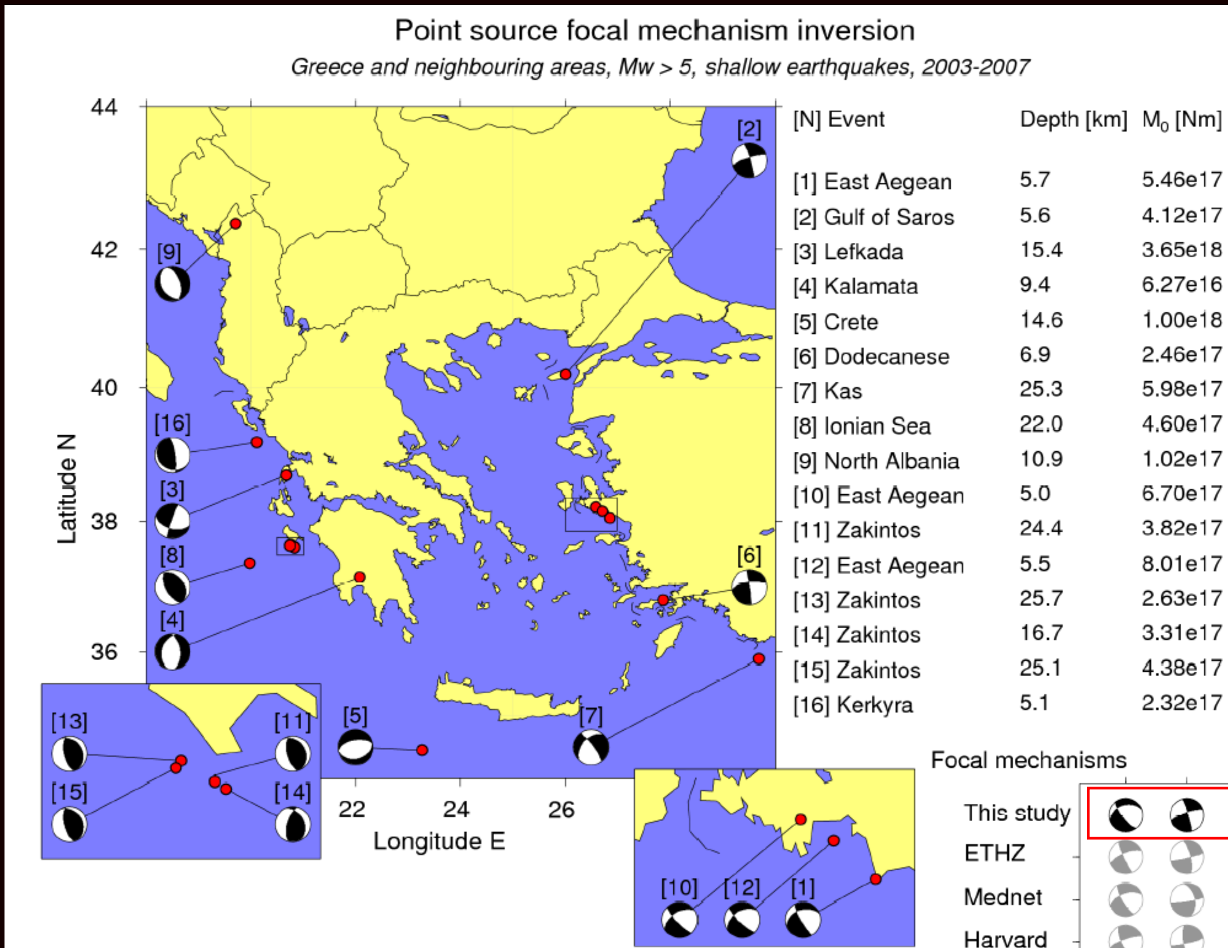

Misfit
Parameter


Misfit
Parameter


Misfit
Parameter


Misfit
Parameter
Probability
Parameter

Example of applications



[N] Event	Depth [km]	M_0 [Nm]
[1] East Aegean	5.7	5.46e17
[2] Gulf of Saros	5.6	4.12e17
[3] Lefkada	15.4	3.65e18
[4] Kalamata	9.4	6.27e16
[5] Crete	14.6	1.00e18
[6] Dodecanese	6.9	2.46e17
[7] Kas	25.3	5.98e17
[8] Ionian Sea	22.0	4.60e17
[9] North Albania	10.9	1.02e17
[10] East Aegean	5.0	6.70e17
[11] Zakintos	24.4	3.82e17
[12] East Aegean	5.5	8.01e17
[13] Zakintos	25.7	2.63e17
[14] Zakintos	16.7	3.31e17
[15] Zakintos	25.1	4.38e17
[16] Kerkyra	5.1	2.32e17

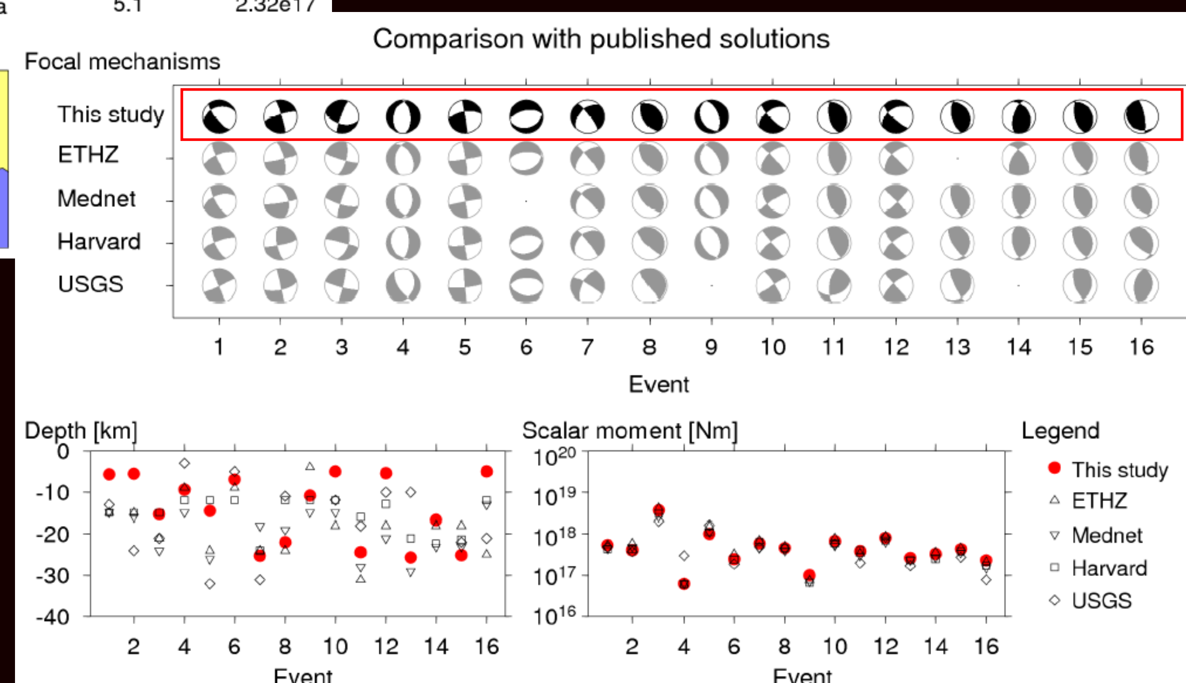
Greece,

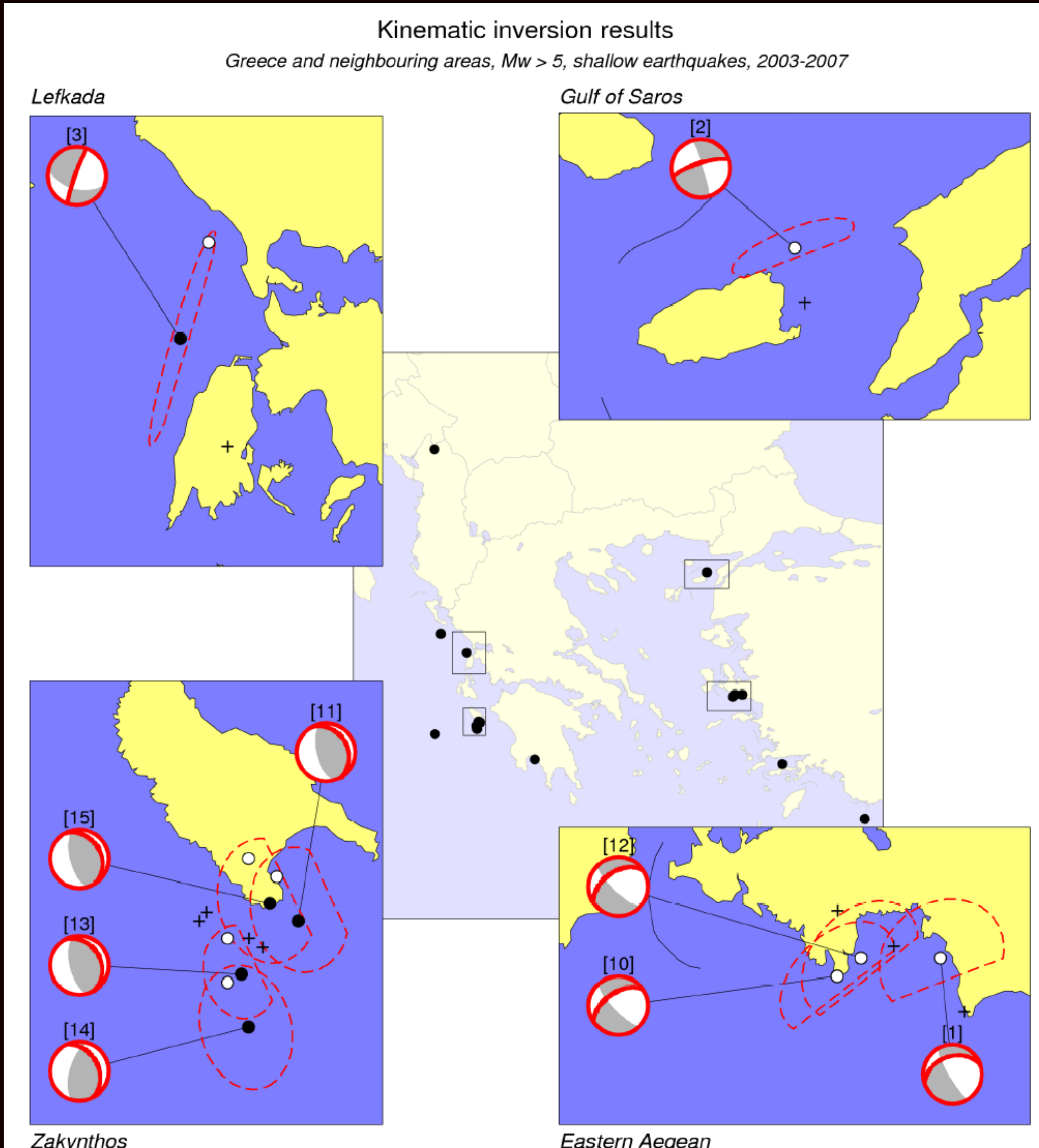
Shallow earthquakes

2003-2007

point sources

Cesca et al. JGR 2010





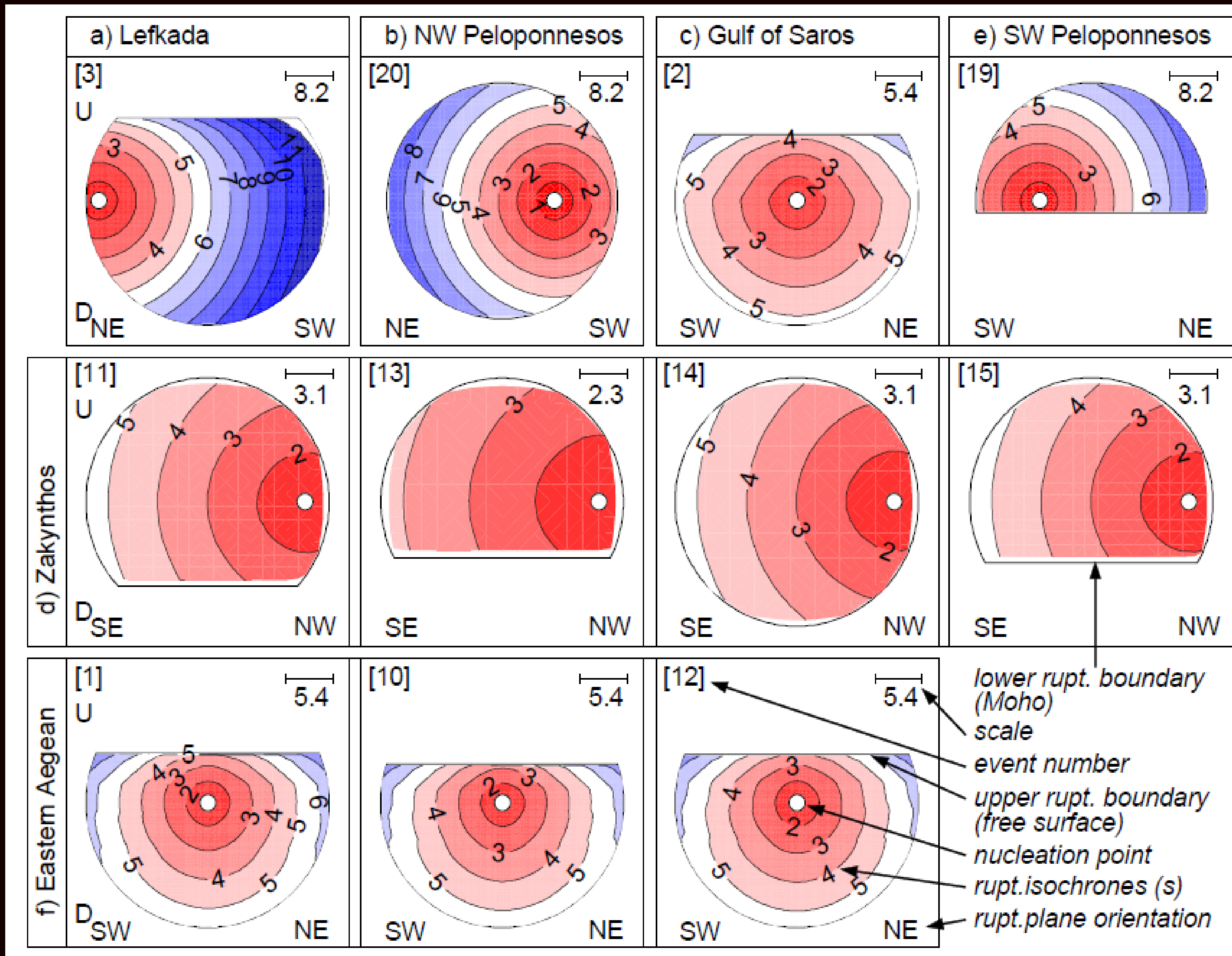
Greece,

Shallow earthquakes

2003-2007

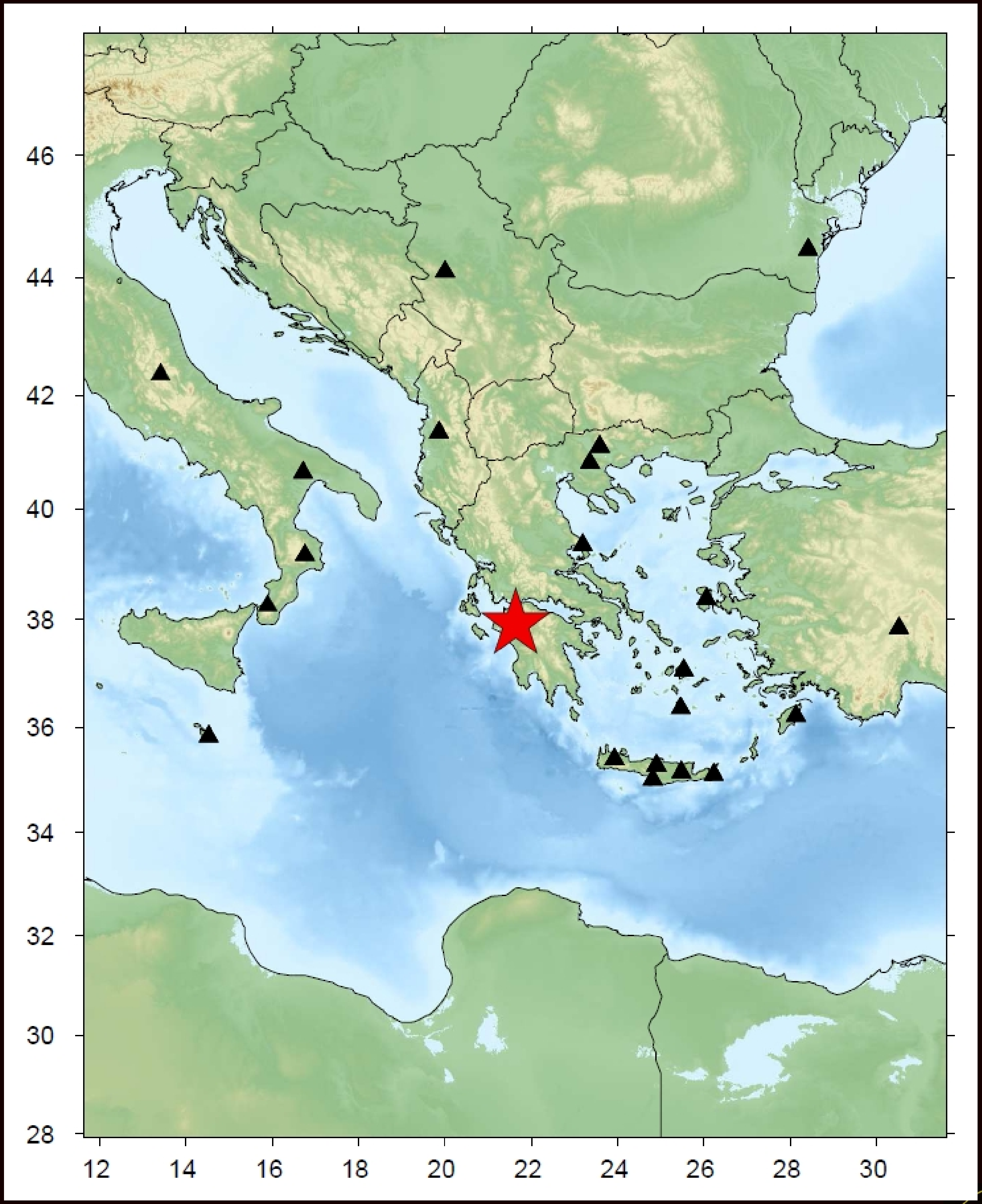
extended sources

Cesca et al. JGR 2010

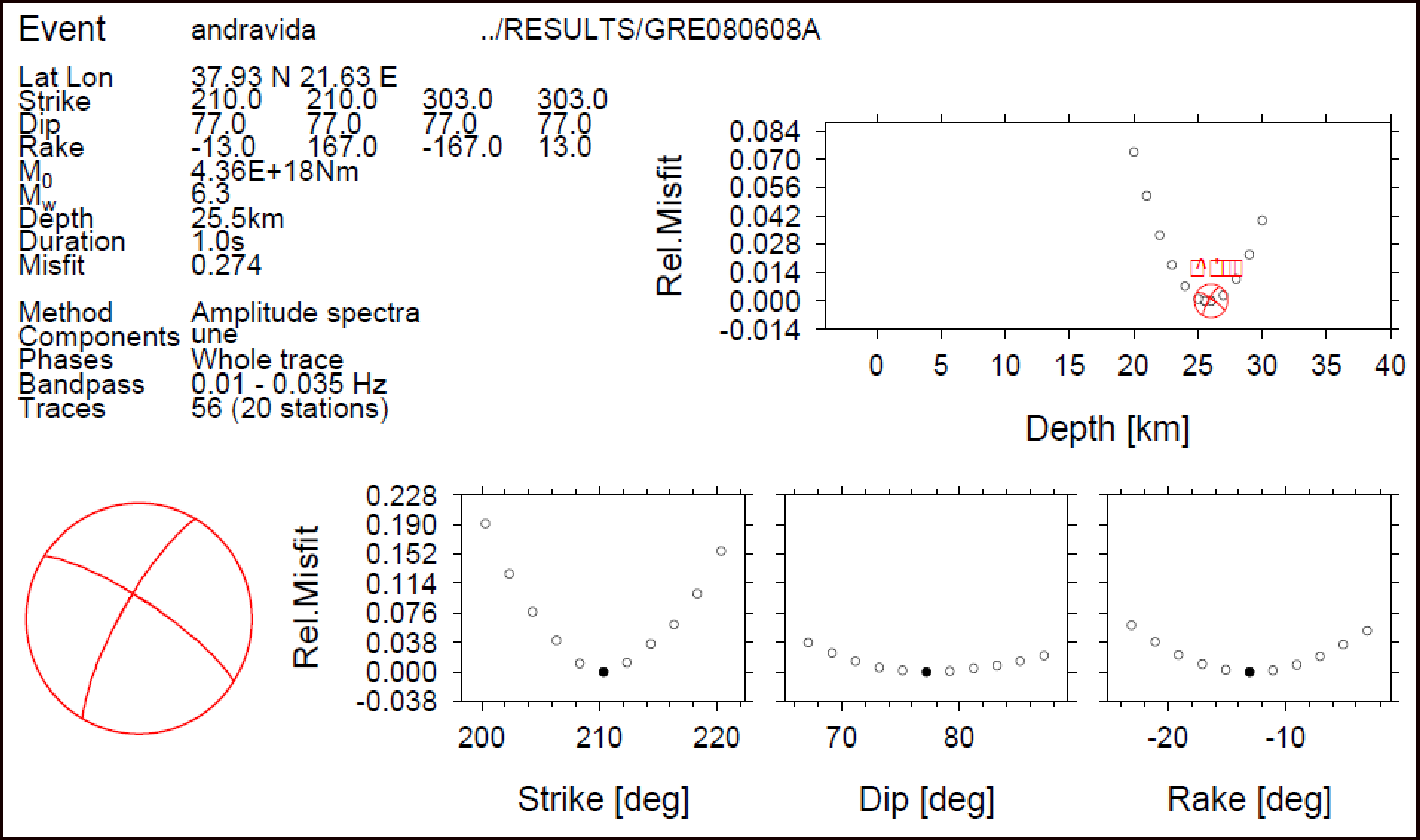


Cesca et al. JGR 2010

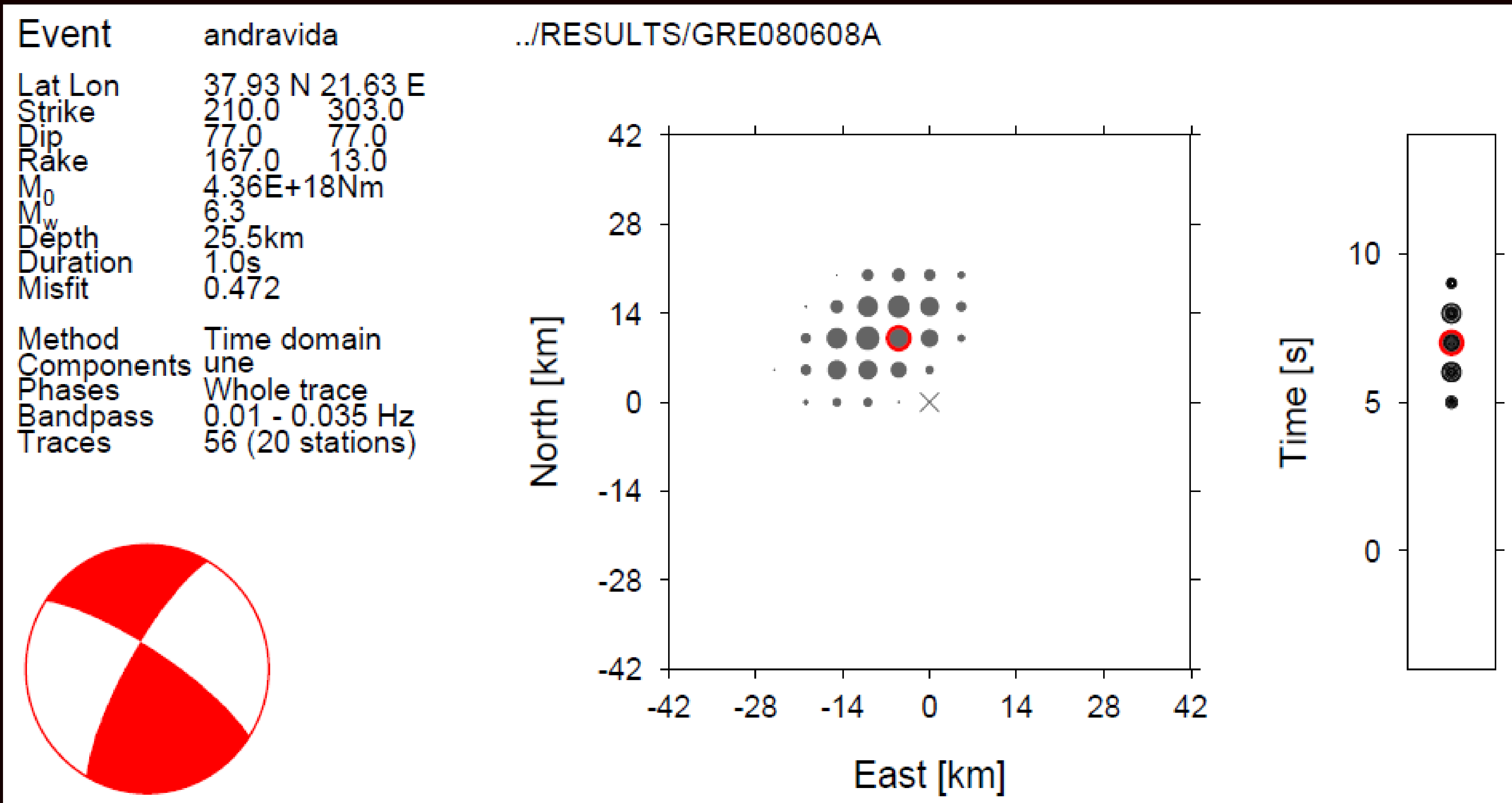
The Andravida earthquake – different inversion approaches



The Andravida earthquake – different inversion approaches

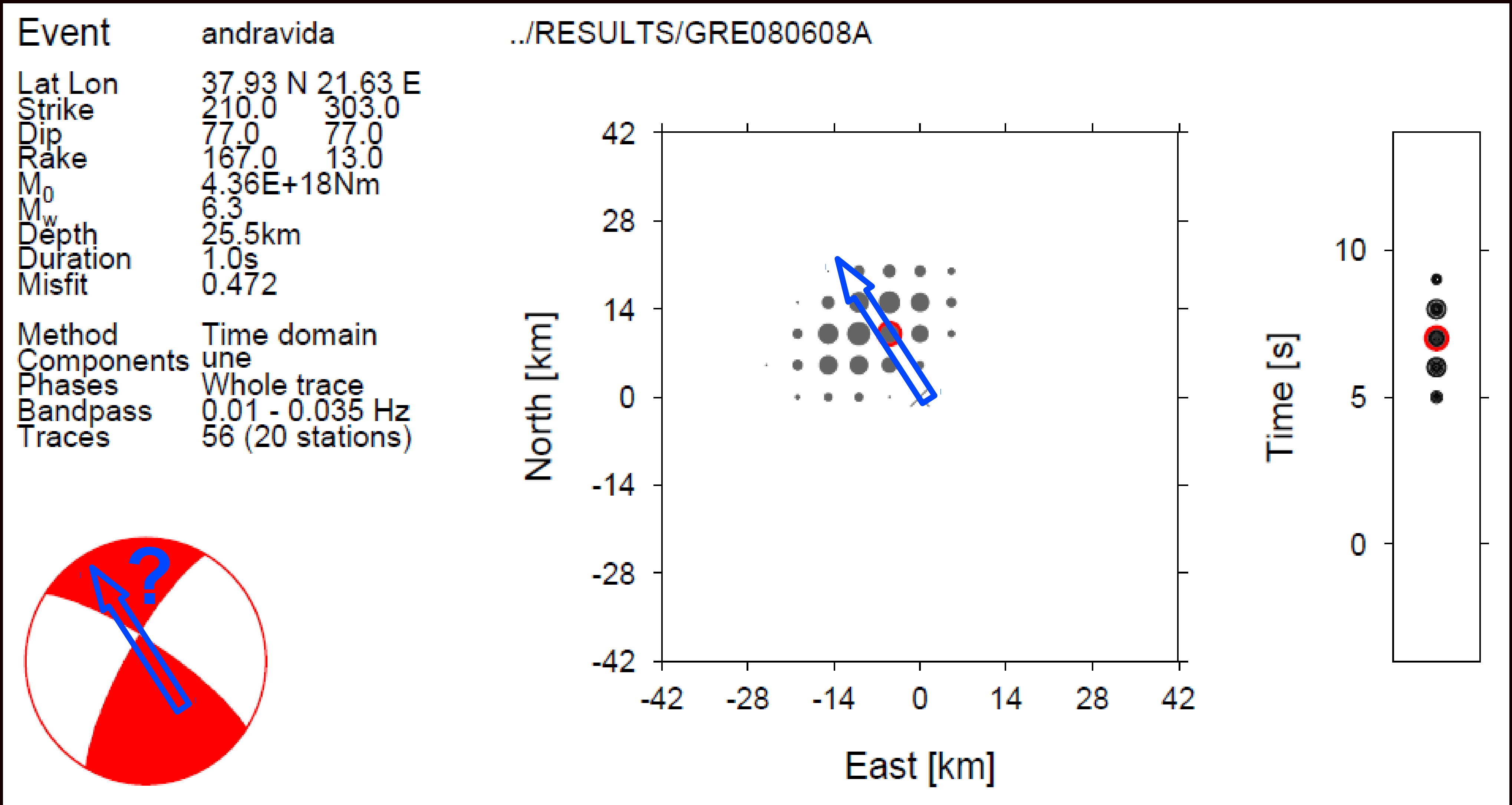


The Andravida earthquake – different inversion approaches

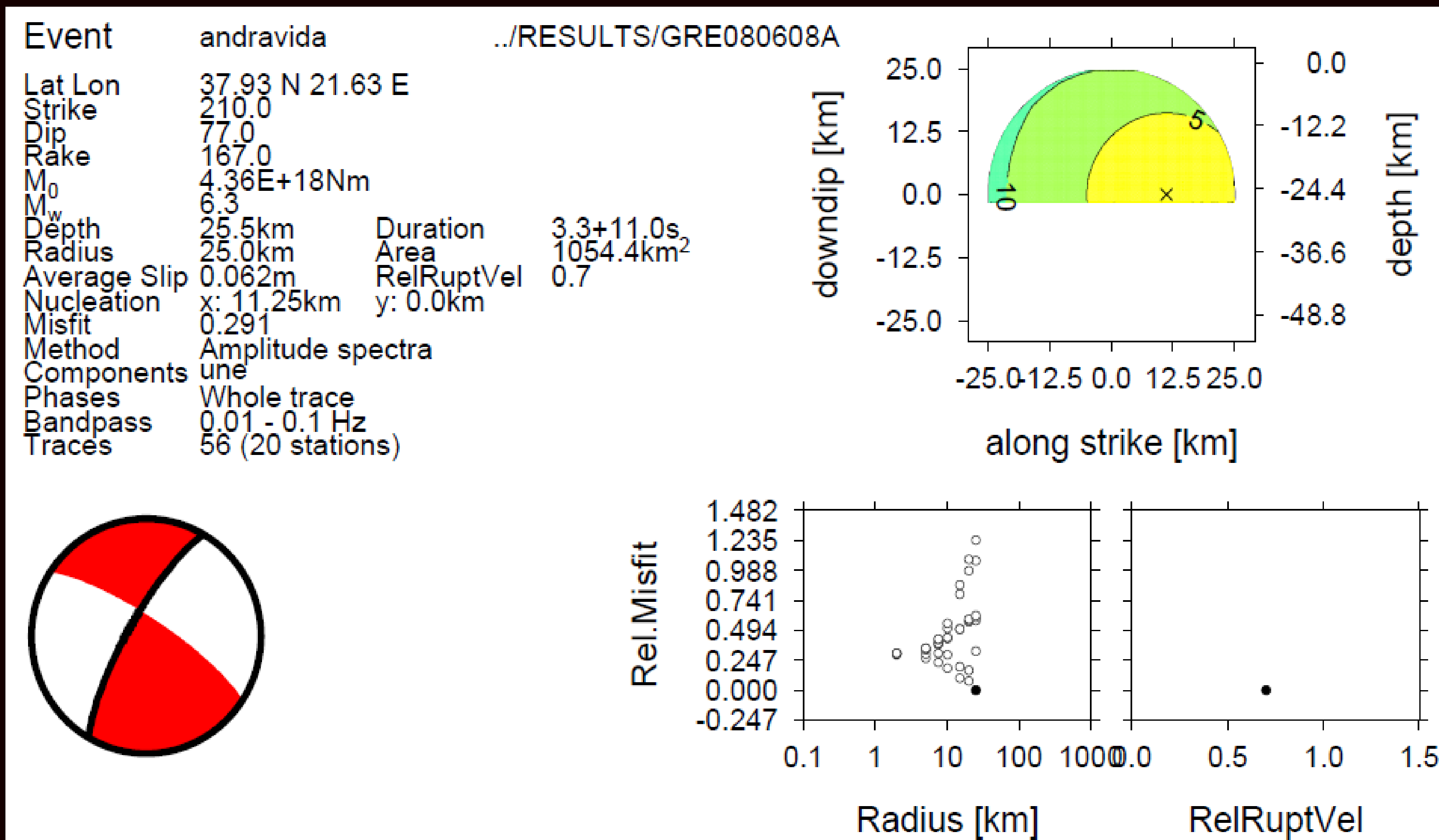


The Andravida earthquake – different inversion approaches

Epicenter – Centroid Relative Location

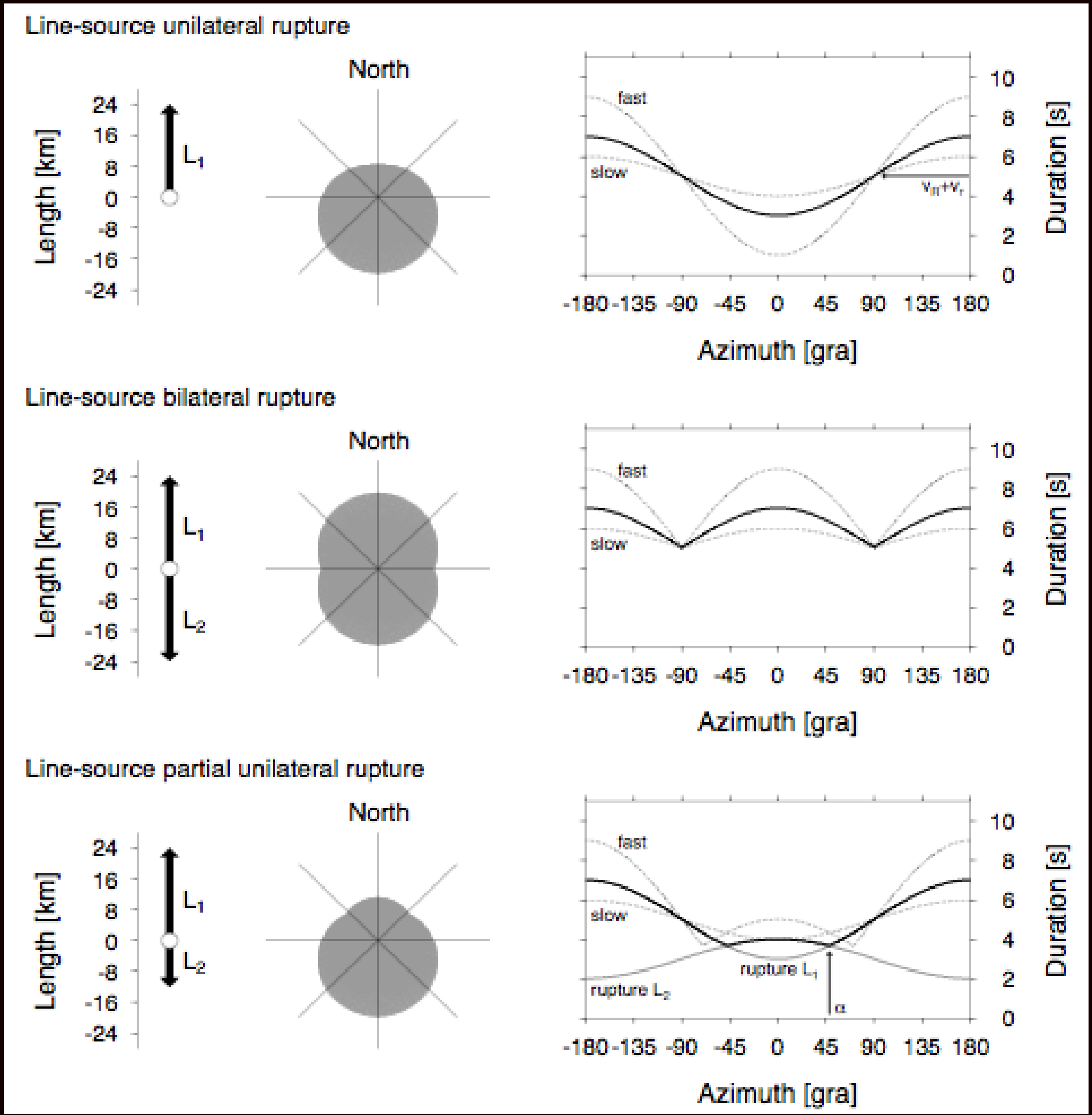


The Andravida earthquake – different inversion approaches

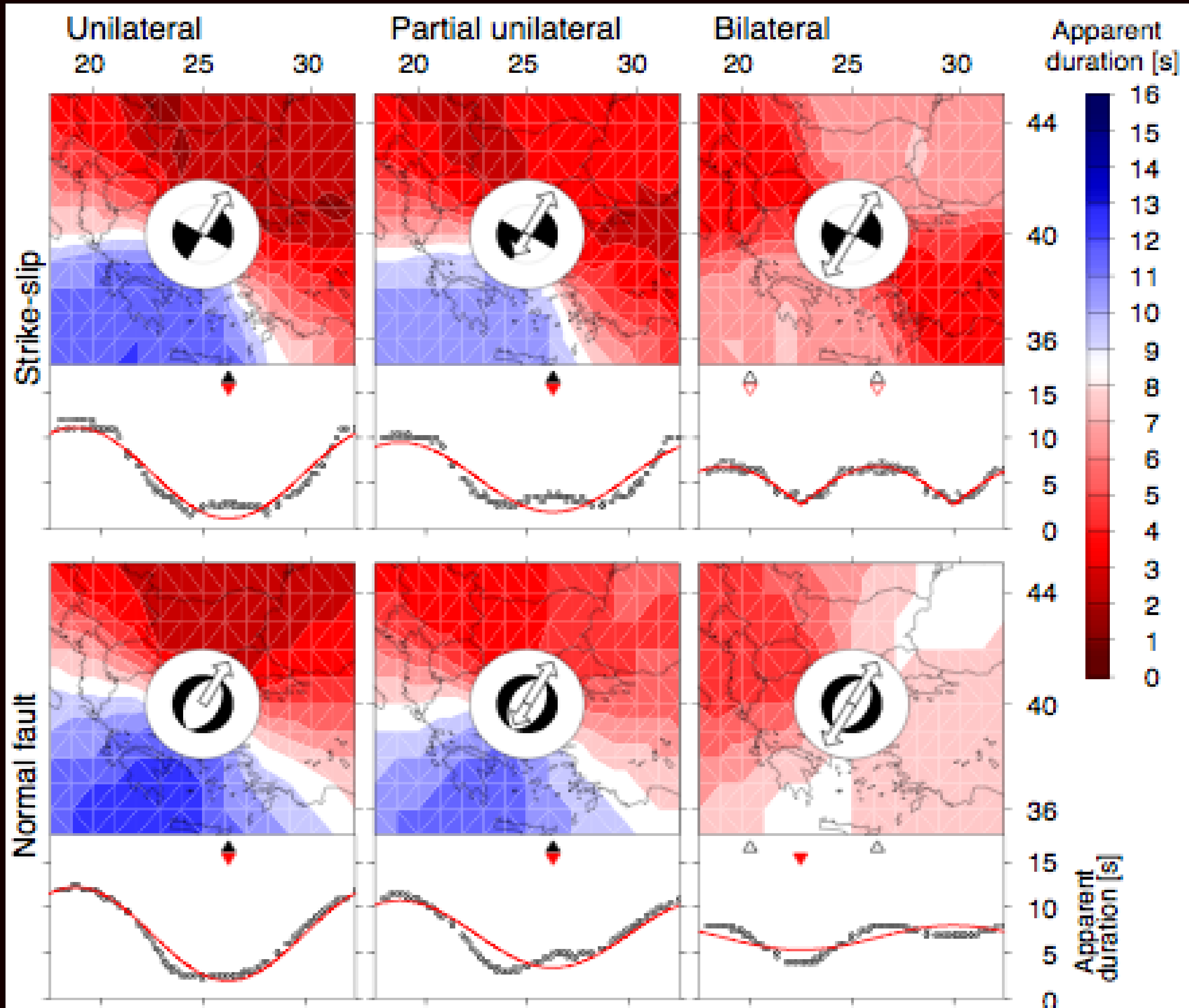


The Andravida earthquake – different inversion approaches

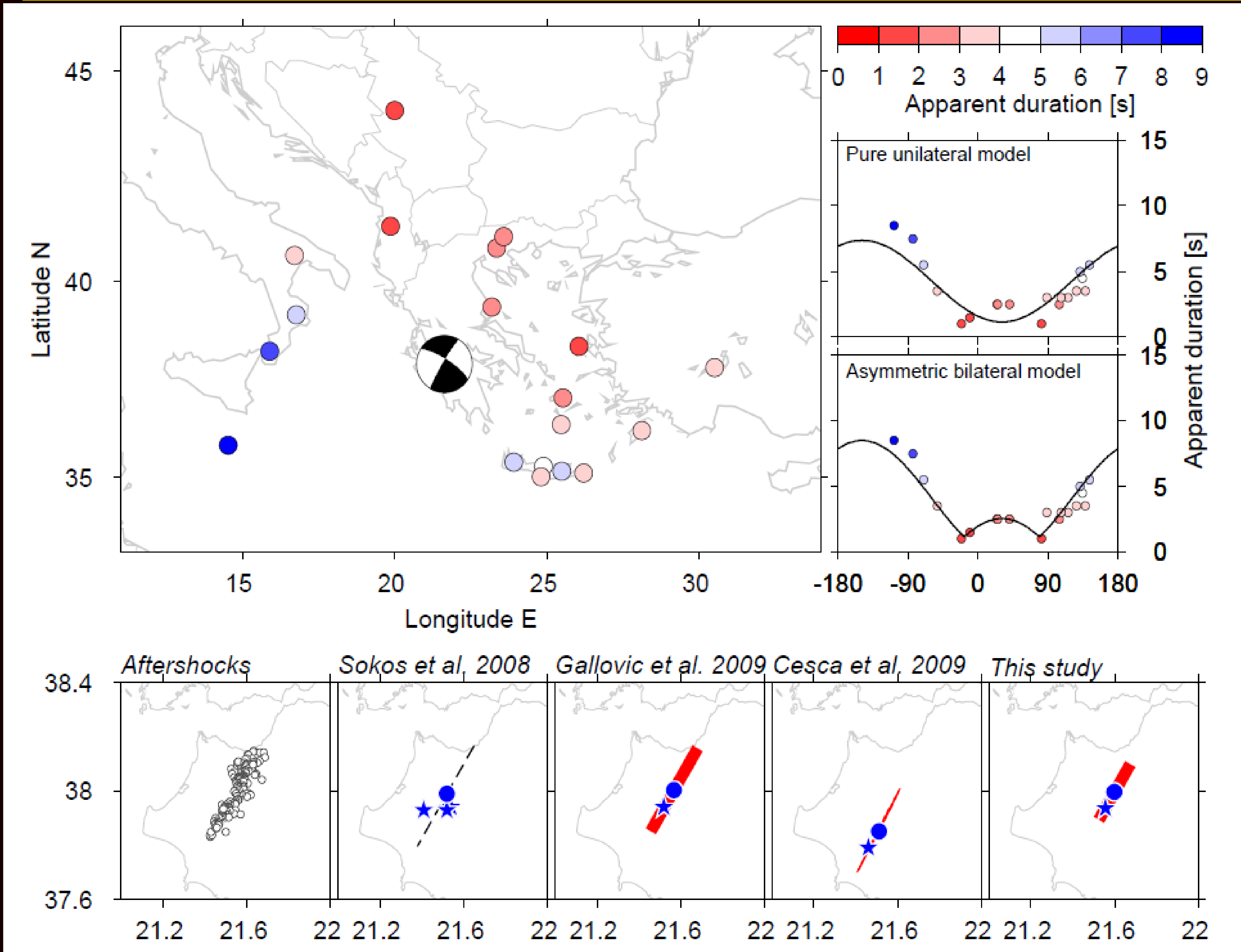
Fast directivity detection using apparent durations



Cesca et al.
J. Seismol. 2011

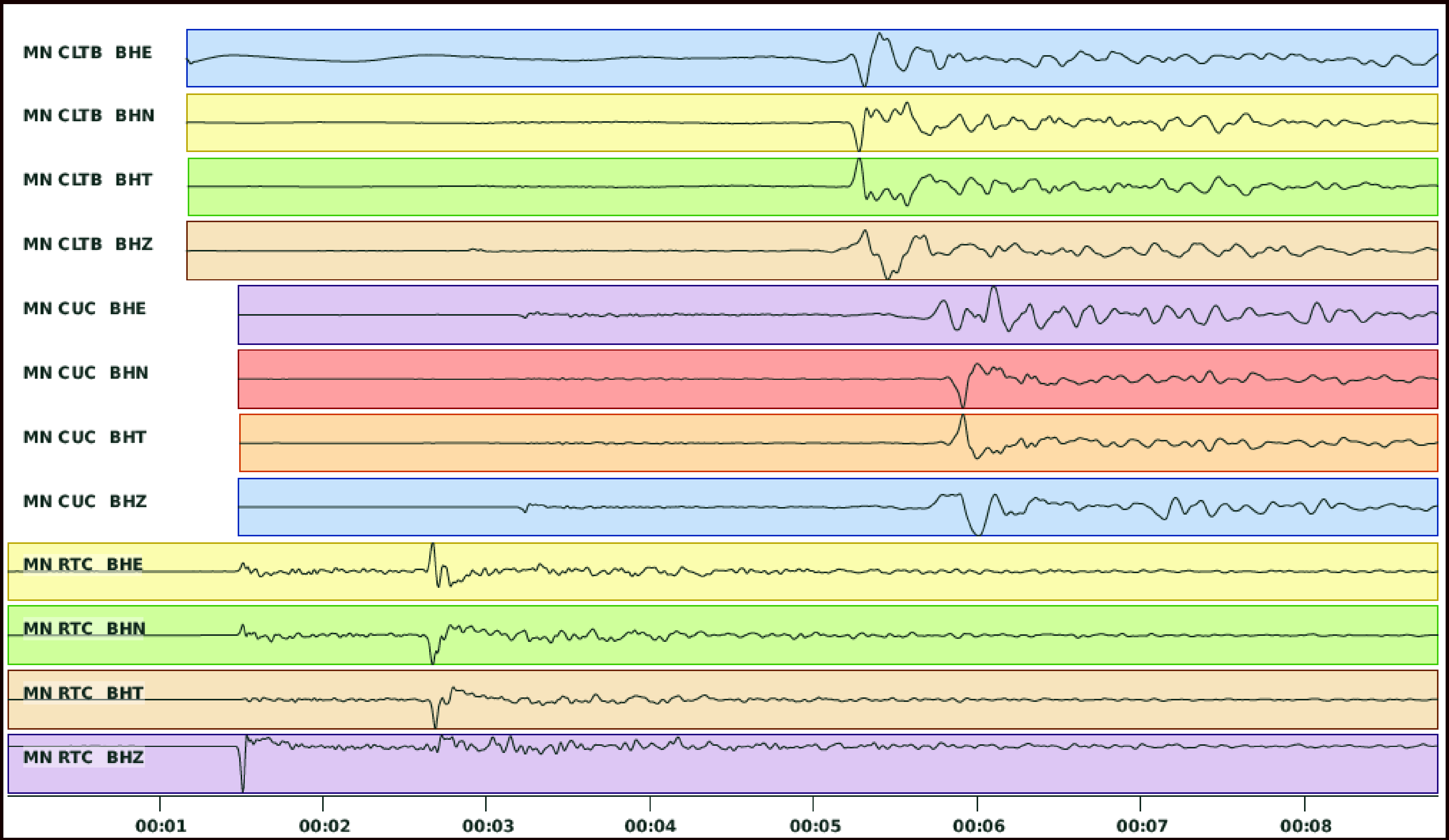


Cesca et al. J. Seismol. 2011

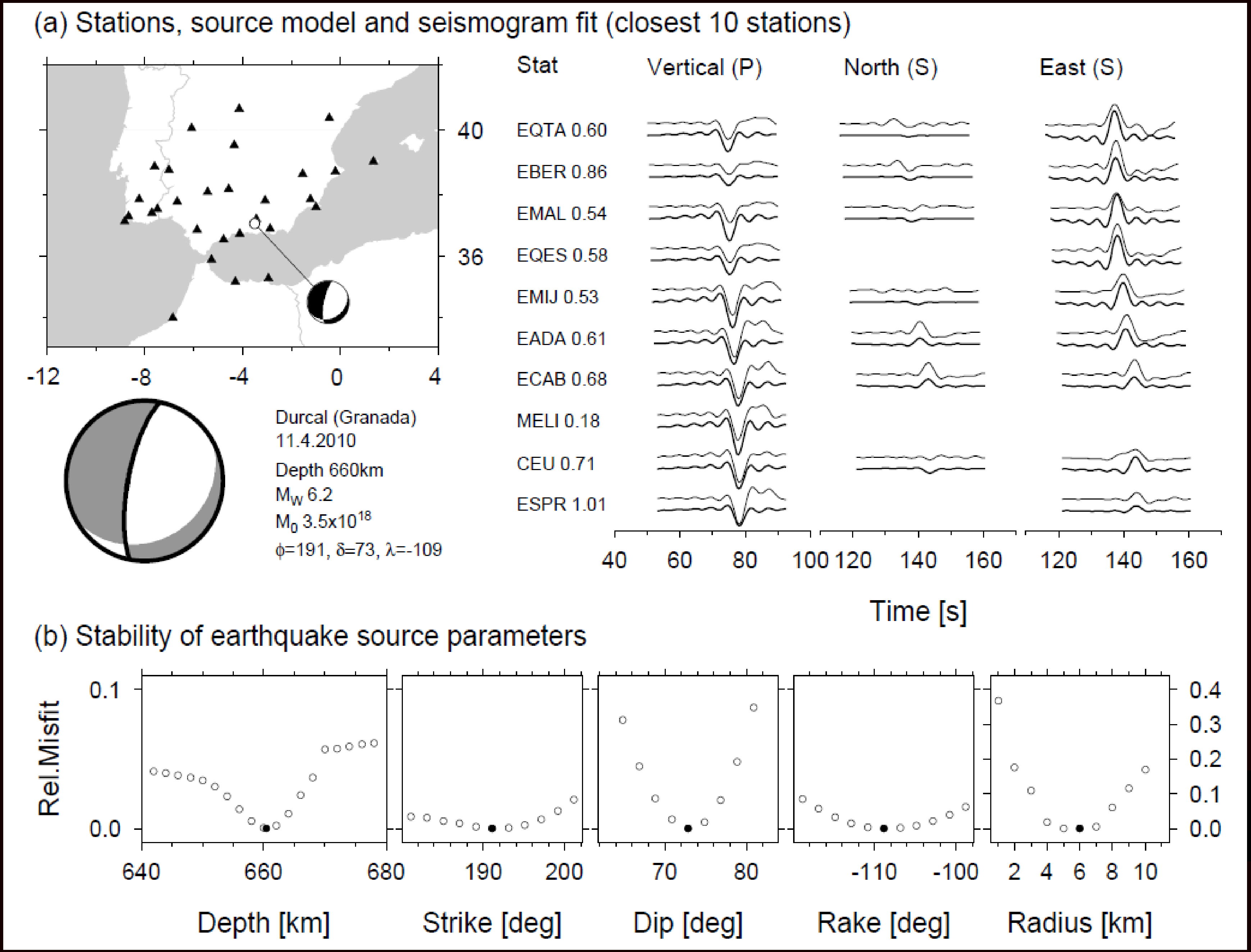


Cesca et al. J. Seismol. 2011

A deep earthquake beneath Southern Spain, the 11.4.2010 Granada earthquake

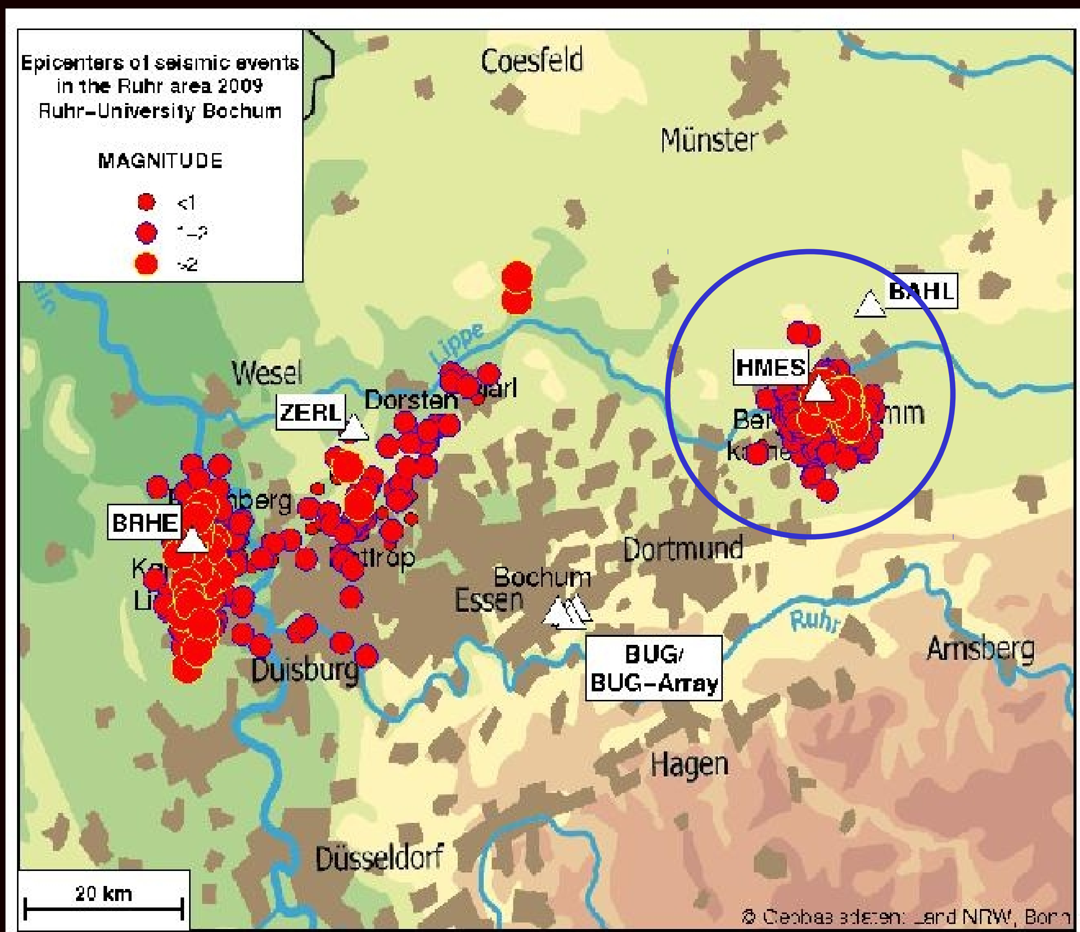


A deep earthquake beneath Southern Spain, the 11.4.2010 Granada earthquake



Buforn et al. BSSA 2011

Microseismicity application, source inversion in mining environments



Bischoff et al. 2010

Coal mining induced seismicity monitored by Ruhr University since 1983

About 1000 events are recorded between $0.7 < ML < 3.3$ every year

Hamm region (blue circle)

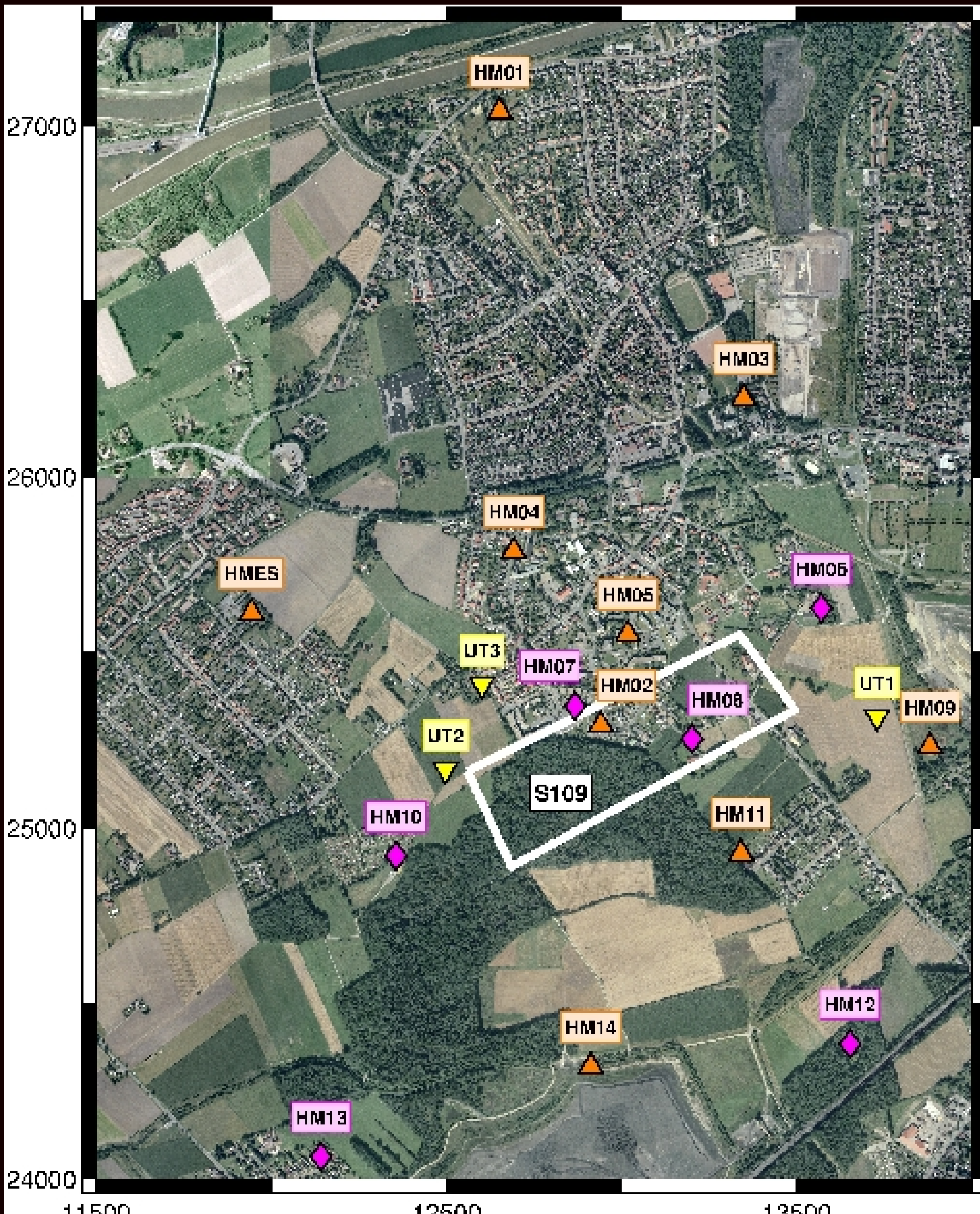
>7000 events in 2006-2007 (14 months)

913 events $0.0 < ML < 2.0$

DC inversion

MT inversion

Kinematic inversion and rupture modeling



Seismicity follows longwall mining,

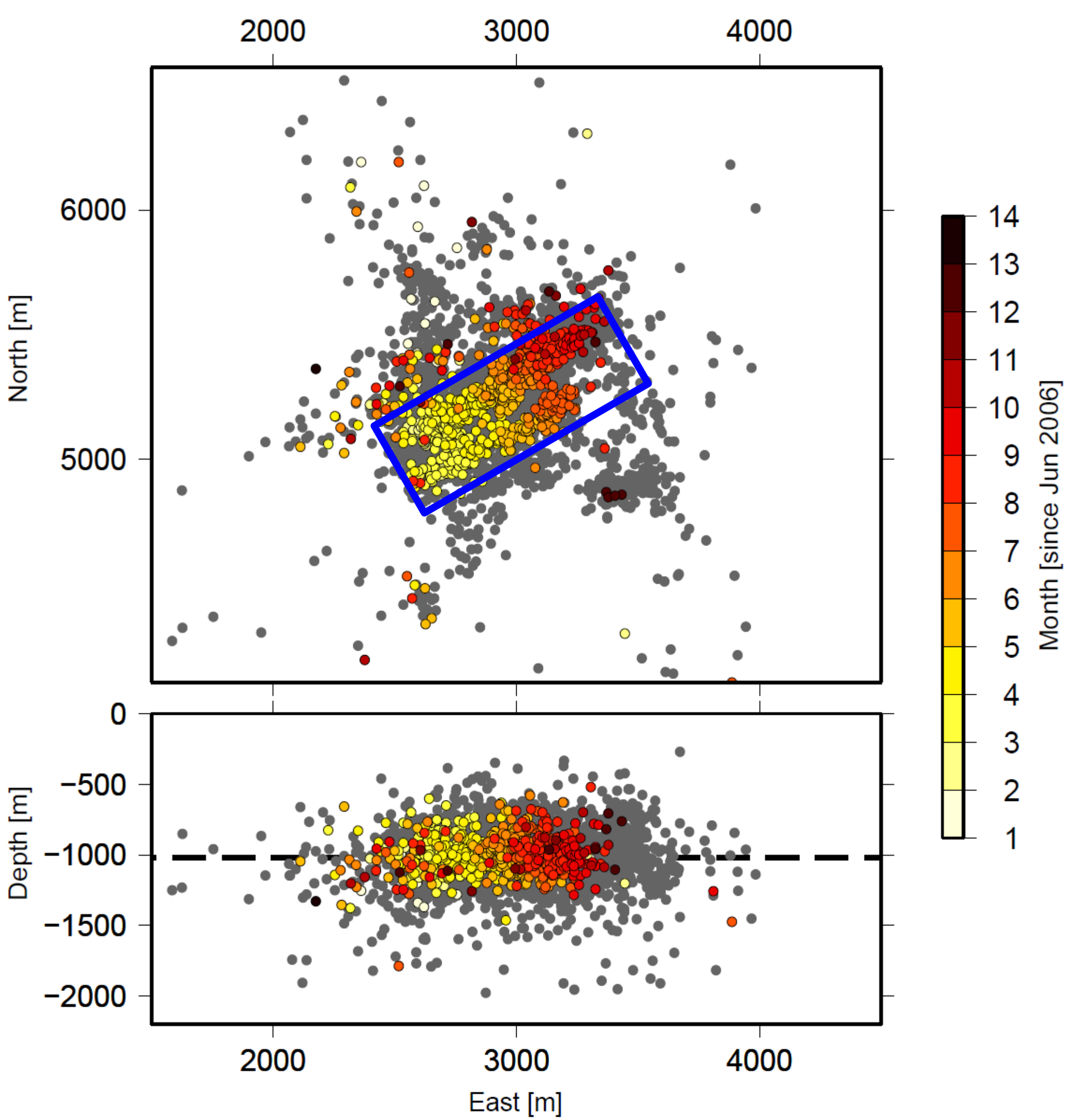
Epicenters are spreaded over an area of about 2x2km

6 broadband stations (5 Guralp CMG, pink; 1 Trillium 40, purple)

9 short-period (Mark L-4C-3D, orange)

3 subsurface stations (yellow)

We work here at 0.5-2Hz or 1-4Hz, combine BB and SP stations

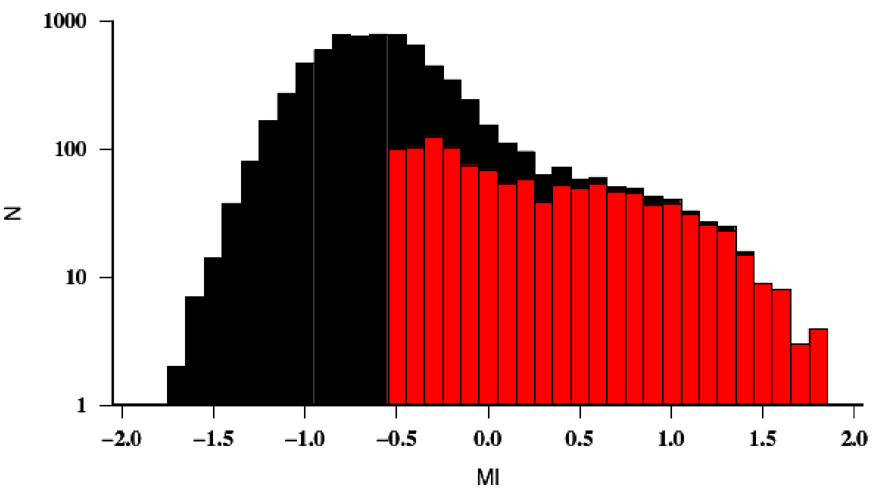


Spatiotemporal evolution of seismicity follows longwall mining

Additional clusters

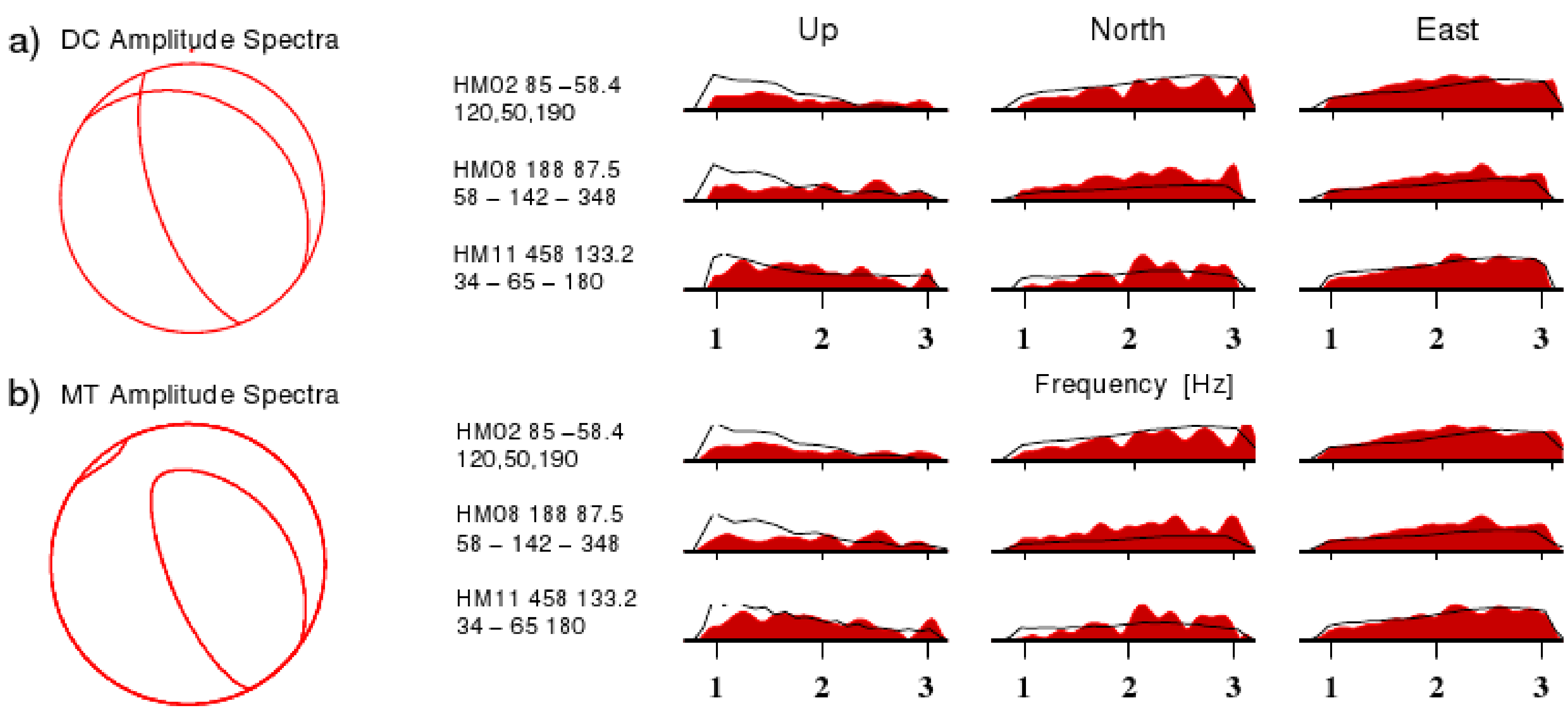
Average depth above the mining level

Bimodal frequency-magnitude distribution

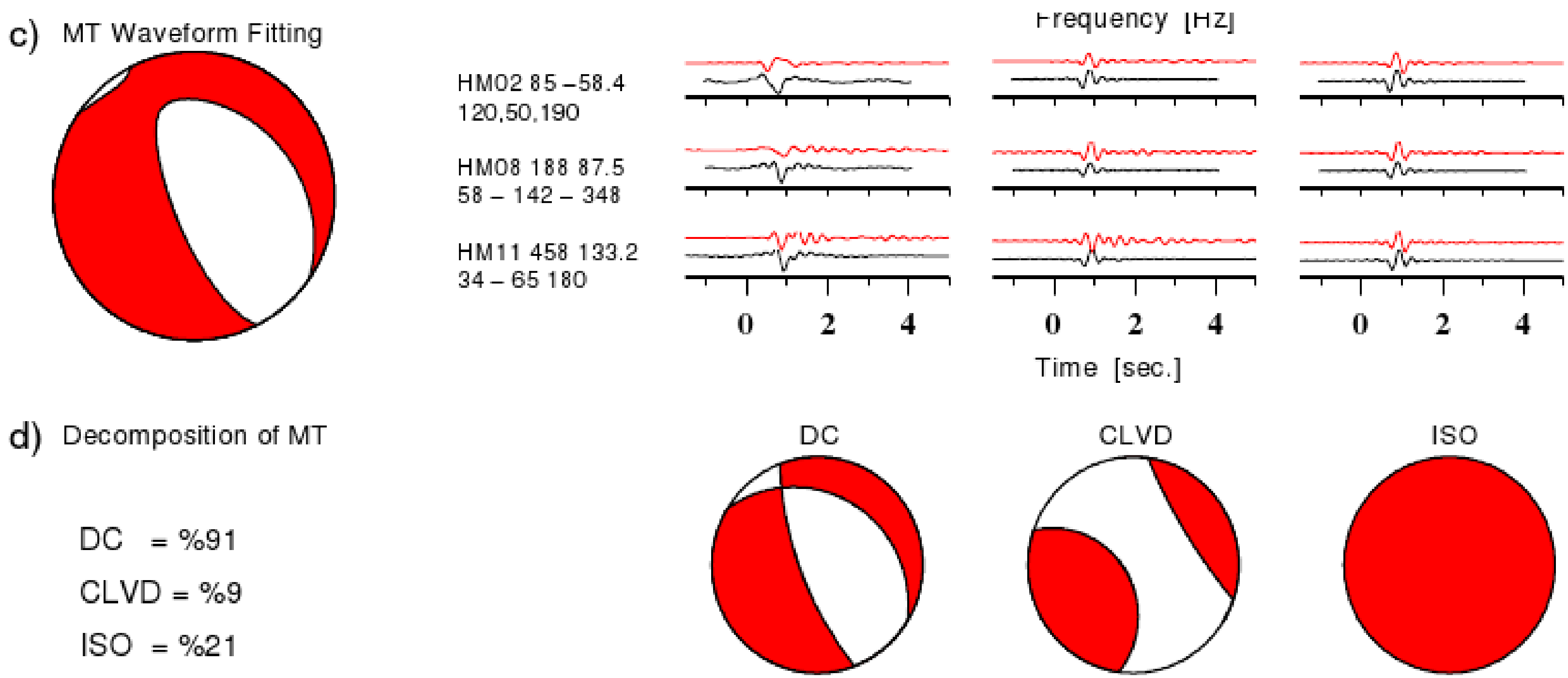


Sen et al. DGG 2012

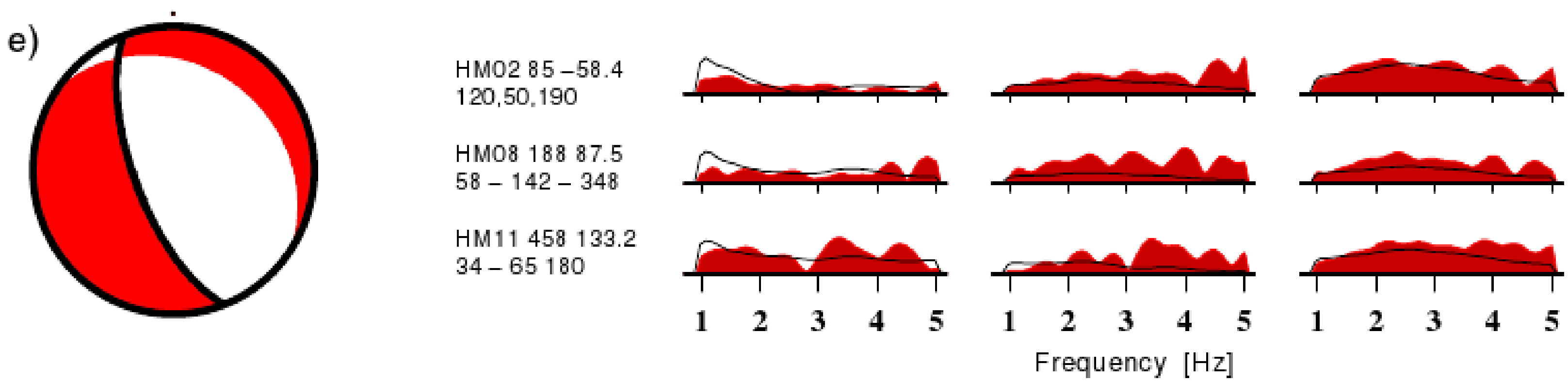
Step 1, 1b Point source inversion (amplitude spectra)

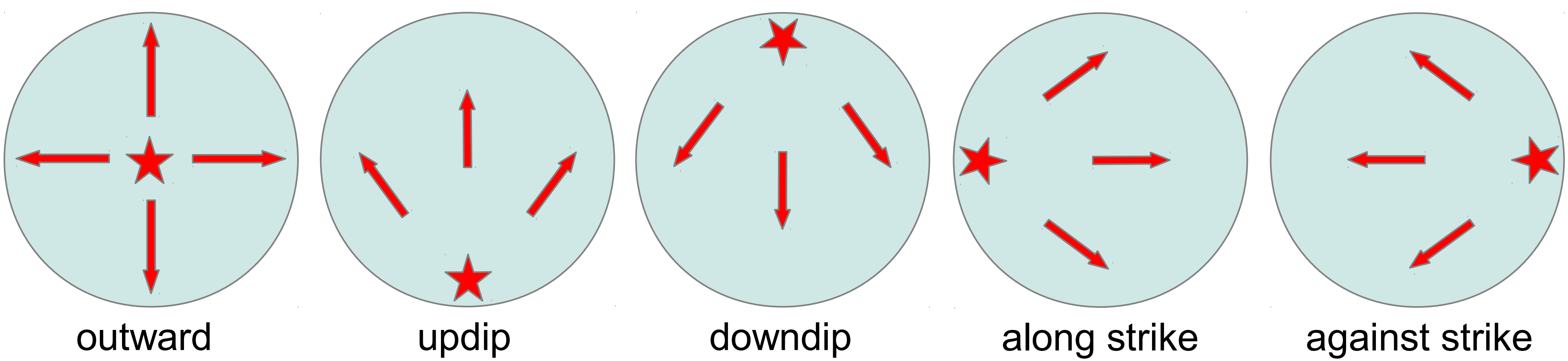


Step 2, 2b Point source inversion (time domain)



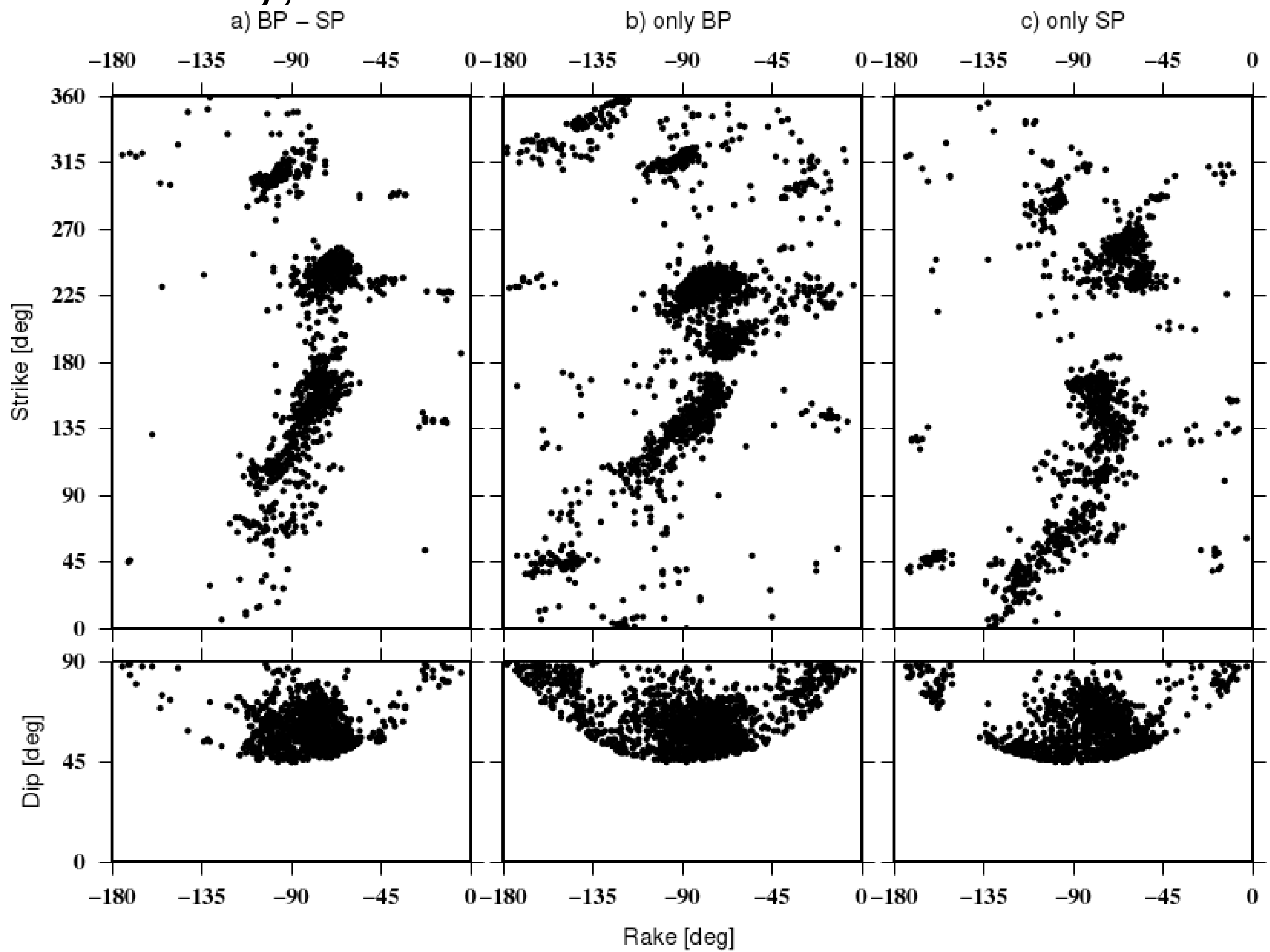
Step 3 Kinematic inversion (amplitude spectra)

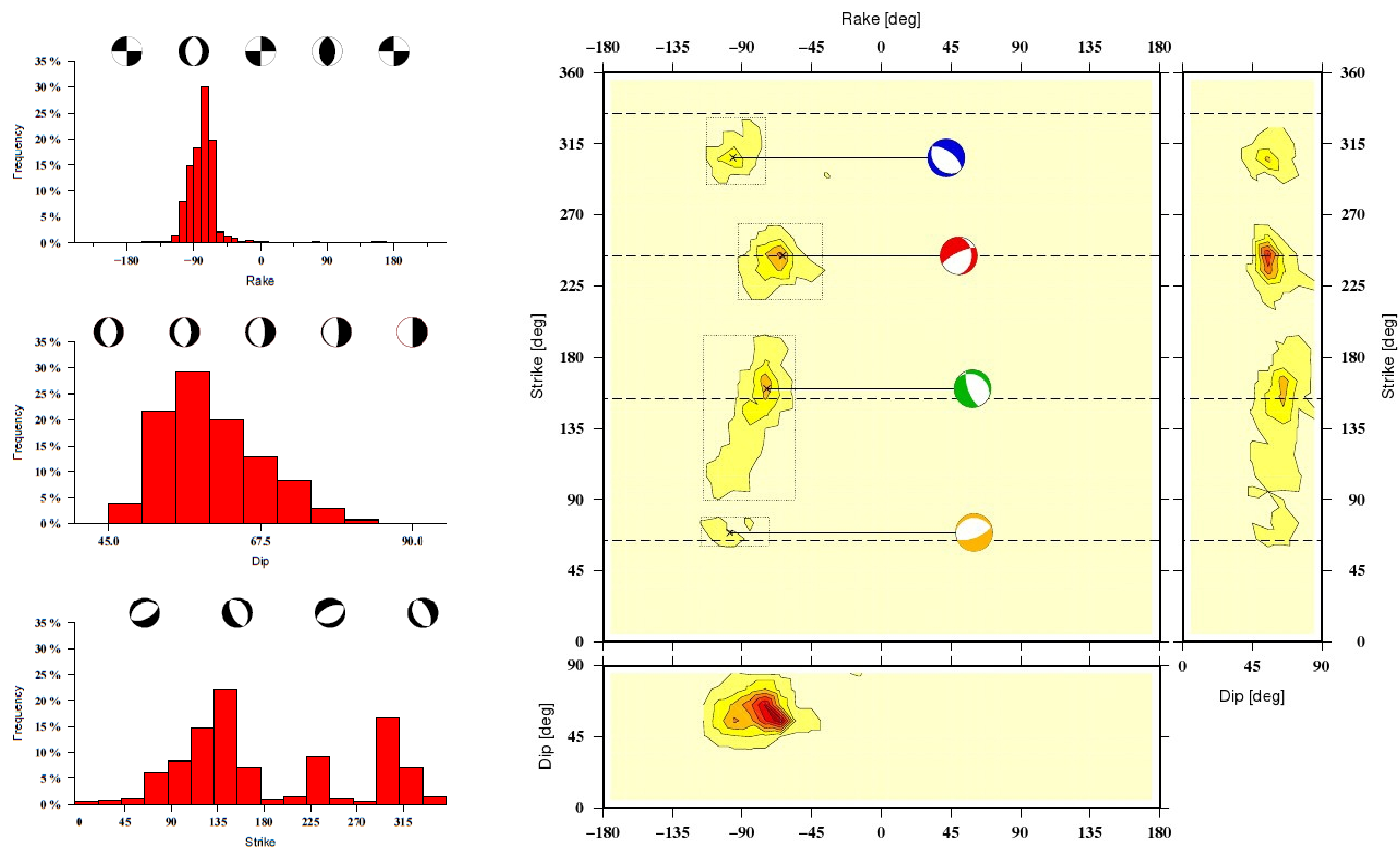




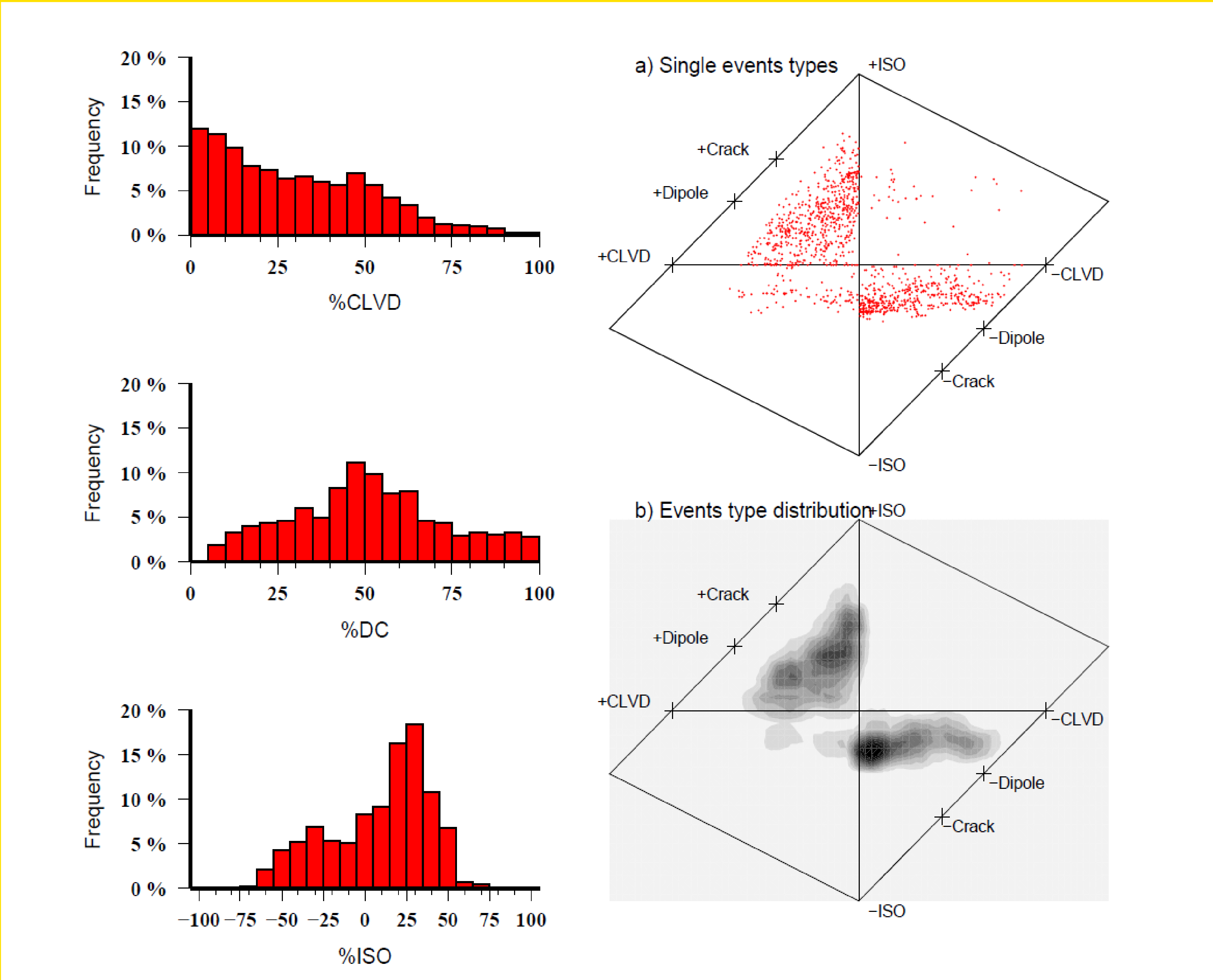
Results stability, different stations

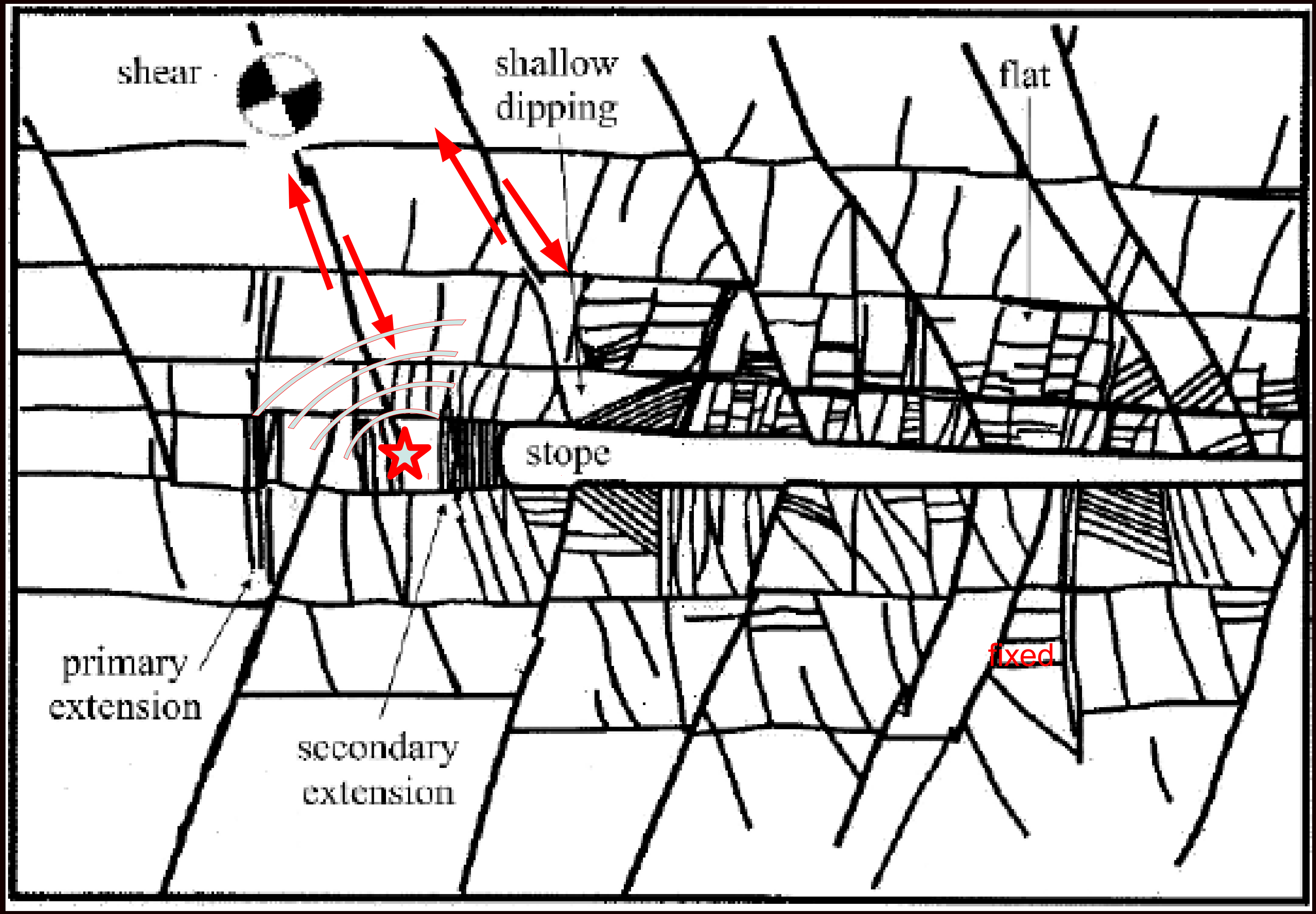
con





Sen et al. DGG 2012


Frequency
20 %
15 %
10 %
5 %
0 %
0
25
50
75
100
%CLVD
%DC
−100 −75 −50 −25 0 25 50 75 100
%ISO
a) Single events types
+ISO
−ISO
+Crack
+Dipole
+CLVD
−CLVD
−Dipole
−Crack
b) Events type distribution



Sen et al. DGG 2012, after Ryder and Jager (2002)

Thanks to:

A. T. Şen, Prof. Dr. T. Dahm, Dr. S. Heimann, A. Rohr

DFG and BMBF project KINHERD, RAPID, MINE

GEOTECHNOLGIEN programme

The Kiwi tools are currently used at:

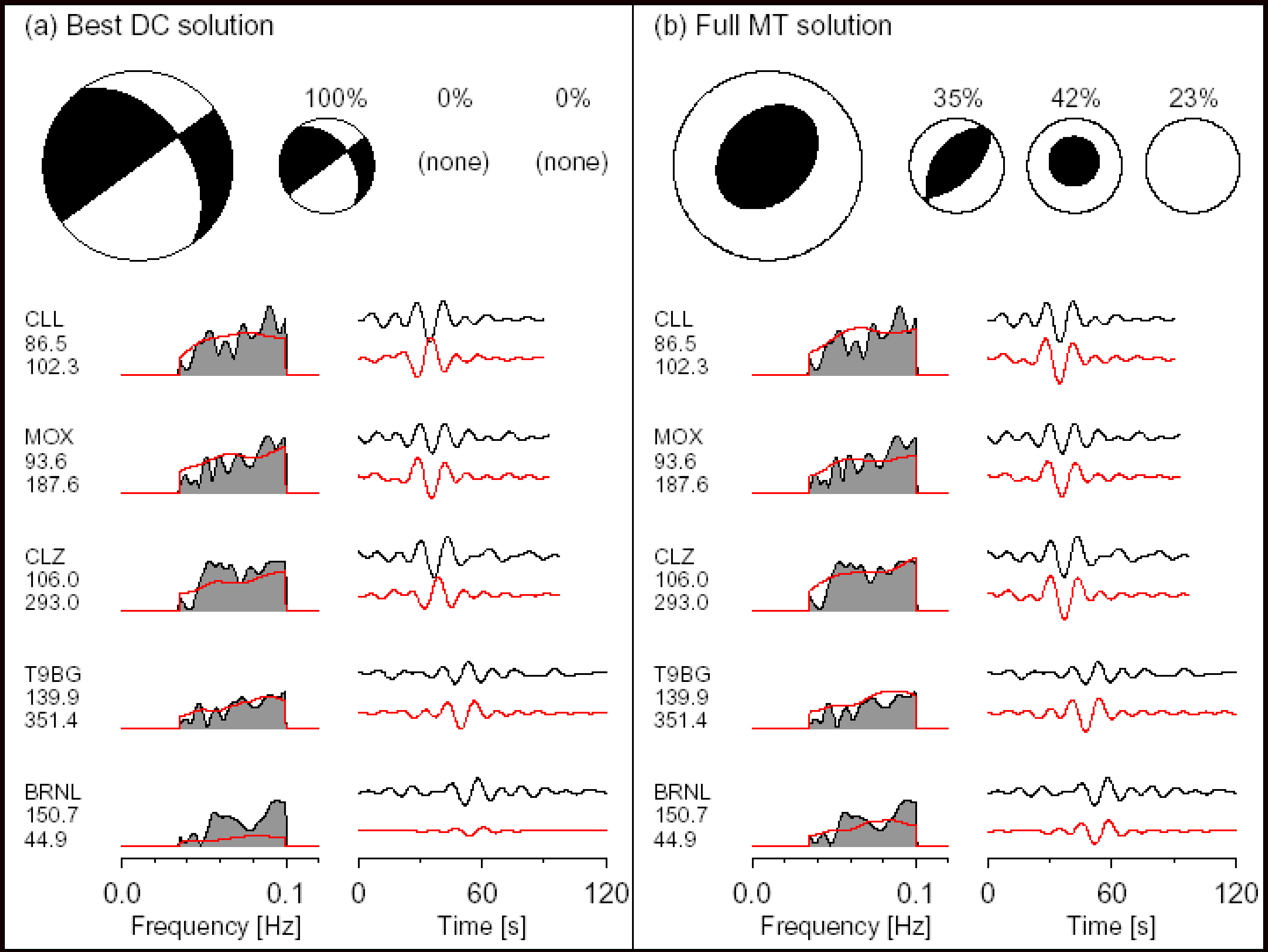
University of Hamburg, University of Potsdam, BGR Hannover, GFZ Potsdam, University of Lisbon, University of Coimbra, Aristotle University of Thessaloniki, Ruhr University Bochum

Further info on software and applications:

http://mine.zmaw.de

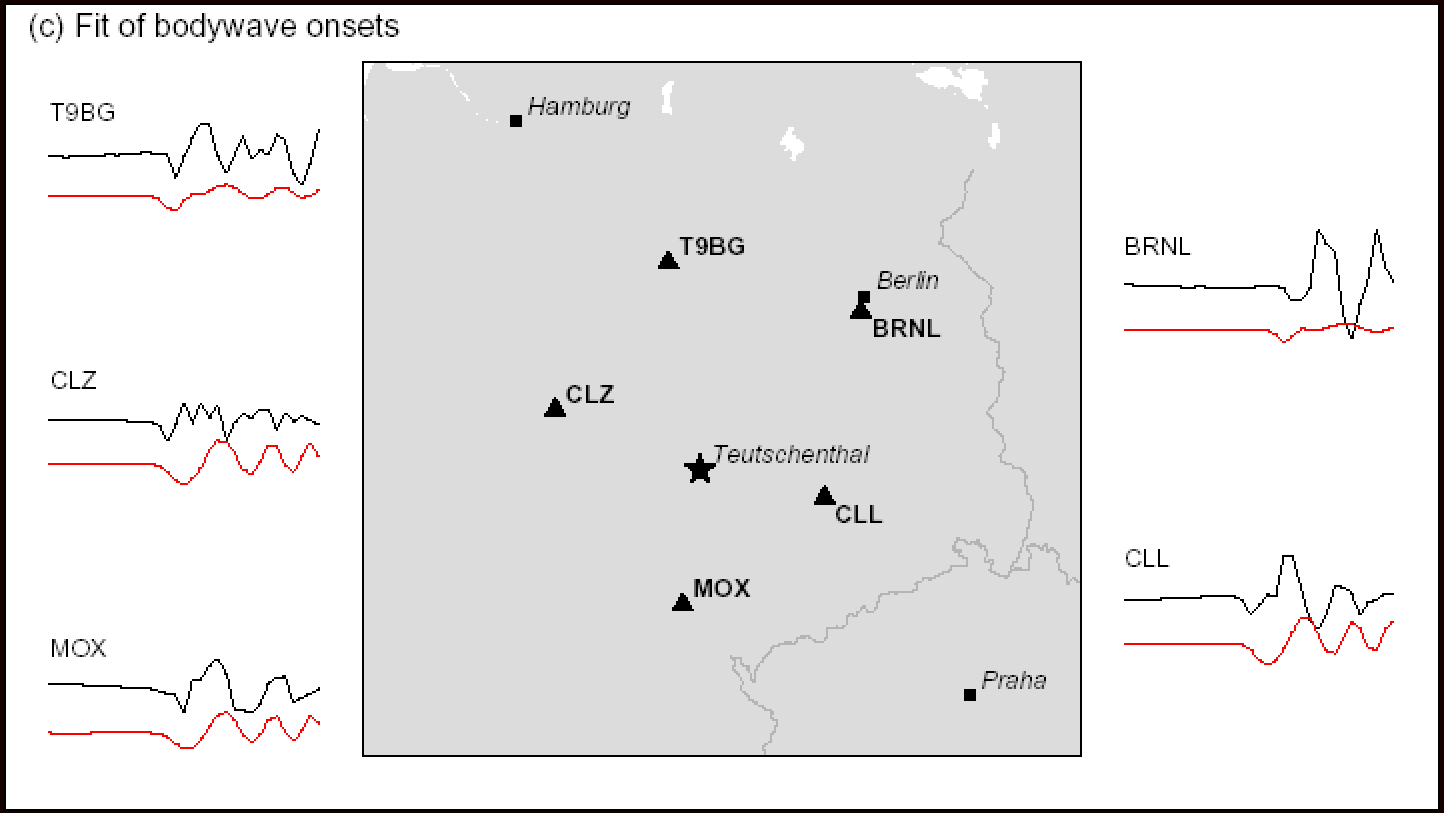
http://kinherd.org

Source inversion, natural and induced seismicity



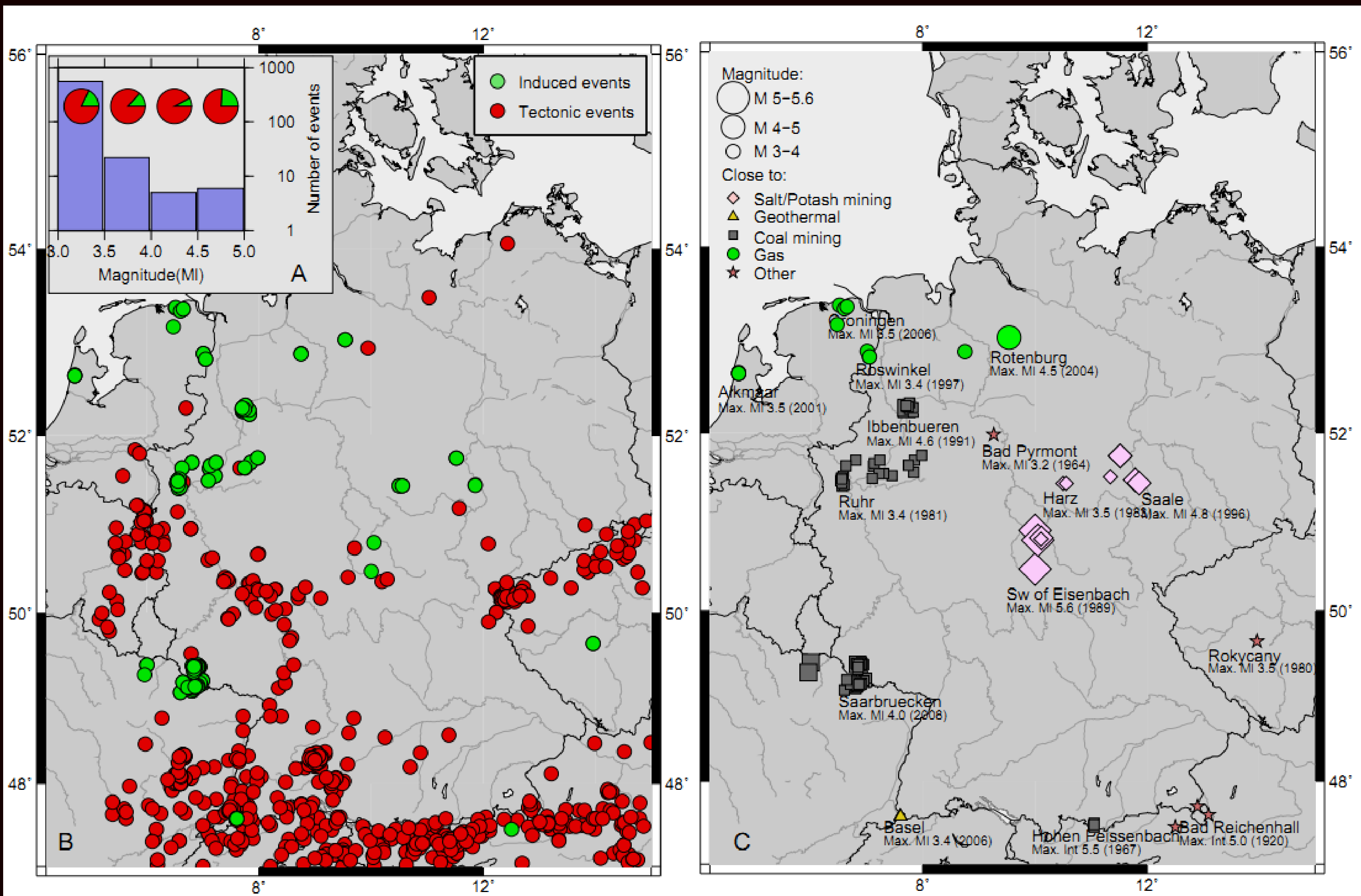
Cesca et al. submitted

Source inversion, natural and induced seismicity



Cesca et al. submitted

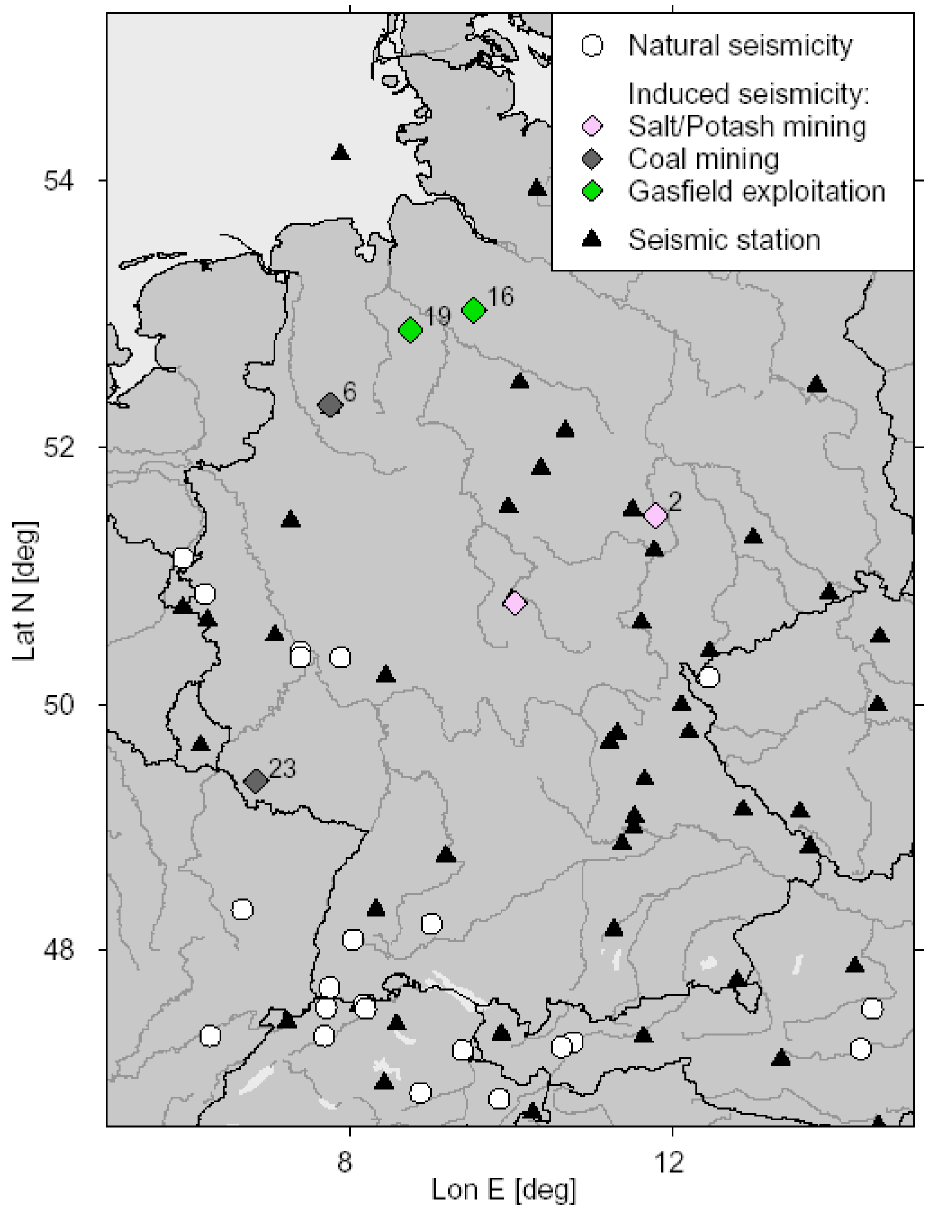
Source inversion, natural and induced seismicity



Cesca et al. submitted

Source inversion, natural and induced seismicity

Selected dataset and network configuration



Event	*Day*	*Ml*
1. Volkerhausen	13.03.1989	5.6
2. Roermond_NL	13.04.1992	5.9
3. Teutschenthal	11.09.1996	4.8
4. Imst_A	05.06.1997	4.4
5. S_Kerkrade	22.07.2002	4.9
6. Ibbenbueren	06.01.2003	3.9
7. Vosgian_mts	22.02.2003	5.9
8. Swaebian_Jura	22.03.2003	4.4
9. Linthal_CH	06.05.2003	4.4
10. Scalettapass_CH	18.07.2003	3.9
11. Murau_A	21.07.2003	4.4
12. Besancon_F	23.02.2004	5.5
13. Koblenz	22.05.2004	3.7
14. Saeckingen	21.06.2004	4.1
15. Laufenburg	28.06.2004	4.2
16. Rotenburg	20.10.2004	4.5
17. Waldkirch	05.12.2004	5.4
18. Olten_CH	12.05.2005	4.1
19. Syke_Bremen	15.07.2005	3.8
20. Laufenburg	12.11.2005	4.1
21. Landeck_A	19.05.2007	4.2
22. Koblenz	03.08.2007	3.9
23. Saarbruecken	23.02.2008	4.0
24. Erzgebirge	10.10.2008	4.2
25. Erzgebirge	14.10.2008	4.0
26. Erzgebirge	28.10.2008	4.1
27. Vaduz_FL	04.01.2009	4.4
28. Admont_A	20.04.2009	4.2
29. Schopfheim	05.05.2009	4.5
30. Koblenz	14.02.2011	4.5

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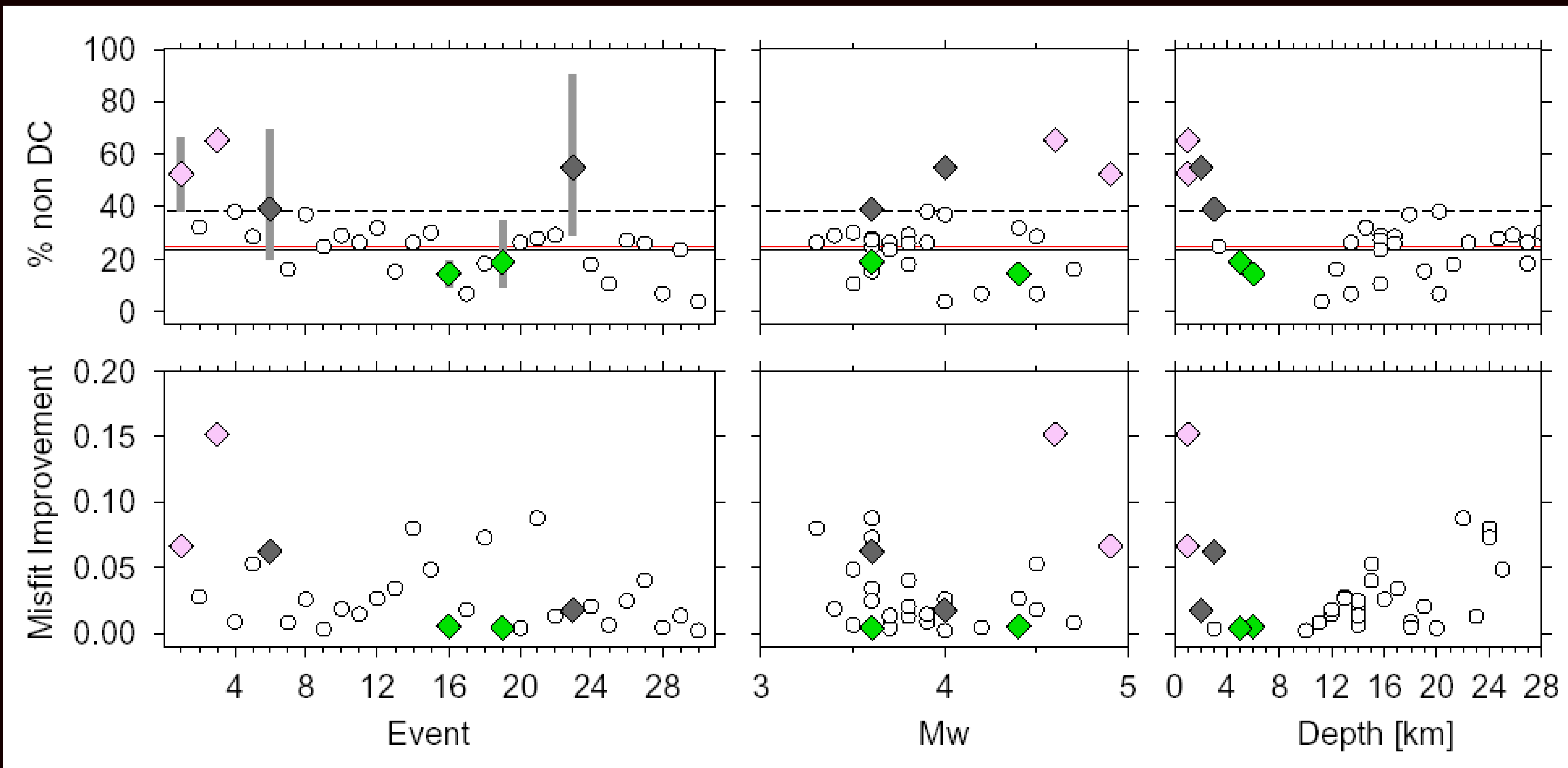
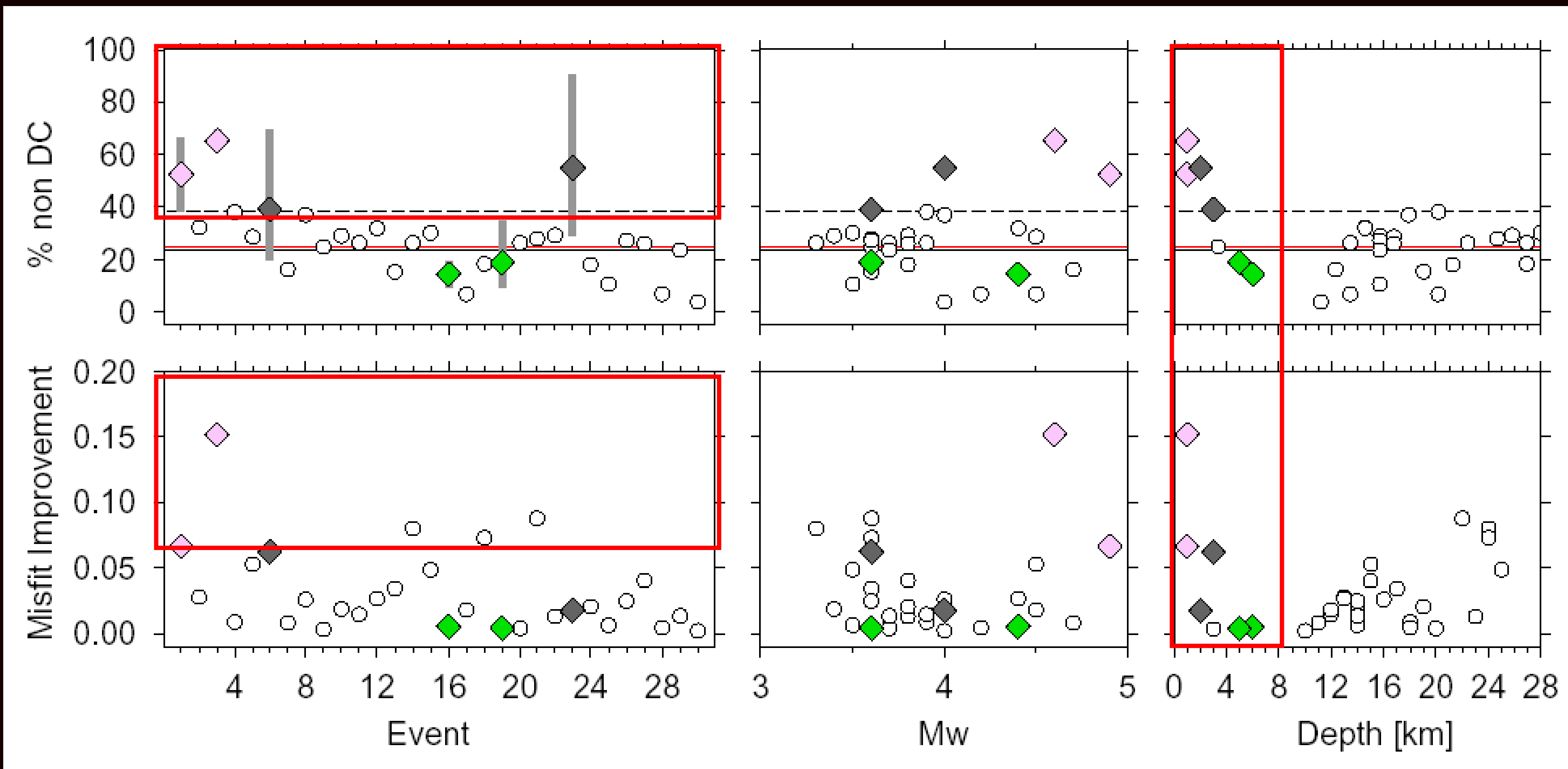
Source inversion, natural and induced seismicity



Cesca et al., submitted

Where to look for induced

(collapses, rockbursts, pillar blasts, explosions) seismicity?



Cesca et al., J. Seismol., R1 submitted

Kiwi Green´s function database