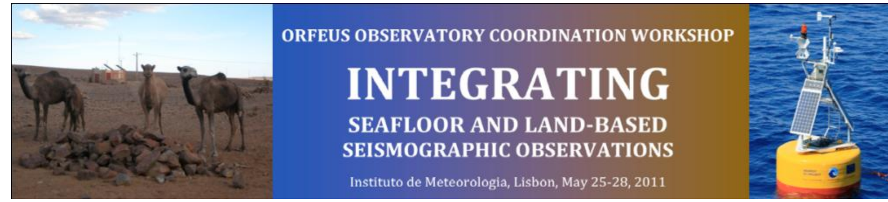

Kinematic Wavefom Inversion: application to SW Iberia Seismicity

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NEAREST/WP3 Working Group

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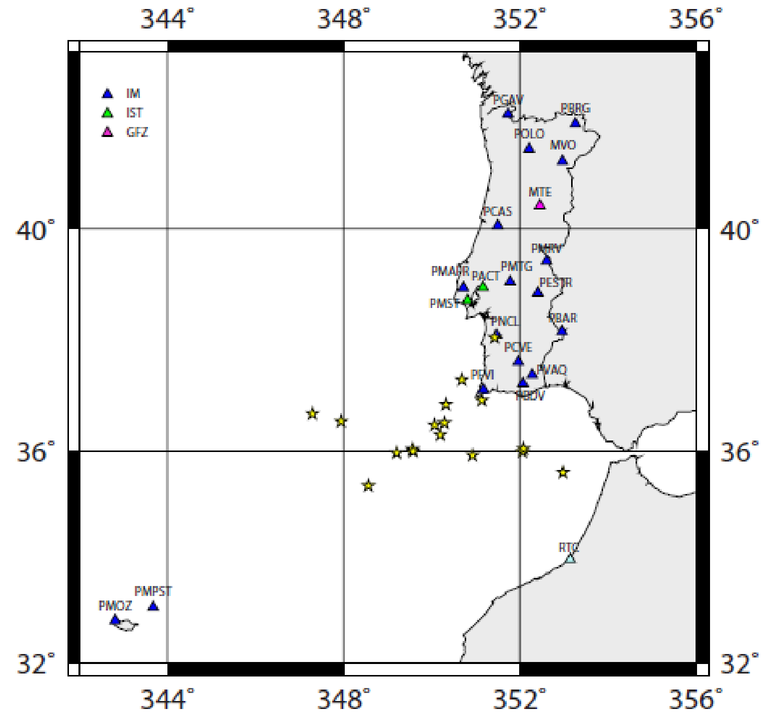
- Motivation
- Theoretical Framework
- Method
- Results & Discussions
- Conclusions & Future Work



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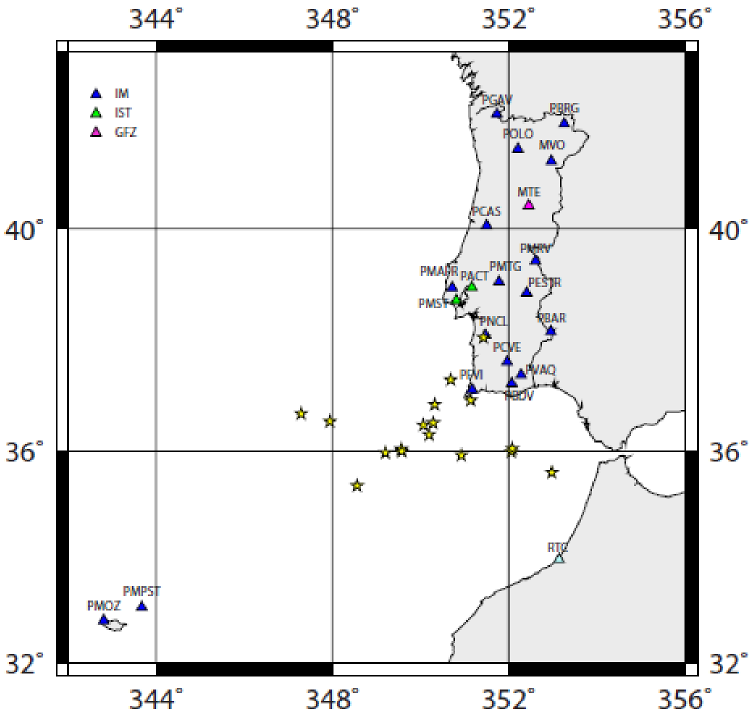


344°
348°
352°
356°
40°
36°
32°
IM
IST
GFZ
PGAV
PBRG
POLO
MVO
MTE
PCAS
PMTG
PACT
PCVE
PMPST
PMOZ

Motivation

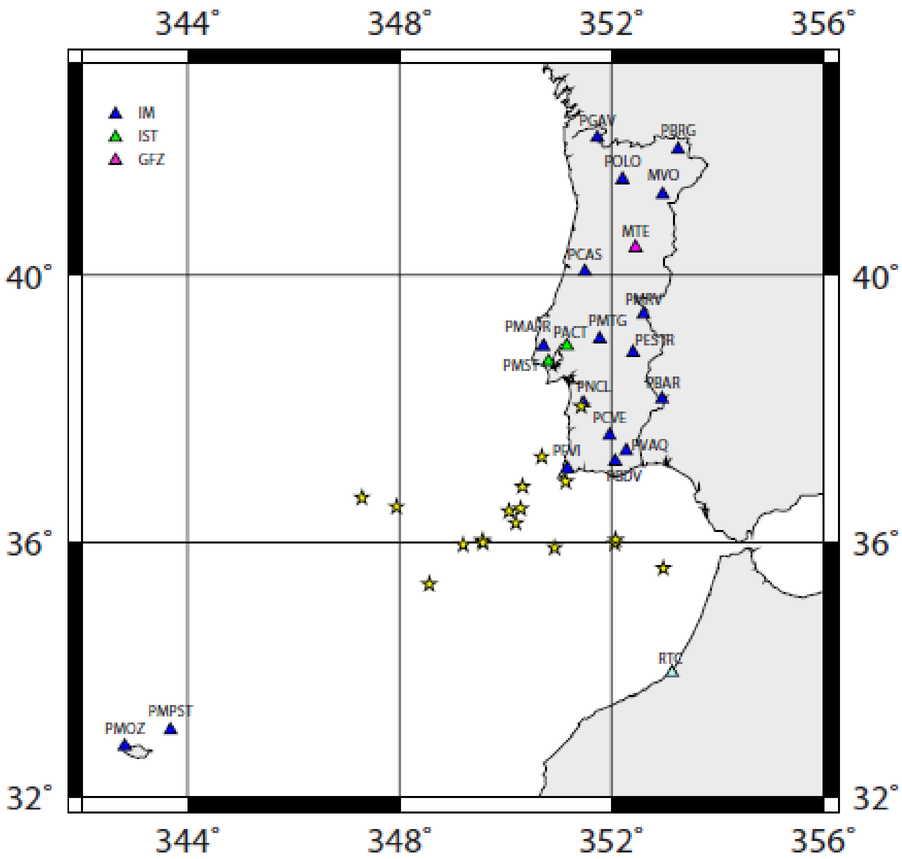
<u>Regional earthquakes:</u>

- Occurred between 2007 and 2009 in Southwest Iberia.
- Magnitude ranges M_l (3.5 – 4.9) provided by IM;
- 16 earthquakes offshore
  1 earthquake onshore
- Depths vary between institutions:

IM: 6 km - 32 km
EMSC: 10 km - 76 km.

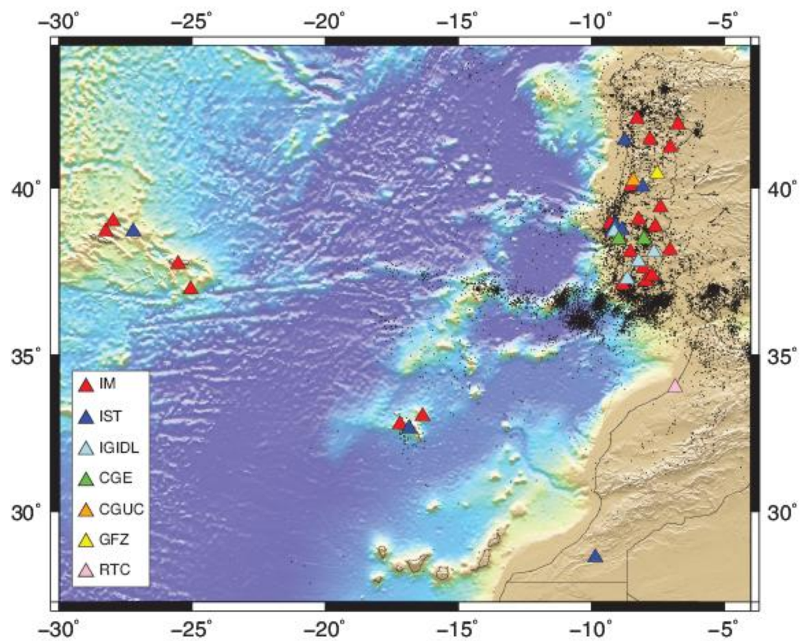
<u>12th of February ,2007 earthquake:</u>

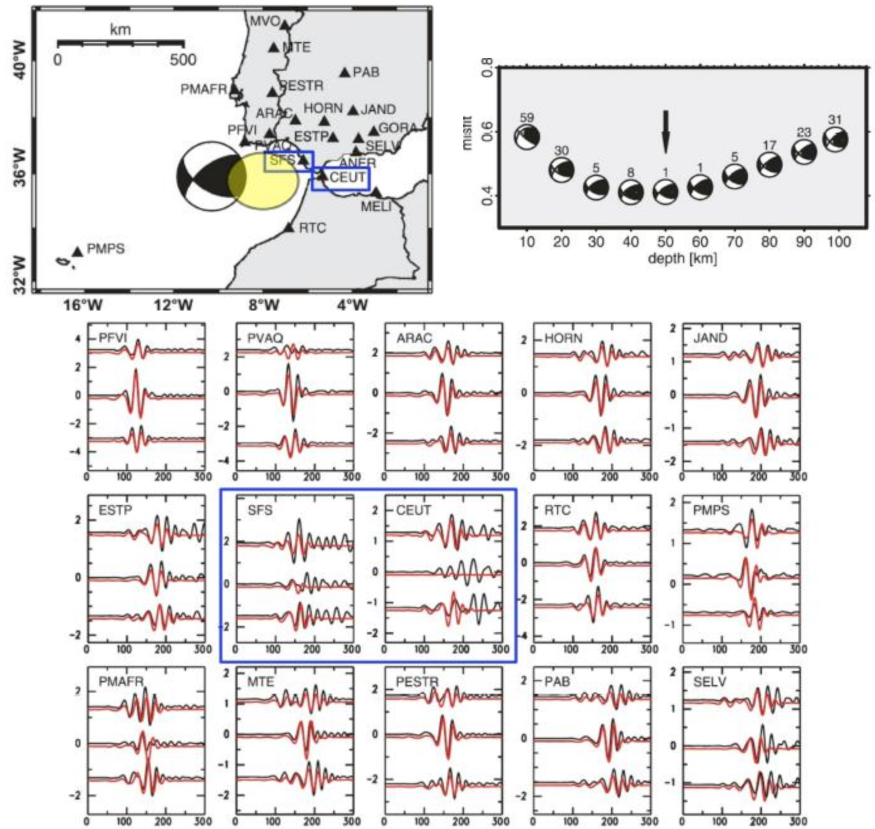
- M_w 5.9
- Occurred beneath the Horseshoe Abyssal Plain



Motivation

- Poor azimuthal coverage
- Heterogeneous Crustal Structure - Effect of the Cadiz sedimentary basin
  - -> Leading to different epicentres for the same earthquake

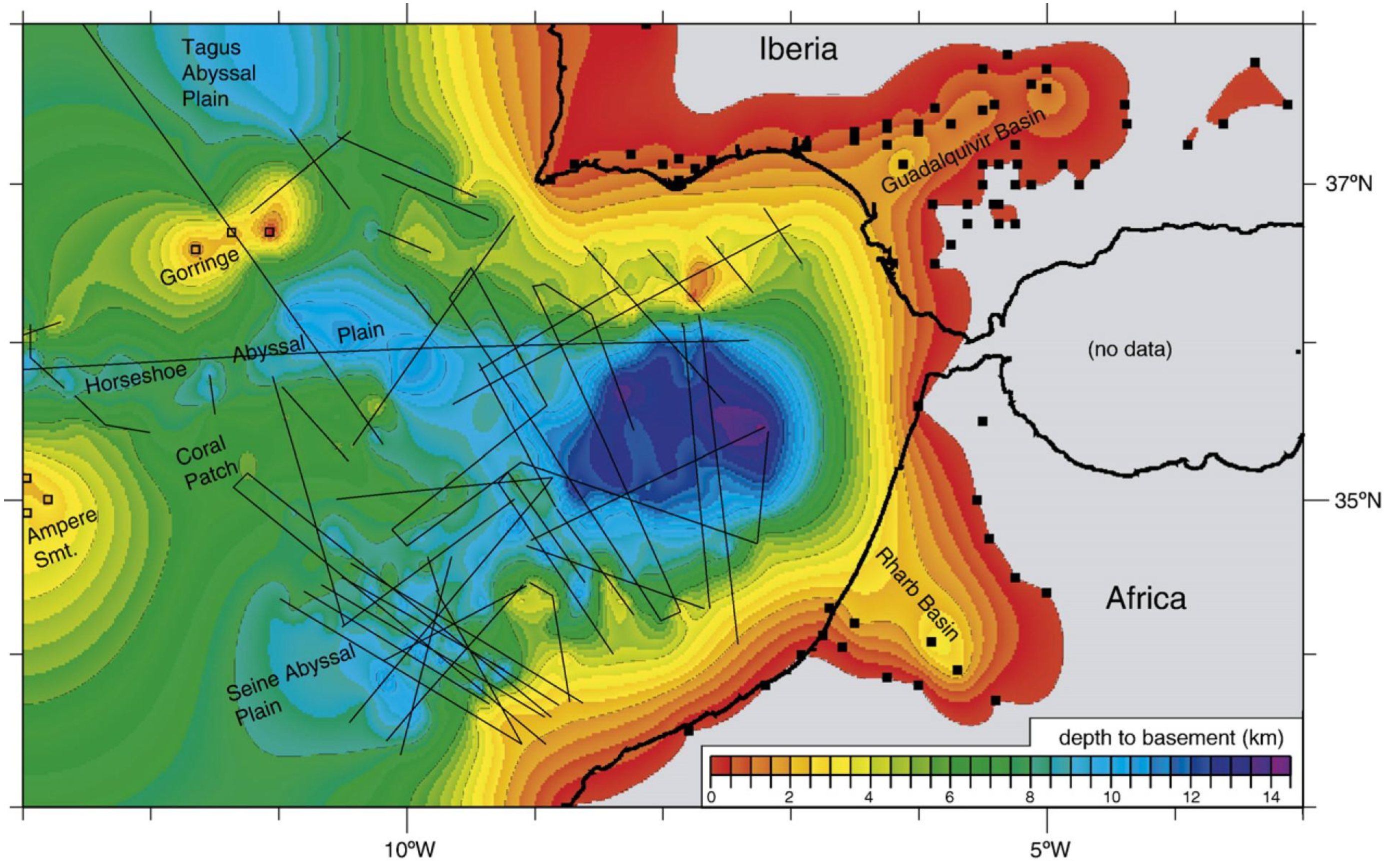




Adapted from Morelli [2009], after Stich et al [2007]

Motivation

- Poor azimuthal coverage
- Heterogeneous Crustal Structure - Effect of the Cadiz sedimentary basin
  -> Leading to different epicentres for the same earthquake



Thiebot and Gutscher. [Tectonophysics 2006]

Contents

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- **Theoretical Framework**
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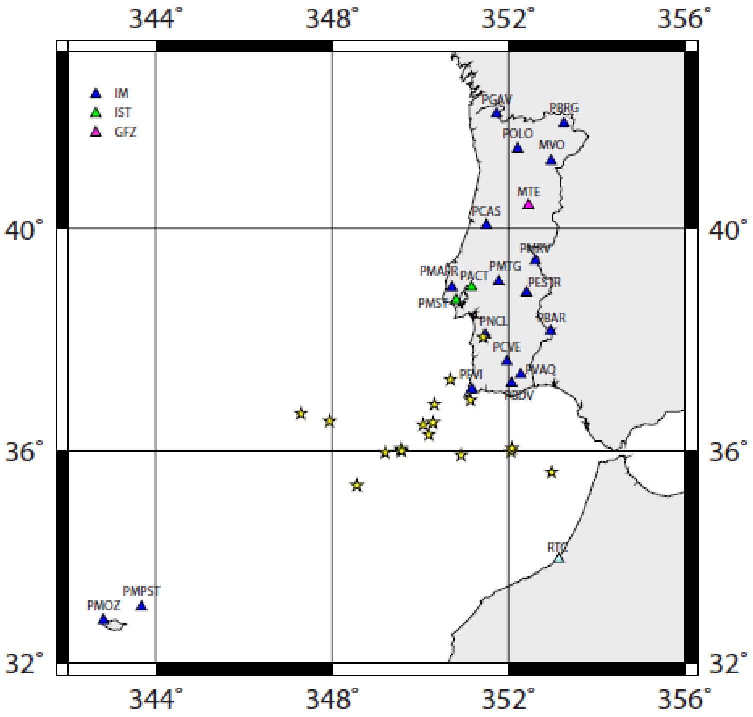


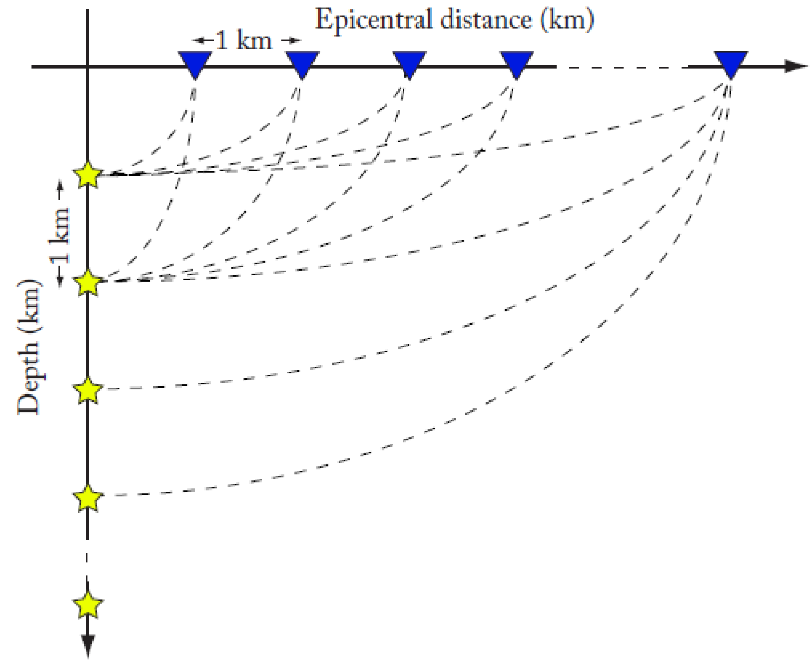
Theoretical Framework

Green's Functions:

- Response of the medium to the unit impulse.
- Earth model: Layered model (1D) [*Stich et al,* 2003]
- Data base generated using QSEIS, a code based on Thomson-Haskell propagator algorithm [*Wang,* 1999].

Range of source depth: 1-80 km (1 km of increment);

Range of epicentral distances: 1-400 km (1 km of increment);



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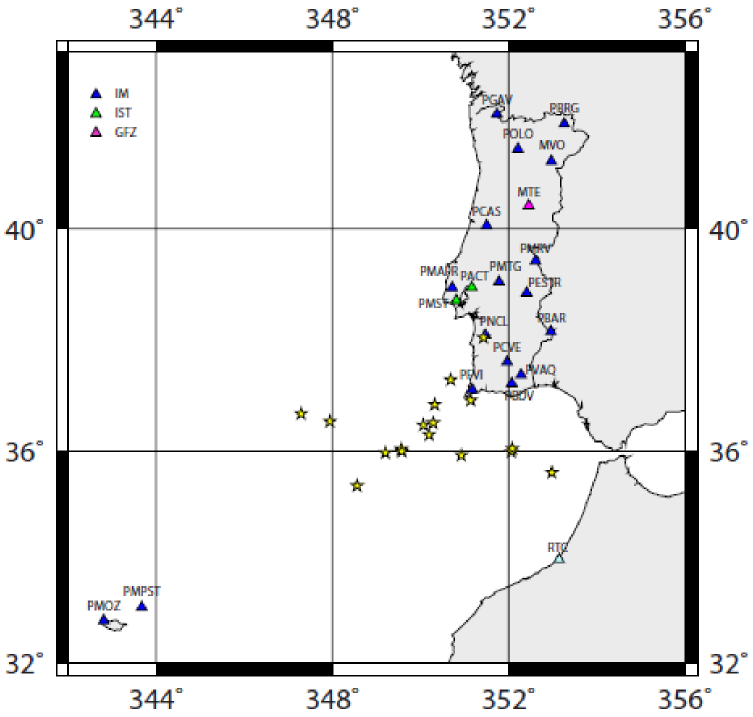


Method

KIWI – KInematic Waveform Inversion:

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

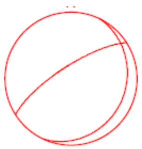
Step 1, 2	Step 3

Method

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

Step 1, Focal mechanism

amplitude spectra inversion



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

Step 2, Centroid Location

time domain inversion

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

Step 3, Kinematic model

amplitude spectra inversion, high frequencies

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

Cesca et al., JGR 2010

Method

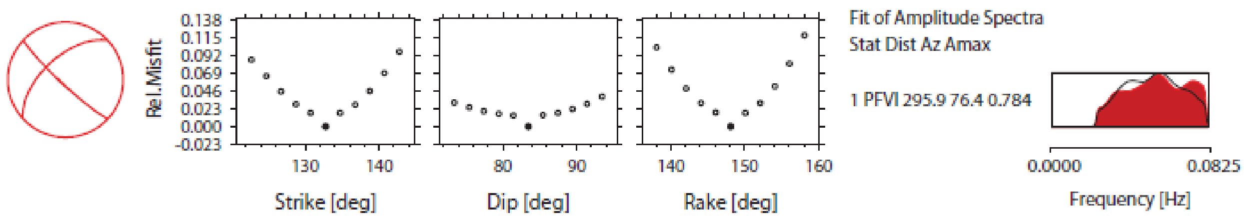
Step 1 – Focal Mechanism

- This is done in the frequency domain, by fitting amplitude spectra.
- Source parameters retrieved after this inversion steps are: strike, dip, rake (4 possible configurations), scalar moment and source depth.

Fixed parameters	Parameters to be retrieved	Domain and Misfit Measure	Inversion Algorithm	Data
Latitude Longitude t_0	Strike (2 values) Dip (2 values) Rake (4 values) M_0 Depth	Frequency domain (L2 norm)	Levenberg-Marquardt	Whole waveform

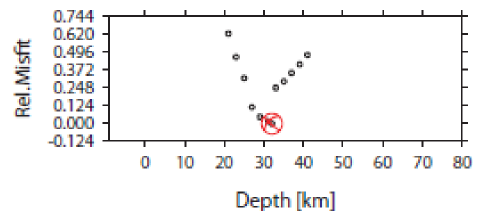
Output

$$\text{Misfit} = \frac{\sum (d_j^{syn} - d_j^{obs})^2}{\sum (d_j^{obs})^2}$$



$$\text{Relative Misfit} = \frac{\text{Misfit} - \text{BMisfit}}{\text{BMisfit}}$$

Lat Lon	36.55 N -12.06 E			
Strike	133.0	133.0	227.0	227.0
Dip	83.0	83.0	58.0	58.0
Rake	148.0	-32.0	8.0	-172.0
M_0	5.54E+15Nm			
M_w	4.3			
Depth	31.9km			
Duration	0.4s			
Misfit	0.362			

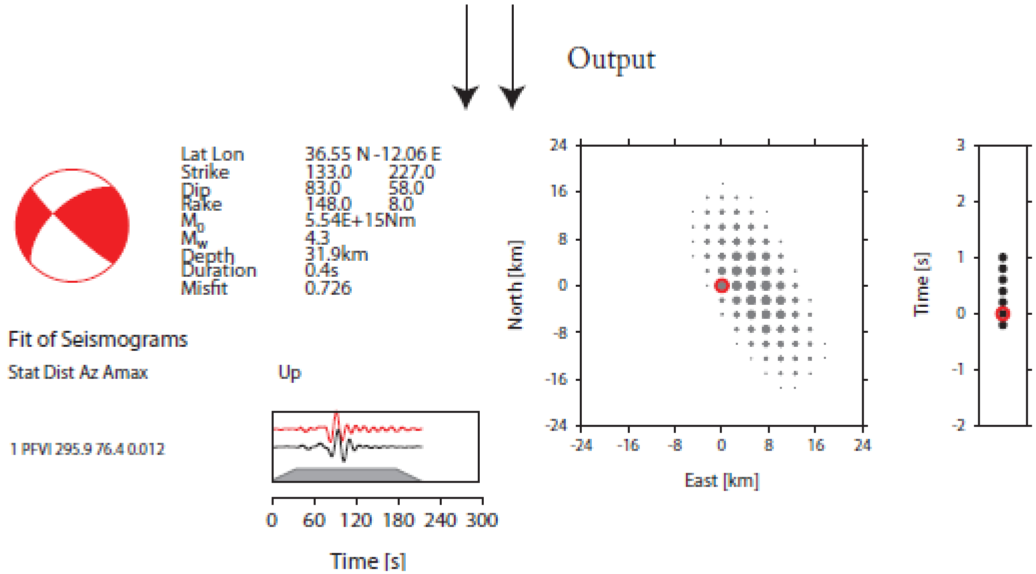


Method

Step 2 – Centroid Location

- This is done in the time domain, by fitting displacements time traces.
- Source parameters retrieved after this inversion steps are: strike, dip, rake (2 possible configurations), centroid relative location (North, East).

Fixed parameters	Parameters to be retrieved	Domain and Misfit Measures	Inversion Algorithm	Data
Strike (2 values) Dip (2 values) Rake (2 values) M_0 Depth	Centroid Latitude Centroid Longitude t_0	Time domain (L2 norm)	Grid walk	Whole waveform



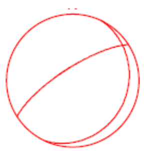
Method

Step 3 – Kinematic Inversion

• Amplitude spectra inversion including high frequencies

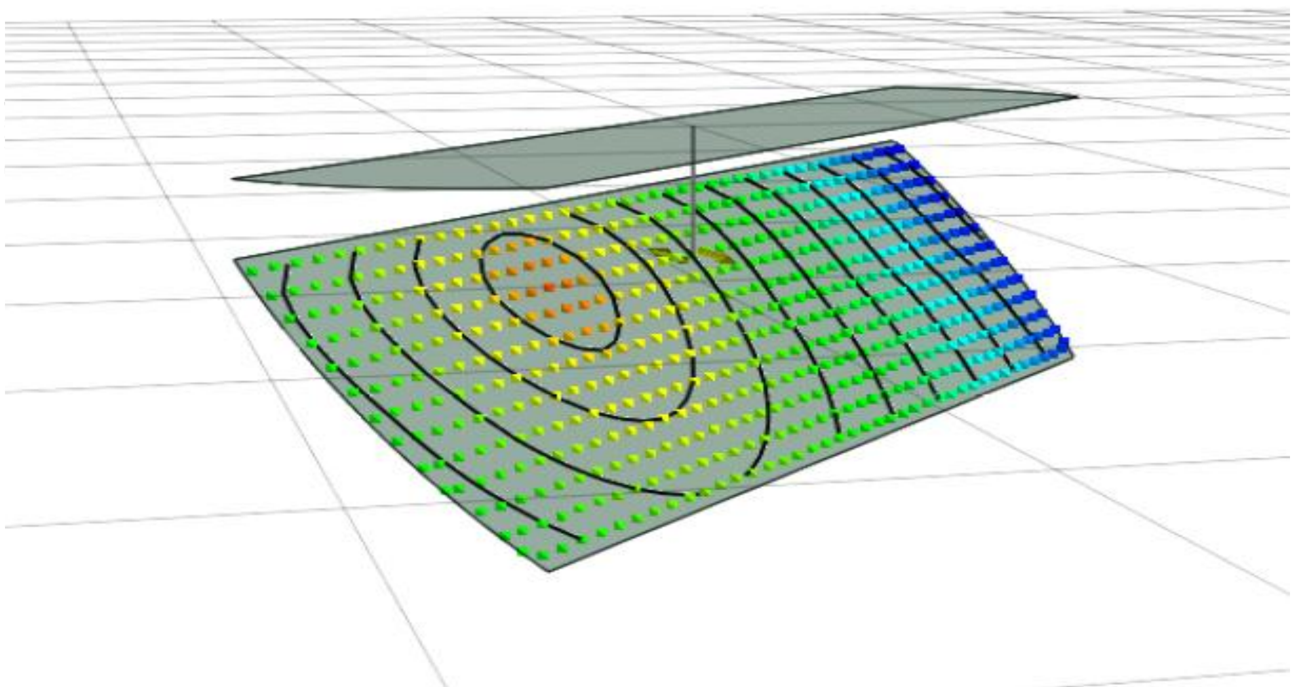
• We fix the fault orientation (considering both the two possible fault planes), the centroid location (center of the extended source model) and the magnitude, and focus on the remaining parameters of the eikonal source model.

Step 1



Step 2

Step 3



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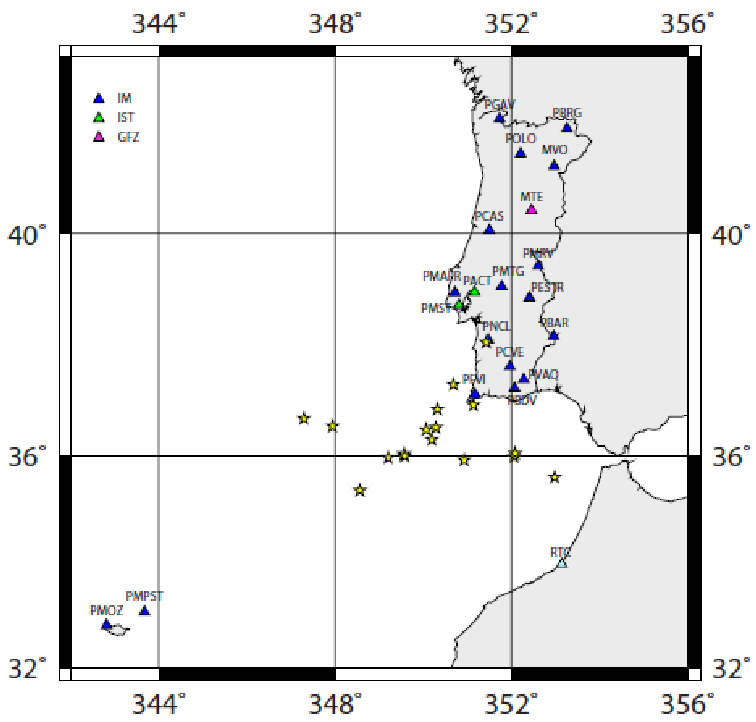


Results

ID	Date	Time	Lat (°N)	Long (°E)	Depth-IM (km)	Depth-EMSC(km)	M_l (IM)
1	17/02/2007	05:43:60	36.000	-10.431	33.0	40.0	3.7
2	06/03/2007	07:50:52	35.363	-11.446	25.0	60.0	3.7
3	10/04/2007	19:46:28	36.931	-8.869	28.0	20.0	3.5
4	01/07/2007	19:03:14	36.554	-12.066	10.0	30.0	4.9
5	06/11/2007	23:09:50	35.925	-9.074	30.0	10.0	3.8
6	11/01/2008	00:21:45	36.480	-9.944	17.0	20.0	4.7
7	14/04/2008	03:33:08	37.304	-9.317	25.0	30.0	3.7
8	10/05/2008	16:33:07	35.970	-10.801	20.0	20.0	4.1
9	17/07/2008	19:22:06	36.301	-9.806	6.0	76.0	3.8
10	09/09/2008	13:36:41	35.610	-7.017	20.0	35.0	3.9
11	17/02/2009	16:00:05	38.070	-8.570	6.0	10.0	3.8
12	22/05/2009	23:58:08	36.863	-9.676	21.0	20.0	3.6
13	05/07/2009	15:50:58	36.042	-10.440	31.0	30.0	4.4
14	18/08/2009	06:56:01	36.049	-7.924	31.0	40.0	4.2
15	05/09/2009	00:47:28	36.695	-12.714	10.0	10.0	4.2
16	08/09/2009	00:04:05	35.995	-7.944	32.0	71.0	4.0
17	18/09/2009	01:27:08	36.522	-9.722	32.0	25.0	3.7

Depending on the magnitude of the event, a bandpass filter is applied:

Magnitude range	Frequency range (Hz)
$M_l < 4.2$	0.05-0.1
$M_l > 4.2$	0.025-0.08

In order to have a better depth solution, a wide range of starting values (5-45 km) to perform the inversions.

Results

ID	Date	$M_w(M_l)$	M_0(Nm)	Dep(km)	D-IM(km)	D-EMSC(km)	S1	D1	R1	S2	D2	R2	M1	M2	St	Q
1	17/02/2007	3.8(3.7)	9.98E+14	25.4	33.0	40.0	38.0	83.0	-108.0	288.0	20.0	-22.0	0.497	1.169	4	C
2	06/03/2007	4.2(3.7)	3.46E+15	35.0	25.0	60.0	225.0	60.0	-0.0	315.0	90.0	-150.0	0.473	1.051	2	D
3	10/04/2007	3.5(3.5)	3.03E+14	25.4	28.0	20.0	180.0	58.0	-6.0	273.0	85.0	-148.0	0.388	0.822	5	A
4	01/07/2007	4.4(4.9)	6.75E+15	32.5	10.0	30.0	131.0	83.0	147.0	225.0	57.0	9.0	0.357	0.804	4	B
5	06/11/2007	3.6(3.8)	4.45E+14	4.8	30.0	10.0	80.0	70.0	-76.0	224.0	25.0	-124.0	0.375	0.887	6	B
6	11/01/2008	4.4(4.7)	6.91E+15	35.3	17.0	20.0	35.0	82.0	54.0	294.0	37.0	167.0	0.289	0.595	7	A
7	14/04/2008	3.6(3.7)	3.73E+14	29.5	25.0	30.0	199.0	74.0	-15.0	293.0	75.0	-163.0	0.381	0.892	8	B
8	10/05/2008	4.1(4.1)	2.14E+15	39.4	20.0	20.0	106.0	11.0	153.0	223.0	85.0	80.0	0.587	1.122	5	C
9	17/07/2008	3.4(3.8)	2.20E+14	15.1	6.0	76.0	8.0	49.0	-157.0	263.0	73.0	-43.0	0.521	1.077	5	C
10	09/09/2008	4.3(3.9)	4.43E+15	44.4	20.0	35.0	105.0	31.0	-140.0	339.0	71.0	-66.0	0.533	1.251	6	D
11	17/02/2009	3.4(3.8)	2.42E+14	15.0	6.0	10.0	34.0	80.0	12.0	301.0	78.0	170.0	0.421	0.800	8	B
12	22/05/2009	3.3(3.6)	1.44E+14	25.0	21.0	20.0	47.0	66.0	43.0	296.0	52.0	149.0	0.399	0.959	9	B
13	05/07/2009	4.1(4.4)	2.69E+15	41.2	31.0	30.0	126.0	84.0	143.0	221.0	53.0	7.0	0.296	0.600	7	A
14	18/08/2009	3.9(4.2)	1.21E+15	36.0	31.0	40.0	97.0	84.0	49.0	360.0	42.0	171.0	0.325	0.930	9	B
15	05/09/2009	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	08/09/2009	4.0(4.0)	1.44E+15	30.3	32.0	71.0	8.0	49.0	150.0	119.0	68.0	45.0	0.499	1.222	7	C
17	18/09/2009	4.4(3.7)	6.66E+15	40.4	32.0	25.0	51.0	73.0	-71.0	182.0	25.0	-136.0	0.598	1.120	6	C

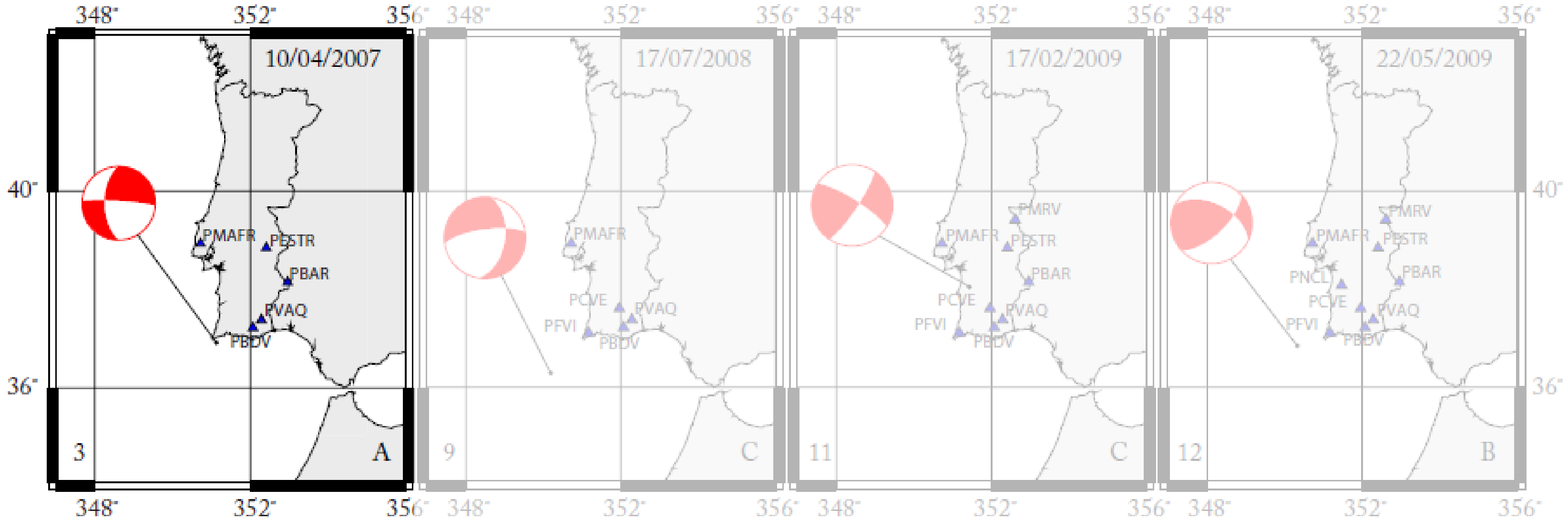
Quality factor criteria:

	Misfit 1	Misfit 2	Nr. of stations
Quality A	< 0.400	< 0.850	≥ 5
Quality B	< 0.500	< 1.000	≥ 4
Quality C	< 0.600	< 1.250	≥ 3
Quality D	< 0.700	< 1.500	≥ 2
Quality E	< 0.800	< 1.750	≥ 1

	#
Quality A	3
Quality B	6
Quality C	5
Quality D	2

Results

Earthquakes with $M_W \leq 3.5$:

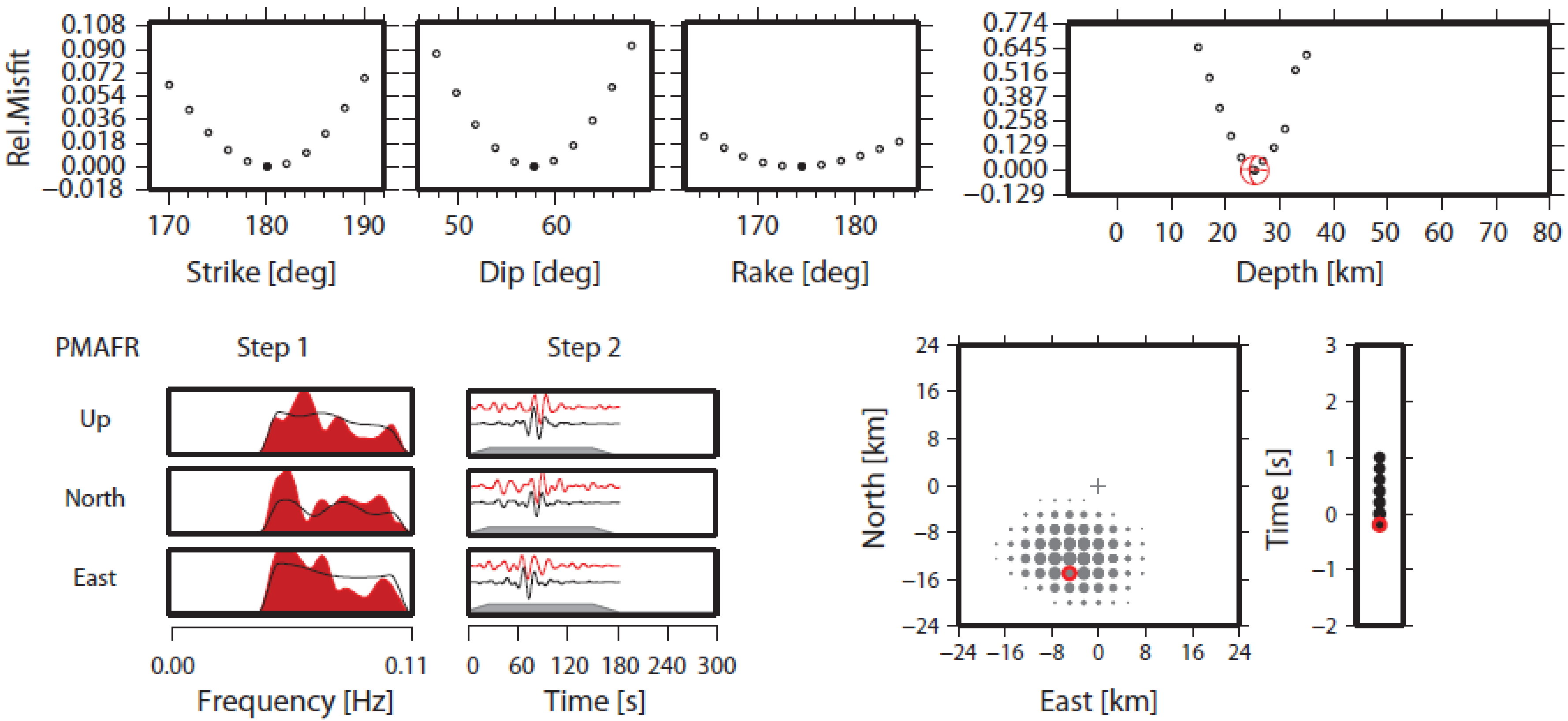


Earthquake 10/04/2007 – Event 3

- Quality A (Misfit 1 – 0.388 Misfit 2 – 0.822 Nr. of stations - 5)
- $M_W = 3.5$
- Depth: 25.4 km (IM- 28 km EMSC – 20 km)
- Strike-slip behaviour with a minor normal component

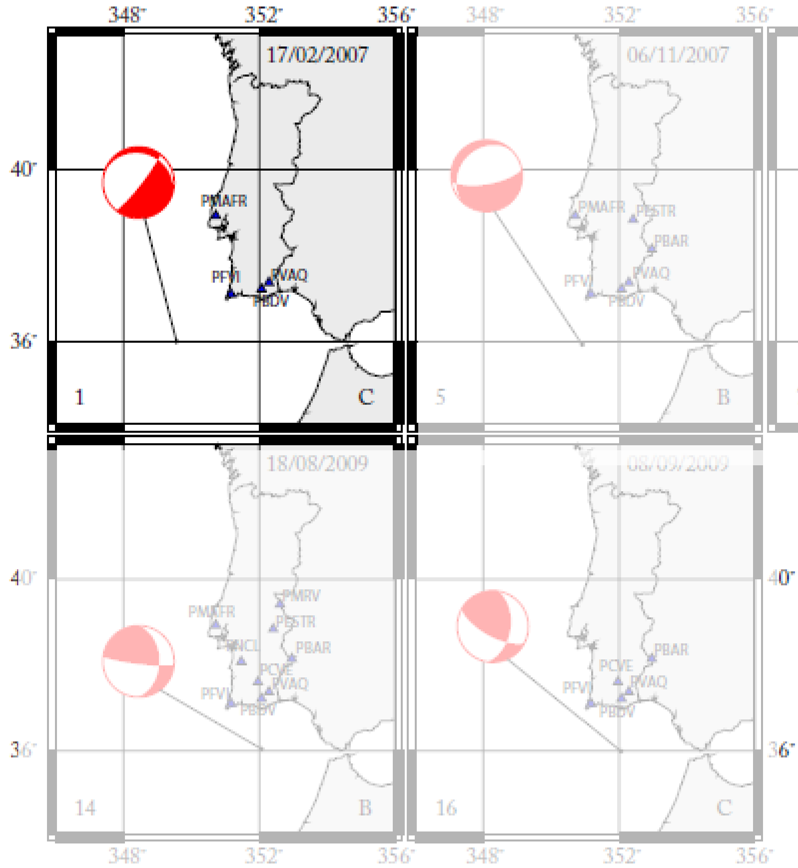
Results

Earthquake 10/04/07 – Event 3:



Results

Earthquakes with $3.5 < M_W \leq 4.0$:

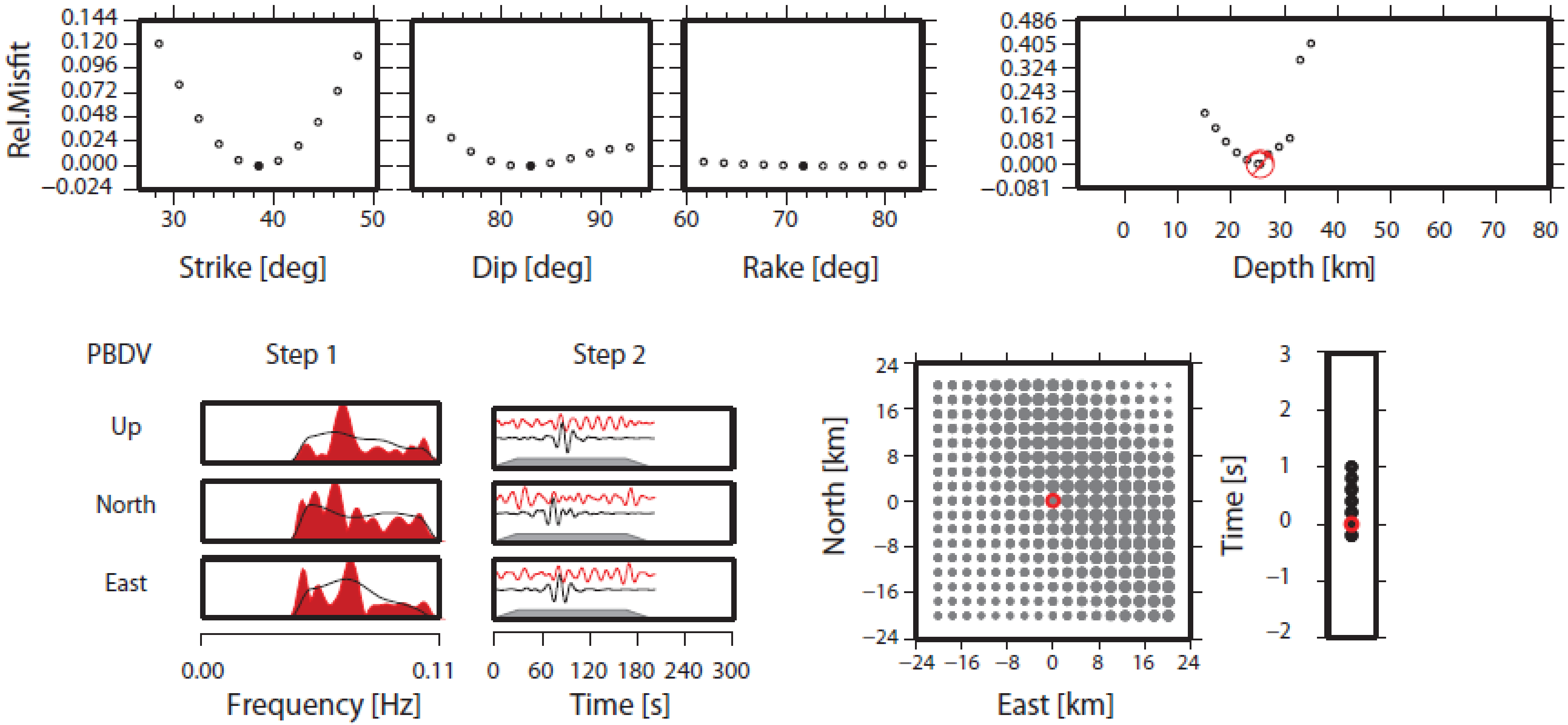


Earthquake 17/02/2007 – Event 1

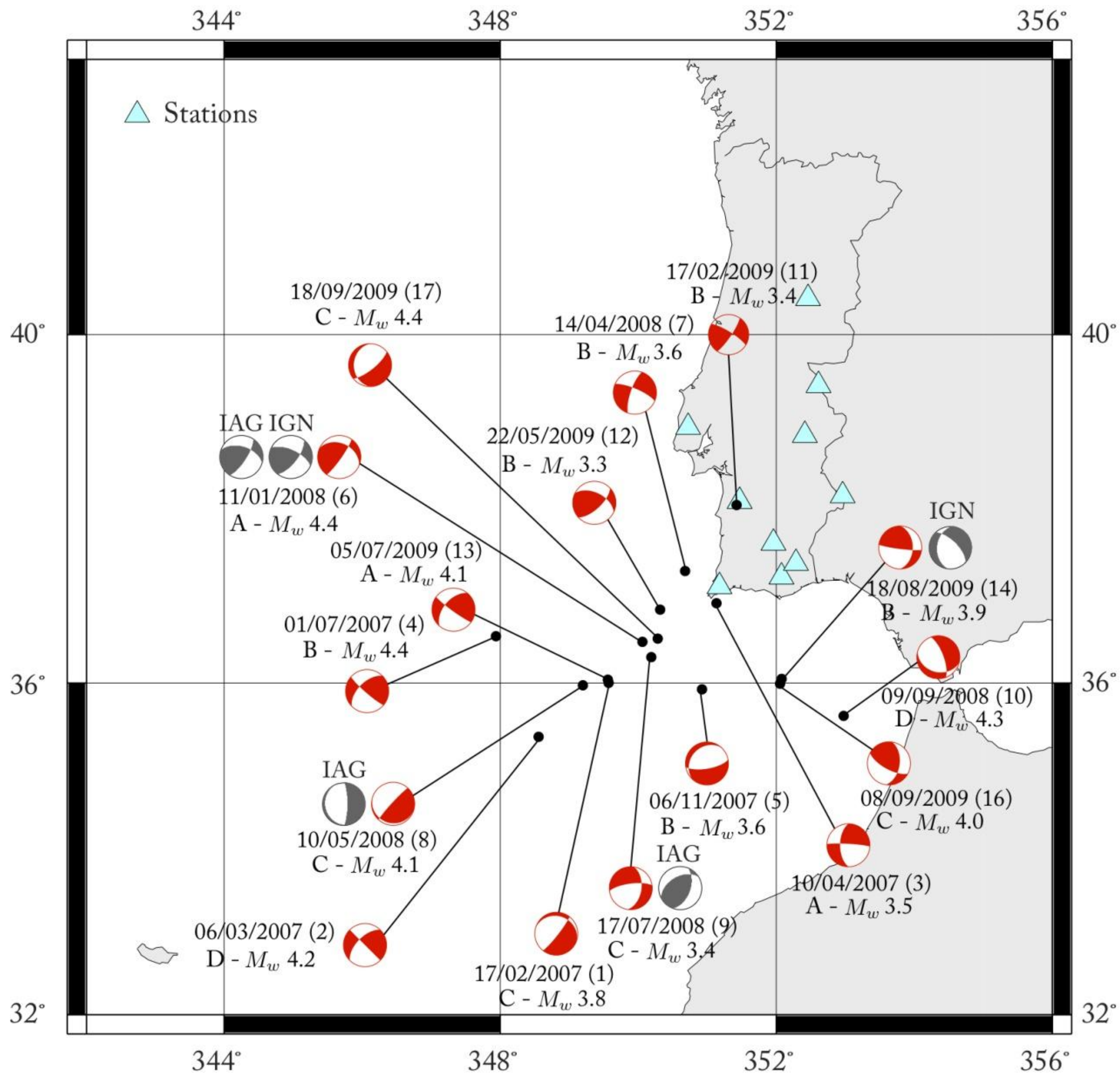
- Quality C (Misfit 1 – 0.497 Misfit 2 – 1.169 Nr. of stations - 4)
- $M_W = 3.8$
- Depth: 25.4 km (IM- 33 km EMSC – 40 km)
- Normal faulting style

Results

<u>Earthquake 17/02/07 – Event 1:</u>



Results



- Good agreement with previous solutions when the quality is good.

- 5 strike-slip
- 4 strike-slip with minor reverse component
- 2 strike-slip with minor normal component
- 4 normal focal mechanisms
- 1 reverse faulting sytle

Results

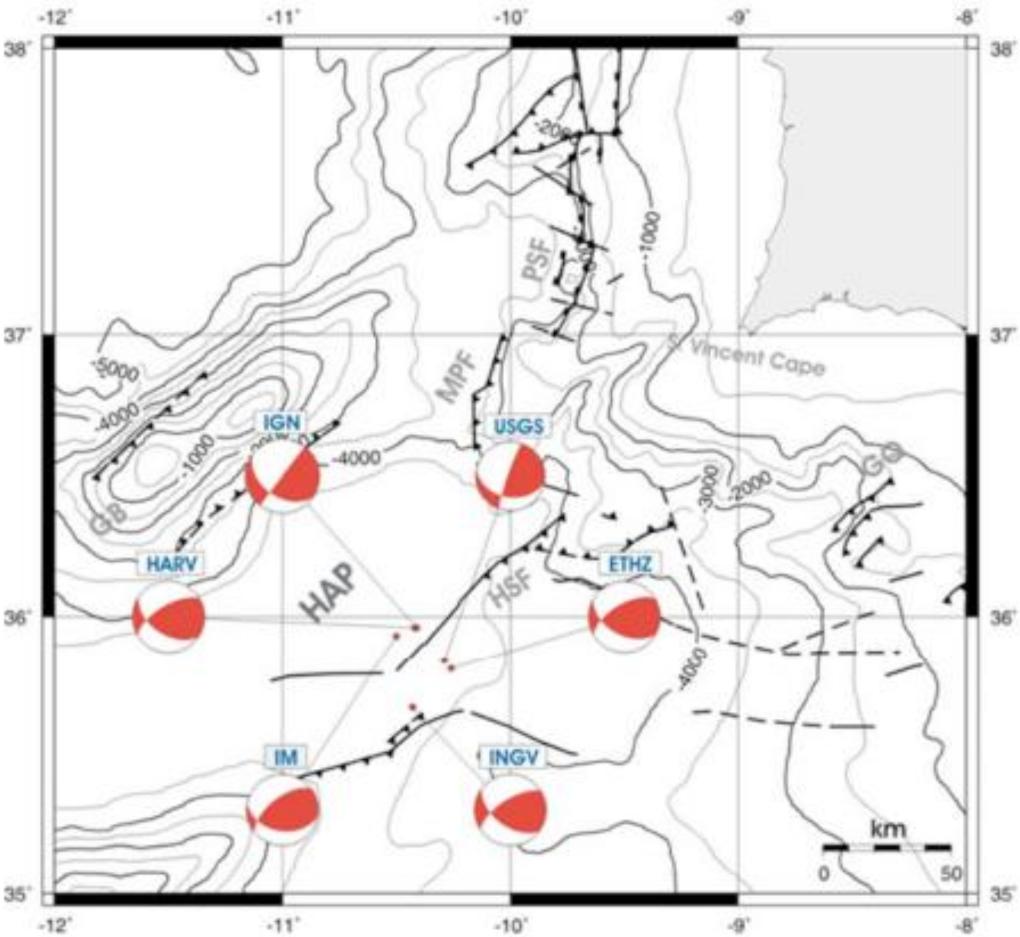
2007 M5.9 Horseshoe Abyssal Plain (HAP) Earthquake

Different epicenters and moment tensor solutions for the Feb 2007 HAP earthquake:

- Different hypocenters for the same earthquake:
    - epicenter differences up to 30 km
    - depth differences up to 70 km

- Moment tensor solutions available based on global and regional networks (HARV, USGS, ETHZ, INGV, IGN, IAG);

- Focal mechanism from first motion polarity (IM).

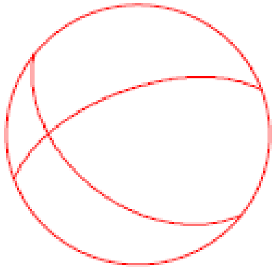


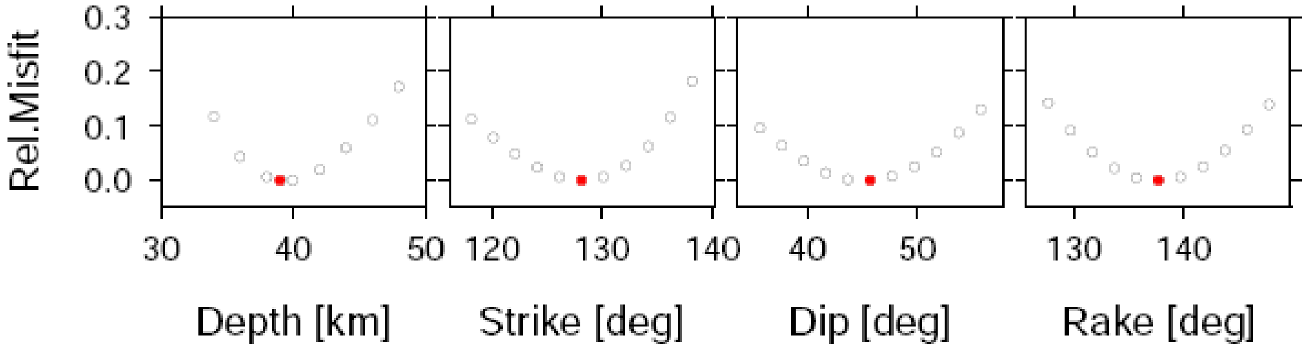
Carrilho et al [2007]

Results

Step 1 – Focal Mechanism

- Regional body waves.
- Frequency-domain inversion.
- Source parameters retrieved: strike, dip, rake (4 possible configurations), scalar moment M_0, source depth.

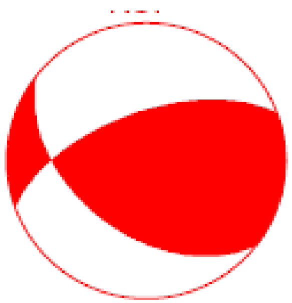


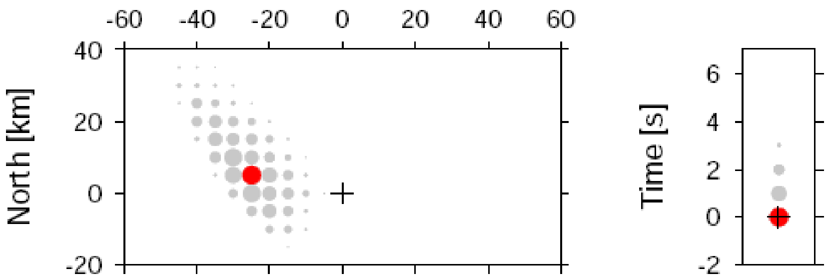


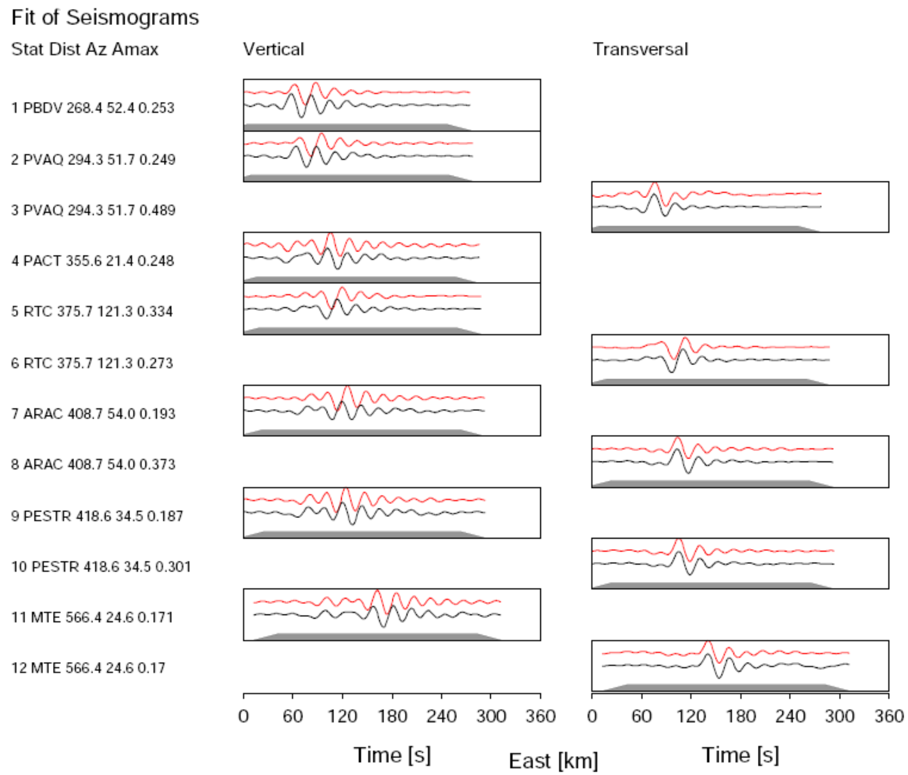
Results

Step 2 – Centroid Location

- Regional body waves.
- Time-domain inversion.
- Source parameters retrieved: strike, dip, rake (2 possible configurations) , centroid relative location (North, East, time offset).



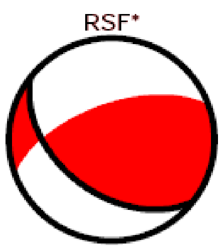


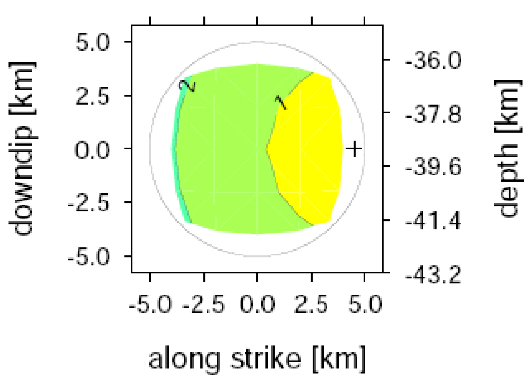


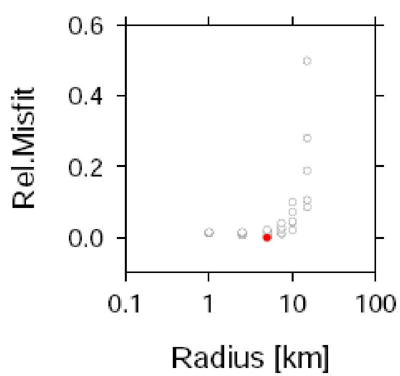
Results

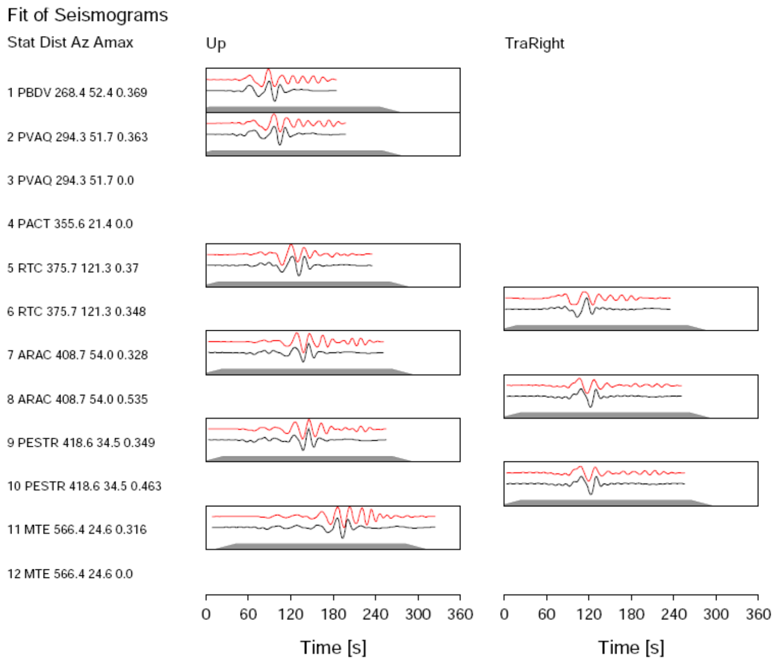
Step 3 – Kinematic Inversion

- Regional body waves.
- Frequency-domain inversion.
- Source parameters retrieved: strike, dip, rake (1 configuration corresponding to true fault plane), radius, area, [rupture velocity], nucleation point coordinates (along-strike and down-dip), [rupture time], average slip.









Results

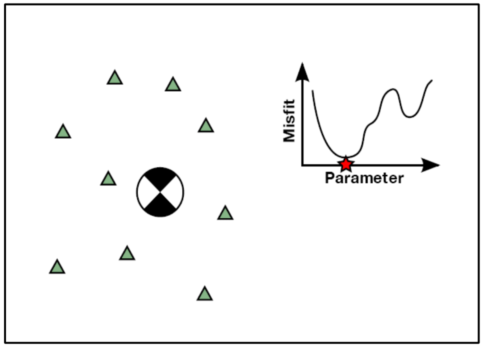
Bootstrap Analysis:

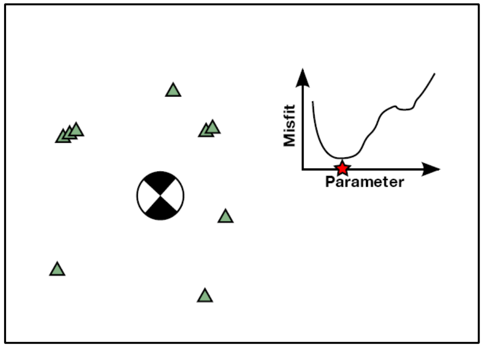
The standard approach is to find a “best” solution that minimizes a certain misfit between the chosen data and synthetics.

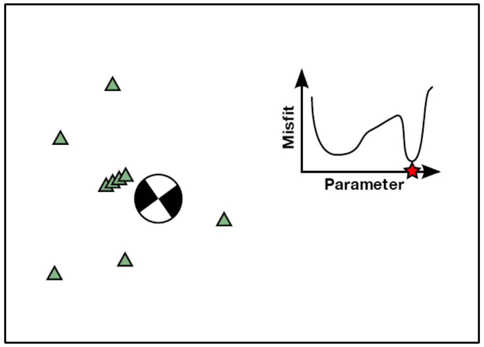
Not only finding a “best” solution…

But evaluating the robustness of the solution using a bootstrap approach.

Simulating 200 different data configurations...

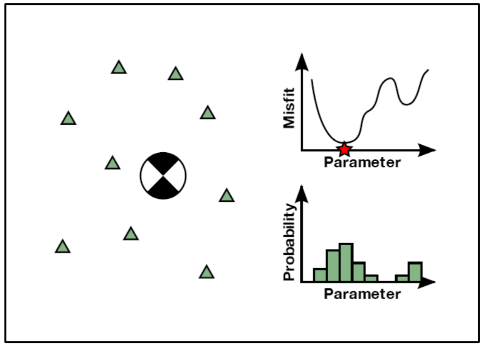






... and analysing the resulting probability

for each source parameter.



Results

<u>Robustness of Source Parameters</u>

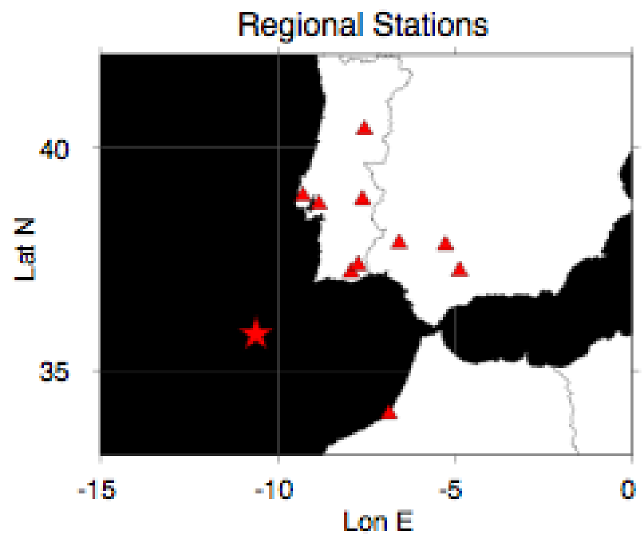
- Different 1D crustal models:
  - PREM
  - Regional model S03 (Stich et al. 2003)

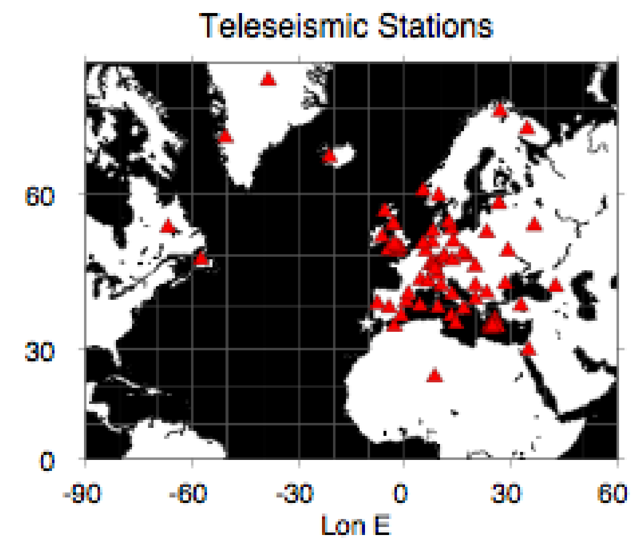
- Different datasets:
  - Regional vs teleseismic data
  - Inclusion/removal of stations towards the East

- Different wave types:
  - Full waveforms vs body waves only

- Bootstrap approach

200 trials per inversion

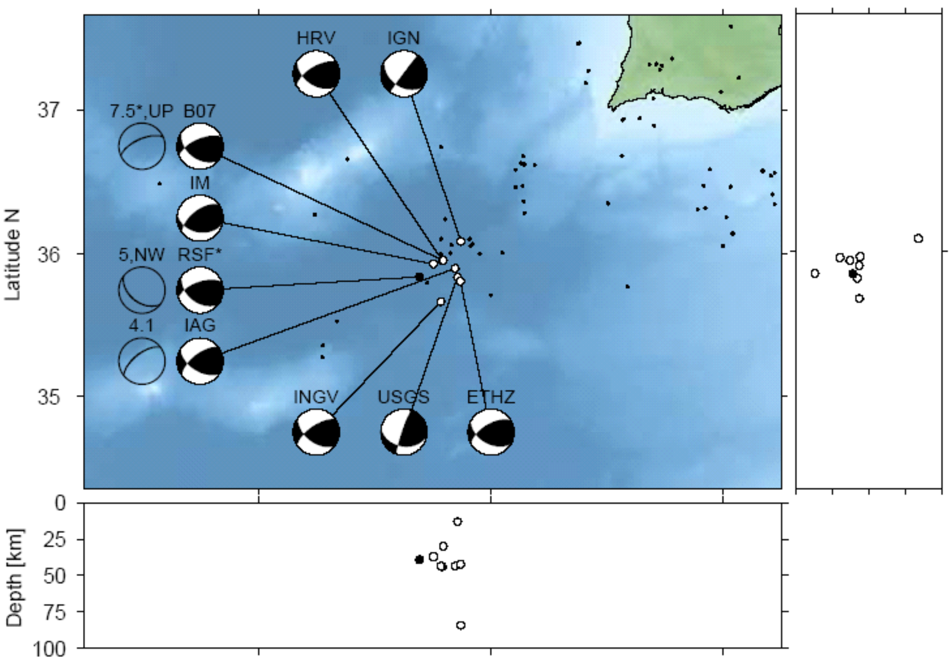




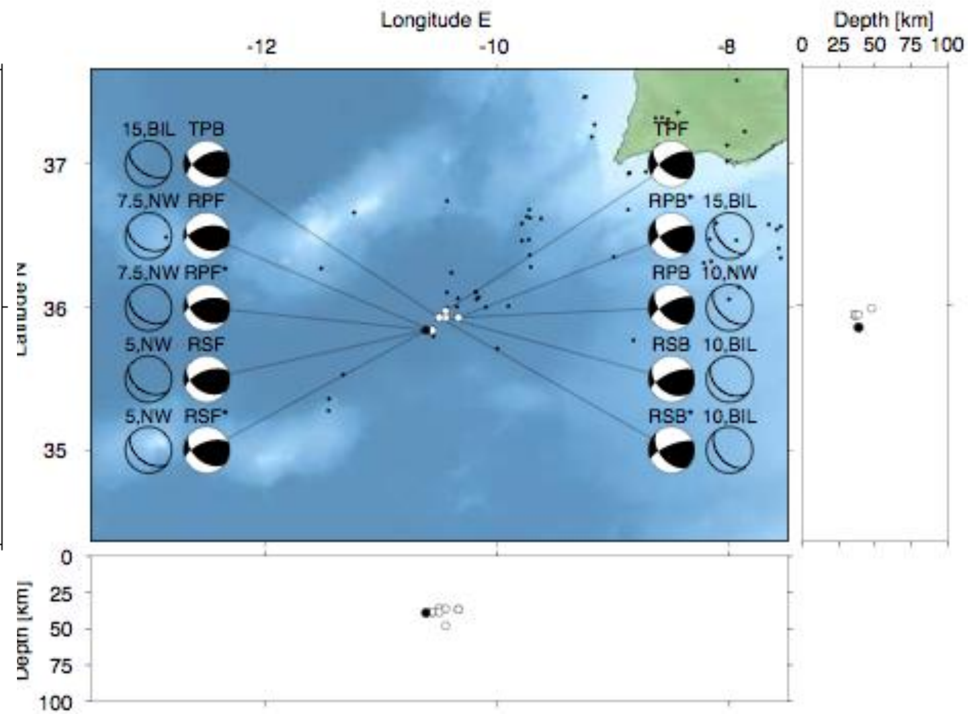
Results

Robustness of Source Parameters

Other Published Solutions



Our Results – Different Inversion Sets

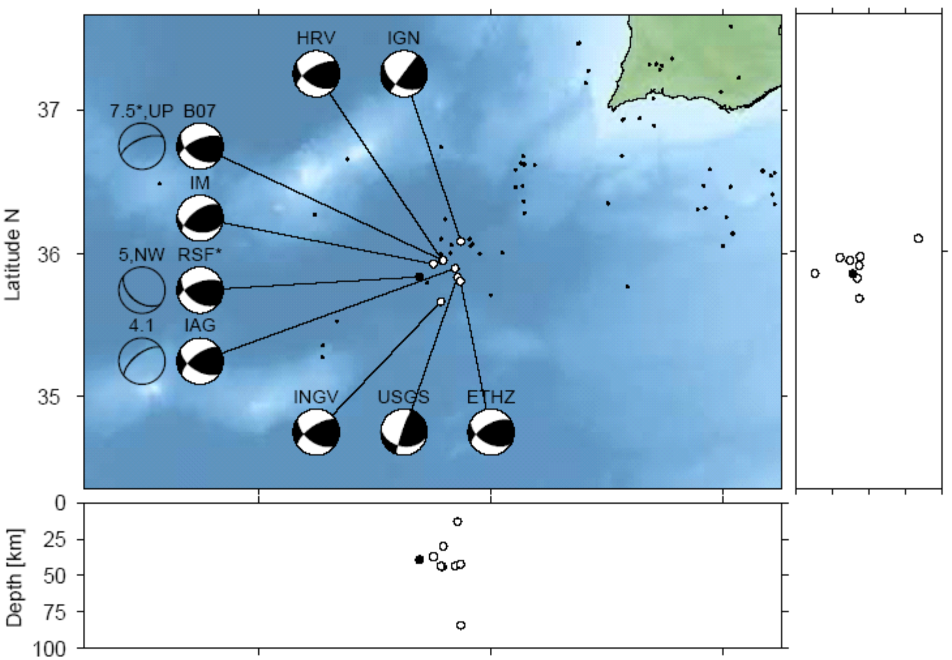


- Agreement on point source solution.
- Source depth estimated in 39 km.
- Moment magnitude Mw 5.9

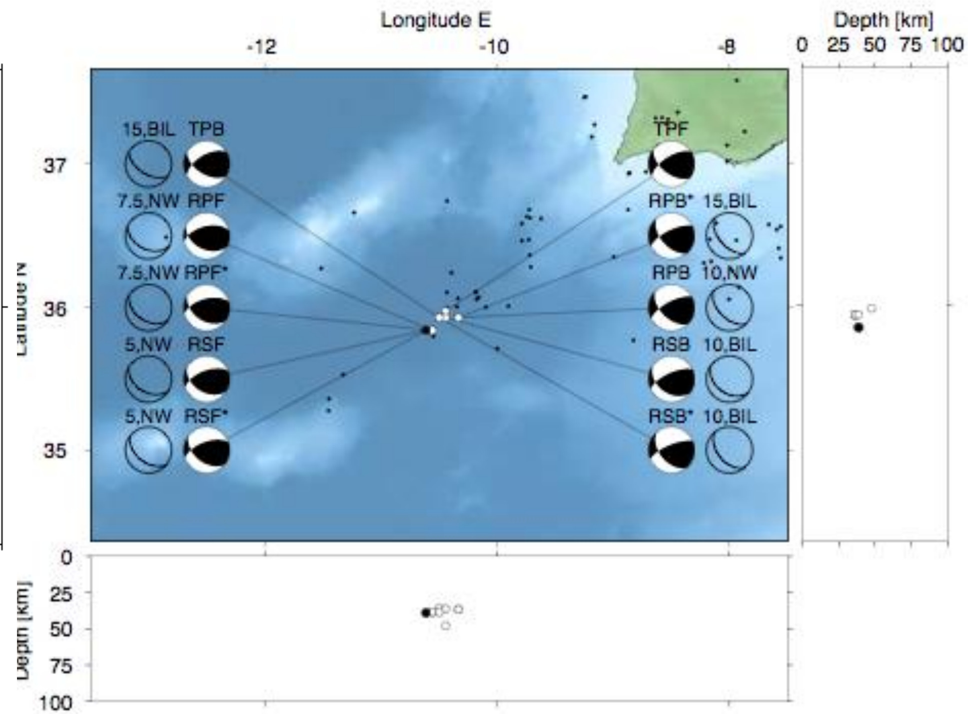
Results

Robustness of Source Parameters

Other Published Solutions

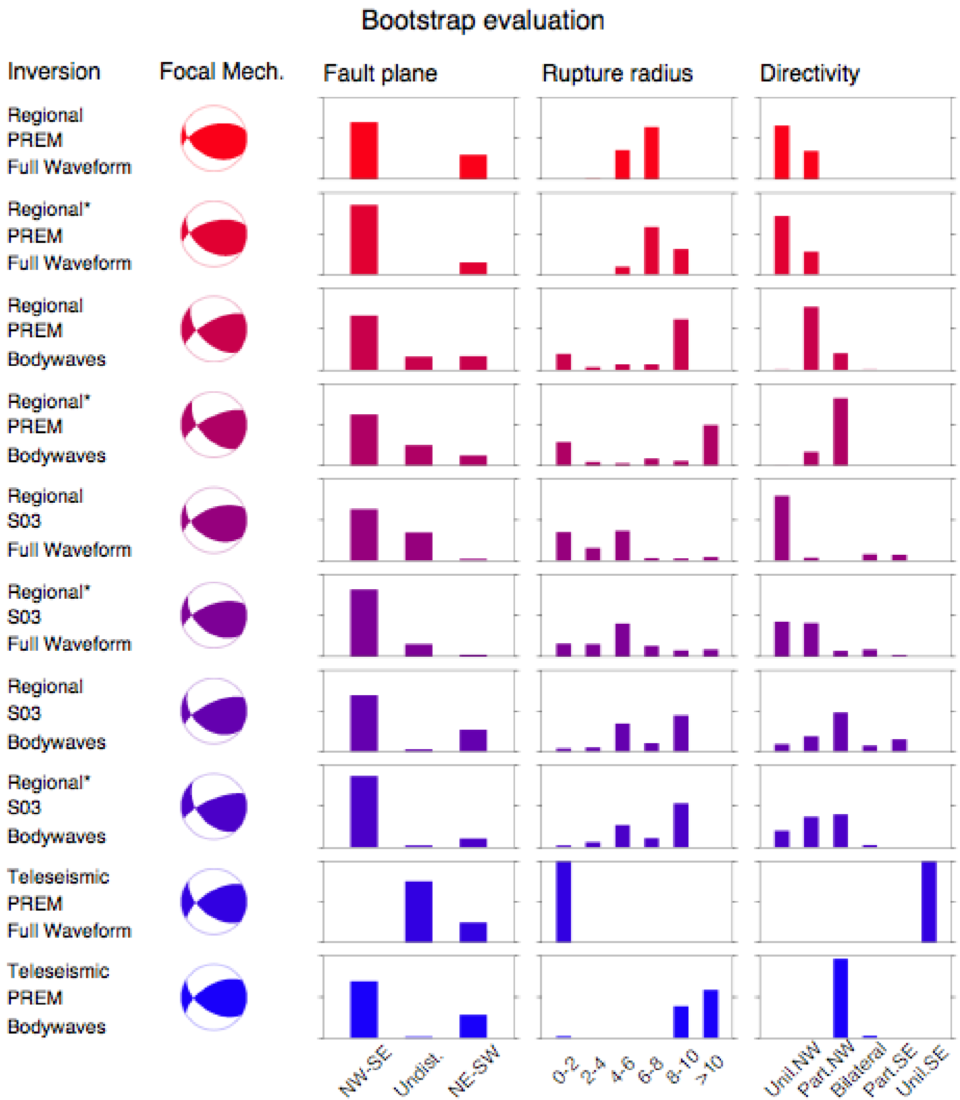


Our Results – Different Inversion Sets



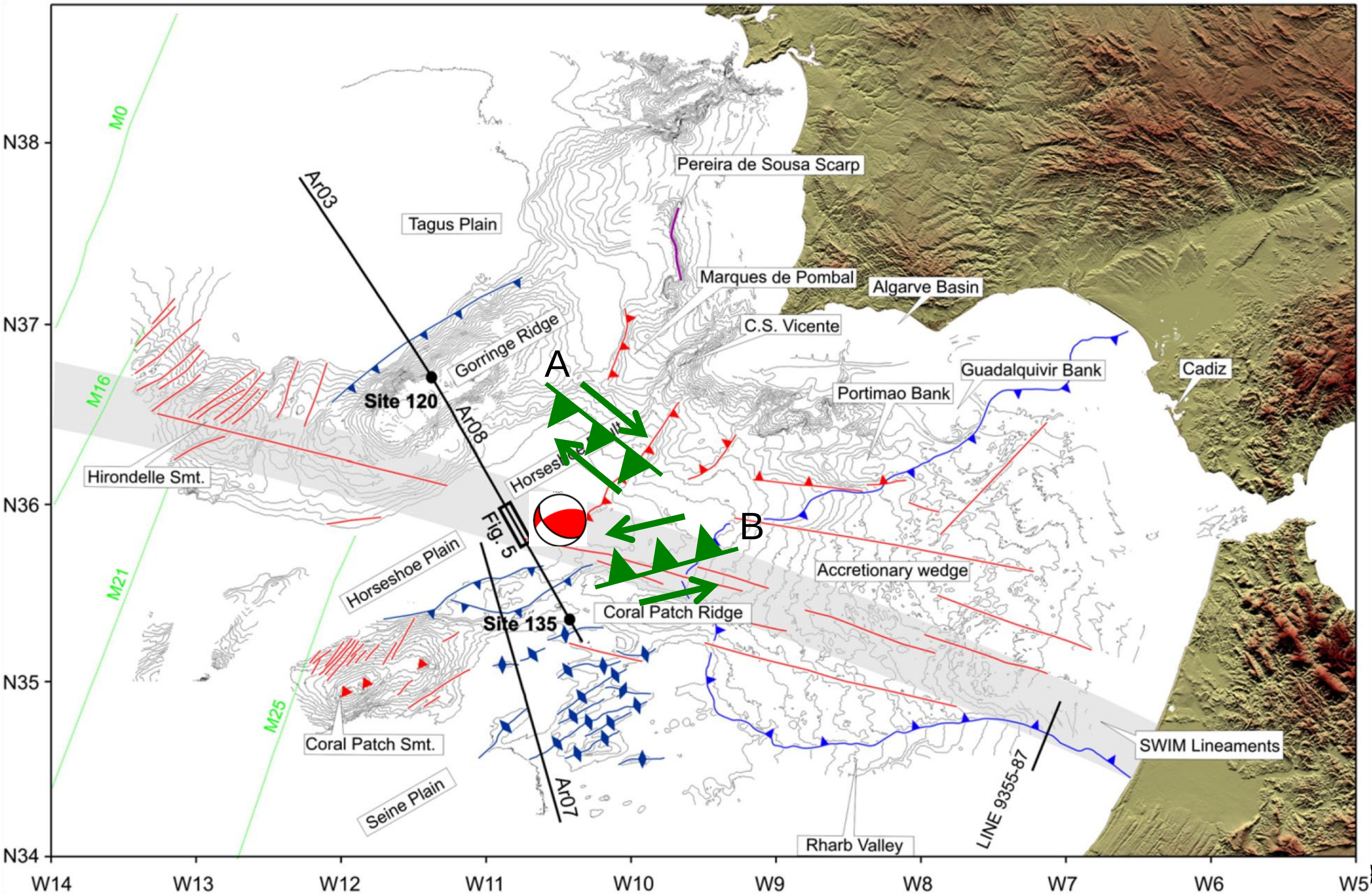
- Better performance for regional full waveforms (and teleseismic body waves)
- Difference in the preferred rupture plane (here NW-SE, with rupture directivity towards NW)
- The difference in misfit associated to the best faulting plane is often very small.

Results



- Point source parameters:
  - Stable results
- Fault plane:
  - Preferred plane trends NW-SE
  - Less resolution in the teleseismic inversion
- Finite source parameters
  - Radius = 4–8 km
  - Average slip = 0.2 m
  - Unilateral to bilateral
  - Rupture towards NW

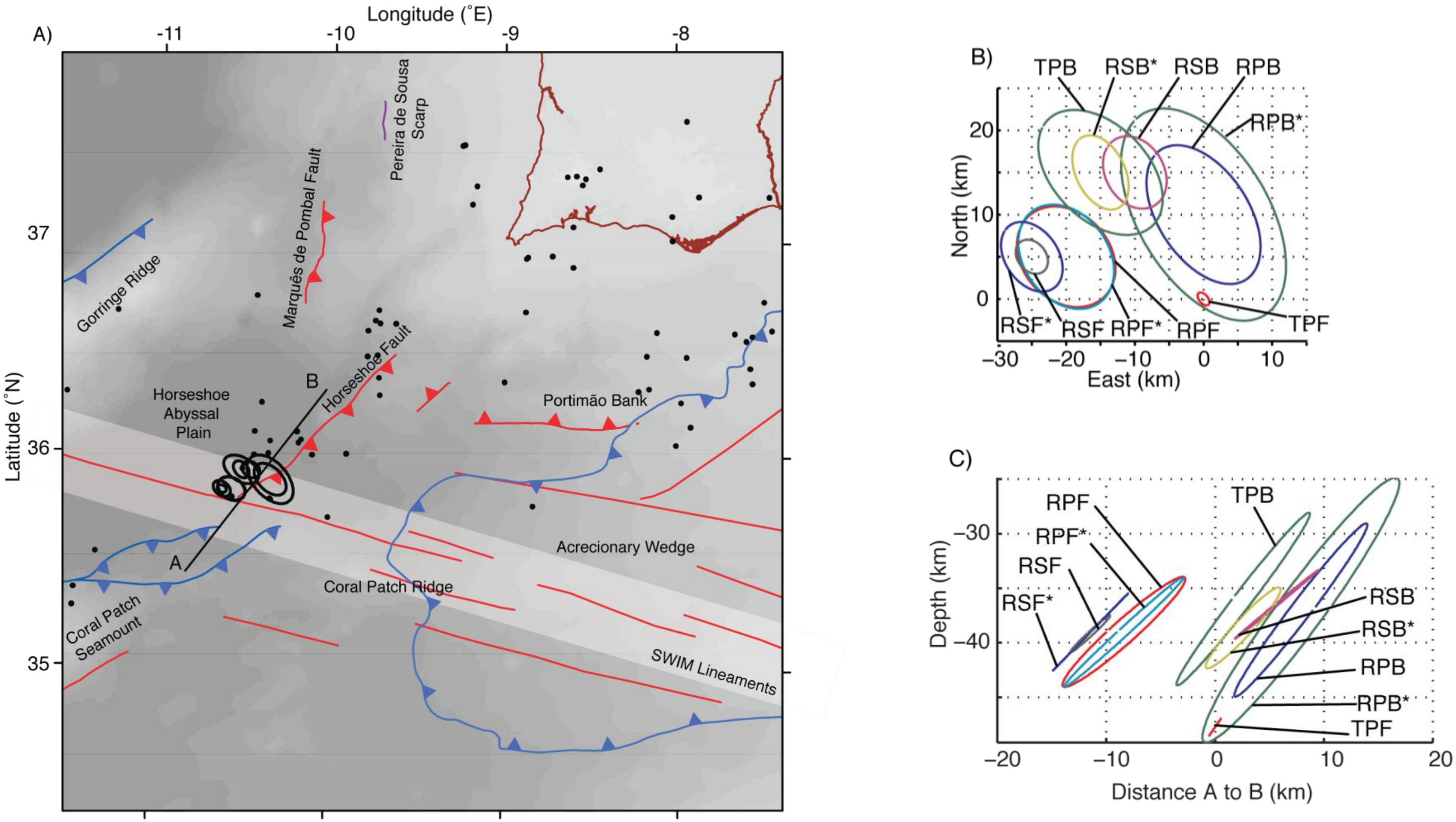
Results



After *Zitellini et al.* [EPSL 2009]

Results

Tectonic Interpretation:



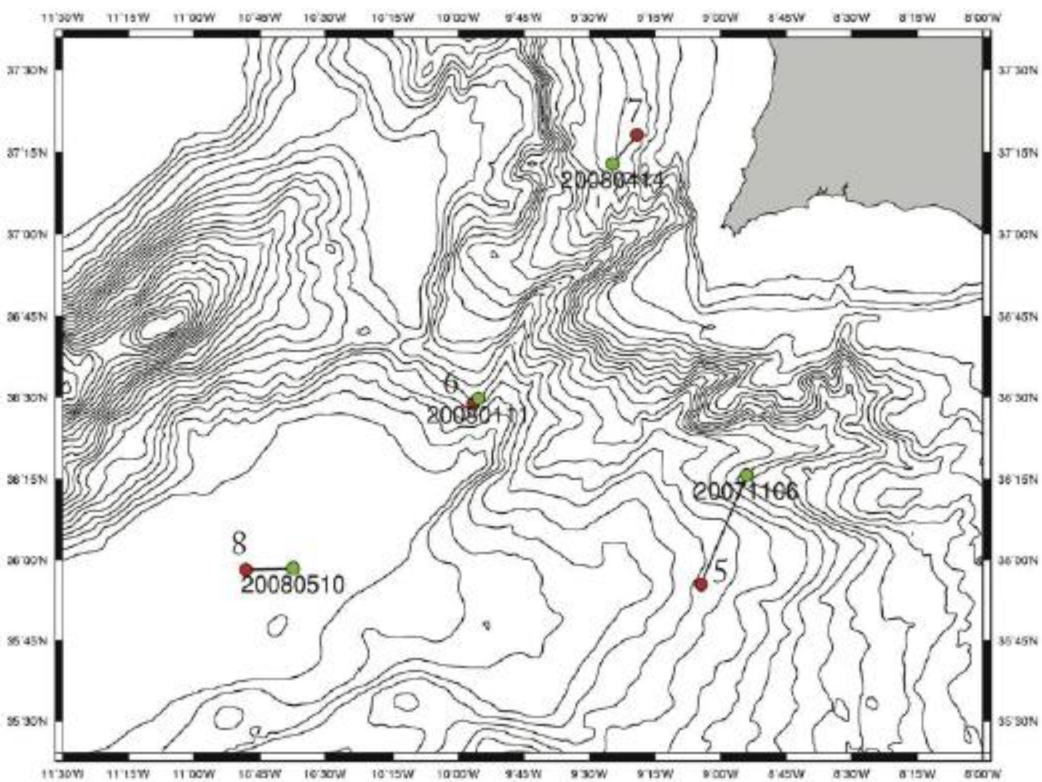
After *Zitellini et al.* [EPSL 2009]

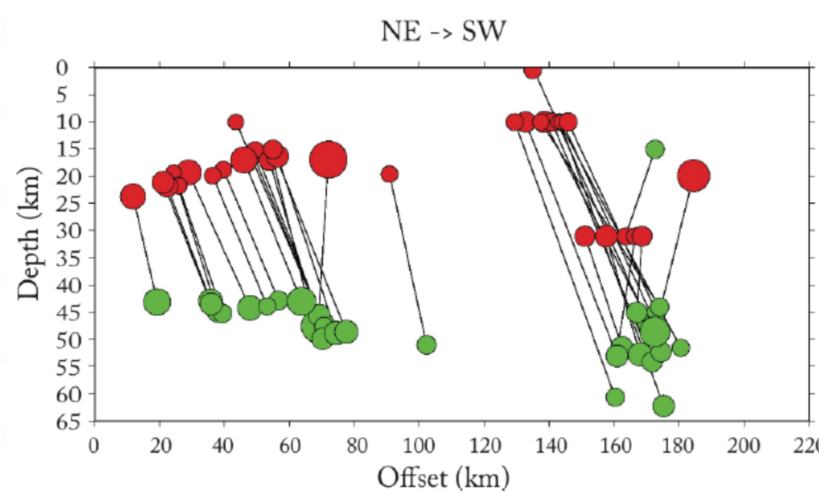
After *Zitellini et al.* [EPSL 2009]

Results

NEAREST project

- Relocated 36 earthquakes occurred between September 2007 and August 2008.
- Based on an OBS network deployed at the Gulf of Cadiz and offshore St. Vincent Cape.
- Four of the events studied by the NEAREST WP3 Working Group are also studied in this thesis.





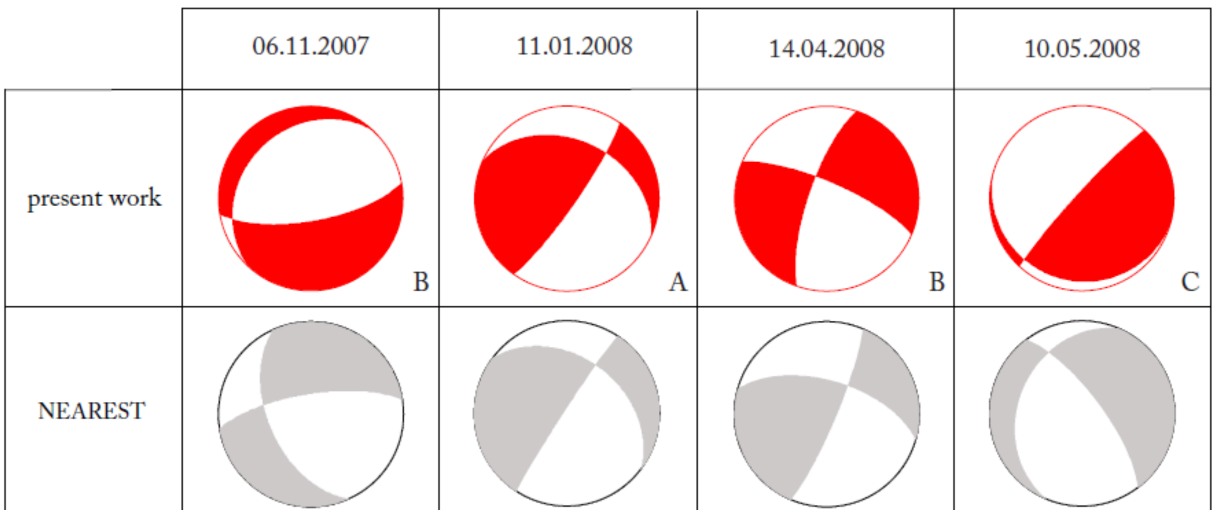
Red – IM locations
Green – NEAREST locations

Figures from Geissler et al. [in press]

Results

Comparison : OBS network vs land network (present study) results

ID	Event	Agency	Lat (°N)	Long (°E)	Depth(km)	Magnitude
5	06/11/2007	IM	35.925	-9.074	30	3.8 (M_l)
		NEAREST	36.263	-8.900	12	3.5 (M_l)
		present study	35.925	-9.074	4.8	3.6 (M_w)
6	11/01/2008	IM	36.480	-9.944	17	4.7 (M_l)
		NEAREST	36.497	-9.928	47	4.2 (M_l)
		present study	36.480	-9.944	35.3	4.4 (M_w)
7	14/04/2008	IM	37.304	-9.317	25	3.7 (M_l)
		NEAREST	37.215	-9.411	25	3.6 (M_l)
		present study	37.304	-9.317	29.5	3.6 (M_w)
8	10/05/2008	IM	35.970	-10.801	20	4.1 (M_l)
		NEAREST	35.974	-10.621	48	3.8 (M_l)
		present study	35.970	-10.801	39.4	4.1 (M_w)



Courtesy of NEAREST WP3 Working Group

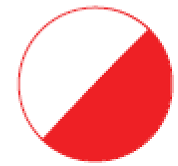
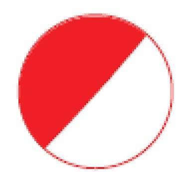
Results

<u>Influence of depth and location on the source results:</u>

A set of simulations were performed using different values for depth and epicentral locations:

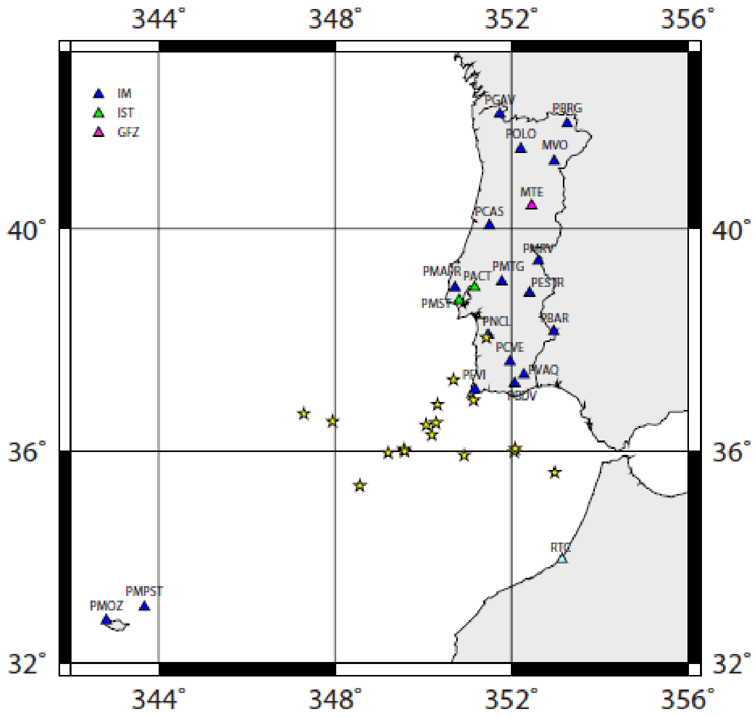
1. Hypocentral location provided by IM using land network;
2. Hypocentral location estimated by the NEAREST WP2 WG with the OBS network;
3. Epicentral location proposed by IM using land network and depth provided by the NEAREST WP3 WG using OBS network;
4. Epicentral location estimated by NEAREST WP3 WG using OBS and depth proposed by IM.

Results

	06.11.2007		11.01.2008		14.04.2008		10.05.2008	
	Land	OBS	Land	OBS	Land	OBS	Land	OBS
	EL: 35.925° N -9.074° E D: 30 km	EL: 36.263° N -8.900° E D: 12 km	EL: 36.480° N -9.944° E D: 17 km	EL: 36.497° N -9.923° E D: 47 km	EL: 37.304° N -9.317° E D: 25 km	EL: 37.215° N -9.411° E D: 25 km	EL: 35.970° N -10.801° E D: 20 km	EL: 35.974° N -10.621° E D: 48 km
Land network (IM)	 Depth: 29.9 km C		 Depth: 29.6 km A		 Depth: 26.2 km B		 Depth: 20 km D	
OBS network (NEAREST)	 Depth: 11.7 km C		 Depth: 33.6 km B		 Depth: 26.1 km B		 Depth: 38.9 km D	
Epicentral location: Land network (IM) Depth: OBS network (NEAREST)	 Depth: 11.8 km C		 Depth: 34.7 km A		 Depth: 26.2 km A		 Depth: 39.4 km C	
Epicentral location: OBS network (NEAREST) Depth: Land network (IM)	 Depth: 29.3 km A		 Depth: 18.4 km A		 Depth: 26.1 km B		 Depth: 20.0 km C	

Contents

- Motivation
- Theoretical Framework
- Method
- Results & Discussions
- Conclusions & Future Work



Conclusions & Future Work

- Results are in good agreement with solutions published by IAG and IGN when the quality is good;

- Point source parameters in agreement with most published solutions of the 2007 Mw 5.9 HAP earthquake;

- Preferred fault plane oriented differently from previously published solutions (NW-SE, rupturing towards NW, radius 5 km);

- Our inversion results are supported by a careful analysis that includes bootstrap, and the use of different datasets and different velocity models.

- The depth is a difficult parameter to retrieve - the Kiwi tools results are closer to the NEAREST values, which we think to be more accurate than those obtained by IM.

- The quality factors are well-calibrated given that the poor quality assigned to the results (C and D) provide unstable solutions;

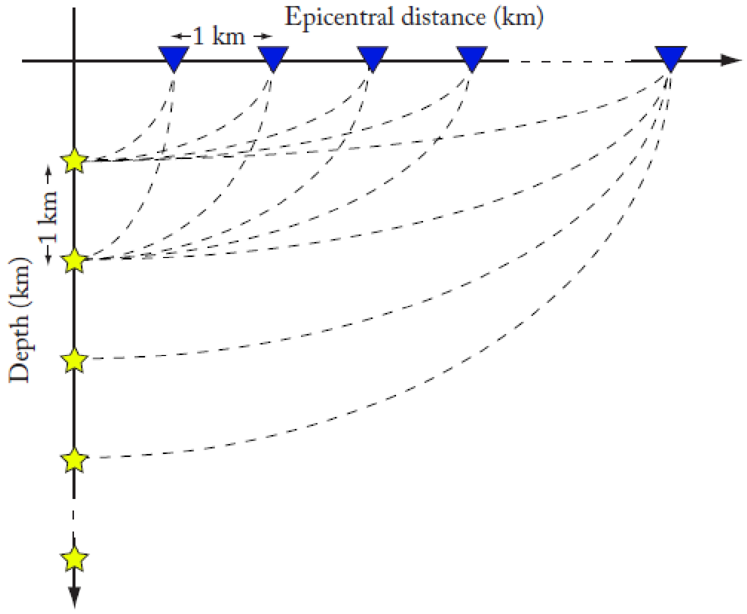
- This work provides an extension of the moment tensor catalogue in southwest Iberia (11 new solutions).

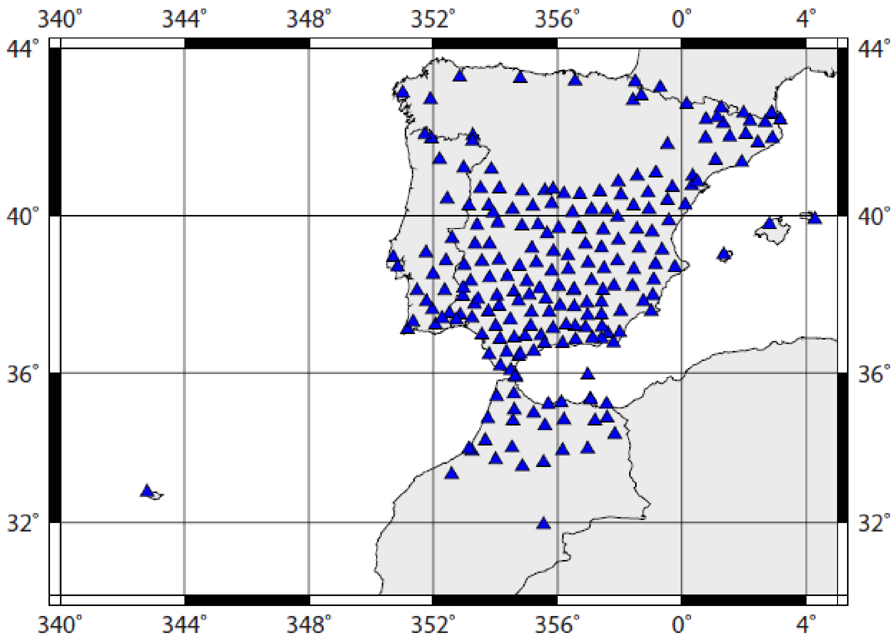
Conclusions & Future Work

New Green's Funtions database

Range of source depth: 1-80 km
(1 km of increment);

Range of epicentral distances: 1-600 km
(1 km of increment);





New data – stations from Spain and Morocco