Regional Waveform Study of Small to Moderate Earthquakes in Southwest Iberia

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SUMMARY:
The study of the portuguese seismicity is conditioned by different issues: the geographic location of Portugal creates a large azimuthal gap. The more frequent earthquakes, which occur offshore, are poorly covered. The large sedimentary Cadiz Basin is another issue. Waves that travel through this basin are strongly affected by reverberation, making the recorded signals distorted. We study 29 regional earthquakes occurred in Southwest Iberia between 2007-2010 with small magnitudes (3.3 to 4.9), with exception of one earthquake with ML 6.0. We used the KInematic Waveform Inversion (KIWI) tools that perform point- and finite-source inversions at regional and teleseismic distances. This inversion is performed in the frequency domain by fitting amplitude spectra over a wider frequency band. We improved estimates of centroid, depth, seismic moment, strike, dip and rake for 15 of the studied events. The most common faulting styles of these earthquakes are thrust, right-lateral strike-slip and mix of both.

Keywords: Moment tensor inversion, Regional seismicity and tectonics

1. GENERAL

A correct characterization of earthquake sources is fundamental for the understanding of tectonics and earthquake dynamics. The main requirements for a first-order characterization of an earthquake are the magnitude and source location. In order to have a complete description of an event, information on the faulting style and finite-fault parameters (rupture area, rupture propagation, and slip distribution) is necessary.

In this paper the KIWI tools were used to study the source mechanism of 29 regional earthquakes with ML 3.5 – 6.0 that occurred between 2007 and 2010. Most of the events are located offshore southwest Iberia. The data used was recorded by broadband (BB) stations in Portugal, Spain and Morocco. The waveform inversion of these events is performed in adverse conditions, providing a good check on the performance of the KIWI tools. Challenges to waveform inversion include: (a) Small magnitude of the earthquakes. Portugal is exposed to moderate and large magnitude earthquakes, however the convergence rates are slow leading to a slow rate of seismic activity (long recurrence intervals) (Vilanova & Fonseca 2007; Fernandes et al. 2007, and references therein); (b) Poor azimuthal coverage due to the geographical location of Portugal; (c) Laterally heterogeneous Earth structure. Several of the studied earthquakes occur in the Cadiz basin, which is a sedimentary basin of large dimensions (Thiebot & Gutscher 2006) that strongly affects wave propagation. Waveforms that travel through the Cadiz basin cannot be modeled with a simple layered crustal model. We assign a quality factor to each event, from A (best quality) to D (poorest quality). We report 15 solutions with reliable qualities A and B. From these 15 events, only 5 have previously published focal mechanisms.

2. DATA

We study 29 earthquakes, two of which are located in mainland Portugal (ML 3.8 and 4.1). The magnitudes of the selected events are in the range ML 3.5 – 4.9, with one exception: the ML 6.0 earthquake of December 17, 2009. Data were collected from broadband stations in Portugal and neighbor countries. The waveforms were imported in SAC format and pre-processed according to the following steps: 1) removal of mean and linear trend; 2) deconvolution of instrumental response; 3) band-pass filtering; and 4) decimation to 0.2 sec. Earthquakes with ML $\leq$ 4.2 were filtered in the passband 0.05 – 0.1 Hz, and earthquakes with ML > 4.2 in the passband 0.025 – 0.08 Hz. The only exception to this rule was the 171209 event, whose data was band passed in the range 0.04 – 0.1 Hz.

3. METHOD

The KIWI routine is a multi-step approach composed of three steps, finding different source parameters at different steps. At first, we assume a point source approximation. We initially retrieve the focal mechanism of the earthquake (strike, dip, and rake), seismic scalar moment M0 and depth. This inversion step is performed in the spectral domain, by fitting amplitude spectra. In the second step, compressive and dilatation quadrants are retrieved; this step is carried out in the time domain. Refined latitude and longitude for the centroid, as well as an earthquake origin time, are also given in this step. The final step of the inversion consists of a simplified finite-fault inversion. We assume the eikonal source model, and determine parameters such as the fault plane orientation (discrimination between fault and auxiliary plane), radius (rupture extension), nucleation point coordinates (indicative of directivity effects) and average rupture velocity of the earthquake. This inversion is performed in the frequency domain by fitting amplitude spectra over a wider frequency band, including higher frequencies. This multi-step approach has the advantage of using different inversion methods, seismic phases and frequencies passbands to infer specific source parameters. The small magnitude of these earthquakes prevents application of the third step of the algorithm (finite-source inversion) and only point-source parameters are determined.

In this study we use the L2 norm to measure the misfit M between recorded (data) and synthetic ground motion:

$$M = \frac{\sum_i (u_i^{syn} - u_i^{obs})^2}{\sum_i (u_i^{obs})^2} \tag{1}$$

In the equation above, u_{obs} and u_{syn} are observed and synthetic displacements, respectively, for station-component i.

In order to separate the good from the poor solutions we attributed a quality factor to each event, ranging from A (best quality) to D (poorest quality). The quality factor is based on the misfit from inversion step 1, misfit from inversion step 2, and number of stations used in the inversion (See Table 1). According to this criterium, inversions that use more stations and have lower misfits in both steps are given a better quality factor.

	Misfit 1	Misfit 2	Nr. of stations
Quality A	<0.450	<0.900	$\geq$ 7
Quality B	<0.500	<1.050	$\geq$ 6
Quality C	<0.600	<1.200	$\geq$ 5
Quality D	<0.700	<1.500	$\geq$ 4

Table 1. Table of the criteria used to qualify the solutions. Misfit 1 and Misfit 2 correspond to the misfit measured between the observed data and the synthetics data in step 1 and step 2 respectively.

4. RESULTS AND DISCUSSION

Table 2 summarizes the results obtained in this study. From the total of 29 events studied, 15 had reliable solutions with quality factors A and B.

ID	M_w	M_0 (Nm)	Latitude (^{o}N)	Longitude (^{o}W)	Depth (km)	Str / Dip / Rk	Str / Dip / Rk	m_1	m_2	Tr/St	Q
070410	3.6	4.17e14	36.93	8.86	31.7	178 / 64 / -22	277 / 71 / -153	0.435	0.802	18/7	A
070701	4.5	1.09e16	36.55	12.06	33.9	98 / 65 / 148	202 / 61 / 28	0.34	0.876	18/8	A
071106^{OBS}	3.5	3.49e14	35.92	9.07	4.9	101 / 89 / -56	192 / 34 / -178	0.435	0.929	22/9	B
080111^{OBS}	4.5	7.94e15	36.47	9.94	44.9	39 / 75 / 28	301 / 63 / 164	0.393	0.736	19/11	A
080414	3.6	3.56e14	37.3	9.31	29.7	201 / 77 / -19	295 / 71 / -166	0.405	0.850	26/11	B
081002	4.6	1.18e16	37.04	5.41	4.8	20/70/76	237/24/125	0.386	0.745	34/13	A
090217	3.4	2.33e14	38.07	8.57	13.2	28 / 74 / -5	120 / 85 / -164	0.437	0.799	26/10	A
090522	3.3	1.65e14	36.86	9.67	25	45 / 73 / 56	291 / 38 / 151	0.427	1.008	21/9	B
090705	4.1	2.62e15	36.04	10.44	40	225 / 54 / 0	315 / 90 / -144	0.378	0.568	14/8	A
090905	4.0	1.5e15	36.69	12.71	45	42 / 66 / 166	138 / 77 / 24	0.418	0.897	9/4	A
091217	5.7	7.00e17	36.51	9.9	51.2	43/88/67	309/23/175	0.4	0.803	26/11	A
100331	3.7	6.12e14	36.76	9.76	24.9	62/74/64	303/31/147	0.414	1.024	20/10	B
100422	3.9	1.20e15	35.32	6.32	1.4	137/77/78	360/18/131	0.428	1.003	15/8	B
100723	3.9	1.11e15	35.93	10.34	45	209/35/ -1	300/89/-125	0.421	0.842	18/6	B
100725	3.8	8.35e14	36.23	7.71	24.7	158/46/-48	285/57/-125	0.414	1.018	23/8	B

^{OBS} Events that were recorded by an OBS temporary network (Geissler et al. 2010)

Table 2. Epicenter, depth, magnitude, strike (Str), dip and rake (Rk) of the studied earthquakes. Also shown are the misfits obtained from step 1 (m1) and step 2 (m2), the number of waveforms and stations used in the inversion (Tr/St), and the quality of the solution (Q).

Figure 1 compares the epicenters and depths reported in this study with those reported by IM, EMSC, and Geissler et al. (2010) (to which from now on we will refer simply as OBS). The epicenters computed by IM, EMSC and OBS are all based on travel times. IM solutions are based on data collected by the Portuguese land network, EMSC on phases reported by different European networks, and OBS on data collected by a temporary deployment of 26 stations offshore (Geissler et al. 2010). The focal depths reported for a same event can differ significantly, due to 1) large azimuthal gap and distance to the nearest land stations, and/or 2) different crustal structures used for earthquake location. Events 071106 and 080111 were recorded with very good coverage by the temporary OBS network. The OBS data provide a unique opportunity to control the errors in the earthquake depths and epicentral locations estimated with land data. Figure 1 shows that earthquake depths inferred with the KIWI tools are normally larger than those provided by IM (Preliminary Seismic Information 2010). This trend is consistent with that reported by Geissler et al. (2010), who locate most earthquakes at depths of 40 – 60 km. In particular, we locate event 071106 at a depth of approximately 50 km, in very good agreement with the OBS result of Geissler et al. (2010). On the other hand, the depth estimated for event 071106 is not in good agreement with the OBS result, which we attribute to the different epicentral locations that resulted from the two analysis. In general, our results indicate shallow onshore earthquakes (down to 13 km) and deeper offshore earthquakes (25 km to 51 km). The centroid of the earthquake 080111 is in good agreement with that estimated using OBS data. In opposition, for event 071106 we do not obtain a good agreement. Event 071106 is not well recorded by the land network and is one of the lowest-magnitude events in our dataset, thus our solution may suffer from lack of resolution. Earthquake centroids are in general good agreement with IM epicenters.

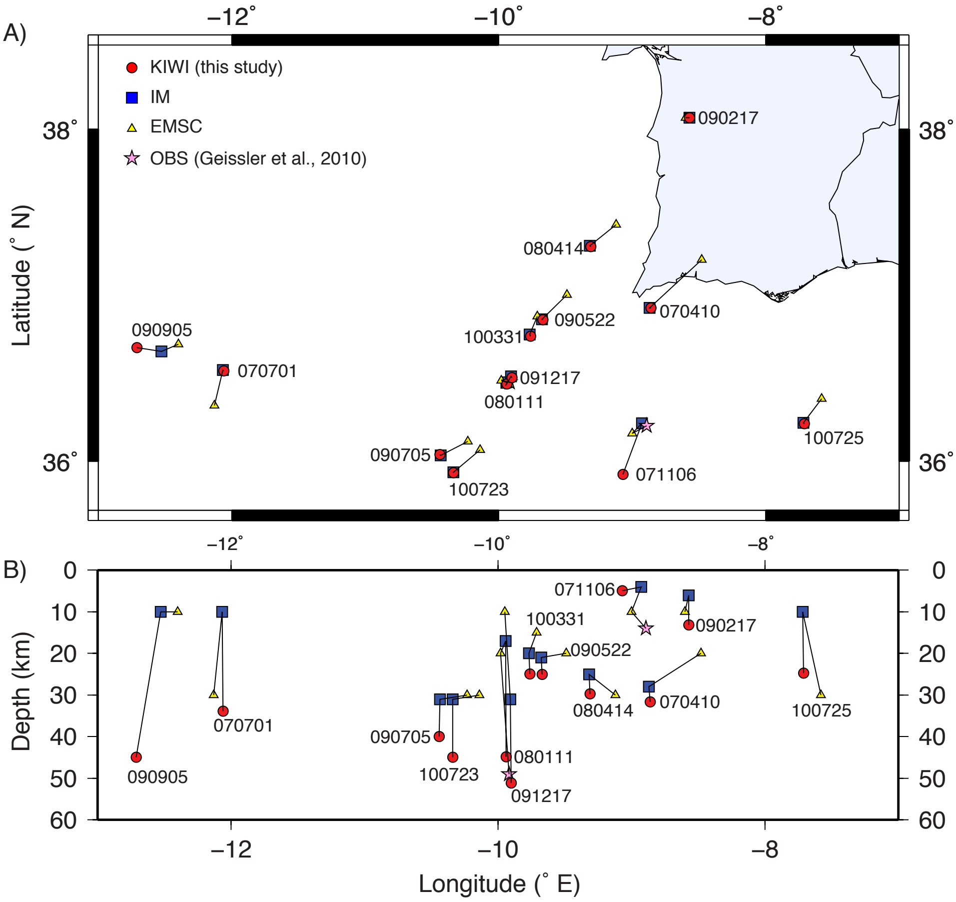

Figure 1. Comparison of epicenter and depths reported by this study (red circles), IM (blue squares), EMSC (yellow triangles), and OBS study of Geissler et al. (2010) (green stars). Only events of reliable qualities A and B are displayed.

The final results of focal mechanisms obtained in this study are presented in Figure 2 along with previously published focal mechanisms. This figure also displays the epicenters of earthquakes that we attempted to model but with no success (qualities C and D). It is interesting to notice that all earthquakes located south of station PBDV, which are in the middle of the Cadiz sedimentary basin, cannot be successfully modeled. In fact, the data generated by these earthquakes are affected by strong reverberations, which we cannot properly model with a one dimensional crustal model. Most other unsuccessful inversions concern earthquakes located far from the stations and/or earthquakes of low magnitude.

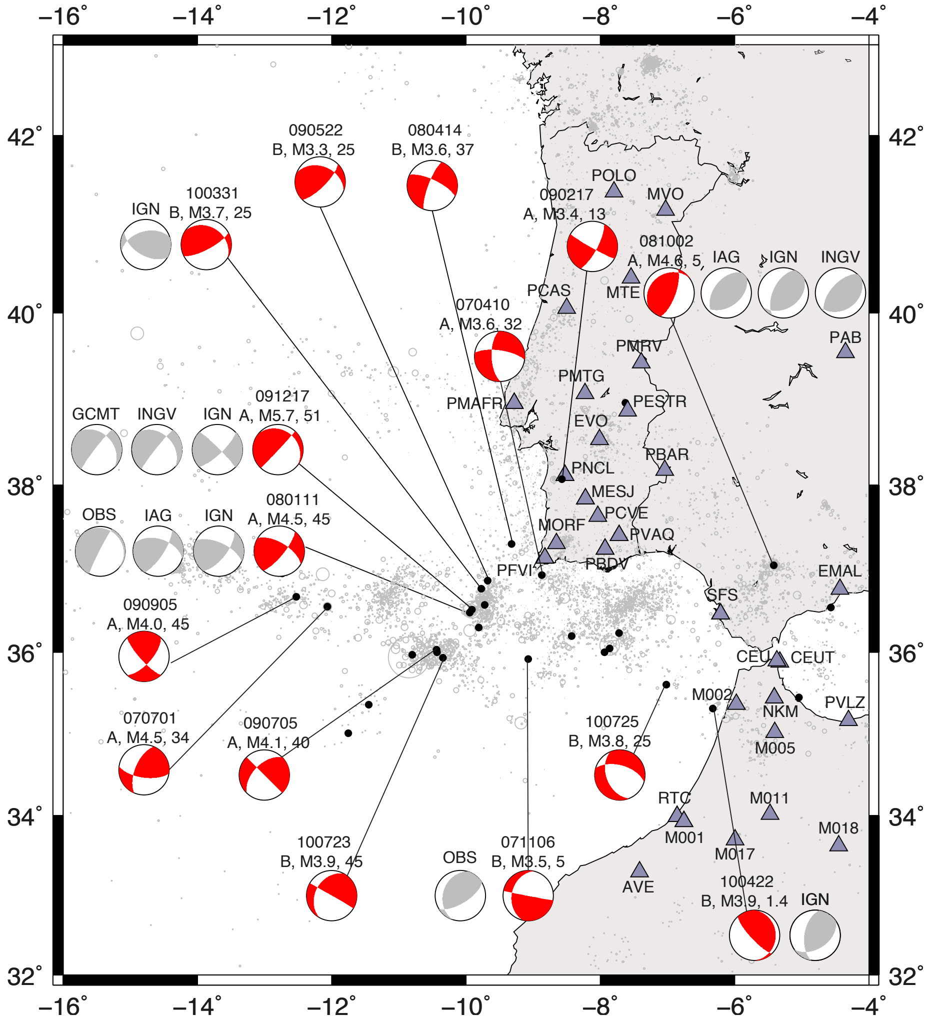

Figure 2. Summary of focal mechanisms and comparisons, when possible, with moment tensor solutions published by other authors: Instituto Geográfico Nacional (IGN), Global Centroid Moment Tensor project (GCMT), Instituto Andaluz de Geofísica (IAG), Istituto Nazionale di Geofisica e Vulcanologia (INGV), Geissler et al. (2010) (OBS). All of the focal mechanisms presented have qualities A and B. Each event is identified by its ID (top), quality factor (bottom left), Mw (bottom center), and depth in km (bottom right). The back dots mark the epicenters of all earthquakes analyzed, including events whose waveform inversion failed (qualities C and D). Also shown are the stations used to perform the inversions (green triangles).

In general, our solutions compare well with previous studies with a few exceptions. Event 100331, located offshore SW Portugal, is well constrained by the data and the focal mechanism compares well with neighbor events. However, it is an Mw 3.7 event located offshore, with limitations on the signal-to-noise ratio (hence its quality B). Event 091217, the largest event on the dataset, was attributed ML 6.0 by IM and was recorded with an excellent coverage. The inversion of this earthquake was straight-forward, generating a quality A solution that compares well with those reported by the Global Centroid Moment Tensor (GCMT) project and INGV. IGN reports a disparate solution for this event. The two focal mechanisms that we can compare with the OBS study of Geissler et al. (2010) are different. The present work and that of Geissler et al. (2010) are truly independent, as they are based on different datasets (land stations vs OBS) and methods (waveform inversion vs first-motion polarities). Event 071106 has a quality B solution but is a low-magnitude event (Mw 3.5). Thus the signal-to-noise ratio of this event is low and the focal mech- anism that we infer may not hold. Event 080111 has a quality A solution, and the focal mechanism that we report is similar to other published solutions. The magnitude of this event is 4.5 and the signal-to-noise ratio of the data recorded at land stations is good. In this case, our solution should hold. In general, we consider solutions with quality A very reliable and quality B solutions acceptable. The event 100422, which occurred offshore northern

Africa, is one of the events for which we obtain a different solution. This event is not well covered by our network. Furthermore, strong reverberations can be observed in our data, probably associated with propagation through the Cadiz sedimentary basin. Our solution has then limited reliability in spite of its B quality.

The focal mechanisms that we obtain indicate faulting styles which are most commonly thrust, right-lateral strike-slip, and a mix of both. The two conjugate faulting planes are often oriented NW-SE and NE-SW. These results are in good agreement with previous studies (e.g. Buforn et al. 1988, 1995; Borges et al. 2001; Stich et al. 2003; Buforn et al. 2004; Stich et al. 2010).

In Figure 2 are also displayed the epicenters of earthquakes that we tried to model but with no success (qualities C and D). It is interesting to notice that all earthquakes located south of station PBDV, which are right in the middle of the Cadiz sedimentary basin, cannot be successfully modeled. In fact, the data generated by these earthquakes are affected by strong reverberations, which we cannot properly model with a one dimensional crustal model. Most other unsuccessful inversions concern earthquakes located far from the stations and/or earthquakes of low magnitude.

5. CONCLUSIONS

In this paper we used the KIWI tools to study small to moderate earthquakes in southwest Iberia. Most of the events are located offshore, and have magnitudes in the range ML 3.5 to 4.9, with the exception of an ML 6.0 event. The KIWI tools implement an inversion scheme where frequency- and time-domain analysis are performed at different steps. The method is robust and allows the easy implementation of different misfit norms and inversion schemes, as well as the use of different frequency bands, portions of the waveform, etc. We conducted synthetic tests, which showed that the KIWI tools are adequate to study the seismicity offshore southwest Iberia.

We were able to successfully analyze 15 of the 29 studied events, extending the moment tensor catalogue for southwest Iberia to include solutions for lower magnitude earthquakes. We obtain centroid locations in good agreement with the epicenters provided by IM. Comparing our results with those based on OBS data (Geissler et al. 2010), we obtain good agreement for one of the events (080111) and disagreement for the other (071106). Event 071106 is not well recorded by the available land stations, has low magnitude, and was given a B quality in our analysis. We find hypocenter depths generally larger than those reported by IM and EMSC. This trend of moderate focal depths is consistent with the results of independent studies (e.g. Stich et al. 2010; Geissler et al. 2010). We obtain seismic moment (Mw) values that are slightly lower than the ML values reported by IM, and much lower than those reported by EMSC. This result may indicate a low-attenuation crust as suggested by Casado et al. (2000); Vilanova et al. (2012). The focal mechanisms that we infer are in general good agreement with those published previously, displaying dominantly thrust and right-lateral strike-slip faulting styles. Due to the strong reverberations that affect the waveforms, we were not able to successfully model earthquakes whose epicenters are located in the middle of the Cadiz sedimentary basin.

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