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First Determination of Source Parameters of Moderate Earthquakes (4.1 ≤ *M* ≤ 5.1) in Morocco from Spectral Analysis

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Abstract

Recent installation of an array of broad band seismological stations in Morocco allowed us to study the records of five recent (2005-2008) moderate earthquakes (4.1 ≤ *M* ≤ 5.1) in order to determine their source parameters (seismic moment, fault slip, rupture area and stress drop) from P-wave spectra. We also studied the older Rissani events of 1992 using teleseismic data. Values of *Mo*, *r*, Δ*u* and Δ*σ* are, respectively, 1.1 × 10^{13} - 6 × 10^{16} Nm; 0.50 - 3.9 km; 0.8 - 5.8 cm and 0.3 - 1.49 MPa. The results are in accordance with the seismotectonic and geodynamic setting of Morocco as, for instance, the amount of slip along the faults with respect to the relative displacement of Nubia to Iberia (~4 mm·yr^{-1}) determined from GPS data, taking into account the period of stress accumulation. However, some events show very variable corner frequency and low-frequency amplitude values which lead to considerably higher stress drop and fault slip values, especially at the nearest stations, which may reflect some site effects or uncertainties on depth and take-off angles.

Keywords

Morocco, Seismicity, Fault-Plane Solutions, P-Wave Spectra, Source Parameters, Seismotectonics

1. Introduction

Morocco is located at the westernmost extremity of the complex Ibero-Maghrebian area, where the Azores-Gi-

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braltar fault zone enters the continental lithosphere of the Betics-Rif-Alboran block. Along this boundary, the present-day convergent plate motion of the Nubian plate with respect to Iberia occurs along a NW-SE trend, as shown by plate kinematic, focal mechanism and GPS studies [1]-[11]. The amount of convergence is about 4 mm·yr^{-1}, most of which is accommodated by earthquakes (**Figure 1**). Within this setting, a remarkable discrepancy is the NE-SW escape of the Central Rif block determined by GPS observations [4] [8] [12]-[14] and fault-plane solutions [10] in conformity with geological studies e.g. [14] [15].

Earthquakes in Morocco have shallow foci [16]-[22], but a few events have focal depths of 100 km beneath the Middle Atlas [20] [23] and in northwestern Morocco and adjacent Alboran area [2] [20].

Although there is a large dataset on the fault-plane solutions of earthquakes in Morocco (see exhaustive compilation in [24]), little information exists on the other source parameters. The published studies were conducted only on the largest shocks, in particular on the 1994 and 2004 Al Hoceima, and the 1992 Rissani earthquakes, on the base of waveform analysis [4] [21] [25], but no studies based on spectral analysis were carried out, with the exception of that published by Bensaid *et al*. [26] on the Rissani earthquakes.

Since 2006, numerous broad band stations (BBS) were installed around the western Mediterranean in the context of international cooperation and projects ([27] [28], **Figure 2**); these BBS provided high-quality digital data which allowed us to obtain a certain number of spectra, and therefore, to attempt determining the source parameters which have been done for other Mediterranean seismogenic areas from P-waves e.g. [29] [30] and S-waves e.g. [31].

In this paper, we expose the results of the study of the source parameters of 5 moderate shocks that occurred in Morocco during the period 2005-2008 together with two stronger shocks in 1992, corresponding to the Rissani earthquakes. Our leading objective was to attempt to determine the source parameters from these shocks from the P-wave spectra, such as the seismic moment, the fault dimension and displacement, the "stress drop", and to compare the results to available data on the kinematics and seismicity of the Africa-Iberia plate boundary.

2. Database and Methodology

2.1. Data and Processing

We selected 5 events with magnitude $M \geq 4$ that occurred during the period 2005-2008 [10], and the Rissani events, two older shocks with magnitudes $M \sim 5.2$ which affected the Anti-Atlas area in 1992 [26] (**Figure 2** and **Table 1**).

As exposed in a previous paper [10], the hypocentral relocations were determined using the revised version of the HYPO71 computer program [32], and a standard crustal model for Morocco with $Vp/Vs = 1.74$ [18].

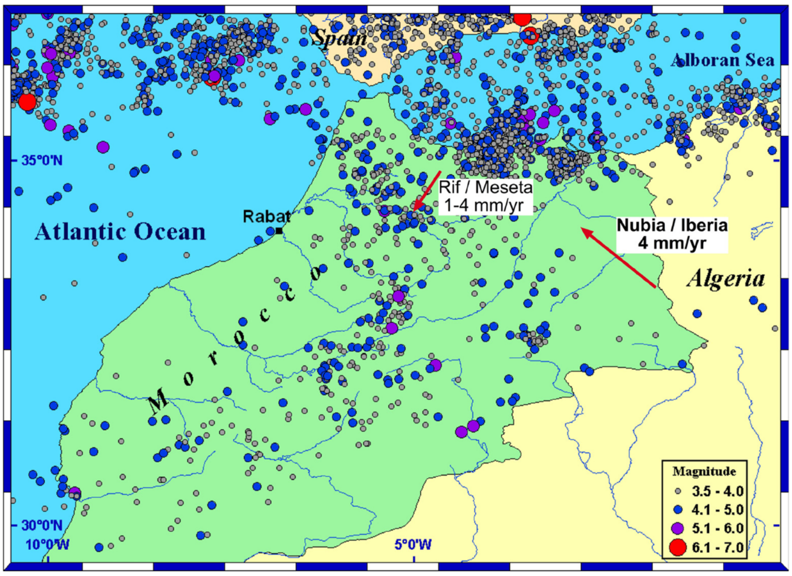


Figure 1. Seismicity of northern Morocco and adjacent area for the period 1990-2010, magnitudes > 3.5 (after [10]).

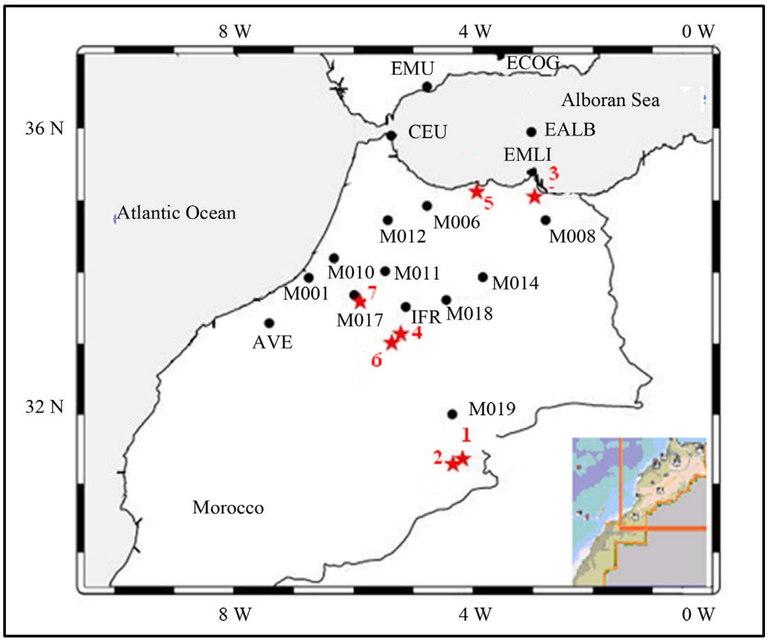


Figure 2. Location of the earthquakes (stars) and Moroccan and southern Spanish stations (dots) used in the present study. See **Table 1** for earthquake parameters.

Table 1. List of studied earthquakes.

Ref	Date (dd/mm/yy)	Time	Latitude	Longitude	Magnitude	Depth in km	Location
1	23/10/1992	09:11:08	31.36	−4.18	5.2	2	Rissani
2	30/10/1992	10:43:58	31.28	−4.34	5.1	2	Rissani
3	22/03/2005	09:03:15	35.05	−2.97	4.7	5	Nador
4	11/08/2007	20:46:01	33.14	−5.21	5.1	7	Khénifra
5	21/01/2008	02:24:03	35,12	−3.94	4.1	8	Al Hoceima
6	25/01/2008	13:19:40	33.01	−5.36	4.3	6	Khénifra
7	28/09/2008	02:11:21	33.59	−5.89	4.5	22	Tiflet

Data in Standard for Exchange of Earthquake Data (SEED) format (FDSN) were retrieved from files of digital stations located in Morocco (Institut Scientifique, ING-CNRST, Siberia and WM networks), Algeria (GEOFON) and Europe (IGN network and German stations) at various epicentral distances between 43 and 2454 km.

SEED data were read using Rdseed software, and then converted into SAC (Seismic Analysis Code) or ASCII formats. SAC software was used to accomplish all mathematical operations such as Fourier transform, spectral estimation, IIR and FIR filtering, decimation, interpolation correlation, seismic phase picking and graphical output.

2.2. Fault-Plane Solutions

Fault-plane solutions based on P-wave arrivals on the recordings of the selected events were already published in previous papers [10] [26]. Summarizing, first motions of P-waves were read on available paper records and digital files of permanent and temporary stations. Take-off angles for stations at regional distances (less than 1000 km) were obtained for a crustal model formed by two flat layers (15 km each) with constant velocities 6.1 km·s^{-1} and 6.7 km·s^{-1}. The IASPEI model was used for stations at larger distances. Solutions were obtained using the algorithm of Brillinger *et al*. [33].

2.3. P-Wave Spectra

The bulk seismograms were cut at the onset of the P- and S-waves. The mean and the linear tendency were removed in order to centre the signal at zero and to stabilize the numerical operations respectively. Since the signal corresponds to velocity, data were integrated to obtain displacements (**Figure 3**). Once picked, the seismogram was deconvoluted by the velocity response of the recording instrument. Spectra were obtained from the original digital records using software SAC (**Figure 3**). Finally, the low-frequency (plateau) part (Ω_o) and the corner frequency f_c were automatically obtained from the signal using software KIV, and subsequently the source parameters.

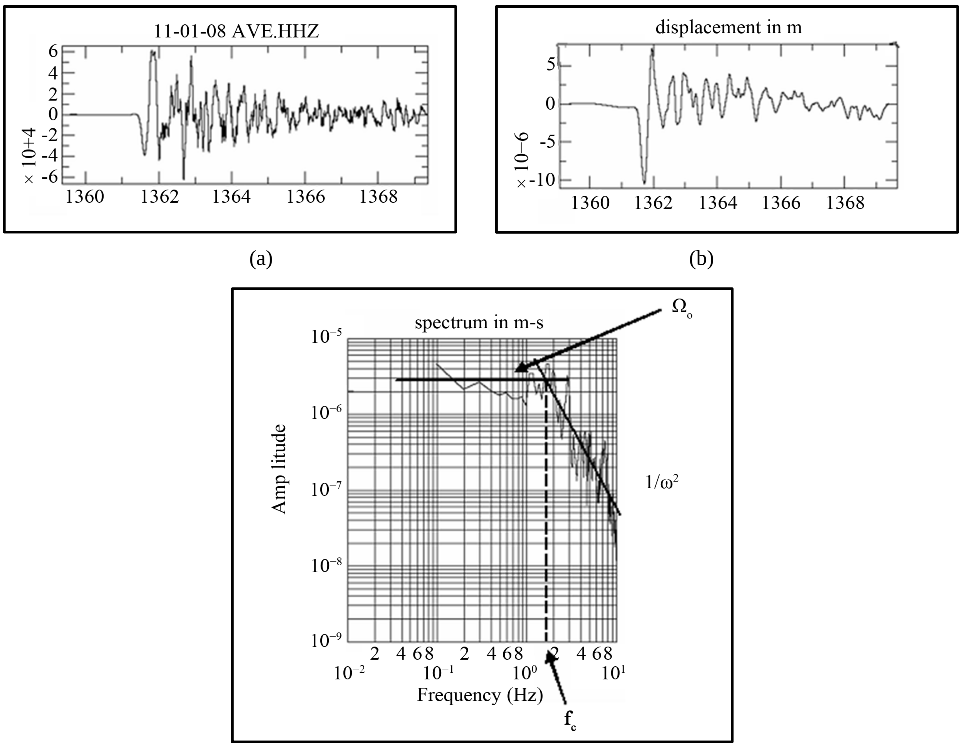
As spectra can be affected by attenuation, we used two to six stations at variable epicentral distances in order to obtain a mean value.

2.4. Source Parameters

The source dimensions and scalar seismic moment were determined by spectral analysis using the circular fault model [34] [35], which is the most suitable for small/moderate earthquakes generated along short faults that generally do not crosscut the Earth's surface and do not show a well-defined aftershock pattern [36].

The radiation pattern (R) for each station was computed from the fault-plane solution, and the scalar seismic moment M_0 was estimated using the amplitude spectra of P-waves [37].

$$M_0 = \frac{4\pi\rho a^3 r}{g(\Delta)C(i_0)} \times \frac{\Omega_0 \exp\left(\frac{\omega r}{aQ}\right)}{R_p(\varphi,\delta,\lambda,i_h)} \quad (1)$$



(c)

Figure 3. P-wave amplitude spectrum at station AVE for the event of 11 January 2008. (a) chosen window in the velocity record; (b) obtained displacement record after removing the instrument effect and integration; (c) amplitude spectrum showing plateau Ω_o and corner frequency f_c.

where ρ is the density, a is the fault radius, r is the distance from the focus to the receiving station, $g(\Delta)$ is the geometric attenuation, $C(i_o)$ is the effect of free surface on amplitude, Ω_0 is the spectral amplitude at low frequency of P-wave displacement, ω is the angular frequency, Q is the quality factor of P-wave (taken here as 300) and $R_p(\phi,\delta,i_h)$ is the radiation factor corresponding to the source orientation given by ϕ,δ,λ, i_h where ϕ is the azimut of the station with respect to the fault, δ is the dip of the fault-plane, λ is the rake and i_h is the take-off angle.

The dimension of the rupture (a) was evaluated from the corner frequency (f_c) [37]:

$$a = \frac{2.33\alpha}{f_c} \tag{2}$$

where α is the P-wave velocity.

The average displacement and stress drop were estimated from the scalar moment (M_0) and dimensions [38]:

$$\Delta\mu = \frac{M_0}{\mu S} \tag{3}$$

The stress drop $\Delta\sigma$ was determined using the equation [34]-[37] [39]:

$$\Delta\sigma = \frac{7M_0}{16a^3} \tag{4}$$

Computations were performed at the Complutense University (Madrid) using softwares KIV and SAC (IRIS [40]) to obtain the spectra of the P-wave, and MOS2 for determining M_0 and source dimensions. The epicentral distance, azimut, and take-off angle were determined with the help of subroutine CASSOL. The radiation pattern R was obtained with MECSTA. The choice of the software was based on its availability at Madrid University and because it is the same than that used by Spanish researchers who have installed the WM network in Morocco.

3. Results

3.1. Focal Mechanisms

The fault-plane solutions and numerical parameters of the studied earthquakes [10] are respectively shown in **Figure 4** and **Figure 5** and listed in **Table 2** respectively. In the central and eastern Rif (solutions 3 and 5), the solutions correspond to either almost-pure normal faulting or to strike-slip faulting with a normal component. The T-axes have an E-W trend. The solutions determined in the Middle Atlas chain and in the Meseta (solutions 4, 6 and 7) show almost-pure reverse faulting in two cases and strike-slip faulting with a normal component in another. In the three cases, the P-axis is oriented NW-SE. Finally, the solutions south of the High Atlas correspond to strike-slip faulting with a NW-SE oriented P-axis.

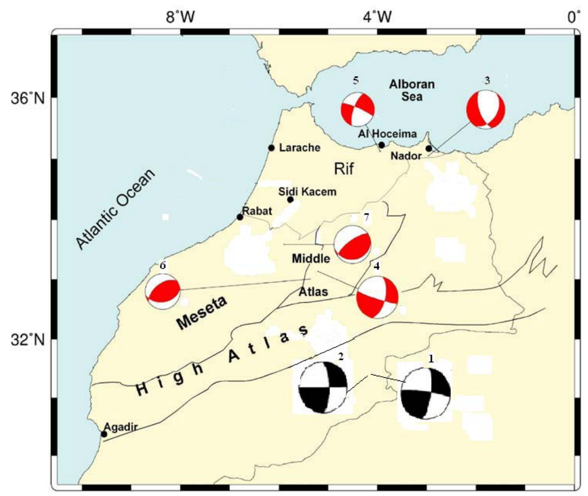


Figure 4. Location of the fault-plane solutions of the studied earthquakes, after [10].

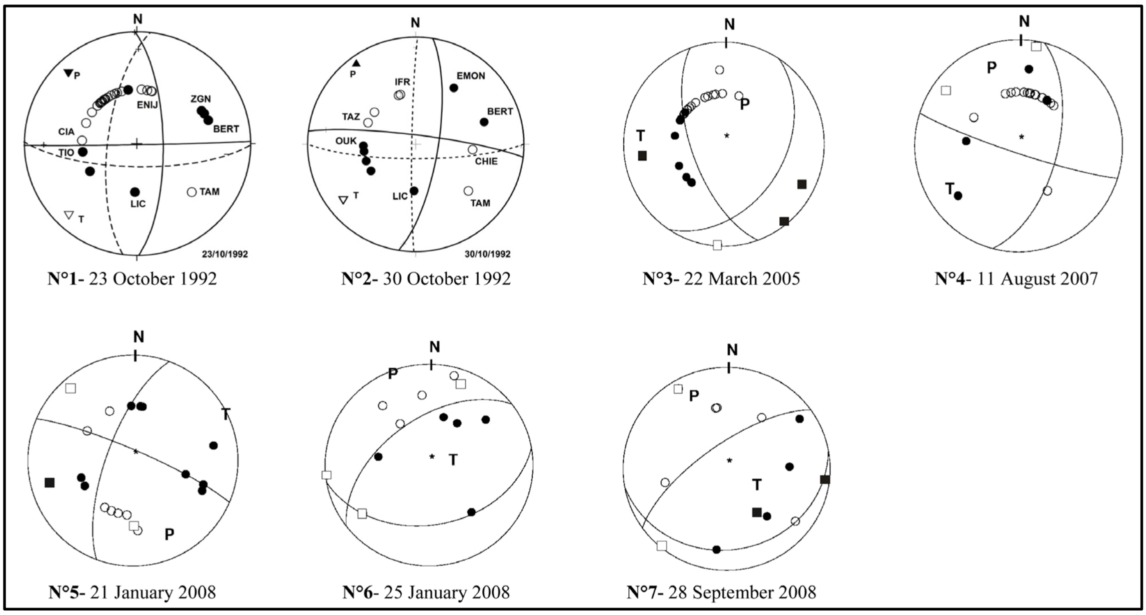


Figure 5. Detailed fault-plane solutions of the studied earthquakes (see **Table 2** for the numerical parameters). Full circles = compression; empty circles = dilatation; squares = direct arrivals; P = pressure axis; T = tension axis; dashed traces in solutions 1 and 2 = solutions given by Harvard.

Table 2. Fault-plane solutions of the studied earthquakes, after [10].

Ref	Date (D/M/Y)	Lat. N Lon. W	*M*	Depth (km)	Fault planes (˚) (Φ, δ, λ)	P axis (˚) (Tr; pl)	T axis (˚) (Tr; pl)	N	Score (%)
1	23/10/1992	31.36˚; 4.18˚	5.2	2 ± 5.2	A: 359 ± 9; 71 ± 9; 1 ± 11 B: 89 ± 11; 89 ± 10; −161 ± 9	316 ± 10; 14 ± 10	223 ± 09; 13 ± 09	30	97
2	30/10/1992	31.28˚; 4.34˚	5.1	2 ± 6.0	A: 9 ± 11; 73 ± 14; 7 ± 11 B: 277 ± 12; 83 ± 10; 163 ± 14	324 ± 12; 7 ± 12	232 ± 11; 16 ± 12	13	100
3	22/03/05	35.05˚; 2.97˚	4.7	5 ± 4	A: 33 ± 59; 40 ± 38; −44 ± 53 B: 160 ± 35; 63 ± 20; −121 ± 52	25 ± 43; 59 ± 45	272 ± 37; 13 ± 19	29	97
4	11/08/07	33.14˚; 5.21˚	5.1	7 ± 3.7	A: 14 ± 13; 59 ± 20; −7 ± 35 B: 108 ± 24; 84 ± 29; −149 ± 21	336 ± 14; 26 ± 19	237 ± 24; 17 ± 31	23	91
5	21/01/08	35.12˚; 3.94˚	4.1	8.2 ± 3.0	A: 200 ± 9; 70 ± 12; −9 ± 20 B: 293 ± 12; 82 ± 19; −159 ± 12	158 ± 9; 20 ± 16	65 ± 11; 8 ± 15	19	95
6	25/01/08	33.01˚; 5.36˚	4.3	5.6 ± 3.5	A: 80 ± 6; 40 ± 4; 69 ± 13 B: 233 ± 24; 53 ± 4; 107 ± 16	335 ± 7; 7 ± 3	90 ± 30; 75 ± 10	12	100
7	28/09/08	33.59˚; 5.89˚	4.5	21.8 ± 2.7	A: 80 ± 7; 21 ± 2; 66 ± 8 B: 234 ± 4; 71 ± 2; 99 ± 3	331 ± 4; 25 ± 2	130 ± 7; 63 ± 2	13	85

3.2. Source Parameters from P-Wave Spectra

The characteristics of 29 spectra of the studied earthquakes such, as the low-frequency spectral amplitudes and the corner frequencies observed are indicated in **Table 3**. Selected examples for each event are shown in **Figure 6**. The source parameters (seismic moment, fault radius, moment magnitude, fault displacement and stress drop) calculated from these data are given in **Table 4**. For the largest events (#1 and 2), which correspond to the Rissani twin earthquakes of 23 and 30 October 1992, the fault radii are close to 4 km, the displacements are about 4 cm and the stress drops are 0.3 - 0.4 MPa.

The three smallest events show very similar parameters with fault radii close to 0.6 km, fault displacements of 1.26 to 2.41 cm and stress drops of 0.96 to 2.45 MPa. However, the parameters of the 22 March 2005 event ap-

Table 3. Spectral characteristics obtained from the stations for each studied earthquakes. *R*: radiation pattern; Ω_0: flat low-frequency amplitude; *fc*: corner frequency.

Ref	Event (dd/mm/yy)	Number of spectra	Stations	Epicentral distance (km)	Take-off angle	$R(\theta, \varphi)$	Ω_0 (m)	*fc* (Hz)
1	23/10/92	4	FUR	2439	32	0.595	5×10^{-6}	0.5
			AQU	1980	39	0.811	1×10^{-5}	0.8
			WET	2439	30	0.624	1×10^{-6}	0.6
			TAM	1350	42	0.638	2×10^{-6}	0.5
2	30/10/92	4	FUR	2294	32	0.025	5×10^{-6}	0.5
			AQU	1980	33	0.812	1×10^{-5}	0.6
			WET	2454	30	0.040	3×10^{-6}	0.5
			TAM	1357	43	0.610	3×10^{-6}	0.5
3	22/03/05	2	EALB	100	62	−0.6035	1×10^{-6}	4
			ECOG	254	41	−0.7285	1×10^{-7}	5
4	11/08/07	5	IFR	43	85	−0.3500	1×10^{-5}	3
			AVE	206	42	0.3700	1×10^{-5}	2
			EALB	370	42	−0.4100	1×10^{-7}	3
			ECEU	380	42	−0.7500	1×10^{-7}	3
			EMIJ	383	42	−0.6900	2×10^{-7}	3
5	21/01/08	6	M006	79	71	0.7619	1×10^{-7}	6
			M008	114	61	−0.1388	1×10^{-7}	4
			M014	134	56	−0.8301	1×10^{-7}	6
			M012	145	43	0.2695	1×10^{-7}	3
			M018	175	43	−0.4706	1×10^{-7}	5
			IFR	211	43	−0.2073	2×10^{-7}	3
6	25/01/08	4	M011	61	75	−0.37019	1×10^{-7}	5
			M017	98	63	−0.75248	1×10^{-7}	4
			M018	109	60	0.35968	1×10^{-7}	5
			IFR	111	59	−0.51466	1×10^{-7}	4
7	28/09/08	5	M010	81	81	−0.8458	3×10^{-7}	6
			M018	133	51	0.6701	1×10^{-7}	6
			M006	184	51	−0.0758	1×10^{-8}	3
			M019	225	51	0.6397	3×10^{-8}	4

pear to be too high with respect to the other events, certainly because of the small number of available spectra. We also had to remove station M010 from the calculations of the 28 September 2008 source parameters, because it led to too high values.

In contrast, the $M \sim 5$ event that occurred in the Middle Atlas on 11 August 2007 shows very variable values of fault displacement (0.8 cm at ECEU to 87 cm at IFR) and stress drops (0.52 MPa at ECEU to 63 MPa at IFR), although the fault radii values are homogeneous (0.83 to 0.99 km). Therefore, we recalculated the source parameters shown in **Table 4** without taking into account stations IFR and AVE, which provided too large values.

4. Discussion

4.1. Influence of the Quality of Data and Processing on the Obtained Results

Our study was initially intended to attempt determining the source parameters of the Moroccan moderate events for seismotectonic analysis. However, the results show that the variability of the parameters that lead to them may have a large influence on the obtained values.

First, it appears that the corner frequency values obtained from the spectra are not always homogeneous for the same event, especially at the nearest stations which display large discrepancies, as for instance in the case of stations IFR and AVE for the event recorded on 11 August 2008. This may be due to several parameters such as:

1) Site effects related to the geological composition of the basement, which may also have an influence on the stress drop.

2) Uncertainty on the hypocentral depth (**Table 2**), which may dramatically influence the estimation of the radiation pattern and subsequent calculations. Such discrepancies may currently be observed even within closely spaced stations, but within 30% of the mean value [41].

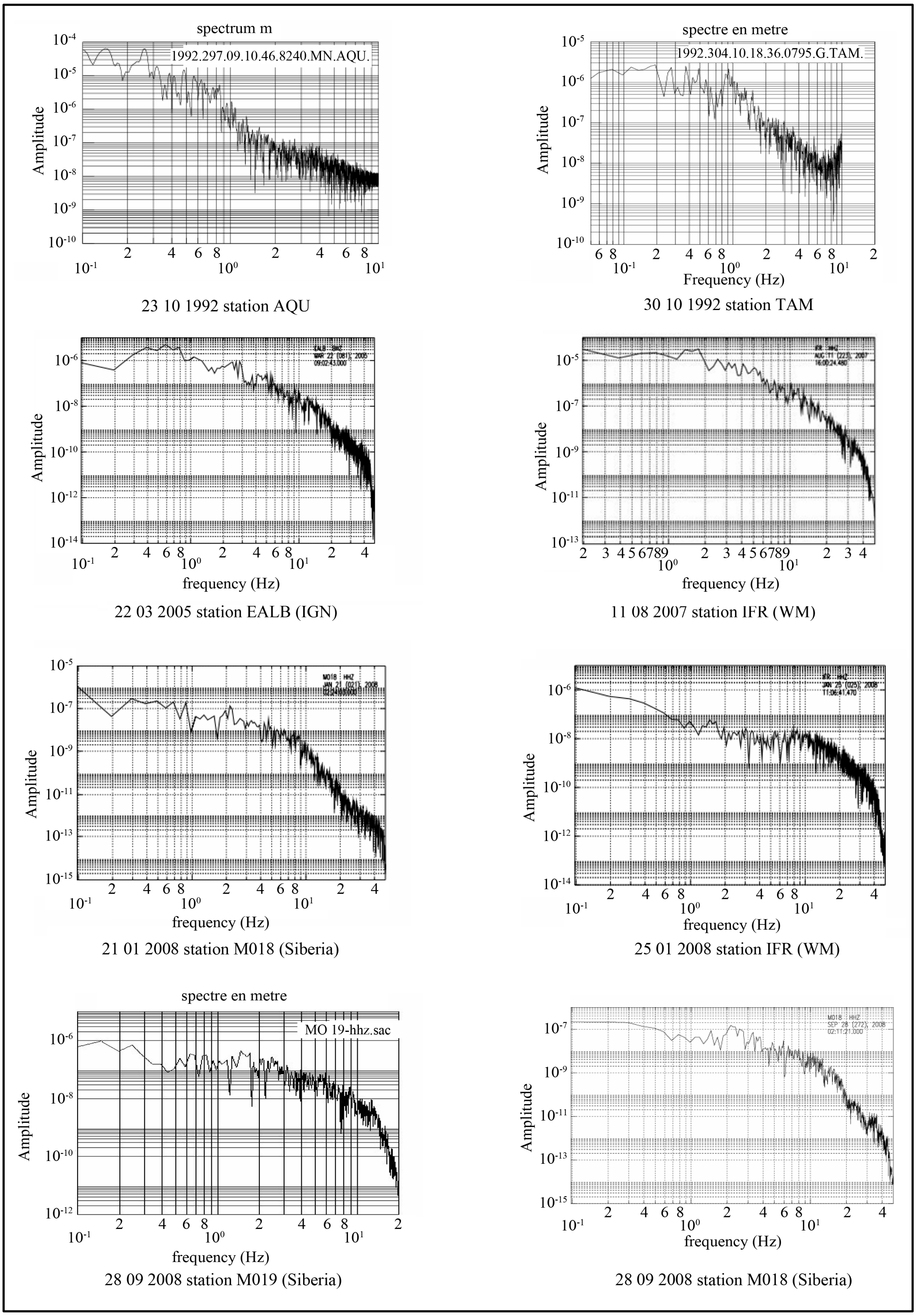


Figure 6. Selected examples of P-wave spectra for the studied earthquakes.

Table 4. Spectral characteristics obtained from the stations for each studied earthquakes. *R*: radiation pattern; Ω_0: plateau amplitude; *fc*: corner frequency.

Ref	Event	Mean M_0 (Nm)	Mean *r* (km)	*Mw*	N	Δu (cm)	(MPa)
1	23/10/92	$6.03 \pm 3.03 \times 10^{16}$	3.90 ± 0.70	5.1	4	4.00 ± 2.10	0.4 ± 0.20
2	30/10/92	$5.07 \pm 2.28 \times 10^{16}$	3.70 ± 0.60	5.0	4	3.70 ± 1.85	0.3 ± 0.16
3	22/03/05	$1.1 \pm 0.6 \times 10^{15}$	0.50 ± 0.00	4.00	2	4.31 ± 2.38	3.8 ± 0.00
4	11/08/07	$5.8 \pm 4.6 \times 10^{15}$	0.88 ± 0.07	5.00	3	5.80 ± 4.80	1.30 ± 0.57
5	21/01/08	$9.1 \pm 0.88 \times 10^{14}$	0.60 ± 0.26	3.90	6	2.04 ± 1.13	1.49 ± 0.62
6	25/01/08	$4.3 \pm 0.22 \times 10^{14}$	0.59 ± 0.05	3.70	4	1.26 ± 0.63	0.96 ± 0.51
7	28/09/08	$2.6 \pm 0.73 \times 10^{14}$	0.62 ± 0.16	3.74	3	0.80 ± 0.44	0.70 ± 0.50

3) The use of the circular fault model of Brune [34] [35], because we consider that a rectangular fault surface would be more realistic tectonically, but it was impossible to use it because of several parameters such as the small size of the earthquakes, the large depth of some of them and therefore the absence of an aftershock series which could have provided more information on the fault surface.

Therefore, we consider that a more systematic study, using a larger number of stations by event is needed in order to constraint the role of each parameter in the determination of the spectrum.

4.2. Seismotectonic Implications and Risk Assessment

As exposed in the first section, the amount of convergence of Nubia to Iberia is about 4 mm·yr^{-1} in Morocco according to the recent GPS studies [4] [5] [8] [11]-[13]. The Rif and High Atlas chains accomodate ~1 mm·yr^{-1} by earthquakes of low to moderate magnitude (maximum *Mw* = 6.3 at Al Hoceima in 2004), while the Alboran area, the Mesetas and the Anti Atlas accommodate the remaining.

Our results show that the moderate earthquakes are associated to fault slip values of 1 - 4 cm, which may represent 10 to 40 years of stress accumulation at a strain rate of 1 mm·yr^{-1} or less at a higher strain rate. This may be a suitable explanation for the diffuse distribution of the Moroccan earthquakes, especially in the Atlas chains, where the shocks occur randomly which indicates that stress may be released at different segments.

Another point is that our results can be used for seismic hazard assessment in Morocco, obviously together with other methods such as Coulomb stress; for instance, it appears that for moderate earthquakes (*M* = 4 - 5), stress is released on faults by slip of about 4 mm to 4 cm. Recent GPS monitoring studies show that in several areas in Morocco, the relative motion of fault blocks can be more or less precisely evaluated. This is the case of the SW-displacement of the Rif units onto their foreland, with velocities of 1 - 4 mm·yr^{-1}. If the date of the last significant earthquake in a given area can be known, the magnitude of the next one can be predicted on the base of the time interval. For instance, we can predict that an earthquake of magnitude *M* = 4 can occur each year in an area showing relative (convergence) velocities of 4 mm·yr^{-1}, or each two years if it is 2 mm·yr^{-1}, and that larger ones with *M* = 5 each 10 years in a 4 mm·yr^{-1} displacement area, as for instance near the city of Fès [14].

5. Conclusion

In this paper, we exposed the first results of the use of P-wave spectra obtained from broad band station recordings in Morocco for determining the source parameters of some moderate earthquakes that occurred in the country. The main conclusion is that the spectra can be useful for determining the source parameters, and provide results which are in accordance with the seismotectonic and geodynamic setting of Morocco. For instance, the amount of slip along the faults with respect to the relative displacement of Nubia to Iberia and that of Morocco to Nubia can be evaluated for earthquakes whose faults do not reach the surface. However, some events show very variable corner frequencies and low frequency amplitudes which lead to considerably higher values of source parameters such as stress drop and fault slip, especially at the nearest stations, which may reflect some site effects or uncertainties on depth and take-off angles. Therefore, it appears necessary to increase the number of studied spectra in order to improve the values of the source parameters.

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