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A Catalog of Main Moroccan Earthquakes from 1045 to 2005

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Online material: A Poissonian North Morroccan Earthquake Catalog

INTRODUCTION

A homogeneous and reliable earthquake catalog is highly desirable in seismic hazard studies. This work, the compilation of as complete and homogeneous a main Moroccan earthquake catalog as possible, has been developed in the context of a project to compute the probabilistic seismic hazard in this region. The result shown here is the outcome of fruitful teamwork among several Spanish, Moroccan, and Algerian institutions.

Previous earthquake catalogs that specifically cover this region (*e.g.* Tadili and Ramdani 1983; Cherkaoui 1986; Benouar 1994), although employed in seismic hazard assessments (Benouar *et al.* 1996; Jiménez *et al.* 1999), did not span the desirable time interval. Many of them did not include pre-1900 events, *i.e.*, large shocks that occurred in the historical period. Moreover, a real magnitude unification process was not performed.

Our initial goal was to catalog all known events from every available published source for the area between 27° to 37°N and 15°W to 1°E, including the southernmost part of Spain and Portugal and the western region of Algeria. We obtained a uniform catalog, using for this purpose several empirical relationships among reported magnitudes, macroseismic intensity, and moment magnitude. Finally, we removed all dependent events, as well as earthquakes with magnitudes smaller than M_W 3.0. The final catalog covers the period from 1045 to 2005 and includes 1,739 mainshocks. It can be downloaded in a self-explanatory Excel file from the University of Jaén Web site at `http://www.ujaen.es/investiga/rnm217/moroccan_catalog.xls`. Tabulated data include agency, origin time, epicenter (coordinates, depth, and location), reported magnitude or maximum intensity and unified magnitude.

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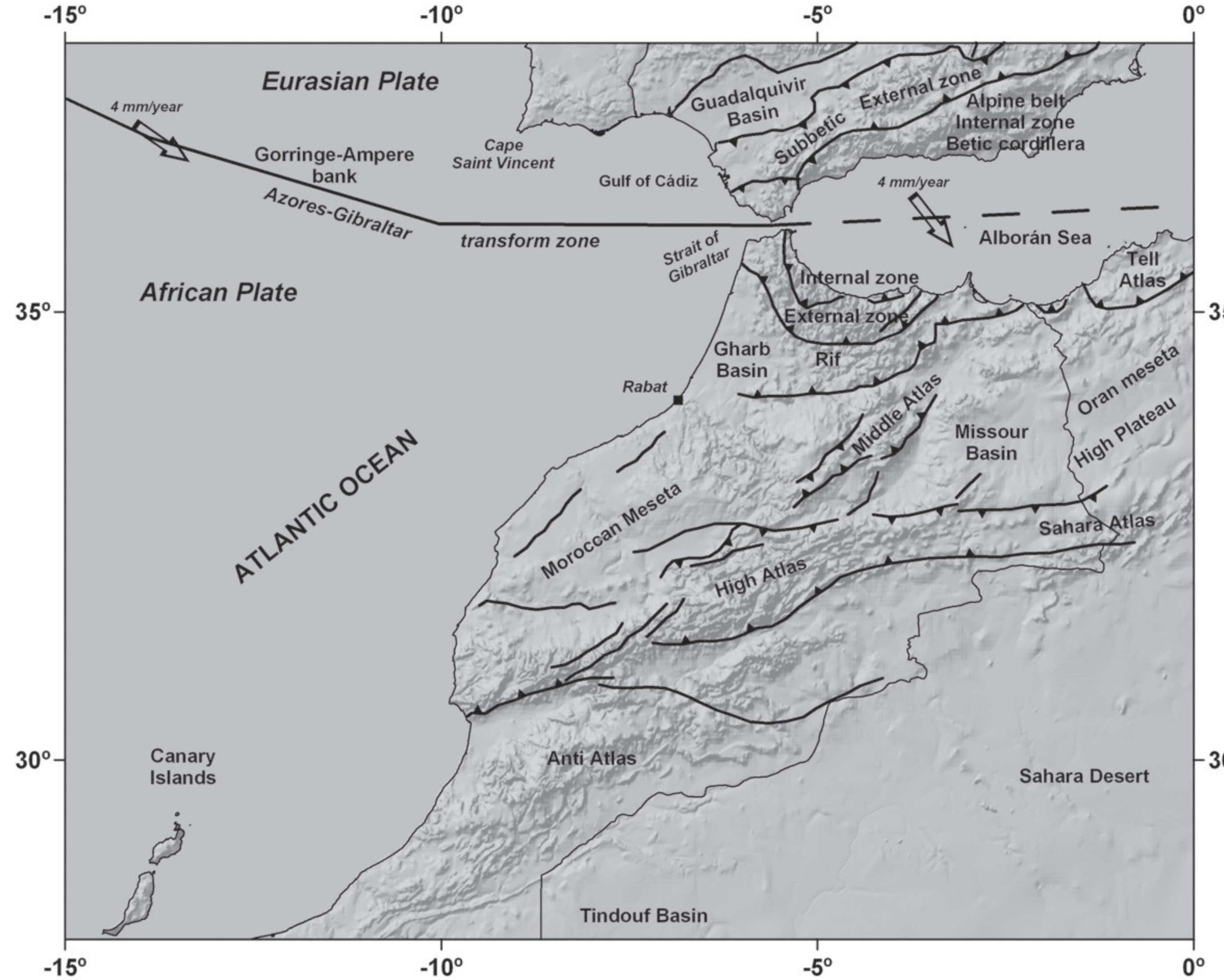
TECTONIC FRAMEWORK OF THE REGION

The analyzed region (figure 1) includes the southernmost part of the Iberian Peninsula, the western portion of the Mediterranean Sea (Alborán Sea), the central-eastern area of the Atlantic Ocean, and the northwestern area of Africa (basically Morocco), located in the boundary between the Eurasian and African plates. This zone is tectonically complex, with moderate to large earthquakes mainly associated with the convergence between Africa and Eurasia. This convergence is oblique with respect to the plate boundary, indicating that some right-lateral component of slip has to be accommodated. Indeed, the largest earthquakes show a consistent N-S to NW-SE orientation of *P* axes, corresponding to the plate convergence direction. This compression coexists with E-W to NE-SW tension in the Betics, Alborán Sea, and northern Morocco. The Alborán Sea is crossed by the Alborán ridge, an important crustal fault that absorbed a great part of the Africa-Europe convergence (Aït Brahim *et al.* 2002; Michard *et al.* 2002).

To the west, this region passes into the complex Azores-Gibraltar dextral transform zone, separating the Central Atlantic and the North Atlantic oceanic crusts, in which the Gorringe-Ampère bank is located (Gràcia *et al.* 2003). This zone, crossed by NE-SW reverse faults, presents intermediate levels of seismicity. Earthquakes in this zone are probably related to the subduction of the African plate.

In Morocco, three main structural domains can be distinguished (figure 1). From north to south they are the Rif, the Atlas Mountains, and the Anti Atlas. These domains, specially the Rif, together with the Betic Cordilleras, constitute the westernmost end of the Alpine orogenic belt in southern Europe and delimit the Alborán Sea and the Algerian Basin.

The Rif and Betic mountain belts are formed by a common, partially metamorphosed internal zone and two different external zones, mostly formed by sedimentary rocks disposed in complex tectonic nappes. These overturned folds



▲ **Figure 1.** Tectonic sketch of Morocco.

were later affected by large faults with NE-SW (Al Hoceima, Nekor), ENE-WSW (Jebha) and E-W directions, many of them affecting the whole crust. The depth of many earthquakes included in this area ($h > 60$ km) has been related to several processes, such as subduction, lithospheric delamination, and detachment or sinking, mainly in the western part of the Alborán Sea (*e.g.*, Platt and Vissers 1989, Blanco and Spackman 1993; Zeck 1996; Seber *et al.* 1996; Buforn *et al.* 1997; Mezcua and Rueda 1997; Morales *et al.* 1999; Calvert *et al.* 2000; López Casado *et al.* 2001; Aït Brahim *et al.* 2002; Michard *et al*. 2002).

The Atlas mountains, formed by Paleozoic, Mesozoic, and Tertiary rocks, are bordered by NE-SW (in the middle Atlas), E-W (in the high eastern Atlas) and ENE-WSW (in the high central Atlas) crustal faults. These faults moved during the Mio-Pliocene and the Quaternary with reverse, sinistral, and oblique displacements and are associated with the formation of folds (Aït Brahim *et al.* 2002).

To the south of the Atlas, and separated by the faults named above, are the Anti Atlas mountains, formed by a Precambrian basement and a Paleozoic cover. The faults limiting the Atlas and the Anti Atlas continue to the southwest and pass by the Canary Islands. In these sectors there is important volcanic activity, especially in the Canary archipelago.

To the west of the Atlas we find the Moroccan Meseta, formed by Paleozoic rocks. Between the Meseta and the Rif there is the Gharb Basin, constituted by Neogene and Quaternary sediments. Offshore is the continental shelf, the Atlantic margin of Morocco. To the east, the Rif continues to the Tell Mountains and the Algerian Atlas, with some Neogene basins such as the Moulouya Basin. These areas have moderate seismicity.

Recent GPS measurements in Morocco show that the Atlasic and Rifain domains absorb the shortening caused by the Africa-Eurasia convergence. In the Atlas, the shortening is less than 2 mm/year, while in the western part of the Rifain belt, shortening is as much as 4.5 mm/year (Azzouzi *et al.* 2005).

USEFUL SOURCES

As mentioned above, in developing this catalog we investigated and employed all available published sources. We used published data from local and international seismological agencies, covering different time periods and different magnitude scales, and several papers and reports on historical and instrumental seismicity. Most of these papers are related to appraisals of surface and moment magnitudes for several instrumental events in this region.

Initially, we had access to the following catalogs:

- ***IGN catalog* / Instituto Geográfico Nacional, Madrid, Spain** (Mezcua and Martínez Solares 1983; Martínez Solares and Mezcua 2002). It includes data in digital format until 2005 and is updated periodically. This has been the basic seismic catalog, completed and corrected with the other sources. The quality of this catalog was appreciated during the Ibero-Maghrebian workshop (under the auspices of the European Seismological Commission) in its 1979 meeting in Rabat (Morocco). It was pointed out that this is the most reliable catalog covering the Ibero-Maghrebian area for regional use. Under the auspices and funding of UNESCO, an enormous effort was invested to complete, homogenize, and improve it. Its authors used 131 catalogs (catalogs in the strict sense of the word plus papers on the seismicity of the region) and 313 papers about specific earthquakes (Mezcua and Martínez Solares 1983). The recent version of the catalog (Martínez Solares and Mezcua 2002) includes pre-1900 moment magnitude reassessments calculated by the Bakun and Wentworth (1997, 1999) method.

  The first Spanish seismological station was operative in 1898. At the present time, more than 40 digital broadband stations comprise the main Spanish seismological network, depending on the IGN agency. In addition to the IGN network, several institutions have installed and preserved local and regional networks in the Spanish territory.
- ***SPG catalog* / Service de Physique du Globe, Rabat, Morocco** (Tadili and Ramdani 1983). The SPG catalog includes data from 1900 until 1983 and has recently been updated in digital format up to 1999. Before 1966, the event locations are macroseismics (from macroseismic data) or else provided by international organizations. The first seismological station was installed in 1937, and it was not until 1978 that a proper seismological network became available in the Moroccan territory.
- ***CRAAG catalog* / Centre de Recherche en Astronomie, Astrophysique et Géophysique, Algiers, Algeria** (Mokrane *et al.* 1994; Yelles Chaouche *et al.* 2002, 2003). The CRAAG catalog includes data for Algeria from 1365 to 2002; recently it has been updated in digital format up to 2005. The first North Algerian seismological station was installed at Algiers in 1910. Soon after, others were installed at Setif, Beni Abbes, and Oued Fodda. Some of them were in working order until the 1985 installation of the current telemetric seismological network, which includes approximately 32 stations and covers the whole of northern Algeria (Bezzeghoud *et al.* 1994).
- ***USGS/NEIC-PDE catalog* / U.S. Geological Survey, National Earthquake Information Center—Preliminary Determination of Epicenters** (USGS 2006). This includes data from 1973 to 2005.
- ***ISC catalog* / International Seismological Centre** (ISC 2006). The ISC catalog includes checked and unchecked data from national and local agencies updated to 2005.

We preferred different catalogs depending on the epicenter location. For earthquakes located inside a given seismological network, the prevailing location usually was the one given by that agency. We always gave priority to local agencies (IGN, SPG, and CRAAG) over international agencies (USGS and ISC).

In addition to the catalogs, we have used data concerning evaluations and reassessments of moment and surface magnitude from the following agencies and authors:

- ***IGN online catalog***. Automatic computation of seismic moment tensor. Instituto Geográfico Nacional, Madrid, Spain. http://www.ign.es/ign/es/IGN/BBDD_sismicos_CATMS.jsp
- ***IAG online catalog***. Regional moment tensor project. Instituto Andaluz de Geofísica, Granada, Spain. http://www.ugr.es/%7eiag/tensor/
- ***Harvard CMT catalog***. Harvard Centroid Moment Tensor Catalog. http://www.globalcmt.org/CMTsearch.html
- ***EM RCMT catalog***. European-Mediterranean Regional Centroid Moment Tensors. http://www.ingv.it/seismoglo/RCMT/

The papers employed in this work that include magnitude reevaluations are those by Samardjieva *et al.* (1998), Bezzeghoud and Buforn (1999), Badal *et al.* (2000), Braunmiller *et al.* (2002), Buforn and Coca (2002), Moratti *et al.* (2003), Rueda and Mezcua (2002), Stich *et al.* (2003), Mezcua *et al.* (2004), and Rueda and Mezcua (2005). We must point out the paper by Johnston (1996b), which included an assessment of the moment magnitude from seismic intensity observations of the 1755 Lisbon earthquake, the most energetic and destructive shock in the region of study (M_W 8.7, $I_{\max} = X$) (*e.g.*, Levret 1991; Baptista *et al.* 1998; Martínez Solares and López Arroyo 2004). Johnson's paper placed the Lisbon earthquake on the south flank of the Gorringe Ridge, to the southwest of the St. Vincent Cape. In addition, we want to distinguish the work by El Mrabet (2005), which includes a comprehensive review of the historical seismicity in the Maghreb region. This review has been the main bibliographical source for significant historical earthquakes in the study area.

For magnitudes provided by the previously quoted catalogs and papers, the magnitude preference order was: M_W, M_W^{BW}, M_S, m_{bLg}, m_b, M_L, M_D and $I_{\max}$, where M_W^{BW} is the moment magnitude computed from intensity data using the Bakun and Wentworth (1997, 1999) approach.

CONVERTING SIZES TO M_W

One of the main goals of this work was to unify magnitudes. Moment magnitude was used as the unifying magnitude because it is the most commonly used magnitude in recent seismic hazard studies. Several empirical relationships between reported magnitudes, maximum intensity, and moment magnitude have been employed. These relationships are the ones considered to be the most reliable after carefully studying all the available magnitude relationships in the scientific literature. In the final catalog, in addition to the unified moment magnitude, the initially reported magnitude has been included. This will allow users to use other types of magnitude to unify the catalog or to use other relationships to calculate unified magnitude if they wish.

The equivalent moment magnitude (M_W*), *i.e.*, the final unified moment magnitude, was computed for each set of reported magnitude data from one of several relationships. For M_S magnitudes the empirical relationship by Johnston (1996a) between M_S and M_W was used. For m_{bLg} magnitudes the relationship by Rueda (2002) and Rueda and Mezcua (2002) between m_{bLg} and M_W was used. This relationship was developed specifically for the Iberian Peninsula and the surrounding region. In particular, m_{bLg} is the main type of magnitude reported by the Spanish IGN. For m_b magnitudes the Johnston (1996a) relationship between m_b and M_W was used. Where the M_L magnitude was reported, we have considered that this value is equal to the moment magnitude in our range of interest, following the criterion by Thatcher and Hanks (1973), Bakun (1984), and Heaton *et al.* (1986). M_L is the main magnitude type reported by the Algerian CRAAG. Where M_D was the reported magnitude, as occurs in most earthquakes cataloged by the Moroccan SPG agency, m_{bLg} was initially computed from the empirical relationship by Mouayn *et al.* (2004) between M_D and m_{bLg}. Then, the equivalent moment magnitude was computed from m_{bLg} as stated above.

Finally, where I_{max} was the reported earthquake size, M_W* was computed from the empirical relationship between maximum intensity and moment magnitude proposed by Mezcua (2002) for southern Spain. Where I_{max} was the reported size and the epicenter was located offshore, we previously computed the epicentral intensity from I_{max}, using the empirical regionalized attenuation relationships proposed by López Casado *et al.* (2000) for the Iberian Peninsula and surroundings.

In the final catalog, we employed a key to inform readers about the method used to obtain the equivalent moment magnitude for each event (see table 1).

DECLUSTERING THE CATALOG

After the uniform catalog was compiled, dependent (non-Poissonian) earthquakes were removed; this is necessary in any time-independent seismic hazard assessment. Main algorithms use magnitude to detect dependent events.

In this work, dependent events were identified using the classical sliding-time-and-distance algorithm (windowing routine) proposed by Gardner and Knopoff (1974). Given an earthquake with a certain M_W magnitude, a scan within distance $L(M_W)$ and time $T(M_W)$ was performed for the entire catalog. The largest earthquake found in this search was considered to be the mainshock. The chosen criterion for L and T values was very similar to the one adopted by these authors. For a M_W 3.0 earthquake L and T values of 20 km and 10 days, respectively, were used. For a M_W 8.0 earthquake, values of 100 km and 900 days, respectively, were used. A logarithmic interpolation was performed between these values to obtain L and T values for a given magnitude.

After this process, the catalog was cut off below magnitude M_W 3.0. These magnitudes are not significant for seismic hazard studies. In addition, we cannot be sure about the catalog completeness below this value, even for recent periods.

RESULTS AND CONCLUSIONS

Using this process, we obtained a Poissonian catalog of 1,739 events. They span the years from 1045 to 2005, within a region bounded by 27°–37°N and 15°W–1°E. A map showing the distribution of epicenters is depicted in figure 2. We can see that the largest density of earthquakes is located: a) offshore, along the Azores-Gibraltar transform zone and the Alborán Sea, and b) onshore, in the Rif mountains in northernmost Morocco and the Tell Atlas mountains, in northwestern Algeria (figures 1 and 2). The two largest earthquakes in the region, the M_W 8.7 November 1755 Lisbon and the M_W 7.9 February 1969, are located southwest of Cape St. Vincent, at the edge of the Azores-Gibraltar fault.

Table 1 shows the earliest (pre-1800) earthquakes included in the catalog and contains seven of the 10 compiled largest events in the region. A file including a complete list can be downloaded from the University of Jaén Web site at http://www.ujaen.es/investiga/rnm217/moroccan_catalog.xls. In this file the unified equivalent moment magnitude was included, as well as the initially reported size (maximum felt intensity or computed magnitude) by the authoritative reporting agency. This is in deference to those researchers who prefer to unify magnitudes using relationships different from the ones in this work.

The contributing agencies have been the Spanish IGN, with 74.1% of the reported earthquakes in the final catalog, and the Moroccan SPG, with 19.0%. Lesser contributors were the Algerian CRAAG, with 3.4% of the reported earthquakes and the North American NEIC, with 1.3% of cataloged events. The remaining 2.2% of events were collated from the ISC and the various online catalogs mentioned earlier.

Reported earthquakes have systematically had an associated depth since 1964. Most earthquakes are located in the crust (61.6%), but there are a significant number with depths between 30 and 100 km (16.0%). The majority of those with depths between 30 and 100 km are located in the western Alborán Sea (López Casado *et al.* 2001). The m_{bLg} 7.0, 1954 Dúrcal earthquake (*e.g.*, Hodgson and Cock 1956; Richter 1958, 415; Chung and Kanamori 1976) with a depth of 657 km, the m_{bLg} 4.0, 1973 Lentejí earthquake (*e.g.*, Buforn *et al.* 1991; Frohlich 1998) with a depth of 660 km, and the m_{bLg} 4.8, 1990 Dúrcal earthquake (*e.g.*, Buforn *et al.* 1991, 1997; Frohlich 1998) with a depth of 627 km are the deepest earthquakes in the catalog and all are located in Spain. These events

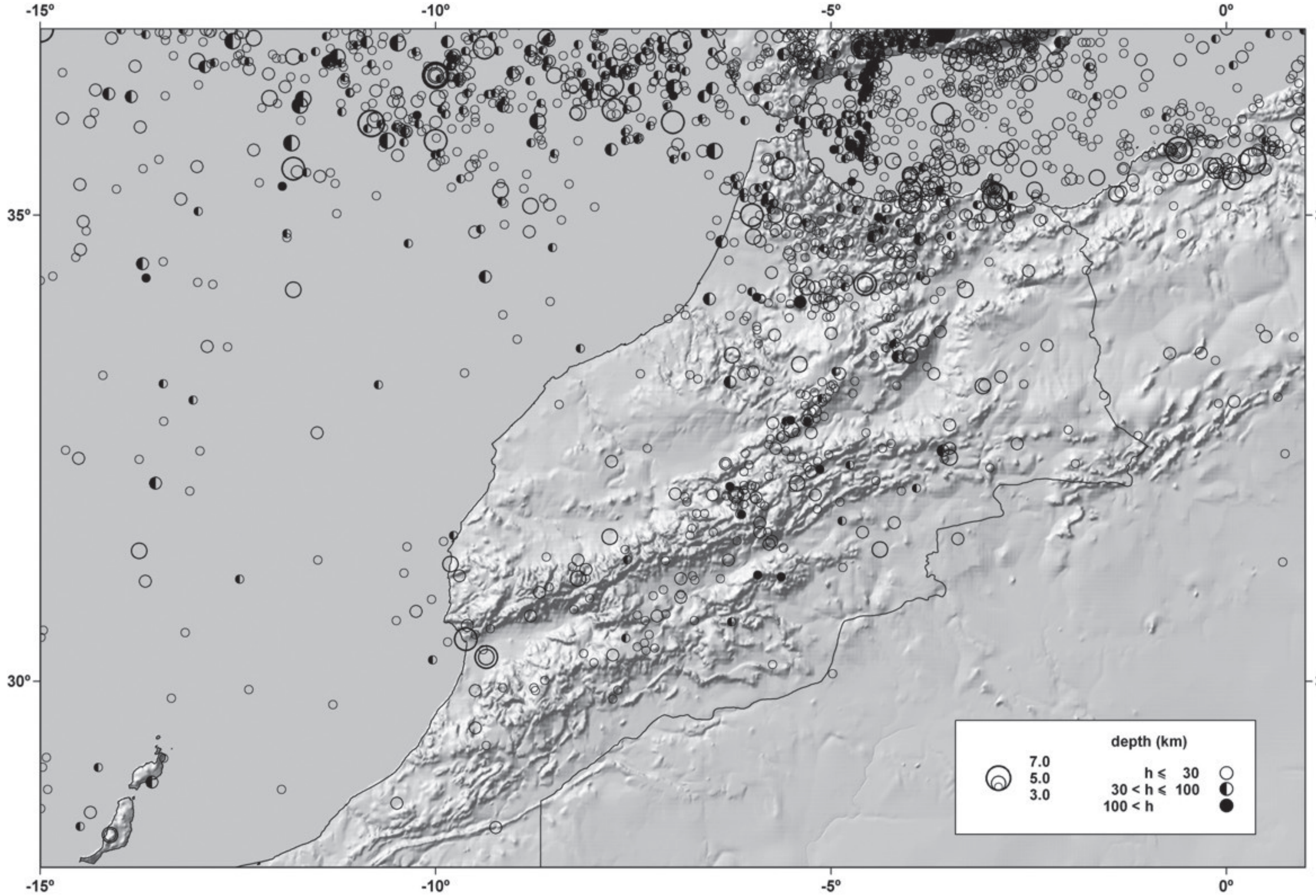
TABLE 1 Pre-1800 Cataloged Earthquakes								
Date mm/dd/yyyy	Hour GMT	Longitude	Latitude	Depth	Reported Magnitude	Maximum Intensity	Location	Final M_W
00/00/1045	—	–5.000	34.050	—	—	VIII	Fès. Morocco	5.8[1]
00/00/1079	—	–6.000	35.000	—	—	IX	W Ouazene. Morocco	6.4[1]
08/24/1356	—	–10.000	36.500	—	—	VIII	SW Cape St. Vincent	6.7[2]
11/00/1487	—	–2.467	36.833	—	—	VIII	Almería. Spain	5.8[1]
01/26/1494	20:00:00	–4.333	36.583	—	—	VIII	S Málaga. Spain	5.8[1]
09/22/1522	10:00:00	–2.667	36.967	—	M_W 6.5[3]	VIII-IX	W Alhama de Almería. Spain	6.5[3]
04/13/1529	07:00:00	–2.467	36.833	—	—	VI	Almería. Spain	4.6[1]
04/19/1550	—	–2.467	36.833	—	—	VI	Almería. Spain	4.6[1]
10/21/1578	04:00:00	–2.933	35.267	—	—	VIII	Melilla. Spain	5.8[1]
06/18/1581	07:30:00	–4.417	36.717	—	—	VII	Málaga. Spain	5.2[1]
05/11/1624	—	–4.570	34.260	—	—	IX-X	Fès. Morocco	6.7[1]
10/16/1663	—	–5.190	35.530	—	—	VII	Fès. Morocco	5.2[1]
12/31/1658	07:00:00	–2.467	36.833	—	—	VIII	Almería. Spain	5.8[1]
08/05/1660	18:00:00	–2.917	35.167	—	—	VII	Melilla. Spain	5.2[1]
10/09/1680	07:00:00	–4.600	36.800	—	M_W 6.8[3]	VIII-IX	NW Málaga. Spain	6.8[3]
00/00/1686	—	–2.950	36.850	—	—	VI-VII	Berja. Spain	4.9[1]
10/21/1713	20:30:00	–2.917	35.167	—	—	V	Melilla. Spain	4.0[1]
07/00/1719	—	–4.570	34.260	—	—	VIII	Fès. Morocco	5.8[1]
08/29/1722	05:15:00	–4.417	36.717	—	—	VI	Málaga. Spain	4.6[1]
12/27/1722	17:30:00	–7.767	36.400	—	M_W 6.9[3]	VIII	Gulf of Cádiz	6.9[3]
00/00/1731	—	–9.360	30.260	—	—	IX	Agadir. Morocco	6.4[1]
11/01/1755	10:16:00	–10.000	36.500	—	M_W 8.7[3]	X	SW Cape St. Vincent	8.7[3]
11/27/1755	11:00:00	–5.302	34.228	—	—	VII	Meknes. Morocco	5.2[1]
03/31/1761	12:15:00	–9.383	36.800	—	M_W 6.7[3]	VI-VII	SW Cape St. Vincent	6.7[3]
04/09/1761	—	–9.360	30.260	—	—	VII	Agadir. Morocco	5.2[1]
10/11/1763	08:15:00	–10.000	36.500	—	—	V	SW Cape St. Vincent	5.2[2]
07/16/1767	02:00:00	–4.400	36.800	—	—	VI	N Málaga. Spain	4.6[1]
04/06/1772	00:06:00	–10.000	36.500	—	—	V-VI	SW Cape St. Vincent	5.5[2]
04/12/1773	05:15:00	–7.000	36.000	—	—	VII	Gulf of Cádiz	6.7[2]
05/10/1777	13:30:00	–6.283	36.517	—	—	IV-V	Cádiz. Spain	3.7[1]
10/09/1790	01:15:00	–0.600	35.700	—	—	IX-X	Oran. Algeria	6.7[1]
04/19/1791	—	–4.250	35.200	—	—	VI-VII	Peñón de Vélez de la G. Spain	4.9[1]
11/27/1791	22:20:00	–10.000	36.500	—	—	VI	SW Cape St. Vincent	4.6[1]
10/01/1792	—	–4.250	35.200	—	—	V	Peñón de Vélez de la G. Spain	4.0[1]

1. From I_{max}.
2. From reappraised epicentral intensity for offshore epicenters (see text).
3. Computed from intensity data using the Bakun and Wentworth (1997, 1999) approach.

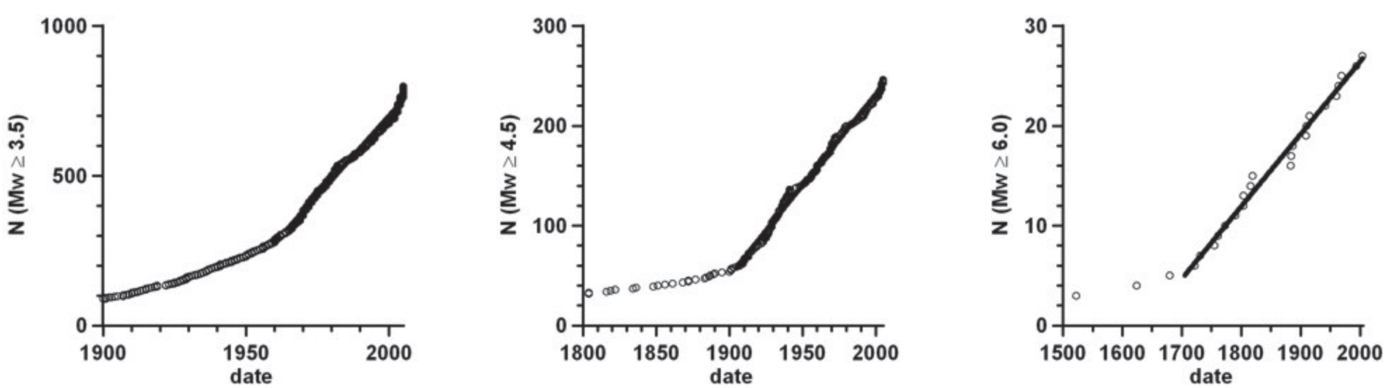
are attributed to fractures in a detached fragment of cold and rigid plate that is sinking into the deep mantle (*e.g.*, Platt and Vissers 1989; Blanco and Spackman 1993; Zeck 1996).

By considering only the shallow earthquakes ($h < 30$ km) and plotting the cumulative number of events above different magnitudes versus time, we obtained a measure of the catalog completeness. Using this test, we found that the entire catalog is most likely complete in the past 40 years for magnitudes above M_W 3.5 with a rate of 10.6 events/year, in the past 100 years for magnitudes above M_W 4.5 (1.8 events/year), and in the past 300 years for magnitudes above M_W 6.0 (0.07 events/year) (see figure 3).

We recognize that the compiled catalog has deficiencies. For example, as usual in this kind of work, subjective criteria were occasionally used (relationships between reported earthquake size and moment magnitude, or declustering algorithm and parameters), and it is not as complete and uniform as could be desirable for seismic hazard studies. However, we are confident



▲ **Figure 2.** Map showing cataloged earthquakes.



▲ **Figure 3.** Cumulative number of earthquakes above different magnitude values (see text).

that, to date, it is the most complete catalog aimed toward seismic hazard studies that has been compiled for this region.

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REFERENCES

Aït Brahim, L., P. Chotin, S. Hinaj, A. Abdelouafi, C. Nakhcha, D. Dhont, F. Sossey Alaoui, A. Bouaza, H. Tabyaoui, and A. Chaouni (2002). Paleostress evolution in the Moroccan African margin from Triassic to present. *Tectonophysics* **357**, 187–205.

Azzouzi, R., M. Ettarid, H. Semlali, A. Rimi, A. Trache, M. Aït Belaid, and L. Aït Brahim (2005). Actual horizontal displacements and parameters deformations determinations of African and Eurasian tectonic plates in the Western Mediterranean region. *Workshop on Fracture*

Dynamics: Theory and Applications to Earthquakes. In Honour of Prof. A. Udías. 26–28 September 2005, Madrid, Spain.

Badal, J., E. Samardjieva, and G. Payo (2000). Moment magnitudes for early (1923–1961) instrumental Iberian earthquakes. *Bulletin of the Seismological Society of America* **90**, 1,161–1,173.

Bakun, W. H. (1984). Seismic moments, local magnitudes, and coda-duration magnitudes for earthquakes in Central California. *Bulletin of the Seismological Society of America* **74**, 439–458.

Bakun, W. H., and C. M. Wentworth (1997). Estimating earthquake location and magnitude from seismic intensity data. *Bulletin of the Seismological Society of America* **87**, 1,502–1,521.

Bakun, W. H., and C. M. Wentworth (1999). Erratum to "Estimating earthquake location and magnitude from seismic intensity data." *Bulletin of the Seismological Society of America* **89**, 557.

Baptista, M. A., S. Heitor, J. M. Miranda, P. Miranda, and L. M. Victor (1998). The 1755 Lisbon tsunami: Evaluation of the tsunami parameters. *Journal of Geodynamics* **25**, 143–157.

Benouar, D. (1994). An earthquake catalog for the Maghreb region 20°–38°N, 10°W–12°E for the period 1900–1990. *Annali di Geofisica* **37**, 511–528.

Benouar, D., G. L. Molas, and F. Yamazaki (1996). Earthquake hazard mapping in the Maghreb countries: Algeria, Morocco, Tunisia. *Journal of Earthquake Engineering and Structural Dynamics* **25**, 1,151–1,164.

Bezzeghoud, M., A. Ayadi, A. Sebai, and H. Benhallou (1994). Seismogenic zone survey by Algerian Telemetered Seismological Network—Case study of Rouina earthquake, 19 January 1992. *Physics of the Earth and Planetary Interiors* **84**, 235–246.

Bezzeghoud, M., and E. Buforn (1999). Source parameters of the 1992 Melilla (Spain, Mw = 4.8), 1994 Alhoceima (Morocco, Mw = 5.8), and 1994 Mascara (Algeria, Mw = 5.7) earthquakes and seismotectonic implications. *Bulletin of the Seismological Society of America* **89**, 359–372.

Blanco, M. J., and W. Spackman (1993). The *P*-wave velocity structure of the mantle below the Iberian Peninsula: Evidence for subducted lithosphere below southern Spain. *Tectonophysics* **221**, 13–34.

Braunmiller, J., U. Kradolfer, M. Baer, and D. Giardini (2002). Regional moment tensor determination in the European-Mediterranean area—initial results. *Tectonophysics* **356**, 5–22.

Buforn, E., A. Udías, J. Mezcua, and R. Madariaga (1991). A deep earthquake under South Spain, 8 March 1990. *Bulletin of the Seismological Society of America* **81**, 1,403—1,407.

Buforn, E., P. Coca, A. Udías, and C. Lasa (1997). Source mechanism of intermediate and deep earthquakes in southern Spain. *Journal of Seismology* **1**, 113–130.

Buforn, E., and P. Coca (2002). Seismic moment tensor for intermediate depth earthquakes at regional distances in Southern Spain. *Tectonophysics* **356**, 49–63.

Calvert, A., E. Sandvol, D. Seber, M. Barazangi, S. Roecker, T. Mourabit, F. Vidal, G. Alguacil, and N. Jabour (2000). Geodynamic evolution of the lithosphere and upper mantle beneath the Alborán region of the western Mediterranean: Constraints from travel time tomography. *Journal of Geophysical Research* **105,** 10,875–10,898.

Cherkaoui, T. E. (1986). Fichier informatisé des séismes du Maroc et des régions voisines. *Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Terre* **10**, 55–56.

Chung, W. Y., and H. Kanamori (1976). Source process and tectonic implications of the Spanish deep-focus earthquake of March 29, 1954. *Physics of the Earth and Planetary Interiors* **13**, 85–96.

El Mrabet, T. (2005). The great earthquakes in the Maghreb region and their consequences on man and environment. CNRS-LAG report, Rabat, Morocco (in Arabic).

Frohlich, C. (1998). Does maximum earthquake size depend on focal depth? *Bulletin of the Seismological Society of America* **88**, 329–336.

Gardner, J. K., and L. Knopoff (1974). Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian? *Bulletin of the Seismological Society of America* **64**, 1,363–1,367.

Gràcia, E., J. Danobeitia, J.Verges, and the Parsifal team (2003). Mapping active faults offshore Portugal (36°N–38°N): Implications for seismic hazard assessment along the southwest Iberian margin. *Geology* **31**, 83–86.

Heaton, T. H., F. Tajima, and A. W. Mori (1986). Estimating ground motions using recorded accelerograms. *Surveys in Geophysics* **8**, 25–83.

Hodgson, J. H., and J. I. Cock (1956). Direction of faulting in the deep-focus Spanish earthquake of March 29, 1954. *Tellus* **8**, 321–328.

ISC (2006). International Seismological Centre, online bulletin, http://www.isc.ac.uk , Thatcham, United Kingdom.

Jiménez, M. J., M. García Fernández, and the GSHAP Ibero-Maghreb working group (1999). Seismic hazard assessment in the Ibero-Maghreb region. *Annals of Geophysics* **42**, 1,057–1,065.

Johnston, A. C. (1996a). Seismic moment assessment of earthquakes in stable continental regions—I. Instrumental seismicity. *Geophysical Journal International* **124**, 381–414.

Johnston, A. C. (1996b). Seismic moment assessment of earthquakes in stable continental regions—III. New Madrid 1811–1812, Charleston 1886 and Lisbon 1755. *Geophysical Journal International.* **126**, 314–344.

Levret, A. (1991). The effects of the November 1, 1755 Lisbon earthquake in Morocco. *Tectonophysics* **193**, 83–94.

López Casado, C., S. Molina, J. Delgado, and J. A. Peláez (2000). Attenuation of intensity with epicentral distance in the Iberian Peninsula. *Bulletin of the Seismological Society of America* **90**, 34–47.

López Casado, C., C. Sanz de Galdeano, S. Molina Palacios, and J. Henares Romero (2001). The structure of the Alborán Sea: An interpretation from seismological and geological data. *Tectonophysics* **338**, 79–95.

Martínez Solares, J. M., and J. Mezcua (2002). *Seismic Catalog of the Iberian Peninsula (880 B.C.–1900)*. Madrid, Spain: Ed. IGN (in Spanish).

Martínez Solares, J. M., and A. López Arroyo (2004). The great historical 1755 earthquake: Effects and damage in Spain. *Journal of Seismology* **8**, 275–294.

Mezcua, J., and J. M. Martínez Solares. (1983). *Seismicity of the Ibero-Maghrebian Region*. IGN report, Madrid, Spain (in Spanish).

Mezcua, J., and J. Rueda (1997). Seismological evidence for a delamination process in the lithosphere under the Alborán sea. *Geophysical Journal International* **129**, F1–F8.

Mezcua, J. (2002). *Seismic Engineering Course*. Universidad Politécnica de Madrid report, Madrid, Spain (in Spanish).

Mezcua, J., J. Rueda and R. M. García Blanco (2004). Reevaluation of historic earthquakes in Spain. *Seismological Research Letters* **75**, 75–81.

Michard, A., A. Chalouan, H. Feinberg, B. Goffe, and R. Montigny (2002). How does the Alpine belt end between Spain and Morocco? *Bulletin de la Société Géologique de France* **173**, 3–15.

Mokrane, A., A. Aït Messaoud, A. Sebaï, N. Menia, A. Ayadi, and M. Bezzeghoud (1994). *Earthquakes in Algeria from 1365 to 1992.* CRAAG Report, Algiers, Algeria (in French).

Morales, J., I. Serrano, A. Javaloy, J. Galindo-Zaldivar, D. Zhao, F. Torcal, F. Vidal, and F. Gonzalez-Lodeiro (1999). Active continental subduction beneath the Betic Cordillera and Alborán Sea. *Geology* **27**, 8,735–8,738.

Moratti, G., L. Piccardi, G. Vannucci, M. E. Belardinelli, M. Dahmani, A. Bendkik, and M. Chenakeb (2003). The 1755 "Meknes" earthquake (Morocco): Field data and geodynamic implications. *Journal of Geodynamics* **36**, 305–322.

Mouayn, I., B. A. Tadili, L. Aït Bahim, M. Ramdani, M. Limouri, and N. Jabour (2004). Duration magnitude scale and site residuals for Northern Morocco. *Pure and Applied Geophysics* **161**, 1,061–1,080.

Platt, J. P., and R. L. M. Vissers (1989). Extensional collapse of thickened continental lithosphere: A working hypothesis for the Alborán Sea and Gibraltar arc. *Geology* **17**, 540–543.

Richter, C. F. (1958). *Elementary Seismology*. San Francisco: W. H. Freeman and Company.

Rueda, J. (2002). Assessing seismic source parameters from spectral analysis. Case study of the September 2001, Pego (Alicante) seismic sequence. Universidad Politécnica de Madrid scientific report, Madrid, Spain (in Spanish).
Rueda, J., and J. Mezcua (2002). Study of the 23 September 2003, Pego (Alicante) earthquake. Obtaining a m_{bLg}–M_W relationship for the Iberian Peninsula. *Revista de la Sociedad Geológica de España* **15**, 159–173 (in Spanish).
Rueda, J., and J. Mezcua (2005). Near-real-time seismic moment-tensor determination in Spain. *Seismological Research Letters* **76**, 455–465.
Samardjieva, E., G. Payo, J. Badal, and C. López (1998). Creation of a digital database for 20th century historical earthquakes occurred in the Iberian area. *Pure and Applied Geophysics* **152**, 139–163.
Seber, D., M. Barazangi, A. Ibenbrahim, and A.Demnati (1996). Geophysical evidence for lithospheric delamination beneath the Alborán sea and Rif-Betic mountains. *Nature* 379, 785–790.
Stich, D., J. Batlló, J. Morales, R. Macià, and S. Dineva (2003). Source parameters of the Mw = 6.1 1910 Adra earthquake (southern Spain). *Geophysical Journal International* **155**, 539–546.
Tadili, B. A., and M. Ramdani (1983). Computer file of Moroccan earthquakes. *Bulletin of the Seismological Society of America* **73**, 653–654.
Thatcher, W., and T. C. Hanks (1973). Source parameters of southern California earthquakes. *Journal of Geophysical Research* **78**, 8,547–8,576.
USGS (2006). United States Geological Survey online catalog, http://neic.usgs.gov/neis/epic/epic_global.html.
Yelles Chaouche, A. K., A. Deramchi, A. Ferkoul, and K. Aoulaiche (2002). *Earthquakes in Algeria from 1992 to 2001*. CRAAG report, Algiers, Algeria (in French).
Yelles Chaouche, A. K., A. Deramchi, A. Ferkoul, K. Aoulaiche, K. Meghnine, S. Haned, F. Chaoui, D. Aini, and K. Talbi. (2003). *Seismic Catalog 2002*. CRAAG report, Algiers, Algeria (in French).
Zeck, H. P. (1996). Betic-Rif orogeny: Subduction of Mesozoic Tethys lithosphere under eastward drifting Iberia, slab detachment shortly before 22 Ma, and subsequent uplift and extensional tectonic. *Tectonophysics* **254**, 1–16.

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