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ORIGINAL ARTICLE

Neo-deterministic seismic hazard assessment in North Africa

T. Mourabit · K. M. Abou Elenean · A. Ayadi · D. Benouar · A. Ben Suleman · M. Bezzeghoud · A. Cheddadi · M. Chourak · M. N. ElGabry · A. Harbi · M. Hfaiedh · H. M. Hussein · J. Kacem · A. Ksentini · N. Jabour · A. Magrin · S. Maouche · M. Meghraoui · F. Ousadou · G. F. Panza · A. Peresan · N. Romdhane · F. Vaccari · E. Zuccolo

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Abstract North Africa is one of the most earthquake-prone areas of the Mediterranean. Many devastating earthquakes, some of them tsunami-triggering, inflicted heavy loss of life and considerable economic damage to the region. In order to mitigate the destructive impact of the earthquakes, the regional seismic hazard in North Africa is assessed using the neo-deterministic, multi-scenario methodology (NDSHA) based on the computation of synthetic seismograms, using the modal summation technique, at a regular grid of 0.2×0.2°. This is

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T. Mourabit · A. Cheddadi
Département de Géologie, Université Abdelmalek Essaadi, BP. 416, 90001 Tangiers, Morocco

K. M. Abou Elenean · M. N. ElGabry · H. M. Hussein
National Research Institute of Astronomy and Geophysics, NRIAG, 11421 Helwan, Cairo, Egypt

A. Ayadi · A. Harbi (✉) · S. Maouche · F. Ousadou
Centre de Recherche en Astronomie, Astrophysique et Géophysique, CRAAG, BP. 63, Bouzaréah, Algiers, Algeria
e-mail: harbi.assia@gmail.com

A. Harbi
e-mail: naget@ictp.it

D. Benouar
Faculté de Génie Civile, Université de Bab Ezzouar (USTHB), BP. 32, El Alia, Algiers, Algeria

A. Ben Suleman
Tripoli University, Tripoli, Libya

M. Bezzeghoud
Evora University, Evora, Portugal

M. Chourak
OLMAN-RN, Faculté Pluridisciplinaire, Nador, Université Mohamed I, Oujda, Morocco

M. Hfaiedh
Nuclear Power Project, Société Tunisienne de l'Electricité et du Gaz, STEG, Tunis, Tunisia

J. Kacem
Faculté des Science de Sfax, Sfax, Tunisia

A. Ksentini · N. Romdhane
Ecole Nationale des Ingénieurs de Tunis, Tunis, Tunisia

N. Jabour
Centre National de Recherche Scientifique et Technique, Rabat, Morocco

A. Magrin · G. F. Panza · A. Peresan · F. Vaccari
ESP Section, SAND Group, The Abdus Salam International Centre for Theoretical Physics, ICTP, Strada Costiera 11, 34014 Trieste, Italy

A. Magrin · G. F. Panza · A. Peresan · F. Vaccari · E. Zuccolo
Dipartimento di Matematica e Geoscienze, Università di Trieste, Via Weiss, 4, 34128 Trieste, Italy

the first study aimed at producing NDSHA maps of North Africa including five countries: Morocco, Algeria, Tunisia, Libya, and Egypt. The key input data for the NDSHA algorithm are earthquake sources, seismotectonic zonation, and structural models. In the preparation of the input data, it has been really important to go beyond the national borders and to adopt a coherent strategy all over the area. Thanks to the collaborative efforts of the teams involved, it has been possible to properly merge the earthquake catalogues available for each country to define with homogeneous criteria the seismogenic zones, the characteristic focal mechanism associated with each of them, and the structural models used to model wave propagation from the sources to the sites. As a result, reliable seismic hazard maps are produced in terms of maximum displacement (D_{max}), maximum velocity (V_{max}), and design ground acceleration.

Keywords North Africa · Seismotectonics · Deterministic seismic hazard · Seismogenic zone · Design ground acceleration

1 Introduction

Earthquake hazard in Northern Africa constitutes a constant threat to human life and property, causing major economic losses and disruption. The past few years have seen an unprecedented level of damage from seismicity in active regions of North Africa, which has focused the attention of scientists and local communities on geohazards. The May 2003 Zemmouri earthquake (M_w=6.8) that occurred east of the city of Algiers is the largest felt since that in February 1716 (I_0=IX EMS). In February 2004, the city of Al Hoceima and the Rif Mountains of Morocco were struck, once again, by a large earthquake (M_w=6.4), 10 years after the May 1994 (M=6.0) event. The city of Cairo was struck in October 1992 by an M_w=5.8 magnitude earthquake, which caused large damage. In 1935, the Syrte region in Libya experienced an M=6.9 earthquake with severe damage (Suleiman and Doser 1995; Suleiman et al. 2004). Generally, North Africa has experienced moderate earthquakes. However, the region remains vulnerable due to the shallow character of its seismicity, the poor mechanical properties of its soil and local site conditions, and the consequent strength of the ground shaking. The damaging earthquakes of Agadir, Morocco, in 1960 (M_w=5.9, 1,5000 people were killed); El Asnam, Algeria, in 1980 (M_w=7.3, 3,000 people were killed); Cairo, Egypt, in 1992 (M_w=5.8, 541 people were killed); Zemmouri, Algeria, in 2003 (M_w=6.8, 2,278 people were killed); and Al Hoceima, Morocco, in 2004 (M_w=6.4, 600 people were killed) resulted in damages worth US $11.5 billion (Benouar 2005).

Rapid urbanization; development of critical structures and lifelines, such as dams and oil facilities; industrialization of cities; and the concentration of populations, living or settling in hazardous areas, are all matters of growing concern. Indeed, the recent social and economic development exposed to earthquake hazards implies future heavier loss of life and economic damage, unless reliable preventive actions are enforced following the rapid rise of interest about environment concerns and increased official and public awareness about earthquake hazard in Northern Africa.

The assessment of seismic hazard in North Africa is relatively new and started at the end of the last century. It consists of regional and local studies using mainly the probabilistic approach (probabilistic seismic hazard approach, PSHA; El-Sayed et al. 1994; Benouar 1996; Benouar et al. 1996; Hamdache et al. 1998; Hamdache and Retief 2001; Giardini et al. 1999; Pelaez et al. 2003, 2005, 2006, 2007; Hamouda 2011; Wyss et al. 2012). These studies severely underestimate the values of the expected peak ground acceleration (PGA), as in the cases of the Zemmouri, Algeria, earthquake in 2003 (observed=0.3–0.4 g, PSHA=0.08–0.16) and Al Hoceima, Morocco, earthquake in 2004 (observed=0.2–0.3 g, PSHA=0.08–0.16).

In order to carry out a realistic and reliable estimate of the seismic hazard in some North African countries (Egypt, Algeria, and Morocco), some authors (Aoudia et al. 2000; El Sayed et al. 2001; Vaccari et al. 2001; Harbi et al. 2007) used the neo-deterministic, multi-scenario procedure (NDSHA) that takes into account the physical process generating the earthquakes as well as wave propagation in a realistic medium, and it is particularly suitable when earthquake recordings are scarce.

In this paper, after an introduction to the seismotectonic context of North Africa, we (1) briefly describe the

M. Meghraoui
Institut de Physique du Globe, UMR 7516, 5 rue R. Descartes, Strasbourg, France

G. F. Panza
Institute of Geophysics, China Earthquake Administration, Beijing, China

NDSHA (Panza et al. 2001, 2012; Zuccolo et al. 2011) method adopted for the assessment of seismic hazard in North Africa (NAF) in view of the limited strong ground motion data; (2) describe the input information (earthquake catalogue, earthquake sources, and focal mechanisms), on the basis of which we delineate 39 zones in NAF; (3) provide two databases—(a) the fault-plane solutions of the NAF region (Fig. 1a, b) and (b) the available data concerning seismicity, active faulting, and structural models in each seismogenic zone; and (4) present the results obtained as maps of the distribution of maximum displacement ($D_{\max}$), maximum velocity ($V_{\max}$), and design ground acceleration (DGA). These thematic maps about earthquake hazard in NAF constitute important basic information necessary for the sustainable social and economic development of North Africa.

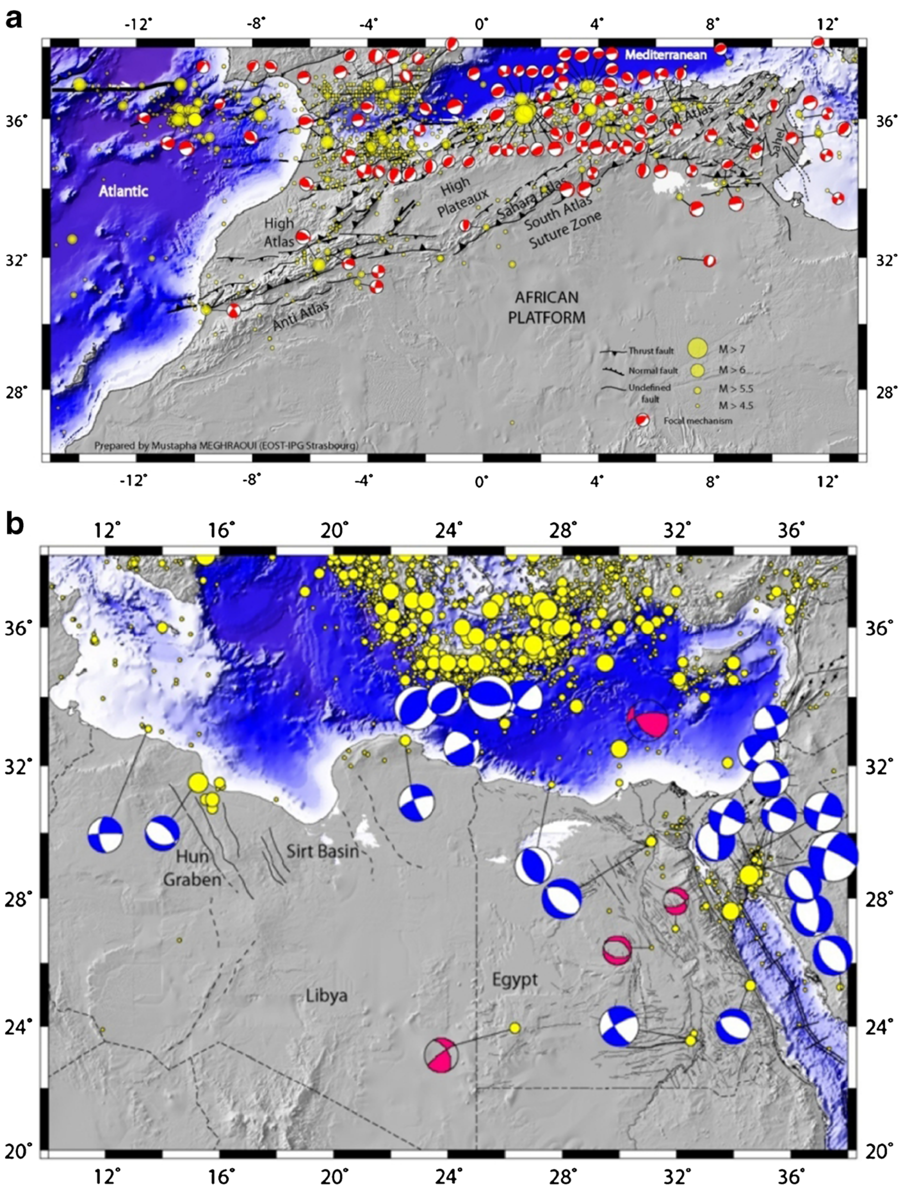

Fig. 1 Seismicity with $M>4.5$ of Northern Africa and adjacent areas. **a** Maghreb. **b** Egypt–Libya seismicity data (1900–2008) are from the NAF1.0 earthquake catalogue (Peresan et al. 2009). Focal mechanisms are from CMT-Harvard and mednet (Meghraoui and Pondrelli 2012) and Hussein (*pink*, in preparation)

2 Seismotectonics and crustal deformation in Northern Africa

Northern Africa is located in a complex tectonic system that results from the interaction between a seismically active plate boundary (Africa/Eurasia) and fault systems. The African plate has been divided into six different seismotectonic provinces, based mainly on the active tectonics, present-day continental deformation, and background seismicity (Meghraoui 2011a, b). Two of these provinces concern North Africa: the Northwest African fold-and-thrust belt and the Northeast African tectonic zones of Libya and Egypt.

2.1 The Northwest African Atlas Mountains and Maghrebides fold-and-thrust belts

This region includes Morocco, Algeria, and Tunisia (Fig. 1a). The deformation in the Maghreb region is evident in the currently active Atlas system and the Maghrebides (Dewey et al. 1989; Udias and Buforn 1991; Morel and Meghraoui 1996; Frizon de Lamotte et al. 2000; Gomez et al. 2000) and the 4- to 6-mm/year NW–SE plate convergence (Nocquet and Calais 2004; Fadil et al. 2006; Serpelloni et al. 2007; Koulali et al. 2011). The Atlas system is an intraplate inversion structure, whereas the Maghrebides are the southwestern prolongation of the Apennines–Maghrebides subduction zone whose southern arm in northwestern Africa is overprinted by the relative Africa–Eurasia convergence (Gueguen et al. 1998). Seismicity in this region results from the NNW/SSE-trending plate convergence of Africa toward Eurasia (Table 1; Benouar 1994; Harbi et al. 2010; Tahayt et al. 2008). The focal mechanisms of recent earthquakes display consistent WNW/ESE- and NW/SE-trending reverse and right-lateral strike slip, respectively, in the Gulf of Cadiz (Buforn et al. 1995). Furthermore, the seismotectonic characteristics show NE/SW-trending left-lateral strike slip in the Rif region related to the 26th May 1994 (M_w=6.0) and 28th February 2004 (M_w=6.4) Al Hoceima earthquakes (Calvert et al. 1997; Buforn et al. 1997; Bezzeghoud and Buforn 1999; Çakir et al. 2006; Akoglu et al. 2006); NE/SW-trending thrust faulting across the Tell Atlas as indicated by the 10th October 1980 El Asnam earthquake (M_s=7.3; Ouyed et al. 1981; Ruegg et al. 1982); the 29th October Tipasa earthquake (M_w=6.0; Meghraoui 1991); and the 21st May 2003 Zemmouri earthquake (M_w =6.8; Meghraoui et al. 2004). Shortening of the Moroccan Atlas has accommodated 17–45 % of the total African–Eurasian plate convergence since the Early Miocene, whereas the majority of the plate convergence is accommodated in the Rif–Betic–Alboran region (Gueguen et al. 1998; Gomez et al. 2000). The Maghreb region experienced many destructive or damaging earthquakes, some of them triggering tsunami, in historical and recent times as well (Turki 1990; Benouar 1994; Ayadi et al. 2003; El Mrabet 2005; Harbi et al. 2003a, 2007, 2010, 2011; Maouche et al. 2008; Suleiman et al. 2004; Tahayt et al. 2008; see Table 1).

2.2 The Northeast African tectonic zones of Libya and Egypt or the southeastern Mediterranean region

This region (Fig. 1b) is limited by the Gulf of Aqaba and Red Sea in the East. This eastern region of North Africa is also the corner contact between the African plate, the Arabian plate, and the Eurasian/Anatolian plate. These plates are involved in the geodynamic reconstructions of the southern part of eastern Mediterranean (Abou Elenean 2007). The plate tectonic models indicate that the African plate is moving northward relative to the Eurasian plate at a slip rate of ~6 mm/year (Salamon et al. 2003; Mahmoud et al. 2005; Reilinger et al. 2006), while the Arabian plate is moving north–northwest relative to Eurasia at a rate of about ~18 mm/year (Wdowinsky et al. 2004; Reilinger et al. 2006). These movements cause crustal spreading along the axis of the Red Sea and left-lateral slip along the Dead Sea transform zone. The differential motion between Africa and Arabia (~12 mm/year) is considered to be taken up predominantly by a left-lateral motion along the Dead Sea transform fault (McClusky et al. 2003; El Fiky 2000). The global model of plate tectonics suggest NNW convergence between the African and Eurasian plates in the north of Libya (DeMets et. al. 1990), but focal mechanisms for Libyan earthquakes suggest a rapid change in the orientation of maximum compressive stress (NNW to NE–SW) within the onshore section of the African plate. There also appears a significant change in the stress regime across Libya, with NNW/SSE-trending normal faulting more common in eastern Libya. The large number of strike-slip earthquakes in western Libya suggests that the existing normal faults are being reactivated in a stress regime related to the convergence of the African plate and the Eurasian plate (Suleiman and Doser 1995). Near Sicily, the

Table 1 Significant, moderate, and large earthquakes in North Africa (earthquakes mentioned in this table may be subject to revision)

Date	Site	Intensity or magnitude	Observations	References
600 BC	Thebes, Egypt	6.1		Maamoun et al. (1984)
28 BC	Thebes, Egypt	6.1		Maamoun et al. (1984)
262	E. Mediterranean, Libya	XII	Cyrene destroyed. After an extensive destruction by the earthquake, Cyrene was rebuilt by the general Probus, who renamed it after the reigning emperor (Claudius II Gothicus) in AD 268	Guidoboni et al. (1994); Vita-Finzi (2010)
320	Alexandria, Egypt	6.0		Maamoun et al. (1984)
365	Leptis Magna, Sabratha, Libya	XII	Cyrene destroyed	Polidori et al. (1999); Stiros (2001)
410 or 412	Utique, Tunisia	X	Utique destroyed, many aftershocks during a week	Sieberg (1932); Rothé (1970)
704	Murzk (Sabha), Libya	XII	Spurious, mislocated in Libya	Suleiman et al. (2004)
796 April	Gulf of Aqaba	6.0		Maamoun et al. (1984)
854 or 855	Kairouan, Tunisia	X	13 villages destoyed	Ambraseys (1962); Rothé (1970)
856 December	Tunis, Tunisia	X	45,000 victims	Ambraseys (1962); Rothé (1970)
956 January 01	Alexandria, Egypt	6.0		Maamoun et al. (1984)
1068 March 18	Gulf of Aqaba	IX		Zilberman et al. (1998)
1079 October	Morocco	IX		El Mrabet (2005)
1111 August 31	Lower Egypt	7.2		Ambraseys et al. (1994a)
1365 January 3	Algiers, Algeria	X	Sea wave of ~2 m	Harbi et al. (2007)
1624	Fez, Morocco	IX-X		El Mrabet (2005)
1716 February 03	Algiers-Douéra, Algeria	IX	20,000 victims	Harbi et al. (2007)
1719 July	Morocco	VIII		El Mrabet (2005)
1731	Agadir, Morocco	IX		El Mrabet (2005)
1754 October	Gulf of Suez	6.6		Ambraseys et al. (1994a)
1755 November 27	Meknes, Morocco		Destructive, thousands of victims	El Mrabet (2005)
1758 January	Constantine and Tunis	VIII	Most of the houses of Tunis destroyed, thousands of victims	"Journal Historique sur la matière du temps" of March 1758; Vogt (1993)
1790 October 09	Oran, Algeria	X	2,000 victims	Roussel (1973)
1811	Libyan–Egyptian boarder	VIII		Maamoun et al. (1984)
1819	Mascara, Algeria	IX		Roussel (1973)
1825 March 2	Blida, Algeria	X	7,000 victims	Roussel (1973)
1847 August 7	Cairo, Egypt	5.8	Hundreds of victims	Maamoun et al. (1984)
1856 August 22	Djidjelli, Algeria	6.6	Widely felt in the Mediterranean, tsunami on 21 and 22 August	Harbi et al. (2011)
1867 January 2	Mouzaia, Algeria	X–XI		Roussel (1973)
1869 November 9	Biskra, Algeria	VIII		Harbi et al. (2003a)
1885 December 3	M'sila, Algeria	IX		Harbi et al. (2003a)
1881 June 27	Gabès, Tunisia	VI	Many shocks at Gabès and in southern Tunisia	Sieberg (1932); Vogt (1993), the French consul of Gabès
1891 January 15	Gouraya, Algeria	6.0		Maouche et al. (2008)
1910 June 24	Aumale, Algeria	6.6		Benouar (1994)
1920 February 25	Thibar, Tunisia	VIII	Important event, widely felt at Tunis	Rothé (1970)

Table 1 (continued)

Date	Site	Intensity or magnitude	Observations	References
1926 June 226	North Libya	7.1		Ambraseys et al. (1994b)
1935 April 19	Al-Qadahia, Libya	6.9		Suleiman and Doser (1995)
1954 September 9	Orleansville, Algeria	6.7	1,409 victims	Benouar (1994)
1955 September 12	Alexandria, Egypt	6.0		Maamoun et al. (1984)
1960 February 29	Agadir, Morocco	5.6		El Mrabet (2005)
1969 March 31	Shedwan, Egypt	6.1		Maamoun et al. (1984)
1980 October 10	El-Asnam, Algeria	7.3	3,000 victims	Benouar (1994)
1994 August 18	Mascara, Algeria	5.9	171 victims	Benouar et al. (1994)
1992 October 12	Cairo, Egypt	5.8	541 victims	Abou El Enean et al. (2000)
2003 May 21	Zemmouri, Algeria	6.8	2,278 victims, tsunami on the Balearic coast	Ayadi et al. (2003)
2004 February 24	El-Hoceima, Morocco	6.4	600 victims	Tahayt et al. (2009)

direction of plate convergence is estimated to be approx. North–South (Serpelloni et al. 2007). An alternative view has been proposed by Corti et al. (2006) who suggested that Red Sea rift is transferred to western Egypt and Libya, entering into the active rifting of the Sicily channel. Significant earthquakes, some of them widely felt and causing widespread damage to local houses and public buildings, affected the southeastern Mediterranean region (Maamoun et al. 1984; Ambraseys et al. 1994a; Zilberman et al. 1998; see Table 1).

3 Methodology

By definition, seismic hazard describes a natural phenomenon associated with an earthquake, such as ground shaking, fault rupture, tsunami, liquefaction rockfall, landslide, etc. It is generally quantified by three parameters: (a) the level of severity expressed by intensity I, magnitude M, and peak ground acceleration and (b) spatial (occurrence site) and (c) temporal (occurrence frequency) characteristics.

A thorough discussion of the different approaches available for seismic hazard assessment is beyond the purposes of the present work. The PSHA method is commonly used for seismic hazard assessment and is widely described in the literature (Cornell 1968; Bommer and Abrahamson 2006 and references therein). It has been the subject of intensive debate in recent years. In PSHA, seismic hazard is defined as ground motion with an annual probability of exceedance, calculated from a mathematical model (not a physical one) and based on the statistical relationships of earthquake and ground motion. In PSHA, the hazard maps are only defined in terms of PGA, neglecting the relevance of other factors, like, for instance, ground shaking duration. The spectral properties of ground shaking, extremely important for the correct evaluation of the damaging potential of earthquakes, are either neglected by PSHA or are treated in an overly simplified way, usually reading the spectral acceleration on a response spectrum whose artificial shape is associated with classes of soil types. Well-documented criticisms have been expressed on the probabilistic method by many authors (e.g., Krinitzsky 1998; Castaños and Lomnitz 2002; Klügel 2007; Wang 2011; Kossobokov and Nekrasova 2012) who evidenced some relevant limits in the models and in the basic assumptions. Several issues related with the PSHA approach and possible alternatives are discussed in the *Topical Volume of Pure and Applied Geophysics* (Panza et al. 2011) and in Panza et al. (2012), where the NDSHA method is described in detail.

NDSHA allows overcoming the shortcomings of PSHA (e.g., Wyss et al. 2012), particularly where earthquake catalogue completeness is poor and strong earthquakes are expected (Zuccolo et al. 2011). In NDSHA, seismic hazard is defined as the maximum ground motion from a single earthquake or from a set of earthquakes, including maximum credible earthquake, calculated considering the available physical knowledge on earthquake sources and wave propagation processes by means of deterministic models. At the regional level, the ground shaking scenario is defined through the computation of synthetic seismograms generated from the set of potential sources distributed in the active seismogenic zones recognized in the studied area. To define the sources, the NDSHA procedure makes use of information about the space distribution of large-magnitude earthquakes ($M>5$), which can be defined from historical, instrumental, and geological observations. The seismograms are efficiently computed with the modal summation technique (Panza 1985; Florsch et al. 1991). Hypocentral depth is taken as a function of magnitude (10 km for $M<7$, 15 km for $M\geq7$). As specified by Panza et al. (2001), keeping the hypocentral depth fixed (for classes of magnitude) and shallow is important due to the large errors generally affecting the hypocentral depth for historical events reported in the earthquake catalogues. Layered anelastic models are considered for wave propagation, which are representative of the average properties of the crust and upper mantle along the considered source site paths. From the set of complete synthetic seismograms, various engineering parameters can be extracted and mapped on a grid that covers the investigated area. Typically, they are the maximum displacement (D_{max}), maximum velocity (V_{max}) and DGA. DGA is obtained by computing the response spectrum of each synthetic signal for periods of 1 s and longer (the periods considered in the generation of the synthetic seismograms, consistent with the detail of knowledge about earthquake sources and propagation media). The spectrum is extended at frequency higher than 1 Hz using the shape of the design response spectrum for the bedrock, which defines the normalized elastic acceleration response spectrum of the ground motion, for 5 % critical damping; for details, see Panza et al. 1996). DGA is comparable to the PGA since an infinitely rigid structure (i.e., a structure having a natural period of 0 s) moves exactly like the ground (i.e., the maximum acceleration of the structure is the same as that of the ground, which is the PGA). This is why PGA has been used over the years to provide a convenient anchor point for the design spectra specified by various regulatory agencies. Moreover, DGA is practically equivalent to effective peak acceleration, which is defined as the average of the maximum ordinates of the elastic acceleration response spectra within the period range from 0.1 to 0.5 s, divided by a standard factor of 2.5, for 5 % damping (Panza et al. 2003, 2013). At each node of the grid, not only the peak values are available, generated by the nearby earthquake sources, but also the full time series from which the peak values are extracted. Those time series can be taken as the seismic input by civil engineers in the design of seismo-resistant structures. Therefore, one of the advantages of NDSHA is the possibility of obtaining a set of earthquake scenarios and simulating the associated synthetic signals without having to wait for a strong event to occur.

NDSHA has been successfully tested worldwide (Panza et al. 1996, 1999, 2002; Alvarez et al. 1999; Aoudia et al. 2000; Bus et al. 2000; Markusic et al. 2000; Zivcic et al. 2000; El-Sayed et al. 2001; Vaccari et al. 2001; Parvez et al. 2003; Zuccolo et al. 2011) and has proved its efficiency, particularly for recent earthquakes (e.g., the Zemmouri-Boumerdes, Algeria, 2003 and Gujarat, India, 2011 events), where the PSHA method has failed to predict the level of ground motion observed. Its application to the NAF region is shown in Section 5.

4 Data

To model ground motion using the modal summation technique and compute realistic synthetic seismograms (Panza et al. 2001), the information required consists of (a) the level of seismicity and the distribution of maximum observed magnitude inferred from the earthquake catalogue, which is the most essential and important input parameter; (b) the available knowledge of the physical process of earthquake generation (seismogenic source zones); and (c) structural models to be used in the wave propagation in anelastic media. The input data used for the NAF region are briefly described below.

4.1 The earthquake catalogue

An updated unified and homogeneous catalogue has been jointly compiled and prepared specifically for the seismic hazard assessment in North Africa: “the NAF1.0 earthquake catalogue” (Peresan et al. 2009).

The unified catalogue has been compiled following two main phases: (a) national catalogue revision and internal homogenization and (b) assessment, comparison, and merging of the different national catalogues into a unified data set. A detailed description of the input data and of the merging procedure is provided in Peresan and Ogwari (2010).

A number of available sources were considered, including (1) catalogues and bulletins of national and international centers (CNRST, Morocco; CRAAG, Algeria; INM, Tunisia; LCCRS, Libya; NRIAG, Egypt; IGN, Spain; INGV, Italy; NEIC, ISC, EMSC); (2) recent local and regional earthquake catalogues assembled by authors (Cherkaoui 1991; Benouar 1994; El Alami et al. 2004; Pelaez et al. 2007; Hussein et al. 2008; Harbi et al. 2010); and (3) specific works on historical seismicity (Turki 1990; Ambraseys et al. 1994a, b; Suleiman and Doser 1995; Harbi et al. 2003a, 2007, 2011; Suleiman et al. 2004; El Mrabet 2005; Maouche et al. 2008). The input data for the compilation of NAF1.0 consist essentially of the Egypt, Libya, Tunisia, Algeria, and Morocco national catalogues, which are described in some detail in Peresan and Ogwari (2010). In most cases, the national catalogues contain M_s, M_b, and M_l magnitudes that, for historical events, were derived from intensities. In the Algeria catalogue, magnitude homogenization was performed in terms of M_s by Benouar (1994) and Harbi et al. (2010). The moment magnitude, which is currently considered an appropriate quantification of earthquake size, is reported in some national catalogues only for the largest recent events. Some national catalogues, such as the Egyptian catalogue (Hussein et al. 2008) and the Moroccan catalogue (Pelaez et al. 2007), provide moment magnitude for all earthquakes. The homogenization of available magnitude estimates in terms of M_w was performed using specifically defined empirical relations. When different magnitude estimates are present for the same event, to be conservative, we choose the maximum magnitude. Only earthquakes with magnitude $M \geq 3.0$ are included in the catalogue. To allow for an appropriate merging of national data sets, a preliminary analysis is performed for each individual catalogue by evaluating earthquake distribution versus magnitude and time as well as by analyzing the frequency–magnitude distribution for different time spans. Spatial coverage is evaluated as well, according to Kossobokov et al. (1999) and using the NEIC and ISC global catalogues as reference data sets, so as to assess the spatial completeness level of each national catalogue. This analysis permits outlining the territory where the different data set should be used. Finally, the national catalogues are merged together and possible duplicated records, particularly at the boundaries between different countries, are carefully identified and eliminated. The resulting unified catalogue, which is complete for magnitudes $M \geq 5.0$ at least since 1900, is updated using the ISC (2012) global catalogue since 1994.

The NAF1.0 earthquake catalogue includes for the first time the whole data compiled separately so far in the NAF region. Ongoing research is devoted to the further improvement of the completeness and magnitude homogeneity for this unified data set, accounting for recent studies about historical seismicity and new incoming data. The present-day completeness threshold of the NAF1.0 earthquake catalogue severely questions the validity of the existing and future PSHA results in NAF countries.

4.2 Earthquake sources: seismogenic zones and focal mechanisms

Thirty-nine seismogenic zones were delineated in North Africa (Fig. 2a) from causal relationships established between geological structures and earthquakes. We first defined the seismogenic zones for each NAF country and then properly merged the zones at the boundaries for the definition of the new unified seismotectonic zoning. This delineation of the seismogenic zones of the NAF region is presented here for the first time for Tunisia and Libya. In Algeria, Egypt, and Morocco, assessment of earthquake hazard using NDSHA has already been performed by Aoudia et al. (2000), El-Sayed et al. (2001), and Vaccari et al. (2001), respectively.

Starting from the first definition of seismotectonic source zones in Algeria by Aoudia et al. (2000) and our current state of knowledge and understanding of the seismicity and tectonics of the area, we properly modified the geometry of the zones, taking into account the new elements provided by the study of (a) historical earthquakes of eastern Algeria and the Algiers region (Harbi et al. 2003a, b, 2007; Maouche et al. 2008; Harbi et al. 2011) and (b) recent earthquakes: Ain Temouchent 1999, M_w=5.7 (Belabbès et

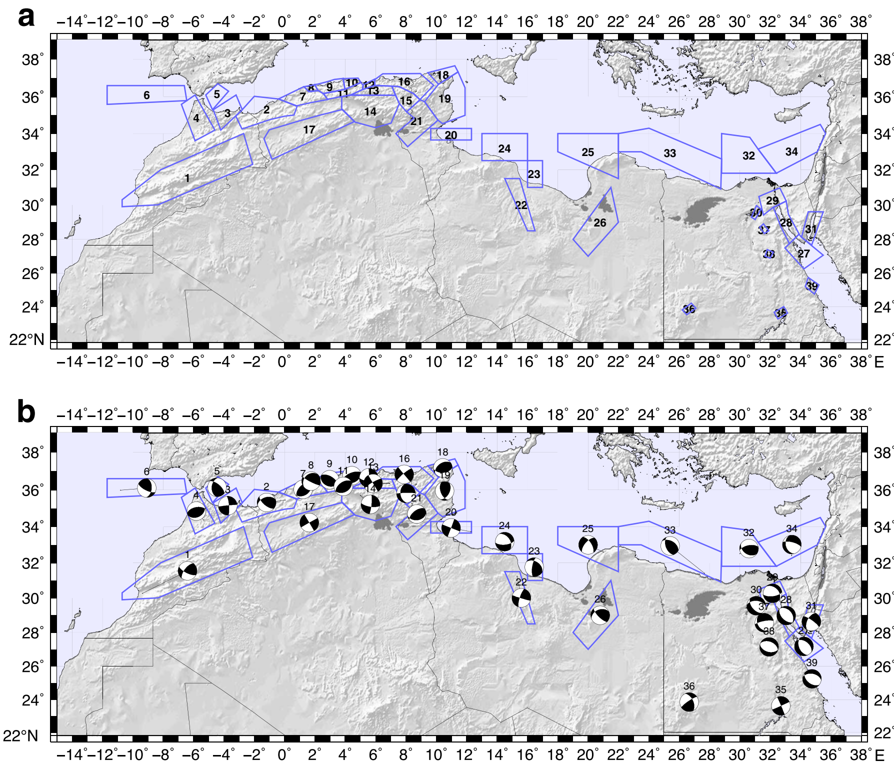

Fig. 2 **a** North African seismogenic zones (the order of zone numbering is arbitrary from the west to the east). **b** Average focal mechanisms assigned to each

al. 2009a); Beni Ourtilane 2001, M_w=5.7 (Bouhadad et al. 2003); Zemmouri 2003, M_w=6.8 (Ayadi et al. 2003; Meghraoui et al. 2004; Alasset et al. 2006; Laouami et al. 2006; Ayadi et al. 2008; Belabbès et al. 2009b); and Laalam 2006, M_w=5.2 (Beldjoudi et al. 2009).

A similar revision, based on several geological and geophysical studies, has been carried out for Egypt (Cochron et al. 2005; Korrat et al. 2005) and Morocco (Ait Brahim et al. 2002; Michard et al. 2002; Gracia et al. 2003; Baptista et al. 2003; Ait Brahim et al. 2004; Biggs et al. 2006; Tahayt et al. 2008). However, the seismogenic zones for Morocco and Egypt were completely revised and a new version is given here. Most of the seismogenic NAF zones are described in details in the Electronic supplementary material (ESM) Online Resource. The seismogenic zones are very dense along the collision plate boundary, i.e., along the Atlas range (Morocco, Algeria, and Tunisia) and Eastern Egypt

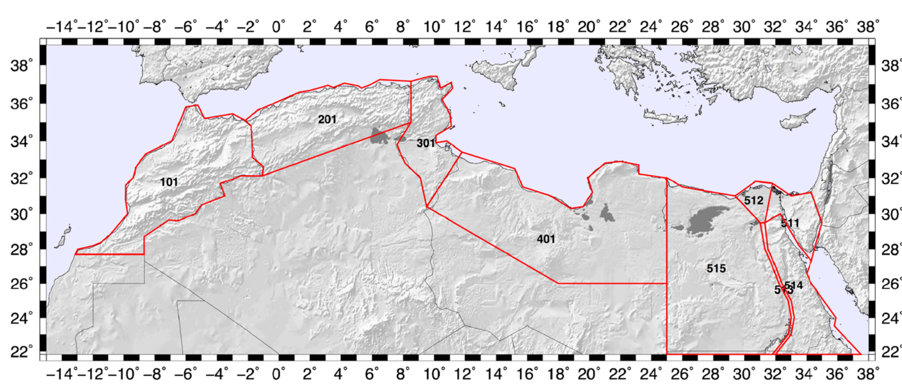

Fig. 3 Regional polygons characterized by an ASM representing the lithospheric properties at a regional scale

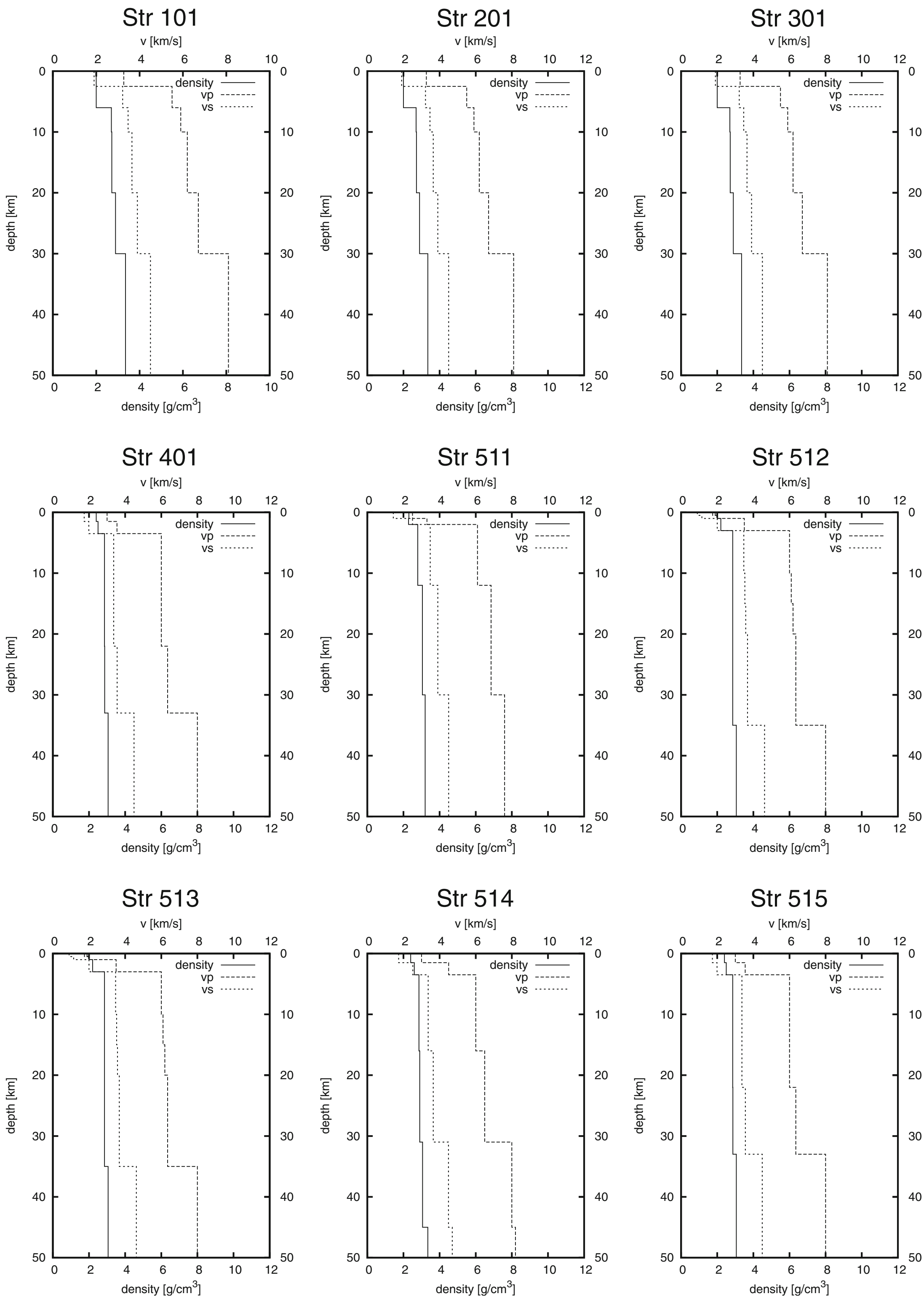

Fig. 4 Average structural models defined in each zone

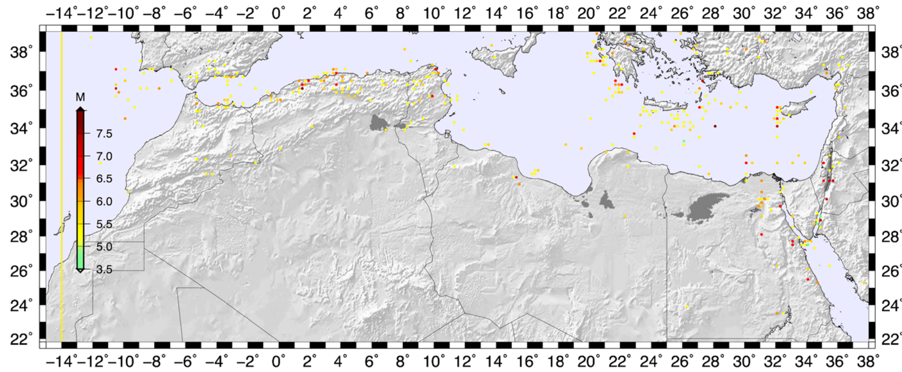

Fig. 5 Discretization of the epicentral punctual distribution into cells. In each cell, only the maximum event magnitude is retained and represented in a graphical magnitude range classification

along the Red Sea, whereas some gaps may be observed in the Saharan Atlas, Libya, and in southern Egypt (Fig. 2a).

We adopted published fault plane solutions derived from the literature (e.g., Girardin et al. 1977; Hatzfeld 1978; Buforn et al. 1988; Medina and Cherkaoui 1991; Bezzeghoud and Buforn 1999; Buforn et al. 2004; Abou Elenean and Hussein 2007; Abou Elenean et al. 2000; Hussein et al. 2006; Abou Elenean 2007) and CMT solutions to define source mechanisms. A representative fault mechanism, which is generally associated with the largest event, is defined for each seismogenic zone. When no reported mechanism is available, we assigned the zone a typical fault mechanism, compatible with the tectonic regime and the geology of the area. In the computation of the synthetic seismograms, all the sources belonging to a seismogenic zone will have the properties of the representative focal mechanism assigned to the zone (Fig. 2b). The NAF region is dominated by reverse and strike-slip faults in the Maghreb, in agreement with the NS shortening along the Africa–Eurasia boundary, while normal faults are present in Egypt in relation to Red Sea opening.

4.3 Structural models

Regional polygons define structural models that separate areas characterized by different lithospheric properties. For Morocco, Algeria, and Egypt, the initial boundaries of the polygons are adopted from Vaccari et al. (2001), Aoudia et al. (2000), and El-Sayed et al. (2001), respectively, and have been further modified on the basis of the results given in more recent studies as reported above and in the ESM Online Resource. The structural models of the media beneath the site of interest are represented by a number of flat layers with different thicknesses, densities, P- and S-wave phase velocities, and attenuation (corresponding Q values). In order to propose a suitable structural model for all North Africa, all available geophysical and geological information is considered here (Marillier 1981; El-Gamili 1982; Cherkaoui 1991; Marzouk 1995; Barazangi et al. 1996; Nyblade et al. 1996; Du et al. 1998; Calvert et al. 2000a, b; El Mozoughi and Ben

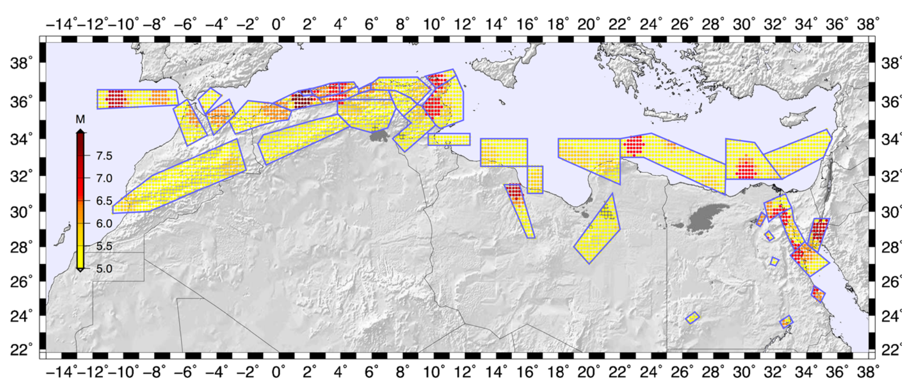

Fig. 6 Seismogenic sources corresponding to the intersection between windows smoothed seismicity and the predefined 36 seismogenic zones. Only the considered events inside the seismogenic sources are used in the computations

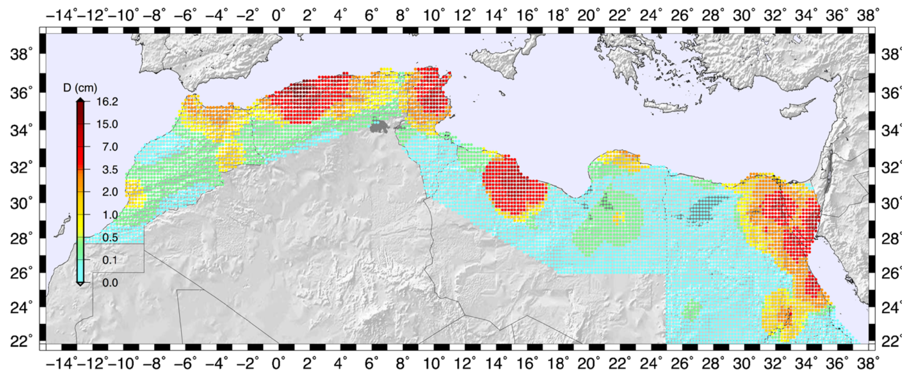

Fig. 7 Maximum computed displacement distribution map

Suleman 2000; Lee et al. 2001; Xie and Mitchell 1990). Since the computation is aimed at a first-order seismic zoning, the structural models do not explicitly account for local site effects, but are representative of regional average properties (bedrock) within each polygon (Fig. 3). In the present study, the NAF region is subdivided into nine average structural models (ASM; Fig. 4).

5 Computation and results

The NDSHA approach is applied here at the NAF scale by computing seismograms at the nodes of a grid with the desired spacing. Earthquake epicenters reported in the catalogue are grouped into 0.2×0.2° cells, assigning to each cell the maximum magnitude recorded within it. A smoothing procedure is then applied to account for errors in the location of the source and for its extension in space (Panza et al. 2001). Only cells located within the seismogenic zones are retained for the definition of the seismic sources that are used to generate the synthetic seismograms. Data are graphically represented and symbols are associated with magnitude ranges (Fig. 5). In most of cases, the smoothing obtained by considering just the discretized cells is not sufficient. A centered smoothing window is then considered so that earthquake magnitudes are analyzed not only in the central cell but also in the neighboring ones. The distribution of the maximum magnitude given by the intersection between the smoothed seismicity and the geometry of the seismogenic zones appears quite reasonable (Fig. 6). Each colored dot in Fig. 6 represents a source, for which the synthetic seismograms will be computed using the modal summation technique (Panza 1985; Florsch et al. 1991) for sites located within a distance of 150 km. Sites are defined on a grid with step 0.2×0.2° that covers the NAF region. Looking at the structural regional polygons of Fig. 3 in the computation of the synthetic seismograms, lateral heterogeneities are taken into account in a rough way: if the source site path crosses one or more boundaries between adjacent structural models, the signal is computed assuming the model of the site as representative of the whole path.

At this stage, we do not have a complete database of the resonance period of buildings in all the NAF areas. The synthetic signals are computed for an upper

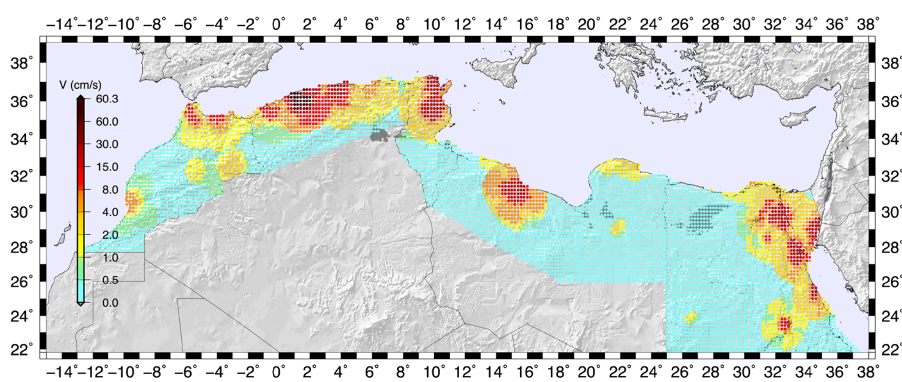

Fig. 8 Maximum computed velocity distribution map

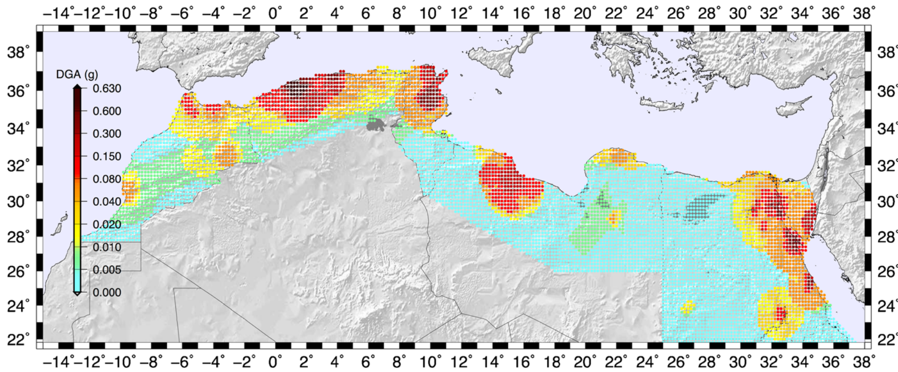

Fig. 9 Maximum computed DGA distribution map

frequency content of 1 Hz, which is consistent with the level of detail of the regional structural models, and the point sources are scaled for their dimensions using the spectral scaling laws proposed by Gusev (1983), as reported in Aki (1987), and are scaled according to the smoothed magnitude distribution. The seismograms are computed for a hypocentral depth, which is a function of magnitude (10 km for $M<7$, 15 km for $M\geq 7$), but it is also possible to assign to each source an average depth determined from the analysis of the available catalogues.

The maps of seismic hazard obtained for the whole NAF area are shown in Figs. 7, 8, and 9 for D_{max}, V_{max}, and DGA, respectively. The Fourier spectra of displacements and velocities show that an upper frequency limit of 1 Hz is sufficient to take into account the dominant part of seismic waves (Panza et al. 1999). Values between 8 and 60 cm s^{-1} are obtained all along northern Algeria and Tunisia including the eastern Tell and Atlas Mountains, in Tripoli, and Gulf of Aqaba regions. In the same areas, displacement peak values range from 2.0 to 16.2 cm.

The maximum values obtained for DGA range between 0.15 and 0.63 g and are located mainly in northern Algeria, Eastern Tunisia, around Tripoli in Libya, around the Gulf of Aqaba, and the entrance of the Gulf of Suez in Egypt (Fig. 9). The highest values are assigned to Chlef city and the surroundings reaching 0.63 g that is related to the 1980 El Asnam earthquake (M_s=7.3). In Morocco, maximum values range between 0.154 and 0.3 g. They were obtained for Agadir and the Alhoceima regions, where the recent largest events of 28th February 1960 and 24th February 2004 occurred, respectively. The same range of values is computed for Cairo and surrounding areas in Egypt and throughout eastern Tell and Tunisian Atlas. Values ranging between 0.08 and 0.150 g are obtained in Tangiers region (NW of Morocco) and in Fes city at Rif Mountain and the Middle Atlas margin. They are also obtained in Libyan shores in Benghazi and Tripoli cities and in Alexandria city in the Egyptian territory.

The predominant factor in terms of seismic hazard seems to be in general linked to the occurrence of moderate-sized earthquakes at short distances (i.e., the Agadir 1960 earthquake, M_w=5.9; the Alhoceima 1994 and 2004 earthquakes, M_w=5.7 and 6.4, respectively; the Al-Asnam 1980 and Zemmouri 2003 earthquakes, M_w=7.3 and 6.8, respectively; the Cairo earthquake in 1992, M_w=5.8) rather than to strong earthquakes that are known to occur at larger distances along the Atlantic Azores islands in the western NAF area or in the western part along northern Red Sea and the Gulf of Suez (e.g., the Shedwan earthquake in 1969, M_w=6.9; the Gulf of Aqaba earthquake in 1995, M_w=7.3) as well as offshore Egypt in the Mediterranean Sea (i.e., the Alexandria earthquake in 1955, M_s=6.8; the Cyprus earthquake in 1996, M_w=6.8; the Ras El-Hekma earthquake in 1998, M_w=5.4; Abou Elenean 2007).

6 Conclusion

The NDSHA maps in terms of D_{max}, V_{max}, and DGA have been prepared for the NAF region. The analysis and resulting maps obtained in this study represent the outcome of a mutual effort between the North African Group for Earthquake and Tsunami Studies (NAGET[1]) members and collaborators who took up the big challenge of the homogenization and unification of different data sources with the aim of assessing seismic hazard in

[1] http://naget.ictp.it/.

North Africa using the first-order neo-deterministic method. This technique has already been used to produce NDSHA maps for many areas of the world, among which are Morocco (Vaccari et al. 2001), Algeria (Aoudia et al. 2000), and Egypt (El-Sayed et al. 2001). The deterministic modeling of hazard for the Algeria territory, for example, yielded results validated by recent observations made in connection with events that occurred after 2000. This is why it seemed to us essential to apply that method to Tunisia and Libya too and to take this opportunity to update the seismic hazard maps obtained previously in Morocco, Algeria, and Egypt to assess the seismic hazard not only at the scale of a country but at the scale of a region: North Africa, which is one of the most earthquake-prone areas of the Mediterranean. The results obtained reflect our actual state of knowledge (see ESM Online Resource). However, we draw the user's attention that in the NAF region, some faults are poorly known (blind or offshore faults in most of cases) and many seismogenic faults remain unrecognized. The insufficiency of geological, geophysical, and geodetic data as well as the characteristics of some active faulting in North Africa led us to estimate the seismic hazard based only on information from earthquakes. One should emphasize on the relevance and need to integrate information about the observed seismicity (i.e., from available earthquake catalogues) with additional geological/geophysical evidences of the seismogenic potential of an area. The NDSHA approach permits doing it in a very natural and straightforward way, as shown by Aoudia et al. (2000) and Panza et al. (2012, 2013). The relevance of such additional information, for reliable seismic hazard assessment, is clearly demonstrated by Zuccolo et al. (2011). Therefore, we should increase our knowledge of both the distribution and rate of slip across active faults in North Africa. This is one objective of utmost importance in NAGET activity. However, at this stage of knowledge, we believe that the data we present in this paper may contribute to a better understanding of the seismic hazard in North Africa. In addition to the seismic hazard assessment results, this paper presents the state of the art on seismicity, tectonics, and seismic hazard in NAF covering five countries and could be very helpful for future research works.

Acknowledgments This work, dedicated to the memory of the first coordinator of the North African Seismological Group (NASG), the late Attia El-Sayed, started in 2005 at LBE-USTHB (Algiers), carried on at the Geology Department of Abdelmalek Essaadi University (Tangiers) in 2007 and recently at ENIT (Tunis) in 2012. It is a fruit of a collaborative effort of the first core of NASG members when the network was restricted to 15 scientists and five countries only (Sudan has joined in 2010 and the number of NAGET (formerly NASG; see http://naget.ictp.it/) members increased to 136). This research benefited from the ICTP-OEA (Trieste) Programme in the framework of the North African Group for Earthquake and Tsunami studies (NAGET) activities. The seismotectonic investigations were supported by the IGCP 601 project "Seismotectonics and Seismic Hazards of Africa." The authors are indebted to the ICTP-SAND Group for making available algorithms, software and computational resources that made this work possible. We are particularly grateful to Carlo Doglioni for his advices and comments about the structural geology and geodynamics modeling of the study area.

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