

A Probabilistic Seismic Hazard Model for North Africa

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Abstract African seismicity is predominantly localized along the East African Rift System (EARS), which is the major active tectonic feature of the Sub-Saharan Africa. Besides the EARS, however, non-negligible seismicity also occurs along a wide belt bounding the Mediterranean coastline. This tectonically active region extends discontinuously from Morocco to Egypt and its activity is controlled by the complex interaction between the Nubian and Eurasian plates, structurally varying from fold-and-thrust in the west, to a mixture of strike-slip and extensive motion to the east. A record of large earthquake events is documented for the whole region, some of them causing a non-negligible level of damage, mostly because of the high vulnerability of local buildings and structures, condition which is still largely persistent in many areas. Currently, a number of seismic hazard models exist at local and national scales for North Africa, developed within independent projects and created using inhomogeneous or incomplete data sources and different processing techniques. Unfortunately, such diversity makes their direct comparison problematic, obscuring the differences in seismic hazard across neighbouring areas and preventing the development of comprehensive long-term risk mitigation strategies. In fact, the last effort to produce a homogenized model for the whole Africa continent dates back to the GSHAP project, which is almost twenty years old. The creation of a unique seismic hazard model for North Africa, uniform across countries, is therefore a main concern.

Since its inception, the Global Earthquake Foundation (GEM) is committed with the creation of a worldwide mosaic of high-quality, reproducible and openly accessible seismic hazard models, uniformly represented using the format adopted by the OpenQuake engine, a state-of-the-art, free and open-source software for seismic hazard and risk assessment. We summarize in the following the progress done in the creation of a new comprehensive PSHA model for North Africa using GEM tools.

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1 Introduction

Unlike the most internal parts of the continent, characterized by the presence of large and stable cratons of Precambrian origin, the Northern margin of Africa is known to be tectonically active. The complex interaction between the European and African plates, varying from transpressional in the west to transtension and transform in the east, is responsible for large crustal deformations, often associated with the development of a moderate although noticeable on- and off-shore seismicity. Several earthquakes causing non-negligible level of damage and a number of fatalities are reported on a wide seismic belt of more than 5000km, extending almost continuously from Morocco to Egypt. As a matter of fact, after the East African Rift System (EARS), North Africa is recognized as the second most hazardous province of the continent.

In recent times, the rapid development of North Africa countries, together with the progressive concentration of population in unfavourable areas, has further increased the potential impact of large future earthquakes on the society. [current status of building codes]

Several hazard studies have been carried in the past, either using probabilistic or deterministic approaches (REF: some examples). Nonetheless, most of these studies were conducted for specific target areas or at national scale, while very few attempts are documented for the evaluation of the seismic hazard at regional or either at continental level. The first important effort in this direction dates back to the 1999 with the GSHAP project (ref.). OTHER EXAMPLES

With the goal of establishing common earthquake risk mitigation strategies, then, a state-of-art assessment of the seismic hazard of this region – homogenous across countries – is therefore fundamental.

In this paper, we describe a new probabilistic seismic hazard model developed for North Africa by the GEM secretariat. Such model is based on the most up-to-date information available from global datasets and literature

The model is free and openly-accessible to the community, ...

2 Seismotectonic Settings of North Africa

2.1 North-West Africa (Ibero-Maghreb domain)

Geodynamics of North-West Africa is primarily controlled by the interaction between the Nubian and Eurasian plates (e.g. Patriat et al, 1982). From west to east, relative motion along such plate boundary is highly variable (Cherkaoui & El Hassani, 2012), ranging from the divergence of the Central Atlantic ridge system, pure strike-slip with dextral displacement of the Azores (e.g. Gloria fault), to a more complex compressional regime along the continental margin between Iberia and Morocco (Gibraltar region), with oblique convergence with respect to plate boundary (Pelaez et al., 2007). This last tectonic setting is responsible for great part of the continental seismicity of North Africa, with development of large thrust systems and orogenic belts (Atlas and Betic/Rif chains). Convergence rate in this region is rather variable, with values ranging from 3 to 6mm/yr (e.g. Argus et al, 1989; De Mets et al, 1990).

2.1.1 Morocco

Seismicity of Morocco is moderate, although destructive earthquakes are reported from historical and instrumental catalogues, such as the Agadir (Mw 5.9) and Al Hoceima (Mw 6.3) events, which caused respectively about 12000 and 629 fatalities each (Cherkaoui & El Hassani, 2012).

On-shore seismicity can be grouped in at least two main seismic provinces of the Atlas and the Rif structural domains. The Atlas chain extends from Agadir as High Atlas to northeast and is ideally in continuation with the Saharan Atlas orogenic belt. Two adjacent but formally separated sub-provinces of the Middle Atlas and the Anti-Atlas can also be identified by a moderate seismicity and by a complex system of reverse and potentially active faults. The Rif structural domain is an orogenic system (the Maghrebides) that extends to Iberian Peninsula through the Strait of Gibraltar as the Betic Cordilleras, encompassing the extension-related Alboran Sea and the Algerian basin (Pelaez et al., 2007). The Rif extends to the east into the seismic province of the Algerian Tell Atlas.

Off-shore seismicity is predominantly located in the Atlantic along the Azores-Gibraltar shear belt and within the Mediterranean basin in the Alboran Sea. The two domains are characterised by different geodynamic evolution of the underlying lithosphere, as evidenced by the distribution of earthquake source mechanisms. While the former domain shows mostly large and well-localised strike-slip events, the latter exhibits a more diffuse seismicity (Jimenez-Munt et al. 2001) with extensive (normal) and generally smaller magnitude earthquakes (Cherkaoui & El Hassani, 2012).

Hypocentral depths are in most cases quite shallow (<30km), although several events have been generated at intermediate (>30km) to large depth (>60km), particularly on the reverse faults of the High Atlas and the Rif/Western-Alboran province (Pelaez et al., 2007; Medina et al., 2011).

2.1.2 Algeria

Algeria shows a considerable seismicity, particularly in the northern part of the country, mostly related to the orogenic compressional domains of the Tell Atlas and (to a minor extent) the Sahara Atlas (Benouar and Laradi, 1996). The Tell is the ideal continuation of the Moroccan Rif, and it has been originated within a similar tectonic regime. Local systems of folds and thrusts with roughly NE-SW alignment (Bouhadad and Laouami, 2002; Hamdache 2010) are responsible for the development of several important clusters of seismicity (Meghraoui, 1988; Hamdache et al, 2012). On the contrary, seismicity of the Saharan Atlas is lower and less localized, with few moderate earthquakes. The two chains are separated by relatively aseismic region of elevated topography (the High Plateaux) assumed tectonically stable, as no significant Meso-Cenozoic deformation is evident (Pelaez et al., 2003). Moving to the east along the coastline, at the border with Tunisia, seismicity sensibly decreases.

The largest and most destructive earthquake recorded in recent time was the 1980 El Asnam event (Mw 7.1, Ms 7.3; Ouyed et al., 1983), although many damaging events with magnitude larger than 5.5 have been reported along the Tell Atlas (Benouar, 1994; CRAAG, 1994). Several epicentres have been localized in the vicinity of Quaternary basins (e.g. Meghraoui 1986; Hamdache 2010), whose geometric configuration and un-compacted neogene sediments increase the possibility for site-specific amplification effects on the ground motion. Moreover, the earthquake risk is here exacerbated by the concomitance of high population density, building typology and the high seismicity along the coastal region (Benouar, 1993)

2.1.3 Tunisia

Tunisia is located at the eastern edge of the Atlas chain, where the two main tectonic provinces of the Tell and Saharan Atlas gradually approach each other before intersecting the Zaghouan fault system, which is the most significant tectonic feature of the region (Ambraseys 1962) crossing the country roughly NE-SW. Seismicity is mostly localized in the central and north part of the country (Ksentini & Romdhane, 2014), on a number of structures accommodating a sequence of compressive (folds and thrusts) and extensive (normal back-arc) regimes, often through the development of left-later strike-slip mechanisms (Ben Ayed, 1993; Bouaziz et al., 2002). Later quaternary seismic activity in Tunisia is overall moderate, but locally intense (Mejri et al., 2010). Although instrumental seismicity does not exceed magnitude 6 (Ksentini &

Romdhane, 2014), a few large damaging earthquakes have been reported in historical times, such as the 408 AD in Utique and the 856 AD in Tunis (Vogt, 1993).

2.2 North-East Africa

In contrast to North-Western Africa, the geodynamic of the North-Eastern is controlled by the relative movements of three plates: Nubian, Eurasian and Arabic. While Nubian and Eurasian have relative convergent motion, Africa moves progressively away from the Arabic peninsula, due to incipient spreading of the Red Sea oceanic ridge. The relative (left-lateral) motion of the two margins is then accommodated by the presence of a transform region, the Dead Sea fault system, where the largest earthquakes have been historically recorded.

2.2.1 Egypt

Seismicity of Egypt is low to moderate if compared to North-Western Africa and, in particular, to the high-seismicity of the neighbouring Hellenic and Cyprus subduction arcs and the Dead Sea transform region. Nonetheless, local moderate earthquakes pose a major threat to the population (Sawires et al., 2015), as evidence by the 1992 Cairo event (mb 5.8, Ms 5.9), which caused 561 fatalities, and by the historical 1847 event (Ms 5.8; Ambraseys et al. 1994). Furthermore, highly populated areas are often located on top of the fertile Nile alluvium (e.g. Said, 1981), whose low seismic velocities have large potential for site-amplification effects (e.g. Adly et al., 2017), greatly increasing the local earthquake risk (Badawy et al., 2016).

In relation to the trans-tensional stress regime originated by the spreading Red Sea margin, the large majority of earthquakes are characterised by normal fault style with variable strike-slip component, increasing toward the edge of the Sinai sub-plate. Only a minority of events have reverse focal mechanisms, mostly inland (Badawy, 2005).

2.2.2 Libya

The instrumental earthquake record of Libya is largely incomplete, due to the lack of appropriate seismological networks in the country till recent times (Hassen, 1983), with the establishment of the Libyan National Seismological Network (LNSNS). Regional seismicity is presently considered moderate to low. Nonetheless, large historical earthquakes are reported in literature (Campbell, 1968), such as the 1183 event, responsible for the destruction of Tripoli and that caused more than 20000 fatalities (Kebeasy, 1980) and the more recent Ml 7.1 earthquake (1935), in the area of NW-SE trending Hun Graben (Suleiman et al., 2004).

With the exception of few known and potentially seismogenic geological structures in the North-West (e.g. the Hun Graben), the overall inland seismicity appears rather diffuse, as typical of stable continental tectonic conditions (Al-Heety & Eshwejdi, 2006). On the contrary, the offshore has a non-negligible activity, tectonically controlled by the presence of the nearby Calabrian and Hellenic subduction zones (Lagesse et al., 2017).

3 Methodology

In this study, the seismic hazard of the North Africa is evaluated probabilistically (e.g. Cornell, 1968, McGuire 2004) following the methodological formalism of Field et al. (2003) as implemented in the *OpenQuake*-engine (Pagani et al., 2014), an open source seismic hazard and risk calculation software developed, maintained and distributed by the Global Earthquake Model (GEM) Foundation.

The proposed seismic source model consists in a combination of distributed seismicity and finite faults, the former calibrated on occurrence analysis of publicly

available earthquake information, while the latter derived from a thorough evaluation of information from both geological literature and direct analysis of GPS velocity fields.

In the following we describe in detail the different components of the North African hazard model, including the creation of a homogenised earthquake catalogue for the region, the active fault database and the seismicity analysis (occurrence model, source mechanism distribution, spatial pattern of hypocentres). Separate chapters are then dedicated to the regional selection of most suitable ground motion prediction models and to the treatment of the epistemic uncertainties using a logic-tree approach.

4 Homogenised Earthquake Catalogue

The use of a sufficiently complete (in space and time) earthquake catalogue with homogeneous magnitude representation is an unavoidable requirement for the proper definition of the past (and forecasting of future) earthquake occurrences in probabilistic seismic hazard assessment. Although several attempt to create an earthquake catalogues exist for the region (e.g. Pelaez et al., 2007; Medina 2010; OTHER REFS), most of these have been compiled for relatively small areas, generally within national projects, or lacking a proper magnitude homogenisation (REF). For the purpose of having a unique catalogue valid for the whole North Africa, we have created a new M_w -homogenised earthquake catalogue by assembling globally and locally available sources. The GEM implementation of the North Africa Earthquake Catalogue (hereinafter GEM-NAEC), presently consists of 5170 events with $4 \leq M_w \leq 8.5$, covering a period from 1016 to 2013.

4.1 Source Information

Information from several sources has been combined for the creation of the GEM-NAEC, which includes:

- ISC-GEM catalogue (REF); we assume this to be the most reliable and complete compilation, but is limited in the its time span (> 1900) and minimum magnitude ($> M_w 5.5$);
- ISC-REV, the manually reviewed bulletin from the International Seismological Centre (ISC 2013);
- GCMT/Harvard Bulletin (REF);
- IGN catalogue (REF);
- EMEC catalogue (REF);
- GEM Global Historical Earthquake Catalogue (GEM-GHEC).

Table 1 Main characteristics of the catalogue sources used in this study. The values are referred to the buffer region selected for North Africa (see **Figure 1**)

Catalogue	Covered Period	Magnitude Range	No. Events
ISC-GEM	1927 – 2012	5.5 – 7.8	65
ISC-REV	1910 – 2013	0.7 – 8.1	11428
GCMT	1977 – 2013	4.7 – 7.2	97
IGN	1393 – 2017	-2.0 – 7.3	81396
EMEC	1016 – 2006	4.0 – 8.7	3699
GEM-GHEC	1033 – 1891	6.0 – 8.5	25

4.2 Hypocentral Location Selection

An important mandate of the International Seismological Centre (ISC, Ref.) is to collect earthquake information from several seismological organisations worldwide. In most cases, however, different magnitude and location (including origin time) solutions are available from the different reporting agencies for a specific event. ISC also provides own solutions, relying on picked phases and waveforms directly provided by local and global networks. When multiple hypocentral locations are then available, ISC flags its preferred choice as “Prime”, which is often -but not always- the ISC own solutions. In this study, we assume the Prime solutions always being the most reliable within the ISC compilation (Table 2).

Prioritisation of location solutions when comparing other catalogues, however, requires more attention. As a rule, we consider the hypocentre locations from the ISC-GEM catalogue as best estimates, due to the accurate review process undergone. Unfortunately, a rather limited amount of events is available in North Africa from that compilation (see Table 1). The GCMT bulletin uses in most cases ISC solutions and therefore no selection is usually required, with the exception of very few events. Similarly, IGN is a reporting agency of ISC (with code MDD), however, not always considered as Prime. We use then the IGN solutions only for the subset of events not included or not yet reviewed by ISC (e.g. after 2014). Finally EMEC and GEM-GHEC are mostly used to complement historical seismicity information. Given the rather uncertain hypocentre locations of historical events, we assigned the lowest priority in the ranking.

Table 2 Comparison between total number of hypocentral location solutions (subdivided per agency) and Prime solutions from the ISV-Review bulletin within the investigated region.

	Agency (Number of available location solutions > 10)
All Solutions	ISC (9321), MDD (6951), NEIC (4991), CSEM (3847), INMG (2320), LDG (2273), ISCJB (1707), IPRG (1386), CNRM (1330), IDC (1210), IGIL (1131), JSO (1070), CRAAG (1020), LIS (877), SFS (762), MOS (728), ATH (691), EHB (553), NEIS (526), NAO (507), SPGM (456), GII (443), RYD (433), HLW (432), EIDC (423), HFS (373), BJI (348), BCIS (343), RBA (297), STR (292), ROM (265), LAO (234), NIC (199), ISK (189), NSSC (187), THE (180), GRAL (169), USCGS (131), SNSN (127), MED_RCMT (123), HFS2 (115), SGS (113), IASPEI (109), IAG (108), TUN (101), ZUR_RMT (97), PDG (90), DDA (81), HRVD (78), SZGRF (72), ISS (54), HFS1 (54), PEK (52), ZUR (42), DUSS (40), CENT (39), GCMT (35), GUTE (31), BER (27), CGS (25), PDA (25), BGS (24), PTO (23), TTG (23), BEO (11), TEH (10)
Prime Selection	ISC (9321), MDD (1025), IPRG (207), IDC (123), CRAAG (97), CSEM (85), INMG (81), JSO (62), HLW (61), RYD (52), CNRM (37), SPGM (37), ROM (33), GUTE (29), LIS (25), TUN (24), BCIS (22), LAO (16), RBA (14), NEIC (13), SGS (10), GII (10)

4.3 Duplicate Finding and Catalogue Merging

Once assigned a priority rank to the solutions, a non-trivial task is the identification of duplicated events between catalogues. In this study, the search is done using duplicate finding algorithm based on spatial and temporal matching of the solutions within pre-defined windows, whose length is tuned according to the expected accuracy of the solution in a specific time period. In Table 3 it is presented the length of the time (Δt) and space (Δd) windows used for the three main periods of analysis. As it can be seen, the window size decreases from historical to more recent times.

It is worth mentioning that, being an automated process, misidentification errors are possible. As a matter of fact, no unique window length exists that allows capturing all duplicated events between catalogues, without erroneously including a fraction of independent events. Window size is then manually adjusted to obtain best trade-off between the two edge cases. Fortunately, in most cases erroneous duplications are

found between events of an aftershock sequence, which are nonetheless removed afterwards when declustering is applied (see section X).

Once duplications between catalogues have been identified, merging is then performed. Corresponding duplicated events are collapsed into a single event with multiple solution representation, while unique events are simply added. As a final step, the preferred solutions are selected according to the previously defined priority rules. The result of such selection is presented in **Table 4**.

Table 3 Size of time and spatial windows used to identify potentially duplicate events when comparing and merging earthquake catalogues. Windows have different length depending on the analysed period.

	Historical (<1900)	Pre-instrumental (1900-1963)	Instrumental (>1963)
Δt	2 day	10 minute	120 second
Δd	150Km	100Km	50Km

Table 4 Comparison between total number of events available from each earthquake catalogue, and the number of events after duplicate finding and location solution selection.

	ISC-GEM	ISC-Rev	GCMT	IGN	EMEC	GEM-GHEC
Total	67	10,429	101	6,840	3,782	25
Selection	67	10,374	3	1,817	1,960	5

4.4 Magnitude Homogenisation

A key point in the homogenisation process is representing all available earthquake events using a unique target magnitude. In this study, we use as a reference type the moment magnitude M_w (Hanks and Kanamori, 1979), due to its direct relation to released energy and the lack of a saturation effect. Unfortunately, M_w has been systematically reported by global agencies only since relatively recent times (e.g. after 1976 for the GCMT catalogue). Moreover, although M_w is nowadays widely accepted as most suitable representation of earthquake size, many agencies are still reporting in other formats, sometime for backward compatibility or simply for lack of expertise.

Magnitude conversion is nonetheless not a straightforward process (REFERENCES), often affected by large uncertainties and biased by the effect of magnitude saturation, inconsistent processing algorithms and/or intrinsic regional variability. Moreover, the quality of the reported magnitude is highly variable between agencies, mostly due to network limitations (e.g. number of stations, distance, azimuthal coverage). For all these reasons, we apply in this study a magnitude homogenisation approach that is two-steps; first through an extensive data selection and by subsequently performing magnitude conversion.

4.4.1 Agency and Magnitude Type Selection

In a first step, we explore the availability of different magnitude types from each available reporting agency. A ranking scheme is created based on the definition of priority rules, similarly to what was done for location solution selection. In general, prioritisation is made based first on a magnitude type classification (from higher to lower reliability: $M_w \rightarrow M_s \rightarrow m_b \rightarrow M_l \rightarrow M_d$) and then following agency-specific selection criteria. The proposed priority rules are summarized in **Table 5**.

By applying these rules, a single “best” magnitude estimate is then selected for each event with multiple magnitude representation (either natively reported from ISC or after catalogue merging).

Table 5 Magnitude agency selection rules, sorted within groups of magnitude types, from high to low priority. In bold are the catalogue data, while with normal font are ISC reported solutions.

Group	Agency (Magnitude type)
Reference (M_w)	GCMT-NDK , GCMT, HRVD, NEIC, HRVD-NEIC, USGS-NEIC, IGN , CSEM, IPRG, GII, NIC, IAG, MED_RCMT, ZUR_RMT, ISC-GEM
Reliable types (Ms and mb)	ISC (MS, Ms), IDC (MS), NEIC (MS, MSZ, Ms), NEIS (MS), CSEM (Ms), ISC (mb), IGN (mb), NEIC (mb), NEIS (mb), CSEM (mb), USCGS (mb), MDD (mb)
Less-reliable types (mb, ML)	IDC (mb,mb1), IPRG (mb), GII (mb), IPRG (mL), CSEM (ML), GII (ML), CNRM (ML)
Converted M_w	GEM-GHEC (M_w , Ms, mb), EMEC (M_w)
Poorly calibrated agencies	IGN (MbLg, mbLg, MDs), JSO (ML, mL), MDD (MD), CNRM (MD), JSO (MD), LIS (MD), RYD (MD, md), HLW (MI), LDG (MI, mL), ATH (MD), RBA (md)

4.4.2 Magnitude Conversion

When converting between magnitude scales, best practice would be to locally calibrate ad-hoc conversion rules for each reporting agency and magnitude type against the reference scale (in this case, M_w). However, the amount of records available for North Africa was not sufficient to perform ad-hoc calibrations, with the exception of very few agencies, such as Ms and mb magnitudes from ISC and NEIC. For these cases, however, the African subset is in close agreement with globally calibrated models, such as those in Weatherill et al. (2016) or Di Giacomo et al. (2015). For other agencies and magnitude types with too few reported events, some grouping was necessary to perform a reasonable statistical analysis. We therefore decided to rely on just globally calibrated relations (see Table 6). It has to be noted that duration magnitude is usually calibrated on a separate dummy magnitude type, which is variable between the different reporting agencies. Due to the aforementioned lack of magnitude calibration pairs and the significant data scatter, it appeared more appropriate to just apply a simple 1:1 transformation, assigning nonetheless an arbitrary high uncertainty to the conversion.

Table 6 Conversion rules used to convert different magnitude types into M_w . Events outside the range of applicability of the rule have been discarded.

Type	M_w Conversion rule	Range
Ms (MS, MSZ)	Bilinear - Weatherill et al. (2016)	$3.5 \leq M \leq 8.0$
mb (mb1)	Linear - Weatherill et al. (2016)	$3.5 \leq M \leq 7.0$
ML (MI, mL, MbLg, mbLg)	Polynomial – Edwards et al. (2016)	$M \leq 6.0$
MD (md)	1:1 conversion	--

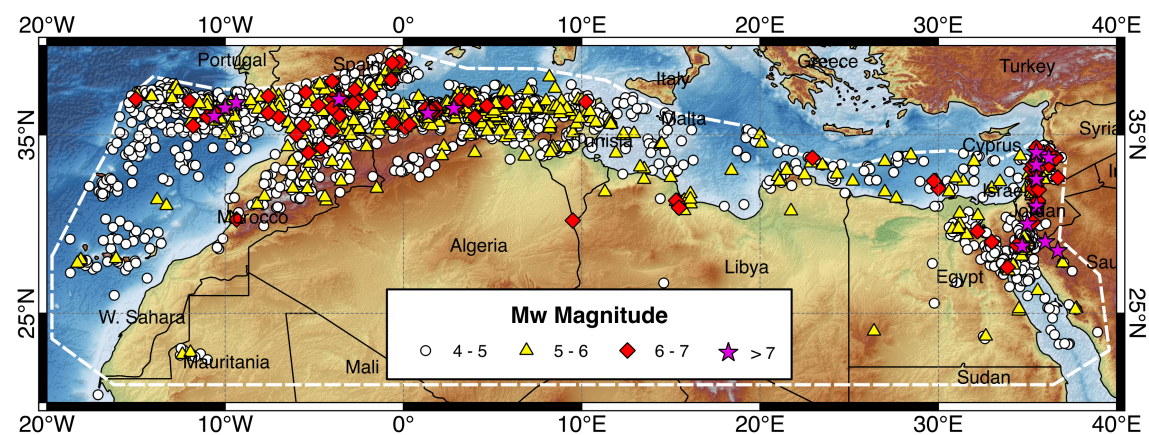


Figure 1 – The Mw homogenised earthquake catalogue for North Africa. Dashed polygon shows the investigation area.

5 The active fault database

In order to provide sources for fault-based PSHA, a new dataset of active faults in North Africa was created, containing ~135 active fault traces. Faults were mapped on topographic data (typically 30m SRTM) based on mapping in the literature as well as interpretation of topographic, seismic and geodetic data. A small amount of metadata, including attributes for each fault trace describing the geometry, kinematics, slip rate, and epistemic uncertainties were collected for each fault if present in the literature, or estimated from the raw data otherwise. The faults are publicly available at https://github.com/GEMScienceTools/n_africa_active_faults in a variety of GIS formats. Fault sources for hazard modeling were made from this data, with a few small or geometrically uncertain faults removed, and slip rates estimated for all structures even if no published rates were available. Slip rate estimates were made through expert judgement of the geodetic and seismic data, as well as consideration of geomorphic expression and similar, better studied faults in the region.

5.1 High and Middle Atlas

The major seismogenic features in the High and Middle Atlas are range-bounding reverse faults that dip towards the interior of the mountains. Though active faulting seems restricted to the rangefronts (e.g., Sébrier et al., 2005), the fault geometries are moderately complex, as many of them are reactivated normal faults from an earlier (Mesozoic) phase of extensional deformation, but others were created as new reverse faults during the Cenozoic Alpine orogeny [**ref**]. As normal faults are typically much steeper than reverse faults, there is quite a bit of variation in fault geometry and segmentation. The major phase of activity on these faults ended in the [Miocene?], but they show signs of slow deformation throughout the Quaternary and are therefore still potential seismic sources.

The western High Atlas are bound by the North and South Atlas Faults, on their respective sides of the range. These are 250-500 km long, moderately-dipping reverse fault zones, capable of large earthquakes. The North Atlas Fault appears continuous at the surface along much of its length, though the South Atlas Fault is clearly segmented. The shortest, westernmost segment was likely responsible for the 1960 Ms 5.9 Agadir earthquake (Meghraoui et al., 1999), which killed ~15,000 people (Paradise, 2005). Slip rates on these faults are estimated at 0.1-0.5 mm/yr (e.g., Meghraoui et al., 1999). A few short (10-50 km) thrust faults cut Quaternary sediments north of the North Atlas Fault. These faults appear to be primary (not reactivated) and show geomorphological evidence of very shallow dips. These faults are secondary to the main North Atlas Fault and therefore have slip rates probably under 0.1 mm/yr, but the largest is less than 10 km from Marrakesh (population ~1,000,000) and therefore poses some risk to the city.

Farther east, the High Atlas is bound on the north by the Beni-Mallal Fault, which is quite similar to the North Atlas Fault (Arboleya et al., 2006). The southeastern High Atlas, faulting on the southern side is expressed in discontinuous thrusts in the northern Ouarzazate Basin; Pastor Castilla et al. (2012) have estimated shortening rates here of 0.1 mm/yr.

Reverse faulting is more distributed but no faster through the Middle Atlas. A suite of discontinuous reverse and reverse-sinistral faults is present in the Middle Atlas and the Midelt Basin between it and the High Atlas; those that have been studied yield slip rates around 0.5 mm/yr (e.g., Gomez et al., 1996; Rigby, 2008).

Though seismicity is present in the Saharan Atlas, it is largely strike-slip on either NE- or NW-striking fault planes. No similar structures are evident in the topography, suggesting that these earthquakes occur on immature faults that have not yet propagated to the surface and caused significant displacement.

5.2 Rif

The Rif Cordillera in northern Morocco is a complicated segment of the African-European plate boundary. The zone is arcuate, with sinistral-reverse faults in the south and southwest, reverse faults in the west, and normal faults in the east accommodating the transition to the Tell Atlas. The faults are long and fairly straight, and segmentation is unclear; our interpretation of the topography and literature suggests segment lengths of ~150 km. Geodetic and geologic evidence suggests that these faults slip ~1 mm/yr. Several of these faults are close to major Moroccan cities such as Tangier, Fes and Meknes, and therefore are the greatest sources of earthquake risk in Morocco.

5.3 Tell Atlas and offshore faults

The Tell Atlas stretch along the North African coast from the Morocco-Algeria border through northern Tunisia. Deformation is transpressional (reverse and dextral) along ~ENE-striking faults (e.g., Meghraoui and Pondrelli, 2011). In the western half, most active faults onshore are reverse or reverse-dextral faults in a valley between the coast and the high interior of the range. This set of faults crosses the coast in a zone from Algiers to Bejaia, though a narrow zone of dextral faulting, the Constantine-Guelma Fault Zone, continues east at this latitude towards Tunisia (Bouhadad et al., 2003). These faults have slip rates ~1 mm/yr (e.g., Meghraoui et al., 1988; Maouche et al., 2011) and have produced a number of upper crustal earthquakes of up to M 7.1 in the past century (e.g., Kariche et al., 2017); some of these have been extremely damaging, particularly the 1980 Mw 7.1 event on the El Asnam fault, which killed several thousand people (Ambraseys, 1981) and caused damages of 22% of Algeria's GDP (GEM-ECD).

Another set of reverse and reverse-dextral faults exists north of the Maghreb coastline. These faults break the submarine crustal surface about 20 km offshore, and dip southward at shallow angles (e.g., Mauffret, 2007); therefore, the coastal cities overly the deeper (but still seismogenic) sections of the faults. These faults are largely known through marine geophysical imaging, and little information exists as to their slip rates or lateral continuity. Nonetheless, they probably accommodate at least half of the ~5 mm/yr of convergence between Europe and Africa at this longitude (e.g., Serpelloni et al., 2005).

5.4 Tunisia

Within the Aurès Mountains of Tunisia and easternmost Algeria, faulting is less structured. Normal faulting on NW-striking planes is present in the center of the Aurès creating several prominent grabens; these may have some dextral shear as well, and dextral strike-slip faults are found with similar strikes ~50 km farther south (Said et al., 2011). The eastern margin of this zone is transpressive, with sinistral-reverse slip on the N-S Axial Fault, a major north-striking structure (Soumaya et al., 2015). To the north, at the eastern terminus of the Tell Atlas, seismicity is distributed throughout but the geomorphology is complicated by previous deformational episodes, and no clear Quaternary faults can be distinguished.

The southeastern margin of the Atlas in eastern Algeria and western Tunisia is characterized by thrusting that is well exposed in the Quaternary sediments. These faults are large, distributed and very shallowly dipping, but the slip rates are much slower than in the Tell Atlas to the northwest. Shortening rates on the measured structures are ~0.1 mm/yr (Saïd et al., 2011), and the unmeasured structures nearby have similar geomorphic and structural expression, suggesting similar deformation rates.

5.5 North-Eastern Africa

Deformation in northeastern Africa is largely extensional, relating to intraplate stresses and the transtensional motion of the Arabian plate with respect to Africa rather than Africa-Europe dynamics.

Although both normal fault and strike-slip focal mechanisms are present throughout northern Libya, the only mappable faults with confirmed Quaternary activity are the normal faults making up the Hun Graben (e.g., Abdunasser and McCaffrey, 2015).

Northeastern Egypt is very active seismically, relating to the ongoing extension across the Red Sea and the Gulf of Suez. Most faults on both the African and Sinai margins of the Gulf of Suez are normal fault striking NNW, parallel to the Gulf (e.g., Sharp et al., 2000). Those closest to the Gulf accommodate much of the extension between Sinai and Africa (e.g., Bosworth and Taviani, 1996), with slip rates of 0.5-1 mm/yr, based on the ~ 2 mm/yr GPS velocity gradient (Mahmoud et al., 2005). The northeastern Egyptian coast also has faults striking perpendicular and obliquely to the main structural trend. The most prominent faults are those bounding Wadi Araba and the Galala Plateau. Though they are not previously mapped as such, the topography and satellite imagery strongly indicate that Wadi Araba is an active graben, albeit with a very low extension rate (~ 0.1 mm/yr), and potentially only a few hundred meters of offset. Small normal faults with a variety of orientations are also mapped by Hagag in the Cairo-Suez District; slip rates are similarly unknown but probably very low.

Notable recent seismicity in the Nile Corridor includes earthquakes in the Dahshour Seismic Zone near Cairo (Hussein et al., 2013) and near the Aswan High Dam much farther south. Despite damaging earthquakes, no surface faults in the Dahshour Seismic Zone or the surrounding region could be identified in the topographic or satellite imagery that may be related to these events, or display other indication of Quaternary activity; therefore regional earthquakes may be of only small to moderate size. The 1981 Aswan earthquake likely ruptured a section of the Kalabsha Fault (Mekkawi et al., 2005), and is thought to have been triggered by the impoundment of the Aswan Reservoir. Nonetheless the Kalabsha Fault is prominent in imagery extending far west of the reservoir, and other sections may be active as well.

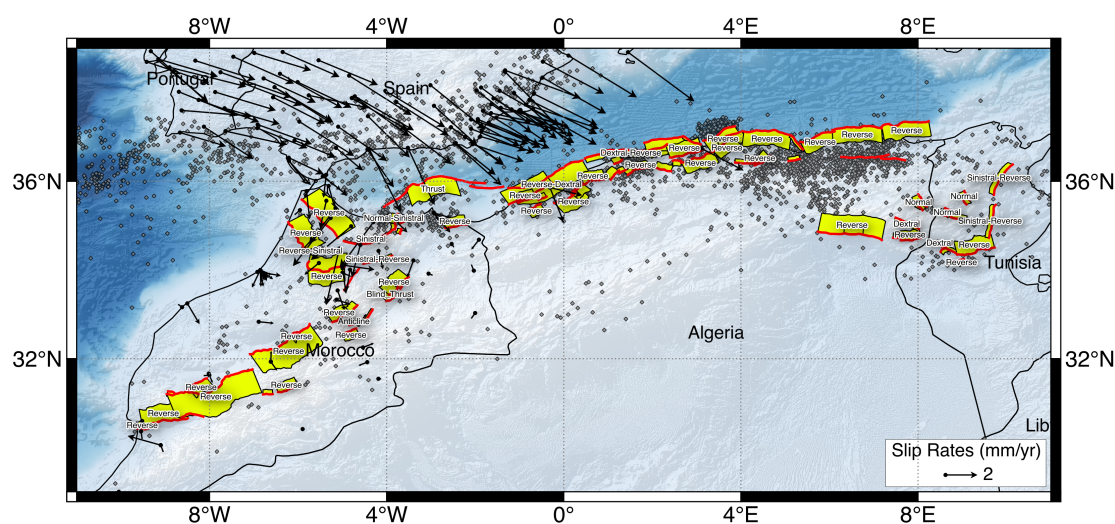


Figure 2 – Trace (in red) and surface projection (in yellow) of the modelled active faults of the Maghreb region. Measured GPS velocities are shown with black arrows, while black dots are the events from the NAEC catalogue.

6 Creation of an Hybrid Source Model

The North Africa earthquake source model consists of a combination of distributed seismicity and finite faults. In the following, the main characteristics of the two source typologies are discussed.

6.1 Distributed Seismicity

6.1.1 Source Zonation

The study area has been initially discretized into 54 independent source zones, following the guidelines proposed by Villanova et al. (2014) that provide a set of objective criteria to delineate regions of supposedly homogenous seismic potential. The main constrain for the development of the source model came from the analysis of the earthquake catalogue (stationarity of the completeness periods, evaluation of the mean activity rate, distribution of seismogenic depths) and from a set of geological and seismotectonics considerations, such as style, geometry and distribution of existing faulting systems and their relation to the local stress and deformation regimes (see discussion in sections X and X). Local and regional source models from previous hazard studies (e.g. EXAPLES) have also been taken into great consideration as starting point for the proposed zonation and to assure compatibility across the borders, particularly with the SHARE (Woessner et al., 2015) and EMME (Giardini et al., 2016) models.

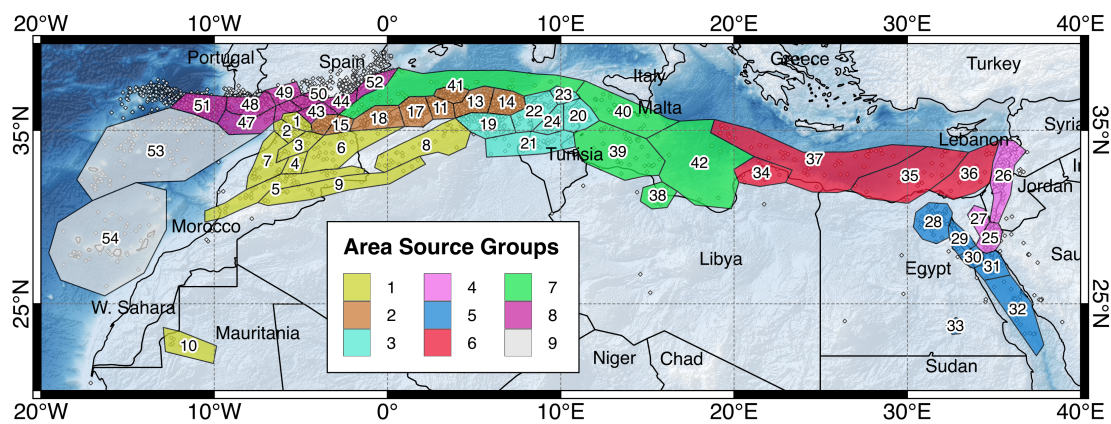


Figure 3 – The proposed source zonation for North Africa. Different colours are used to represent the 9 main tectonic groups (see Table X) of the region.

The 54 source zone has then been gathered into 9 main tectonic domains (Figure 3), assumed to have comparable rheological and mechanical behaviour with respect to the underlying crustal geology under the regional stress regime. Source grouping is particularly useful for earthquake occurrence analysis in low seismicity regions (Poggi et al., 2017), where the limited earthquake record might be insufficient for the proper calibration of poorly constrained seismicity parameters, such as the maximum magnitude or the slope (b -value) of the assumed frequency-magnitude occurrence model (see following section for further details). As well, tectonic grouping has also been used for the regional characterization of main faulting style and hypocentral depth distribution of the seismic source model.

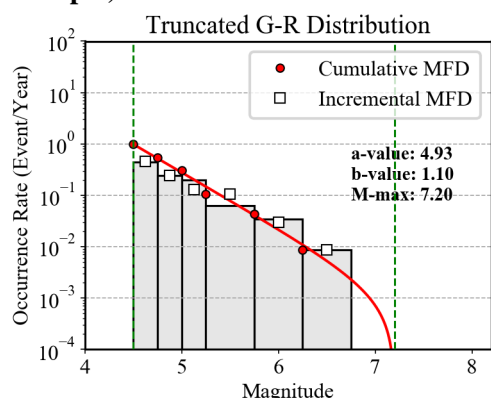
6.1.2 Occurrence Model and Maximum Magnitude

Earthquake occurrence of the distributed sources is modelled using a double truncated Gutenberg-Richter (GR) relation. Minimum magnitude has been arbitrary assigned to 4.5 for all zones, while maximum magnitude is variable between zones and generally derived as the size of the largest observed event plus 0.5 magnitude

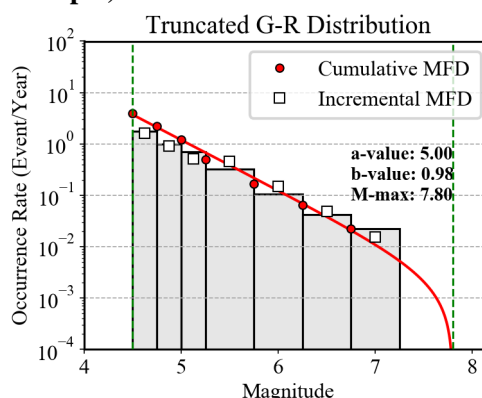
units. Such increment is assumed as sufficiently conservative choice for the region, although further uncertainty is nonetheless accounted for in the source model logic tree (see section 9). It must be noted, however, that the definition of such parameter is not critical for the calculation at 10% probability of exceedance (475 years return period), which is mostly controlled by the intermediate magnitude range.

Fit of the GR relation is done in each zone on the observed annual rates obtained after completeness analysis of the declustered earthquake catalogue. Fit is performed in two separate steps and by mean of a non-linear least square approach on non-cumulative rates (Poggi et al., 2017). In a first step, a preliminary occurrence model is obtained for each seismotectonic group (**Figure 4**). From that, regional *b*-values are derived. In a following step, then, activity rates (*a*-values) are obtained for the single zones using the previously defined regional *b*-value of the corresponding group. Such procedure proved to be particularly helpful in those areas of the study region with rather short of incomplete earthquake records to obtain more stable results. A summary of the derived seismicity parameters is given in **Table 7**.

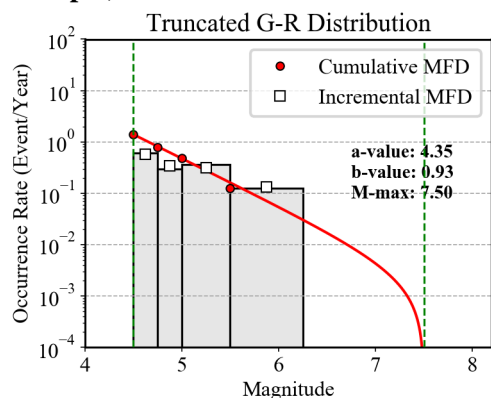
Group 1)



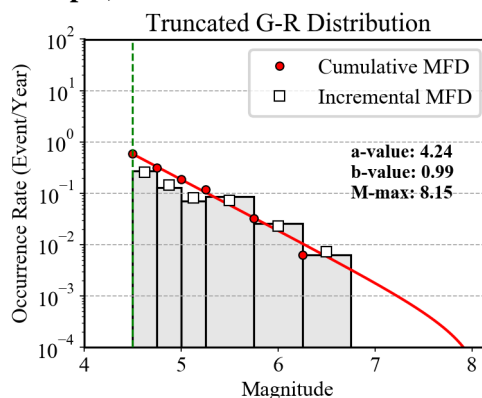
Group 2)



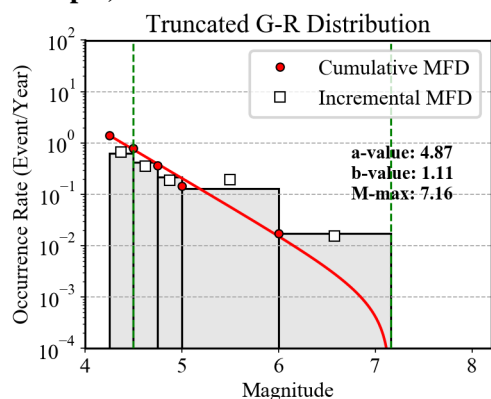
Group 3)



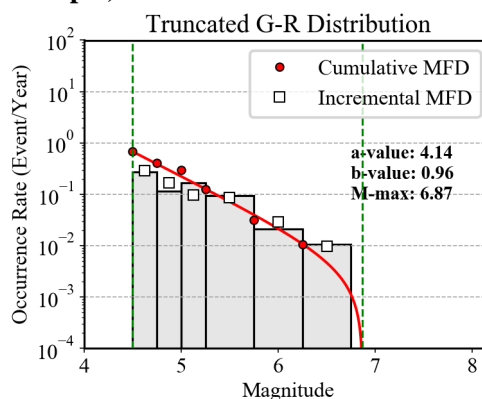
Group 4)



Group 5)



Group 6)



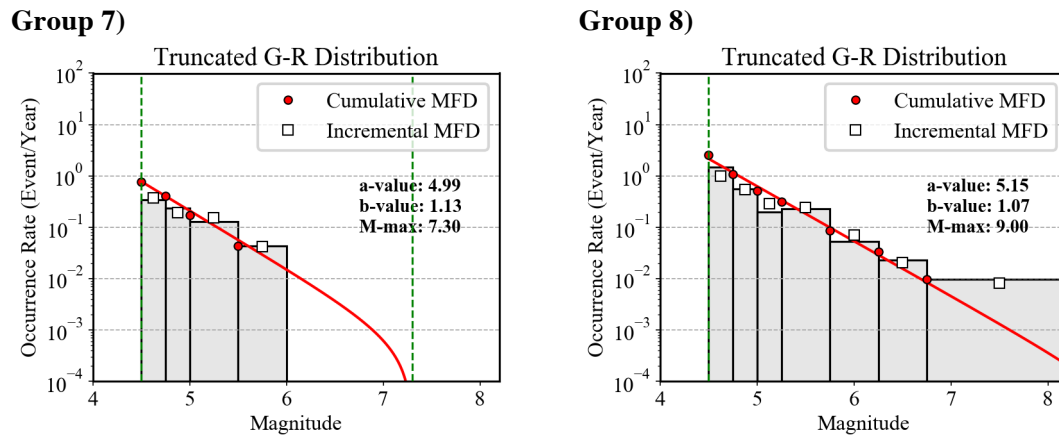


Figure 4 - Magnitude occurrence relations of the North Africa seismicity model for the first 8 tectonic groups. The double truncated Gutenberg-Richter model is presented with red line for the cumulative rates and with grey histogram for the incremental (non-cumulative) rates.

Table 7 Seismicity parameters of the North Africa source zonation model

Group	Source	<i>a</i> -value	<i>b</i> -value	M^{\max}
1 - High / Middle Atlas	1	4.31	1.10	6.9
	2	4.08		6.9
	3	4.39		7.2
	4	4.01		5.7
	5	4.45		6.9
	6	4.08		5.8
	7	3.92		6
	8	4.09		6.3
	9	4.22		6.11
	10	4.15		5.58
2 - Rif / Tell Atlas	11	4.09	0.98	7.8
	12	3.76		7.34
	13	4.47		7
	14	4.34		6.33
	15	3.89		6.3
	16	3.72		6.86
	17	4.11		7.6
	18	4.12		7.5
3 - West Algeria / Tunisia	19	3.64	0.93	6.5
	20	3.41		6.3
	21	3.83		5.83
	22	3.81		6.3
	23	3.13		7.5
	24	3.39		6.3
4 - Dead Sea Fault Zone	25	3.67	0.99	7.71
	26	4.06		8.15
	27	3.37		5.3
5 - On-Shore Egypt / Red Sea	28	4.18	1.11	7.16
	29	4.12		6.7
	30	4.35		7.1
	31	4.27		5.4
	32	3.99		6.01
	33	3.72		6.33
6 - Off-Shore Egypt	34	3.42	0.96	6.13
	35	3.61		6.73
	36	3.27		6.38

	37	3.88		6.87
7 - Libya	38	4.27	1.13	7.3
	39	4.54		6.32
	40	4.25		5.3
	41	4.52		5.97
	42	4.09		6.4
8 - Iberia	43	4.00	1.07	7.2
	44	3.99		7
	45	4.23		7.3
	46	4.00		5.9
	47	3.95		7.2
	48	4.50		7.1
	49	3.83		6.6
	50	4.24		8.3
	51	4.75		9
	52	3.99		7.2
9 - Atlantic Off-Shore / Canary Islands	53	4.87	1.12	6.8
	54	4.74		5.75

6.2 Spatial Variability of Earthquake Occurrences

To better represent the spatial variability of seismicity across the study area, the annual occurrence rates previously obtained for the homogenous source zones have been redistributed within each polygon using a procedure that accounts for the irregular spatial pattern of the observed events. The procedure shares some similarity with the popular smoothed seismicity approach (e.g. Frankel, 1995), but is more convenient in that a unique fit of the magnitude-frequency distribution is here required for each zone, while the corresponding total earthquake occurrence is only a-posteriori spatially reorganised as a function of the epicentral distance to all neighbouring events. Moreover, the combined use of zones gives the possibility to account for different modelling parameters (b-value, depth distribution, rupture mechanism) in separate regions.

The procedure is described as follow. In a first stage, each source zone is discretized into a grid of point sources. A spacing of 0.1 degrees (about 11km) is used, which provides a rather dense sampling of the area but is at the same time not computationally demanding. For each discrete location i , then, the occurrence rate is assigned a fraction of the total annual rate (R) for the zone, scaled by a normalized weighting function (W) that accounts for the relative distance to all neighbouring events j :

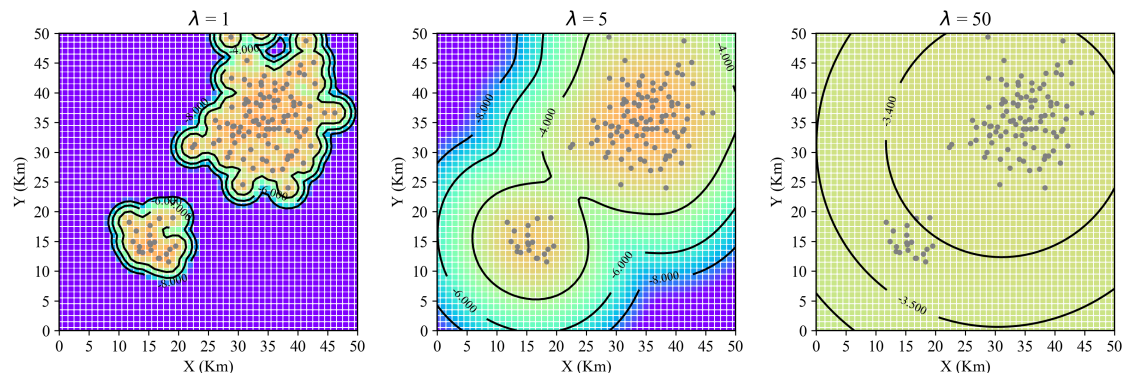
$$R_i = \frac{W_i}{\sum_{k=1}^{N_{tot}} W_k} R \quad \text{Eq. 1}$$

where N_{tot} is the total number of points in which the area has been discretized. In such way, more seismically active region of a source zone are modelled using point sources of proportionally higher productivity. It is important to notice that, due to the normalisation, the overall rate balance for each zone is nonetheless preserved when summing the activity rates from all the discrete point sources.

The weighting function is calculated from all the events (E_{tot}) within the zone (plus a small buffer of about 0.1 degree to minimize edge artefacts) as:

$$W_i = \sum_{j=1}^{E_{tot}} e^{-\left(\frac{D_j}{\lambda}\right)^2} \quad \text{Eq. 2}$$

where D is the epicentral distance and λ is a distance decay parameter controlling the influence of far events and therefore influencing the “smoothing” of the rates across the area. A theoretical infinite value of λ would produce a homogenous area source.



Unfortunately, the choice of an optimal decay parameter λ is still under investigation and currently rather subjective. Although we found that a value of 50 provides a more realistic seismicity pattern for the seismogenic model of the study area (Figure 5), the proposed value might not be generalized for other regions, e.g. with lower activity and significantly incomplete catalogues. To account for the epistemic ambiguity of this parameter, however, three different values of 10, 50 and 100 are used with variable weight in a logic tree approach (see Section 9).

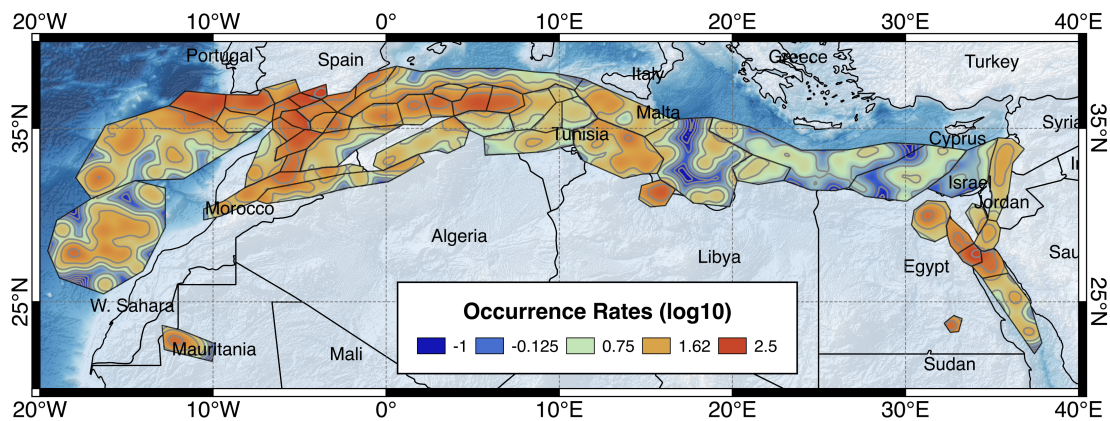


Figure 5 – Example of spatial redistribution of the cumulative annual rates ($M > 0$) using a decay parameter (λ) of 50. Rates are intended by unit area of 0.1 deg^2 (about 11 km^2).

6.2.1 Hypocentral Depth Distribution

Seismicity regime reflects the transition between a stable continental crust, characterised by low attenuation and relatively deep earthquake hypocentres, to active shallow crust.

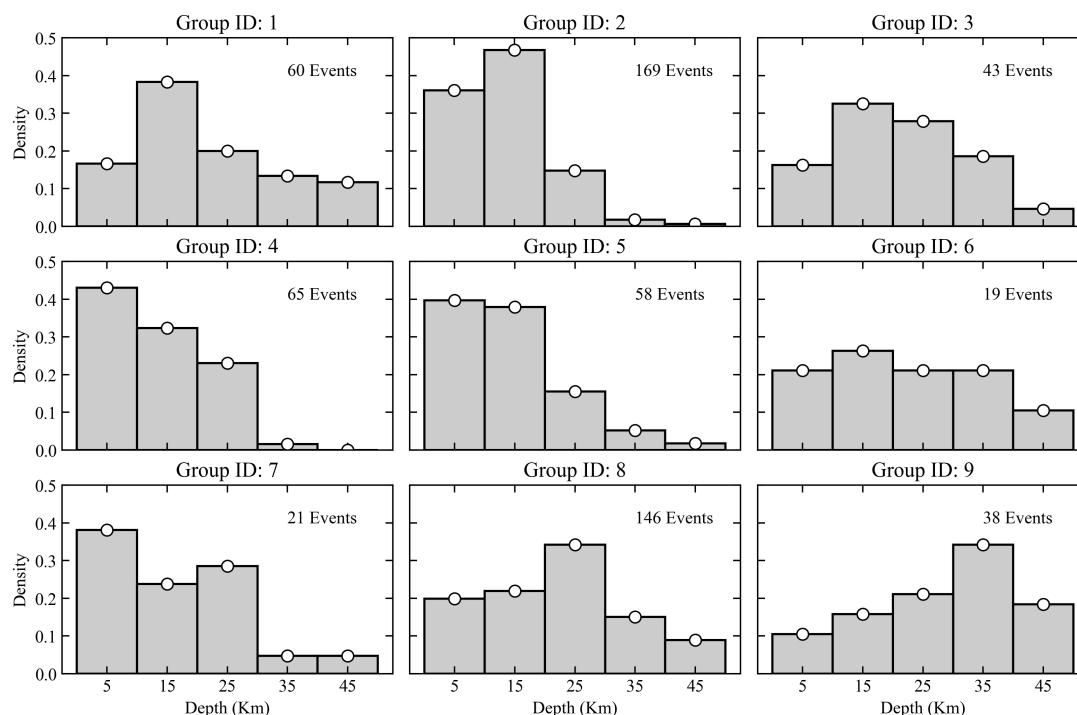


Figure 6 - Earthquake hypocentral depth distribution of the nine seismotectonics groups of the North Africa source model.

6.2.2 Source Mechanism Distribution

The definition of the dominant rupture mechanisms is an important part of the source model construction, as this is necessary information when using ground motion attenuation relationships depending on fault geometry and orientation for distance metric calculation (e.g. R_{jb} , R_{rup} , [References](#)). Such assessment is preferentially done by statistical analysis of the available fault-plane solutions from moment tensor inversion, but other constraints -such as the regional stress regime and local geological structures- can be integrated in case of lack of recordings or non-univocal rupture orientation.

We have analysed the available moment tensor solutions for the region from the GCMT catalogue. About 73 events were found, which have been analysed using the program FMC (Álvarez-Gómez, 2014). The program produces a Kaverina et al. (1996) type classification diagram (e.g. [Figure 7](#)) as presented in Kagan (2005), where events are classified into seven main faulting styles, depending on the relative comparison of the B, P and T axis following the convention of Aki and Richards (1980). Unfortunately, the lack of events made impossible the use of such classification in some regions, where the decision on the dominant mechanism was then based on seismotectonics considerations. The result of the analysis for individual source groups is presented in [Table 9](#), in the format required by the *OpenQuake* software.

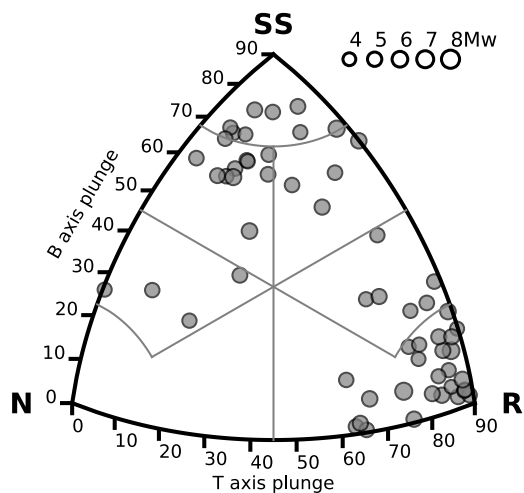


Figure 7 – Example of ternary diagram for the classification of the dominant rupture mechanism of zone 2.

Table 8 Source mechanism distribution parameters for each seismotectonics group of the North Africa source model.

Group	Prob.	Strike	Dip	Rake	Description
1	0.6	240	60	45	Combination of R and SS faults. SS (mostly LL) is dominant in the South, while R is more evident in the North.
	0.4	240	45	90	
2	0.2	240	60	135	Combination of R and SS faults. R is always dominant. SS is mostly LL in the West, RL in the East.
	0.4	240	45	90	
	0.2	240	60	45	
3	0.6	240	60	135	Combination of R and SS faults. SS (mostly RL) is dominant in the South, while R is more evident in the North.
	0.4	240	45	90	
4	0.5	20	90	0	Pure SS, considering both LL and RL.
	0.5	20	90	180	
5	0.4	300	60	-90	Mostly N faulting, with some contribution from RL oblique slip faults.
	0.4	120	60	-90	
	0.2	60	90	180	
6	0.4	60	90	180	Mostly N faulting, with some contribution from RL slip faults.
	0.6	110	60	-90	
7	0.4	110	90	180	Mixture of RL SS, pure R and N mechanisms.
	0.3	110	60	-90	
	0.3	110	45	90	
8	0.5	110	90	180	Pure LL SS according to the main fault mapped in the paper of Gonzalez. Likely the mechanism is similar along the whole offshore.
	0.5	240	60	135	
9	1	30	90	0	Pure LL SS (simplified)

R = reverse, N = normal, SS = strike slip; LL = left-lateral; RL = right-lateral

7 Modelling of the fault sources

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8 The Ground Motion Model

The choice of an appropriate ground motion model is a critical step in definition of the hazard scenario. As for the standard practice, if a locally-calibrated ground-motion model is not available, a set of most representative Ground Motion Prediction

Equation(s) for a region should be selected through direct comparison against local earthquake recordings, in a range of magnitude and distance that are meaningful for the analysis.

Unfortunately, the scarce availability of strong-motion recordings for the whole analysed North Africa belt makes a direct comparison impractical, or even impossible in some areas. Therefore, non-direct selection criteria have to be used instead, with special regard to matching of the tectonic context and suitability of the GMPE functional form (e.g. Cotton et al., 2006).

As for the case of a previous seismic hazard study for the East African Rift (Poggi et al. 2017), a combination of different seismotectonic conditions is expected for North Africa. While a low-attenuation stable continental crust (SCC) is to be expected in the most internal part of the continent, active shallow crust (ASC) conditions are likely at the more seismically active regions close to plate boundaries, such as the mountain chain of the Rif and Tell Atlas and regions surrounding the Red Sea. In this study, we rely on the global tectonic zonation proposed by Chen et al. (2017, **Figure 8**), which is based on Fuzzy Logic analysis of both seismological and geological information. Using this approach, North African source zones have been classified either as SCC (group A) or ASC (group B). An additional buffer region (group C) is also prescribed for transition zones of intermediate characteristics between SCC and ASC, in order to avoid abrupt variations of ground motion predicted by GMPE calibrated for different tectonic settings.

Following this classification, the same combination of ground motion prediction equations selected in Poggi et al. (2017) has been used, with respectively two models for ASC (Chiou and Youngs 2014; Akkar et al. 2014) and two models for SCC (Atkinson and Boore 2006; Pezeshk et al. 2011). The selected GMPEs and their corresponding weights assigned to each tectonic group are summarized in **Table 9**.

Table 9 Grouping of sources by tectonic similarity and weighting scheme for the GMPE logic-tree

Group ID	Type	Source Zone ID	CY	AK	AB	PZ
A	ASC	1, 2, 3, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 22, 23, 24, 25, 26, 29, 30, 31, 32, 41, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52	0.5	0.5	0	0
B	SCC	4, 5, 6, 7, 8, 9, 21, 27, 28, 36, 38, 39, 40	0	0	0.5	0.5
C	ASC/SCC	10, 33, 34, 35, 37, 42	0.25	0.25	0.25	0.25

The four selected attenuation models (CY Chiou and Youngs 2014; AK Akkar et al. 2014; AB Atkinson and Boore 2006; PZ Pezeshk et al. 2011) have been applied with different weight to each zone belonging to a specific tectonic group (A, B, C)

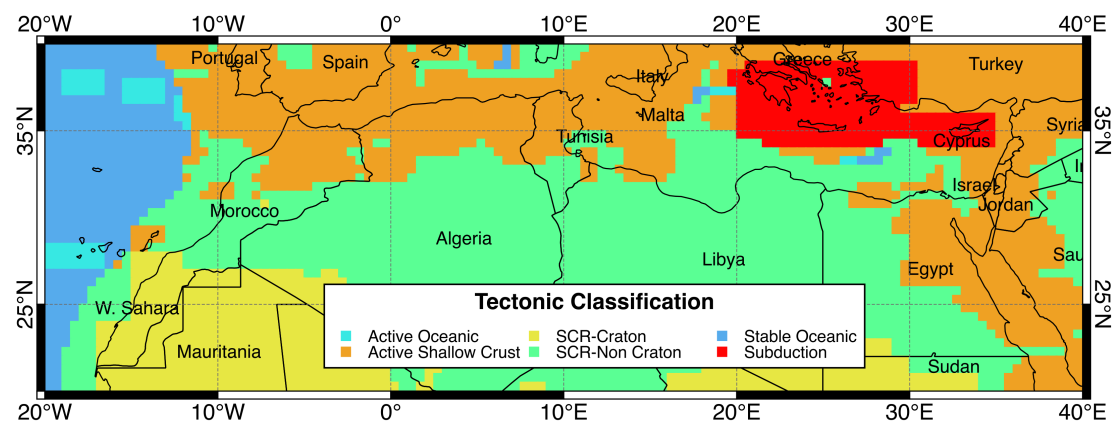


Figure 8 – Tectonic classification proposed by Chen et al. (2017) used to guide the regionalisation of the North Africa seismic source zones (see **Table 9**).

9 Source Model Uncertainties

To explore the epistemic variability of uncertain model parameters, a source model logic-tree has been implemented. The logic-tree structure includes three cascading branching levels, each representing the assumed distribution of uncertainty of a specific and independent model parameter.

The first branching level addresses the uncertainty about the length of the smoothing kernel, whose definition is highly subjective. In this study we have selected three different smoothing distances (10, 50 and 100), used to produce three independent seismicity models. According to our judgement, the model computed using a length of 50 is the most representative of the observed seismicity distribution. For that, a weight of 0.4 has been assigned. A slightly lower significance is then given to the two remaining edge models, each with a probability of 0.3.

The second and third branching levels are about the uncertainty on the maximum magnitude and the b-value, respectively. For the first parameter we have assigned a relative possible error of ± 0.2 , while a variability of ± 0.05 is admitted for the second. In both cases, we assumed a normal distribution of the probability, with a weight of 0.5 for the central estimate and 0.25 for the edge values.

A representation of the whole logic-tree structure is give in Figure 9, including the branching levels for both the source and the ground motion model uncertainties.

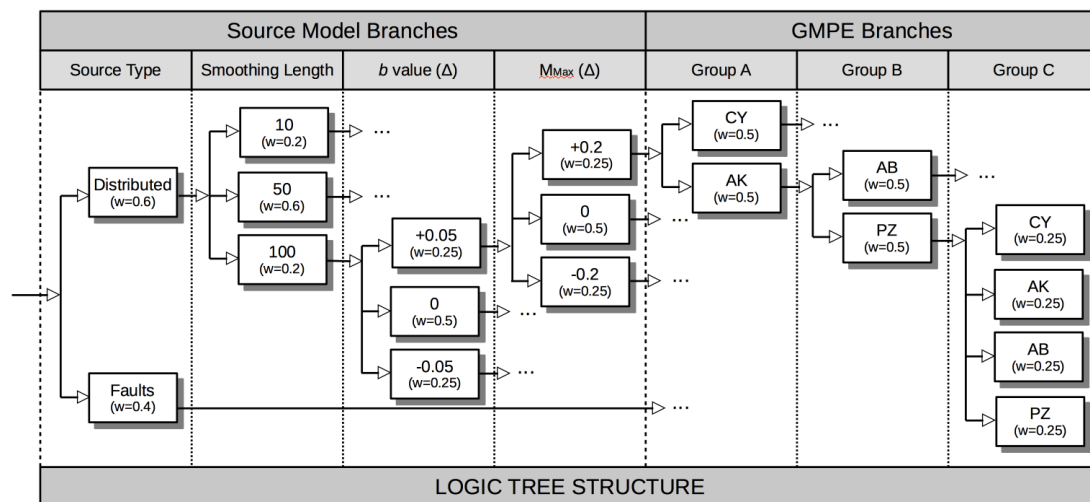
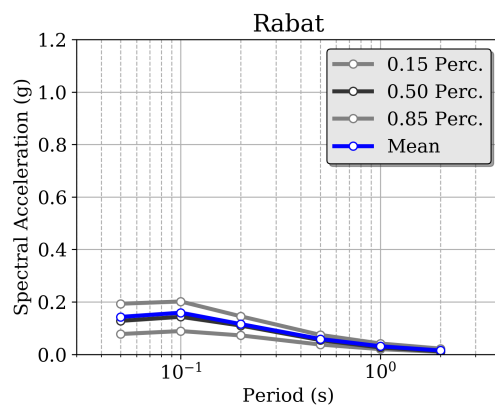
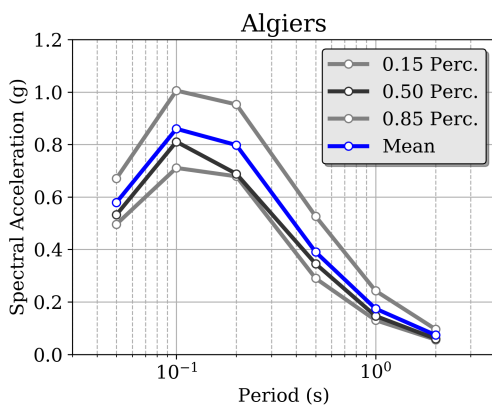
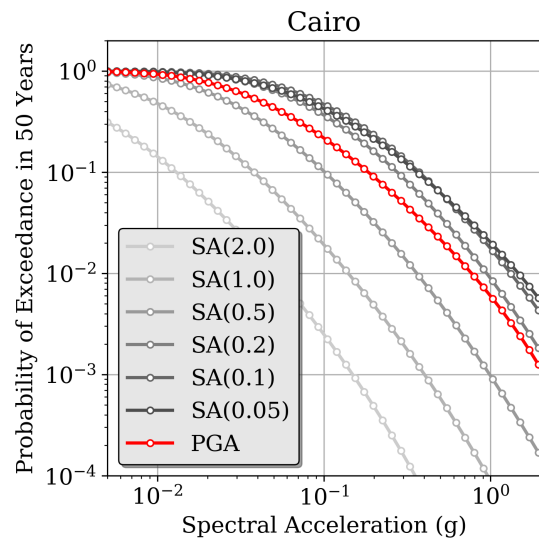
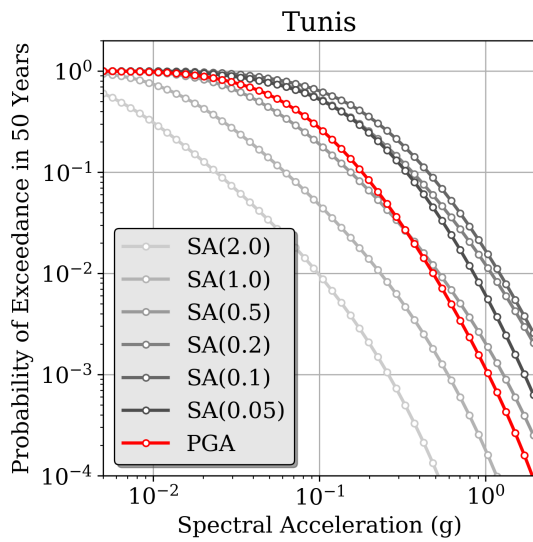
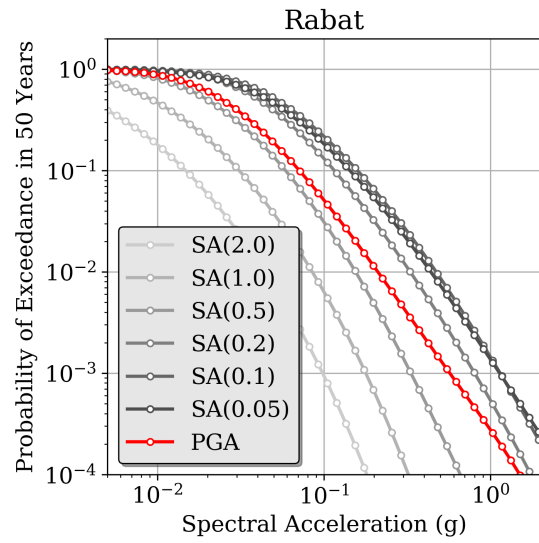
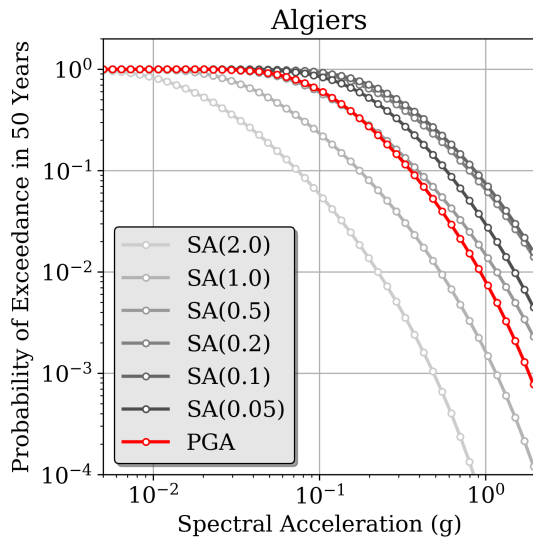
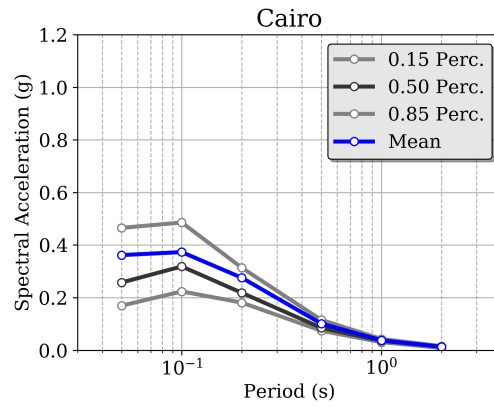
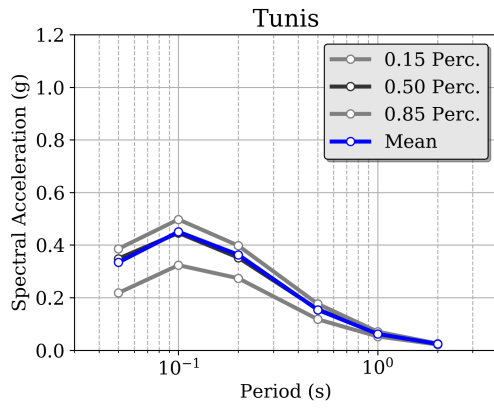


Figure 9 – Diagram representation of the logic-tree structure of the North Africa hazard Model. The implementation consists of 432 branches, distributed over 6 levels (3 for the GMPE and 3 for the source model).

10 PSHA Results





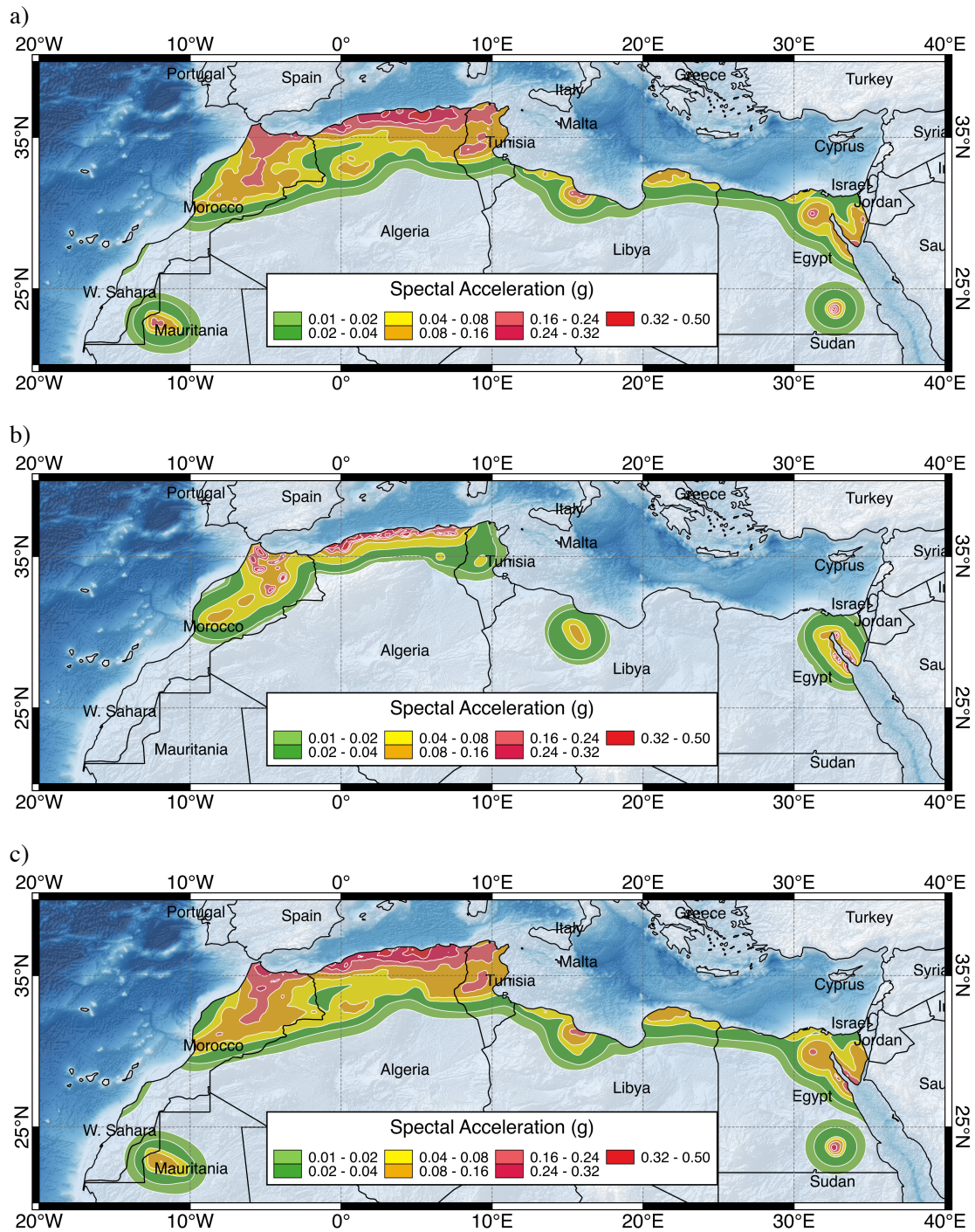


Figure 10 – Maps of spectral acceleration at PGA (g) calculated for 10% probability of exceedance in 50 years for the three modelling strategies: smoothed rates (a), faults (b) and combined sources (c).

11 Discussion and Conclusions

Text

Outlook: 3d smoothing

Acknowledgments

Text

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