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Re-examination of the historical 11 May, 1624 Fez earthquake parameters

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Abstract. The 11 May 1624 Fez earthquake is one of the worst natural disasters in the history of Morocco, and caused serious damage in the city of Fez and its surroundings. It occurred in one of the most active seismic zones in the country, and in an area that is now densely populated.
The 1624 earthquake occurred at a crucial time in the history of Morocco (decline of the Saadian dynasty and outbreak of internal wars) which explains the lack of sufficient information on the extensive devastation that resulted from the earthquake. We consulted several Moroccan and European sources, whenever possible first hand. A complete historical review of testimonies and journals of the time describing this particular earthquake has been carried out. Correlation these effects with the local geological setting and the most recent seismological data shows that the focal region of the 1624 Fez earthquake is likely to be located somewhere along the E—W trending Rides Prérifaines, the main frontal thrust of the Rif. An evaluation of the magnitude of the earthquake is proposed, on the basis of existing empirical relationships. Understanding this earthquake may improve the seismic hazard assessment of the region.
Keywords: Historical seismicity; macroseismic data; earthquake parameters; tectonic; Fez; Morocco.

[es] Reevaluación de los parámetros del sismo mayor de Fez del 11 de mayo de 1624

Resumen. El terremoto del 11 de mayo de 1624 está considerado como una de las peores catástrofes naturales de la historia de Marruecos. El seísmo se produjo en una de las zonas sísmicas más activas y pobladas del país, provocando la pérdida de vidas humanas y daños considerables en Fez y sus alrededores.
El terremoto de 1624 se produjo en un momento crítico de la historia de Marruecos (decadencia de la dinastía saadí y guerras internas), lo cual explica la ausencia de informaciones suficientes sobre los daños. Se ha consultado fuentes primarias marroquíes y europeas. Se ha llevado a cabo una revisión completa de testimonios históricos y revistas que describen este terremoto. En una segunda etapa, hemos intentado relacionar esos efectos con el contexto geológico local y los datos sismológicos recientes. Y finalmente reexaminando las fuentes históricas de la distribución de la intensidad sísmica. La región del epicentro del terremoto de 1624 estuvo probablemente situada a lo largo de los relieves montañosos alineados E-W que constituyen las *Rides Prérifaines*. Para la evaluación de la magnitud del seísmo se han utilizado las relaciones empíricas establecidas para Marruecos.
Es evidente que la comprensión de este terremoto podrá ayudar a mejorar la evaluación del riesgo sísmico de la región.
Palabras clave: Sismicidad histórica; datos macrosísmicos; parámetros del seísmo; tectónica; Fez; Marruecos.

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Introduction

Historical seismicity of Morocco was only known up to about thirty years ago through the catalogs of Perrey (1847, 1848), Hée (1932), Galbis (1932, 1940), Roux (1934), Munuera (1963), Kárník (1969), Mezcua Rodríguez & Martinez Solares (1983). Investigations for original sources and collection of documents (Vogt 1985, Levret 1991, Elmrabet 1991, 2001), with the latest Spanish catalog (Martinez Solares & Mezcua Rodriguez 2002) made it possible to establish lists of historical events felt in Morocco before 1900 (Fig. 1).

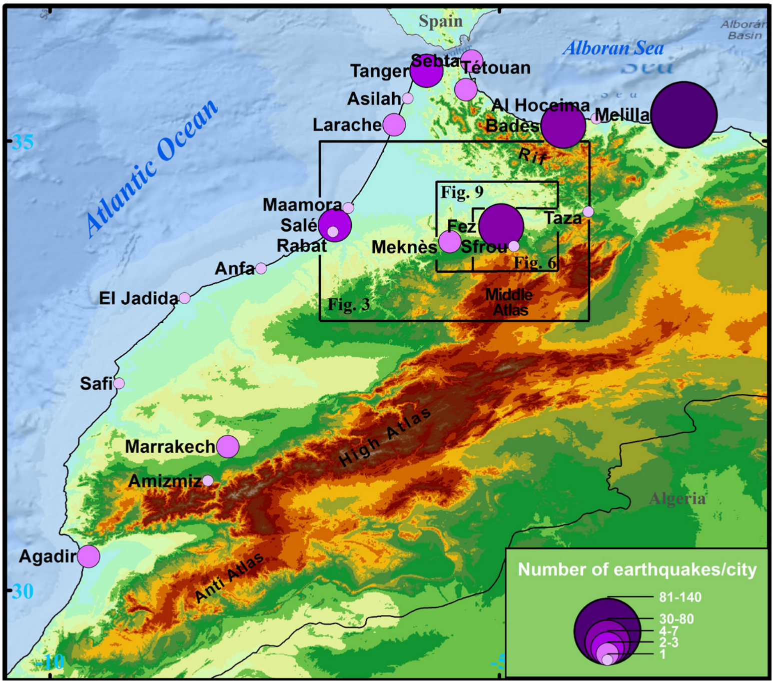

Figure 1. The number of earthquakes (including aftershocks) identified by historical sources with location of most of the following figures. It can be observed the presence of small towns such as Badès, Maamora and Amizmiz, because, probably, of their strategic importance at the time, while large cities such as Marrakech and Casablanca (Anfa) are mentioned only 2 or 1 times, this can be explained by the absence of seismicity for Marrakech, while Casablanca was a small town until the beginning of the 20th century (Cherkaoui et al. 2017).

Examination and analysis of these data, often contradictory, require an enormous effort in order to explore the maximum documentary sources, as there are many potentially interesting documents, which most of the time contain no seismic information. About 10% of the archives are considered to provide usable information, but the remaining 90% has to be re-examined (Société Géologique de France, 2002). It is also essential to verify the exact nature of the described phenomenon, especially when destruction is involved. An event that occurred in 1909 in the region of Ghomara (northern Morocco) was first described and considered as an earthquake before finding out that it was only a large landslide without any seismic cause (Cherkaoui and El Hassani, 2015).

The analysis of these data shows that:

- A majority of past earthquakes occurred in Morocco's main historical cities such as Fez, Marrakech, Salé, Sebta, Tangier, Meknès, etc. which corresponds to only part of the reality.
- Morocco has been hit by destructive earthquakes in the past (881, 1356, 1531, 1624, 1755, 1757, etc.)
- For the rest of Morocco, apart from some details concerning major events (November 1, 1755 earthquake), the historical data remain fragmentary. The currently available documentation, relating to earthquakes which have partially or totally destroyed the cities of Rabat-Salé (1755), Fez (1522, 1624, 1755), Meknès (1755) Agadir (1731, 1761), etc. lack precisions and, often, contradictory.

The absence of earthquakes before the ninth and during the tenth centuries for example, does not mean that there were no earthquakes, but rather due to periods of political instability, that the country went through, either before the foundation of the Moroccan State (IXth century), or to the transition from a dynasty to another. The same phenomenon was noticed in the twentieth century during the two World Wars (Fig. 2).

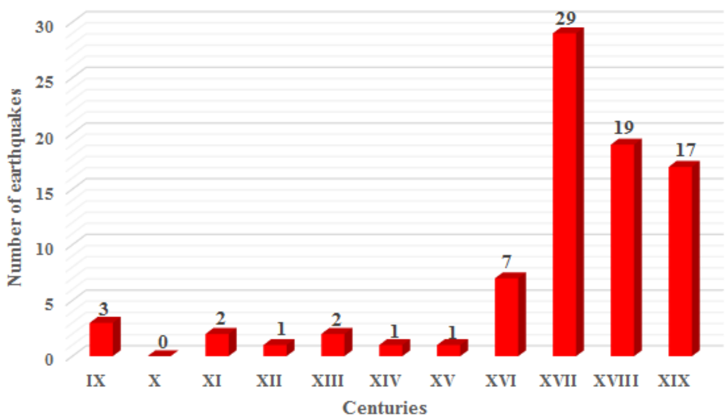

Figure 2. The absence of seismicity before the ninth and during tenth centuries does not necessary mean that there was no earthquakes, but rather due to periods of instability in the country before the establishment of the state of Morocco (IXth century) or during the transition from one dynasty to another, etc. Same observation during the first half of the XXth century during both World Wars. The figure shows the number of historical earthquakes per century excluding premonitories and aftershocks (Cherkaoui et al. 2017).

One of the most important and best documented historical events was the 1755 earthquake. It was named by Moroccan historians the earthquake of "*Meknassa Ez-Zaytouna"* (Meknes the olive tree). The city also had suffered considerable damages, even in localities of about 500 km from the epicenter. Damages in Morocco were particularly severe along the entire Atlantic coast from Tangier to Agadir, and inside the country into Fez and Meknes. In addition to seismic shaking, the coastal areas were wiped out by a one of largest tsunamis of the history of mankind (e.g. Baptista et al., 1998; Omira et al., 2009).

1. Seismicity of Fez and its surroundings

Historical seismicity: The data of historical seismicity contain many imprecisions (and even inaccuracies) not only about the degree of knowledge of the facts, but also about the assessment of the impact of earthquakes. Therefore, it is necessary to conduct a complementary collection of information, in addition to analysis and interpretation work. It is within this perspective that this present work is incorporated.

Consultation of historical documents related to seismicity of Morocco over 11 centuries of observation, shows that the city of Fez and its surrounding region have been hit several times in the past by violent destructive earthquakes (Table I).

Instrumental seismicity: The map of the figure 3 shows the seismicity of the area located between latitudes 33.00 ° N-35.00 ° N and longitudes 4.00 ° W-7.00 ° W, for the period of time starting from 1901 to 2016. The data were taken from the Moroccan National Earthquake Catalogue published by the Scientific Institute (Mohammed V University, Rabat) for the 1901 — 1984 period (Cherkaoui 1988), completed by shocks recorded from 1985 to 2016 (Cherkaoui personal data, https://mtcherkaoui.wixsite.com/site).

Examination of this map shows: (***i***) a concentration of epicenters in the northeast of the area. These events are probably related to the tectonic activity of the second-order N-S faults, located westward of the Nékor major fault; (***ii***) to the south of the area, a second cluster of epicenters, located on the southern and western border of the Middle Atlas; (***iii***) an important alignment of epicenters striking NW-SE, which runs from the vicinity of Fez city in the southeast, crossing Ouezzane in the northwest, and continuing to the gulf of Cadiz along a line located between Asilah and Larache. This seismic activity is probably related to the major dextral strike-slip intrarif external fault extending until the Azores-Gibraltar transform fault zone (Fig. 3).

2. The 11 May, 1624 (23 Rajab 1033 H) Fez earthquake and effects

The 11 May, 1624 (23 Rajab 1033 H) Fez earthquake is probably the most important historical earthquake, that had struck the city of Fez, after the major event of 1755, for which we have direct and first-hand data. Three sources deserve a special mention, for the raison of their detailed descriptions and their chronological proximity. These are:

- a letter from Abdelkader Al Fassi (eyewitness), sent to members of his family, which included Al-Qâdiri (died in 1773);
- two Hebrew texts of Moroccan Jews, Saül Serero and Maymun b. Sa'dyna Ibn Danan (translated to French by Vajda, 1948);

- a testimony Albert Ruyl's[4], who was living in Safi city at the time of the earthquake (De Castries, 1912).

Table 1. List of significant earthquakes felt strongly in Fez region.

Date	*Time (UTC)*	*Epicentral area*			*Description*	*Ref.*
		Lat.N-Long.W	*Location*	*Io/M_w*		
437H 1045-1046		(34.0°-5.0°)	Fez	>VI	Violent earthquake in Fez killing people and destroying houses.	7, 13
811H 1408		(34.0°-5.0°)	Fez	≥VI	Destruction of several homes and battlements d'Al Bira rampart (Fez).	13
23/9/1033 h 11/5/1624	3h-4h	(34.1°-5.1°)	Fez	VIII-IX 6.0	A catastrophic earthquake destroyed almost completely Fez and has killed thousands of people and cause huge damage. Several other localities have been severely affected by the earthquake, as Baddis and Meknes. The earthquake was felt in Sefrou, Taza and Beni Ouaryaghel (in the region of Al Hoceima) in Salé and in Safi.	3, 10, 11, 12, 13
14/3/1074H 18/10/1663	At night	(34.0°-5.0°)	Fez	≥VI	A strong earthquake destroyed several houses particularly at Talaâ (Fez).	3, 4, 5, 11, 13
25/9/1074H 21/4/1664	At night	(34.0°-5.0°)	Fez	≥V	There was a lot of destruction.	3, 4, 11, 13
13/11/1119H 2/2/1708	At dawn	(34.0°-5.0°)	Fès	≥VI	A strong earthquake at the time of Al-Fajr's call to prayer, which killed a number of people, caused widespread damage and left several thousand homeless.	3, 4, 9, 13
01/11/1755	9h 30	36.5°-10.0°	Atlantic	X 8.5-8.7	VIII: Fez, Meknès; VII: entire Atlantic coast between Tangier and Agadir and Marrakech; VI: Ceuta, Tétouan and Agadir. Tsunami	1, 2, 3, 4, 6, 10, 11, 12, 13, 14, 15, 16, 17
18/11/1755 19/11/1755	22h 2h,5h,9h	36.5°-10.0°	Atlantic	VIII	VII: Fez, Meknes and Zerhoun; VI: Taza, Tangier and Tétouan.	1, 2, 3, 6, 11, 13, 14, 15, 16, 17
12/4/1773	5h 15	35.5°-6.8°	Gulf of Cadiz	VII	≥VI: Tangier and Fez, (V): Salé.	8, 10, 11, 13, 15, 16
6/6/1776		(34.0°-5.0°)	Fez	≥VI	A violent earthquake caused the deaths of several people under the rubble of their homes.	10, 11, 13

References: 1) Padre Guardiam (1756), 2) Berg (1757), 3) Al-Qâdiri (1712-1773), 4) Eddaif (1751-1822), 5) Az-Zayani (1833), 6) En-Nassiri (1835-1897), 7) Anonym (~1842), 8) Perrey (1847), 9) Al-Fassi (1899), 10) Galbis (1932, 1940), 11) Roux (1934), 12) Vogt (1985), 13) Elmrabet (1991, 2001), 14) Levret (1991), 15) Martínez Solares J.M. & Mezcua Rodríguez J. (2002), 16) Stucchi et al. (2013), 17) Cherkaoui et al. (2017).

[4] Albert Cornelius Ruyl, was appointed Commissioner of the United Provinces (Netherlands) to the King of Morocco Moulay Zidane, was installed in Safi between 1623 and 1624.

We also consulted other second-hand documents, and their complete list is given in the reference list.

Despite the importance of the 1624 earthquake for the assessment of the seismic hazard in the Fez region, it has not been extensively studied, thus it should be interesting to review these different parameters (location of the epicenter, intensity and magnitude) proposed in previous studies (Poirier and Taher, 1980; Ramdani et al., 1989; Peláez et al. 2007).

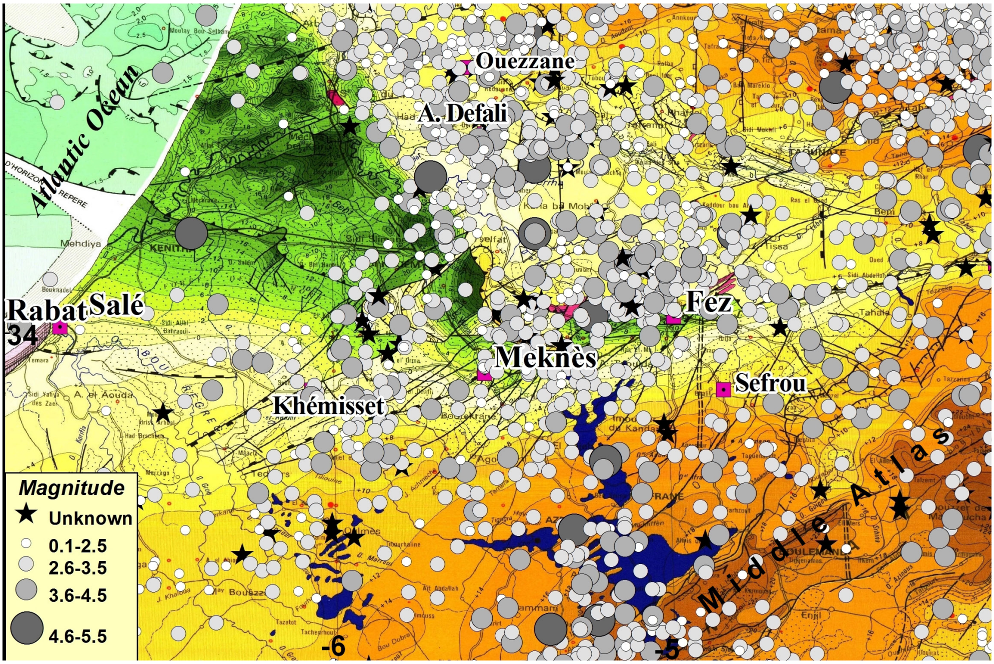

Figure 3. Seismicity in Rharb and Prérif between 1901 and 2016 (Background extract of Morocco neotectonic map 1/1 000 000, 1994).

3. The earthquake effects

The first document reported serious damages in Fez*:"[…] the walls of houses were cracked in Fez, making buildings to collapse and burying an incalculable number of victims under rubble. Few houses have escaped from the disaster […] the disaster cost life of entire families […] such a disaster has never been seen before […]"* (Al-Qâdiri).

The second document is more explicit, precise and rich in landmarks, however its exploitation is difficult *"[…] such large earthquake, that we and our fathers have never known before […] Many houses collapsed in the mellah*[5]*, by*

[5] The mellah of Fez (Jewish Quarter) is the first of its kind in Morocco was established in 1438.

the grace of God, there were no casualties. At Fez el Jedid[6]*, eleven Muslims died; at Fez el Bali*[7]*, there were more than fifteen hundred dead […]"* (Vajda, 1948). In another reference text, the influence of the religion is explicit, We counted *"more than two thousand five hundred perished people in Fez el Bali, In addition to countless children, and their houses had become their graves, while the Israelites had no loss to be regretted" and that " God made distinction between Israel and the Gentiles"* (Vajda, 1948).

From these texts, we can notice that old constructions of the city, that had been built between 789 and 808, located in districts of *Fez el-Bali*, have suffered from the earthquake more than districts located in the southwest (*Fez el-Jedid*), built in 1276 and the *mellah*, which was built in 1438 (Fig. 4).

Other localities were also hit by the earthquake including Meknès, where "*two people were killed and two towers were demolished, but no Jew died*", Sefrou, where "*four houses collapsed, but there was no victim*", and in Salé, where "*we were told that two towers had collapsed during the earthquake*" (Vajda, 1948). According to Ruyl (De Castries, 1912), the earthquake was felt until Safi with no victims or damage. The tremor was also felt "*at Taza, Beni Zeroual and Beni Ouriaghel*" (Al-Qâdiri, 1773).

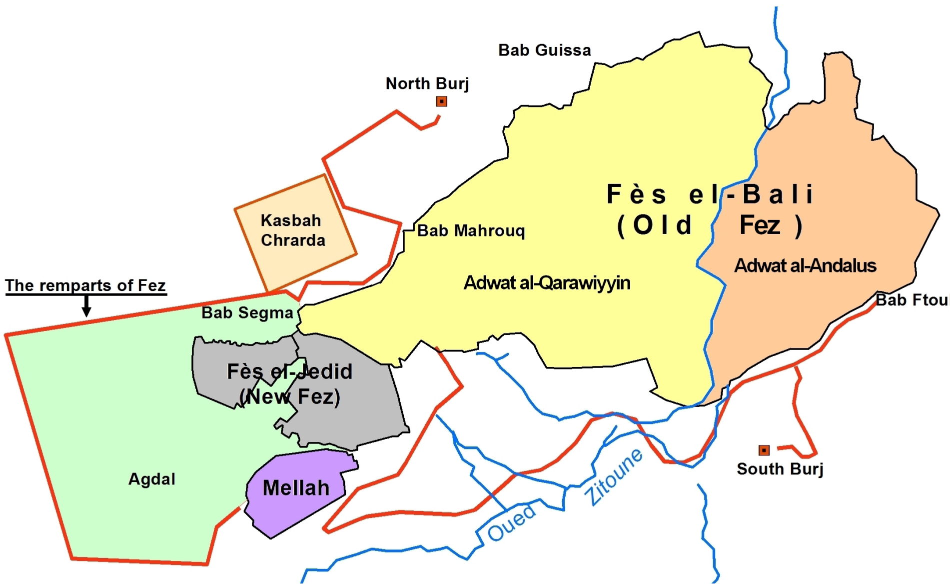

Figure 4. The old city of Fez with main districts.

Galbis (1932, 1940) used again the information reported by Morales y Mendigutía (1921), whereby "*The same day (11 May 1624), violent shocks were felt in the Peñon de Velez de la Gomera; bells rang and the fortress opened like a grenade.*"

[6] Fez-The-New
[7] Fez-The-Old

Whereas in Melilla, a tremor shaking was also felt (Morales y Mendigutía, 1920). Curiously, Moreira de Mendoça (1758) reported that "*on May 11th of the same year (1624), at about half past three in the morning, there was a big earthquake in Seville, causing a panic of the population.»*

The maximal intensity (MSK-64) of the earthquake was observed in Fez, and estimated at VIII-XI by Poirier and Taher (1980), at IX-X by Pelàez et al. (2007) and at X by Ramdani et al. (1989).

4. Possible sources of the 1624 earthquake

It has been proved that the Saïss plain has been a seismically active area since at least the Late Pliocene (3.6 Myr), as inferred from the presence of intra-formational hydroplastic perturbations (seismites) within the lacustrine and fluvial formations of the Saïss basin (Plaziat and Ahmamou, 1998), so the seismic and seismotectonic history of the area should be considered with some detail.

In this section, we review the available surface and subsurface geological data on the Fez region, in order to determine the possible sources of the 1624 earthquake.

4.1. General tectonics of the Rif front area

The Fez area belongs to the southern front of the Rif-Betics arc, the western termination of the Alpine peri-Mediterranean chain, which was created in Late Tertiary times after the uplift and subsequent collapse of the Alboran block (Chalouan et al., 2006). The present-day pattern is related to the NW-SE convergence of Nubia and Iberia, which probably causes a SW-directed escape of the central Rif, as inferred from geodetic data (Vernant et al., 2010; Koulali et al., 2011; Chalouan et al., 2014).

The frontal zone, to which the Fez area belongs (Fig. 5), is characterized by emerging thrust structures, in which the hanging walls form elevated anticlines called the Prerif Ridges (*Rides prérifaines*, e.g. Faugères, 1981). The main formations of these ridges are Triassic evaporites and calcareous deposits of Early and Middle Jurassic age which were related to the subsiding Tethyan rift at its southwestern edge (Faugères, 1981; Zizi, 1996). The structural evolution of the Triassic-Liassic basin was strongly controlled by basement faults, in particular the NE-striking Sidi Fili and Ain El Orma faults (Faugères, 1981; Zizi, 1996), and other faults oriented WNW-ESE and N-S (Fig. 5). Of interest to our study is the fact that the E-W trend appeared during the Jurassic, which means that the recent faults with the same strike may be inherited from older ones.

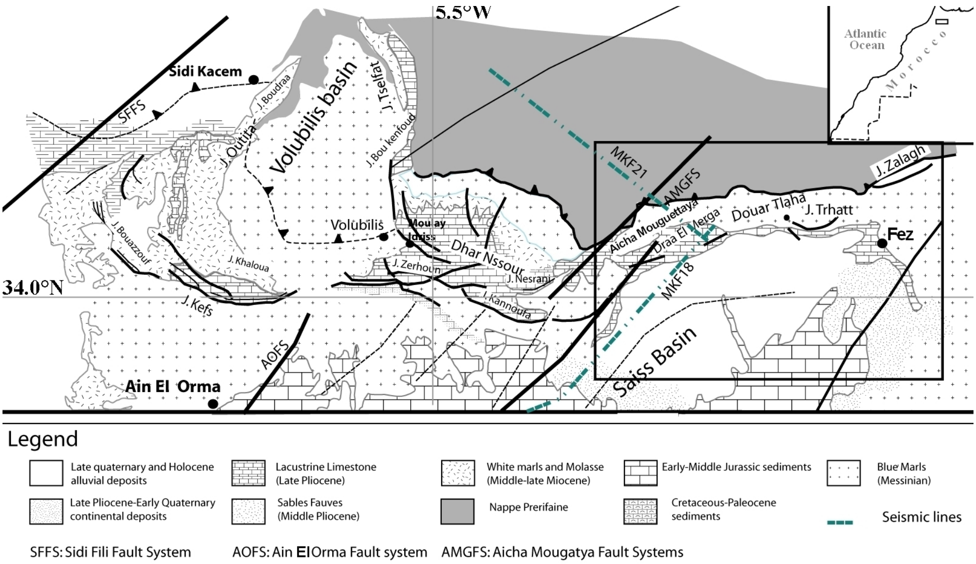

Figure 5. Simplified structural map of the South Rif Front in the Fez area (compiled from several sources, see text), and location of seismic profiles MKF18 and MKF21. The square shows the Fez area studied in this paper.

Outcrops of Cretaceous formations are scarce, and the formations of this period overlie the Early and Middle Jurassic ones with a stratigraphic gap of Late Jurassic sediments. The Mesozoic formations are overlain by Middle Miocene and younger formations, which belong to the Prerif Nappe accretionary wedge complex, and to the late Miocene post-Nappe marine deposits related to the Rif corridor. These are overlain by the Pliocene lacustrine deposits of the Saïss plain, which emphasize a regressive phase (Taltasse, 1950; Ahmamou, 2002).

The recent history, consisting of 5 stages (Faugères, 1981), is characterized by the compression related to the convergence, which generated the main thrusts. Among these stages, two major ones were initially recognized by Faugères (1981): a NE-SW oriented horizontal compression during the Mio-Pliocene, followed by a NNW-SSE compression in Plio-Quaternary times. The following authors also adopted the same chronology.

The most conspicuous E-W ridges produced by compression are, from ENE to WSW (Fig. 5), Zalagh, Trhatt, Aicha Mouguettaya, Nesrani, Kannoufa and Zerhoun. This trend shifts to N-S at Volubilis, forming the Bou Kenfoud and Tselfat mountains, and is repeated westwards forming an arcuate line of ridges towards Sidi Kacem (Faugères, 1981; Zizi, 1996; Roldán et al., 2014). The emplacement of the Prerif Nappe during the Middle Miocene was contemporaneous to the creation of the ridges.

This phase was followed by deposition of about 2 km of "post-Nappe" sediments consisting of yellow and blue marls in a marine corridor at the front of the Rif. Regression of the sea during the Pliocene caused the withdrawal of the sea, and the area was subject to continental deposition with lacustrine and palustrine sediments (Taltasse, 1950; Ahmamou et al., 1989; Ahmamou, 2002).

4.2. Main geological structures around Fez

Numerous neotectonic (Pliocene and Quaternary) structures were described near Fez by Ahmamou and Chalouan (1988), Dridri and Fedan (2001), Moratti et al. (2003), Bargach et al. (2004) Sani et al. (2007) and Poujol et al. (2017) and local structural sketches of each structure were given by Benmakhlouf (2001). In addition, the area is punctuated by numerous thermal springs such as the famous Moulay Yacoub thermal station (e.g. Benmakhlouf, 2001; Tassi et al., 2006). In the following, we describe the major ones, which are the Zalagh and Trhatt ridges, and the Aicha-Mouguettaya-Draa El Merga system.

The Zalagh ridge, located just 5 km to the NE of the city (Fig. 5), is a 7 km-long, ENE-WSW trending narrow anticline involving the Jurassic and Miocene formations. The anticline is affected at its limbs by longitudinal high-angle faults and is delimited by transverse faults which make the detailed structure relatively complex. Fresh fault planes striking ENE-WSW were described from the back fault of the ridge, with a reverse displacement on the SSE to S-dipping planes (Moratti et al., 2003). This anticline is considered by Charroud et al. (2007) as part of a frontal thrust system involving other thrusts located southwards. Structural analysis carried out by Ait Brahim (1983) shows two stages: a latest Miocene NNE-SSW compression followed by a NNW-SSE one during the Pliocene-Quaternary. A contemporaneous NE-SW to WNW-ESE extension has been observed by this author at the western edge of the anticline.

The 4 km-long, ENE-trending Trhatt ridge is the closest structure to Fez, and is at present overlooking the new districts of the western part of the city (Fig. 5). It consists of an asymmetrical to overturned anticline with a NNW-dipping axial plane, involving the Jurassic formations at its core overlain by the Miocene and also vertical Plio-Quaternary formations at the southern limb (Bargach et al., 2004; Charroud et al., 2007). The anticline is bounded at its periclinal terminations by vertical faults oriented NNW-SSE (dextral strike-slip) in the west and NNE-SSW (sinistral strike-slip) in the east. It is interpreted by Charroud et al. (2007) as a fault-propagation fold developed over a shallow thrust. Growth of this anticline is related to two stages: in the first one, the state of stress corresponds to a late Miocene horizontal compression oriented NNE-SSW followed by a NNW-SSE compression of Plio-Quaternary age, which is well recorded in the Pliocene conglomerates showing progressive tilting which attest for its neotectonic character (Ruano et al., 2006).

The frontal fold of Jbel Trhatt continues westwards until Jbel Aicha Mouguettaya (Bruderer et al., 1950; Tilloy, 1950). The southern limb of the fold is emphasized morphologically by a crest of almost-vertical strata of the Saïss Plio-Quaternary formations overlying the Miocene marls. Within this structure appears a salient where Poujol et al. (2017) recently described at Douar T'laha E-W faults striking E-W with dips of 30° (external younger fault) and 60°N (internal older fault). The scarps have vertical displacements of 0.9-1.7 m in the most recent terrace and a (cumulative) 12 m vertical displacement respectively, affecting older deposits that they relate to the displacement of the frontal fault during the 1755 earthquake. Poujol et al. (2017) obtained OSL dates of 5.2±0.2 ka for a minimum burial age and a 8.1±0.9 ka for a weighted average age. For the internal fault, ^{14}C dating of offset charcoal beds yield ages at 1685±21 AD and 1709±20 AD, which they associate to the 1755 event.

West of Fez appears the NE-SW striking Nzala des Oudayas fault system to which are related two main structures: the Aicha Mouguettaya Ridge and the Draa El Merga anticline. Within the Aicha Mouguettaya ridge, the Pliocene formations are folded to a vertical position or even overturned. In addition, their strike shifts from ENE-WSW in the east to N-S in the west at the proximity of the NE-SW fault bounding the Saïss basin to the NW against the Nzala des Oudayas salt dome. Structural analysis data from Ait Brahim (1983) show a N-S horizontal compression; however, Ahmamou and Chalouan (1988) observed that numerous faults are in fact normal faults that were rotated during the compressional stages. Sani et al. (2007) determined two tensors with the horizontal compressive stress oriented NE-SW (older) and NW-SE (younger). South of the Aicha Mouguettaya structure appears the Draa El Merga anticline, which gently affects the Pliocene lacustrine formations (Ahmamou and Chalouan, 1988; Sani et al., 2007; Poujol et al., 2017). According to Ahmamou and Chalouan (1988), the ENE-WSW trending anticlinal zone is delimited by left-lateral strike-slip faults and includes en echelon fold axes with a NNW-SSE trend related to a NNE-SSW compression. These folds are affected by a second compression with a NNW-SSE trend which could have accentuated the structures and reactivated the nearby Aicha Mouguettaya thrust with a dextral displacement. Precise DEM elaborated by Poujol et al. (2017) confirm the structure and the right-lateral offset and also shows that the fold is asymmetrical, the northern limb having a smaller dip angle.

Westwards, the Nzala des Oudayas Fault system (Sani et al., 2007), to which belongs the Aïcha Mouguettaya Ridge, offsets the Rif front to the SW. The western branch includes fault-propagation folds such as the Kannoufa and Zerhoun ridges, which have been or are still active, as attested by surface ruptures that may have been created during the Meknès earthquake in 1755 (Vogt, 1984; Moratti et al., 2003). As they are closer to Meknès than to Fez, Meknès should have suffered more their seismic activity, as during the 18 November 1755 major earthquake (Moratti et al., 2003).

South of Fez, the only seismogenic structures may be the right offset en echelon faults bounding to the NW the Middle Atlas chain, and named the Agourai-El Hajeb-Ain Cheggag Fault system (Sani et al., 2007). These faults, striking NE-SW, show some recent activity expressed by small normal faults (Sani et al., 2007, their figures 10 and 12, their site 2 corresponding to horizontal extension, not compression). In addition, this area is close to the Quaternary volcanic sources of the Middle Atlas chain.

4.3. State of stress

The state of stress determined by several authors on the base of stress inversion from slickenslides (Ait Brahim, 1983; Ahmamou and Chalouan, 1988; Ruano et al., 2006) corresponds to a NE-SW to NW-SE horizontal maximum compressive stress, with some variations. For instance, Ait Brahim (1983) suggested two phases: a NNE-SSW compression, followed by a NNW-SSE one. Sani et al. (2007) describe some sites with ENE-WSW compression, which we interpret as reflecting the direction of escape of the Rif. One of their sites is located in the lacustrine Plio-Quaternary formation west of the Zalagh Ridge. Stress tensors determined by Sani et al. (2007) at Draa El Merga correspond to NNW to NNE horizontal compression.

Only two focal mechanisms were determined in the area. The first was determined by Medina and Cherkaoui (1992) for the $\boldsymbol{M_d}$=4.6 earthquake of 2 July 1971 (34.05°N; 5.03°W) which corresponds to strike-slip faulting with a E-W pressure axis. However, data are scarce for this event (11 stations with a large azimutal gap). The second corresponds to the earthquake of 27 September 2000 ($\boldsymbol{M_d}$=4.6), located at 34.26°N; 5.22°W, which shows pure reverse faulting (ETHZ) or with a small strike-slip component (MED) (Medina, 2008). The P-axis trend is 355°, 00° (ETHZ) or 196°, 34° (MED).

4.4. Geodetic and seismotectonic data

Since the early 2000s, GPS data are available for Morocco, and have been used to determine the present-day relative motions of Europe in relation to Nubia (Tahayt et al., 2008; Vernant et al., 2010; Koulali et al., 2011). More recent studies that have focused on the displacement of the structural blocks in Morocco (Rif, Atlas, Meseta) in relation to fixed Nubia, have shown that these blocks may have different displacement directions and different velocities. North of the Fez area, the general motion of the Central Rif is SW, which may be interpreted as an escape of the chain due to the toothpaste effect of the NW-SE general convergence. Following the initial general studies of Vernant et al. (2010) and Koulali et al. (2011), who showed the general displacement towards the southwest, a more detailed study was carried out by Chalouan et al. (2014), who installed GPS stations at Zalagh and Trhatt ridges. The most important result (Fig. 6) is that the Trhatt ridge moves rapidly to the SSW (4-5 mm.yr^{-1}) relatively to Nubia and to the centre of the Saïss basin, while the Zalagh ridge moves slowly to the east. The stations installed in the Middle Atlas also show displacements of about 2 mm.yr^{-1} which corresponds to right-lateral displacement with a normal component along the bounding faults.

The only quantitative data on fault displacements are available from Poujol et al. (2017) who have measured offsets of Quaternary terraces and calculated the source parameters. On the base of the bed offset of the most recent terrace dated at 1685±21 AD and 1709±20 AD, they find a net coseismic slip of 0.9-1.7 m (for a single event), which should have triggered an earthquake of magnitude $\boldsymbol{M_w}$ = 6.5-7 after deposition and a 30 km rupture according to the equations of Wells and Coppersmith (1994). They assign the whole displacement to the 1755 AD event (5.2 after Pelaez et al., 2007). For the internal fault, they measured a mean Holocene slip rate of 3.5 mm/yr, a value that they consider in conformity with GPS measurements. From all previous data, they find a recurrence interval of 383±100 yr, and they use the events of 1522 and 1755 to ascertain it. However, we have indicated that the 1522 event was located in the Almeria region, where it caused a tsunami.

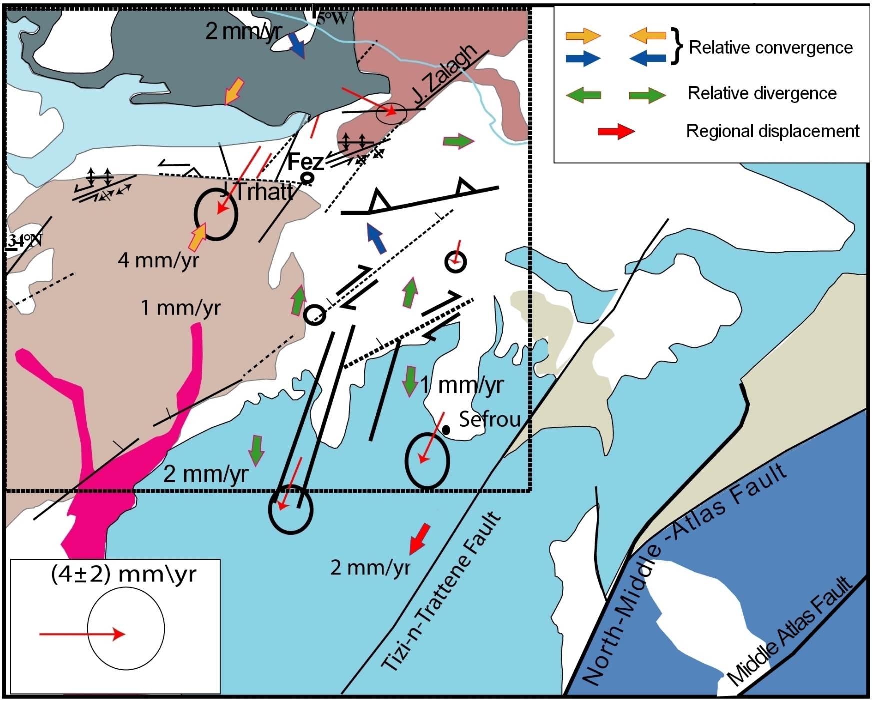

Figure 6. GPS data from various sites in the Fez area showing the relative displacements of blocks. The error ellipse are 95% confidence. Simplified from Chalouan et al. (2014).

4.5. Subsurface data

Because of the proximity of the productive Gharb basin, the Fez-Meknès-Sidi Kacem area has been relatively well explored by boreholes and cartography since the 1950s (Tilloy, 1950) and more recently by means of seismic reflection lines, which have been published by Zizi (1996), Sani et al. (2007), Roldán et al. (2014) and Capella et al. (2017).

The seismic lines show a typical Atlas-like “ejective style”, with narrow anticlines and wide synclines (see plates in Zizi, 1996). The post-Triassic cover appears to be decolled from the evaporitic Triassic formations, especially above the Sidi Fili and Ain El Orma basement faults. The role of diapirism has certainly been important during the compressional stage but not before, because of the absence of the typical changes in thicknesses induced by halokinesis. Another particular pattern in the seismic profiles is the emplacement of the Prerif Nappe which is clear in synclinal areas such as the Volubilis basin and on the folds’ limb (Zizi, 1996; Sani et al., 2007; Roldán et al., 2014).

This very peculiar pattern of extruded thrusts has been modeled by Sani et al. (2007) and seems to be controlled by the pre-existing extensional structures. Their model, based on pre-existing NE-SW basement faults and two-fold compression stages (NE-SW, and N-S horizontal compression), leads to similar real structures so it may be a good approximation to the generation of the Rides.

Near Fez, profile MKF18 (Zizi, 1996), oriented NE-SW, illustrates the thickening of the Mio-Pliocene sediments towards the South Rif Front (Fig. 7). At its north-eastern termination near the SRF, the Saïss formations are affected by a fold whose northern limb is faulted, making the anticline appear as a pop-up or flower structure. This fold corresponds to the deep expression of the Draa El Merga anticline.

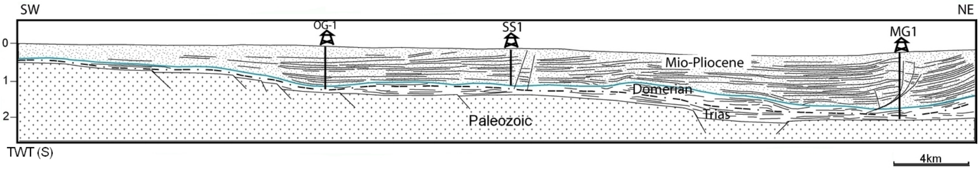

Figure 7. Seismic section MKF18 across the Saïss basin (location in figure 5). Redrawn from Zizi (1996).

Another interesting profile (MKF-21) was published by Sani et al. (2007). The profile, oriented NW-SE, illustrates the importance of the Nzala des Oudayas diapiric structure and its large high-angle bounding faults (Fig. 8). The Nzala des Oudayas high-angle bounding fault to the SE seems to extend into the deep basement at 4 s TWT, and overthrusts the Saïss formations. The latter are affected by an anticline (Draa El Merga) interpreted by these authors as related to the rise of the Triassic salt.

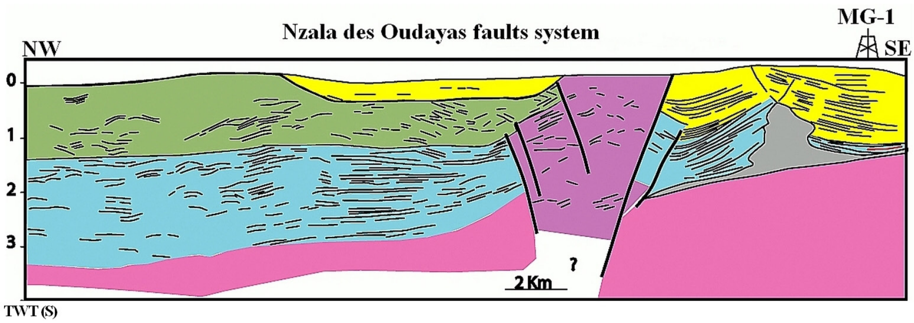

Figure 8. Seismic section MKF21 across the Nzala des Oudayas structure (location in figure 5). Redrawn from Zizi (1996). Light red = undefined Palaeozoic basement units; violet = Triassic units and evaporites; light blue = undefined Jurassic units; light brown = Early Middle Miocene foredeep units below the NP; light green = Nappe Prerifaine complex; yellow = Late Miocene foredeep and recent deposits of Saïss basin.

4.6. Seismicity in the vicinity of Fez

The seismicity map of the immediate vicinity of Fez shows concentration of earthquakes in the area just west and north-west of the City. This is the region where the seismicity is most active and manifest itself from time to time by earthquakes with $M_w \geq 4.5$. The epicenter of the major earthquake of May 11, 1624 was probably located at 34.1°N and 5.1°W, about ten kilometers west of Fez (Fig. 9).

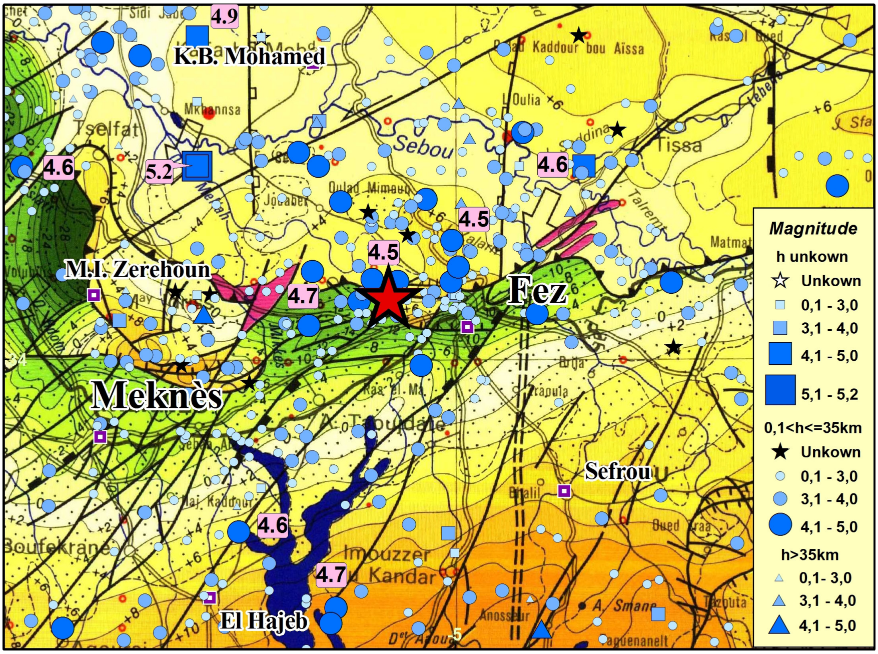

Figure 9. Seismicity of Fez and surrounding area (1901-2016). The red star shows the probable location of the epicenter of the 1624 Fez earthquake.

5. Evaluation of macroseismic intensities

According the authors, the epicentral intensity of the 1624 earthquake was estimated between VIII-XI and X (Poirier and Taher, 1980; Ramdani et al., 1989; Pelàez et al., 2007). In order to assess the effects engendered by historical earthquakes, several empirical relationships between the intensity values and epicentral distance were established. The most commonly used is the Kövesligethy-Sponheuer law which is written as (Sponheuer, 1960):

$$I_o - I_n = 3 \log \left(\frac{\sqrt{R_n^{\,2} + h^2}}{h^2}\right) + 1.3\, \alpha \left(\sqrt{R_n^{\,2} + h^2} - h\right)$$

Where $\mathbf{I_o}$ is the epicentral intensity, $\mathbf{I_n}$ is the local intensity at the epicentral distance $\mathbf{R_n}$, **h** is the focal depth and **α** is the attenuation coefficient. For computing intensities that would have been observed during the historical earthquake of 1624, we used the attenuation law established for the Saïss region of where **α** = 0.0010 ± 0.0005 and ***h*** = 22.5 km ± 8.7 km (Cherkaoui, 1991); the computed results are shown in Table 2. We tested values from $\mathbf{I_o}$ = VII-VIII to $\mathbf{I_o}$ = X (MSK-64) by using the attenuation relation of Kövesligethy-Sponheuer (Sponheuer, 1960). The value Io = VIII-IX (MSK-64) is the one which best corresponds to the historical macroseismic observations (Figs. 10, 11).

Table 2. Local intensity values ($\mathbf{I_n}$) as function of the epicentral intensity $\mathbf{I_o}$.

Locality	Distance (km)	I_o=8	I_o=8.5	I_o=9	I_o=10
		I_n	I_n	I_n	I_n
Fez	12	7.8	8.3	8.8	9.8
Sefrou	40	7.0	7.5	8.0	9.0
Meknès	50	6.8	7.3	7.8	8.8
Beni Zeroual	70	6.4	6.9	7.4	8.4
Taza	100	5.9	6.4	6.9	7.9
P.V. Gomera	140	5.4	5.9	6.4	7.4
Beni Ouriaghel.	155	5.4	5.9	6.4	7.4
Salé	160	5.3	5.8	6.3	7.3
Melilla	240	4.6	5.1	5.6	6.6
Safi	435	3.6	4.1	4.6	5.6

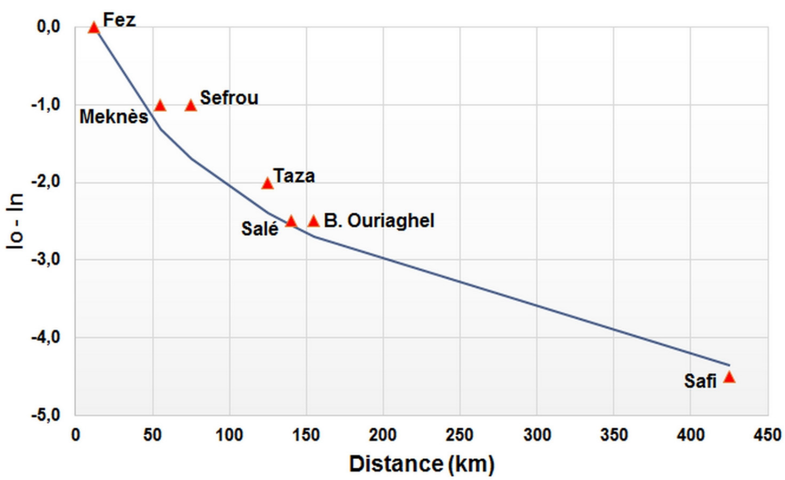

Figure 10. Kövesligethy-Sponheuer intensity attenuation curve as a function of the epicentral distance for the 1624 Fez earthquake. Where h=22.5km, α=0.0010 and Io=VIII-IX (MSK-64).

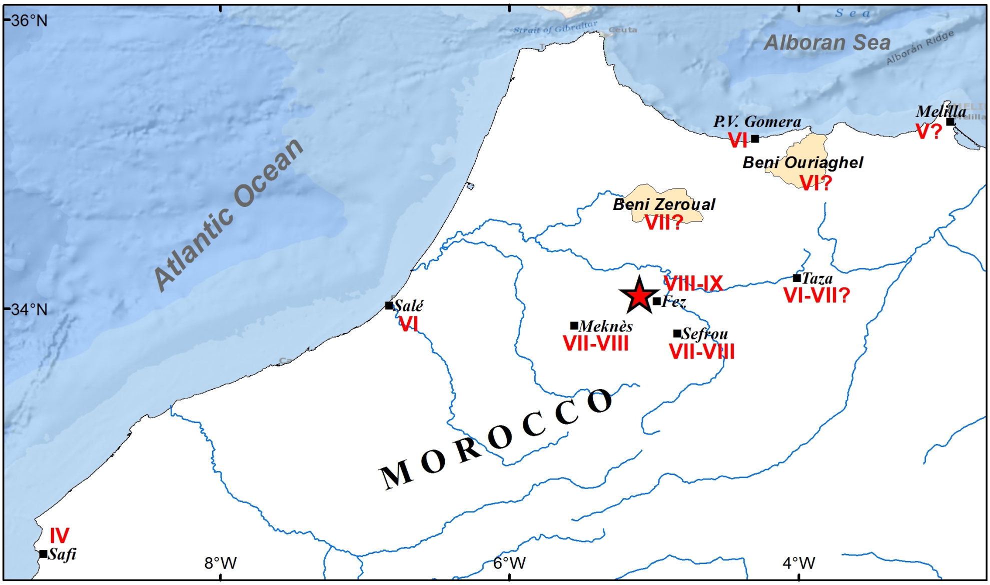

Figure 11. Macroseismic map of the May 11, 1624 earthquake.
The epicenter is indicated by a red star.

6. Evaluation of earthquake magnitude

To calculate the magnitude of the 1624 Fez earthquake, we have used Magnitude-Intensity relationships valid in Morocco:

a. $M_d = 0.430\ I_o + 1.706 \pm 0.652 \quad (IV \leq I_o \leq X)$
b. $M_d = 0.578\ I_o + 0.849 \pm 0.646 \quad (V \leq I_o \leq X)$

To convert the magnitude duration M_d to the moment magnitude M_w, we use the following relations (Rueda and Mezcua 2002):

c. $M_d = 0.91 \times M_{bLg} + 0.32$
d. $M_w = 0.311 + 0.637 \times M_{bLg} + 0.061 \times M_{bLg}^{2} \; (2.5 < M_{bLg} < 5.7)$

For an epicentral intensity Io =VIII-IX (MSK-64), the magnitude values (M_d, M_w) are given in the Table 3:

Table 3. Magnitude values (M_d and M_w) of 1624 earthquake are calculated from a, b, c and d relationships for an epicentral intensity I_o = VIII-IX (MSK-64).

Relation	**a**	**b**
M_d	5.36	5.76
Relation	c and **d**	
M_w	5.71	6.30

For this historical earthquake, we retain the average magnitude $M_w = 6.0$.

7. Discussion

We have identified several historical earthquakes sufficiently violent to cause loss of lives and significant destruction that are poorly known and need more work. (Tab. I). The historical sources are poor of information about earthquakes and often contradictory. The 1624 Fez event is probably the most destructive earthquake, after the 1755 Lisbon earthquake, which has ever occurred in this area since the IXth century. Yet despite its importance, only few papers have been devoted to this event.

Concerning the source of the 1624 earthquake, we have reviewed several clearly neotectonic structures that have been described in detail by various authors. However, all these structures (Zalagh, Trhatt, Douar T'hala, Aicha Mouguettaya and Draa El Merga) are segments that are aligned along the South Rif Front for about 30 km. As the rupture for a M_w=6 earthquake is about 10 km with a displacement of 1 m, we may suggest that the western part of this fault zone was the source of the earthquake.

Although there are conspicuous ground ruptures in the field, we think that they only represent surface effects associated to a deeper plane (the rupture may reach 100 km^2 during a M_w=6 event), such as those appearing in the seismic profiles published by Zizi (1996) and later authors. Among these, the most likely candidates are the Draa El Merga and Nzala des Oudayas faults, which cut the basement with a high angle dip.

If we admit that the SRF in this part was the source of the 1924 and other events, an important issue is to extrapolate the displacement along the E-W fault. Ahmamou and Chalouan (1988) indicate a left-lateral transpression along the limbs of the Draa El Merga anticline, but the last stress direction they determined is almost perpendicular to the strike of the SRF, as also found by Sani et al. (2007). Interpretation of seismic profiles may also suggest a flower structure at Draa El Merga, so it is not excluded that the displacement was strike-slip.

Conclusion

Morocco has a moderate seismicity characterized by small events of order of magnitudes smaller than five, but destructive earthquakes have struck the country periodically throughout its history. The use of historical earthquake information is essential when performing seismic hazard assessment. The 11 May 1624 earthquake can be considered, with the 1755 Lisbon quake, as the strongest historical seismic event that have severely affected Fez and its surroundings. They left over many human life losses and caused a large number of damage affecting the infrastructure as well as the environment. It occurred in one of the most active seismic zones in central Morocco, and near heavily populated regions at present, understanding this earthquake may have implications for seismic hazard assessments of the region.

In this paper, we have investigated the major 1624 earthquake using available contemporary documents. These documents provide more detailed information about the damage caused by the earthquake in Fez and in other localities. The analysis of the macroseismic data allowed us to evaluate the epicentral intensity of the earthquake and therefore its magnitude. The use of the geological, tectonic, geodetic and recent seismic data of Fez area, allowed us to locate the epicenter of the earthquake, in the Draa El Merga - Nzala des Oudayas area.

This research demonstrates that this particular earthquake should not be neglected, and we recommend, that this event has to be incorporated in the seismic catalogues to complete the list of important earthquakes that have occurred in this area.

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