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Maximum Magnitudes and Accelerations Determination in the Rif Mountain Belt, Northern Morocco

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Abstract: *The Rif mountain-belt is considered the most seismically active chain in Morocco. In this study we use deterministic approach to assess the seismic hazard within the Rif region, in long term. For this purpose, we apply empirical formulas in order to compute the maximum credible earthquake (MCE) taking into account several criteria related to seismic potential of the fault. The results show that for the Rif region, the MCE has a magnitude of 6.9 that could occur every 10000 years (period of reference for the MCE). Using a suitable empirical attenuation law for our study region, we compute the accelerations that could be generated by the maximum magnitude estimated for each fault. A maximum accelerations contour map is then produced. This map shows zones with high seismic hazard, particularly; along the El Jebha fault with an acceleration value 0.33g. Some important Moroccan cities like Tetouan, Tangier and Rabat has moderate seismic hazard with accelerations values around 0.23g and 0.25g . This map is a useful tool for decision makers that will help them to take into account this significant aspect of the risk for territorial and urban planning.*
Keywords: *acceleration, magnitude, maximum credible earthquake, deterministic approach, Morocco, Seismic hazard.*

I. Introduction

In the last century, Morocco experienced several violent earthquakes. This seismic activity is mainly attributed to its position at the collision boundary between the African and the Eurasian plates. Also, historically, Morocco knew some destructive earthquakes such as the November 1st, 1755 Lisbon earthquake, with magnitude was evaluated close to 8.7 [20,14]. This event generated a large tsunami that devastated most of Moroccan Atlantic coastal cities: Tangier, Asilah, Larache, Rabat…[10]. Other earthquakes were caused by the tectonic compression along major faults onshore Northern Morocco.

The region of Al Hoceima located in North of Morocco was struck by strong earthquakes in two times, on Mai26th 1994 with magnitude $M_d = 5.6$ and on February 24th 2004, with magnitude $M_w = 6,5$. The epicentral area was located 10 km south of the Al Hoceima city . At least 600 people were died and many thousands of people were left homeless [13].

Since, it is still not yet possible to predict the exact time and location of an upcoming important earthquake, it is necessary to take suitable measures to limit losses in human lives and material damages. For prevention purposes, it is important to initially delimit areas prone to earthquakes through a seismic zoning and to establish seismic hazard maps.

In this paper, we undertake a deterministic hazard study within a long-term framework. This study aims at the assessment of maximal accelerations that could be generated by the faults within the Rif intermountain-belt. Our study area ranges between latitudes 33.5° and 36° N and longitudes 2.5° and 7° W. The object of this study is to draw a map of maximum ground accelerations that could be generated in this region in a period range of nearly ten thousand years.

II. Geological Setting

The study area covers the whole Rif intermountain belt, which is characterized by multiple folding, often accompanied by metamorphism and by the phenomenon of over-thrusting napes that progress towards the south, due to a NNW-SSE compression. This zone has undergone a large deal of crustal instability [18] and is considered to be geodynamically very complex.

Three great paleogeographic domains constituted the Rif chain [9, 4, 7, 24]. From the interior to the exterior of the chain (Fig.1), we note three important domains: i) the internal Rif; made by a stack of napes resulting from the Alboran block which installation has an Alpine age, ii) the flysch domain considered as an entirely immigrant domain, it surrounds the internal zones from the Strait of Gibraltar till the Al Hoceima city. It is constituted by several units of which the most significant are; the Tisirene nape, the Beni Ider nape, the

Melloussa-Chouamat nape and the Numidienne nape [1], iii) the external Rif which includes two units: the Subrif and the Prerif.

Figure 1: Major structural domains of the Rif-Mountains. 1- Internals zones 2- Flyschs domains 3- Externals zones 4- post-orogenics basins.

III. Neotectonic Analysis

The northern part of Morocco is situated between the northern boundary of the West African Craton and the Alboran Sea. It was affected in the Neogene by a system of faults governed by the compressive motion of the African and Eurasian lithospheric plates. In the Miocene, the direction of the principal stress changed in the Rif Mountain and its foreland due to the motion to the west of the Alboran microplate between Spain and Morocco [15]. In the Tortonian- Messinian, the stress direction changed from NE-SW to N-S and in the Plio-quaternary from the N-S to NNW-SSE [2,17].

The neotectonics and the present evolution of the Northern part of Morocco are guided by four main trends of faults NE-SW, N-S, NW-SE and E-W (Fig. 2). These faults directions are clearly visible in "Map of Recent Movements in the Rif" at 1/500000 [19]. and consist of normal faults; strike-slip faults, morphological accidents, thrust faults (napes) and some undifferentiated faults.

In the present work, we digitized all significant faults and accidents on Morel et al.'s map and attributed to each fault an identification number. We identified 117 significant accidents labeled from N°1 to N° 117; it lengthened on four major directions:

- Faults with NE-SW directions. These are generally normal faults like the Oued-Laou fault (N°14) or strike slip faults like the El Jebha fault (N°3) and the Nekor fault (N°8). We note also some undifferentiated faults along this direction,
- Faults with NW-SE directions are generally thrust-sheets like faults: N°52, N°53 and N°54 or undifferentiated faults like the Tangier-chefchaouen fault (N°22,N°23, N°24). The thrust-sheets occur in fact along an arc of circle parallel to the Gibraltar Arc. They are thus oriented NW-SE in the western side of our study area and change direction to become NE-SW in the eastern part,
- Faults with E-W direction, most of it are normal faults. They are observed particularly in the Tangier peninsula, such as the one along the Martil River (N°2) near Tetouan city. It is parallel to the fault responsible for the collapse of the Strait of Gibraltar (N°1) in the lower Pliocene [1]. Also, the Rabat-Tiflet axis (N°18) is situated in the southwest part of our study area,
- Faults with N-S direction. These are generally morphological accidents. The most significant ones are the Chefchaouen (N°4) and the Ghafsai accidents (N°45, N°46, N°47, N°48). Other faults are normal, such as the Trougout fault (with a strike-slip component) (N°90) and the Jbel Hammam corridor (N°75 and N°76).

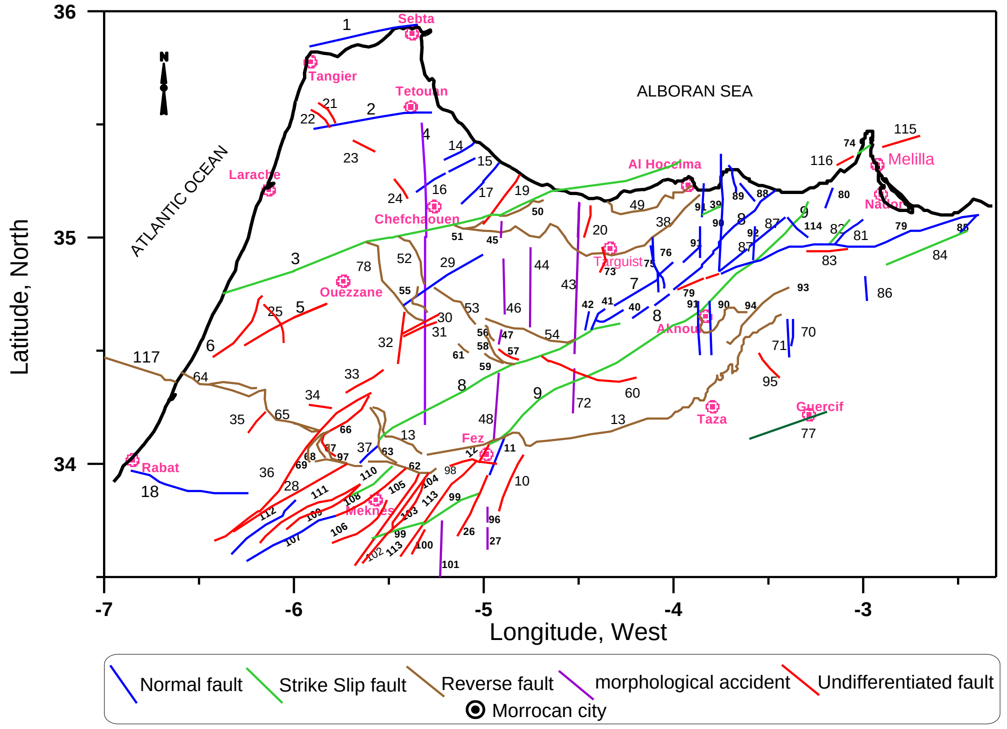

Figure 2: Study area and type faults in the Rif Mountain belt, Northern Morocco. The faults reported in this map are digitized from the "map of recent movements in the Rif "at 1/500 000 (Morel et al.,1992), values correspond to the identified number of each fault.

IV. Seismic Data

In this study, we use seismic data recorded by the Moroccan seismic network. Seismic data extends from 1990 to 2010 with magnitudes ranging between 2.0 and 6.5.The depth of the events is mostly between 2 and 30 Km, rarely it reaches 70Km. In order to have not a condensed map, we decided to remove aftershocks with magnitude less than 3.0 that follow the two destructives events which Al Hoceima region has known in 1994 and 2004.

The seismic map (Fig.3) shows that the seismicity is rather diffuse. However, we note some concentrations of epicenters corresponding to the seismic activity of these zones, the clearest one is in the Al Hoceima region. We also notice some seismic alignments, in particular those along NW-SE directions, this seismic activity is probably due to the imbricate napes being under movement in the Rif Mountain.

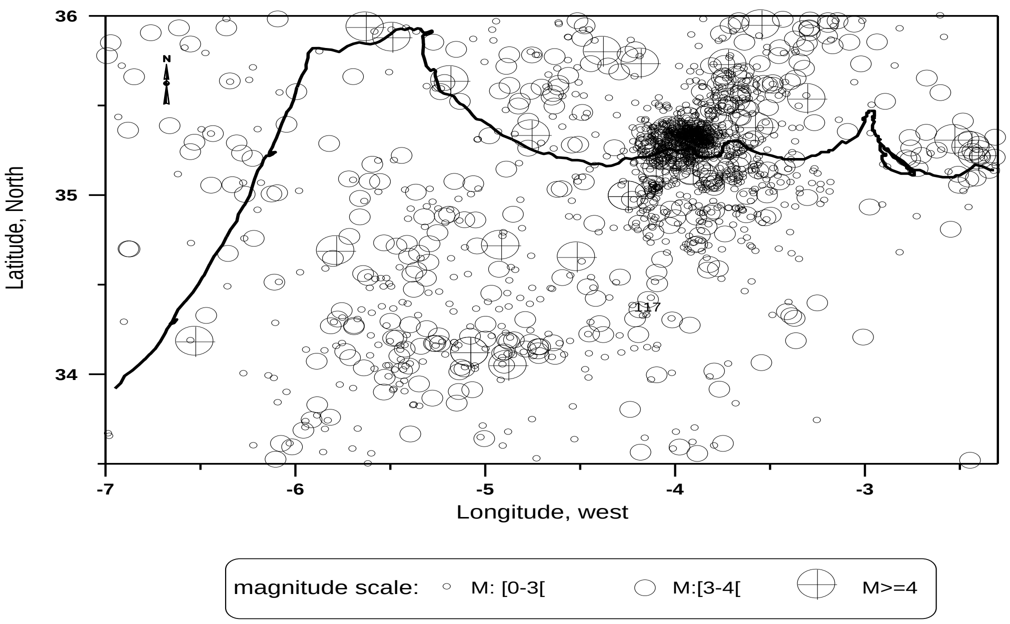

Figure 3: seismic activity in the study area for the period from 1990 to 2010.

V. Seismotectonic Analysis

The comparison of the seismicity and mapped faults (Fig. 4) reveals a good correlation between seismicity and the observed faults, in particular with the NE-SW and N-S directions. The analysis of this map shows three seismotectonic zones : i) a seismotectonic zone with NE-SW direction along strike-slip faults. The longest fault being the Nekor fault (N°3), ii)a seismotectonic zone with N-S direction where some seismic events are located and lined up along N-S faults like the Chefchaouen accident (N°4) and the Ghafsai accident (N°45, N° 46, N°47, N°48), iii) a seismotectonic with NW-SE direction. It covers the thrust faults (napes) existing in the study area witch knew significant seismic activity in the past.

The mentioned seismotectonic zones are merely identified on the basis of the seismic activity lining up along major fault directions in the area. It's however, quite difficult to associate separate seismic events to particular faults. It is also noteworthy that all important events recorded in this time-period, occur along strike-slip faults.

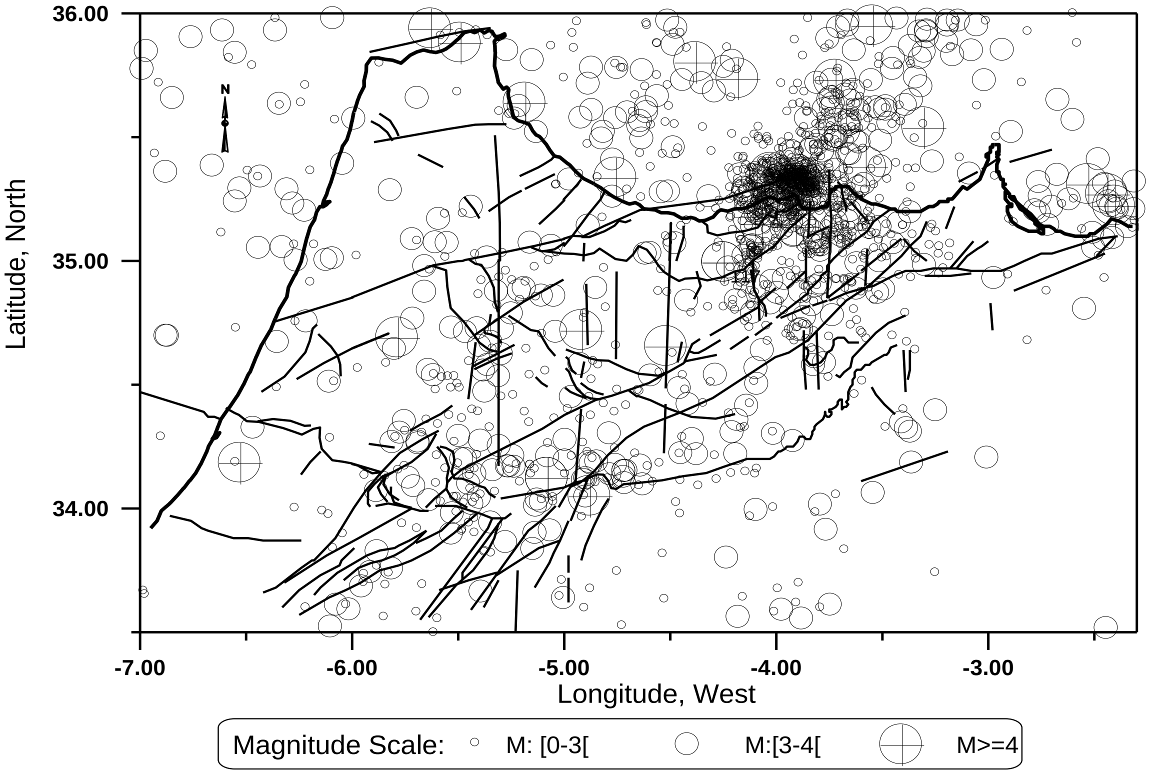

Figure 4: Seismotectonic map of the Rif area. Note the activity lining up along the thrust sheets in an E-W to a NW-SE direction.

VI. Maximum Credible Earthquake (MCE) and Faults Surface Rupture Length

Maximum credible earthquake (MCE) is a seismic event, which is based on the evaluation of the maximum seismic potential of a fault. It evaluates the movements of the ground that can cause the most damage to buildings. The MCE occurs once in nearly 10 000 years (ICOLD, 1989). The evaluation of the seismic potential of faults depends on various criteria related to the seismicity, recent deformations, and the dimensions of the active faults in the study area. Assessing seismic potential of a fault is generally reduced to estimate its parameters of rupture, in particular, its length or its displacement [22, 12, 8]. Several empirical relations connect magnitude to various parameters of the fault, other parameters were also used such as displacement with the length of rupture, magnitude with the maximum displacement on the surface or with total length of the fault, etc. [5, 6, 21].

In this study, we use the formulas developed by Wells and Coppersmith [23] to calculate the maximum magnitude M that could be generated by the surface rupture length of a fault. The assumption that the magnitude M is maximal is valid only if the parameters used are considered also as maximum values.

Initially, we proceed by estimating the potential surface rupture lengths (srl) for the existing faults. This assumption depends on the total length of the fault. In case the fault is rather short and linear, we take the whole length of the fault. While the fault is rather lengthy (over a hundred kilometers) and presents some discontinuities, we take the longest linear segment of the fault. The srl is then determined by equation (1):

$$M = A + B \log (srl) \qquad (1)$$

Where M is maximum magnitude, srl is surface rupture length(Km) and A and B are coefficients which the values depend on the fault nature. They are taken from the formulas developed by Wells and Coppersmith [23]. In our study area, we enumerated 117 faults, which are distributed as follows; 33 normal faults, 6 strike-slip, 25 reverse faults, 11 morphological accidents and 42 undifferentiated faults.

After computation, The results show that magnitudes vary between 6.0 and 6.9 (Table1). Consequently, the MCE could be generated by local faults (N°3) or (N°65), which are the El Jebha fault (senestral strike-slip) and one of the thrust faults (nape) respectively. Thus, the MCE in our zone of study would have a magnitude of about 6.9 and may occur once in 10000 years (period of reference for the MCE).

Table1: Major faults used in this study with estimated surface rupture length (SRL) and computed maximal magnitudes (M)

Number and name of known faults	**SRL (Km)**	**M**	**Number and name of known faults**	**SRL (Km)**	**M**	**Number and name of known faults**	**SRL (Km)**	**M**
F1	20.0	6.6	F40	10.0	6.2	F79	30.0	6.8
F2 (Martil River)	17.5	6.5	F41	7.0	6.0	F80	10.0	6.2
F3 (EL Jebha)	**35.0**	**6.9**	F42	10.0	6.2	F81	18.0	6.5
F4 (Chefchaouen Accident)	22.5	6.6	F43 (Tiflouest)	21.0	6.6	F82	15.0	6.4
F5	22.0	6.6	F44 (Taounate)	21.0	6.6	F83	10.0	6.2
F6	10.0	6.2	F45	10.0	6.2	F84	32.0	6.8
F7	25.0	6.7	F46	27.0	6.7	F85	12.0	6.3
F8 (Nekor)	25.0	6.7	F47 (Rafsai)	6.0	6.0	F86	12.0	6.3
F9	30.0	6.8	F48	27.0	6.7	F87	17.0	6.5
F10	12.0	6.3	F49	25.0	6.7	F88 (Boudinar)	11.0	6.2
F11	22.0	6.6	F50	22.0	6.6	F89	10.0	6.2
F12	13.0	6.4	F51	15.0	6.4	F90 (Trougout)	25.0	6.7
F13	25.0	6.7	F52	30.0	6.8	F91	26.0	6.7
F14 (Laou River)	15.0	6.4	F53	25.0	6.7	F92	16.0	6.4
F15	15.0	6.4	F54	25.0	6.7	F93	25.0	6.7
F16	17.0	6.5	F55	10.0	6.2	F94	13.0	6.4
F17	15.0	6.4	F56	10.0	6.2	F95	16.0	6.5
F18 (Rabat-Tiflet axis)	22.0	6.6	F57	12.0	6.3	F96	15.0	6.4
F19 (Bni Bouchra)	20.0	6.6	F58	25.0	6.7	F97	15.0	6.4
F20	10.0	6.2	F59	18.0	6.5	F98	10.0	6.2
F21	12.0	6.3	F60	10.0	6.2	F99	30.0	6.8
F22	14.0	6.4	F61	11.0	6.3	F100	13.0	6.4
F23 (Tanger-Chefchaouen)	12.0	6.3	F62	15.0	6.4	F101	22.5	6.6
F24	11.0	6.3	F63	15.0	6.4	F102	17.0	6.5
F25	12.0	6.3	F64	23.0	6.7	F103	14.0	6.4
F26	13.0	6.4	**F65**	**35.0**	**6.9**	F104	22.0	6.6
F27	10.0	6.2	F66	12.0	6.3	F105	33.5	6.8
F28	25.0	6.7	F67	15.0	6.4	F106	19.0	6.6
F29	20.0	6.6	F68	15.0	6.4	F107	18.0	6.5

F30	15.0	6.4	F69	20.0	6.6	F108	18.0	6.5
F31	15.0	6.4	F70	12.0	6.3	F109	15.0	6.4
F32	13.0	6.4	F71	17.0	6.5	F110	10.0	6.3
F33	16.0	6.5	F72	21.0	6.6	F111	15.0	6.4
F34	12.0	6.3	F73	7.0	6.1	F112	12.0	6.3
F35	13.0	6.4	F74 (Cherrana)	7.0	6.1	F113	18.0	6.5
F36	20.0	6.6	F75	15.0	6.4	F114	14.0	6.4
F37	15.0	6.4	F76 (Jbel Hammam corridor)	20.0	6.6	F115	10.0	6.2
F38	25.0	6.7	F77	16.0	6.5	F116	15.0	6.4
F39	10.0	6.3	F78	25.0	6.7	F117	13.0	6.4

VII. Maximum Accelerations Map

7.1. Attenuation law:

The attenuation relationship is a crucial piece of information in the process of a seismic hazard analysis. The development of these relations is based exclusively on recorded seismic events. They are called "attenuation laws" or "attenuation models" and generally include magnitude (M) and distance (r) as independent variables. The general form of the equation is given in equation (2)

$$\log(\gamma) = c_1 + c_2 M + c_3 r + c_4 \log(r) \qquad (2)$$

Where "γ" is the parameter to be predicted. It could be the maximum value of acceleration, velocity or displacement of the ground. While c_1, c_2, c_3 and c_4 are coefficients representing effects of the magnitude (M) and the distance (r) on the parameter γ.

Since, the seismic activity in northern Morocco is moderate and only few strong motion instruments are operating in the region, the strong motion data available are not sufficient to develop a regional attenuation model. That's why in this study, we use the equation of horizontal peak accelerations developed by Ambraseys [3], based on an extended data set recorded from events occurred in the Euro-Mediterranean region in an environment quite similar to the Rif region, in some cases. The Ambraseys' attenuation law used is given by equation (3):

$$\log(acc) = A + B{*}M + C \log(R) + D{*}R \qquad (3)$$

Where 'acc' is the maximum acceleration in g, M is the maximum magnitude; R is the hypocentral distance between the fault and considered site (Km). In our case R is the shortest distance between the considered fault and the site at which the maximum acceleration is calculated. Also, the coefficients are given by: A = -1.06; B = 0.245; C =-1.016 and D = -0.00045.

7.2. Maximal Accelerations calculation:

The first step in the calculation of the maximum acceleration was to divide the study area into cells of 0.125° by 0.125° (nearly 12 Km side). In the center of each cell, the accelerations were computed as generated by each of the 117 faults considered. The program compares all the values calculated and then the maximum value is kept. This computation is repeated for all the cells of the grid within our study area. We, thus, obtained 760 values of horizontal accelerations. With these values a contour map of isovalues of maximum acceleration was drawn. The equidistance is 0.02g (Fig.5).

The minimum value obtained is 0.03g and the maximum value is 0.33g. Maximum values are being clearly concentrated along the El Jebha-fault (N°3). Even though, this fault has not manifested any important seismic activity in this last century, it could still be quite active, since the whole area is subject to a strong compression.

Important values (0.29g) are observed along the Nekor fault (N°8) and also along the Chefchaouen accident (N°4). Other concentration of important values is noted near Kenitra city (0.27g) due to the existence of thrust napes in these regions. Near Tangier the maximal acceleration is about 0.25g, it's caused by the normal fault being in this area (N°1). The same value is observed near Tetouan city due to the fault (N°2) along Martil River. Areas with white colors have minimum values due to the absence of mapped fault, especially in the Atlantic Ocean and the SE part of the study area.

The zoning carried out in this study takes into account seismic risk rather on a regional scale. For particular large construction projects, it would be judicious to undertake additional seismic studies in order to take into account any specific site effects.

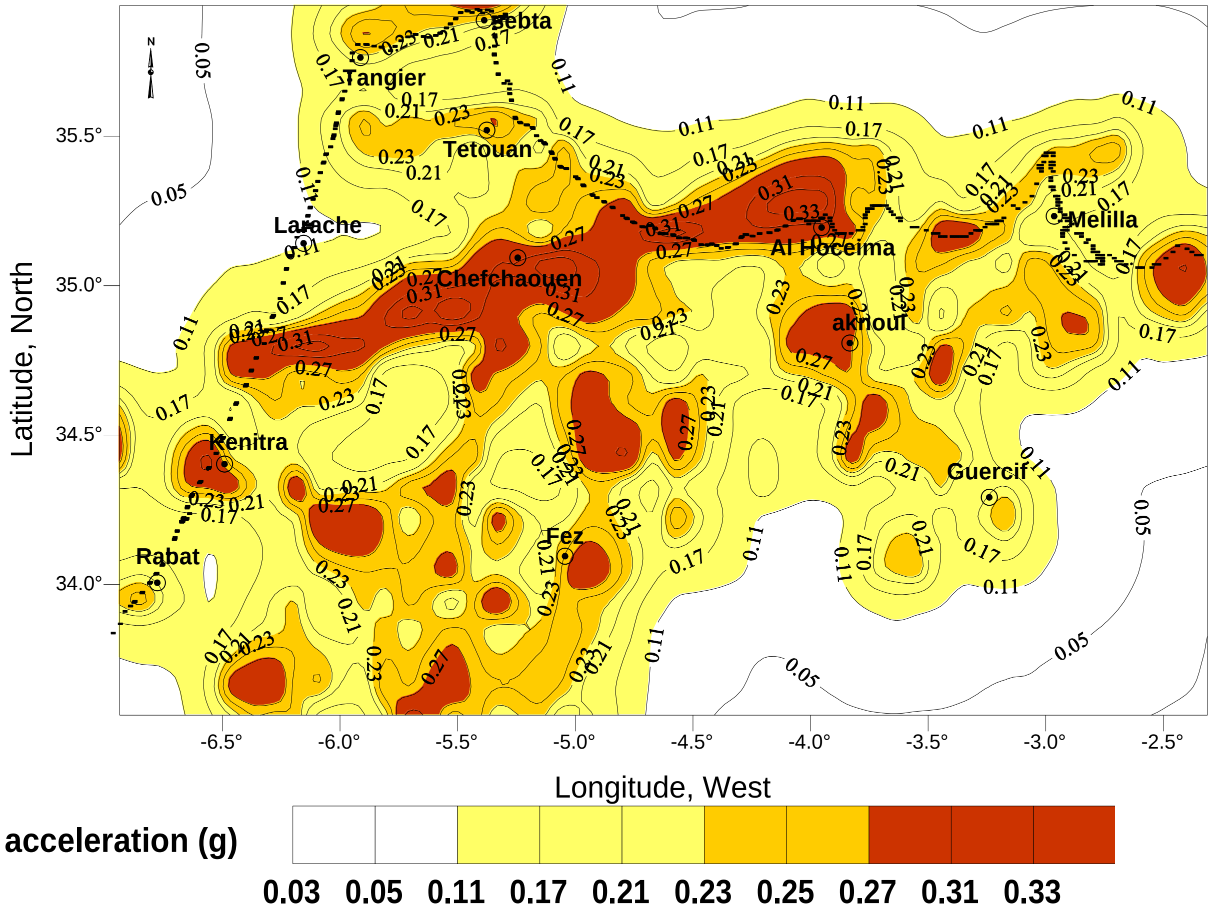

Figure 5: contour map of isovalues of maximum acceleration (in g). The equidistance is 0.02g**.** The area of highest accelerations (0.31 to 0.33g) occurs along the NE-SW oriented El Jebha fault.

VIII. Conclusion

The Rif region in northern Morocco is a complex geological area that is characterized by a diffuse seismicity and an important seismic risk. In this work, we use a deterministic approach for seismic hazard assessment in the long term. It is based on the hypothesis that the longest segment of the fault could mainly generate maximum magnitude. This approach is considered as a first approximation to the evaluation of the seismic potential of the different faults mapped in the area. The results thus obtained, can be improved by further refining the technique for the evaluation of the maximum magnitude that can be generated by each considered fault. Also, there may be blind faults that are not apparent in the surface and that could generate important events.

The map of maximum accelerations obtained gives an idea on the distribution of maximum accelerations expected in Northern Morocco. It shows that the maximum accelerations that could be generated in the Rif region can reach 0.33g along the NE-SW Jebha fault. Furthermore, we find in the Al Hoceima region, which shows a strong earthquake activity, an acceleration of 0.32g. In the last earthquake of February 24th 2004, the value of acceleration was about 0.24g; it was recorded near the Abdelkrim Khattabi dam located south of Al Hoceima at 12 km from the hypocenter, this acceleration is compatible with the acceleration value assessed in this region.

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