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Seismic Potential of the Main Active Faults in the Granada Basin (Southern Spain)

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Abstract — The main active faults of the Granada Basin are located in its central-eastern sector, where the most important tectonic activity is concentrated, uplifting its eastern part and sinking the western border. Several parameters related to the seismic potentiality of these active, or in some cases probably active, faults in this basin are used for the first time. Many of these faults can generate earthquakes with magnitudes larger than 6.0 M_W, although this is not the general case. The fault situated to the N of Sierra Tejeda, probably the one responsible for the big earthquake of 25/12/1884, stands out, because it could generate an earthquake with magnitude 6.9 M_W. Although at present all the data needed are not fully known, we consider that the final results show, as a whole, the average expected return periods of the faults in the Granada Basin.

Key words: Granada Basin, active faults, seismic potential of faults, Betic Cordillera.

Introduction

The Granada Basin is located in the central sector of the Betic Cordillera (Fig. 1) and is filled by upper Miocene, Pliocene and Quaternary sediments, covering the contact between the Betic Internal and External zones. There exist many faults that individualize the basin, also affecting its interior. In the basin and nearby there is a noticeable, generally moderate to very moderate seismicity, although in its southern sector occurred the so called "Andalusian Earthquake" (25/12/1884), $I_{o\ MM}$ = IX, the most important one known in the region. Also, other earthquakes of remarkable intensity occurred in this area.

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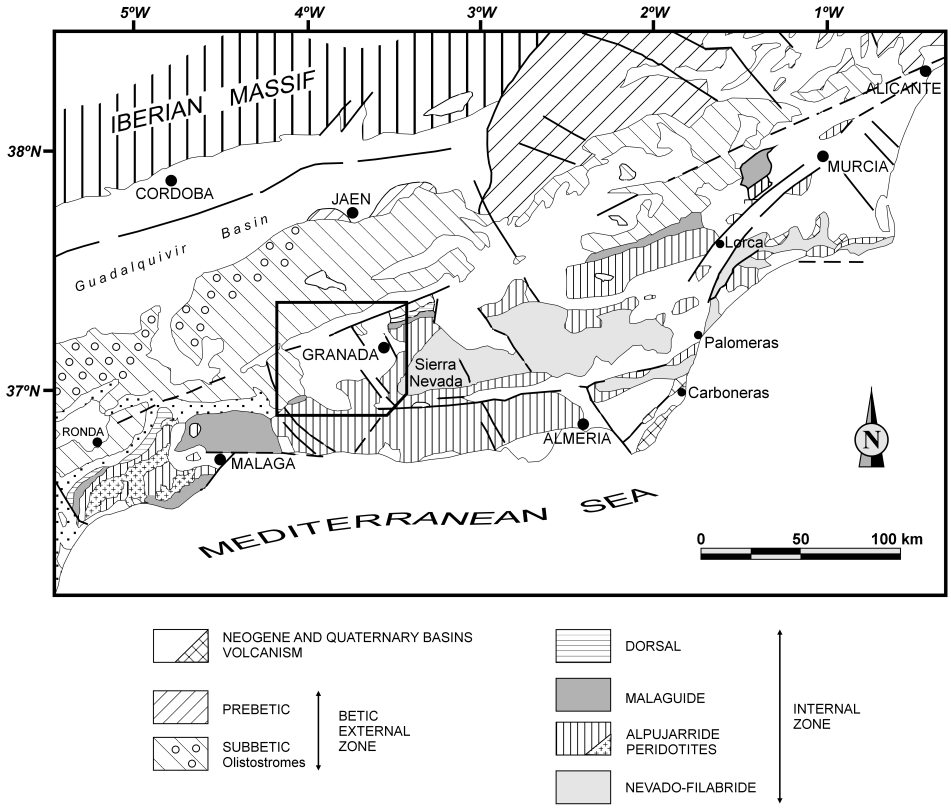

Figure 1
Geologic setting of the Granada Basin in the Betic Cordillera, in southern Spain.

In this paper we present the seismic potentiality of the active, or probably active faults of the Granada Basin (these active faults are also presented here for the first time, especially the map where they are represented). We start with the creation of a database of faults in the Granada Basin, as was done in other works (WGNCEP, 1996; CDC-DMG, 1996). Initially, we consider the faults moving *sensu lato* during the Neotectonic period, that is to say, during the last 10 Ma, although several of them were older. Initially the number of faults considered was very large (507 faults), but those shorter than 5 km have been eliminated, and among these remaining, we only considered the faults with clear active features, or probably active. Here, a fault is assumed to be active in a wide sense, that is to say, when it affects the Pleistocene sediments. Nevertheless, in the Granada Basin, most of the faults considered active have associated seismicity and other very recent geologic features, such as geomorphologic scarps (see the notes of Table 1).

The database is focused on the knowledge of the seismic potentiality in the area and will be useful as complementary information in the valuation of the seismic

Table 1

The most potentially dangerous faults in the Granada Basin, according to the maximum magnitude that they can generate and to their return period of magnitude 6.0 M_W. We first give the active faults followed by those considered as probably active, always ordered according to the estimated value for the maximum magnitude that they can generate. l is the total longitude, p the depth, δ the dip, v is the slip rate and t the return period.

Fault name and geometry[1]	Segment endpoint N and S (lon./lat.)	l (km)	p^2 (km)	δ	v^3 (mm/yr)	Máximum magnitude[4] M_W, σ_{Mw}	t^5 (yr) to $M_W = 6.0$	Nearby towns	Notes
1. N of Sierra Tejeda, sl - n **Active**	−4.184, 36.964 −3.956, 36.924	23.1	> 10 (g)	60°–90°	0.125 [10 Ma]	**6.7, 0.2[a]** **> 6.4, 0.1[c]** 6.6, 0.7[a] 6.9, 0.3[b] > 6.3, 0.5[c]	< 1300 (8)	Zafarraya, Ventas de Zafarraya	Evidence of recent motion. Possibly responsible for the 25/12/1884 earthquake.
2. Granada, n **Active**	−3.597, 37.188 −3.521, 37.083	16.8	> 10 (s)	60°	0.38 [0.8 Ma]	6.5, 0.7[a] 6.6, 0.2[b] > 6.3, 0.5[c]	< 510 (1)	Granada, Huétor Vega, Cájar, Monachil	This fault has 300 m of throw and affects the Pleistocene deposits. It moved noticeably since 0.8 Ma ago.
3. Padul, n **Active**	−3.696, 37.097 −3.576, 37.003	15.2	> 5 (g)	50°–60°	0.16 [5 Ma] 0.35 [1 Ma]	6.4, 0.6[a] 6.6, 0.2[b] > 5.9, 0.4[c]	< 1200 (5)	Dúrcal, Padul, La Malahá	This fault is spectacular and has very clear signs of being active. It moves jointly with the Padul-Dúrcal fault.
4. Santa Fe, n **Active**	−3.728, 37.204 −3.647, 37.107	13.0	> 10 (g)	60°	0.2 [5 Ma]	6.3, 0.6[a] 6.5, 0.2[b] > 6.1, 0.4[c]	[< 1200] (6)	Santa Fe, Gabia la Grande, Alhendín, Otura	This fault is inferred from its geomorphic features and the different nature of materials at both sides. This fault and its parallel have associated a noticeable seismicity.
5. Padul - Dúrcal, n **Active**	−3.638, 37.049 −3.531, 36.977	13.0	> 5 (g)	40°–60°	0.2 [5 Ma] > 0.35 [1 Ma]	6.3, 0.6[a] 6.5, 0.2[b] > 5.9, 0.4[c]	< 1300 (9)	Nigüelas, Dúrcal, Padul	This fault is spectacular and has very clear signs of being active. It moves jointly with the Padul fault.

Table 1

Continued

Fault name and geometry[1]	Segment endpoint N and S (lon./lat.)	l (km)	p^2 (km)	δ	v^3 (mm/yr)	Máximum magnitude[4] M_W, σ_{Mw}	t^5 (yr) to $M_W = 6.0$	Nearby towns	Notes
6. Atarfe, n **Active**	−3.744, 37.257 −3.662, 37.193	10.3	> 10 (g − s)	60°	0.15 [5 Ma]	6.2, 0.6[a] 6.5, 0.2[b] > 6.0, 0.4[c]	< 2100 (10)	Atarfe, Pinos Puente, Caparacena	This fault presents an important scarp and has substantial associated microseismicity. This could help to adjust better the width.
7. El Fargue - Jun, n **Active**	−3.632, 37.255 −3.546, 37.179	11.7	> 10 (s)	60°	0.35 [0.8 Ma]	6.3, 0.6[a] 6.4, 0.2[b] > 6.1, 0.4[c]	< 790 (2)	El Fargue, Pulianas, Pulianillas, Peligros	This fault presents a clear activity during the Quaternary. It has associated a very clear seismicity (serie of June, 4th, 1998).
8. Belicena - Alhendín, n **Active**	−3.703, 37.188 −3.638, 37.110	10.4	> 5 (sp)	60°	¿0.2? [5 Ma]	6.2, 0.6[a] [6.4, 0.2[b]] > 5.7, 0.4[c]	[< 3100] (12)	Belicena, Gabia la Grande, Alhendín	It is known from seismic prospection and seems to have identified with many earthquakes.
9. Albuñuelas, n **Active**	−3.665, 36.928 −3.561, 36.916	9.8	> 5 (g)	40°–60°	0.14 [5 Ma]	6.2, 0.6[a] 6.4, 0.2[b] > 5.8, 0.4[c]	< 4200 (13)	Pinos del Valle, Albuñuelas	It affects the upper Miocene and recent Quaternary deposits. It is, therefore, active.
10. Pinos Puente, n **Active**	−3.757, 37.265 −3.689, 37.201	9.4	> 10 (s)	60°	0.4 [5 Ma]	6.1, 0.6[a] 6.3, 0.2[b] > 6.0, 0.4[c]	< 860 (3)	Pinos Puente, Atarfe	This fault has a great seismicity associated with it. Its throw is about 2 km. It presents important scarps.
11. Dílar, n **Active**	−3.592, 37.104 −3.533, 37.048	8.3	> 10 (g)	60°	0.16 [5 Ma] > 0.33 [1 Ma]	6.1, 0.6[a] 6.3, 0.2[b] > 5.9, 0.4[c]	< 1200 (7)	Gójar, La Zubia, Dílar	This fault is clearly active because it affects the Pleistocene deposits.

12. Alitaje, n **Active**	−3.774, 37.265 −3.732, 37.219	6.4	> 5 (sp)	40°–60°	0.1 [5 Ma]	5.9, 0.5[a] 6.3, 0.2[b] > 5.6, 0.4[c]	< 9000 (14)	Pinos Puente, Anzola, Pedro Ruiz	This fault is known from seismic prospection. It affects the Pleistocene-Quaternary deposits, and probably moves jointly with the Pinos Puente fault.
13. Obéilar - Pinos Puente, n - sl **Active**	−3.757, 37.270 −3.845, 37.257	7.9	> 10 (sp−g)	60°–90°	0.5 [5 Ma]	6.0, 0.6[a] 6.2, 0.2[b] > 5.9, 0.4[c] **6.2, 0.2[a]** **> 5.9, 0.1[c]**	< 910 (4)	Zujaira, Casa Nueva	This fault is deduced by seismic prospection and is also observable in the field. It shows recent motion. Its throw is of the order of 2500 m and forms the northern border of a very subsident sector. The horizontal displacement is not calculated.
14. Pedro Ruiz, n **Active**	−3.784, 37.263 −3.751, 37.216	5.9	> 5 (sp)	40°–60°	0.1 [5 Ma]	5.9, 0.5[a] 6.2, 0.2[b] > 5.5, 0.4[c]	< 9700 (15)	Casa Nueva, Anzola, Pedro Ruiz	This fault is known from seismic prospection. It affects the Pleistocene-Quaternary deposits, and probably moves jointly with the Pinos Puente fault.
15. Huenes, sl - n **Active**	−3.504, 37.133 −3.529, 37.101	5.0	> 10 (g)	60°–70°	0.25 [0.4 Ma]	**5.9, 0.2[a]** **> 5.7, 0.1[c]** 5.8, 0.5[a] 6.0, 0.2[b] > 5.7, 0.4[c]	< 2800 (11)	Monachil	It affects middle Pleistocene sediments and presents very recent and well conserved scarps. The horizontal displacement is not calculated.
16. Escúzar, n **Probably active**	−3.665, 37.040 −3.840, 37.036	16.4	> 5 (g)	60°	> 0.03 [10 Ma]	6.5, 0.7[a] ~ 6.8, 0.3[b] > 5.9, 0.4[c]	< 13000 (30)	Agrón, Escúzar, Padul	This fault is probably active, although its displacement is not important.

Table 1

Continued

Fault name and geometry[1]	Segment endpoint N and S (lon./lat.)	l (km)	p^2 (km)	δ	v^3 (mm/yr)	Máximum magnitude[4] M_W, σ_{Mw}	t^5 (yr) to $M_W = 6.0$	Nearby towns	Notes
17. Alcaucín, n - sl **Probably active**	−4.101, 36.918 −4.010, 36.864	13.6	> 10 (g)	60°–90°	0.175 [10 Ma]	6.3, 0.6[a] 6.6, 0.2[b] > 6.1, 0.4[c] **6.4, 0.2[a]** **> 6.2, 0.1[c]**	< 1500 (16)	Alcaucín, Canillas de Aceituno, Sedella	It does not affect modern material, but continuing to the E, faults of this type affect the Pliocene-Quaternary. They are strike-slip and normal faults. The horizontal motion is not given because appropriate references are not available.
18. Vélez de Benaudalla, n - g **Probably active**	−3.445, 36.898 −3.522, 36.835	14.1	> 3 (g)	< 30°	> 0.15 [10 Ma]	6.4, 0.6[a] ~ 6.6, 0.2[b] > 5.9, 0.4[c]	< 2900 (20)	Vélez de Benaudalla, Órgiva	It moved during the neotectonic period, but we ignore its depth and if it is active today. Probably it is active, according to the geomorphologic indexes.
19. Sedella, n **Probably active**	−4.078, 36.873 −3.978, 36.846	10.8	> 10 (g)	60°–90°	0.175 [10 Ma]	6.2, 0.6[a] 6.5, 0.2[b] > 6.0, 0.4[c]	< 1900 (17)	Sedella, Archez, Canillas de Aceituno	It does not affect modern material, but continuing to the E, faults of this type affect the Pliocene-Quaternary. They are strike-slip and normal faults. The horizontal motion is not given because appropriate references are not available.

20. Guájar - Fondón, n **Probably active**	−3.674, 36.896 −3.595, 36.834	9.8	> 5 (g)	60°	> 0.12 [5 Ma]	6.2, 0.6[a] ~6.5, 0.2[b] > 5.7, 0.4[c]	< 5500 (22)	Guájar Alto, Guájar-Faragüit, Guájar-Fondón	It affects the upper Miocene deposits. This fault is clearly neotectonic, but we don't know if it is active at present.
21. Escóznar, n **Probably active**	−3.842, 37.243 −3.788, 37.167	9.7	> 3 (g)	60°	0.1 [5 Ma]	6.2, 0.6[a] 6.5, 0.2[b] > 5.5, 0.4[c]	< 11000 (27)	Escóznar, Cijuela, Láchar, Romilla Nueva	The fault can be recognize by its morphology only. It must have affected Pliocene-Quaternary materials.
22. N of Silleta, n **Probably active**	−3.553, 37.053 −3.641, 37.050	8.2	> 5 (g)	60°	0.04 [10 Ma]	6.1, 0.6[a] 6.5, 0.2[b] > 5.6, 0.4[c]	< 20000 (34)	Dílar	This fault is probably active, although its displacement is not important.
23. N of Sierra de Lújar, sl - n **Probably active**	−3.422, 36.897 −3.519, 36.894	8.8	> 10 (g)	90°	> 0.15 [10 Ma]	**6.2, 0.2[a]** **> 6.0, 0.1[c]** 6.1, 0.6[a] 6.4, 0.2[b] > 5.9, 0.4[c]	< 2800 (19)	Ízbor, Órgiva	This is a segment of the fault that extends to the E for several kilometers and affects the Upper Miocene deposits. This fault is clearly neotectonic, but we don't know if it is active at present.
24. NW of Játar, n **Probably active**	−3.954, 36.974 −3.894, 36.912	9.1	> 5 (g)	60°	0.08 [10 Ma]	6.1, 0.6[a] 6.4, 0.2[b] > 5.7, 0.4[c]	< 8900 (24)	Játar	It affects the upper Miocene deposits, without evidence of recent motion.
25. Tocón - Obéilar, n **Probably active**	−3.866, 37.265 −3.963, 37.250	8.8	> 3 (sp)	30°–60°	0.1 [5 Ma]	6.1, 0.6[a] 6.4, 0.2[b] > 5.5, 0.4[c]	< 10000 (26)	Tocón, Alomartes	This fault is known by geophysics. It affects the upper Miocene and Pliocene-Quaternary deposits.
26. N of Cubillas, n **Probably active**	−3.657, 37.329 −3.748, 37.305	8.6	> 5 (sp)	40°–60°	0.06 [5 Ma]	6.1, 0.6[a] 6.4, 0.2[b] > 5.7, 0.4[c]	< 11000 (28)	Cortijo de Berbe Bajo, Embalse de Cubillas	This fault is known by seismic prospection. It affects the Pliocene-Quaternary deposits.

Table 1

Continued

Fault name and geometry[1]	Segment endpoint N and S (lon./lat.)	l (km)	p^2 (km)	δ	v^3 (mm/yr)	Máximum magnitude[4] M_W, σ_{Mw}	t^5 (yr) to $M_W = 6.0$	Nearby towns	Notes6. Atarfe, n **Active**
27. NW border of Sierra Arana, n **Probably active**	−3.528, 37.362 −3.556, 37.307	6.7	> 10 (g)	60°	> 0.12 [5 Ma]	5.9, 0.6[a] < 6.3, 0.2[b] > 5.8, 0.4[c]	< 4000 (21)	Deifontes, Cogollos de la Vega, Iznalloz	This fault has been very active during the Pliocene-Pleistocene.
28. Zafarraya, n - sl **Probably active**	−4.172, 36.971 −4.098, 36.960	7.0	> 5 (g)	60°–70°	0.1 [5 Ma]	6.0, 0.6[a] 6.3, 0.2[b] > 5.5, 0.4[c] **6.1, 0.2[a]** **> 5.6, 0.1[c]**	< 9700 (25)	Zafarraya, Ventas de Zafarraya	This fault has acted during the neotectonic period, but the present evidence does not look important.
29. Daimuz Bajo, n **Probably active**	−3.871, 37.258 −3.830, 37.204	7.0	> 3 (sp)	60°	0.08 [5 Ma]	6.0, 0.6[a] 6.3, 0.2[b] > 5.3, 0.4[c]	< 19000 (33)	Daimuz Bajo, Escóznar, Láchar	It is only a probable fault. It seems to have affected Quaternary materials.
30. Tablate, n - sl **Probably active**	−3.508, 36.960 −3.529, 36.917	5.1	> 5 (g)	60°	> 0.08 [5 Ma]	5.8, 0.5[a] < 6.2, 0.2[b] > 5.4, 0.4[c] **5.9, 0.2[a]** **> 5.5, 0.1[c]**	< 16000 (31)	Béznar	It affects the upper Miocene materials, but we don't know if it is active at present. Considering its morphological features, it should be.
31. Béznar - Ízbor, n **Probably active**	−3.546, 36.927 −3.513, 36.885	5.5	> 5 (g)	70°	0.08 [5 Ma]	5.8, 0.5[a] 6.2, 0.2[b] > 5.4, 0.4[c]	< 16000 (32)	Ízbor, Béznar, Pinos del Valle	It affects the upper Miocene materials, but we don't know if it is active at present. Probably it is active, according to the geomorphologic indexes.
32. Eastern Cubillas, n **Probably active**	−3.669, 37.324 −3.644, 37.284	5.1	> 3 (sp)	50°	0.08 [5 Ma]	5.8, 0.5[a] 6.2, 0.2[b] > 5.3, 0.4[c]	< 23000 (35)	Embalse de Cubillas, Calicasas	It is known by seismic profiles. It affects the Pliocene-Quaternary materials. Possibly it continues to act.

33. W of Cubillas, n **Probably active**	−3.720, 37.300 −3.693, 37.260	5.0	> 4 (sp)	60°	0.15 [5 Ma]	5.8, 0.5[a] 6.1, 0.2[b] > 5.3, 0.4[c]	< 11000 (29)	Caparacena, Embalse de Cubillas	This fault is known by seismic prospection. It affects the Pliocene-Quaternary materials.
34. Canales, sl - n **Probably active**	−3.442, 37.172 −3.506, 37.134	7.5	> 10 (g)	70°–90°	> 0.08 [5 Ma]	**6.1, 0.2[a]** **> 5.9, 0.1[c]** 6.0, 0.6[a] 6.4, 0.2[b] > 5.8, 0.4	< 6100 (23)	Güéjar Sierra, Pinos Genil	It affects the upper Miocene materials and appears to have modern motion according to its morphology. The horizontal motion is not estimated.
35. Lanjarón, sl - n **Probably active**	−3.421, 36.921 −3.495, 36.919	6.6	> 10 (g)	90°	> 0.3 [10 Ma]	**6.1, 0.2[a]** **> 5.8, 0.1[c]** 5.9, 0.6[a] 6.2, 0.2[b] > 5.8, 0.4[c]	< 1900 (18)	Lanjarón	It affects the upper Miocene materials but there is no direct signs that it is active today, although some of its geomorphologic indexes are very high. This fault is a segment of the one that continues to the E through the Alpujarras corridor.

[1] (sl) - strike-slip, (g) - low angle normal fault, (n) - normal. The first typology is the dominant
[2] (g) - by geologic data, (sp) - by seismic prospection, (s) - by associated seismicity
[3] Calculated from the vertical displacement observed in the last [‡ Ma]
[4] ([a]) - using the relationship $M_W = M_W(l)$ of WELLS and COPPERSMITH (1994), ([b]) - using the relationship $M_W = M_W(l,v)$ of ANDERSON *et al.* (1996), ([c]) - using the relationship $M_W = M_W(A)$ of WELLS and COPPERSMITH (1994). In boldface, acting as strike-slip faults
[5] The number in parenthesis gives the position in terms of hazard according to the return period obtained. Active faults are first numbered and secondly those considered as probably active. The calculation of return period is carried out assuming that they act as a normal fault

hazard. That allows us to open a new application of probabilistic methods to hazard assessment, called probabilistic fault displacement hazard analysis (COPPERSMITH and YOUNGS, 2000).

The obtained information must be gradually completed and corrected, because the used data must be improved as the geologic and seismic knowledge of this area increases. The trend and length of the fault, its geometry and the slip rate, have been considered in the cases when it can be known from the accumulated throws. We used empiric relations between the longitude and the surface of the fault and the greater magnitude that it could generate. On the contrary, the existing paleoseismic information in this basin is very scarce and consequently the paleoseismic intervals of recurrence are not known, nor paleoseismic estimations of the displacement occurred in earthquakes.

The aim of this paper is to estimate the seismic potentiality of the faults affecting the Granada Basin, mind full of future applications such as the determination of the seismic hazard.

The Network of Faults in the Granada Basin

This basin is affected by many faults distributed in three sets.

The faults of N70E to E-W direction form the first set. They are the longest and oldest because many of them moved during the early and middle Miocene. Then they moved as dextral strike slip, but from the late Miocene rested paralyzed or moved as reverse and normal faults, according to its location. This occurred because from this last time, the Betic Cordillera was affected by an approximate NNW-SSE compression, combined with a near perpendicular extension, that in many points is more important than the compression. At the same time, the region as a whole was rising.

The second set includes the NNE-SSW faults, which are very important, especially to the east of the cordillera (e.g., faults of Lorca, Palomares and Carboneras). They are present on the eastern border of the Granada Basin in its limit with Sierra Nevada and further south. Its motion is normal, locally very important, combined in some points with left lateral displacements (sometimes dominant). They moved from the late Miocene to the present.

The approximate NW-SE faults form the third set. These faults are also present in the eastern sector of the basin as well as in its interior, affecting areas such as Sierra Elvira, Granada, Padul, etc. They basically move as normal faults, locally very important and, as in the previous set, moved from the late Miocene to the present. Some of them show a constant and noticeable microseismicity.

Moreover, there are low angle faults on the border of Sierra Nevada and more to the South affecting the contact between the tectonic units of the Nevado-Filabride and Alpujarride complexes (these complexes are the two lower ones of the Betic Internal Zone). The displacement of these faults is in accordance with the direction of

extension (NE-SW), moving the hanging blocks to the SW; its present importance generating earthquakes is not known, but seems to be negligible because there are no earthquakes that could be associated with them.

These three set of faults that individualize the basin from the beginning of the Pliocene are distributed in two systems: one is formed by the set of N70E to E-W faults and the second by the other two sets. Owing to the stress orientation existing from the late Miocene, the first system is not very active, as indicated by the geologic features, and when it moves presents basically normal motions. Nevertheless, at present this system can easily accumulate energy, and for this reason cannot be discarded that it could move, even as reverse faults. Although both the focal mechanism of the Andalusian earthquake (25/12/1884) and the exact position of the hypocenter are not known, probably correspond to the movement of one of the E-W faults of the South of the Granada Basin (the N of Sierra Tejeda fault).

The second system is very active and is responsible for many earthquakes affecting the central and eastern sectors of the basin. The trend of the faults of its two sets facilitates the extension, generally producing small to moderate earthquakes.

Figure 2 shows the total number of faults affecting the basin, presenting displacements which occurred in the neotectonic period *sensu lato*. As can be observed, some of them have an important length, particularly that of the N70E to E-W strike. In the database they have been divided into their different segments;

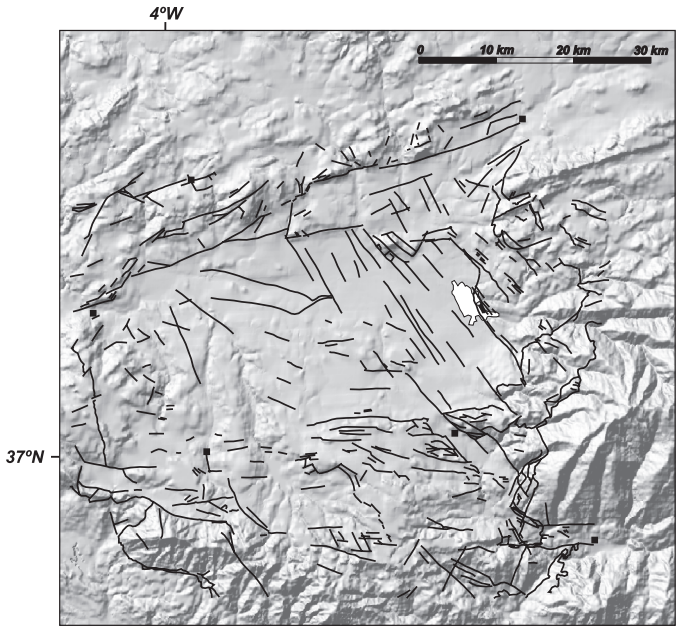

Figure 2
Net of faults of the Granada Basin presenting movements during the Neotectonic *sensu lato* period.

otherwise in the calculation of the maximum magnitude that potentially could generate, should result, unexpected high values.

The Database of Faults

To create the database we used the published cartography of the faults known in the Granada Basin and its proximity, taken primarily from the geologic maps of the region at 1:50000 scale, published by the Instituto Geológico y Minero de España (IGME), although their trace has been corrected at many points with our own data. Some of the faults have been known from seismic profiles made by Chevron® (RODRÍGUEZ-FERNÁNDEZ and SANZ DE GALDEANO, 2001). The map obtained was reduced to 1:100000 scale and digitized. For each fault we have considered the following information.

Trace and total length of the faults. The location of each fault and the geometry of its trace in the topography are needed in any evaluation of seismic hazard, as well as in determinig different derived geometric parameters. The errors introduced during the digitalization of the faults are usually less than 100 m and never exceed 150 m.

Given that generally there is no other type of reliable information, as could be paleoseismic data, the total length of the fault obtained from its length trace is considered as the maximum possible rupture of the fault. This is the value used in the relationships between the length of the rupture and magnitude. Some authors (WELLS and COPPERSMITH, 1994) consider that the rupture observed in surface during an earthquake is only of the order of 75% of the length of the rupture which occurred below the surface. According to this criterion, when using the length of a fault as the maximum length of rupture, the seismic potentiality is possibly underestimated. These and other authors (WYSS, 1979; ANDERSON *et al.*, 1996; PAVLIDES *et al.*, 2000), established relationships between the observed dimension of the fault (total length of the trace of the fault or rupture length in surface) and the maximum magnitude. Using these relationships would avoid the underestimate of the maximum magnitude that the studied fault is able to generate.

At first we had 507 faults able to generate earthquakes, potentialy active, using the terminology of MACHETTE (2000). Their distribution is shown in Figure 2.

Using the lengths computed from the digitized traces, we have plotted the cumulative number of faults N with length longer than a given value l (see Fig. 3). Different authors (SCHOLZ and COWIE, 1990; WALSH *et al.*, 1991; MARRETT and ALLMENDINGER, 1992) have found, in some areas, that these two variables are related through a relationship of the type

$$N \propto l^{-C}.$$

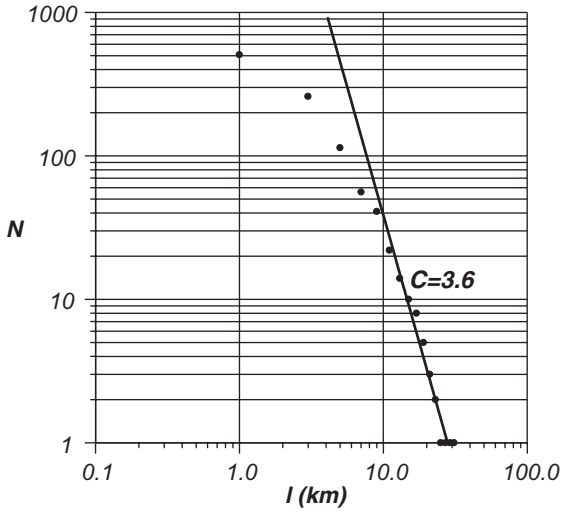

Figure 3
Accumulative number of faults *vs.* length. A power-law fit for faults longer than 10 km has been computed.

In a log-log plot, such as in Figure 3, we should see, in case the faults under study follow this kind of distribution, a straight line with slope given by the C parameter. We can assume that this power law behavior agrees with the fault length distribution in the Granada Basin and its surroundings, at least for the faults longer than 10 km, approximately.

Concerning the study of the potentiality of the faults in the basin, we have considered only those with a length greater than 5 km. This diminishes the number of faults to be considered to 71.

Depth of the fault. In contrast to previous studies in which the lack of information led to a consideration of most faults with equal depth (e.g. CDC-DMG, 1996), in this work we try to establish, if not a value of the depth for every fault, at least an estimation of it (a minimum value). In order to do so, we have used data of associated seismicity, of seismic profiles and, when it has not been possible, simply through several geologic features. We are aware that these estimations have a clear margin of error, especially in the last case.

From this value, together with the length and dip, we estimated the fault-plane surface, which was also used to estimate the maximum magnitude that the fault could generate. The dip used was that detected on the surface, but numerous faults in the Granada basin have listric geometry. This circumstance has been taken into account in some cases.

According to MORALES *et al.* (1997) and GALINDO-ZALDÍVAR *et al.* (1999), the seismicity in the Granada Basin is concentrated at a depth of about 15 km in its

northeastern part and towards the west until a depth of 20–25 km. This implies that many of the faults of the basin reach these depths, approximately locating there the main detachment level of the bottom of the basin.

Slip rate. To calculate this parameter, the throw obtained from the displacement of several reference levels has been taken into account. The Tortonian marine calcarenites, deposited approximately 8 Ma ago, are especially used because they now reach very different heights. These range between 1830 m, in the western sector of Sierra Nevada, and less than the present level of the sea in several sectors of the Granada Basin: in the Cubillas and Pinos Puente areas (RODRÍGUEZ-FERNÁNDEZ and SANZ DE GALDEANO, 2001). The estimation of the throw of the faults that displaced the reference levels and the interval of time in which it has been occurring gives average values of the slip rate of the fault. In some cases the Pleistocene levels permit obtainment of the slip, as it occurs in the Granada town and its surroundings. In other cases some geologic features, such as the escarpment height, provide estimates of slip rate of the fault blocks.

Activity of the faults. As previously indicated, the faults with a length greater than 5 km are only 71, all of them studied in detail. 37 of them have been discarded because the known geologic and seismic data show that they have nonexistent, or practically nonexistent, activity during the Quaternary. Among the discarted faults some of the longest are included.

We have estimated only 15 faults of the Granada Basin as clearly active. These faults show clear geologic features of recent activity and/or an associated seismicity. Twenty other faults are considered as probably active. These 35 faults directly considered are included in Table 1 and in Figure 4.

Maximum magnitude. To estimate the maximum magnitude that each fault is capable of generating, and considering that generally there are no data of earthquake magnitudes associated with a specific fault, we used different relationships proposed by several authors between the maximum magnitude and the length or the surface of the fault; additionally, the slip rate has been included in the estimation of the maximum magnitude, as proposed in recent works. In this way we calculated several values that enable us to verify the consistency of the results.

Independent of the value of the maximum magnitude obtained from the distinct relations used, we estimated the error of the value obtained. For this, given that the parameters appearing in the different proposed lineal relationships are accompanied by their respective variance, simulations were performed using the Monte Carlo method (RUBINSTEIN, 1981) when determining the variance (uncertainty) of the estimated result.

The relationships used are the following: First, that proposed by WELLS and COPPERSMITH (1994) between the moment magnitude M_W and the length of the surface rupture l. Also, we used the one proposed by these authors between the moment magnitude and the rupture area A; this latter relationship is statistically more robust than the former, in the sense that a greater number of earthquakes was used to estimate the parameters and to establish the relationship, and as a result the errors were slightly lower. Finally, we also used the relationship proposed by ANDERSON *et al.* (1996) between the moment magnitude, the length of the surface rupture and the slip rate v of the fault. With this relationship, since it includes the fault-slip rate, we attempt to improve the fit between M_W and l, thus reducing somewhat the maximum magnitude expected for faults with high slip rates.

Although the previous relationships are established for the moment magnitude, as indicated by WELLS and COPPERSMITH (1994), there is no significant difference between the magnitudes M_W and M_S in the range 5.7 to 8.0. This is precisely the range of values of interest to us. Above the 8.0 value the M_S scale saturates and we have to work using M_W instead. Below the 5.7 value the M_S magnitude is systematically smaller than M_W. When expressing the maximum magnitude in different scales for this area, the relationship proposed by LÓPEZ CASADO *et al.* (2000) can be used in order to relate the M_S and m_b scales for the Iberian Peninsula, in addition to the cuadratic relationship proposed by the same authors between the m_b scale and the macroseismic intensity I_0.

Return period. It would be desirable to determine the return period for a given magnitude using the palaeoseismic information by studying the displacements detected in the fault and taking into account the epochs on which these occurred, however in this region such information is scarce.

To calculate the return period t, we used an approximation based on empirical relationships. The expression used was

$$t = d/v.$$

v is the slip rate, known for at least the main faults in the region. This is determined, as indicated previously, from the displacement detected in the fault during a given time interval, although in some cases this may not be the present value of this variable; this one could be known with geodetic measurements made during an interval of years long enough to yield more confident results that those obtained from geologic data. The variable d is the average coseismic slip, which again would be useful to know from palaeoseismicity (movement that has generated a certain earthquake in the fault). From the definition of seismic moment M_0

$$M_0 = \mu \cdot A \cdot d,$$

where μ is the rigidity modulus and A the surface rupture, we can calculate the displacement d that caused an earthquake with seismic moment M_0, or equivalently, we can use the know relationship of HANKS and KANAMORI (1979)

$$M_W = \frac{2}{3}\log M_0 - 10.7$$

to calculate the value of d that causes an earthquake of moment magnitude M_W.

The slip rate, although barely influenzing on the maximum magnitude that a fault may generate, considerably affects the return period of a given earthquake. The faster a fault is, the lesser is the maximum magnitude that it can generate (ANDERSON *et al.*, 1996), given that it has less capacity to accumulate stress, and otherwise the return period for a given earthquake is shorter because the average coseismic slip will be already reached.

Results: The Distribution of the Active Faults in the Granada Basin; Their Slip Rate and Their Seismic Potentiality

Table 1 shows the potentially more dangerous faults of the Granada Basin; those considered active or at least probably active. The rest, particularly those included in the list of the 71 longer than 5 km, could move, but in fact they moved insignificantly during the Quaternary, according to the geologic and tectonic features existing in each case.

The 35 faults considered have been classified according to the maximum magnitude that they can generate. Similarly they have been classified in accordance with the return period for the magnitude 6.0 M_W ($I_{0\ MM} \sim$ IX, using the relationship of LÓPEZ CASADO *et al.* (2000) for the region), considered as an indicator objective enough of their potential risk. In Table 1 are initially firstly indicated the faults considered active, arranged by the maximum magnitude that they could generate (we use the relationship of ANDERSON *et al.* (1996) to obtain this classification, taking into account the slip rate and the total length of each fault). Also, in the column where the return period for magnitude 6.0 M_W is indicated, an ordinal is marked, indicating the relative importance of the potential seismic of each fault in the basin (this is in relation with the return period obtained in every case). The faults considered as probably active are situated immediately after; equally arranged. In every case we indicate the typology, the total length of the surface trace (l), the depth (p), the dip (δ), the slip rate (v), the maximum magnitude that they can generate together with their uncertainty, the return period (t) calculated/estimated for a 6.0 M_W earthquake, and the villages nearest the trace. Finally, notes and comments are added in each case.

The maximum magnitude to be expected is of the order of 6.9 M_W in the case of the so-called N of Sierra Tejeda fault, with a length of about 23 km and a slip rate of 0.125 mm/yr. This fault was probably the one which generated the Andalusian earthquake (25/12/1884) (Fig. 5). Considering the length in the Granada Basin there

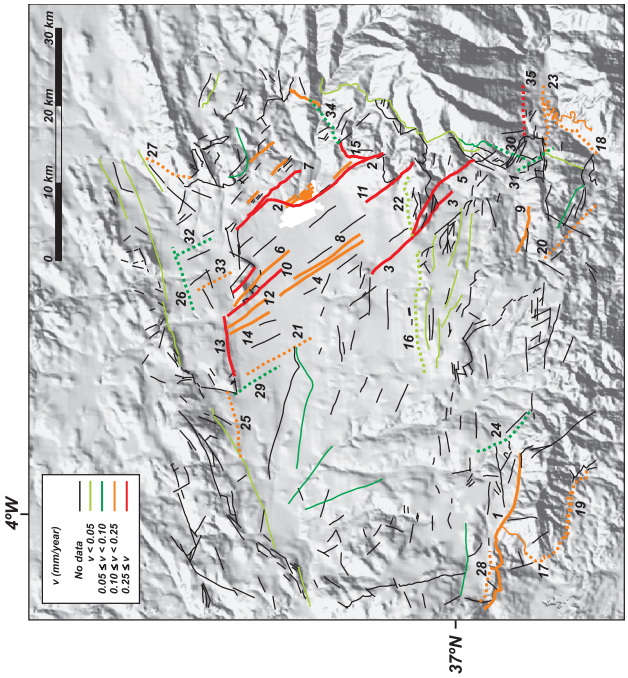

Figure 4
Slip rate of the faults of the Granada Basin. The faults considered active are marked with thick continuous lines and those probably active with thick dashed lines. The number indicates their relative seismic potential (see Table 1).

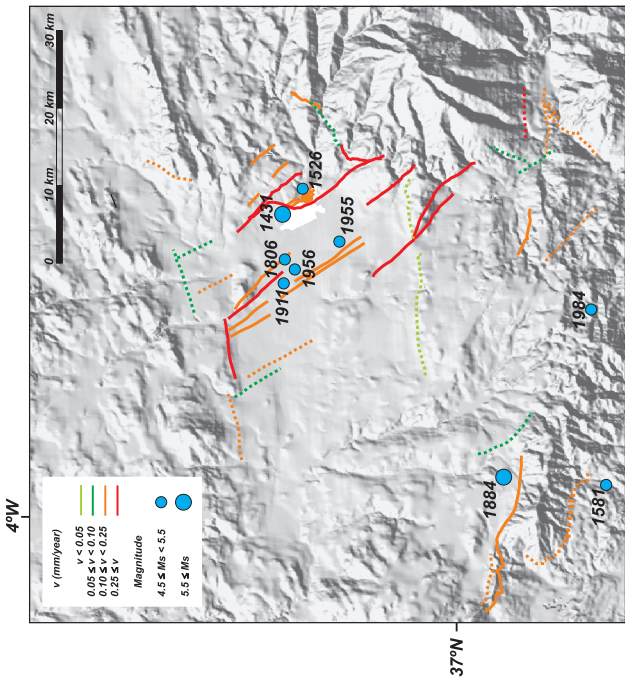

Figure 5
Location of the most energetic earthquakes which occurred in the Granada Basin in the last 600 years, together with the active and probably active faults. The earthquakes of Atarfe in 1431 and Arenas del Rey (Andalusian earthquake) in 1884 stand out. The epicenters of the historical earthquakes and their magnitudes are assigned from macroseismic data.

are about thirty faults that could generate earthquakes with magnitudes higher than 6.0, although some of them have not been included in Table 1 because they do not present clear displacements during the Quaternary.

The faults presenting higher slip rates are, from N to S: Obéilar - Pinos Puente, Pinos Puente, El Fargue - Jun, Granada, Belicena - Alhendín, Dílar, Padul y Padul - Dúrcal and Lanjarón. These and others also important, although with lesser slip rate, are shown in Fig. 4. Principally, the first ones are the faults presenting the shorter recurrence periods. Among them the El Fargue - Jun and Granada faults stand out by their slip rate. These two faults have produced important modern throws clearly visible (they affect the Pleistocene sediments that are a good reference to calculate the vertical slip). In both faults the age of 0.8 Ma has been taken in a conservative estimation, as the epoch when the displacements began. Estimations of 0.6 Ma or even 0.4 Ma also can be supported. Indeed, there is a group of faults, previously cited, whose slip rate can be considered very similar, and moreover, that are very active from the seismic point of view. This great activity can prevent the accumulation of energy required to produce earthquakes with high magnitudes. Nevertheless, these faults concentrate most of the important earthquakes of the Granada Basin (with the important exception of the largest one, that of 1884). This fact can mean that they easily recharge the energy after an earthquake and, consequently, that they continue moving at present as actively as during the Quaternary.

The database permits the plotting of Figures 4 and 5 in which, for the first time, the active and probably active faults of the Granada Basin are shown. The inspection of these maps allows deduction of an interesting geologic feature: presently the more active faults of the Granada Basin are located in its central-eastern part and correspond to NW-SE faults. Beyond doubt, this sector concentrates the most important tectonic activity, while during the late Miocene the faults with higher motion were the more eastern ones. Probably in the future the same mechanism will work again, and the higher activity will be translated to the west, likely in the area of Agrón (East of Alhama de Granada), where several recent earthquakes are located.

The movement of the present active faults uplifts as a whole, with some exceptions, its eastern block, while sinking on the western side. This same mechanism occurs in other sectors of the Betic Cordillera.

Conclusions

In this paper the estimation of diverse parameters related to the seismic potential of the main faults of the Granada Basin is carried out for the first time. However, estimations have some limitations, probably because the net of the faults is not totally known in that some of them do not outcrop or their traces are hidden among marly sediments and growings. Nevertheless, we think that the most important faults are certainly shown in this work. Another limitation is that the geometry of the faults

is not well known, mainly as concerns the dip and depth. For this reason we have adopted conservative estimations, avoiding exaggeration.

In any case, we consider that the final results accurately indicate the average return periods to be expected in the Granada Basin, and additionally that they define clearly several very active faults. From north to south are the faults of Obéilar - Pinos Puente, Pinos Puente, El Fargue - Jun, Granada, Belicena - Alhendín, Dílar, Padul, Padul - Dúrcal and Lanjarón. The return period marks an exaggerated seismic hazard in several faults, according to their seismic data; this variable is known with more uncertainty than the maximum magnitude expected. It is necessary to take into account that the return period is inversely proportional to the slip rate and to the length of total rupture. It is possible that in some cases the slip rate was overestimated. Also the length of the faults may have been overestimated, in that the segmentation of faults is not always well known. Moreover, it is highly unlikely that the faults move along their entire length in every earthquake, especially in the longer ones.

Many of those faults can potentially generate earthquakes with magnitudes higher than 6.0 M_W, although this is not expected. In this sense the N of Sierra Tejeda fault stands out because it could generate an earthquake of 6.9 M_W, and probably caused the earthquake of 25/12/1884.

Although this last fault presents the greater seismic potentiality in the basin, the main active faults are located in its central-eastern sector, in the area where the present tectonic activity is more important, uplifting the oriental block as a whole and sinking the western one. Figure 5 points out the high correlation existing between the more energetic seismicity of the area and the active faults with higher seismic potentiality and higher rate of slip of the Granada Basin.

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