Journal of
Iberian Geology
AN INTERNATIONAL PUBLICATION OF EARTH SCIENCES

Main active faults in the Granada and Guadix-Baza Basins (Betic Cordillera)

Principales fallas activas de las Cuencas de Granada y Guadix-Baza (Cordillera Bética)

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Abstract

   The Granada and Guadix-Baza Basins, the largest Neogene-Quaternary intramontane basins of the Betic Cordillera (southern Spain), undergo active deformation with an associated moderate level of seismic activity. This deformation is controlled by a NNW-SSE compressive regime and an approximate orthogonal tensional regime. The compression produced N70ºE to E-W folds of several scales, the Sierra Nevada antiform being the largest one. The tension is accommodated mainly by NW-SE active normal faults, the most notable being the Baza Fault, in the Guadix-Baza Basin, and the Granada, Sierra Elvira-Dílar and Padul-Dúrcal Faults, in the Granada Basin. In addition, other active faults with different orientations also exist, such as the Alfahuara-Botardo and the Galera faults in the Guadix-Baza Basin, and the Huenes, Obéilar-Pinos Puente and N of Sierra Tejeda Faults in the Granada Basin. Moreover, in several sectors, the presence of orthogonal normal fault sets suggests alternating trends or even radial extension. Slip rates of these active faults, based on geologic markers, vary between 0.06 and 0.5 mm/year. Estimates for the maximum expected magnitude of earthquakes caused by these faults vary between M_W 6.0 and 7.0. The N of Sierra Tejeda and the Baza Faults, the larg-

est faults in the Granada and Guadix-Baza Basins, respectively, have the greatest seismic potential. They could cause events up to a magnitude of M_W 6.5-7.0, although their reference earthquakes, computed for a return period of 475 years, are on the order of M_W 5.0-5.5.

Keywords: Active Tectonics, seismotectonics, Granada Basin, Guadix-Baza Basin, Betic Cordillera.

Resumen

   Las Cuencas de Granada y Guadix-Baza, las mayores cuencas intramontañosas del Neógeno y Cuaternario de la Cordillera Bética (sur de España), experimentan una deformación activa y tienen asociada una actividad sísmica moderada. La deformación está controlada por una compresión NNO-SSE y una tensión aproximadamente perpendicular. La compresión ha formado pliegues de dirección N70ºE a E-O de muy diferentes tamaños, siendo el antiforme de Sierra Nevada el mayor. La tensión se acomoda sobre todo por fallas normales NO-SE, siendo las más notables de ellas la falla de Baza, en la cuenca de Guadix-Baza, y las de Granada, Sierra Elvira-Dílar y Padul-Dúrcal, en la cuenca de Granada. Además, existen otras fallas activas con diferentes orientaciones, tales como la de Alfahuara-Botardo y la de Galera en la cuenca de Guadix-Baza y las de Huenes, Obéilar-Pinos Puente y norte de Sierra Tejeda en la cuenca de Granada. Además, en varios sectores, la presencia de juegos de fallas ortogonales sugiere cambios en el elipsoide de esfuerzos e incluso una extensión radial. Las tasas de desplazamiento de estas fallas activas, calculadas a partir de marcadores geológicos, varían entre 0,06 y 0,5 mm/año. La estimación del potencial sísmico indica que la máxima magnitud esperable de los terremotos producidos por estas fallas varía entre M_W 6,0 y 7,0. La falla del N de Sierra Tejeda y la de Baza, las mayores respectivamente en las Cuencas de Granada y Guadix-Baza, tienen el mayor potencial sísmico. Podrían causar eventos con magnitudes del orden de M_W 6,5-7,0, aunque sus terremotos de referencia para un periodo de retorno de 475 años son del orden de M_W 5,0-5,5.

Palabras clave: Tectónica activa, sismotectónica, cuenca de Granada, cuenca de Guadix-Baza.

1. Introduction

   The Granada and Guadix-Baza Basins are located in one of the most seismically active zones of the Iberian Peninsula (Fig. 1). This area is characterized by: (1) the lowest minimum Bouguer anomaly values in the entire Betic Cordillera and a crustal thickness between 34 and 38 km (according to Banda *et al.*, 1993); (2) the highest relief of the Iberian Peninsula as well as the maximum uplift rates of 0.5 mm/year in Sierra Nevada (Sanz de Galdeano and López Garrido, 1999; Braga *et al.*, 2003; Sanz de Galdeano and Alfaro, 2004) and the highest fluvial incision rates (Pérez-Peña *et al.*, 2009a; 2009b); (3) notable depocentres, such as that of the Pinos Puente-Santa Fe, with Tortonian marine deposits located 1200 m below sea level in the Granada Basin (Rodríguez-Fernández and Sanz de Galdeano, 2006), and other similar ones located in the Baza sub-basin (Alfaro *et al.*, 2008); (4) the last destructive earthquake in the Iberian Peninsula, the well-known 1884 Andalusian earthquake; (5) the highest instrumental seismicity rate of the Iberian Peninsula (Peláez *et al.*, 2003; Sanz de Galdeano *et al.*, 2003; Sanz de Galdeano and Peláez, 2011), and (6) the highest seismic hazard of the Iberian Peninsula, according to the Spanish Building Code. The last three points pertain to the Granada Basin.

   The aim of this paper, taking into account the previous characteristics, is to summarize the active faults of the Granada and Guadix-Baza Basins and their seismic potential.

1.1. Geodynamic setting

   From the late Miocene to the present (the neotectonic period in the western Mediterranean), the region has been subjected to a compressive stress field running NNW-SSE with an associated ENE-WSW tension (Galindo-Zaldívar *et al.*, 1999; Sanz de Galdeano *et al.*, 2010). The compressive regional stress field, related to the approximately NW-SE convergence of the Eurasian and African plates, has led to folding of the basal metamorphic rocks of the Betic Internal Zones as well as the Neogene-Quaternary sedimentary infill. Especially noteworthy is the NE-SW antiform of the Sierra Nevada. The uplift of this sector of the Cordillera, amounting to at least 4000 m (Sanz de Galdeano and López-Garrido, 1999), began some 8-9 million years ago (Johnson *et al.*, 1997), is responsible for the present day relief of the Sierra Nevada, separating the Granada and Guadix-Baza Basins.

   Tensional deformations were accommodated mainly by NW-SE normal faults. In many cases, the extension was much more conspicuous than the compression and, in some cases, particularly in the area of the Sierra Nevada, a radial extension pattern occurred, in such a way that all the sets of faults sometimes moved as normal faults.

   Linked to this progressive uplift, during the late Neogene, both basins became isolated from the sea, beginning their endorheic character.

   Many of the faults are located on the borders of the basins, particularly in those on the W and NW borders of the Sierra Nevada, encouraging differential vertical
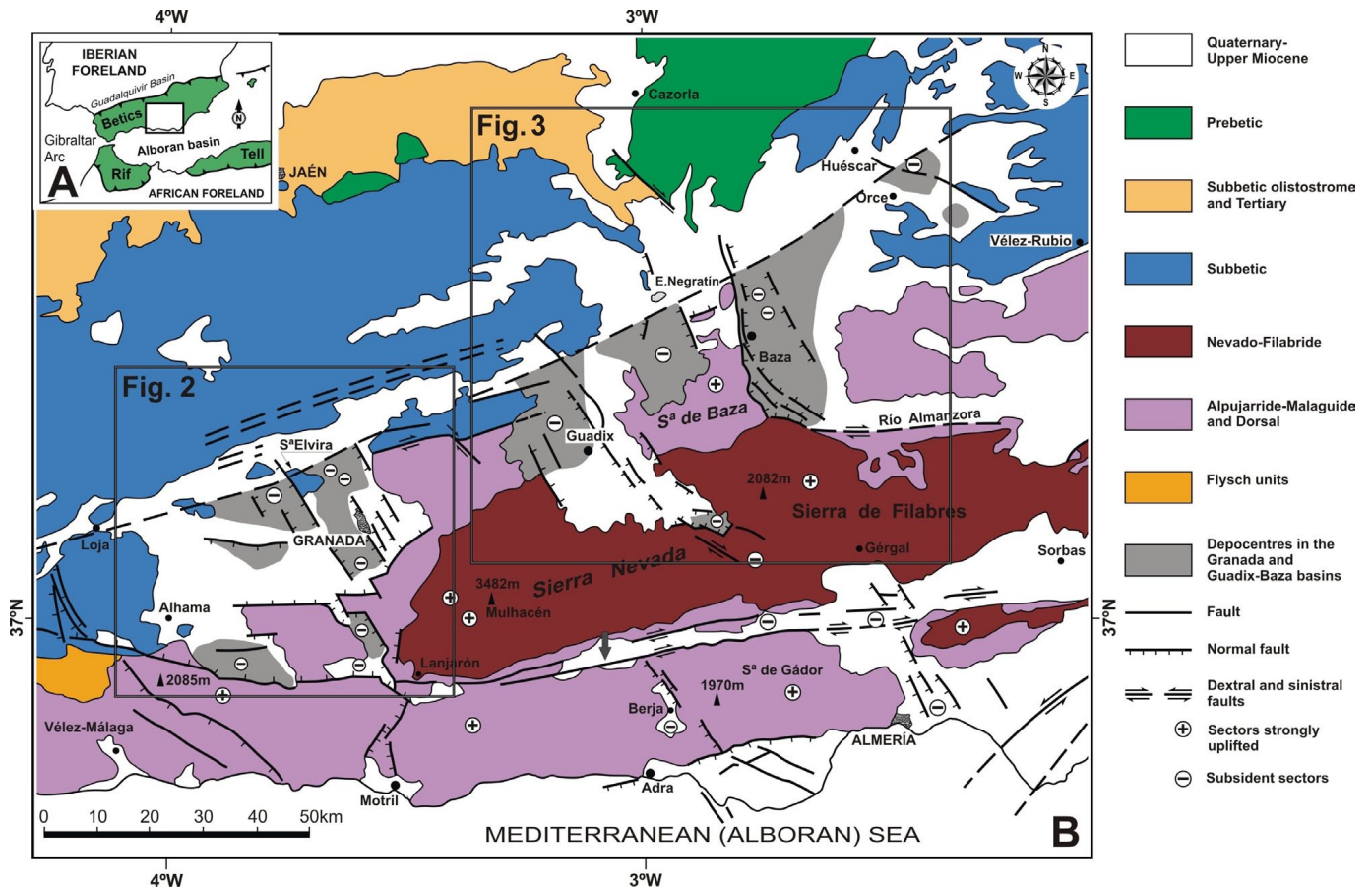
Fig. 1. Regional setting of the Granada and Guadix-Baza Basins. A: location of the study area in the Betic Cordillera, southern Spain. The small square indicates the position of B. B: geological sketch of the central part of the Betics. The squares mark the position of the Granada and Guadix-Baza Basins.

Fig. 1. Situación regional de las Cuencas de Granada y Guadix-Baza. A: situación de ambas cuencas en las Béticas, sur de España. El recuadro pequeño indica la posición de B. B: Esquema geológico del sector central de las Béticas. Los recuadros marcan la posición de las Cuencas de Granada y Guadix-Baza.

movements. Also, large faults developed in the interior of the basins, some of which at present show diverse tectonic, morphologic or seismic features that allow them to be considered as active faults.

1.2. Main geological features of the Granada and Guadix-Baza Basins

Both of these intramontane basins developed at the contact between the External, to the north, and Internal, to the south, zones of the Betic Cordillera.

The Granada Basin (Fig. 2), the second largest intramontane basin of the cordillera, has probably the highest tectonic activity and seismic rate of the Iberian Peninsula. This tectonic activity has formed five depocentres (Cubillas, Pinos Puente, Granada, Arenas del Rey, and Padul-Dúrcal; Rodríguez-Fernández and Sanz de Galdeano, 2006). All of these are controlled by high-angle

NW-SE faults and are situated in the central and eastern part of the basin, with the exception of that of the Arenas del Rey, controlled mainly by E-W faults and located to the south. In addition to these features, the eastern border of the basin (western end of Sierra Nevada) shows high tectonic activity, as indicated by the present pattern of strong fluvial incision (Pérez-Peña *et al.*, 2009a). Galindo-Zaldívar *et al.* (1999) deduced the existence of an extensional detachment, which is the main compensation level of the high-angle normal faults. This detachment is located at approximately 9 to 16 km deep in the NE of the Granada Basin, while it is progressively deeper towards the west, between 20 and 25 km deep in the SW sector of the basin.

The Guadix-Baza Basin, with more than 4000 km², is the largest intramontane basin of the Betic Cordillera (Fig. 3). Its endorheic character persisted till the late Pleistocene (Viseras, 1991; García Tortosa *et al.*, 2011). The

basin is divided in two sub-basins according to its sedimentary facies, the Guadix sub-basin to the west, which is largely filled with fluvial sediments (Viseras, 1991), and the Baza sub-basin to the east, with a predominance of lacustrine sediments (Vera 1970, Gibert *et al.* 2007). This distribution is due to the tectonic control of the Baza Fault (Alfaro *et al.*, 2008; García Tortosa *et al.*, 2008a). This fault is the limit between the two sub-basins and its movements caused the subsidence of the hanging wall, with the development of a large lake in the eastern part of the basin (the Baza sub-basin) that existed till the late Pleistocene. The sequence is capped by a 0.5-1 m-thick calcrete interpreted as a glacis surface, which outcrops in a widespread area (more than 1200 km^2) of the Guadix Basin and is one of the best markers of the recent deformation in the basin (García Tortosa *et al.*, 2011). Its age ranges between 600 and 205 ka (Scott and Gibert, 2009; Díaz-Hernández and Julià, 2006). The topmost laminar horizons of the calcrete, which are pedogenic in origin, have been dated at 45 ka (Azañón *et al.*, 2006; Pérez Peña *et al.*, 2009b).

1.3. Seismic activity

Seismicity in the Betic Cordillera is defined by the contact between the Eurasian and the African plates. Broadly, the Betic Cordillera is characterized by a broad low to moderate background seismicity that defines a low to moderate seismic hazard (Fig. 4; Peláez and López Casado, 2002). In addition, the historical period is marked by several destructive earthquakes. In most cases, it is not possible to find a clear link between the main epicentres and the main fault observed on the surface, although in some instances significant earthquake clusters have been linked to the main fault system.

The Granada Basin may be the most seismically active area in the entire Iberian Peninsula, having a significant level of low-magnitude earthquakes distributed from 10 to 25 km in depth. Instead, the most energetic earthquakes are clearly associated with the most active fault areas, those bordering the Granada Basin to the south, east, and west. This area has experienced some strong earthquakes throughout history. Two destructive events in the Betics are the 1884 Andalusian earthquake (with felt intensities IX-X, also called the 1884 Arenas del Rey or the Alhama de Granada earthquake), and the earlier 1431 S Granada earthquake (VIII-IX). In fact, the 1884 earthquake, with an assigned macroseismic magnitude of the order of M_w 6.5, has been one of three earthquakes in the Betics felt with intensity IX-X. Its location is clearly associated with the N of Sierra Tejeda Fault (Reicherter *et al.*, 2003).

The most significant instrumental events located in the Granada Basin were the 1955 SW Armilla (m_b 5.1, VII), formerly called the 1955 La Zubia earthquake, and the 1956 NW Purchil (m_b 5.0, VIII) earthquakes. Both of them, as well as many earthquakes located in the basin with magnitude greater than 4.0, are associated with the NW-SE fault system to the north-west of the basin.

Earthquake swarms are frequent in this region. In the instrumental period, for example, the 1985 Loja and the 1988 Agrón seismic swarms are notable. The main earthquakes of these two swarms had magnitudes of m_D 3.9 and m_D 4.0, respectively. More than 300 events were identified for each of these swarms.

In the Guadix-Baza Basin, the seismicity rate is clearly lower than in the Granada Basin. Earthquakes are located mostly in the Baza sub-basin. They are shallow events, and in this region a clearer relation appears between earthquakes and fault systems. The only significant historic earthquake was the 1531 Baza earthquake (VIII-IX), which was probably related to the Baza Fault. If site effects are not considered, this event would have a magnitude of the order of M_w 6.0.

The instrumental events located in this region, with some exception, are low-magnitude earthquakes. The two events with the highest magnitude were the 1962 SE Caniles (m_{bLg} 4.7) and the 1964 SW Galera (m_{bLg} 4.8) earthquakes. The latter was felt with intensity VIII. The 1962 earthquake appears to have been associated with the Caniles Fault, and the 1964 earthquake with the Galera Fault. In the Guadix sub-basin, the most remarkable event is the 1935 Huélago (m_D 4.2) earthquake, an event barely felt.

2. Active faults in the Granada Basin

In the Granada Basin (Fig. 2), many faults affect late Miocene to Quaternary sediments, having a clearly neotectonic character. However, some do not show clear evidence of recent movements and thus cannot be considered active. This is the case of some N70ºE to E-W faults, and even of some NW-SE faults situated on the NE border of the basin. Other faults affect Quaternary sediments, showing geomorphologic evidence of recent displacements or seismicity associated with them. These are the active faults, although in this study, we have considered only the main ones (longer than 10 km) with a total of 14 faults (Table 1). For a more complete list of faults, active and probably active, see Sanz de Galdeano *et al.* (2001, 2003) and Sanz de Galdeano and Peláez (2011). Several faults might be connected, as they are geometrically aligned, but we lack firm evidence of this
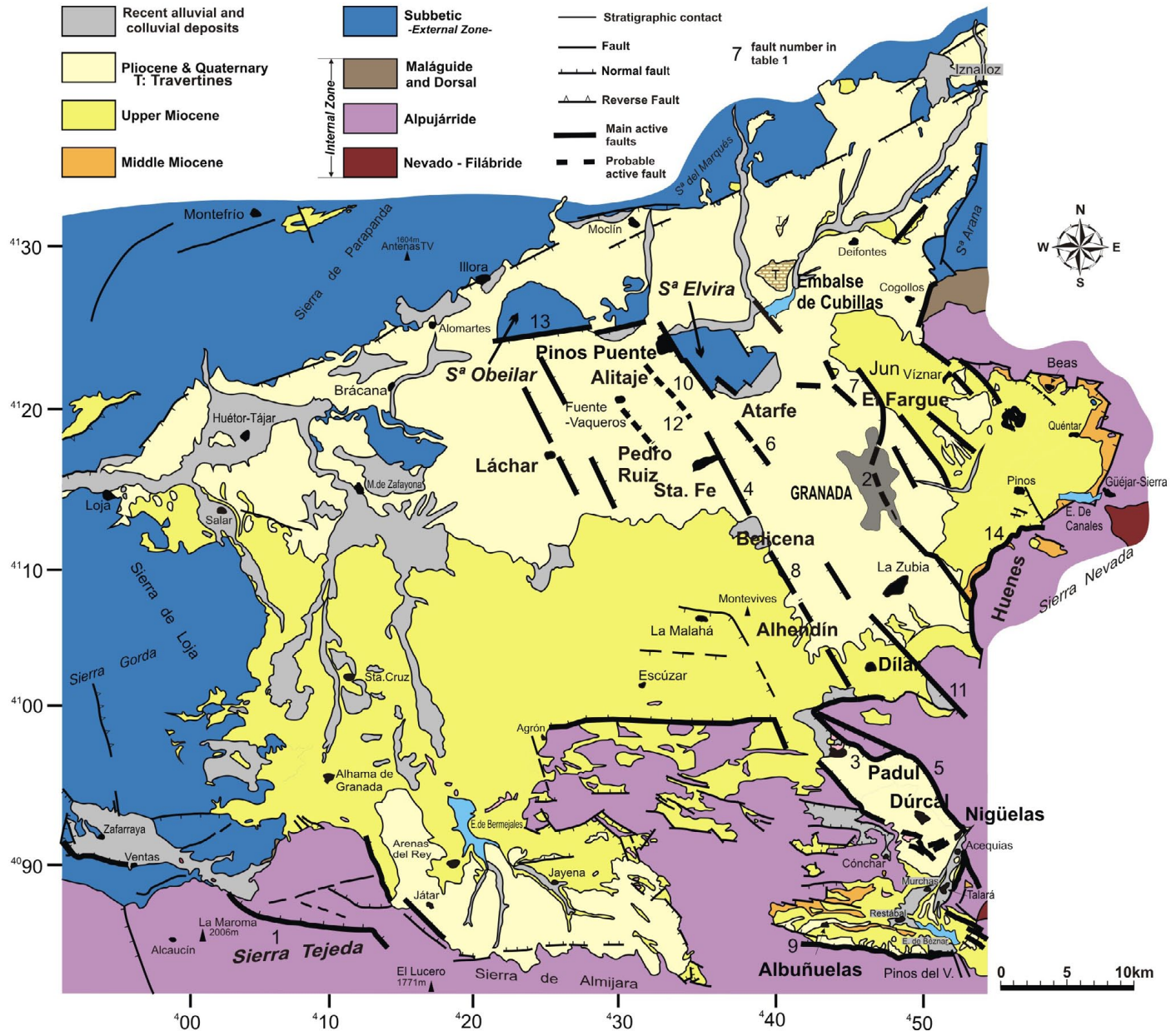
Fig. 2. Simplified geologic map of the Granada Basin. Its position is marked on Figure 1. The numbers correspond to faults described in Table 1.

Fig. 2. Mapa geológico simplificado de la cuenca de Granada. Su posición se indica en la Figura 1. Se indican los números de fallas de la Tabla 1.

possibility. Some faults have been revealed from seismic profiles (Rodríguez-Fernández and Sanz de Galdeano, 2006), such as the Alitaje Fault, parallel to the major Pinos Puente Fault.

Most of the main active faults of the basin are concentrated in the area from Sierra Elvira to Padul, passing through the area of Granada. These have a NW-SE direction and a normal character. Some of the characteristics of these faults are showed in Table 1. The main faults are described below.

The *Fargue-Jun Fault* dips to the SW, cutting through alluvial rocks of the Alhambra Formation, and is Pliocene-Pleistocene in age. Its scarp, developed in Pleistocene sedimentary rocks, indicates its recent activity.

The *Granada Fault* also dips to the SW and crosses the city of Granada. Its scarp is preserved only to the N and S of the city; it cannot be traced through the urbanised parts of Granada. Upper Pliocene-Pleistocene sediments of the Alhambra Formation are affected by several splays of this fault which produce topographic steps in the NW

Number, name and geometry[1]	Endpoints (lon./lat.)	l (km)	d[2] (km)	δ	v[3] (mm/yr)	Maximum magnitude[4] M_w, σ	Reference earthquake[5] M_W	Remarks
1. N of Sierra Tejeda, sl-n	394600,4091533 414853,4086868	23.1	> 10 (g)	60°-90° N	0.125 [10 Ma]	**6.7, 0.2[a]** **> 6.4, 0.1[b]** 6.6, 0.7[a] > 6.3, 0.5[b] 6.9, 0.2[c]	> 4.9	Evidences of recent motion. Possible responsible for the 12/25/1884 earthquake.
2. Granada, n	447012,4115895 453693,4104206	16.8	> 10 (s)	60° WSW	0.12 [2.5 Ma]	6.5, 0.7[a] > 6.3, 0.5[b] 6.7, 0.2[c]	> 4.9	This fault has 300 m of throw and affects the Pleistocene deposits. It moved noticeably since 0.8 Ma ago.
3. Padul, n	438150,4105859 448751,4095360	15.2	> 5 (g)	50°-60° WSW	0.16 [5 Ma] 0.35 [1 Ma]	6.4, 0.6[a] > 5.9, 0.4[b] 6.6, 0.2[c]	> 5.3	This fault is spectacular and has very clear signs of being active. It moves jointly with the Padul-Dúrcal fault.
4. Santa Fe, n	435398,4117751 442512,4106938	13.0	> 10 (g)	60° ENE	0.2 [5 Ma]	6.3, 0.6[a] > 6.1, 0.4[b] 6.5, 0.2[c]	> 5.2	This fault is inferred from its geomorphic features and the different nature of the materials on both sides. This fault and its parallel seemingly have noticeable associated seismicity.
5. Padul - Dúrcal, n	443269,4100498 452739,4092452	13.0	> 5 (g)	40°-60° WSW	0.2 [5 Ma] 0.35 [1 Ma]	6.3, 0.6[a] > 5.9, 0.4[b] 6.5, 0.2[c]	> 5.3	This fault is spectacular and has very clear signs of being active. It moves jointly with the Padul fault.
6. Atarfe, n	434024,4123642 441246,4116488	10.3	> 10 (g, s)	60° WSW	0.12 [2.5 Ma]	6.2, 0.6[a] > 6.0, 0.4[b] 6.5, 0.2[c]	> 4.9	This fault presents a large scarp and has substantial associated low-magnitude seismicity.
7. El Fargue - Jun, n	443955,4123348 451532,4114869	11.7	> 10 (s)	60° WSW	0.06 [5 Ma]	6.3, 0.6[a] > 6.1, 0.4[b] 6.6, 0.2[c]	> 4.5	This fault presents clear activity during the Quaternary. It clearly has associated seismicity (series of June 4th, 1998).
8. Belicena - Alhendín, n	437603,4115959 443314,4107265	10.4	> 5 (ss)	60° ENE	0.2 ? [5 Ma]	6.2, 0.6[a] > 5.7, 0.4[b] [6.4, 0.2[c]]	[> 5.0]	It is known from seismic profiles and is seemingly associated with many low-magnitude earthquakes.
9. Albuñuelas, n	440774,4087091 450029,4085700	9.8	> 5 (g)	40°-60° N	0.14 [5 Ma]	6.2, 0.6[a] > 5.8, 0.4[b] 6.4, 0.2[c]	> 4.8	It affects the upper Miocene and recent Quaternary deposits. It is, therefore, active.
10. Pinos Puente, n	432879,4124538 438856,4117392	9.4	> 10 (s)	60° WSW	0.4 [5 Ma]	6.1, 0.6[a] > 6.0, 0.4[b] 6.3, 0.2[c]	> 5.6	This fault has seemingly a great low magnitude seismicity associated with it. Its throw is about 2 km. It presents important scarps.
11. Dílar, n	447397,4106573 452605,4100330	8.3	> 10 (g)	60° W	0.16 [5 Ma]	6.1, 0.6[a] > 5.9, 0.4[b] 6.3, 0.2[c]	> 5.0	This fault is clearly active because it affects the Pleistocene deposits.
12. Alitaje, n	431371,4124551 435056,4119418	6.4	> 5 (ss)	40°-60° S	0.1 [5 Ma]	5.9, 0.5[a] > 5.6, 0.4[b] 6.2, 0.2[c]	> 4.6	This fault is known from seismic profiles. It affects the Pleistocene-Quaternary deposits, and probably moves jointly with the Pinos Puente fault.
13. Obéilar- Pinos Puente, n-sl	432883,4125093 425068,4123717	7.9	> 10 (ss, g)	60°-90° S	0.4 [8 Ma]	6.0, 0.6[a] > 5.9, 0.4[b] 6.2, 0.2[c] **6.2, 0.2[a]** **> 5.9, 0.1[b]**	> 5.5	This fault is deduced by seismic profiles and 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.
14. Huenes, sl-n	455234,4109745 452993,4106207	5.0	> 10 (g)	60°-70° W	0.25 [0.4 Ma]	**5.9, 0.2[a]** **> 5.8, 0.1[b]** 5.8, 0.5[a] > 5.7, 0.4[b] 6.0, 0.2[c]	> 5.3	This fault affects middle Pleistocene sediments and presents very recent and well-preserved scarps. The horizontal displacement has not been calculated.

l is the total longitude, d the depth, δ the dip (dip direction is showed), and v is the slip rate.

[1] (sl) strike-slip, (n) normal, (r) reverse. The first typology indicated in each case is the dominant.

[2] (g) by geologic data, (ss) by associated seismicity, (s) by seismic surveying, (gs) by gravity surveying.

[3] Calculated from the vertical displacement observed in the last [‡ Ma].

[4] ([a]) using the relationship $M_w = M_w(l)$ of Wells, Coppersmith (1994), ([b]) using the relationship $M_w = M_w(A)$ of Wells, Coppersmith (1994), ([c]) using the relationship $M_w = M_w(l,v)$ of Anderson *et al.* (1996). In boldface, acting as strike-slip faults. In brackets, non-reliable result.

[5] For a return period of 475 years and acting as normal faults. In brackets, non-reliable result.

Table 1.- Main active faults in the Granada Basin.

Tabla 1.- Principales fallas activas en la cuenca de Granada.

part of the city (Azañon *et al.*, 2004). There is a prominent low-magnitude activity of seismicity along its length and is associated with a wider fault zone, but there is no evidence of the occurrence of large earthquakes associated with this fault.

The *Sierra Elvira-Dílar Fault.* This name refers to the linkage of the faults of Pinos Puente, Atarfe and Dílar (Fig. 2) indicated in Table 1. If this association is valid, they can be considered different segments of a single fault. In total, the fault has a length of approximately 33 km and dips to the SW. Particularly, near the ends of the fault there is good evidence of recent deformations. A significant number of low-magnitude earthquakes can be attributed to this fault, specially in its northern part. Probably this fault was responsible for the 1956 (m_D 5.0) NW Purchil earthquake, which was felt with intensity VIII in the epicentral area, also situated in the northern part.

The *Alhendín-Santa Fe Fault.* This fault comprises the Belicena-Alhendín and Santa Fe faults which are described as separated faults in Table 1. These faults dips to the NE and can be considered as a conjugate fault set to the Sierra Elvira-Dilar Fault. Although the scarp of the fault, particularly in its northern part, is not well preserved, both seismic profiles (Rodríguez Fernández and Sanz de Galdeano, 2006) and gravimetric data show a larger throw than observed in field. Some low-magnitude earthquakes could be also associated with this system.

In the area of Padul, two major faults, the Padul and Padul-Dúrcal Faults, are parallel and probably converge in depth, and could be considered as different splays of a single fault. They are separated in Table 1, and also here.

The *Padul Fault.* This fault dips to the SW and separates the metamorphic basement of the Internal Zone from upper Miocene and Plio-Quaternary sediments. This fault has very well-expressed triangular facets, fault scarps, and recent peat layers are tilted towards the fault (Lhénaff, 1965; Estévez and Sanz de Galdeano, 1983; Riley and Moore, 1993; Calvache *et al.*, 1997, Sanz de Galdeano and López-Garrido, 1999).

The *Padul-Dúrcal Fault.* It is also called the Nigüelas Fault, being parallel to the Padul Fault. Santanach *et al.* (1980) estimated a large throw even reaching 800 m or more from the late Miocene. Both faults display a spectacular geomorphology (Fig. 5), and are among some of the best examples of active tectonics in the Betics (for details of displacement rates, *etc.*, see Table 1). However, seismicity associated with these faults is absent at present (Alfaro *et al.*, 2001; Ruiz et al., 2002).

The *North of Sierra Tejeda Fault* is situated in the south border of the Granada Basin. It is probably the largest E-W fault of the basin. It forms the southern border of the basin and has been associated with strong subsidence since the Messinian. It was probably responsible for the 1884 Andalusian earthquake, one of the most destructive earthquakes known in the Betics. This fault continues to the west in the area of Zafarraya, and in some cases is named after it (Reicherter *et al.*, 2003, Galindo-Zaldívar *et al.*, 2003). During the early and middle Miocene, it moved mainly as a dextral strike-slip fault, but from the late Miocene its movement has been predominantly vertical, in some places on the order of a thousand metres, forming the impressive wall of the Tejeda and Almijara Sierras.

To the east, the Sierra Tejeda Fault continues as the *Albuñuelas Fault*, which locally exposes some Quaternary sediments in its scarp. Moreover, near the south of the basin lie other E-W faults, in some cases possibly active.

The E-W striking *Obéilar-Pinos Puente Fault* marks the northern limit of the Pinos Puente and other NNW-SSE faults. Indeed, it corresponds to a segment of the former Cádiz-Alicante Fault (Sanz de Galdeano, 1983 and 2008), and contributes to the formation of the depocentre of the area of Pinos-Puente and Santa Fe.

The *Huenes Fault* is the only NNE-SSW fault cited here. It is situated to the SE of Granada and is part of the western limit of Sierra Nevada. The recent aspect of its scarp is notable, and the striae of the scarp indicate normal-sinistral displacements. Southwards, this fault is linked into the Granada Fault.

In addition, low-angle faults in Sierra Nevada affect the contact between the tectonic units of the Internal Zone. The displacement of these faults generally agrees with the direction of tension (NE-SW), the hanging blocks in most cases moving to the SW. These low-angle normal faults may extend below the Granada Basin and its reactivation interacting with the high-angle fault sets may be responsible for part of the seismicity.

3. Active faults in the Guadix-Baza Basin

In this basin we have identified 35 faults affecting late Miocene to Quaternary sediments. Some of them offer no clear evidence of deformation of the more recent Quaternary sediments or are too short in length to be included in this study. For example, the Tíscar strike-slip Fault (Foucault, 1971; Sanz de Galdeano *et al.*, 2006) or the Guadiana Menor and Alcóntar faults (Fig. 3) deform rocks of late Miocene, Pliocene or early Pleistocene age, but they lack clear evidence of deformation of the more recent Quaternary sediments that fill the Guadix-Baza Basin. Another fault revealed from a gravity survey is the Benamaurel Fault (Sanz de Galdeano *et al.*, 2007), which

Number, name and geometry[1]	Endpoints (lon./lat.)	l (km)	d[2] (km)	δ	v[3] (mm/yr)	Maximum magnitude[4] M_w, σ	Reference earthquake[5] M_W	Remarks
1. Galera, n-sl	545161,4183859 527690,4169581	23.0	> 5 (g, s)	70° NW	0.28 [0.5 Ma]	6.6, 0.7[a] > 6.0, 0.4[b] 6.8, 0.2[c] **6.7, 0.2[a]** **> 6.1, 0.1[b]**	> 5.1	Potentially responsible for the June 9, 1964 (m_{bLg} 4.8, VIII) SW Galera earthquake. It shows clear normal and sinistral fault features.
2. Alfahuara-Botardo, sl-r	537584,4185153 557440,4177944	22.0	> 5 (gs)	85° NNE	0.03 [5 Ma]	**6.7, 0.2[a]** **> 6.1, 0.1[b]** 6.6, 0.4[a] > 6.2, 0.2[b] 7.0, 0.3[c]	-	This has been an active fault since the Late Miocene but not always with a clearly visible fault plane (mostly hidden). Considering its seemingly associated seismicity, it appears more active in its western section. It is potentially responsible for the March 21, 1973 (m_{bLg} 4.0) NE Orce earthquake. The magnitude of its lateral (dextral) motion is not known.
3. Baza, n	516671,4167332 530022,4134197	37.1	> 10 (g, gs, ss)	65° E	0.22-0.37 [5 Ma]	6.9, 0.7[a] > 6.6, 0.5[b] 7.0, 0.2[c]	> 5.4	Potentially responsible for the September 30, 1531 (macroseismic M_S 6.0, VIII-IX) Baza earthquake. It induced a significant sinking in the eastern side. Considering its seemingly associated seismicity, it appears to be more active in its northern part.
4. Graena Lugros, n-sl	480861,4130061 483954,4126171	10.4	> 10 (g, s)	70° NE	0.06 [8 Ma]	6.2, 0.6[a] > 6.0, 0.4[b] 6.5, 0.2[c] **6.3, 0.2[a]** **> 6.1, 0.1[b]**	> 4.4	Movements during the Miocene-Pleistocene are evident, but not recent ones. The displacement has a dextral component. It has associated low-magnitude earthquakes.
5. Zamborino (a), n	482583,4148473 496896,4123938	25.0	> 5 (g)	65° SW	0.10 [0.5 Ma]	6.7, 0.7[a] > 6.1, 0.4[b] 6.9, 0.3[c]	> 4.6	It forms morphologic scarps affecting the glacis of the basin.
6. East of Guadix, n	486185,4135153 492908,4126713	10.8	~ 5 (g, s)	90°	0.10 [0.5 Ma]	6.2, 0.6[a] 5.7, 0.4[b] 6.5, 0.2[c]	~ 4.5	In the field it appears as great vertical joints, partially eroded by the glacis of the Guadix-Baza Basin. There is some seismicity seemingly related. Linked geological features are scarce.
7. N of Cúllar, n?	541781,4173412 535638,4167059	8.9	~ 5 (s)	-	-	[6.1, 0.6[a]]	-	Inferred from seismicity data, not from geological data. Its line and features should be taken with caution.
8. W of Cúllar, n	534154,4163281 538335,4155976	8.5	~ 10 (s)	-	-	[6.1, 0.6[a]]	-	Inferred from seismicity data, not from geological data. Its line and features should be taken with caution.
9. Benamaurel, n	524014,4159917 532378,4143303	18.7	> 10 (gs, s)	60° SW	0.20 [5 Ma]	6.5, 0.7[a] > 6.3, 0.5[b] 6.7, 0.2[c]	> 5.2	Inferred from gravity surveying and seismicity data. It is antithetic of the Baza fault set. It is potentially responsible for the November 16, 2003 (m_{bLg} 4.1, IV) SW Benamaurel earthquake.

l is the total longitude, d the depth, δ the dip (dip direction is showed), and v is the slip rate.

[1] (sl) strike-slip, (n) normal, (r) reverse. The first typology indicated in each case is the dominant.

[2] (g) by geologic data, (ss) by seismic surveying, (s) by associated seismicity, (gs) by gravity surveying.

[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 $M_w = M_w(A)$ of Wells and Coppersmith (1994), ([c]) using the relationship $M_w = M_w(l,v)$ of Anderson *et al.* (1996). In boldface, acting as strike-slip faults. In brackets, non-reliable result.

[5] For a return period of 475 years and acting as normal faults. In brackets, non-reliable result.

Table 2. Main active faults in the Guadix-Baza Basin.
Tabla 2. Principales fallas activas en la cuenca de Guadix-Baza.

has no surface-deformation features associated with it. In addition, some faults have been inferred exclusively from seismic data (*e.g.,* N, NE, E and W Cúllar faults, see Fig. 3). These faults have some associated seismic activity, such as the May 14, 1979 (m_{bLg} 4.2) E Cúllar earthquake. Finally, other faults show recent activity, but their length is shorter than 10 km (Hijate, W of the Negratín, SW of the Negratín and Alicún faults, see Fig. 3).

As in the Granada Basin, in the Guadix-Baza Basin only the main active faults (length > 10km) have been considered. They must exhibit associated seismicity or evidence of associated deformation of Middle to Late Pleistocene rocks (approximately the last 500 ka). These faults, which deform the glacis of the Guadix-Baza Basin, are the following (Table 2).

The *Galera Fault zone* (García Tortosa *et al.* 2007, 2011) is a left-lateral normal fault, which is 23 km long and strikes N48ºE (Fig. 3). The fault zone is 1.5 km wide with several parallel splays dipping NW between 40º and 60º, although vertical dips have also been noted locally. The more common pitch of the striae corresponds to approximately 40ºSW, which implies sinistral-normal movement. This fault displaces the glacis about 50 m in its central segment. From the displacement of the glacis, the mean vertical slip rate ranges between 0.08 and 0.24 mm/year. Most probably, it caused the June 9, 1964 (m_{bLg} 4.8) SW Galera earthquake (Fig. 4).

The *Baza Fault zone* (Alfaro *et al.*, 2008; García Tortosa *et al.*, 2008a, 2011) is a 37 km long normal fault (Figs. 3 and 6). The fault strikes NW-SE in its southern segment and N-S in its northern segment, and its dip ranges between 45º and 65º to the east. Within the broader fault zone, there are several roughly parallel splays, more numerous in the southern segment, that converge towards the north. The striations visible on different surfaces indicate purely normal movements. The fault displaces the glacis surface of the basin about 100 m. Part of this throw could be induced by the isostatic rebound linked to the differential erosion between the two subbasins (Fernández-Ibáñez *et al.*, 2010). From the displacement of the glacis, the mean vertical slip rate ranges between 0.17 - 0.49 mm/yr. The longer term vertical displacement has led to the development of a 30 km long mountain front. Alfaro *et al.* (2008), taking into account the total throw of the fault from the late Miocene (ranging from 2000 to 3000 m) and the dip (between 45 and 60º), deduced a vertical slip rate of 0.22 - 0.37 mm/yr.

This fault, the largest in the basin, was probably responsible for the 1531 Baza earthquake (Fig. 4), the most significant shock recorded in the historical seismic catalogue of the area. Considering its associated seismicity, the Baza Fault seems to be more active in its northern part.

The *Solana de Zamborino Fault zone* (García Tortosa *et al.*, 2008b, 2011) is a SW-dipping, NNW-SSE striking normal fault zone, of over 25 km length (Fig. 3). It has a wide fault zone, similar to the Baza Fault, with several splays that produce small topographic escarpments that in several sectors have been eroded. The southern splay has low-magnitude earthquakes associated with it. Like the Baza and Galera Faults, the Solana del Zamborino Fault zone cuts Pliocene and Quaternary sediments, displacing the glacis about 50 m. Using this value, the late Quaternary vertical slip rate ranges between 0.08 - 0.24 mm/yr.

The *Graena-Lugros Fault zone* (Fig. 3) consists of several NW-SE striking normal faults with associated hot springs. This fault zone developed at the contact between the basement rocks of Sierra Nevada, belonging to the Internal Zone, and the sediments of the Guadix-Baza Basin. These SE-dipping faults, each of them around 10 km long, produce metric to decametric vertical displacements in Pleistocene fluvial rocks and an accumulated displacement of around 40 m across the glacis. Using this value, the late Quaternary vertical slip rate ranges between 0.07 - 0.19 mm/yr. Several minor earthquakes are located in the graben of the Zamborino and Graena normal Fault.

The *Alfahuara-Botardo Fault* (Sanz de Galdeano *et al.*, 2007; García Tortosa *et al.*, 2011) is a dextral-slip fault with a WNW- ESE strike (Fig. 3). This fault is associated with an anticline structure that produces a N120ºE elongated structural high of more than 20 km length. This is a growth fold affecting upper Miocene to Pleistocene rocks. Several travertines, some noticeable local silicifications, and discontinuous small faults could be related to a blind fault. This structure probably also displaces the glacis of the basin. It was probably the fault that caused the March 21, 1973 (m_{bLg} 4.0) NE Orce earthquake. Due to a higher level of background seismicity associated with its western section near Huéscar (Fig. 3), in the junction with the Galera Fault, we consider this part to be the most active.

4. Seismic potential of the study area

The computed maximum magnitudes that each fault is able to generate can be initially considered to be an estimation of the seismic potential for each active fault and therefore, for the whole basin. To estimate these values, considering that in most cases there are no historical earthquakes associated with specific faults, we used different relationships proposed by several authors between the maximum magnitude and the length or the surface of
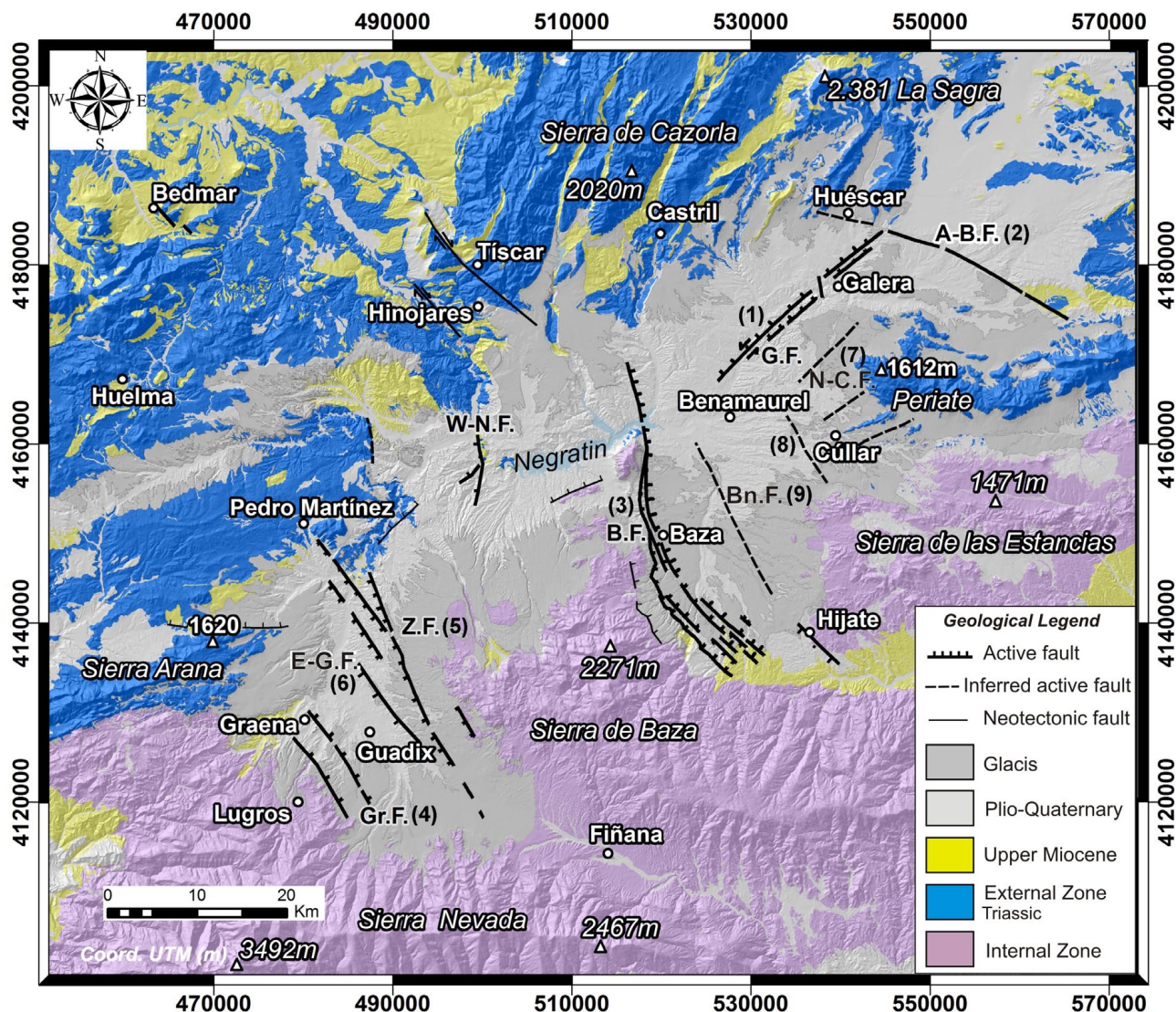
Fig. 3. Simplified geologic map of the Guadix-Baza Basin, showing the main structures. B.F.: Baza Fault zone; G.F.: Galera Fault zone; Gr.F.: Graena Fault zone; Z.F.: Solana del Zamborino Fault zone; A-B.F. Alfahuara-Botardo Fault zone; E-G. F.: E-Guadix Fault; W-N.F.: W-Negratín Fault; B.F.: Benamaurel Fault; N-C. F.: N-Cúllar Fault. Its position is marked on Figure 1. Fault numbers in Table 2 are indicated.

Fig. 3. Mapa geológico simplificado de la cuenca de Guadix-Baza, que muestra las principales estructuras. B.F.: zona de falla de Baza; G.F.: zona de falla de Galera; Gr.F.: zona de falla de Graena; Z.F.: zona de falla del Zamborino; A-B.F. zona de falla de Alfahuara-Botardo; E-G. F.: falla del E de Guadix; W-N.F.: falla del W del Negratín; B.F.: falla de Benamaurel; N-C. F.: falla del N de Cúllar. La posición del mapa se señala en la figura 1. Los números corresponden a las fallas de la Tabla 2..

the fault (Wells and Coppersmith, 1994). Moreover, the slip rates were also included in the estimation of the maximum magnitude, as proposed in other works (Anderson *et al.*, 1996). Thus, we have computed several values that enable us to verify the consistency of the results.

Another informative variable in seismic potential studies proposed by the authors of this work is the so-called reference earthquake, which in fact is more critical than the previously quoted expected maximum magnitude. It is a probabilistic value considered in the Joyner and Fumal (1985) approach to compute the seismic hazard

generated by a fault. From the mean slip rate of a certain fault, given a return period, and presuming that the observed fault displacement is fully seismic, the Joyner and Fumal (1985) approach considers that the fault displacement is due to two identical earthquakes. That is, given a certain return period, the method considers that for a given time interval, the fault generates two identical earthquakes that cause the total displacement detected. A clear advantage of this approach is that, as demonstrated by the authors in a previous work (Peláez *et al.*, 2003) using a sensitivity analysis of results, the individual vari-

1. 04/24/1431   S Granada (VIII-IX)
2. 09/30/1531   Baza (VIII-IX)
3. 10/27/1806   Pinos Puente (VIII)
4. 12/25/1884   Arenas del Rey (IX-X)
5. 05/31/1911   Santa Fe (VIII)
6. 01/08/1954   Arenas del Rey (VIII, 4.2 mD)
7. 04/19/1956   NW Purchil (VIII, 5.0 mD)
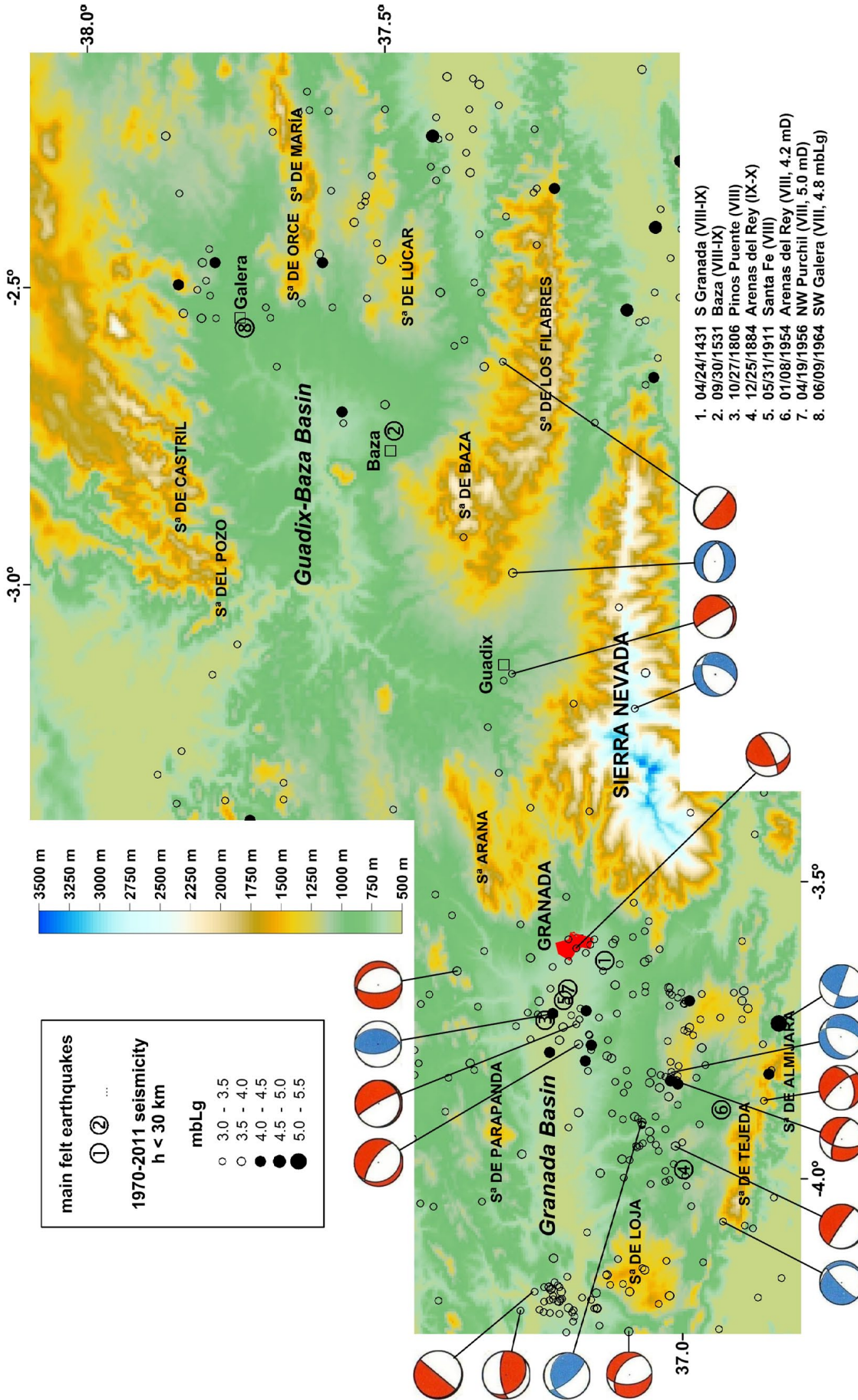8. 06/09/1964   SW Galera (VIII, 4.8 mbLg)

Fig. 4.- Main felt events, both historic and instrumental ones, and best located (since 1970) crustal earthquakes in the Granada and Guadix-Baza Basins. Focal mechanisms computed in the Proyecto SIGMA (CSN, 1998) are also included. The earthquakes corresponding to the main trend of compression (N120-140E) are represented in red, and the ones related to the secondary direction (N30-60E) are represented in blue colour (always according to the terminology of the last cited reference).

Fig. 4. Mapa de los principales eventos sentidos, históricos e instrumentales, y de los terremotos corticales mejor localizados (desde 1970) en las Cuencas de Granada y Guadix-Baza. Se muestran mecanismos focales incluidos en el proyecto SIGMA (CSN, 1998). En rojo los de terremotos correspondientes a la dirección predominante de compresión –moda- (N120-140E) y en azul a la secundaria (N30-60E) (de acuerdo con la terminología de la última referencia citada).

ation of the different analytical parameters is not key in the final result.

This approach considers, as noted above, that for seismic hazard studies, in a probabilistic context, the earthquake sequence of a fault can be replaced by a simulated sequence of two earthquakes in the requested return period. The choice of the return period must be useful to make probabilistic estimates of ground motions corresponding to probability levels of interest, as for example in seismic engineering studies. These two equal shocks, called reference earthquakes, must explain the total slip generated by the fault in such a time interval. Seismic moment for each reference earthquake is given by (Joyner and Fumal, 1985)

$$ M_{0\,ref.\,earthq.} \cong \frac{\mu}{\alpha} \left(\frac{T}{2} v \right)^2 w $$

Where μ is the rigidity modulus, T the considered return period, v the slip rate, w the fault width, computed from depth and dip, and α an empirical parameter relating the length of rupture and the displacement observed at surface. The moment magnitude is computed from the assessed seismic moment by using the known Hanks and Kanamori (1979) relationship.

Tables 1 and 2, showing active faults in the Granada and Guadix-Baza Basins, include estimated maximum magnitudes. Moreover, estimated reference earthquakes are shown for a return period of 475 years, *i.e.* for a 10% probability of exceedance in 50 years.

In the Granada Basin, the maximum magnitude to be expected is on the order of M_w 6.9. This value is for the N of Sierra Tejeda Fault, which was probably the fault that generated the 1884 Andalusian earthquake. Based on their lengths, several faults not included in Table 1, could generate earthquakes with estimated magnitudes higher than M_w 6.0, though it seems unlikely because they do not present clear Quaternary displacements.

In the NE sector of the Granada Basin, we have assumed that several segments are joined in single and longer fault zones (Alhendín-Belicena and Santa Fe are segments of the Alhendín-Santa Fe Fault, and Dílar, Atarfe and Pinos Puente are segments of the Sierra Elvira-Dílar Fault). For this study, we have estimated the seismic potential for each independent segment.

In the Guadix-Baza Basin, values on the order of M_w 6.9 have also been obtained for the Baza Fault when using the relationship by Wells and Coppersmith (1994) between the moment magnitude and the rupture length. This is the most active fault in this region, considering not only the observed displacement among fault blocks but also from the computed mean maximum magnitude.

Therefore, it can be considered to be the fault with the greatest seismic potential in the region. Considering their lengths as rupture lengths, mapped active faults in this region are able to generate earthquakes with magnitudes in the range M_w 5.4-6.9. Considering also its mean vertical slip rate from the Anderson *et al.* (1996) relationships, they could cause earthquakes in the range M_w 5.8-7.0.

5. Conclusions

The Granada and Guadix-Baza Basins are two of the most active areas of the Iberian Peninsula. Tectonically, both basins are characterized primarily by notable NW-SE to NNW-SSE active normal faults which accommodate the present ENE-WSW extension. In the Granada Basin, most of these faults develop from Sierra Elvira (to the north of Granada) to the SSE, reaching the western border of Sierra Nevada and shaping part of its SW border in the Padul-Dúrcal graben. In the Guadix-Baza Basin, the Baza, Zamborino and Graena-Lugros are the most notable NW-SE normal faults.

In addition to these faults, important E-W faults in the Granada Basin include the N of Sierra Tejeda Fault, continued in the Albuñuelas Fault. In the area of Sierra Elvira, the Obéilar-Pinos Puente Fault constitute the northern limit of the NNW-SSE faults. Also, in both basins, active faults with other strike directions include the Huenes Fault (striking NE-SW), the NE-striking Galera Fault and the WNW- striking Alfahuara Fault, both in the Guadix-Baza Basin. Geologic and geomorphic markers of different ages indicate that slip rates of these active faults vary between 0.06 - 0.5 mm/yr.

Seismically, the two basins show different behaviours. In the Granada Basin, seismicity is dispersed, and in many cases not related to known active faults, with the exception of the more energetic earthquakes. Moreover, a significant seismicity rate of low-magnitude events can be observed.

The background seismicity shows that, apart from the currently known active faults in the basin, there are others with characteristics and locations that have not yet been determined. On the contrary, in the Guadix-Baza Basin, earthquakes are clearly related to the main active faults, in this case, with a lower seismicity rate.

The faults with the greatest seismic potential, and thus implying the most serious seismic hazard, are the North of Sierra Tejeda Fault in the Granada Basin and the Baza Fault in the Guadix-Baza Basin. The probably caused the 1884 Andalusian and the 1531 Baza earthquakes, respectively. Their expected maximum earthquakes are the larg-
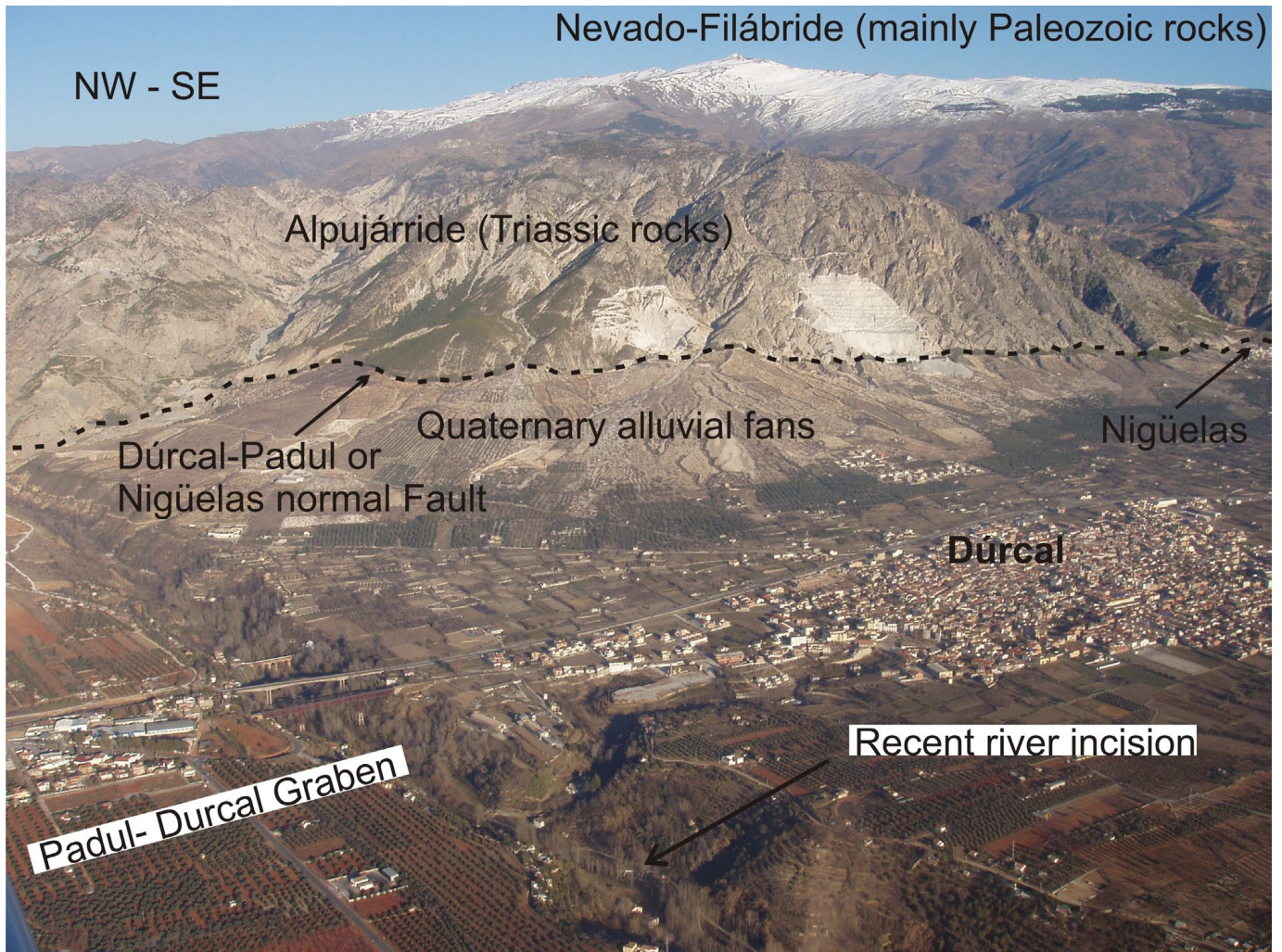
Fig. 5. View of the southern part of the Padul-Dúrcal Fault. Its throw reaches nearly 1000 m in some places. Photo by J. Sanz de Galdeano.

Fig. 5.- Vista de la parte meridional de la falla del Padul-Dúrcal. Su salto vertical es de casi 1000 m en algunos puntos. Foto de J. Sanz de Galdeano.
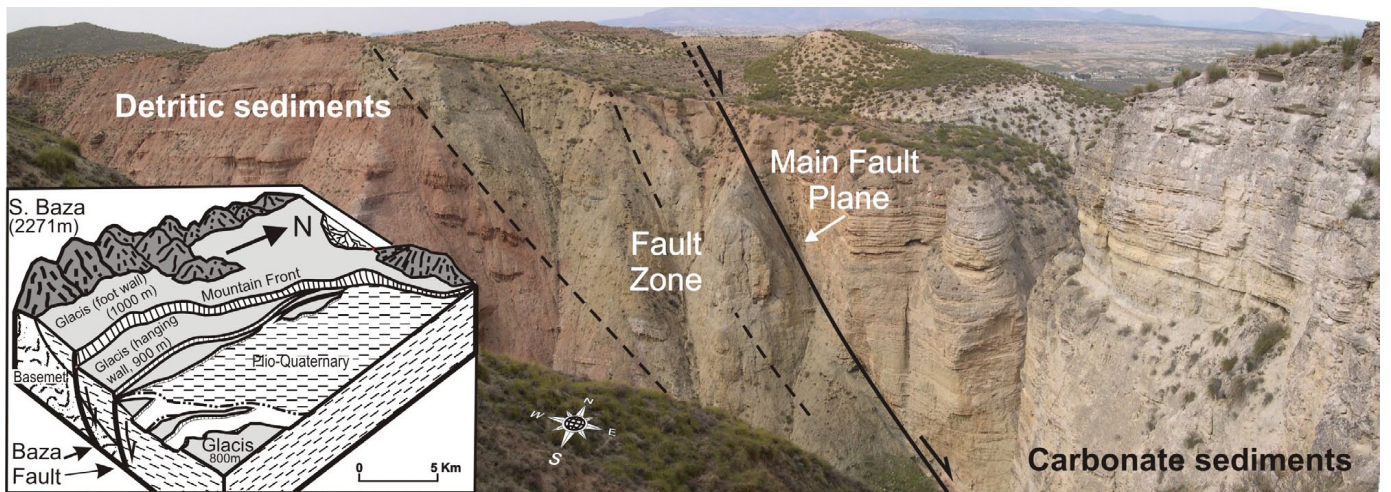
Fig. 6.- Detail of the Baza Fault zone, including a 3-D tectonic sketch of the deformation. The photo is located near the northern part of the fault.

Fig. 6.- Detalle de la zona de falla de Baza, incluyendo un esquema tectónico tridimensional de la deformación. La foto se localiza cerca de la parte norte de la falla.

est in their respective basins.

The appraised seismic potential in terms of the expected maximum magnitude shows that moderate to strong earthquakes, *i.e.* earthquakes in the range M_w 6.0-7.0, could be generated if the main faults mentioned above (particularly the Baza Fault) broke along their length or surface. In probabilistic terms, for a return period of 475 years, moderate earthquakes (M 5.0-6.0) could have their origin in the Baza, Galera and Benamaurel Faults, and minor to moderate earthquakes (M 4.0-5.0) could be generated by the most of the other active faults in the region. In any case, this region must be considered as a moderate seismic-hazard area.

Acknowledgements

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