



Seismic hazard of the Granada Fault

Peligrosidad sísmica de la Falla de Granada

Azañón, J.M. ^(1, 2); García-Mayordomo, J. ⁽³⁾; Insua, J.M. ⁽⁴⁾; Rodríguez-Peces, M.J. ⁽⁴⁾

(1) Dpto. de Geodinámica, Facultad de Ciencias, Universidad de Granada. C/Fuentenueva, s/n, 18002, Granada, España.
Email: jazonon@ugr.es

(2) Instituto Andaluz de Ciencias de la Tierra, CSIC-Universidad de Granada.

(3) Instituto Geológico y Minero de España (IGME). C/La Calera, 1, 28760, Tres Cantos (Madrid), España.

(4) Dpto. de Geodinámica, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid. C/José Antonio Novais, 2, 28040, Madrid, España.

Abstract

The City of Granada is placed at the margin of a flat area known as the Granada Basin (Betic Cordillera, SE Spain) surrounded by mountains. The seismic activity in the Granada Basin is high, with a large number of earthquakes, all of them of moderate to low magnitude ($m_b \leq 5.5$). Historically, earthquakes in this area have produced important material damage and human casualties; however, it is hard to evaluate their magnitude. Seismicity has its origin mostly at depths between 5 and 17 km and the focal mechanisms indicate a present stress field dominated by a tensional tensor with an associated NE-SW extensional axis. The sedimentary cover of the Granada Basin is mostly coeval with the activity of faults that bound the basin, which have controlled the stratigraphic architecture. These faults are normal, mostly with a NW-SE orientation, and dipping towards the SW. Basinwards migration of the extensional front has exhumed the footwalls of older faults, uplifting the previous Tortonian sedimentary cover, which presently outcrops as emerged ranges at the margins of the basin. This work presents preliminary results of a paleoseismic study of the Granada Fault, an NW-SE active normal fault that produces a Plio-Quaternary throw of 300 m. According to these data, slip rate has been estimated in 0.38 mm/yr. Several paleosoils, Pleistocene in age, have been affected by this fault. These paleosoils were sampled and dated using the thermoluminescence method to constrain these estimates. Three different seismic events can be recognized from the accumulative throw. The vertical slip per event ranges from 5 to 7 cm. Following empirical relationships, a moment magnitude between 5.9 and 6.0 can be preliminary assessed for these events.

Key words: Central Betics; Granada; Paleoseismicity; Seismic hazard; Slip rate.



Resumen

La ciudad de Granada está situada en el margen de un área llana rodeada de montañas conocida como la Cuenca de Granada (Cordillera Bética, SE España). La actividad sísmica en la Cuenca de Granada es alta, con un gran número de terremotos, todos ellos de moderada a baja magnitud ($m_b \leq 5.5$). Históricamente, los terremotos en este área han ocasionado importantes pérdidas materiales y de vidas humanas; sin embargo, es difícil de establecer su magnitud. La sismicidad se origina a profundidades de entre 5 y 17 km y los mecanismos focales indican un campo de esfuerzos actual dominado por un tensor extensional asociado a un eje de extensión NE-SO. El relleno sedimentario de la Cuenca de Granada es sincrónico con la actividad de las fallas que limitan la cuenca, las cuales han controlado la secuencia estratigráfica. Estas fallas son normales, la mayoría con una orientación NO-SE, y buzamientos hacia el SO. La migración hacia el interior de la cuenca del frente extensional ha exhumado los bloques de muro de las fallas más antiguas, elevando la cobertera sedimentaria Tortonense previa, que actualmente afloran como sierras emergidas en los márgenes de la cuenca. Este trabajo presenta los resultados preliminares de un estudio paleosísmico de la Falla de Granada, una falla normal activa con orientación NO-SE que produce un salto Plio-Cuaternario de 300 m. Según estos datos, la tasa de deslizamiento se ha estimado en 0,38 mm/año. Varios paleosuelos, de edad Pleistoceno, han sido afectados por esta falla. Estos paleosuelos se muestrearon y dataron por el método de termoluminiscencia para precisar estas estimaciones. Se pueden reconocer tres eventos sísmicos a partir del salto acumulativo. El salto vertical por evento es de 5 a 7 cm. A través de relaciones empíricas, preliminarmente se ha establecido una magnitud momento entre 5.9 y 6.0 para estos eventos.

Palabras clave: Béticas Centrales; Granada; Paleosismicidad; Peligrosidad sísmica; Tasa de deslizamiento.

1. Introduction

The Granada Town is located in the NE corner of an intramontane basin called with the name of the City. The Granada basin is situated in the central part of the Betic Cordillera (SE Spain), within a wide active collision zone between the African and Eurasian plates, which converge at approximately 5 mm/yr (Argus *et al.*, 1989; DeMets *et al.*, 1994). Seismotectonic studies in the central sector of this Alpine orogen reveal that nowadays the region is subject to a NW-SE compression with a NE-SW linked extension (Galindo-Zaldívar *et al.*, 1999; Herraiz *et al.*, 2000; Galindo-Zaldívar *et al.*, 2003). The NE-SW extension is accommodated by normal faults with several orientations, amongst which the NW-SE set is the dominant one.

The basement of the Granada basin is formed by metamorphic rocks (schists, phyllites and marbles) of Palaeozoic to Mesozoic ages and by sedimentary rocks of Triassic to Cretaceous

ages. The sedimentary infilling of the basin is up to 1.5 km-thick (Rodríguez-Fernández *et al.*, 1989; Rodríguez-Fernández and Sanz de Galdeano, 2001). The oldest sediments in the basin are conglomerates, calcarenites and marls deposited in marine environments. The continental infilling is represented by conglomerates, lutites and sandstones deposited in relation to rivers and alluvial fans that drained the surrounding mountains. Limestones and fine-siliciclastic sediments formed in lacustrine environments are found in the central sector of the basin (Günter and Skowronek, 2001).

The sedimentary succession of the Granada basin is mostly coeval to the activity of faults, which bound the basin and have influenced the stratigraphic architecture. These are normal faults, mostly SW-dipping (Fig. 1). Migration of the extensional front basinwards has exhumed the footwalls of older faults, uplifting the Tortonian rocks, which presently outcrop in ranges along the margins of the basin

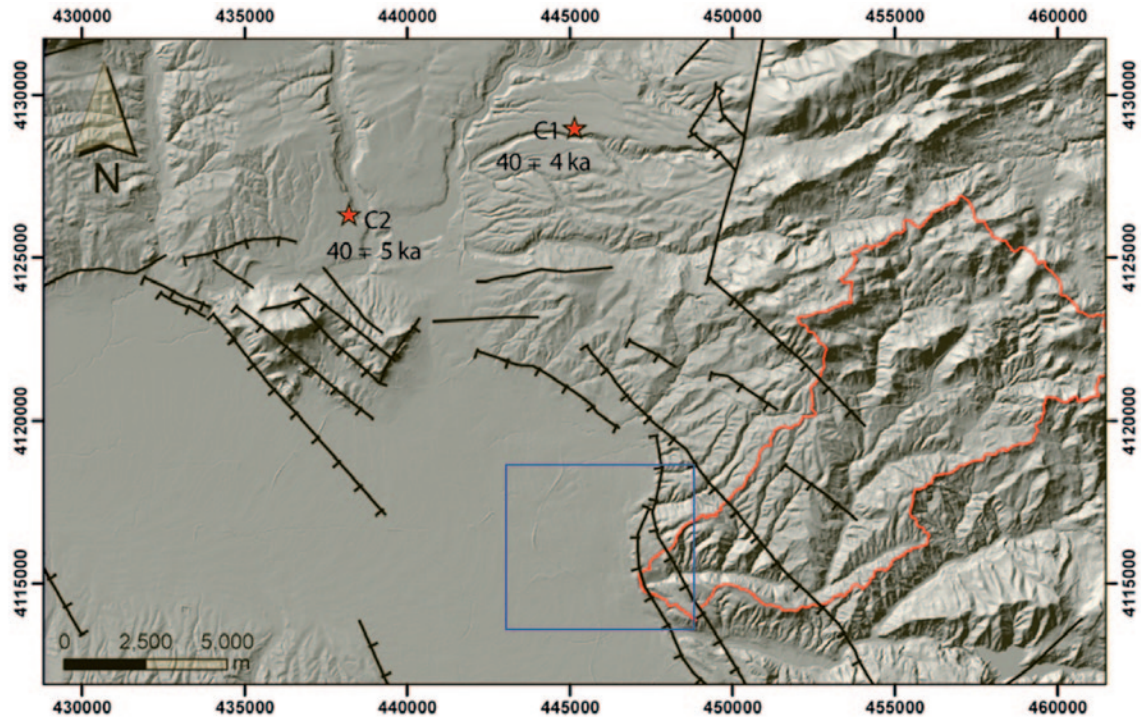


Figure 1. NW-SE normal faults outcropping in the northeastern border of the Granada basin. City of Granada is located in the blue square. C1 and C2 indicate the position of two calcretes which have been dated by U/Th radiometric method.
 Figura 1. Fallas normales con orientación NO-SE que afloran en el borde nororiental de la Cuenca de Granada. La ciudad de Granada está localizada en el cuadrado azul. C1 y C2 indican la localización de dos calcretes que han sido datadas mediante el método radiométrico de U/Th.

(Martín and Braga, 1997). This migration of the mountain front also involved the Pliocene and Quaternary sediments, which presently constitute uplifted blocks in the eastern and northeastern borders of the Basin (Fig. 1). The sedimentary formations show unconformable relationships in the margins of the basin, which correlate with paraconformities towards the centre of the basin; however, in many places the present-day contacts between formations are normal faults.

2. Faults in the northeastern border of the Granada Basin

The present-day relief of the margins of the Granada depression is strongly conditioned by the activity of some of the aforementioned faults, together with the incision produced by several rivers that drain the area. The faults produce large steps in the relief

(Fig. 2). The most important topographic step corresponds to the faults bounding the basement of the basin; these faults are characterized by meter- to hectometer-scale scarps with associated slicken-surfaces and striations; the footwalls of these faults are uplifted blocks with strong relief and deeply incised by rivers. Several steps are found between the flat area of the Granada basin and the ranges where the basement outcrops, which could represent fault scarps variably degraded by erosion of the soft sediments. These steps show NW-SE orientations, in accordance with the orientation of the majority of the normal faults mapped in the margin of the basin.

The seismic activity in the Granada depression is high, with a large number of earthquakes, all of them with a moderate to low magnitude ($m_b \leq 5.5$) (De Miguel *et al.*, 1989; Muñoz *et al.*, 2002). The seismicity has its origin mostly



Figure 2. Topographic steps produced by the NW-SE normal faults.
Figura 2. Escalones topográficos producidos por las fallas normales con orientación NO-SE.

at depths between 5 and 17 km (Morales *et al.*, 1997; Serrano *et al.*, 2002) and the focal mechanisms indicate a present-day stress state dominated by a NE-SW extensional axis. This extensional stress field coincides with palaeo-stress determinations from Tortonian and younger sediments, and is perfectly compatible with NW-SE striking normal faults and NE-SW directed extensional transport (Galindo-Zaldívar *et al.*, 1999; Martínez-Martínez *et al.*, 2002; Galindo-Zaldívar *et al.*, 2003). Taking into account the length of the seismic faults in the area (approximately 17 km) the “realistic” maximum magnitude of an earthquake would be 5.1 (De Miguel *et al.*, 1989; Peláez Montilla *et al.*, 2002). An earthquake of this magnitude at depths of 5 km would produce maximum

vertical displacements of 3 mm in the vertical of its focus (Peláez Montilla *et al.*, 2002).

A detailed study about the longitude and segmentation of the NW-SE active faults outcropping in the surrounding areas of the Granada Town is critical to evaluate the seismic hazard in this place. In a previous analysis, Peláez Montilla *et al.* (2002) attributed a maximum longitude to the Granada fault of 17 km. However, deformation induced by the Granada fault is distributed in a wide area of several kilometers. In this area, it can be appreciated that the fault is segmented in multiple discontinuous planes. By instance, in the Alhambra hill and surrounding areas, the outcropping rocks are affected by several faults with centi-

meter throws. The lateral continuity of these faults is less than 10 km.

3. Paleoseismological assessment

The seismic capability of the NW-SE faults of the Granada City is assessed studying one of these faults affecting several paleosoils. The studied fault has been located in a vertical urban talus at the suburb of Granada (UTM 30N: X-445083; Y-4117927; Datum ETRS89).

The fault, with strike N125°E and dipping 86° southwards, affects several well-developed soil horizons (Figure 3). The brown and

reddish-brown horizons have been taken as markers to estimate the accumulative displacement of the fault. We took into account the top and the bottom of these dark horizons because their diffuse limits. In addition, we took three samples for thermoluminescence dating (TL) in order to estimate some recurrence of the seismic events and the slip rate of the fault. The result of the accumulative slip, coseismic slip and mean coseismic slip of the fault is presented in the Table 1.

With such a mean coseismic slip of 5.86 cm within a range of 4.8 to 7.0 cm, this fault would be capable to generate events with magnitude 5.9-6.0 following the relationships

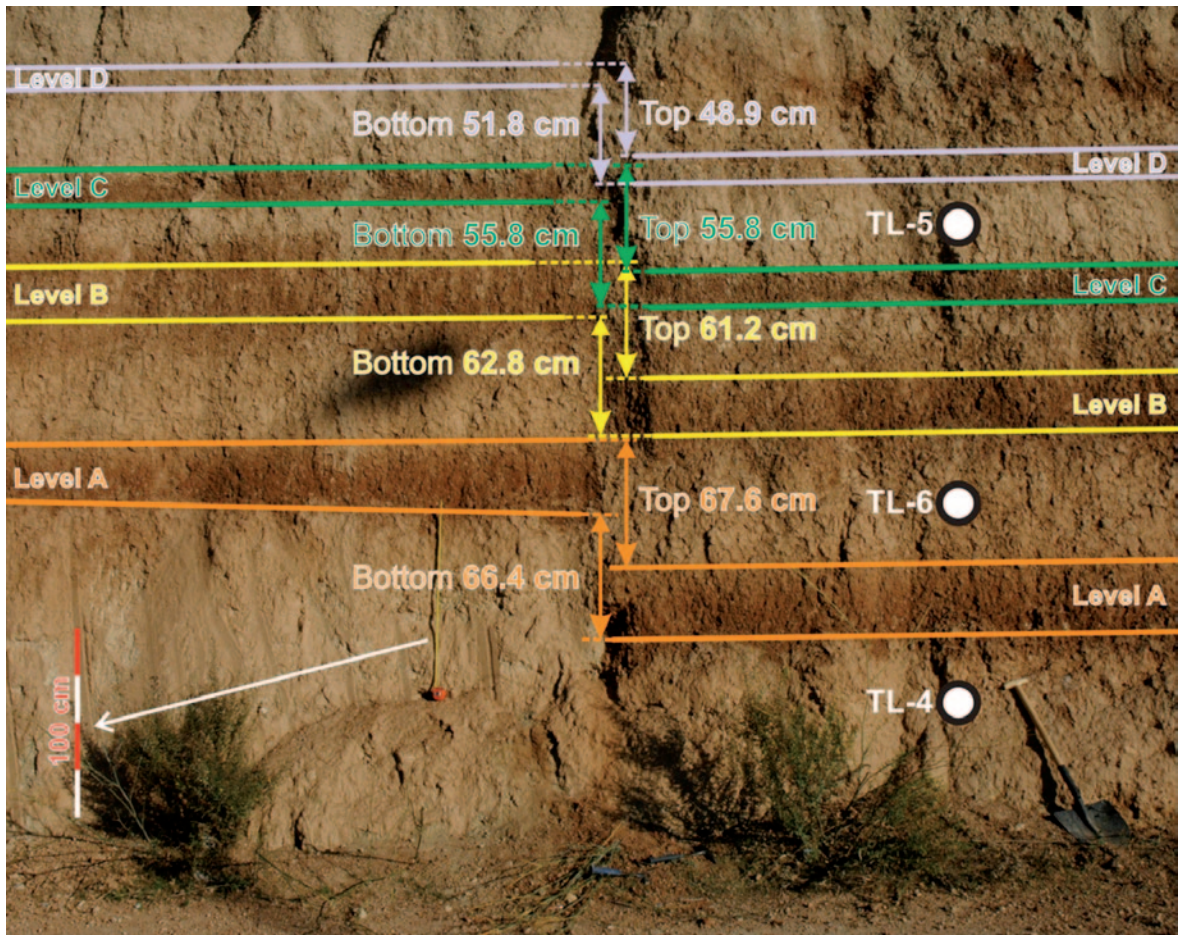


Figure 3. Paleoseismological analysis of the Granada Fault. TL-4 and TL-6 are the selected points to thermoluminescence dating.
 Figura 3. Análisis paleosismológico de la Falla de Granada. TL-4 y TL-6 son los puntos seleccionados para la datación mediante termoluminiscencia.

between moment magnitude and average displacement of Wells and Coppersmith (1994). The accumulative displacement remaining of 50.0 cm of the level D might be generated by 8-9 events considering the mean coseismic slip. Unfortunately, the ages of the samples TL-4, TL-5 and TL-6 are all beyond the age range of the dating technique (150 ka). In any case, we can estimate some extreme values of recurrence period and slip rate of the fault. In this way, considering the youngest material affected by the fault (Level D) like older than 150 ka, we estimate a seismic recurrence period longer than 16.7 ka. On the other hand, the slip rate of the fault should be considered as a maximum value of 0.003 mm/yr, which is remarkable lower than that given by Sanz de Galdeano *et al.* (2003) as 0.38 mm/yr in these faults since Medium Pleistocene (800 ka). The difference of these two values should be understood as a distribution of the deformation in a complex set of faults that limit the Granada Basin at this edge. Nevertheless, we cannot discard a deceleration of the rate during the Late Pleistocene.

Table 1. Results of the paleoseismological analysis of the Granada Fault.

Tabla 1. Resultados del análisis paleosismológico de la Falla de Granada.

Level	Accumulative slip (cm)	Coseismic slip (cm)
D	50.0	
C	55.8	
B	62.8	
A	67.6	
	Mean coseismic slip (cm)	5.86

4. Implications in Seismic Hazard

Sanz de Galdeano *et al.* (2003) assessed the seismic potential of the Granada Fault. They estimated a 6.3-6.6 maximum moment magnitude (M_w), and a recurrence time of less than 510 years for a $M_w=6.0$ earthquake. Recurrence time was obtained using a 0.38 mm/yr slip rate, which results from considering 300 m accumulated vertical offset since Me-

dium Pleistocene (800 ka). According to these data, the authors classified the Granada Fault as the most active one in the whole Granada Basin. Even though their observations could be regarded as very interesting at the time they were produced, the absence of absolute dating and precise measurements of coseismic deformation, makes their conclusions very arguable.

According to the results obtained in our paleoseismological analysis, the interest in modeling the Granada Fault as a particular seismogenic source is very limited. A $M_w=6.0$ maximum magnitude does not represent a particular large value in the tectonic and/or historical seismicity context in the Granada Basin. Furthermore, a minimum mean recurrence time of 16.7 ka means a very low frequency when compared to the extrapolation of the Gutenberg-Richter law of the area (~100 years in Morales *et al.*, 1999).

Nevertheless, these results agree with a model of distributed deformation at this border of the Granada Basin. In this model, the Granada Fault represents a shear band composed of multiple small faults, in contrast to a single large fault which accumulates most of the deformation. In this context, elastic energy is released preferentially by small earthquakes and, exceptionally, by moderate size ones ($M_{w\text{máx}} \approx 6.0$).

5. Discussion and Conclusion

According to the paleoseismological results obtained from TL dating and direct measurement of coseismic deformation, we regard the seismic hazard of the Granada Fault preliminary as low. However, these results shall be confirmed in following studies. Our study remarks the importance of performing absolute dating and direct measurement of coseismic deformation in recent sediments (Late Pleistocene, at least) in order to evaluate properly the current activity and, subsequently, the seismic hazard of particular faults. In this context, the actual activity of many faults in the

Granada Basin —which have been assessed based on Plio-Quaternary markers (ca. 5 Ma), could be much lower than it is currently believed.

Finally, the Granada Fault is capable of producing earthquakes as large as 6.0 (± 0.3). Whether these earthquakes will be catastrophic or not depends much more on the observance of seismic code provisions by builders and on Civil Protection Plans, rather than on the seismic potential of the Granada Fault.

If we consider the rupture of the total length of this fault (<10 km), the maximum magnitude estimated with the relationships between moment magnitude and surface rupture length of Wells and Coppersmith (1994) would be between 6.1-6.2. This magnitude is quite similar to that obtained in our paleoseismological assessment attending to the average displacement ($M_w=5.9-6.0$). This result is much higher than that given by De Miguel *et al.* (1989) or Peláez Montilla *et al.* (2002) as the “realistic” maximum magnitude of 5.1.

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