THE 2012-2013 TORREPEROGIL (EASTERN GUADALQUIVIR BASIN, SPAIN) SEISMIC SERIES - A TECTONIC SEISMIC SWARM OF LOW MAGNITUDE EARTHQUAKES IN A LOW SEISMIC HAZARD AREA

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ABSTRACT

Since October 2012 till now, more than 2200 low magnitude earthquakes have been located in the vicinity of the towns of Torreperogil and Sabiote (Jaén), in the easternmost part of Guadalquivir Basin, Spain, an area considered of low seismic hazard. Specific tectonic studies in the region are barely available due to the scarce deformation of Mesozoic and Cenozoic cover. However, the re-interpretation of former seismic reflection profiles reveals blind faults in the Variscan basement that could host the swarm.

In this work we show the characteristics of the seismic series, including the relocation of earthquakes with magnitude above m_{bLg} 1.5 using the well-known HypoDD code. In addition to a disperse seismicity composed by very low magnitude events that could not be relocated, two clear seismicity clusters with different characteristics were observed. Both clusters showed an approximate N-S striking, probably related to two N-S striking structures. Additionally, we also assessed a statistical analysis of the sequence.

The detailed survey carried out in the epicentral area verified the existence of some fault zones. Although it is also possible to observe dip-slip movements, the main zone shows a tectonic fabric with lateral sense of shearing. Their strike and kinematics are in agreement with one of the two nodal planes of the computed focal mechanism.

INTRODUCTION

On October 20th, 2012, in the easternmost part of the Guadalquivir Basin (figure 1), southern Spain, began a seismic series including more than 6000 low magnitude earthquakes. The Spanish Instituto Geográfico Nacional (IGN) has only located by the order of 2200 earthquakes, the biggest one with

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magnitude m_{bLg} 3.9 (M_W 3.7). One year after its beginning, the seismic series can be considered finished, although it is observed a residuary very low magnitude seismicity not observed in the region previously to this series.

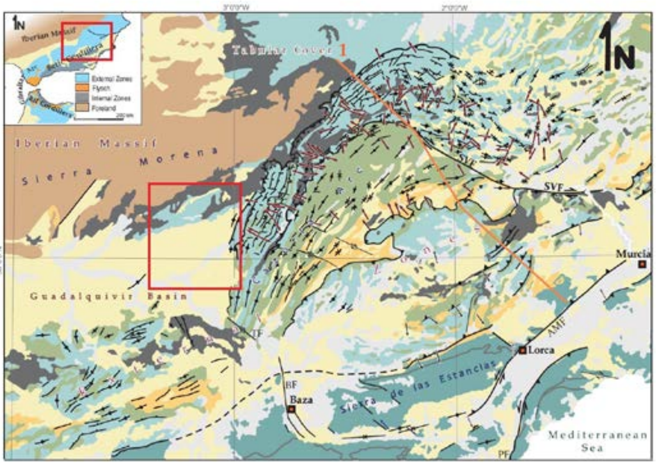

Figure 1. Geological sketch of the seismic series (after Pedrera *et al.*, 2013).
Inner red square delimitates epicentral area.

The tectonic seismic series found in Spain has the biggest number of recorded events. This is one of the reasons, which explain why it has been one of the most studied series. The population felt many events (about 200-250 earthquakes); this became a very important concern in the population, and thus making a significant impact in the media. The Spanish Senate ordered a scientific research, in which some of the authors of this work collaborated (García Tortosa *et al.*, 2013; Lozano *et al.*, 2013; Sánchez Gómez *et al.*, 2013), among other outstanding Spanish researchers. In this work, we present some of the most conspicuous results concerning the studies carried out, including the seismic data analysis and the tectonic studies.

The seismic swarm is one of the most important swarm that has occurred in recent years in the upper course of the Guadalquivir River. Recently, two other seismic swarms occurred in the region, the seismic series of Arquillos, 2010-2011, and Baeza, 2011 (Peláez *et al.*, 2012).

SEISMIC DATA

Figure 2 displays the temporal distribution of the seismicity, showing three clear phases, stages or sub-series, delimited in the evolution of the seismic series. Phase #1 start on October 20th, finished approximately one month later, on November 25th, 2012. Although it was not so pronounced like the two subsequent phases, it responds to a typical pattern of tectonic seismic series. The biggest earthquakes in this first phase were two earthquakes with magnitude m_{bLg} 2.1 on October 22th, and November 24th, 2012, respectively. The entire released energy during this phase was equivalent to an earthquake with magnitude m_{bLg} 2.9.

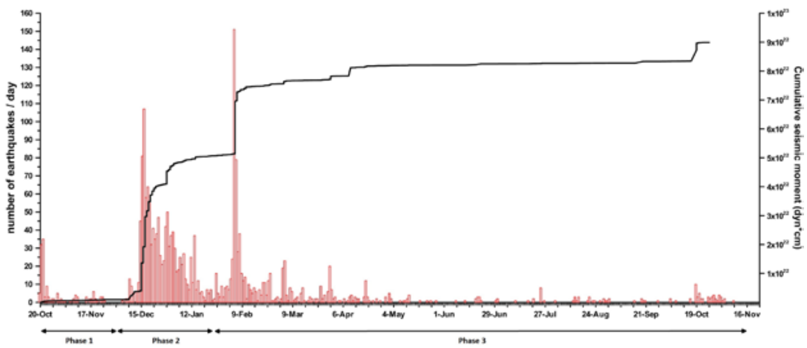

Figure 2. Temporal distribution of the seismicity. Number of recorded earthquakes by day
(data from Spanish IGN) and accumulated seismic moment.

The phase #2 spans from December 5th, 2012, to January 24th, 2013, approximately. The most energetic event during this phase was an earthquake with magnitude m_{bLg} 3.7, which occurred on December 15th, 2012. The released energy in this second phase was equivalent to an earthquake with magnitude m_{bLg} 4.2. The released seismic moment, as can be also seen in figure 2, is clearly biggest than the released seismic moment in the previous phase.

Finally, the phase #3 spans from January 25th, to December, 2013, including the residuary very low magnitude seismicity recorded in the second half of the year 2013.The released energy and the released seismic moment in this phase were the same with that in the previous phase, although with less number of earthquakes. This phase recorded the biggest earthquake of the entire seismic series, an event with magnitude m_{bLg} 3.9 (M_W 3.7) on February 5th, 2013, and felt in the town of Torreperogil with intensity V (EMS-98 scale). It was recorded just 24 s after another earthquake with magnitude m_{bLg} 3.6, constituting both earthquakes a doublet. The focal mechanism solution for this event was computed by the Spanish IGN and depicted in figure 3.

A relocation of the seismic series (figure 3) using the well-known HypoDD code (Waldhauser and Ellsworth, 2000; Waldhauser, 2001) was carried out. The phase data provided by the Spanish IGN was used. We relocated only earthquakes above magnitude m_{bLg} 1.5 recorded at least by 10 seismic stations. In order to reduce the errors in the relocations, we used only the P phase, employing differences among couples of events with at least 12 different values, and the distances between couples of events and seismic stations less than 200 km. The final number of relocated events was 559, with errors below 100 m.

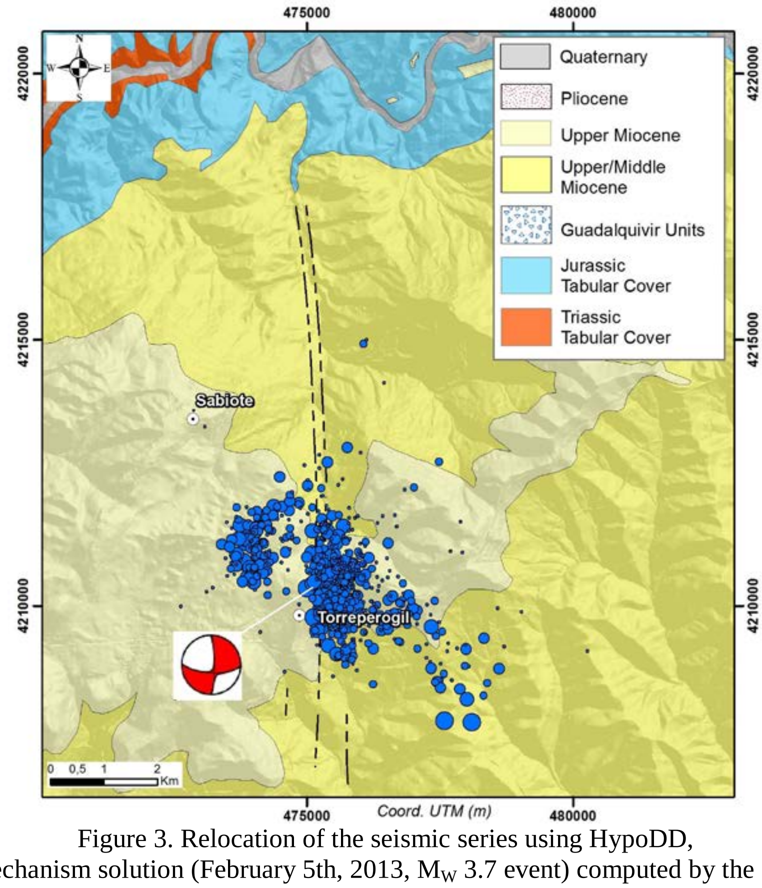

Figure 3. Relocation of the seismic series using HypoDD,
and focal mechanism solution (February 5th, 2013, M_W 3.7 event) computed by the Spanish IGN.

In the figure 3, two clear seismicity clusters can be observed. One of them, just to the east of Torreperogil (cluster #1), while the second one is between Torreperogil and Sabiote (cluster #2), with a lesser number of earthquakes. Moreover, we also observe some disperse seismicity (cluster #3) to the SE of cluster #1.

Seismicity in phase #1 (figure 2) was entirely located in cluster #1 (figure 3). The *b*-value of the Gutenberg-Richter relationship for the phase #1 is equal to 1.84 (σ = 0.10), a high *b*-value, considering that it is the usual in this type of seismic series. The fractal dimension D_2 of the spatial distribution of epicenters in phase #1 is equal to 1.48 (σ = 0.05), as computed from the correlation dimension (Grassberger and Procaccia, 1983), and from the correlation integral, using to it distances between events ranging from 1.4 to 2.0 km. In order to compute the fractal dimension value, we used only events relocated with HypoDD, while for the *b*-value we used the values of all earthquakes located by the Spanish IGN.

Seismicity in phase #2 (figure 2) is also located entirely in cluster #1 (figure 3). In this case, the *b*-parameter is equal to 1.03 (σ = 0.03), a typical value in this type of seismic series, and the D_2 parameter is equal to 2.40 (σ = 0.01), using the range of distances between events of 0.4-1.0 km.

The beginning of phase #3 (figure 2) coincides with the occurrence of earthquakes in the cluster #2 (figure 3), between Torreperogil and Sabiote, although earthquakes in the cluster #1 repeatedly occur. In this phase, the *b*-parameter is equal to 1.02 (σ = 0.02), and the D_2 parameter is equal to 1.72 (σ = 0.04), using to its computation the range of distances between events of 0.6-1.2 km.

Finally, the residuary seismicity in the last months is equally distributed in the three clusters. Although with a less number of events, cluster #3 was activated during phase #3. For these earthquakes, the *b*-parameter is equal to 0.89 (σ =0.02), a low value, though not unusual.

After relocating events, can be seen earthquake depths in the range 2-5 km, although these values are strongly dependents on the used crustal velocity model. In our case, the used model is that proposed and used by the Spanish IGN for hypocentral locations in the Iberian Peninsula (*v.g.*, Carreño y Valero Zornoza, 2011). Seismicity dips toward the west, particularly seismicity included in cluster #2 (figure 4).

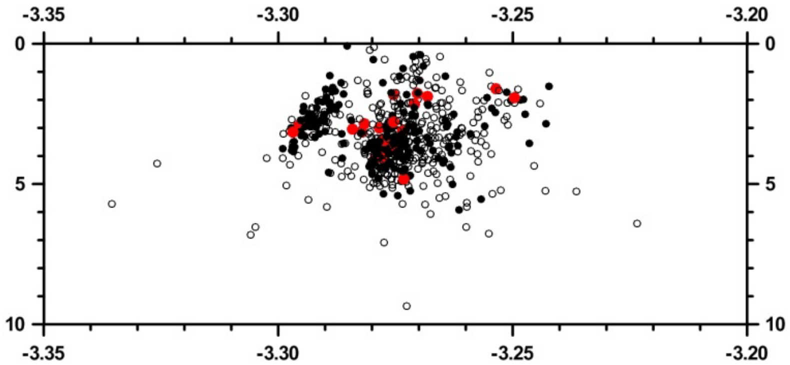

Figure 4. E-W cross-section of seismicity.

The two main alignments observed in the seismicity in figure 3 (and in the cross-section of figure 4) trending N-S, and corresponding to clusters #1 and #2, are in good agreement with the computed focal mechanism, also depicted in the same figure.

FIELD DATA AND PALEOSTRESS ANALYSIS

There are scarce works in the region from a tectonic point of view, due to the apparently low deformation of the Tertiary sediments. However, some studies of hydrogeological nature, some commercial seismic profiles, and geophysical surveys in the area (Rey *et al.*, 1995, 1998; Motis and Martínez del Olmo, 2012) have revealed the existence of normal faults in the Paleozoic basement affecting the Tertiary tabular cover. These normal faults apparently do not reach the topographic surface, and therefore could not be considered active, or could be active as blind faults.

The epicentral area is located near the northern margin of the basin, the less deformed margin. The southern margin is affected by faults and folds, with a debated geometry under the Tertiary sediments. In the northern margin, the only currently known structures are, as indicated previously, those found in commercial seismic profiles, as the re-interpreted profile in figure 5.

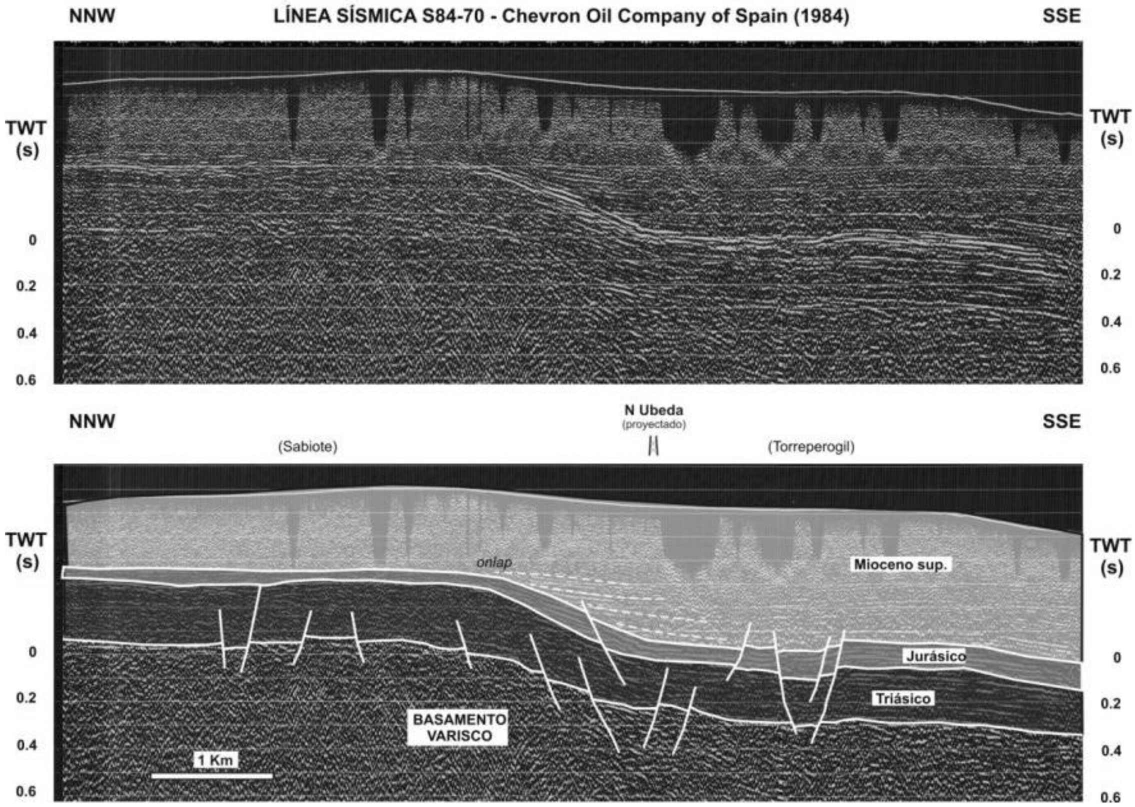

Figure 5. Re-interpretation of a seismic profile carried out by Chevron Oil Company in the studied area.

In this seismic profile (figure 5), a monoclinal antiform, supposedly E-W trending, resembles a horst and graben sequence that generally descend towards the south of the Mesozoic tabular cover (Motis and Martínez del Olmo, 2012). In contrast, horizontal Miocene reflectors onlap the basement faults or folds, thus indicating that they were inactive after this period.

Recent interpretations suggest that faults were re-activated but did not break through the upper part of the sedimentary sequence, thus the deformation was accommodated in the Miocene sediments, which are more ductile and thus resulting in blind faults (Roldan *et al.*, 2013).

After a detailed geological survey of the Torreperogil-Sabiote area, we found the existence of several fault zones. The most important structures (ZFAS) are approximately N-S trending, and can be topographically followed several kilometres east to Sabiote and Torreperogil towns (figures 3 and 6). The main fault zone has been recognized as a tectonic fabric characterized by cataclastic banding, with an average strike and dip N163º/74ºE. Both strike-slip and dip-slip structural alignments can be observed on the fault planes inside the cataclasites. The dip-slip senses of shearing are systematically normal when it is possible to identify, while the strike-slip movements can be either dextral or sinistral. Outcrops are not completely aligned, which suggest that the fault zone is wide or formed by a ramified fault system.

An E-W fault dipping 60ºS was also observed. Both fault systems affect post-Miocene materials and may involve quaternary paleosols.

The kinematic analysis of the fault zone on the main outcrop has provided enough data to obtain paleostress ellipsoids using the Galindo Zaldivar and González Lodeiro (1988) approach. The results showed a predominant σ_1 almost vertical, and a less marked secondary σ_1 nearly horizontal, with approximately N-S trending (positions of σ_1 and σ_2 are exchanged). The position of σ_3 is constant in both primary and secondary ellipsoids, thus indicating that the extension in the direction ENE-WSW leads to the deformation.

The correlation between the two main alignments observed in the seismicity and the focal mechanism of the biggest event showed in figure 3, is in good agreement with the delimited fault zone (figure 6, and schematically showed in figure 3) after the detailed geological survey was carried out, and the σ_1 direction of the secondary ellipsoid was obtained in the paleostress analysis.

Figure 6. Torreperogil-Sabiote fault zone (ZFAS).

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