CHARACTERIZING THE SEISMIC POTENTIAL OF THE EASTERN BETIC SHEAR ZONE (EBSZ), A MAJOR SOURCE OF EARTHQUAKES IN SOUTHEASTERN IBERIA

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Resumen: La sismicidad en el sureste de la Península Ibérica se encuentra repartida en una amplia franja. Esto, junto con la baja velocidad de convergencia tectónica (4-5,6 mm/a) sugiere la existencia de fallas sismogénicas no detectadas, con baja velocidad de deformación y distribuidas ampliamente. Algunas de ellas han producido terremotos históricos catastróficos pero posiblemente gran parte está por detectar ya que su periodo de recurrencia puede ser muy largo. En esta comunicación presentamos una síntesis de los resultados de los estudios paleosísmicos realizados en diferentes fallas de la Zona de Cizalla de las Béticas Orientales (ZCBO). Con ellos se han detectado fallas sismogénicas (fallas de Carboneras, Alhama de Murcia y Bajo Segura) y se ha caracterizado su potencial sísmico (valor máximo de recurrencia entre 10 y 20 ka y Magnitud máxima Mw 7). Para ello se usaron técnicas paleosísmicas aunque, dada la baja velocidad de las fallas y la penetración de algunas fallas en el mar, se realizó un esfuerzo para incorporar otras técnicas como geofísica de alta resolución o métodos de datación como 10Be y OSL en feldespastos potásicos. Los primeros resultados GPS de la zona se integraron también en el estudio.

Palabras clave: Fallas sismogénicas, parámetros sísmicos, fallas lentas, ZCBO, fallas de rumbo

Abstract: The southeastern Iberian Peninsula shows a wide distribution of seismicity, which together with the very slow plate convergence rate (4-5.6 mm/yr) suggests, the presence of a number of hidden seismogenic faults widespread and slow-moving. Few of these faults have produced catastrophic historical earthquakes and the rest have remained silent historically owing to their very long recurrence periods. In this study we present a synthesis of the paleoseismic studies performed along different faults of the Eastern Betic Shear Zone that allowed us to detect seismogenic faults (Carboneras, Alhama de Murcia and Bajo Segura) and characterize their seismic potential (recurrence periods between 10 and 20 ka and likely maximum magnitudes of Mw7). We used a paleoseismic approach, but given the slow moving nature of these faults and the onshore-offshore trace of some faults we had to add other techniques such as high-resolution geophysics or alternative dating techniques (10Be or OSL in K-feldspars). GPS values are also integrated in the study.

Key words: Seismogenic faults, seismic parameters, slow-moving faults, EBSZ, strike-slip faults.

The Iberian Peninsula, in spite of showing low to moderate instrumental seismicity, may be hiding an amount of seismogenic faults that need to be located and characterized to calculate their real contribution to the seismic hazard. The Eastern Betic Shear Zone (EBSZ) is one of the main seismogenic systems contributing to the current deformation of the southeastern zone of the Peninsula and has been lately studied with paleoseismogical techniques.

The plate boundary between Iberia and Africa shows a highly widespread distribution of the instrumental seismicity (a 400 km wide area that includes the Betics, in the Eurasian plate and the Rif-Tell ranges in the African plate). This defines a diffuse collisional boundary, in contrast with the more localized boundary to the east and to the west of the Peninsula. The Spanish seismic catalogue, that covers almost 1000 yr, contains reference of a number of catastrophic earthquakes (up to I=IX-X). Most of them are located in the Betic ranges such as Torrevieja (1829, I=IX-X) or Arenas del Rey (1884, I=IX-X), although some are in the Pyrenees, such as the Qurealbs (1428, I=IX). The occurrence of these large earthquakes shows the seismogenic nature of some faults in the area although many others may be hidden owing to their very long seismic cycle (maybe one or two orders of magnitude longer than the time showed by the historical catalogue).

The far field shortening rate between the two plates in the transverse along the EBSZ is low (4.5-5.6 mm/yr, DeMets et al., 1994, McClusky et al., 2003) and it is mostly absorbed within the African plate, according to the larger amount and size of the earthquakes there. Still, the historical seismicity shows that some amount is being absorbed within the Iberian plate.

The low shortening rate together with the widespread seismic distribution suggests, thus, the existence of a number of slow moving faults being distributed over a wide area. The geomorphology is the key to detect them and paleoseismological studies are needed to characterize them. Comparison with geodetic results (GPS) is also needed to understand the distribution of the deformation over such a large area.
The EBSZ is a transpressive left-lateral NE-SW-trending fault-system composed by several individual faults, from south to north: Carboneras, Palomares, Alhama de Murcia, Carrascoy and Bajo Segura (this last one trends E-W and is reverse). Paleoseismic and geologic studies have demonstrated that Carboneras, Alhama de Murcia and Bajo Segura faults have generated several paleoearthquakes.

**METHODS**

Different techniques were used to characterize the seismic potential of the analyzed faults such as geomorphologic analysis, trenching, onshore and offshore high resolution geophysics, marine sediment analysis and different radiometric dating techniques. The integration of the onshore and offshore results was an important aim on these studies although this was only possible in the Carboneras fault, since in Bajo Segura the fault is hardly outcropping onshore and seems to be blind.

Onshore, the geomorphologic expression of the faults was studied in a first step in order to compare each fault with the geomorphologic expression of known seismogenic faults and to determine their level of recent activity. This included geomorphological mapping at a 1:10000 scale (based on aerial photography and on field work) and the relative age attribution to the Quaternary units. These analyses lead to the selection of the best sites for near-fault paleoseismic studies. In each site a detailed geomorphological analysis was done to select the best position for trenches (this implies a well located fault site within young sediments and requires avoiding high erosional or depositional rates). The geomorphological analysis was key to obtain piercing points to evaluate the amount of long and short-term offset along the fault. To precisely locate the fault across young deposits radar sections were measured using a GPR (Ground Penetrating Radar) with different central frequency antennas (25, 50, 100, 200 and 270 MHz). In addition, ERT (Electrical Resistance Tomography) sections were acquired to complement the GPR data providing images of disrupted reflections of the upper meters below the ground. A high resolution magnetotelluric profile was also carried out across La Serrata (in Carboneras fault) that together with the AMT and BBMT bidimensional data were integrated to a model of the electrical resistivity to characterize the structure down to 100 m depth. Trenches (with an average of 2 m depth and 30 m length) were dug across and parallel to the fault to detect evidence of paleoevents and to detect possible piercing points. DATING of the different layers to constrain the age of the events was done in the trenches by Radiocarbon, U/Th, TL and OSL (in K feldspars that was allowing to date older periods of time than the regular TL technique). Cosmogenics ($^{10}$Be was also used to date the exposure time of the surface on Pleistocene alluvial fans.

Offshore, the geomorphologic of the fault was first analyzed on a swath bathymetry (this was not available for the Bajo Segura fault). The preliminary tectonic interpretation based on this geomorphology was the base for planning future surveys along the structures. For the offshore paleoseismological study, high-resolution seismic acquisition systems with different resolution and penetration were necessary along and across the fault. High-resolution multichannel seismsics (MCS) provided detailed information of the sedimentary units filling the paleobasins (first hundred meters or kilometers below the sea floor). A sub-bottom profiler system was also used to obtain even higher resolution profiles of the first tens of meters below the sea floor. In the shelf, where shallow water prevent a fine MCS image, the first hundred of meters of layers between the sea floor and the multiple reflection where analysed with very high-resolution single-channel seismic profiles (Sparker system) permitting to see the onshore-offshore link of the fault. Seismic lines were planned to cross commercial MCS lines and wells in order to correlate our seismostratigraphy with known age units. Moreover, sub-bottom profiler images helped to select the sites where sediment cores were acquired. The upper meters of sediment were analyzed and dated with $^{14}$C to obtain sedimentation rates and to estimate ages for key reflectors: faulted layers, faulted slide deposits, and horizons draping faulted layers.

**RESULTS**

**Carboneras fault**

The Carboneras fault, one of the longest in the EBSZ, is a NE-SW left lateral fault system cutting NW of Gata cape. It crops out along 50 km onshore and runs south under the Alboran sea for 100 additional km. There is almost no historical seismicity associated with it. Only the 1522 (I=VIII-IX) Almeria earthquake is near its trace (Reicherter et al., 2006), but considering the high uncertainty linked to such an historical offshore earthquake a different source (such as the NW-SE normal faults located W of Almeria that produce most of the instrumental seismicity in the area) cannot be ruled out. In spite of this, its geomorphological expression suggests recent activity.

Geomorphological and structural analyses carried out both onshore and offshore based on seismic and MT profiles, bathymetry and topographic data suggest that the fault is divided in three segments (from north to south these segments are 109 km, 29 km, and 9.5 km, Moreno et al., 2009). The fault dips sub vertically and shows locally a flower structure at the first km below the surface. Seismic profiles show very consistent vertical traces clearly rupturing the sea floor and decreasing in offset towards the south along the central and southern segments (Gracia et al., 2006, Moreno et al., 2009). Onshore, La Serrata range is one of the most expressive features along the fault. Its NW boundary shows the best geomorphological expression along it and was selected to perform a near fault paleoseismic analysis. Five sites were analyzed with microtopography and trenching and evidence of a minimum of 6 paleoearthquakes was detected since the mid-Pleistocene. The 3 younger events occurred in the last 40 ka suggesting a mean recurrence for this period of 13 ka. An offset paleochannel shows evidence of a minimum of 2 events in the last 30 ka being the most recent between 772 and 889 yr AD (Moreno et al., 2009).

The geomorphologic analysis detected evidence of Quaternary left lateral movement onshore and
offshore such as offset channels, beheaded fans, shutter ridges or elongated valleys. Minimum strike-slip rates obtained onshore (0.5 mm/a since 200 ka BP or 0.1 since 30 ka BP) are always larger than dip-slip rates obtained onshore (>0.05 mm/yr since early Quaternary) and offshore (ranging between 0.05 since early Quaternary and 0.1 mm/yr for the last 180 ka). With the study of the fault still in process, we are not yet able to assess if the segments along the fault have independent seismic behavior but considering the complete length of the fault breaking in a single earthquake the magnitude would be Mw>7.

These results show how a complete and integrated onshore-offshore paleoseismic analysis can lead to the detection and characterization of the seismic potential of a fault that has been historically silent. Based on the analysis of the 15 month of data from a newly installed continuous GPS station GATA, we have estimated that the Carboneras fault is continuing to be active and exhibits mainly left-lateral strike slip motion of 1.5±0.7 mm/yr with a minor compressive component of 1.0±0.7 mm/yr.

Alhama de Murcia fault
The Alhama de Murcia fault is also left lateral, strikes NE-SW, runs along 100 km and bounds the Neogene Guadalentin depression to the NW. Its neotectonic activity is well shown by its morphology (triangular facets, aligned valleys, sudden changes in the entrenchment of the creeks along the fault, etc) and by deformation on Quaternary deposits (Silva et al., 1992, Martinez-Diaz et al., 2003). It locally behaves with a reverse component of slip. Based on the tectonic-geomorphologic evolution and the distribution of the seismicity the fault has been divided into five segments, from north to south: Alcantarilla-Alhama, Alhama Totana, Totana-Lorca, Lorca-Puerto Lumbreras and Puerto-Lumbreras-Goñar. Two I=VIII historical earthquakes have been linked to the Lorca-Totana segment (Silva et al., 2003, Martinez-Diaz, 1999, Ortuno et al., in prep). Paleoseismic studies were carried out along two of the segments and also along the reverse Albox fault that may be absorbing the southern movement of the block west of the Alhama the Murcia fault.

In the Lorca-Totana segment the fault is divided in two strands, with one of them dipping to the east and blocking the drainages of the fans towards the Guadalentin depression. This fault shows a better expression for recent activity and left lateral movement. Four trenches were dug and analyzed on two different sites and revealed the seismogenic behavior of the fault showing dammed deposits related to the instantaneous uplift of the upthrown block. Evidence for three paleoearthquakes since 27 ka was found being the last event very recent (not long before 1650 AD, with no strong historical evidence for its occurrence as the 1579 Int VII event, the first in the record along this fault, was not big enough to produce such a rupture). The mean recurrence period for this time span gives us a maximum time between earthquakes of 14 ka (Martinez-Diaz et al., 2001, Masana et al., 2004).

At its southern termination, in the Puerto-Lumbreras-Goñar segment, the Alhama de Murcia fault splays into an array of faults and folds showing a complex kind of a horse-tail termination structure (probably conditioned by previous structures) that cuts through the Quaternary alluvial fans in the Goñar area. The overall structure is the result of oblique-slip with reverse and left lateral movement distributed along a 1.5 km wide area. The geomorphology shows recent activity along most of these faults such as left-lateral deflection of channels or the blockage of alluvial fans (as some of the reverse faults dip to the southeast). Trenching in six sites distributed along the different traces of the fault showed evidence of a minimum of 6 paleoearthquakes with up to 0.8 m of vertical offset per event. Five of these occurred since 170 ka (Ortuno et al., in prep).

More to the southwest the Albox fault cuts the Neogene to Quaternary Huercal-Overa depression. This is an ENE-WSW-striking reverse fault that dips strongly to the N. Quaternary alluvial fans draining the Las Estancias ranges to the south towards the Huercal-Overa depression have been observed deformed by this fault (Garcia-Melendez et al., 2004, Soler et al., 2003). Trenches dug across the fault in two different sites showed evidence for two paleoearthquakes that likely occurred between the XVIII century and 650 yr AD. The youngest being small in magnitude (only centimeters of vertical offset) and taking place shortly after 660 yr AD (Masana et al., 2005).

The event correlation across the different analyzed segments (Lorca-Totana, Puerto Lumbreras-Goñar and Albox fault) indicates that synchronicity along all these segments is possible although the wide time brackets of the events leads to very high uncertainty in this point. The maximum magnitude at Albox fault based on the slip per event is considered Mw 6.5 and 7.0 at Goñar and at Lorca-Totana segments. When the total length of the AMF is considered a maximum magnitude of Mw 8 could be achieved according to the length and considering a seismogenic depth of 15 km. However, this is not likely because the two northern segments show very little geomorphological expression of recent activity.

Bajo Segura fault
This fault constitutes the northernmost fault of the EB SZ. The Bajo Segura and the San Miguel de Salinas faults have been considered as the two possible sources for the 1829 Torrevieja earthquake (I=IX-X). The Bajo Segura fault is an E-W reverse
fault dipping to the south that folds the surface of the Segura Miocene to present depression. Onshore, the fault is not observed to be rupturing the surface, only to fold it. As an alternative source for this earthquake the San Miguel de Salinas fault it has been proposed, a right lateral NW-SE trending fault located to the south of Bajo Segura fault. Both faults might have an offshore trace according to the geologic maps. Given the difficulty to analyze these faults onshore, an offshore survey was carried out at the platform. High resolution seismic profiles were acquired parallel and perpendicular to the coast to detect surface rupture along one of the two candidate faults for being the seismogenic sources. The results show no recent deformation along the San Miguel de Salinas fault and do show sea bottom rupture along several faults that constitute the offshore continuation of the Bajo Segura fault. Intra-Quaternary unconformities and folding were also revealed by these profiles along this same fault zone.

Carrascoy and Palomares faults

These two faults, also part of the EBSZ and with lengths and trends comparable to the previous faults, have not been yet the scope of a detailed paleoseismological study using trenches. In the case of the Carrascoy fault, fault scarps were detected deforming the surface of Quaternary alluvial units and sites for future trenching were selected. The Palomares fault shows no clear evidence of Upper Pleistocene or Holocene deformation although some authors have described secondary structures linked to it and cutting through recent soils (Silva et al., 1997). Further work needs to be done in these two faults in order to determine their seismogenic behavior and their seismic parameters.

GPS

The CuaTeNeo GPS network installed along EBSZ in 1996 (Castellote et al., 1997) and measured in 1997, 2002 and 2006 (Khazaradze et al., 2008), have been crucial to estimate the rates of the Carboneras fault using the GATA CGPS station and HUEB temporary station of CuaTeNeo. As part of the EVENT Project we have re-measured the CuaTeNeo network in 2009, as well as conducted the 1st new measurements of the 6 stations of Regente network of IGN (Quiríos and Barandillo, 1996), extending the spatial coverage to include the Crevillente fault to the north. The preliminary results, based on the analysis of 15 month of data from a newly installed continuous GPS station at Cabo de Gata (GATA), show a mainly left-lateral strike-slip motion along the Carboneras fault of 1.5±0.7 mm/yr with a minor compressive component of 1.0±0.7 mm/yr. The slip rates for the Alhama de Murcia fault, estimated from the CuaTeNeo GPS network, are similar to the geological results in the Carboneras fault, when the associated errors are taken into account.

DISCUSSION

The exposed results show that the EBSZ is a seismogenic system and that it is able to produce very large earthquakes (up to Mw 7). Several faults that were considered to be not seismic based on the historical catalogue were shown here to be seismogenic and their seismic potential was defined. This was done through integrated paleoseismic studies including, onshore-offshore data, different dating techniques (such as 10Be or OSL in K feldspars, apart from the previously used Radiocarbon, TL and U/Th), high resolution geophysical methods (GPR, ERT, AMT, TOPAS, multichannel and single channel seismics), core analysis and GPS.

Even in these slow-moving faults the paleoseismic approach provided useful results. However, the main limitation of the method, so far, is the wide time brackets obtained in the chronology of the paleoevents, which difficults the correlation between different sites and segments. More studies aiming to complete the paleoseismic record in other sectors of the main faults of the EBSZ will constrain this limitation.

The results show that the EBSZ is playing a very active role in absorbing part of the shortening between Iberia and Africa. The slip rates obtained in some of this faults show mostly left lateral movement with a reverse component. As an average the strike slip rates along the system ranges between 0.2 and 0.5 mm/yr while the dip slip, where it is observed (mainly along faults that trend 065° to 090°), is normally an order of magnitude lower. In the case of Carboneras fault the GPS results suggest one order of magnitude larger slip. Part of the shortening between Iberia and Africa could be also absorbed by the Crevillente fault several kilometres to the north of the Bajo Segura fault. This fault trends NE-SW and shows evidence of Quaternary activity, although no paleoseismic studies have been performed there and no evidence of upper Pleistocene and Holocene deformation has been observed.

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