ACTA GEOLOGICA HISPANICA, v. 36 (2001), nº 3-4, p. 315-327

Evidence for coseismic events of recurrent prehistoric deformation along the Alhama de Murcia fault, southeastern Spain

Evidencias de eventos cosísmicos recurrentes en el período prehistórico en la falla de Alhama de Murcia

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ABSTRACT

The Alhama de Murcia fault is a 85 km long oblique-slip fault, and is related to historical and instrumental seismic activity. A paleoseismic analysis of the Lorca-Totana sector of the fault containing MSK I=VIII historical earthquakes was made in order to identify and quantify its seismic potential. We present 1) the results of the neotectonic, structural and geomorphological analyses and, 2) the results of trenching. In the study area, the Alhama de Murcia fault forms a depressed corridor between two strands, the northwestern fault with morphological and structural features of a reverse component of slip, bounding the La Tercia range to the South, and the southeastern fault strand with evidence of sinistral oblique strike-slip movement. The offset along this latter fault trapped the sediments in transit from the La Tercia range towards the Guadalentín depression. The most recent of these sediments are arranged in three generations of alluvial fans and terraces. The first two trenches were dug in the most recent sediments across the southeastern fault strand. The results indicate a coseismic reverse fault deformation that involved the sedimentary sequence up to the intermediate alluvial fan and the Holocene terrace deposits. The sedimentary evolution observed in the trenches suggests an event of temporary damming of the Colmenar creek drainage to the South due to uplifting of the hanging wall during coseismic activation of the fault. Trench, structural and sedimentological features provide evidence of at least three coseismic events, which occurred after 125,000 yr. The minimum vertical slip rate along the fault is 0.06 mm/yr and the average recurrence period should not exceed 40,000 yr in accordance with the results obtained by fan topographic profiling. Further absolute dating is ongoing to constrain these estimates.

Keywords: Geomorphology. Trench analysis. Paleoseismicity. Alhama de Murcia fault.

RESUMEN

Se presentan los primeros resultados del estudio paleosísmico del sector Lorca-Totana (con terremotos históricos de I=VIII) de la falla de Alhama de Murcia, de deslizamiento direccional oblícuo sinestroso, para caracterizar su potencial sísmico. Esto incluye: 1) resultados del estudio neotectónico, estructural y geomorfológico y 2) primeros resultados obtenidos en trincheras. El área estudiada muestra dos zonas de falla, la noroeste, que limita la sierra de la Tercia, con morfología y estructuras típicas de movimiento inverso, y la sureste con evidencias de deslizamiento direccional sinestroso, separadas por un corredor deprimido. La actividad de estas fallas ha atrapado en el corredor gran cantidad de sedimentos en su transporte hacia la depresión del Guadalentín, los más recientes de los cuales se organizan en tres generaciones de abanicos aluviales y terrazas. Las dos trincheras se excavaron en los sedimentos de la generación intermedia de abanicos aluviales y en la de terrazas más recientes deformados por la falla sureste. Los primeros resultados indican deformación cosísmica con deslizamiento inverso. Se interpreta también un bloqueo temporal del drenaje hacia el sur de la rambla de El Colmenar debido al levantamiento del bloque superior de la falla en un proceso cosísmico. Se describen evidencias de hasta tres paleoterremotos que, en un primer análisis sin datos de edad absoluta, habrían tenido lugar posteriormente a 125.000 años. La velocidad de deslizamiento no sería inferior a 0,06 mm/a y el período de recurrencia no sería mayor a 40.000 años. Estos primeros datos se podrán ajustar mediante dataciones absolutas que están en curso.

Palabras clave: Geomorfología. Análisis en trincheras. Paleosismicidad. Falla de Alhama de Murcia.

INTRODUCTION

The Betic Cordillera, in southern Spain, is the region with the highest seismicity in the Iberian Peninsula (Fig. 1). However, the eastern part of the range has not undergone large earthquakes in the instrumental period whereas the historical seismic catalog shows several MSK I VIII earthquakes (Vera 1518, Almería 1522, Lorca 1579, 1674, Dalías, 1804 and Torrevieja 1829), suggesting the real seismic potential of the area. According to Scholz (1990), the expected recurrence interval for major earthquakes in areas affected by intraplate-plate boundary earthquakes, such as the Betic Cordillera, ranges from 10^2 to 10^4 yr. The seismic potential of this area of the Iberian Peninsula has therefore been poorly constrained not only because of the probable incompleteness of the historical catalog but also because of the large gap between the time period observed (the catalog covers 10^3 yr) and the duration of the seismic cycle. Paleoseismology is the key tool given that it can provide data for a longer period of time than the historical catalog.

One of the major active faults of the eastern Betics is the Alhama de Murcia fault. The preserved geomorphic features along this fault suggest that it has undergone considerable activity in the Plio-Quaternary period. Moreover, evidence for coseismic recurrent deformation has been described in natural trenches in the upper parts of the recent Quaternary alluvial fan deposits (El Buitre creek in Lorca-Totana segment, Martínez-Díaz and Hernández-Enrile, 1999). At least two events of 40 cm of coseismic reverse offset have been described in the Pleistocene deposits. A paleoseismological analysis of the Lorca-Totana sector of the Alhama de Murcia fault was performed to characterize its seismic potential. We present the preliminary results obtained from the geomorphological analysis and from the study of two trenches.

THE ALHAMA DE MURCIA FAULT

The Alhama de Murcia fault, first described by Bousquet and Montenat (1974), is a NE-SW 85 km long oblique-slip fault that bounds the Guadalentín depression to the Northwest (Fig. 1 and 2). The reverse and left-lateral strike-slip movement along this fault has controlled the evolution of the Lorca and the Alhama-Fortuna Neogene basins under a compressive stress field with a NNW-SSE to NNE-SSW compression direction since the late Miocene (Bousquet and Montenat, 1974, Bousquet et al., 1976, Armijo, 1977, Silva et al., 1992a, Martínez-Díaz and Hernández-Enrile, 1992). Recent neotectonic studies along this fault show evidence of Quaternary activity under the same compressive stress field (Martínez-Díaz and Hernández-Enrile, 1992, 1996, Baena et al., 1993, Silva, 1994, Silva et al., 1992a, b, 1997).

Silva et al. (1992a, b) performed a neotectonic analysis of the Alhama de Murcia fault and proposed its subdivision into four sectors which display different strike and structural features; from South to North: Huercal Overa-Lorca, Lorca-Totana, Alhama-Alcantarilla and Murcia-Orihuela (Fig 3A). A similar division was proposed by Martínez-Díaz (1998) in a recent study of deformation along this fault by using sedimentological, structural and geophysical features.

The historical seismic catalog contains references to more than ten MSK I>IV earthquakes and to eight MSK I>VI earthquakes linked to the Alhama de Murcia fault. The intensity-magnitude relations

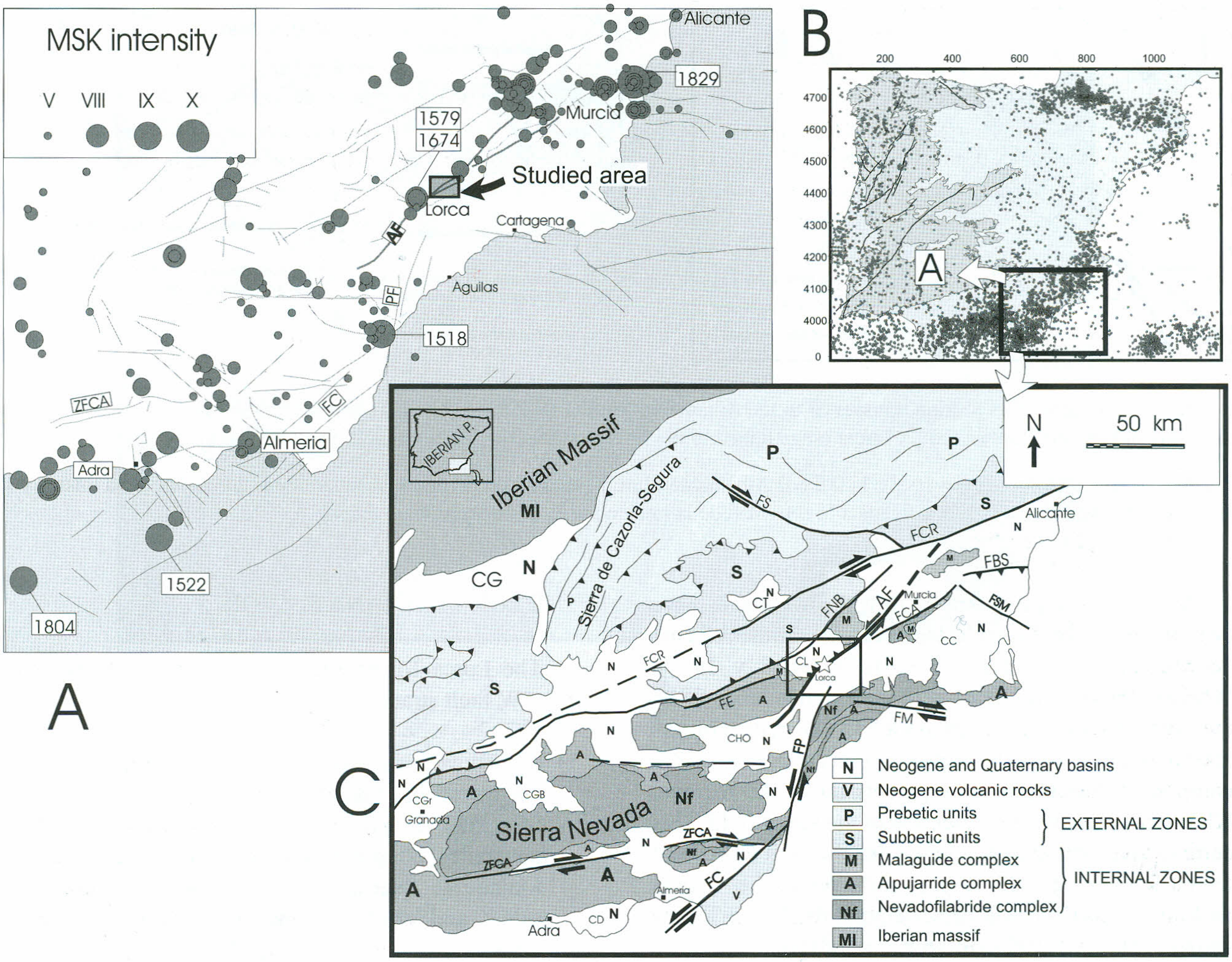


Figure 1. A. Historical seismicity of the eastern part of the Betics with the main active faults, from Martínez-Díaz (1998). Year of occurrence of the I > VIII earthquakes is also shown. ZFCA: Alpujarras corridor. CF: Carboneras fault. PF: Palomares fault. AF: Alhama de Murcia fault. B. Map with the instrumental seismicity for earthquakes of M>2.0 in the Iberian Peninsula. Data from Instituto Geográfico Nacional (IGN). C. Geological map of the southeastern Betic Cordillera in which the studied area is designated by a square (modified from Martínez-Díaz, 1998). AF: Alhama de Murcia fault; FS: Socovos faut; FCR: Crevillente fault; FE: Las Estancias fault; FNB: North-betic fault; FCA: Carrascoy fault; FBS: Bajo-Segura fault; FSM: San Miguel fault; FM: Moreras fault; FP: Palomares fault; ZFCA: Alpujarras fault zone; FC: Carboneras fault.

Figura 1. A. Mapa de la sismicidad histórica de las Béticas orientales y de las principales fallas con actividad reciente. Se indica el año de ocurrencia de los terremotos de I > VIII de la zona. ZFCA: zona del corredor de las Alpujarras. CF: falla de Carboneras. PF: falla de Palomares. AF: falla de Alhama de Murcia. B. Mapa de sismicidad instrumental de la península Ibérica (M>2,0). Datos de IGN. C: Mapa geológico del sureste de la Cordillera Bética en el que se señala con un cuadro la zona de estudio (modificado de Martínez-Díaz (1998). AF: falla de Alhama de Murcia; FS: falla de Socovos; FCR: falla de Crevillente; FE: falla de Las Estancias; FNB: falla Norbética; FCA: falla de Carrascoy; FBS: falla de Bajo Segura; FSM: falla de San Miguel; FM: falla de Moreras; FP: falla de Palomares; ZFCA: falla de Alpujarras; FC: falla de Carboneras.

obtained using instrumental seismicity in this area indicate that MSK intensity VII earthquakes correspond to moment magnitudes close to 6.5 (Martínez-Díaz 1998). The historical description of damage of some of these earthquakes suggests the occurrence of surface deformation along the fault: *"hundimiento de unas tierras entre Lorca y Totana"* (Martínez-Guevara, 1984) -collapse of land between Lorca and Totana- during 1818, Intensity VII, Lorca earthquake.

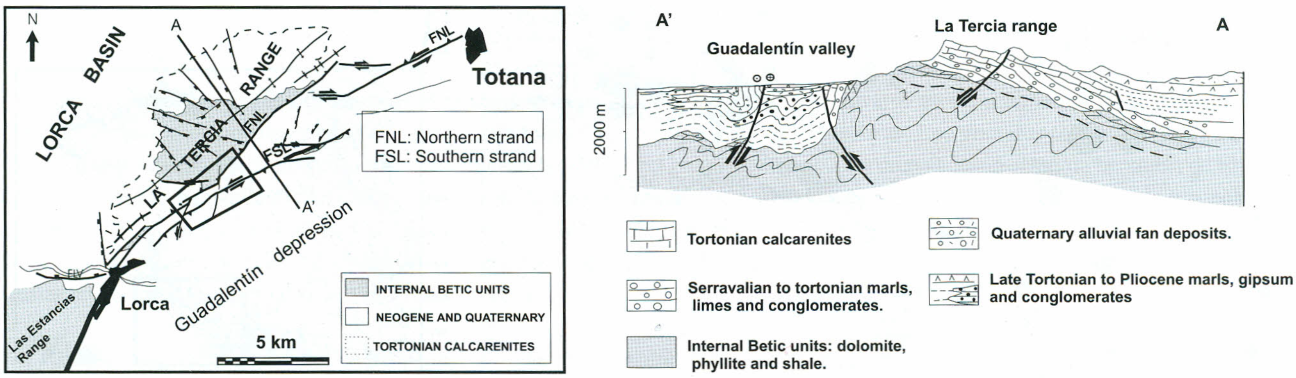


Figure 2. Geological cross section transversal to the Alhama de Murcia fault zone (Lorca-Totana sector) showing the two strands of this fault and the structure of the La Tercia range linked to the reverse slip of the northern fault. See location in the map.

Figura 2. Corte geológico transversal a la falla de Alhama de Murcia (sector Lorca-Totana) mostrando las dos ramas de la misma y la estructura de la sierra de la Tercia ligada a la actividad de la rama norte. Ver situación en el mapa.

A number of widely felt historical earthquakes have been linked to the Lorca-Totana segment of the Alhama de Murcia fault (Lorca, 1579, 1674, 1818 y 1977). Whereas the Alhama de Murcia fault trends NNE-SSW, the Lorca-Totana sector displays a NE-SW trend. For this reason, the Lorca-Totana sector presents a higher reverse component than the other segments under the regional NNW-SSE compression direction of the stress field. This compressive setting may account for the high altitude of the La Tercia range with respect of the rest of the Alhama de Murcia fault. Among these sectors, the Lorca-Totana shows the most suitable conditions for a paleoseismological analysis because 1) several MSK I>VII earthquakes in the historical catalogue are located in this area, 2) historical descriptions of possible coseismic surface deformation linked to the 1818 earthquake are included in the catalog, 3) the surface trace of the fault is well determined, and 4) the slip of the fault favors drainage damming and deposition of sediments.

THE LORCA-TOTANA SECTOR

The Lorca-Totana sector is composed of two main NE-SW fault strands:

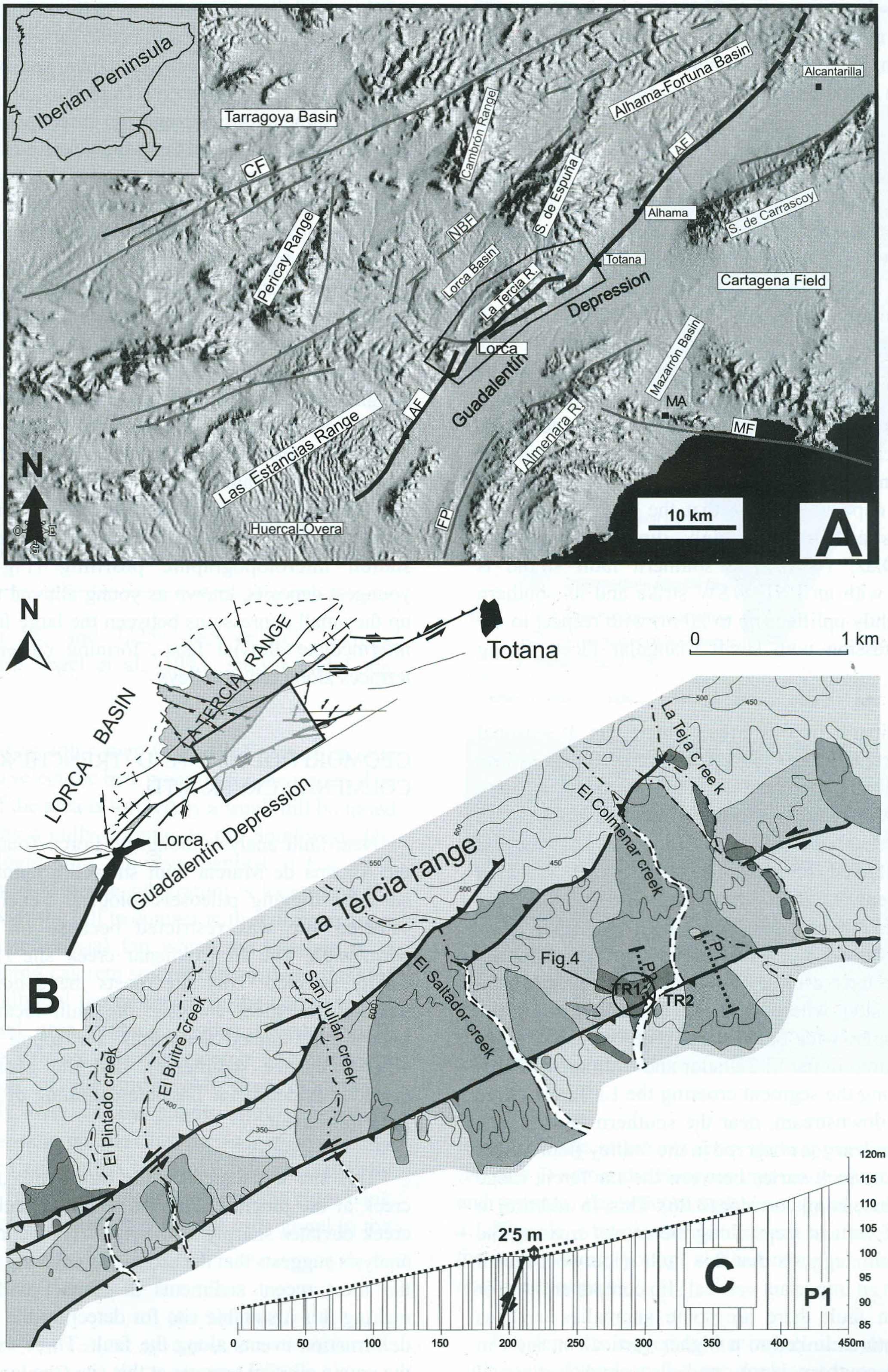
1) a northwestern reverse fault highly dipping to the northwest and bounding the La Tercia range to the SE (Figs. 2 and 3) which is composed of shale, quartzite, conglomerate and dolomite from the Maláguide internal units, and quartzite, dolomite, schist and phillyte from the Alpujárride internal units;

2) a southeastern sinistral oblique-slip fault highly dipping to the southeast and separating Miocene conglomerate, marl and gypsum to the South from Quaternary alluvial fan deposits to the North.

The combined activity of these two fault strands created a NE-SW elongated depressed corridor between

Figure 3. A. Digital elevation model of the Alhama de Murcia fault (AF) and surrounding area. CF: Crevillente fault; NBF: North-betic fault; PF: Palomares fault; MF: Moreras fault. The studied area (Lorca-Totana sector) is one of the main segments of the fault. B: Geomorphologic sketch of the studied area along the Alhama de Murcia fault, between Lorca and Totana (see location on upper part and on Fig. 1). Location of trenches TR1 and TR2 and that of microtopographic profiles P1 and P2 are shown. C. Microtopographic profile P1 performed along the Colmenar alluvial fan surface across the fault. It shows a vertical dislocation of 2.5 m.

Figura 3. A. Modelo digital del terreno mostrando el entorno de la falla de Alhama de Murcia (AF). CF: falla de Crevillente; NBF: falla Norbética; PF: falla de Palomares; MF: falla de las Moreras. El sector aquí estudiado (Lorca-Totana) constituye uno de los segmentos principales de la falla. B. Esquema geomorfológico de la zona estudiada de la falla de Alhama, entre Lorca y Totana (ver esquema de situación). En él se marcan las trincheras 1 y 2 y los perfiles microtopográficos P1 y P2. C: Perfil microtopográfico P1 levantado a través de la falla a lo largo de la superficie del abanico aluvial de El Colmenar. Muestra una dislocación vertical de 2,5 m.



Iberian Peninsula
Tarragoya Basin
CF
Pericay Range
Cambrón Range
NBF
Lorca Basin
La Tercia R.
S. de Espuña
Alhama-Fortuna Basin
AF
Alcantarilla
Alhama
S. de Carrascoy
Totana
Cartagena Field
Depression
Guadalentín
Lorca
Mazarrón Basin
MA
MF
Almenara R.
Las Estancias Range
FP
Huercal-Overa
N
10 km
A
N
Totana
0
1 km
LA TERCIA RANGE
LORCA BASIN
Guadalentín Depression
Lorca
B
La Tercia range
La Teja creek
El Colmenar creek
El Saltador creek
San Julián creek
El Buitre creek
El Pintado creek
Fig.4
TR1
TR2
P1
P2
2'5 m
C
P1
120m
115
110
105
100
95
90
85
0
50
100
150
200
250
300
350
400
450m
Current deposit
Young alluvial terrace
Intermediate alluvial fan
Old alluvial fan
Pre-Pliocene substratum
Active fault
Creek

them (a pop-down structure). This corridor is filled with Quaternary alluvial sediments. These two fault strands converge near the town of Lorca to the South, whereas the southeastern fault strand vanishes to the Northeast, near Totana.

A geomorphologic study of this sector was performed with aerial photograph analysis (1:18,000 and 1:30,000 scale) and structural mapping (1:15,000 scale). Figs. 2 and 3 show a sketch of the main structural and geomorphic features of the area. Both fault strands show a good geomorphic expression. The northern fault strand is formed by an en echelon array of several NE-SW kilometer-long faults. It separates the main relief of the La Tercia range to the NW from the depressed Quaternary pop-down structure. Several triangular facets facing SE with a vertical height of up to 200 m as well as a number of micro and meso-structures affecting Neogene and Quaternary deposits indicate that the recent activity of this fault strand has a mainly dip-slip component (Martínez-Díaz, 1998). The southern fault strand is continuous, with an ENE-WSW strike and its southern block is slightly uplifted (up to 20 m) with respect to the central depression with small triangular facets facing northwest.

The drainage in this area, which has a seasonal character, originates in the La Tercia range and runs into the Guadalentín depression. The drainage is very sensitive to active tectonics and shows some anomalies (deflected channels, captures, gradients of vertical incision, stepped longitudinal profiles, etc.) which indicate recent tectonic oblique-slip activity along this sector of the Alhama de Murcia fault (Martínez-Díaz, 2000). The valleys along the fluvial channels in the La Tercia range have a clear "v" shape with a pronounced vertical incision whereas in the central corridor the channels display wide flat bottoms. The "v ratio" (Mayer 1986) measured in the El Saltador and Colmenar valleys is higher along the segment crossing the La Tercia range (0.72) than downstream, near the southern fault (1.32). The same tendency is observed in the "valley floor-valley height" ratio which varies between the La Tercia range (0.32) and the central corridor (0.06). This, in addition to a number of vertical steps along the creeks crossing the northern fault, suggests that this fault underwent recent activity with an important vertical slip component. As for the southern fault there are some anomalies such as channel captures linked to a higher vertical incision in the uplifted southern block, and also small horizontal offsets in the drainage network, which suggest a horizontal slip component.

The pop-down depression between the two fault strands has a Miocene and Pliocene substratum, which is highly deformed near the main faults, and is filled with Quaternary coarse sediments from the La Tercia range. These sediments are arranged in three generations: old and intermediate alluvial fans, and young alluvial terraces (Fig. 3). The natural southeastern drainage of these alluvial fans was modified by the uplifting of the southern fault hanging wall which temporarily trapped the sediments transported towards the Guadalentín depression. Most of the alluvial fan sediments deposited in the uplifted wall of the southern fault strand were almost completely eroded, and only small remains of such deposits are currently found at the highest points of the hanging wall. Only the Colmenar and El Saltador fans are located in both walls of the southern fault. They show vertical dislocation along the fault although their surfaces can still be correlated across it. In the El Saltador fan the vertical offset reaches up to 20 m while in the Colmenar fan it is only 2.5 m, both offsets being measured by Total station microtopographic profiling (Fig 3C). The youngest deposits, known as young alluvial terraces, fill up the small depressions between the large fans -old and intermediate alluvial fans-, forming currently alluvial terraces along creek valleys.

GEOMORPHOLOGY AND TRENCHING AT THE COLMENAR CREEK SITE

Near-fault analysis along the Lorca-Totana sector of the Alhama de Murcia fault showed a number of good sites for digging paleoseismological trenches, but the selected site was restricted because of absence of permission. The El Colmenar creek site (Fig. 4) was finally selected. This site meets the conditions for a paleoseismological analysis: the fault location is well known, the faulted sediments are young (the young alluvial terrace sediments), and the geomorphology provides evidence for possible damming of drainage by fault movement.

This site is situated on the right bank of Colmenar creek at the juncture with the southern fault where the creek deviates sharply to the right. The geomorphologic analysis suggests that the sediments covering this area are the most recent sediments in contact with the fault, making this a suitable site for detecting the most recent deformation events along the fault. Three samples from the young alluvial terraces at this site (see location in Fig. 4 and 5) were dated with radiocarbon (AMS on bulk soil samples) and gave Holocene ages (1022+/-192 yr BC,

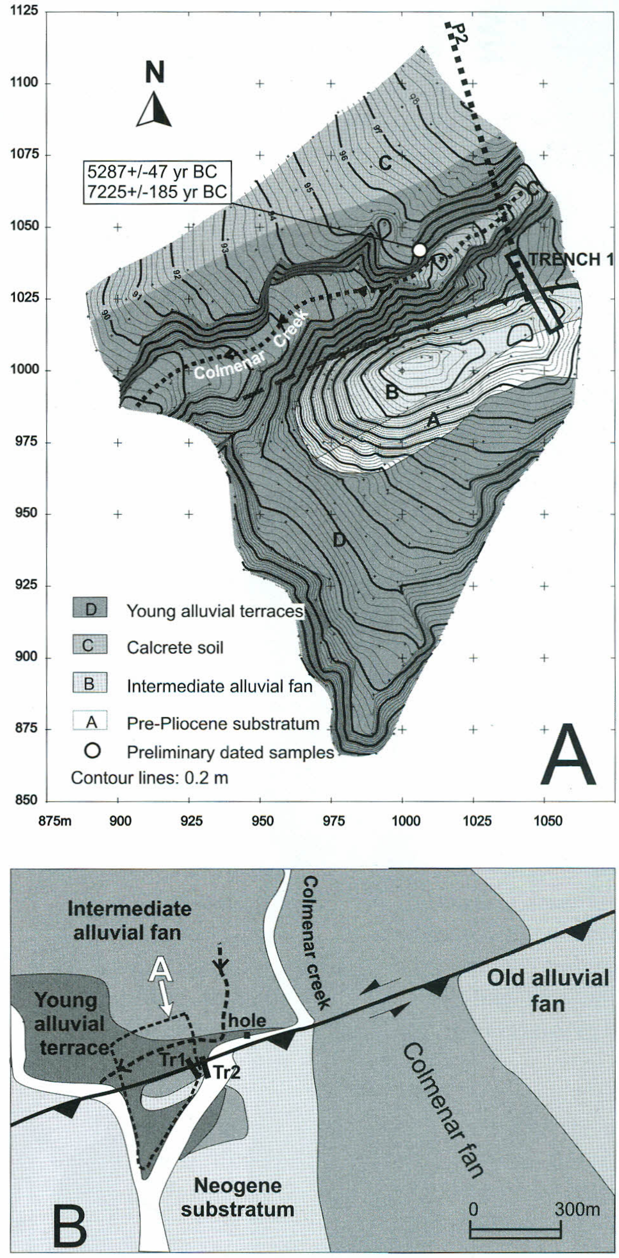


Figure 4. A. Microtopographic map of the right bank of Colmenar creek where it crosses the southern Alhama de Murcia fault. Location of trench 1, microtopographic profile P2 in Fig. 7, and first ^{14}C dating of the young alluvial terrace are shown. B. Sketch of the geomorphic units at Colmenar creek, in the proximity of trenches 1 and 2. The situation of microtopographic map (A) is also marked. This sketch shows the control of the Alhama de Murcia fault trace on the alluvial channels. The trenches were located where the most recent alluvial terrace deposits are in contact with the fault.

Figura 4. A. Mapa microtopográfico de la margen derecha del barranco de El Colmenar donde éste atraviesa la rama sureste de la falla de Alhama de Murcia. También se señala la situación de la trinchera 1, de P2 (perfil microtopográfico que se muestra en la Fig. 7), y la situación de las muestras preliminares. B. Esquema de las unidades geomorfológicas en la zona de la rambla de Colmenar en el entorno de las trincheras 1 y 2. También se marca la situación del mapa microtopográfico (A). Se observa el claro control que ejerce la falla sobre los principales canales aluviales. Las trincheras se localizaron en la zona donde los depósitos de terraza aluvial más reciente aparecen en contacto con la falla.

5287+/-47 yr BC and 7225+/-185 yr BC, 2 sigma calibrated ages, Vogel et al., 1993, Stuiver and Long, 1993).

A microtopographic map (Fig. 4) of part of the site was leveled to select the best position for the trench. The central part of the area is formed by a small hill bounded to the North by a gully draining to the Southwest. The surficial geologic units are also mapped in Fig. 4. A small outcrop of Miocene substratum is located on the southern flank of the hill in contact with sediments from the intermediate alluvial fan which are overlain by a northwest dipping calcrete soil on the northern flank of the hill. This alluvial fan crops out in the northern part of the mapped area dipping southeastwards and is covered with a calcrete soil; this calcrete also crops out at the bottom of the gully. All these units are unconformably overlain by young alluvial terraces. Trench 1 was dug on the flat surface of the young alluvial terrace and across the small hill generated by the fault slip. Trench 2 was excavated on the right bank of Colmenar creek, which was almost orthogonal to the fault.

Trench 1

Trench 1 (Fig. 5) is 35 m long and up to 4 m deep. It was dug across 1) the deposits of the young alluvial terrace, 2) the sediments from the intermediate alluvial fan, and 3) across the Neogene unit made up of marls, silt and gypsum. The western wall was logged completely at a 1:20 scale, whereas the eastern wall was logged only in the area where young sediments crop out, i.e. the northwestern part.

The deposits logged in this trench were divided into eight units, based on the occurrence of tectonic-related uncomformities and abrupt sedimentary changes. From bottom to top, these units are as follows:

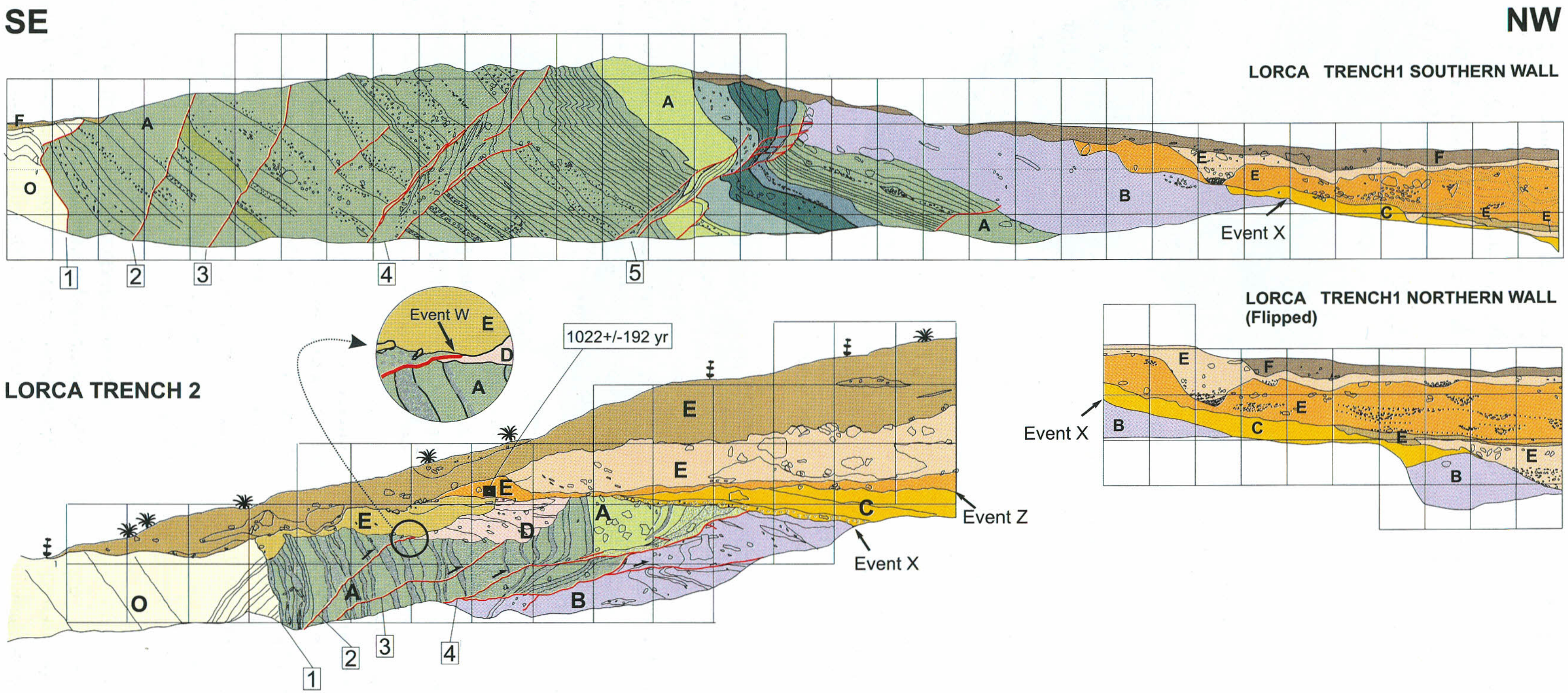


Figure 5. Logs of the southwestern wall and part of the northeastern wall of trenches 1 and 2. The different colors and letters represent the sedimentary units described in the text. The several reverse oblique-slip faults cutting Quaternary units are numbered (see explanation in text). Arrows indicate the position of the different event horizons. Absolute age of unit E_3 using the radiocarbon AMS method is also shown. O: Neogene substratum (marls and gypsum). A: alluvial fan deposits coming from the NW. B: Calcrete layer. C: Fine red sand with a clay rich matrix. The source of this unit is the erosion of unit O. D and E: alluvial deposits from young terraces of Colmenar creek. F: Current soil.

Figura 5. Perfiles geológicos de la pared suroeste y parte de la noreste de la trinchera 1 y de la trinchera 2. Los diferentes colores y letras indican las distintas unidades sedimentarias descritas en el texto. Se han numerado las diferentes fallas inversas con componente direccional que afectan a los depósitos cuaternarios (explicación en el texto). Las flechas indican los diferentes horizontes evento. También se señala la edad absoluta obtenida para la unidad E_3 usando el método del radiocarbono (AMS). O: sustrato neógeno (margas y yesos). A: depósitos de abanico aluvial, procedentes del NW. B: niveles de calcreta. C: arena roja con matriz rica en arcilla. Esta unidad procede de la erosión de la unidad O. D y E: depósitos aluviales de las terrazas más recientes de la rambla de Colmenar. F: suelo actual.

Unit O. Yellowish Miocene marls, silts and gypsum.

Unit A. Wine reddish coarse gravel with a small matrix interlayered with coarse sands. The clasts are mainly made up of angular pebbles, and belong to the La Tercia range metamorphic and carbonate lithologies. The internal fabric and facies indicate that this unit is part of an alluvial fan sequence, which, in the trench, is tectonically tilted 45° towards the NW.

Unit B. Two meter thick carbonated soil layer with laminar calcrete on top. This unit is very hard to dig and was detected in several outcrops of the area always over unit A.

Unit C. Fine red sand layer with finer gray sands in the upper part. This unit contains some sparse pebbles and a red to yellowish clay matrix. It is the only reddish unit observed in an area that is mostly gray in color.

Unit E. Gray gravel with angular pebbles and a fine matrix alternating with sands and occasionally yellowish fine silts. This unit dips slightly to the northwest and onlaps units C and B. Its upper part contains a channel structure situated close to the fault, which is visible in both walls of the trench, suggesting that the preexisting channel path was parallel to the fault. The La Tercia range is the source area of these sediments.

Unit F. Current soil overlaps all the units in the lower topographic parts whereas the intermediate alluvial fan crops out in the higher topographic parts.

Units A and B correspond to the intermediate alluvial fans and units C and E correspond to the young alluvial terraces.

The whole sequence of young deposits is tilted to the North because of the reverse movement of the fault. Four highly SE dipping reverse fault zones were observed. The contact between the deformed and eroded intermediate alluvial fan generation deposits, which are Quaternary in age, and the Neogene marls, silts and gypsum is an almost vertical unconformity (number 1 in Fig. 5). The faults (2, 3 and 4 in Fig. 5) cut the internal beds of this alluvial fan and display a considerable amount of offset (often larger than the trench depth). Fault 4 shows a 70 cm wide shear zone with sigmoid structures. The total displacement of fault 4 is higher than the wall depth. Fault 5 also offsets the overlying calcrete unit by more than one meter. The kinematic behavior of the fault is constrained only on the reverse component of the faults in the trench walls given the absence of slickensides on the fault planes; hence, it was not possible to obtain a strike-slip component in trench 1. Furthermore, kink bands which absorb part of the internal strain of the sediments were observed in the alluvial fan (Fig. 5).

Trench 2

This one-wall trench is 15 m long and up to 5 m high (Fig. 5). It shows a deformed area in the lower part of the wall, produced by several SE low dipping reverse faults which converge in the southeastern-lowermost part of the trench. As in trench 1, the contact between the Miocene marls and the Quaternary beds (alluvial fan A) is an almost vertical unconformity (number 1 in Fig. 5). A 0.4 m thick bed made up of resedimented Miocene marls is intercalated with the regular alluvial fan beds close to the bottom (0.5 m) of the fan. In contrast to the NW source of the regular fan deposits, the resedimented Miocene marls proceed from the SE, the uplifted wall of the fault.

The unconformity is cut by some reverse faults which were evidenced by a small hole dug below the trench outcrop. These faults (numbered 2 to 4 in Fig. 5) show a reverse slip component in the trench. Close to the unconformity some vertical stratigraphical planes separating gravel and silt beds show horizontal slickensides, suggesting an inter-bedding slip with a strike-slip component although dip-slip slickensides were also observed.

The stratigraphic units correlate well with the units described in trench 1 and are tilted in the same direction. Furthermore, trench 2 shows a very local unit D made up of classified and stratified gravel and some silty layers with a reddish matrix that are tilted to the North. Unit E covers this unit by means of an erosive contact with channel structures, but unit C is not in contact with unit D. Thus, unit C is older than unit E but its relative age with respect to unit D is unknown. Absolute dating is necessary to establish this age relationship. Most of the faults are sealed by units C, D and E. Only one fault, the flat southeasternmost one (fault 2), cuts unit D slightly. Geometrical and sedimentary features observed in the two trenches may be used to identify paleoseimic activity. Internal deformation and tilting of units A to E as well as an abrupt sedimentary environment change in unit C were employed to infer coseismic events.

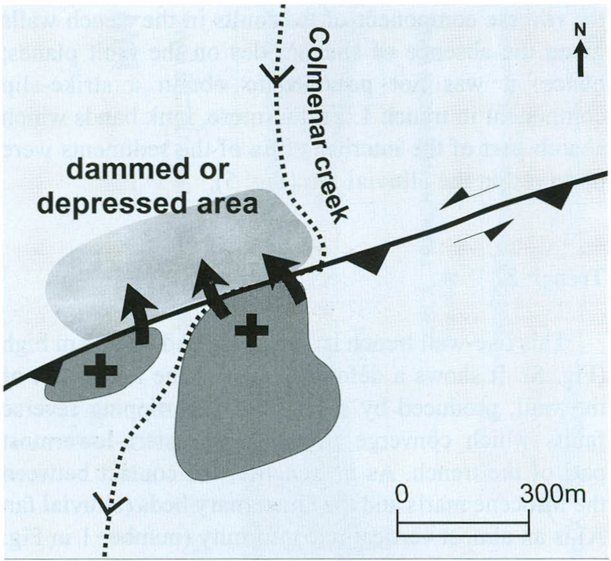


Figure 6. Interpretation of the formation of unit D. Uplift of southern wall of the southern strand of the Alhama de Murcia fault resulted in a dammed area due to the Colmenar creek blockade. Crosses indicate the position of uplifted hills made up of Neogene marls and gypsum. The local erosion of these materials produced the sedimentation of unit C.

Figura 6. Interpretación de la formación de la unidad D. El levantamiento del bloque meridional de la rama sur de la falla de Alhama de Murcia produjo una zona de encharcamiento temporal debido al bloqueo del drenaje de la rambla de Colmenar. Las cruces marcan la posición de zonas elevadas formadas por margas y yesos neógenos. La erosión local de estos materiales produjo la sedimentación de la unidad C.

Nature of unit C

The red sediments of unit C do not resemble the sediments of the stratigraphic units in this area. The only possible source of the yellow clays and silts of the matrix of this unit is the Neogene marls that crop out only in the hanging wall of the southeastern fault strand, i.e. downstream from the site area. The source area of the remaining units which are metamorphic pelitic and calcareous rocks from the La Tercia range is located to the NW. Furthermore, the fine grained sediments of unit C indicate a lower energy depositional environment. They show some sedimentological features associated with sediments formed under damming conditions (probably in a palustrine environment) although this has not yet been confirmed.

Mapping showed that the lateral extent of this unit is restricted to the area next to the fault around Colmenar creek (Fig. 6). A hole in these sediments (2 m deep and one m long) was dug 100 m east from the trenches for: pollen analysis, sampling comparison of petrographic characteristics, and correlation with unit C in trenches 1 and 2. Preliminary results of these analyses suggest that the sediments correspond to less detritic facies of the same depositional event and thus to the same unit. The depositional energy evidenced by the sediments is higher in trench 1 than in the other outcrops. This is the southeasternmost outcrop and could correspond to the margins of the dammed area.

The local outcropping of unit C close to the fault together with the abrupt change in the source area suggests a sudden uplift of the hanging wall of the southeastern fault and the formation of an unstable scarp along the fault. Therefore, deposition of unit C resulted from the erosion of this relief and was deposited in the newly formed depocenter, which was caused by the damming of the Colmenar valley.

DISCUSSION

Event recognition

On the basis of information from trenches 1 and 2, evidence of at least two or three individual events that had taken place since the formation of the carbonated soil B was detected. Evidence of previous events of deformation was observed but the deformation cannot be attributed to individual events or dated and is, therefore, of little use for paleoseismic purposes.

Event Z. Assuming that unit C was palustrine, and thus horizontally deposited, its current NW dip could be attributed to tectonic tilting due to the northwestward pushing of active reverse faults located underneath the trench outcrop. This tilting is clearly observed in trench 1. Unit E is not clearly tilted, suggesting that the deformation occurred after the sedimentation of unit C and prior to the deposition of unit E. The seismic origin of this event is not clear and should be corroborated by correlation with future trenching data.

Event X. The lithology of unit C indicates that its sediments do not proceed from the La Tercia range but from the southeastern hills, formed by the fault movement. Thus, during the deposition of unit C the direction of transport was contrary to the general. Unit C sediments proceeded from the SE: these are reddish in color and of low energy, whereas the rest of the sediments came from the NW and are of high energy. The lowest stratigraphic limit of this unit is very sharp, suggesting that the change in local drainage conditions was sudden. The abrupt uplifting was attributed to a seismic event due to the tectonic offset of the southeastern fault which conditioned the local change in the sediment transport close to the uplifted block. If the palustrine character of unit C was corroborated, it would also point to the existence of event X, suggesting that the Colmenar drainage was dammed by a temporal blocking of the previous exit of the channel. This blocking was probably produced by the vertical component of the fault. The event took place shortly before the deposition of unit C and possibly long after the formation of unit B, which is the youngest deformed layer prior to unit C. We sampled unit C for radiocarbon dating and unit B for U/Th dating. Further absolute dating and pollen analysis, which are currently in progress, will yield more information about this interpretation.

Event W. The base of unit D is ruptured by a reverse fault (see zoom in Fig. 5), indicating that there was an event of deformation after its deposition. Again, the seismic behavior of this event has not been confirmed. This event took place after the deposition of unit D, which is deformed, and before the deposition of unit E, which seals the fault. We sampled these units for radiocarbon and pollen analyses.

Deformation event W can be attributed to a different paleoseismic event, but it can also have been caused by seismic events X or Z. Given the lack of data on the stratigraphical relationships between units C and D, it is not yet possible to establish the definitive relative chronological correlation between these events. If unit C was older than unit D, events W and Z could coincide because both (rupture of unit D and tilting of unit C) occurred in the period after the deposition of unit C and before the deposition of unit E. If unit C was younger than unit D, the deformation described as event W could have been produced either during event Z (the tilting of unit C and the rupture of unit D took place both after the deposition of unit C and before the deposition of unit E), or during event X (the sudden formation of unit C and the rupture of unit D occurred after the deposition of unit D and before the deposition of unit C). At any case, event Z is the youngest event. Further dating will shed light on these possibilities. Events W, X and Y occurred before 1022+/-192 yr BC, which is the age of the sample taken from unit E_3 in trench 2 (Fig. 5) and dated with radiocarbon (AMS in bulk soil).

Old event. The intercalation of resedimented Miocene marls, proceeding from the SE, close to the bottom of the alluvial fan A implies a sudden uplift of the southern fault wall and provides evidence for an old paleoseismic event of unknown age, older than 125,000 yr.

Fault displacement and slip rates

Data allowing the quantification of the possible horizontal slip component of the fault were not found. We performed a microtopographic profile along the intermediate alluvial fan located just northwest of the trenches (Figs. 3, 4 (P2) and 7) to quantify the vertical amount of displacement produced by the fault at this site. The top of this fan shows the calcrete layer (unit B) observed in trench 1 at the top of unit A. The surface of the Colmenar alluvial fan is almost completely preserved due to the hardness of the calcrete soil and thus enables the reconstruction of the original slope of the fan at the site of trench 1. Fig. 7 shows the topographic profile and the undeformed slope of the alluvial fan with the calcrete on top. The lower part of the fan is covered with the young alluvial terrace which in trenches 1 and 2 was composed of units C, D and E. The current location of the calcrete at the bottom of the gully (see figure 4, P2) and in trench 1 reveals a minimum vertical displacement of 8 m. Profile (P1) in Fig. 3 was leveled over the top of Colmenar creek 0.5 km to the East of the trenches. A vertical slip component of 2.5 m was observed in this profile. The uppermost calcrete is covered with younger deposits in this sector, which accounts for its lower displacement.

The value of the vertical slip rate in this sector of the Alhama de Murcia fault depends on the age of the deformed calcrete (unit B in trenches) which was sampled for U/Th dating (currently in progress). In order to obtain a preliminary estimate of the slip rate, we attributed the formation of calcretes to climate conditions in this part of the Mediterranean. Harvey (1984) indicates a general development of calcrete soils on top of pre-Wurm aggradation alluvial fan sequences in southeastern Spain. In agreement with these findings, Villamarín et al., (1999) suggest an important event of calcrete soil formation around 125,000 year ago after dating (U/Th and thermoluminiscence) up to 50 samples of calcrete soils on top of the alluvial fans in Tarragona (northeastern Spain). The correlation of the carbonated soils in the Lorca-Totana sector with the 125,000 yr event of general formation of carbonated soils in eastern Iberia is

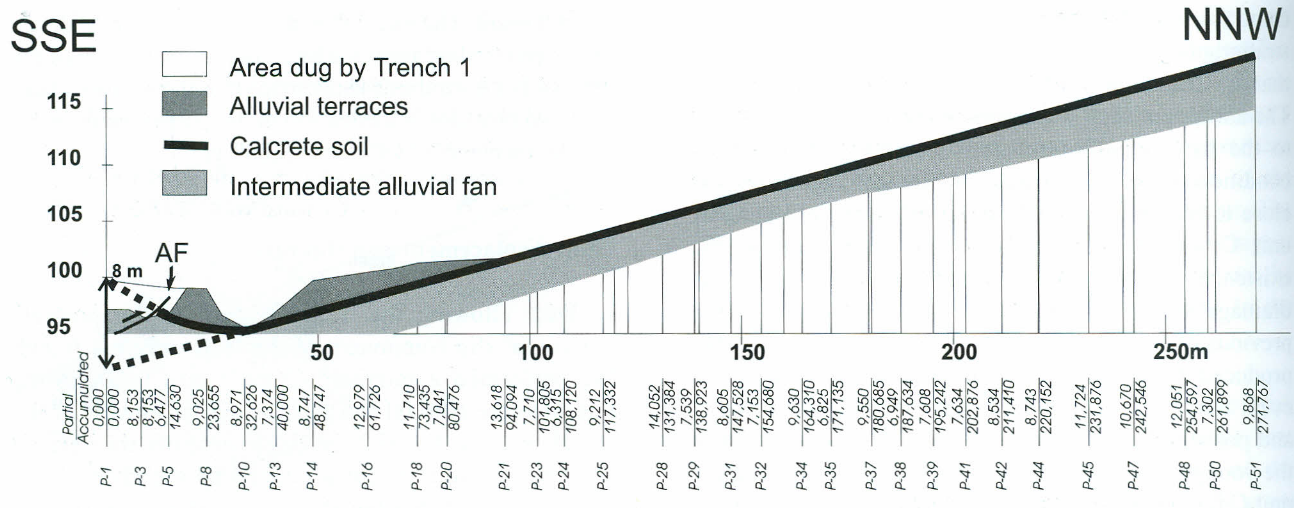


Figure 7. Interpretation of the geological data observed along the microtopographic profile P2 (location in Fig. 4) based on surface and trench 1 data. The calcrete soil formed on top of the alluvial fan and was deformed by the fault. The measured vertical dislocation is a minimum of 8 m (see text for further discussion). Using paleoclimatic criteria the age of this calcrete could be close to 125,000 yr.

Figura 7. Corte geológico basado en el perfil microtopográfico P2 (situación en Fig. 4) y en los datos de superficie y de la trinchera 1. Obsérvese como el nivel de calcretas desarrollado a techo del abanico aluvial se encuentra deformado por la actividad de la falla con una dislocación vertical de 8 m como mínimo (ver texto). La posible edad del nivel de calcreta utilizando criterios paleoclimáticos podría ser próxima a 125.000 años.

proposed despite the fact that there is more than one layer of carbonated soil in some areas around the fault. This would imply a vertical slip rate of 0.06 mm/yr. Given that the two or three events observed in the trenches occurred within the same age interval, an average recurrence time of about 40,000 yr can be estimated.

As the alluvial environment is highly erosive some evidence of earthquakes can be easily degraded; the number of earthquakes observed is, therefore, a minimum. Thus, the inferred recurrence time must also be considered as the minimum value given the possible erosion of evidence and the difficulties encountered when correlating the calcretes. Moreover, the degree of deformation evidenced by the alluvial fan (A and B) and the young alluvial terrace (C to E) suggests a very different age for these formations (since the carbonated soil B is 125,000 yr old, the alluvial terrace must have a very recent age). This lends support to the view that the events probably occurred a short time ago, implying a shorter recurrence period than the one suggested. This agrees with the results obtained in the northern strand of the Alhama de Murcia fault using U-Th dating (Martínez-Díaz and Hernández-Enrile in this volume). Further radiocarbon dating (in progress) will provide additional data to constrain the time of the events and thus a more accurate recurrence interval.

CONCLUSIONS

The paleoseismic method applied to the Alhama de Murcia fault enabled us to characterize its activity. Paleoearthquake evidence for late Quaternary sediments was obtained for the most recent tectonic activity of the fault.

Although work is still in progress and more trenches need to be studied, analyzed data reveal that the Lorca-Totana sector of the Alhama de Murcia fault has undergone a minimum of two or three paleoseismic events. The slip rate is not lower than 0.06 mm/yr –probably higher-, and the recurrence period is shorter than 4 x 10^4yr.

Structural and sedimentary evidence of a paleo-damming of the Colmenar creek drainage due to coseismic deformation was obtained. Damming may account for a number of sedimentary anomalies observed in other sectors of the Alhama de Murcia fault not studied to date.

ACKNOWLEDGMENTS

This study was supported by the FAUST project (ENV4-CT97-0528) and the project AMB97-0523: "Active tectonic analysis of the Murcia region and their application to seismic hazard assessment" (C.I.C.Y.T.). We are indebted to Daniela Pantosti and Hervé Philip for critically reviewing this paper. We also thank Mabel Gómez, Raquel Amores, Angel Martínez, Juan Arregui, and Juanmi Insua for their invaluable help. Thanks are also due to Mrs. Mª. Victoria Tejón for permission to trench on her property.

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