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FAULT-INDUCED DEFORMATION IN HOUSES AND STREETS OF LORCA CITY (SPAIN) DURING THE LAST CENTURIES

Deformación inducida por fallas en casas y calles de la cuidad de Lorca (España) durante los últimos siglos

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Abstract: *Lorca city (SE Spain) lies on the trace of the Alhama de Murcia fault, a NE-SW-oriented, left-lateral strike-slip transcurrent fault. Examination of old historical buildings and streets of this city showed horizontal displacements in facades not related to gravity slip or normal ruin processes. All studied facades are oriented approximately NW-SE and present higher deformation in their lower parts, compatible with a NE left-lateral motion in the underground. Most deformed buildings make up tracks oriented approximately NE. The excavation of five archaeological sites respectively exposed four faults and one fault-related flexure of beds. According to their NE orientation these faults are considered created by the surface splitting of the Alhama de Murcia fault. Both faults and deformed buildings permit to deduce the existence of a wide zone of transcurrent deformations situated under Lorca city. Building rotations oscillate between 0.006°/yr and 0.024°/yr for the last two-three centuries, whereas left-lateral horizontal displacements in individual buildings are up to 5.9 mm/yr for the last 250 yr. These movements were in part aseismic, or low-grade seismic, while in other cases they must be related to big historical earthquakes.*

Key-words: *Alhama fault, deformed buildings, strike-slip rates.*

Resumen: *La ciudad de Lorca en la Región de Murcia (SE de España) se encuentra sobre la traza de la falla de Alhama de Murcia. Un examen cuidadoso de sus edificios históricos y calles muestra que muchas fachadas originalmente rectilíneas se encuentran hoy día deformadas, compuestas por dos planos de orientación diferente. Las fachadas analizadas tienen orientación aproximadamente paralela a la línea de máxima pendiente local, por lo que su deformación perpendicular a ésta, alrededor de ejes de rotación verticales, descarta procesos de deslizamiento gravitatorio. Tampoco cabe invocar procesos de ruina normal que darían orientaciones aleatorias de deformación. Todas las fachadas estudiadas están orientadas aproximadamente NO-SE y presentan mayor deformación en las zonas inferiores, a nivel de calle. Asociamos su deformación a movimientos de subsuelo compatibles con desplazamiento sinistrorso hacia el NE de las partes orientales de las fachadas. Representados en un plano, los edificios deformados se alinean según trayectorias orientadas aproximadamente NE-SO. La excavación arqueológica de cinco solares en el área urbana dejó expuestas cuatro fallas orientadas NE-SO y una estructura tectónica de inflexión atribuible a la acción de una falla oculta. Teniendo en cuenta su orientación general, se consideran estas fallas originadas por la división superficial de la falla principal de Alhama de Murcia. La correlación de fallas y edificios deformados permite deducir la existencia de una zona amplia de deformaciones transcurrentes bajo el suelo urbano de Lorca. La rotación de edificios ha proporcionado valores entre 0.006°/año y 0.024°/año en los últimos 200-300 años. Aunque la tasa de desplazamiento horizontal es menos representativa porque depende de la longitud del segmento rotado del edificio (desplazamiento del extremo SE del mismo), se ha calculado una tasa máxima individual de 5.9 mm/año para los últimos 250 años. Se obtiene así una aproximación cuantificada del juego sinistrorso acompañado de rotaciones de la falla de Alhama de Murcia en niveles superficiales de Lorca. El movimiento de la falla de Alhama fue tanto asísmico (o sísmico de baja intensidad) como sísmico, ligado a grandes terremotos.*

Palabras clave: *Falla de Alhama, edificios deformados, tasas de desgarre.*

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The Alhama de Murcia fault (AMF) is an about 100 km long, left-lateral strike-slip fault of the Eastern Betics Shear Zone (Bousquet, 1979; Montenat *et al.*, 1990; Martínez-Díaz and Hernández Enrile, 1991). Its horizontal movement was produced since the Late Miocene and it has continued during the Quaternary (Martínez-Díaz and Hernández Enrile, 1991; Martínez del Olmo *et al.*, 2006).

This fault moved repeatedly (see the background) affecting many structures and producing numerous victims. But, so far, it has not been reported that there are buildings deformed in a way consistent with the movements of the fault.

Geological setting and background

In proximity to the SW part of Lorca city the AMF splits into several branches affecting the Betic basement, mainly formed by Triassic and even Palaeozoic rocks in some cases affected by the Alpine metamorphism. The fault branches are covered by the Quaternary below the city and towards the NE (*e.g.,* Montenat *et al.*, 1990; IGME, 1993; Booth Rea, 2001; Martínez Díaz, 2002; Sanz de Galdeano *et al.*, 2012; García-Mondéjar *et al.*, 2014a) (Fig. 1).

Two recent geological maps of Lorca show fault traces hypothetically continuing under the Quaternary materials. One of them (Giner Robles *et al.*, 2012, their Fig. 6) represents faults both to the N and S of the Castillo de Lorca, whereas the other one (Sanz de Galdeano *et al.*, *op. cit.*; García-Mondéjar *et al.*, *op. cit.*) shows fault traces only to the S of it (*e.g.,* San Lázaro fault in Fig. 2). For the last authors the split of the AMF in Lorca is attributed to a change in the direction of the master fault, from approximately N040ºN to approximately N055ºE (Fig. 1).

In order to contribute to the better knowledge of the AMF traces below Lorca city, a systematic study of the urban geological and archaeological sites was developed during the last years. Some of the results obtained about the faults especially in the Lorca surroundings were already published (Sanz de Galdeano *et al.*, 2012; García-Mondéjar *et al.*, 2014a, b). In this paper we make use of these studies and new outcrops to complete the results of a careful examination of old houses and streets of the city significantly deformed. We understand by significant that deformation is not related to soil-gravity slip or normal ruin processes. The integration of two sets of data, deformed buildings along preferred orientations and faults seen at excavations, permits to follow hypothetically the main fault lines of the AMF through the Lorca urban area.

The detailed expression of the AMF under the city of Lorca is of prime importance to understand its associated seismicity, especially after occurrence of the high-damaging Mw 5.1 Lorca 2011 earthquake. Since that date, many efforts have been devoted to understand the local seismic response and to better evaluate the "fault zone" effect (*e.g.,* Lenti *et al.*, 2015).

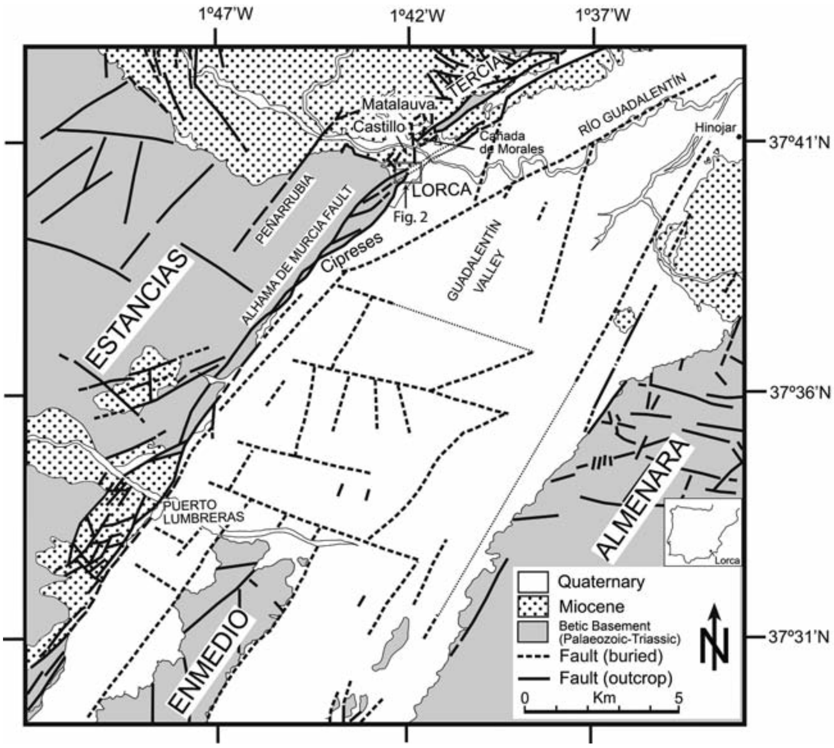

Fig. 1.- Geological map of Lorca area. The left-lateral, strike-slip Alhama de Murcia fault is in the NW border of the Guadalentín valley, and it shows subdivision in traces just to the SW of Lorca. (Modified from García-Mondéjar *et al.*, 2014a).

Historical seismicity and palaeoseismicity in the Lorca area

Lorca city was subjected to strong seismic movements during the last five hundred years. There are historical seismicity reports of five damaging earthquakes in or near the city that occurred in 1579, 1674 (two earthquakes in less than one month interval), 1818 and 2011. Maximum intensities (MSK) were between VII and VIII (IGN, 2010), and the average recurrence period considering the 1674 series as a unique event was 144 yr.

Studies of paleoseismicity in the central sector -including Lorca city- and the southern sector of the AMF revealed that surface ruptures as long as 40 km (earthquakes up to 7 Mw) could have occurred twice: in the time period between 16.7 and 26.9 ka (probably immediately before 16.7 ka), and between 2.8 and 3.8 ka (Ortuño *et al.*, 2012; Martínez-Díaz *et al.*, 2012). Relying also on studies from different authors, Martínez-Díaz *et al.*, (*op. cit.*)

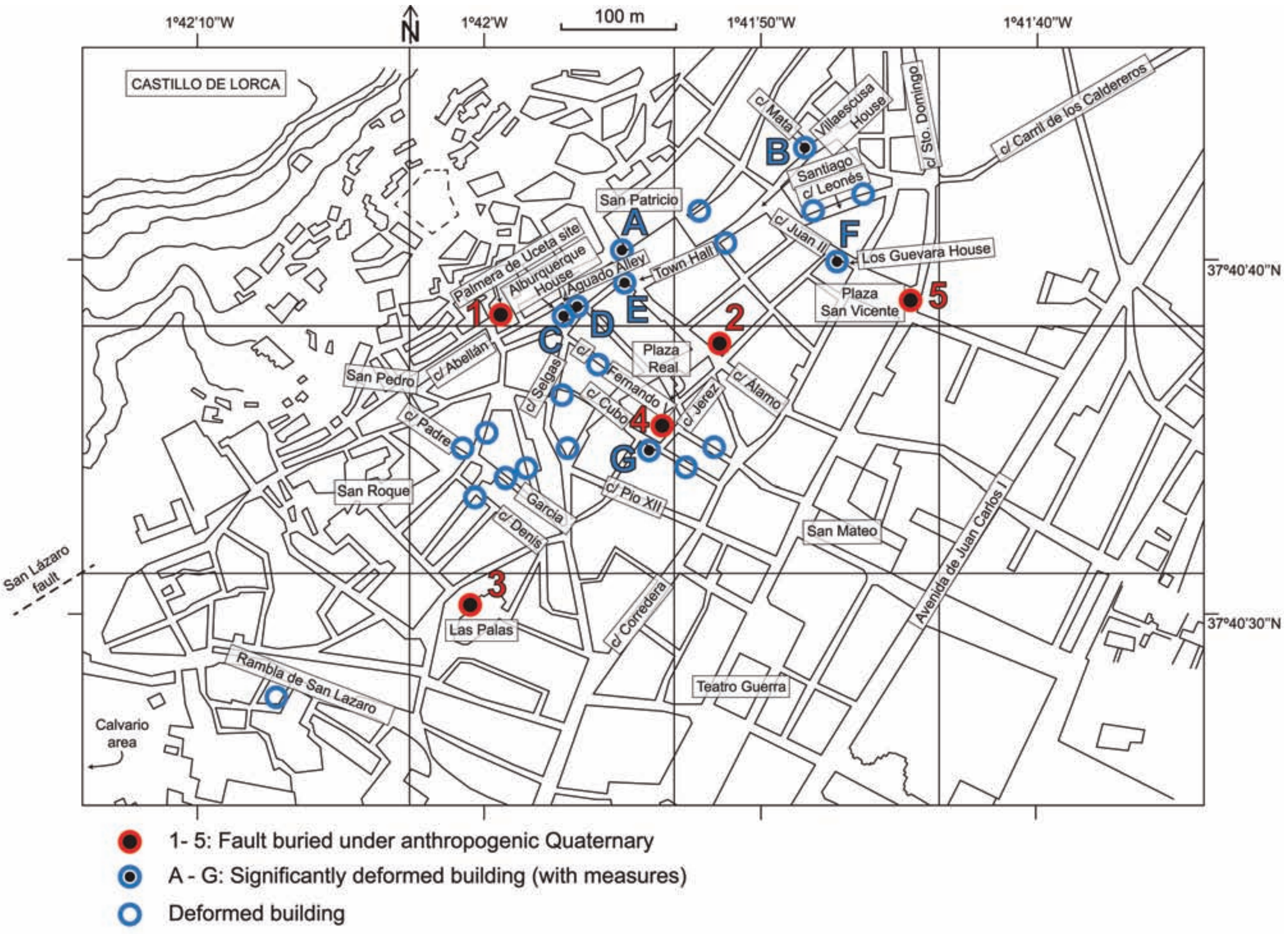

Fig. 2.- Map street plan of the older part of Lorca city with location of buildings with significant deformation and measurements (points A to G: A- San Patricio Church; B- Villaescusa House; C- Alburquerque House; D- Selgas Street House; E- Town Hall Building; F- Los Guevara House; G- Cubo and Jerez streets intersection). Archaeological sites with fault traces are represented by points 1 to 5 (1- Palmera de Uceta outcrop; 2- Álamo Street outcrop; 3- Las Palas outcrop; 4- Plaza Real outcrop; 5- San Vicente outcrop). Other deformed buildings are identified with empty circles.

suggested that the recurrence period for earthquakes more than 6.0 Mw in the central segment of the AMF oscillates from 13 to 24 kyr.

Palaeoseismic reports in the southernmost segment of the AMF (Goñar sector) suggested at least six earthquakes of Mw (6-7), occurred in the last 174-274 ka (Ortuño *et al.*, 2012, their Fig. 7A). Only the two younger earthquakes, PE1 (3-25 ka) and PE2 (21(39)-51 ka), can be correlated respectively with the two occurred in Lorca in the age intervals 2.8-3.8 ka and 16.7-26.9 ka (probably near 16.7 ka) (Ortuño *et al.*, *op. cit.*, their Fig. 7B; Masana *et al.*, 2004). The older Goñar earthquakes cannot be correlated with others in Lorca because of the lack of studied outcrops in this city older than 26.9 ka.

Whether all Goñar palaeoearthquakes or only the two younger ones had equivalency in the Lorca area, it seems that frequency of the major earthquakes occurring simultaneously in the central and southern segments of the AMF has increased during the last tens of thousand years (latest Pleistocene-Holocene).

The earthquakes in SE Spain, finally, are obviously inserted into the convergence process of Africa moving towards Europe at 4.5-5.6 mm/yr (*e.g.*, McClusky *et al.*, 2003).

Objective of the article

This article intends to contribute to knowledge of the movements of the AMF (and its subsidiary branches) in the area of Lorca, showing the existence of deformed buildings and other urban features. Seven significantly deformed buildings are reported and their representing facades measured (A to G in Fig. 2; C and D are two closely spaced buildings). On the other hand, five geological outcrops exposed after archaeological excavation and extraction of the anthropogenic Quaternary showed direct evidence of fault traces (points 1 to 5 in Fig. 2). Details of the methods used to measure the deformed facades of buildings and fault traces are detailed below. A geological map hypothetically connecting the faults seen in outcrops with deformed buildings will be proposed.

A discussion at the end relates faults with deformed buildings, movement rates with other AMF strike-slip rates deduced in Lorca outskirts, and explores possible causes of the described deformations. A final commentary is made about the recent historical seismicity in Lorca and its relation with proposed palaeoseismicity in the central AMF.

Deformed buildings

In this section we describe NW-SE oriented facades of seven historical buildings significantly deformed (Figs. 3 and 4), potentially attributable to active tectonics related with the Lorca fault traces. However, we must indicate that there are more deformations of the same type affecting buildings (not only ancient but also recent ones) and streets, although in the present article we report only some of the most noticeable cases. No horizontal plans of the buildings have been studied, although it is certain that several old houses in Lorca have been repaired and even completely rebuilt inside, leaving untouched their facades to preserve the artistic patrimony. However, at least in one examined case the plan of a whole building block suggests that deformation exceeds the considered facade (Los Guevara House, work in progress).

Measuring of deformed facades of buildings was made with a geological compass, having obtained previously clear evidence of the facade division into a NW and SE part, linked by a nearly vertical hinge line. Several orientation measures of each part of the facade were used to obtain an arithmetic mean, considered appropriate to establish differences in orientation between the two parts. These differences are expressed in degrees plus centesimal fractions. For each case the lengths of the two parts of the facade were measured at the street level, and they were represented in a horizontal plane accompanied by their respective orientations. The SE part of each deformed facade is not exactly vertical, but shows in all cases evidence of upward inclination, *i.e.,* it dips to the NE. This deformation has not been quantified except in one case, but it has been reported accompanying description in each case.

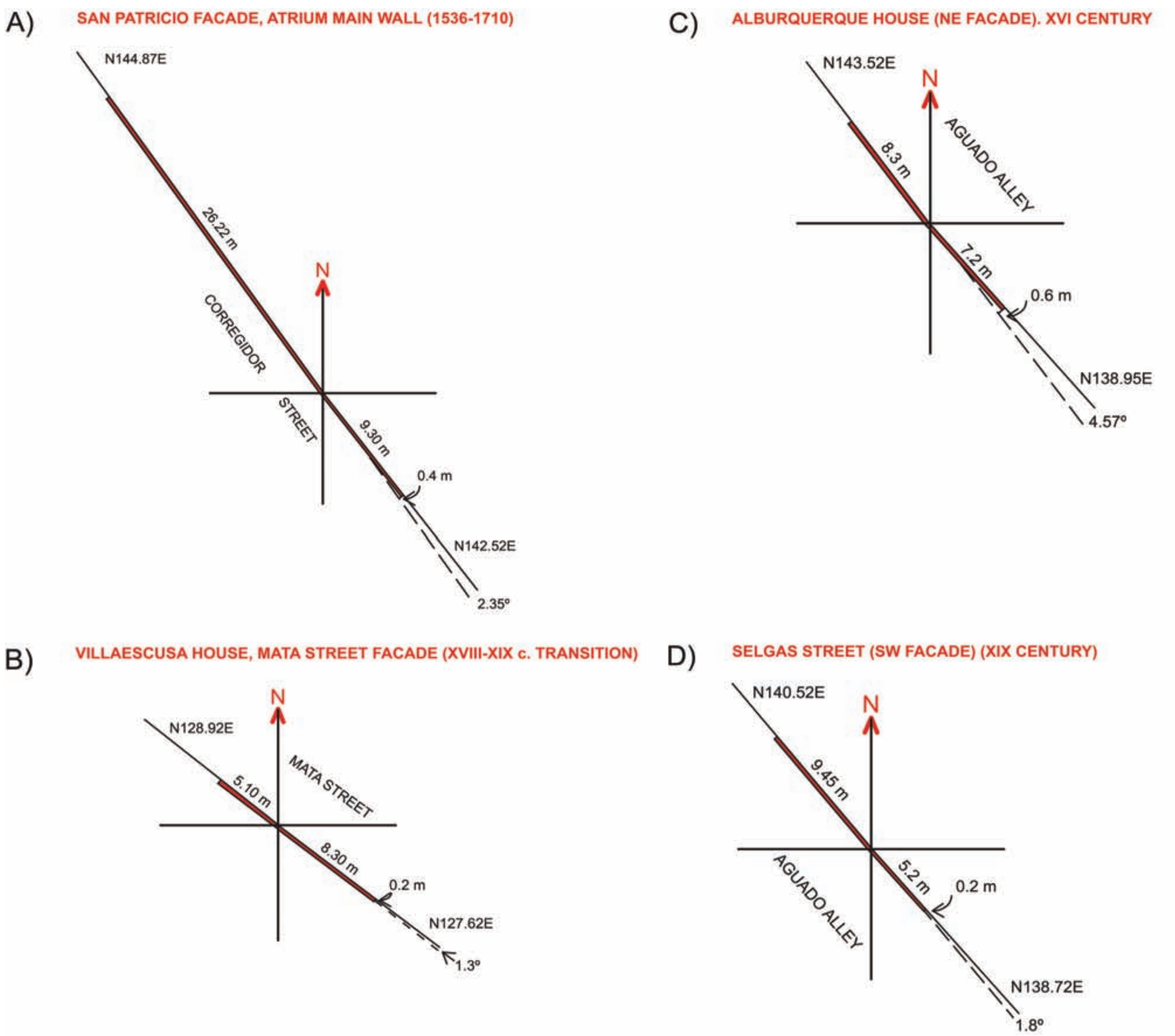

Fig. 3.- Cross-sections of the deformed facades represented in points A to D in Figure 2. A) Horizontal section of the lower part of the atrium main wall in front of San Patricio Church facade (point A), showing two segments deflected 2.35º. B) Horizontal section of the lower part of Villaescusa House, Mata Street facade (point B), showing two segments deflected 1.3º. C) Horizontal section of the lower part of the Alburquerque House, Aguado Alley facade (point C), showing two segments deflected 4.57º. D) Horizontal section of the lower part of Selgas House, Aguado Alley facade (point D), showing two segments deflected 1.8º.

The angles formed by the two integrant parts of the reported facades have been systematized in Table I, to obtain rotation rates and make comparisons among different fault traces. To express the maximum horizontal displacement of a point in a facade with respect to its original position in a rectilinear wall, we have chosen the SE corner point in each case. This is because the SE part of the facade is the most deformed part of the building, both horizontally and vertically. Once selected this corner point the separation distance between its present and its presumed original position, divided by the age of the building, gives the maximum horizontal displacement rate of the SE part of the building for the time considered.

Data appropriate to calculate vertical displacement rates were not obtained. Only in one case (Plaza Real site) cracks on a horizontal floor of a basement, created by the Lorca 2011 earthquake, permitted to have an approximation to these rates, valid for a particular place on a fault strand during an instantaneous shock.

San Patricio Church

This site corresponds to point A in Figure 2. The San Patricio ex-collegiate church was built between 1536 and 1710. The main wall of the atrium, parallel to the main facade of the church is 35.5 m long and is oriented NW-SE. It belongs to a single constructive unit originally plane. However, looking carefully at this wall it is evident that it is made up of two vertical planes with a slight difference in orientation. In horizontal section the atrium wall shows two segments (Fig. 3A). The northern segment is 26.22 m long and is oriented N144.87°E (mean value of 17 geological compass measures). The southern segment is 9.30 m long and is oriented N142.52°E (mean value of 9 geological compass measures). Therefore, both orientations differ in 2.35º and show 0.4 m of maximum deflection. The intersection line between the two planes of the atrium wall does not apparently have any correspondence in the church facade. However there are some vertical cracks in the southern part of this facade in front of that intersection line, and there is evidence that the SE part of San Patricio is the most damaged area of the building (*e.g.*, Rodríguez-Pascua *et al.*, 2012, their Fig. 13).

The deformation described here is, therefore, concentrated in the lowermost part of the building, nearly the street level. Discontinuous stone blocks at the base are seen projected up to 0.1 m out of the vertical plane of the wall, giving testimony of the reported deformation. The outer profile of these blocks draws a straight line 2.8° oblique to the base wall, very close to the 2.35° deformation angle of the atrium reported above. They are interpreted as pieces of wall left behind during the rotation process.

Villaescusa House

The Villaescusa House is located in point B of Figure 2. Its main facade lies in the Villaescusa Street but we analyse here the Mata Street facade (Fig. 3B). This important building was built in the transition between the XVIII and XIX centuries.

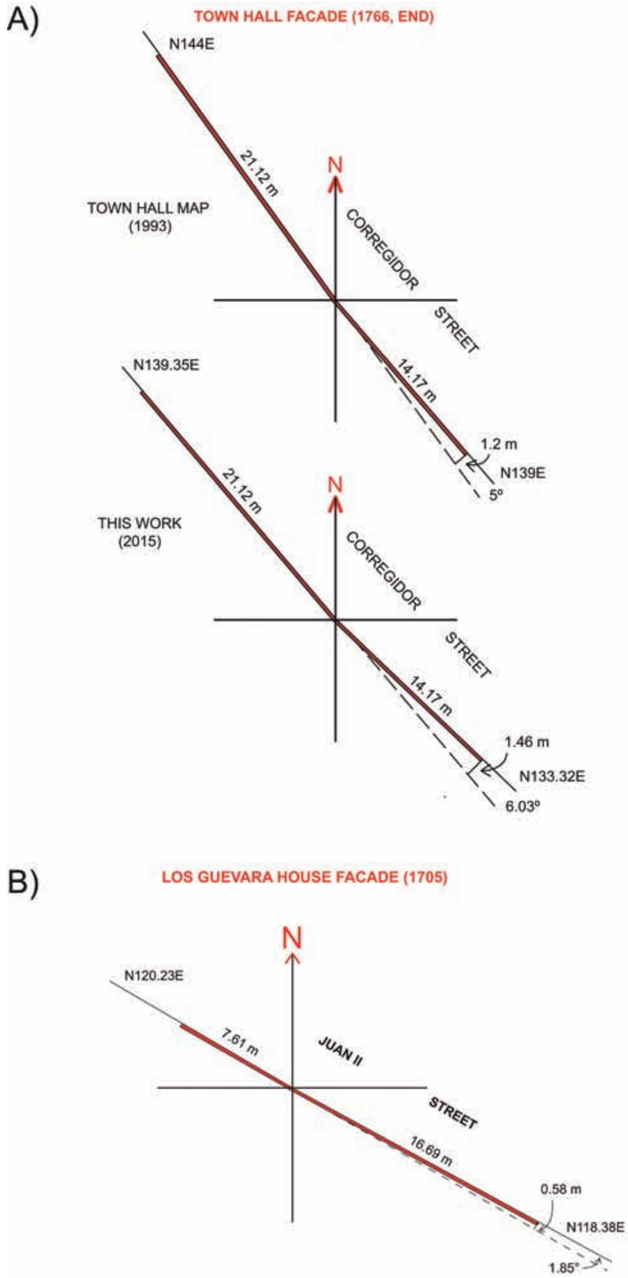

Fig. 4.- Cross-sections of the deformed facades represented in points E and F in Figure 2. A) Horizontal section of the lower part of the Town Hall facade (point E) showing two segments deflected 5º (upper part, Town Hall map 1:500 scale, 1993), and 6,03º (lower part, this work). B) Horizontal section of the lower part of the Los Guevara House facade (Juan II Street, point F), showing two segments deflected 1.85º.

The Mata Street facade is 13.40 m long and is oriented roughly NW-SE. In horizontal section it consists of two rectilinear segments with slightly different orientations. The NW segment is 5.10 m long and is oriented N128.92°E (mean value of 10 geological compass measures). The SE segment is 8.30 m long and is oriented N127.62°E (mean value of 8 geological compass measures). Therefore the difference in orientation is 1.3º and the maximum deflection of the facade is 0.2 m (Fig. 3B). A thing to note here is that the facade deflection is only present in the lower part of the building, with the upper story and eaves rectilinear.

Fault trace	Building	Age (construction start date)	Facade orientation (NW part)	Rotation angle (vertical axis)	Lateral displacement (SE point)	Rotation rate (vertical axis)	Lateral displacement rate (SE point)
Palmera de Uceta	San Patricio Church	1536	N144.87E	2.35°	0.4 m	0.005°/yr	0.83 mm/yr
Palmera de Uceta	Villaescusa House	1800	N128.92E	1.3°	0.2 m	0.006°/yr	0.93 mm/yr
Alburquerque	Alburquerque House	1550	N143.52E	4.57°	0.6 m	0.01°/yr	1.29 mm/yr
Alburquerque	Selgas Street	1850	N140.52E	1.8°	0.2 m	0.011°/yr	1.21 mm/yr
Alburquerque	Town Hall	1766	N139.35E	6.03°	1.46 m	0.024°/yr	5.86 mm/yr
Álamo-Plaza Real	Los Guevara House	1705	N120.23E	1.85°	0.58 m	0.006°/yr	1.87 mm/yr
Las Palas-Plaza Real	Cubo and Jerez streets intersection	1940	N115E	**(horizontal axis)** 0.5°	**(base of hinge line)** 0.11 m	**(horizontal axis)** 0.007°/yr	**(base of hinge line)** 1.45 mm/yr
Las Palas-Plaza Real	Plaza Real	2001			**2011 Vertical displacement (earthquake)** 0.03 m		

Table I.- Construction age, facade orientation and deformation rates of the studied buildigns in Lorca, and their related fault traces.

Alburquerque House

The Alburquerque historical building is represented in point C in Figure 2. Its main facade is in the Selgas Street, but we describe here its NE facade in the Aguado Alley (Fig. 5A left part). The building was built in the XVI century.

The Aguado Alley facade is 15.50 m long and is made up of two rectilinear segments in horizontal section (Fig. 3C). The NW one is 8.30 m long and is oriented N143.52°E (mean value of 8 geological compass measures). The SE one is 7.20 m long and is oriented N138.95°E (mean value of 7 geological compass measures). Both segments differ 4.57º in orientation and 0.6 m in maximum deflection (Fig. 3C).

As in San Patricio Church and Villaescusa House, the maximum deflection is located in the lower part of the building, and it diminishes progressively towards the eaves where it is practically imperceptible (Fig. 5A, left part).

Selgas Street House

This house is represented in point D in Figure 2. We analyse here its SW facade (Aguado Alley, Fig. 3D). The building corresponds to the XIX century.

The Aguado Alley facade is 14.65 m long and consists of two segments in horizontal section. The NW segment is 9.45 m long and is oriented N140.52°E (mean value of 8 geological compass measures). The SE segment is 5.2 m long and is oriented N138.72°E (mean value of 6 geological compass measures). The difference in segment orientations is 1.8º and the maximum deflection is 0.2 m (Fig. 3D). As in previous cases, the deformation of this facade is bigger in the lower part of the building and it diminishes towards its upper part (Fig. 5A, right part).

Town Hall Building

The Town Hall is a historical building with an artistic facade ended in 1766 (Fig. 4A). It is represented in point E of Figure 2. In this paper we include two horizontal sections of the base of that facade, one corresponding to the Lorca map at 1:500 scale made by the Town Hall in 1993 (PEPRI, 1993, Fig. 4A up), with the appropriate enlargement, and the other one made with our own data taken in 2015 (Fig. 4A down).

In the Town Hall map (1993), the Town Hall main facade has a N segment 21.12 m long and oriented N144°E. Its S segment is 14.17 m long and oriented N139°E. The difference in orientation is 5º and the maximum deflection is 1.2 m (Fig. 4A up).

Our Town Hall main facade section has a N segment 21.12 m long and oriented N139.35°E (mean value of 12 geological compass measures). The S segment is 14.17 m long and is oriented N133.32°E (mean value of 5 geological compass measurements). The difference in orientation of both segments is 6.03º and the maximum deflection is 1.46 m (Fig. 4A down). These deviations are clearly seen in a photograph taken from the N (Fig. 5B). As in previous cases deformation is bigger at the base of the facade and it diminishes upwards. In this case the lower colonnade of the southern part of the building is significantly inclined to the SW, accompanying that difference in deformation.

The relative difference in orientation between segments is similar in the Town Hall map section (5º) and our section (6.03º); however, the general orientation of the facade departs around 5º from the Town Hall section to ours. We attribute this difference to a localized error in the drawing of the Town Hall map owing to its small scale.

Los Guevara House

Los Guevara House main facade dates from 1705. It faces Juan II Street and is represented by point F in Figure 2. This facade consists of two rectilinear segments in horizontal section differently oriented (Fig. 4B). The W segment is 7.61 m long and is oriented N120.23°E (mean value of 14 geological compass measures). The E segment is 16.69 m long and is oriented N118.38°E (mean value of 14 geological compass measures). The difference in segment orientations is 1.85º and the maximum deflection is 0.58 m. As in similar cases described previously, the deformation of this facade is bigger in the lower part and it diminishes progressively towards the eaves. Work in progress with other details will complete description of this house in the future.

Cubo and Jerez streets intersection

The house at Cubo and Jerez streets intersection (point G in Figure 2) shows two rectilinear segments in horizontal section differently oriented. The W segment is 7.59 m long and is oriented N115°E (mean value of 5 geological compass measures). The E segment is 5.08 m long and is oriented N111°E (mean value of 5 geological measures). The difference in segment orientation is 4° and the maximum deflection is 0.3 m.

This house was built (rebuilt?) in the mid XX century, too close to the present time to explain the big differences in orientation of its facade as deformation. However we suggest the hypothesis that the feature described was inherited from an old, previous house, since facades in the old part of Lorca are maintained to preserve the local artistic patrimony. This is based in evident differences in inclination between both parts of the facade, with the NW one practically vertical and the SE one inclined to the SW, as in other examples of deformed buildings studied here. In this case the angle of vertical deformation is 0.5°, shown by an offset of the two parts of the facade 0.11 m wide at the street level and 0.05 m wide 6 m above, at eves level.

Fault features visible in Lorca city

We describe here five geological outcrops exposed by archaeological excavations that revealed faults. These faults separate different units, from Betic basement to Miocene or Quaternary.

Palmera de Uceta outcrop

The Palmera de Uceta archaeological site is represented in point 1 of Figure 2. It is in the Palmera de Uceta Street, opposite to Abellán Street. The excavation was made in 2005. The archaeological remains found were Medieval Islamic and Modern (Álvarez Quintana, 2006). A diagram with the geological sections exposed in the walls of the site is shown in Figure 6A.

A main fault oriented N065ºE with dip 57°N separated two sedimentary successions. The northern one consists of fine-grained sandstones and shales (Fig. 6A), attributed to the Betic basement (most probably Permian/Triassic). The southern succession is 4 m thick and consists of greenish lutites with silty and sandy beds and scattered gypsum crystals. In an outcrop 10 m to the NE, these lutites enclosed red polymictic channelized conglomerates. This succession is attributed to the Miocene by comparison with similar facies described in García-Mondéjar *et al.* (2014a).

Therefore, the fault shown in Figure 6A separates series of different age. The main fault plane dipping NW suggests a reverse component, and at least three subordinate

A)

B)

Fig. 5.- Photographs of deformed buildings shown in figures 3 and 4 (points C, D and E in Fig. 2). A) Picture from the Aguado Alley taken from the S. The Alburquerque House (point C) and Selgas Street House (point D) facades are seen to the left and right, respectively. Both and the proper Aguado Alley are deflected in the same direction, towards the NE. The upper part of the Selgas facade shows lesser deformation and the corresponding upper part of the Alburquerque facade is not deformed. B) Picture of the Town Hall main facade taken from the N. The southern part (background) is horizontally deflected to the NE and vertically inclined to the SW, with maximum deformation in the lower colonnade.

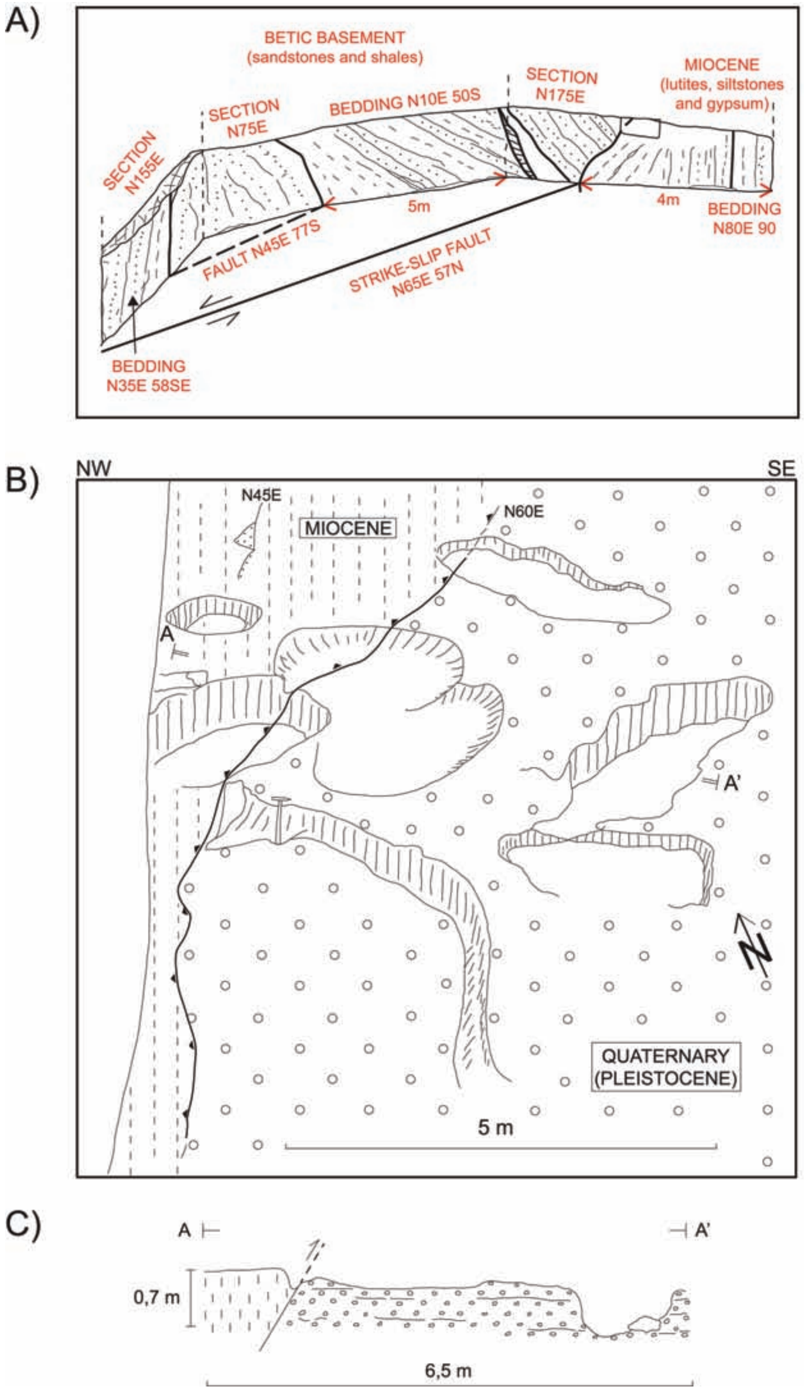

Fig. 6.- Geological outcrops from archaeological excavations in points 1 and 2 of Figure 2. A) Vertical sections with different orientations at Palmera de Uceta Street in 2005 (point 1). Materials of the Betic basement are separated from a Miocene series by a N065°E oblique-reverse fault with three subordinate strands. B) The Álamo archaeological site exposed during a 2007-2008 excavation (point 2). Plan view drawing of the archaeological site after extraction of the anthropogenic Quaternary, taken from a photograph. Miocene (left) and Quaternary (right, Late Pleistocene) are separated by a reverse fault oriented N045ºE-N060ºE. Depressed structures at surface correspond to holes left by the archaeological excavation. C) NW-SE geological cross-section of the Alamo site (see A-Á location in B), showing the vertically-dipping Miocene superposed to the horizontally-dipping Quaternary. Modified from García-Mondéjar *et al.* (2014b, their Fig. 2).

fault planes dip oppositely (antithetic). One of the latter contained a small duplex structure visible in the N175ºE oriented section.

Álamo Street outcrop

This archaeological site is represented by point 2 in Figure 2. It was previously reported in García-Mondéjar *et al.* (2014b). Here we refer its more relevant characteristics (Figs. 6B, C and 7).

The archaeological excavation took place between years 2007 and 2008. The anthropogenic succession contained Calcolithic, Iberian, Roman, Medieval Islamic and Modern remains (Cárceles Díaz *et al.*, 2011). The anthropogenic succession up to the Roman interval and the two geological units of the substratum appeared affected by a reverse fault with southern vergence: Miocene lutites in the NW, dipping vertically and oriented N045ºE, and Quaternary sub-horizontal (Late Pleistocene) materials in the rest of the site (SE) (Figs. 6B, C and 7). The fault is oriented N045ºE in the S and N060ºE in the N of the site and dips 56-63º to the NW (García-Mondéjar *et al.*, 2014b).

Las Palas outcrop

Las Palas hillock is a small outcrop of Betic basement in the Lorca urban area (point 3 in Fig. 2). It was firstly reported in Rodríguez Estrella and Mancheño (1993). The SW-NE elongated topographic relief is made up of black, brecciated, Triassic dolomitic limestone. It rests by means of a fault N057ºE with dip 35°SE on a red-violet shale, very ground, with intercalated fine-grained sandstones oriented N080ºE and dipping 75°S. The shale, attributed to the Betic basement as well as the limestone, contains quartz veins with malachite and a small fault oriented N057ºE and dip of 52°SE. Both reported faults are characterized as reverse by the presence of drag structures oriented to the NE in their respective footwalls.

Plaza Real outcrop

The Plaza Real site (previously Market Square) was excavated in 2001. The site is represented by point 4 in Figure 2. The geological succession discovered is shown in figures 8 and 9. The excavated hole up to 7 m deep mainly exposed the Lorca red conglomerate unit, dipping 50° to the SE (Miocene, Langhian-Serravallian, García-Mondéjar *et al.*, 2014) (Fig. 8B). However, the SE part of the outcrop was made up of materials attributed to the Betic basement:

altered limestone, phyllite and red shale, partly arranged in large and irregular fragments (Figs. 8A and 9).

The units described are separated by a fault coated by a 0.5 m thick phyllite band, approximately parallel to Jerez Street (N038ºE), with 70° dip to the SE (Figs. 8 and 9). According to the exposed data it is a reverse fault with a slightly sinuous trace.

Construction of an underground parking place in Plaza Real in 2001/2002, offered a unique opportunity to estimate the order of magnitude of vertical displacements of a fault strand in Lorca during a major earthquake. The floor of the lowermost basement of that parking place was laid directly onto the geological surface of the excavated site. It was affected by the Lorca 2011 earthquake with formation of large cracks that were more abundant along a band several metres wide oriented NNE. This band followed approximately the underlying fault trace shown in Figure 8A. Some of the cracks presented relief up to 3 cm high (Fig. 10).

San Vicente outcrop

The San Vicente Square was excavated between years 2001 and 2002. This site is represented by point 5 in Figure 2. An anthropogenic series 2.60 m thick provided archaeological remains from the Calcolithic, Roman, Medieval Islamic and the XIX century cultural phases. The lowermost remains (Calcolithic) dated 4650-4550 ^{14}C yr BP (García Blánquez *et al.*, 2002).

The studied geological succession below the anthropogenic unit comprised 3.55 m of yellow silt, red gravel, gray lutite and red conglomerate, from base to top, and they were attributed to the Late Pleistocene (levels 1, 2, 3 and 4 respectively in García-Mondéjar *et al.*, 2014b, their Fig. 2). In that paper, a flexure of the geologic beds in the E part of San Vicente Square was interpreted as the surface expression of a buried fault, with the E block downthrown with respect to the W one. This W block in its turn was contiguous to another more elevated one, raised by the interpreted action of a different fault. The tectonic structure was described as a "bench structure" (Sylvester, 1988), not exactly diagnostic but common in areas subjected to strike-slip motion, where the master fault appears split at surface.

Discussion

In this section we first correlate the faults studied in the excavations with the tracts of deformed buildings seen at surface. Then we analyse the strike-slip rates obtained from measures on deformed buildings, and finally we comment on the differences between previously reported strike-slip rates to the NE of Lorca and those presented here in the urban area.

Fig. 7.- Photograph of the Álamo Street outcrop exposed during the 2007-2008 excavation works (point 2 in Fig. 2). The plan view shows geological units after extraction of the anthropogenic Quaternary. A reverse fault oriented SW (foreground, N045°E) to NE (background, N060°E), separates Miocene lutites (left) from Late Quaternary conglomerates (right). View from the SSW. A schematic drawing is shown in Figure 6B.

Relations among faults at excavation sites and deformed buildings

The faults seen directly at excavations (Palmera de Uceta, Álamo, Las Palas and Plaza Real) and the fault deduced from a tectonic structure (San Vicente) can be related with significantly deformed buildings (San Patricio, Villaescusa, Alburquerque, Selgas, Town Hall, Los Guevara, Cubo and Jerez streets intersection), as well as with other deformed buildings. This has permitted to make up the map in Figure 11.

The outcrops and fault network represented in this map out of the Lorca urban area have been taken from Sanz de Galdeano *et al.* (2012) and García-Mondéjar *et al.* (2014), with fault modifications in the Calvario area made for this paper. On the other hand the Quaternary, Miocene and Betic basement units figured in the urban area are represented discontinuously, since they proceed from direct observations in isolated archaeological excavations made along the years.

The orientations of the AMF traces in the Lorca urban area (N038ºE to N065ºE) have been used as a guide to propose correlations between outcrops of these faults and the neighbour deformed buildings. These latter make up NE-SW tracks that are interpreted as the result of fault action in the subsurface. Moreover, all significantly deformed buildings present facades approximately perpendicular to the NE-SW oriented AMF, and their respective deformations are compatible with the left-lateral horizontal motion attributed to this fault. These facades are mainly parallel to the maximum local slope of the city surface, so that their reported perpendicular deformations are not related to possible gravity slip movements of the anthropogenic soil.

The faults deduced from outcrops and deformed buildings do not necessarily imply that all buildings located along their hypothetical traces should appear deformed. There are many circumstances that characterize every case. We mention first the age of the house. Modern houses (less than approximately 50-60 yr old) rarely show deformation, although there are some exceptions. Older houses can or cannot be deformed. One explanation for this could be the presence or absence of loose anthropogenic deposits below

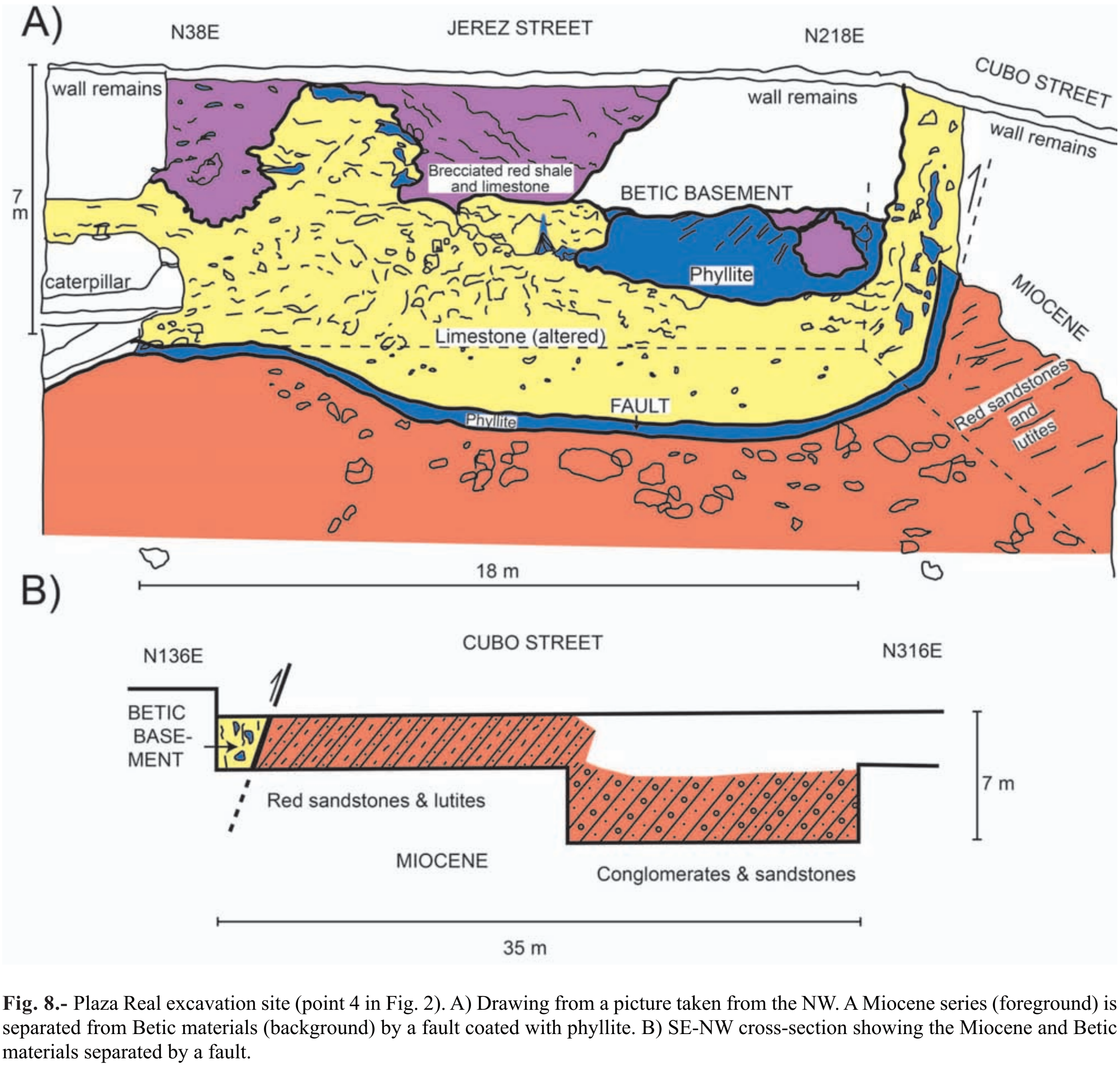

Fig. 8.- Plaza Real excavation site (point 4 in Fig. 2). A) Drawing from a picture taken from the NW. A Miocene series (foreground) is separated from Betic materials (background) by a fault coated with phyllite. B) SE-NW cross-section showing the Miocene and Betic materials separated by a fault.

Fig. 9.- Plaza Real excavation site (point 4 in Fig. 2). Picture taken from the NW. A hole 7 m deep shows a Miocene series in the foreground and, separated by a fault, Betic materials in the background. Caterpillar on the left for scale. A drawing of this outcrop is presented in Fig. 8A.

the building. The thickness of these deposits ranges from nothing (foundations fixed in the local geological series) to 7.5 m. There are also differences in compaction of the underlying geological series, from metamorphic (Betic) basement to loose silts of the Late Pleistocene and Holocene, passing through compact Miocene conglomerates, sandstones and claystones. In any case evidence indicates that older houses at or near presumed fault traces normally show significant deformation.

A second circumstance to mention is that modern rebuilt houses with preserved facades from older houses can show inherited significant deformation.

A third consideration is that the faults seen in outcrops with a certain lateral extension show small variations of their strikes at the scale of a few metres. Perhaps this is explained by the reverse component of the faults at surface in most studied examples. Changes like these can make a fault trace avoid a particular house and continue along an adjacent street, but preserving its general trend.

We finally mention that deformation in Lorca proceeds through multiple earthquakes, normally of low grade but some of them highly destructive. Only the better-built old houses that lie on fault traces have survived the big historical earthquakes. Therefore they are the best indicators of deformation created by underground movements.

The main trace of the AMF seen in outcrop to the S of San Lázaro hermitage (N050ºE, W of Calvario, Fig. 11), is hypothetically followed in the urban area up to Palmera de Uceta outcrop (point 1), as well as to San Patricio Church (point A) and Villaescusa House (point B) deformed buildings. According to observations in A and B buildings it does not show signs of much left-lateral movement for the last four centuries, comparing with other traces in Lorca (Table I). We consider that in Palmera de Uceta site the fault represents movement at least with a reverse component. On the other hand, the deformed and aligned buildings reveal left-lateral strike-slip movement. Finally, taking the displacement of the more distant point in the SE part of each deformed facade, and dividing it by the age of the facade, we obtain the movement rate of the considered point. We assume that fault action at depth provokes conveyer belt or rotation effect in the houses at surface, deforming them. The rates calculated for the Palmera de Uceta fault are 0.005°-0.006°/yr and 0.83-0.93 mm/yr, the latter minimum values since they depend on the length of the rotated segment studied in each case.

The Alburquerque fault trace has been deduced only from significantly deformed buildings. These are Alburquerque, Selgas, and Town Hall (respectively points C, D and E in Figs. 2 and 11). The track is followed hypothetically to the ENE, likely through other deformed buildings in Santiago and Leonés streets. With an argument similar to that used in the Palmera de Uceta fault, the left-lateral movement rates obtained here are 0.01°/yr and 1.3 mm/yr from Alburquerque, 0.011°/yr and 1.21 mm/yr from Selgas, and 0.024°/yr and 5.9 mm/yr from Town Hall. Again the rates in millimetres are minimum values as they depend upon their respective segment lengths.

The next deduced fault trace in the SE direction is also based on deformed buildings. It hypothetically goes along four buildings represented in figures 2 and 11 (from Padre García Street in the SW to Fernando V Street in the NE), all of them with deformation suggesting left-lateral movement. They mark a track that, followed to the SW, would hypothetically limit the S border of the Betic San Roque hillock, and would merge with the master AMF very close to the San Lázaro hermitage.

The Álamo fault trace is defined by the reverse fault observed in the Álamo site (point 2 in Figs. 2 and 11). From hypothetical correlation with related buildings, the most important of which is Los Guevara House (point F), we also deduce left-lateral movement in this fault. The facade of Los Guevara House gives 0.006°/yr and 1.87 mm/yr of minimum rate movements (Table I), that should be attributed to the Álamo and Las Palas converging faults. The Álamo fault trace is proposed to divert from the master AMF about 200 m to the SSW of the San Lázaro hermitage ruins (Fig. 11).

The basement outcrop of Las Palas hillock (point 3 in Figs. 2 and 11) is related with several fault traces that come from the SW (Calvario area). Part of the rock is metamorphic and was followed 150 m to the NE in the urban area, through archaeological excavations. The fault trace can split into two branches toward the NE, one of them merging with the Álamo trace and the other one likely connecting with the deduced San Vicente fault (point 5 in Fig. 11). The eastern branch proposition is based on two respective deformed buildings that suggest left-lateral movement, and are located about 150 m to the NW of San Mateo (Fig. 11).

The fault strand that we interpret to merge with the Álamo fault has been studied in Plaza Real (Figs. 8 and 9). In that outcrop it separates Miocene from Betic basement rocks. However, we defend that in recent times the same fault affected both a neighbour house in Cubo and Jerez streets intersection and the lowermost floor of Plaza Real parking place. At least vertical deformation in the SE part of the mentioned house can theoretically be attributed to the time elapsed since the mid XX century, although we suspect that both its vertical and horizontal deformations could have developed before, possibly in an older house whose facade might have survived up to the present time.

Following the same fault strand, we attribute the appearance of cracks in the deepest floor of the Plaza Real parking place to movement of the fault during the Lorca 2011 earthquake. These cracks suggest at least 3 cm of maximum vertical displacement produced in this accident during an instantaneous shock.

The deduced San Vicente fault (point 5 in Fig. 11) is also hypothetically related with the easternmost fault trace of the Alhama de Murcia system, visible in the basement outcrops to the S of Calvario. This interpretation is indirect, based on the jump of both archaeological and geological structures across the line marked on the map W of the Óvalo site and San Mateo Church (Fig. 11). However no direct evidence of this trace has been obtained from excavations up to the moment.

Fig. 10.- Cracks in the basement floor of the Plaza Real parking place, appeared as a consequence of the Lorca 2011 earthquake. They are concentrated in a band oriented NNE with the crack in the centre showing 3 cm relief. Tape measure opened 10 cm. View from the SW.

Deduced values of fault movement

Certainly we have no used the most precise methods to obtain displacement values in building walls, but we are confident that repetition of measures with the geologic compass is enough to give the real value range in every case. However, more than exact data on deformations, the very interesting feature we report here is deformation itself and its significance.

Fault movement values deduced from the studied deformations are summarized in Table I. In the first column we distinguish fault traces: Palmera de Uceta, Alburquerque, Álamo-Plaza Real and Las Palas-Plaza Real. The other columns are respectively for buildings, construction age, facade orientations (NW part), rotation angle, maximum lateral displacement (extreme SE point), rotation rate around vertical axes, and left-lateral movement rate (extreme SE point). In one case the angle of rotation around a horizontal axis is reported, with the corresponding rotation rate and lateral movement rate (Cubo and Jerez streets intersection). Finally, a vertical displacement on the floor of Plaza Real basement is included, located above a fault trace and appeared as a crack step during the Lorca 2011 earthquake.

Data from the analysed buildings corresponding to Palmera de Uceta fault trace are very concordant. The rotation rates of the two buildings, 0.005°/yr and 0.006°/yr respectively, are practically coincident, with maximum lateral displacement perpendicular to the street slope (0.93 mm/yr). We deduce from these data tectonic movement of the underground. Taking into account that the buildings differ in 264 yr and that the older one is nearly 500 yr old, movement of the fault with the same rate was produced during half a millennium, perhaps through multiple small earthquakes and some big ones.

In the Alburquerque fault trace, two of the affected buildings, Alburquerque House and Selgas Street, are adjacent and are separated by the Aguado Alley. Both buildings and the street in between present the same pattern of deformation: left-lateral rotation of their respective SE parts (Fig. 5A). Their respective rotation rates are practically coincident (0.01°/yr and 0.011°/yr), and the maximum lateral displacement, perpendicular to the street slope, is 1.29 mm/yr. The ages of the two buildings differ in about 300 yr, and the older building is 465 yr old. Again tectonic movement in the underground, capable to move simultaneously two buildings and their separating street, is deduced. The Town Hall Building, presumably located along the same fault trace, departs from the above figures. Its deformation duplicates the rotation angle rate (0.024°/yr) and, although the maximum displacement rate depends on the length of the rotated part and is therefore less significant, it exceeds by more than four times the displacement measured in Alburquerque House. We attribute these figures to local causes discussed in the following section.

The Álamo-Plaza Real confluent fault traces are documented as a hypothetical single fault trace in Los Guevara House. In that point we have calculated 0.006°/yr in rotation rate and 1.87 mm/yr in maximum left-lateral displacement rate, during the last 310 yr.

For Las Palas-Plaza Real fault line, data from a building at Cubo and Jerez streets intersection are not concluding, because the apparent horizontal rotation of its facade may be an original bent feature created towards the mid XX century. However, the SE part of the building facade is inclined to the SW, and it shows a 0.5° separation angle with respect to the vertical. If we take the age of the house (76 yr, mid XX century-present time), a hypothetical rotation rate of the base of the building around a horizontal axis located at eaves is 0.007°/yr, and the corresponding horizontal displacement rate is 1.45 mm/yr. However, as we reported before the facade of this house can be an inherited structure, so that deformation rates may be lower.

The same Las Palas-Plaza Real fault trace also offers an approximation to vertical displacement in the Plaza Real basement floor. The cracks formed as a result of the Lorca 2011 earthquake give up to 0.03 m of maximum vertical displacement (Fig. 10).

In summary, maximum rotation rates of building facades presumably lying on fault traces are 0.006°/yr (Palmera de Uceta), 0.024°/yr (Alburquerque) and 0.006°/yr (Álamo-Plaza Real), for the last two-three centuries. Maximum left-lateral displacement rates range from 0.93 mm/yr (Palmera de Uceta) to 5.86 mm/yr (Alburquerque) and 1.87 mm/yr (Álamo-Plaza Real), for the same two-three last centuries. Part of these rates can be attributed to aseismic displacements or, better, to frequent low-grade seismic events, that explain progressive deformation of the buildings along time.

Slip rates discrepancy between data in Lorca and its surroundings

There are several studies that propose left-lateral slip rates of the AMF in outcrops to the NE of Lorca. From older to younger we quote them here, accompanied by their corresponding time intervals and methods employed in each case.

Martínez-Díaz *et al.* (2003), based on channel pattern analysis in an old alluvial fan 7 km to the NE of Lorca, deduced 0.21 mm/yr in the Lorca-Totana segment for the last 130 kyr. Masana *et al.* (2004) deduced 0.06-0.53 mm/yr from trenching analysis of an alluvial fan in Lorca-Totana segment, 7 km to the NE of Lorca, for the last 30 kyr. Echeverria *et al.* (2012) reported 0.55 mm/yr based on GPS measures in Lorca (PURI) for the present day (2011). Ferrater *et al.* (2015) calculated 0.024-0.039 mm/yr from deformed archaeological remains in Totana, for the last 4 kyr. Finally, Ferrater *et al.* (2016) established 0.9±1 mm/yr from buried channel analysis in the Lorca-Totana segment, 7 km to the NE of Lorca, for the last 15.2±1.1 to 21.9-22.3 kyr.

A comparison of the AMF strike-slip rates deduced from deformed buildings in Lorca with the rates obtained to the NE of the city shows a clear discrepancy, with individual values about six times higher in the case of deformed buildings in the urban area. However, we defend that the exposed data on deformed buildings can be attributed to tectonic action in the subsurface. This is based on the following arguments. First, there are houses that although separated by a street present the same style of horizontal deformation, with coincident movement rates perpendicu-

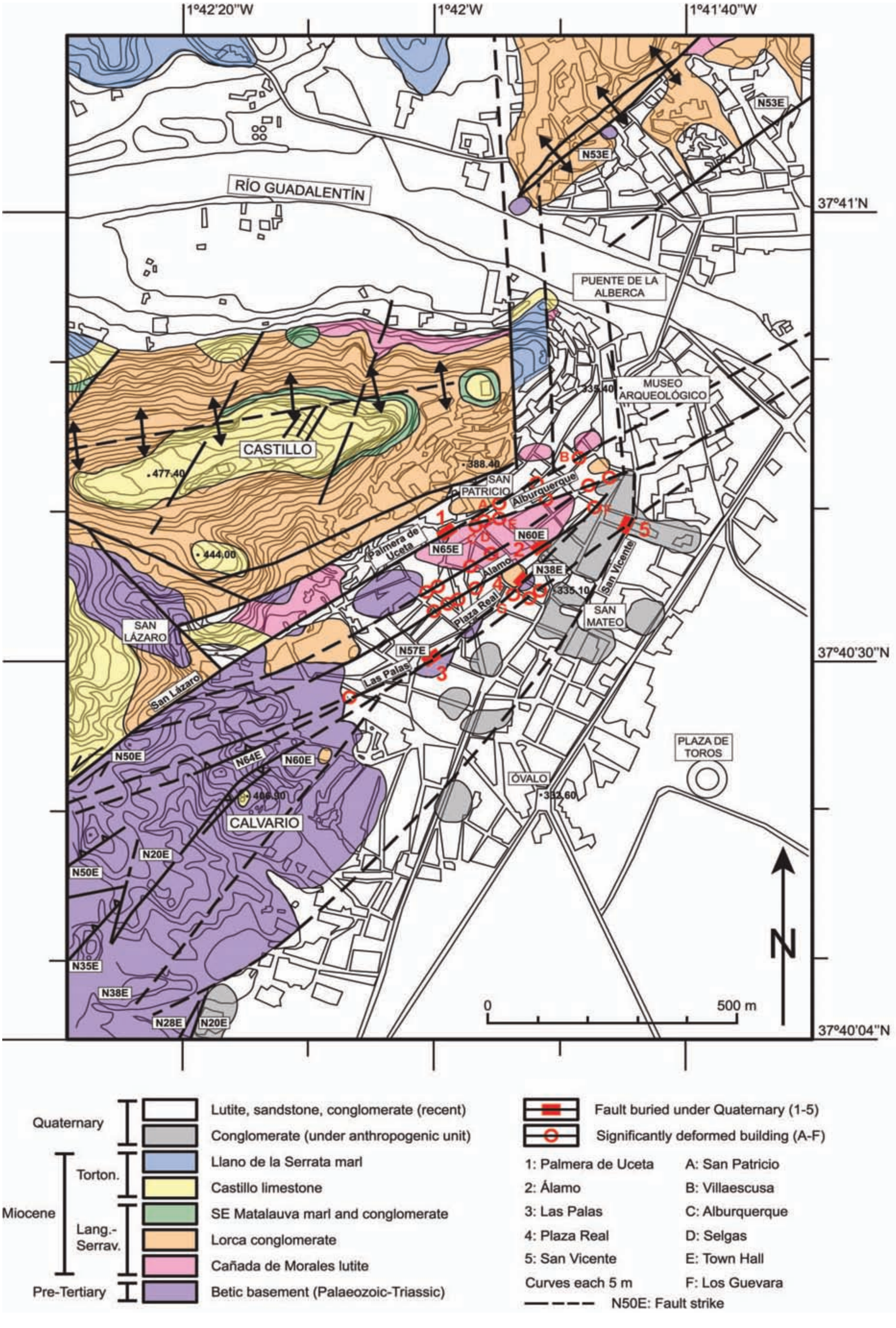

Fig. 11.- Geological map of Lorca with outcrops in the surroundings of the city and subcrops in the urban area, the latter obtained through archaeological excavations. Circles refer to deformed buildings (A to F) and rectangles to faults seen at excavations (1 to 5). Fault traces drawn in the urban area hypothetically link fault outcrops and deformed buildings. Unit names as in Sanz de Galdeano *et al.* (2012) and García-Mondéjar *et al.* (2014a).

lar to the city slope. Second, there are many buildings with the SE parts of their NW-SE oriented facades rotated to the NE, compatible with the left-lateral movement attributed to AMF in Lorca. In fact, nearly all significantly deformed buildings in Lorca -with bent facades- are oriented NW-SE. Finally, there are several faults with NE-SW orientations exposed by excavations close to significantly deformed houses, and these latter form tracks that hypothetically can be correlated with the faults.

To account for the expressed difference in slip rates, we mention again the split of the AMF in Lorca into several faults. As it is represented in figures 1 and 11, the AMF fault traces are distributed in a band that narrows towards the NE. It is 1000 m wide 2 km to the SW of Lorca, 500 m wide in the Calvario area, 400 m wide in Las Palas, and 170 m wide in San Vicente. We defend that left-lateral movement with a compressive component in that tectonic band can tear off slices in the uppermost crust. Once these slices are freed from their roots, they hypothetically can move laterally at different speeds than their supporting plate, for instance when shaken by earthquakes.

There is another argument that can account for the high lateral displacement rates deduced from deformed buildings and for their variability. Each deformed building shows clear features of rotation around a vertical axis. Rotation of small blocks has been described in many areas subjected to strike-slip, especially where shear is distributed. The blocks range in size from metres to kilometres. Rotation explains variable slip rates of blocks, along with many other features. However, it requires a detachment surface at depth (*e.g.,* Nicholson *et al.*, 1986). Rotation also implies secondary transverse faults with strike-slip that in Lorca would be right-lateral (the master fault, AMF, is left-lateral). We have found minor examples of dextral faults in an excavation site near the Alburquerque House, with N303°E orientation, 70°N dip and small horizontal throws (0.5 m).

Owing to the narrow crustal slices delimited by the suggested fault traces in Lorca city, that range from 40 to 200 m, we can hypothesize that blocks able to rotate would have very shallow detachment surfaces at depth.

The proposed subdivision of the AMF into several strands under the urban base ground of Lorca, represents the NE convergent end of a strike-slip contractional duplex, in the meaning of Woodcock and Fisher (1986) (previously reported in Sanz de Galdeano *et al.*, 2012 and García-Mondéjar *et al.*, 2014a). In the Betic basement to the SW of Lorca up to seven fault traces of the AMF line were distinguished, with orientations ranging from N035ºE to N064ºE; other subordinate faults were oriented N020ºE to N028ºE (Calvario area, Fig. 11). The appearance of this subdivided wedge structure was attributed to a change in direction of the master fault, which in Lorca urban area was from N050ºE in the SW to N060ºE in the NE. This fault bend explains the reverse component of near all split branches as the faults in Lorca are not always vertical, but frequently obtain dips that characterize them as reverse in addition to strike-slip.

The contractional duplex model applied to the AMF splitting in Lorca can explain at least some of the building rotations at surface. As reported before, the duplex is attributed to a restraining bend in the fault trace (Fig. 1). More precisely the city lies on a splay of small faults in the NE end of the duplex. As it is shown in figures 1 and 11, the faults are curved and their orientations tend to shift to the N in their NE parts. For example, the interpreted trace of Las Palas fault changes direction from N064ºE to N057ºE and N038ºE (from SW to NE, Fig. 11). Therefore, the NE faults of the duplex tend to converge northeastwards.

If we imagine the duplex faults with inward-dipping geometry, *i.e.,* converging at depth into a single shear zone (push-up model proposed by Woodcock and Fisher, 1986), then movement in the underground towards the NW by converging plates (*e.g.,* Echeverria *et al.*, 2012) would develop variable rates of horizontal movement towards the NE in different split faults. These rates would be conditioned by the local characteristics of each fault (orientation, dip, materials in contact, locked or unlocked stage, presence or absence of detachment surface at depth, convergence or relay with other faults), and would determine different amounts of lateral escape or block rotation at surface. Therefore, different old buildings lying on the same fault trace do not necessarily have to present equal deformation, as each building responds to the local characteristics of the underlying fault, or rotating block, in the time considered.

A mention to moving plates is introduced here. If we consider the values of McClusky *et al.* (2003) indicating movement of Africa towards Europe at 4.5-5.6 mm/yr, there is an apparent incongruence with the values obtained from building deformations in Lorca. But probably this incongruence is only apparent because the plate convergence is in SE-NW direction, and the described deformations presumably correspond to lateral escapes and rotations, whose values are not strictly limited by the cited value of 4.5-5.6 mm/yr.

To end the discussion we make a commentary to local seismicity. Although the historical seismicity in Lorca refers to earthquakes of smaller magnitude than those deduced from palaeoseismicity, data from the Álamo fault motion during historic times in association with Las Palas fault, proposed in this paper for the last 0.3 ky and in other article for prehistoric times (work in progress), suggest that the historical earthquake phase can be considered a part of the late Holocene palaeoseismic period of the central AMF. This period is defined by the 2.8 - 3.8 ka Event Z and 1.5 - 2.2 ka Event 1, reported by Ortuño *et al.* (2012, their Fig. 7B) and Martínez-Díaz *et al.* (2012). The inference obtained from the exposed data in this paper about high rates of slip movement, even though at superficial levels, is that presently (last 0.5 kyr) we may remain in the course of a relatively intense seismic period of the AMF in the Lorca segment, but perhaps with fault stress dissipation in part through aseismic movement of the faults or through frequent low-grade seismic movements.

Conclusions

1. The study of old buildings in Lorca from the XVI-XX centuries showed many NW-SE oriented facades vertically bent, with deformation diminishing from the ground floor to

the upper storeys. Six of the buildings present horizontal deflections ranging from 1.3º to 6.03º, compatible with the left-lateral character of the AMF. Maximum rotation rates of building facades oscillate between 0.006°/yr and 0.024°/yr, for the last two-three centuries.

2. Geological outcrops exposed after archaeological excavations in the urban area discovered four faults oriented NE-SW and one tectonic structure common in strike-slip areas ("bench", a kind of ledge between a buried fault and a fault scarp). They show features of reverse and reverse oblique slip.

3. Hypothetical prolongation of the faults visible at excavations coincides with tracks of significantly deformed buildings, and they can be related with faults outcropping to the SW of the city.

4. Strike-slip rates were calculated for the different faults in Lorca. Their maximum values range from 0.93 mm/yr (Palmera de Uceta, last two centuries) through 1.87 mm/yr (Álamo-Las Palas, last three centuries), to 5.9 mm/yr (Alburquerque, last three centuries). The higher of these values exceeds up to six times other values proposed from outcrops of the AMF to the NE of Lorca for the last 15-22 kyr. All of them exceed present-day estimations obtained from GPS values.

5. An explanation of the discrepancy between slip rates of faults obtained in Lorca and in outcrops to the NE of the city, or from GPS measurements, is based on a strike-slip contractional duplex model applied to the AMF in the urban area. A tectonized band with possible torn off slices and detachments at depth in Lorca, can determine left-lateral escape or block rotation movement rates bigger than those calculated from geology to the NE of the city, or from plate convergence between Africa and Europe.

6. The progressive deformations observed in numerous old buildings of Lorca that cannot be attributed to sudden and destructive displacements provoking earthquakes, suggest that part of the movements of the AMF in the city can be considered aseismic, or low-grade seismic, perhaps owing to shear distribution in the urban area. However high deformation rates in some buildings and big historical earthquakes also support maintenance of the late Holocene palaeoseismic period of Lorca described from geology.

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