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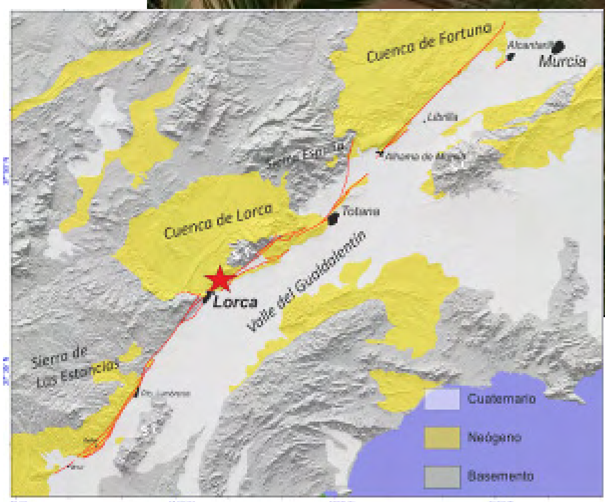
GEOLOGICAL PRELIMINARY FIELD REPORT OF THE LORCA EARTHQUAKE (5.1 M_w, 11TH MAY 2011)

Translation from the original report in Spanish



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1. Motivation of this report and Acknowledgments

On the occasion of the occurrence of a catastrophic low-sized earthquake in Lorca (Mw 5.1) (Southeast Spain) on May 11, 2011 at 18:47 (local time), we present a preliminary geological quick report. This report includes a description of the first geological data related to the possible geologic source of the earthquake, the seismotectonic characteristics of the seismic series, and the earthquake effects, related to the damage of buildings and the surface geological effects. A few hours after the event, a group of specialists in earthquake geology from different institutions: Geological Survey of Spain (IGME), Group of Active Tectonics, Paleoseismicity and related risk (UCM), Universidad Autónoma de Madrid (UAM) and the Universidad Rey Juan Carlos de Madrid (URJC), travelled to the epicentral area in order to compile all available field data related with ground effects associated with rupture and shaking, and damage of buildings as well. Besides, we have used instrumental data recorded from the IGN (Instituto Geográfico Nacional) and geological data from previous studies. The results and interpretations presented here are preliminary and they respond to the analysis of the preliminary evidence.

We thank the National Seismic Network (*Instituto Geografico Nacional*), for providing us the instrumental seismic data presented in this report, especially to Emilio Carreño and Juan Rueda for the focal mechanism solutions of the major events, and to Resurrection Anton for providing the detailed parameters of the events.

2. Seismotectonic characterization of the seismic series of Lorca and geological analysis of the earthquake source.

José J. Martínez Díaz (UCM)
José A. Álvarez Gómez (IH Cantabria – UCM)

2.1. Seismotectonic characterization of the seismic series of Lorca and its major events, M_W 4.5 and M_W 5.1 of 11/05/2011.

We present an initial characterization of the seismic series began on May 11, 2011 to the May 17, 2011; with the seismic data of the National Geographical Institute. A preliminary interpretation of the relationship with the tectonics of the area is done.

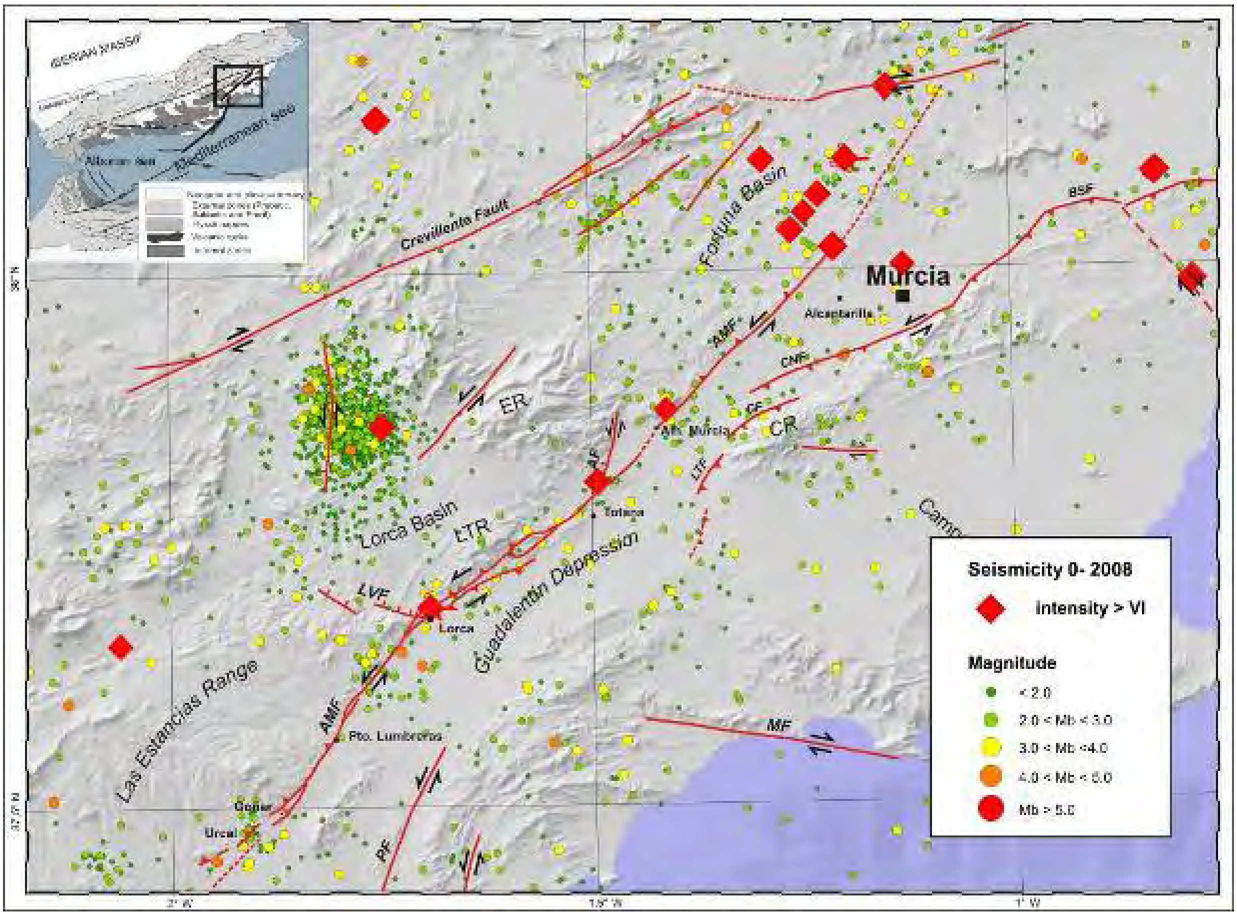

Figure 2.1: Map of seismicity in the area until the year 2008. The red diamonds indicate the position of destructive historical earthquakes. The circles show the epicenters of earthquakes with the color depending on the magnitude of the event. The red lines show the traces of major active faults..

Map of seismicity in the area until the year 2008. The red diamonds indicate the position of destructive historical earthquakes. The circles show the epicentres of earthquakes with the colour depending on the magnitude of the event. The red lines show the traces of major active faults.

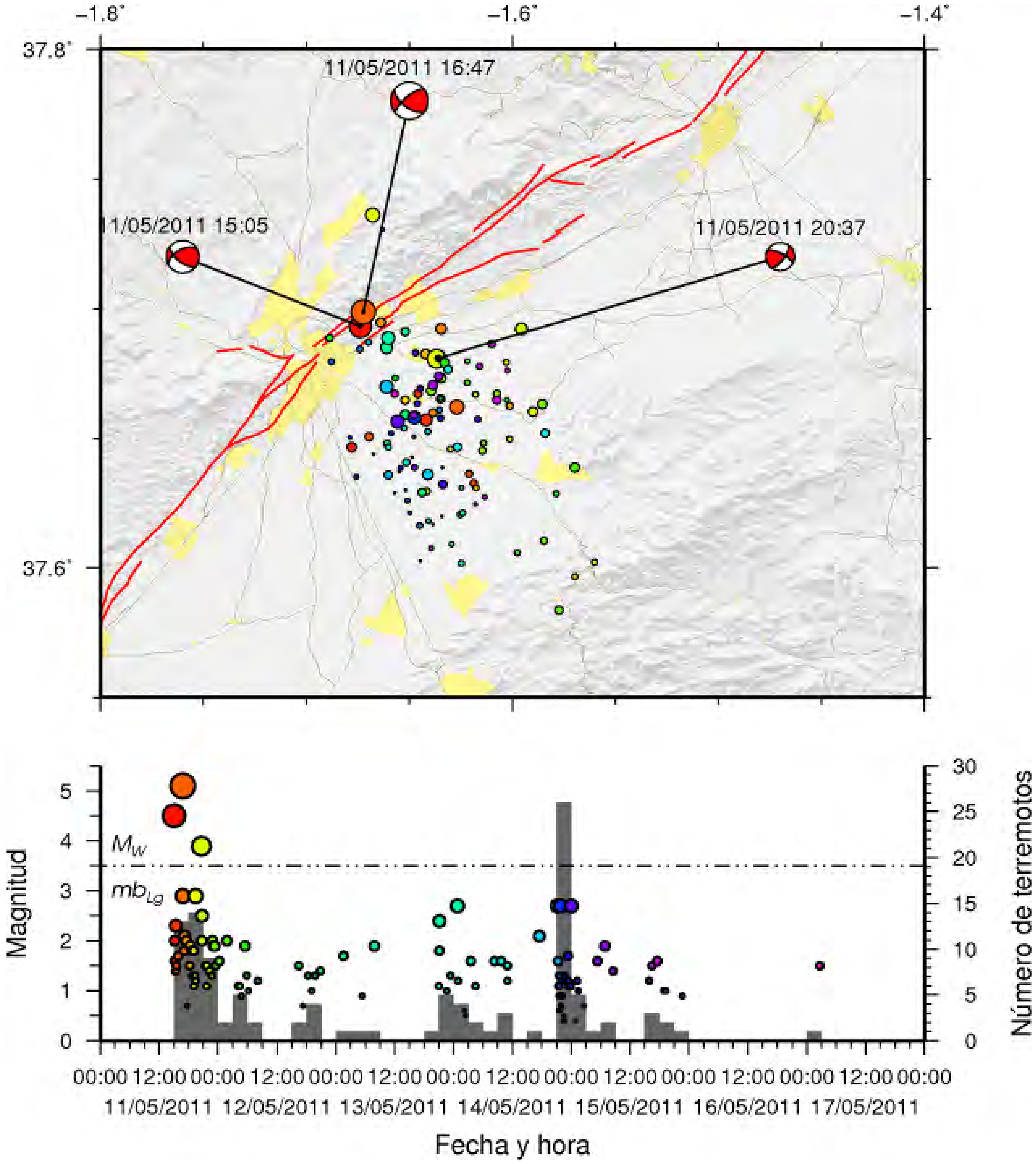

Figure 2.2. Map showing the seismic series. The size of the circles is proportional to the magnitude of the event. The colour is a function of its position in the series as shown in the bottom graph of temporal evolution. Focal mechanisms of major events show the characteristics of movement of the rupture, in this case are left-lateral strike-slip faults with reverse component. In red line the traces of the main active structures are shown. The chart below shows the time evolution of the series. Circles represent each event with size proportional to the magnitude (left Y axis), its colour is a function of position in the series. The gray bars show the number of events in intervals of 3 hours. Notably the peak of activity on the night of 14 to 15 May. The dashed line shows the threshold at which the magnitudes are expressed as MW instead of as mbLg.

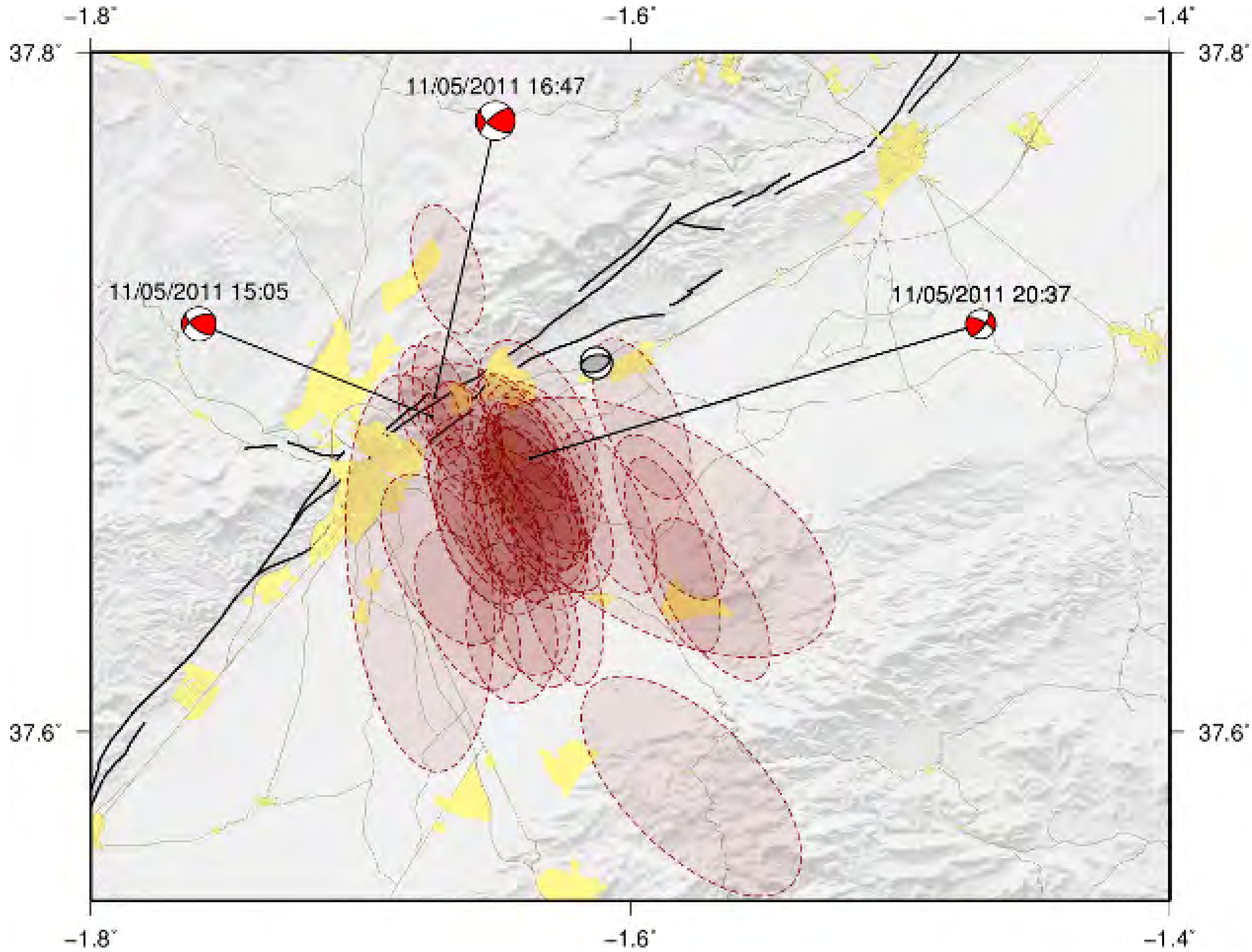

Figure 2.3. Map of error ellipses on the location of seismic events in the series with mbLg magnitude higher than 1.5. Focal mechanisms shaded in red correspond to the three main events of the series occurred on 11/05/2011, gray focal mechanism corresponds to an event occurred on 08/03/2006.

We have also conducted a preliminary analysis of Coulomb stress transfer. This methodology looks at the degree of influence of an earthquake rupture on the surrounding faults. Depending on the direction of the fault and its position with respect to the earthquake-generating fault, these surrounding faults can be increased in their likelihood of rupture (of generating an earthquake) or decreased. Figures 2.4 and 2.5 show these tests. The red colours imply a positive change in Coulomb stress, and it could be interpreted as an increasing of the probability of occurrence of another event in these areas. Blue colours in contrast show areas where the stress has fallen so that lowers the probability of occurrence of earthquakes. However, we must bear in mind that these calculations are done on determined fault planes and that increased stress in one fault plane, for example, N-S, does not preclude that other fault planes, eg E-W, may show a decrease of stress.

In Figure 2.4 we show the calculated stress changes produced by the main earthquake of magnitude 5.1 MW assuming a rupture with NE-SW direction, calculated on fault planes with the same strike and dip, ie the type of FAM plane. In Figure 2.5 we show the same calculation but assuming the plane NW-SE as the responsible of the earthquake. Regardless of which of the two planes has caused the event, the Coulomb stress change on the fault plane of the FAM is practically the same. There are two lobes of increased stress on the ends of the segments Puerto Lumbreras - Lorca (south) and Lorca - Totana (north) and two orthogonal lobes. On the southern lobe of the latter is being developed the series of aftershocks. The two lobes of increased stress on the two segments of the FAM implies that the probability of generating a new event in this fault has increased. These results should be refined once the rupture is better defined.

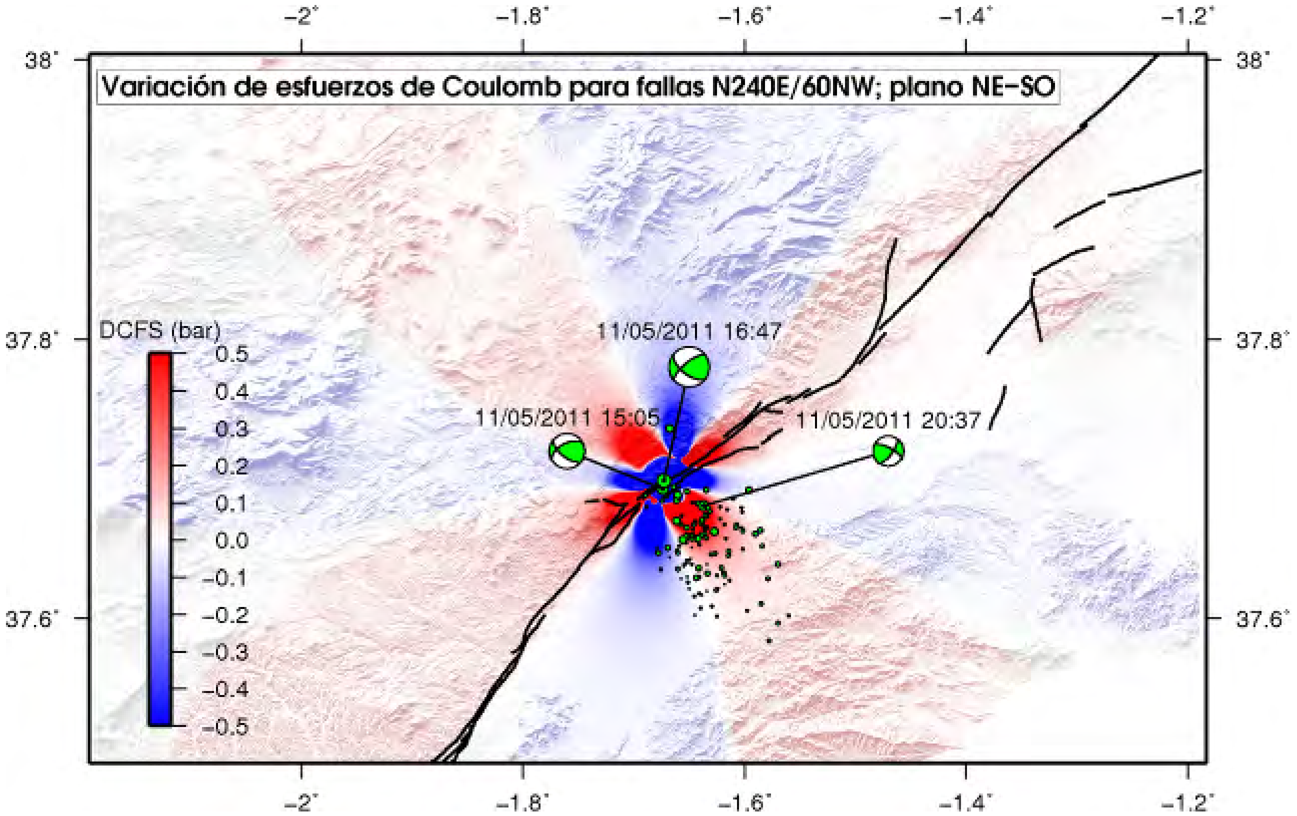

Figure 2.4. Map of Coulomb stress variation on NE-SW fault planes (type FAM) generated by the NE-SW plane of the focal mechanism of the main event of the series. The colours indicate the variation of stress (shown in colour scale). The red colours indicate an increased likelihood of generating new events.

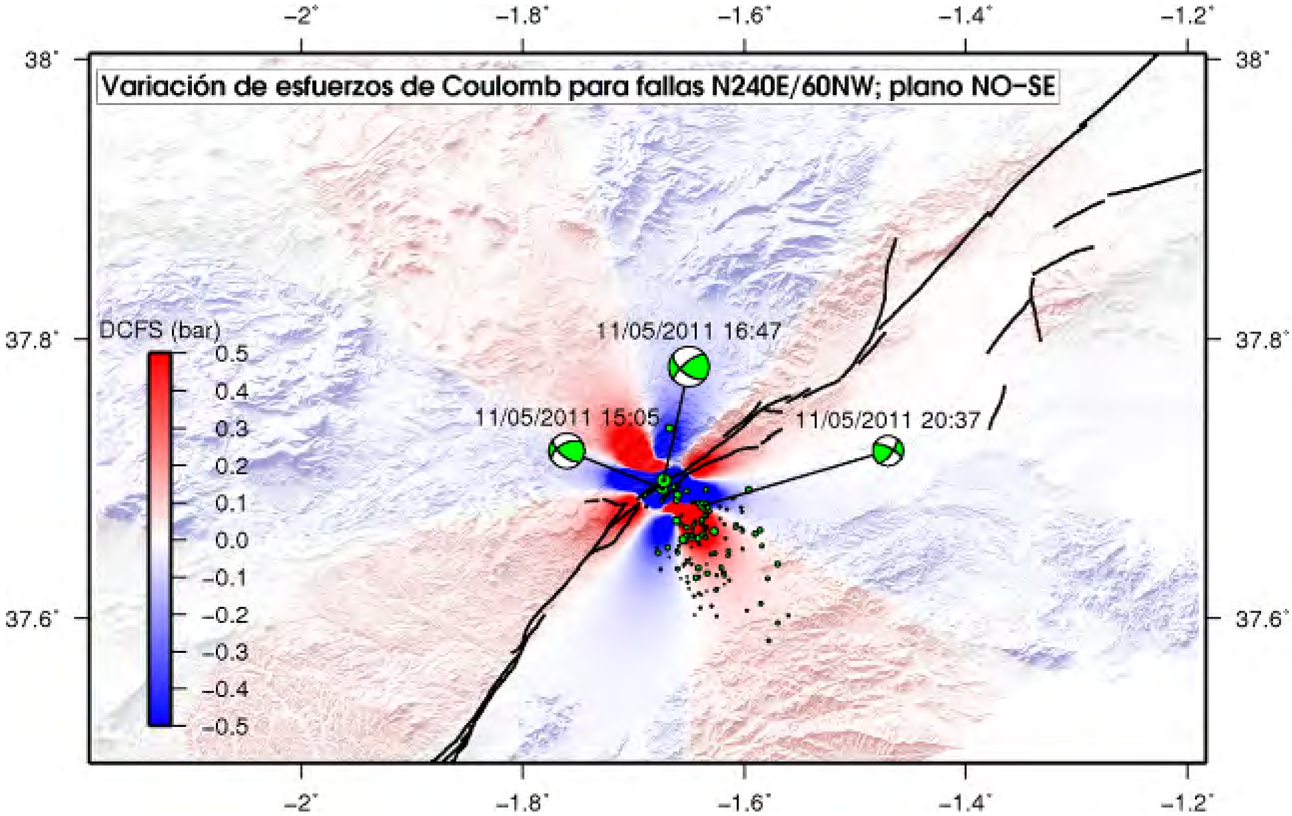

Figure 2.5. Map of Coulomb stress variation on NE-SW fault planes (type FAM) generated by the NW-SE plane of the focal mechanism of the main event of the series. The colours indicate the variation of stress (shown in colour scale). The red colours indicate an increased likelihood of generating new events.

2.2. Analysis of the geological source of the earthquake: "The Alhama de Murcia Fault?

The position of the epicentres of the Mw 5.1 main shock and the Mw 4.5 foreshock is spatially consistent with the location of the Alhama de Murcia (FAM) fault trace 2 km northeast the city of Lorca (Figure 2.6). The FAM was first described by Bousquet et al. (1979) and it was the subject of a number of structural, seismotectonic and paleoseismic analysis and works showing its quaternary activity and high seismogenic potential (Silva et al., 1997; Martínez-Díaz, 1998; Martínez-Díaz et al., 2003; Masana et al., 2004). The FAM is oblique-slip sinistral strike slip fault with a reverse component (Martínez-Díaz 2002). It extends along the north-western flank of the Guadalentín depression, from Alcantarilla to Goñar, reaching a total length of at least 85 km. The fault is structured in several segments with variations in strike and degree of complexity along the fault (Figure 2.7).

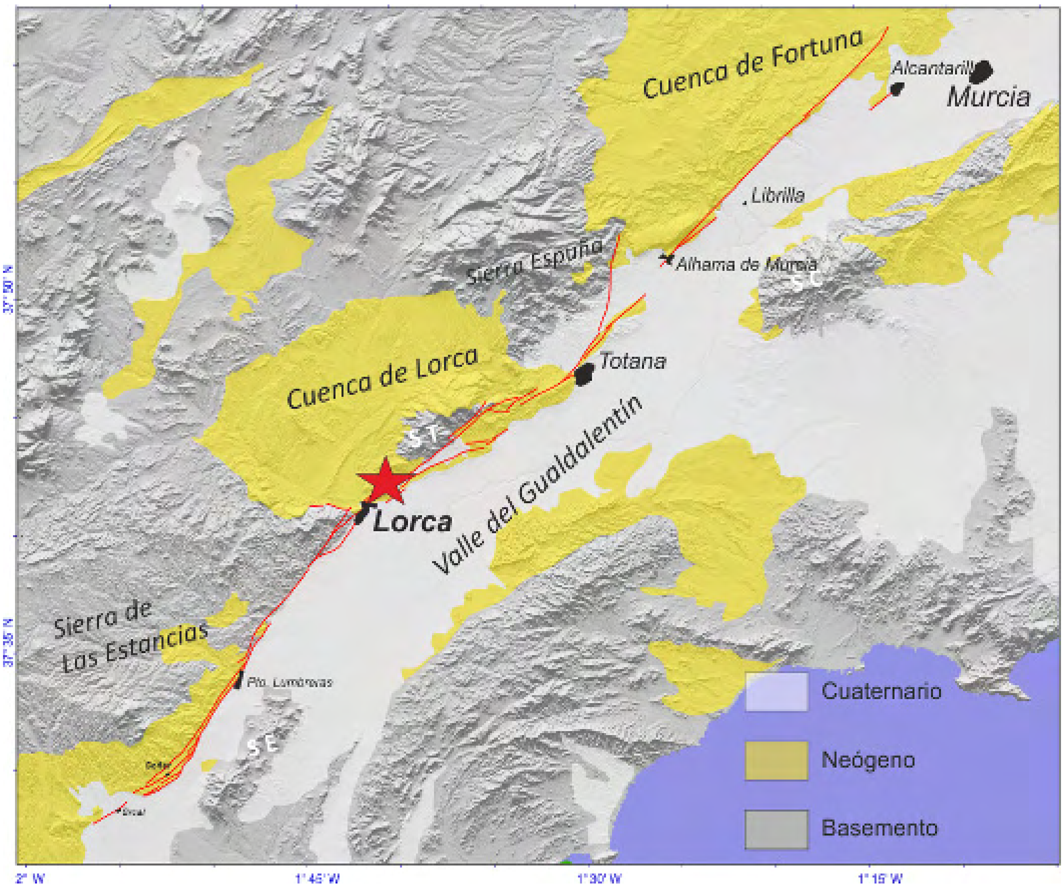

Figure 2.6: Map of the fault trace of the Alhama de Murcia Fault. The star indicates the position of the epicenter of the Mw 5.1 mainshock.

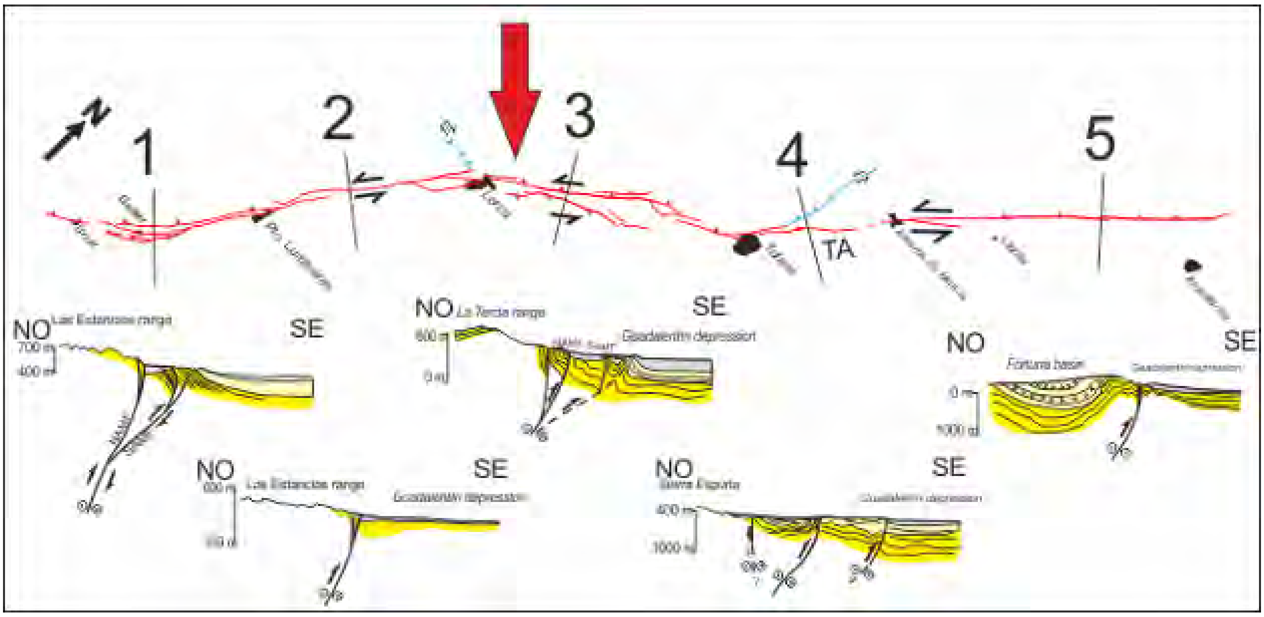

Figure 2.7: Structure of the Alhama de Murcia fault taken from Martínez-Díaz et al. (2010). The red arrow marks the position of the epicentre of the Lorca Mw 5.1 earthquake that is located at the western tip of the Lorca-Totana segment. In the lower part we show the cross section structure of the fault interpreted from surface geological data.

Focusing on the epicentral area the position of the larger events seem to be related to an area where the FAM has a rather complex structure (Figure 2.8), with two main branches with opposite dip: The Northern Lorca Corridor dipping to the NW and the South Lorca Corridor dipping to the SE. The uncertainty ellipse of the epicentre location calculated by the National Geographic Institute indicate that they could be related to either of the two branches, although it seems more likely the location associated with the Northern Corridor. This corridor consists of a compressional strike-slip duplex structure formed with two parallel branches one of which run to the SW below the town of Lorca and the other pass along the NW flank of the Castle of Lorca hill (see Figure 2.9). In any case the structure of the fault as it passes through Lorca is quite complex. It undergoes a slight change of direction and could have several active branches in the underground of the town. The geometry and kinematics of one of the two planes of the two focal mechanisms (plane NE-SW high dipping to the NW) is coherent with the two faults that form the duplex, since they present a sinistral strike-slip movement with reverse component during the Quaternary, also consistent with the plane solutions.

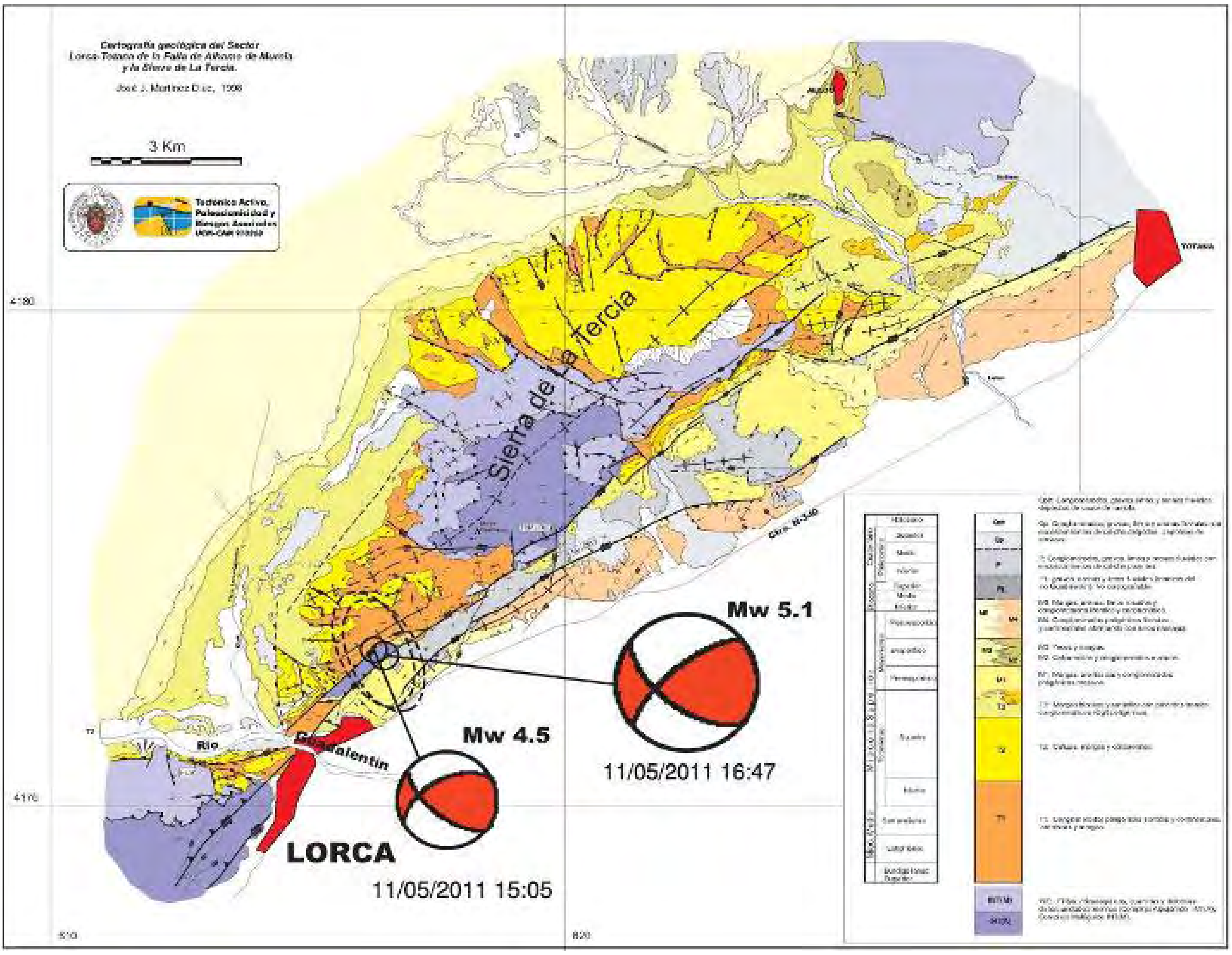

Figure 2.8: Geological map of the Lorca-Totana sector of the Alhama de Murcia fault with the epicentres of the two major earthquakes and the focal mechanisms calculated by the Instituto Geografico Nacional. Geological mapping is taken from Martínez-Díaz (1998).

Figure 2.9: Panoramic view of Lorca taken from the epicentral area. The red traces show the position of the main branches of the FAM. The two faults that go towards the city bound the duplex structure formed by a block of basement rocks uplifted under a transpressional regime and flanked by Miocene sedimentary rocks.

Uncertainties in the interpretation of the earthquake source

While the analysis of the surface geology and the position of the epicentres clearly point to the FAM as responsible for destructive earthquake, the position of most of the aftershocks located to the SE of the mainshock, into the Guadalentin valley, would not fit with this interpretation. One possible explanation is that the aftershocks respond to the reactivation of minor faults located within the valley away from the FAM and triggered by the mainshock. In this case no aftershocks are being producing around the rupture zone in the FAM. Another possibility is the existence of a localization misfit due to the high uncertainty of the location of low magnitude aftershocks using the regional seismic network. A third possibility is that the fault responsible is not the FAM but an unknown NW-SE, crossing from the epicentre to the valley. The higher number of seismic observations of the mainshock, coherent with the smaller size of error ellipses, makes less probable this third possibility. In any case it is necessary to carry out a relocation of the aftershocks and mainshocks hypocenters in order to make a definitive interpretation.

3. Geological searching of the epicentral area and the Alhama de Murcia Fault (FAM)

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J.García Mayordomo (IGME)
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The shallow hypocentral depth (2 km) calculated by the Instituto Geografico Nacional for this destructive earthquake of magnitude Mw 5.1, which is consistent with the high intensity of the damage, increases the chances of rupture along the Alhama de Murcia Fault had reached the surface. Given the magnitude of the earthquake a hypothetical surface rupture should not exceed a few centimetres. We carried out a field survey in the epicentral area and along trace of the FAM during the three days following the earthquake, paying special attention to structures and man-made elements as roads, tracks or concrete fences where it could be possible to observe fractures with centimetric displacements associated with the rupture on the fault. We present in this chapter a summary of this field reconnaissance.

In the village of Lorca we walked along the Guadalentín river banks where the FAM crosses the river. In this are the river course is flanked by two masonry walls more than 6 m high and a concrete channel passing through the city (Fig. 3.1). The orientation of the walls is N113° E in the western section and N140 ° E in the eastern part. The walk was 600 m long on both margins and no evidences of ground breaking associated with fault displacement were found. The numerous cracks present on the walls do not show movements throughout the wall, and they not have continuity in the bed of the valley. It is noteworthy that the north wall (Fig. 3.2) has more cracks and pill offs than the southern wall that is only affected by several cracks.

Figure 3.1. Masonry wall along Guadalentín river bank passing through Lorca, used as a marker.

Figure 3.2. Northern Wall of the Guadalentin river valley.

In the epicentral area located by the IGN 2 km NNE of Lorca a field reconnaissance was done along the Alhama de Murcia fault traces following the two branches: the South and North Corridors. We walked the old military camp of Carraclaca (37 ° 41'54 "N, 1 ° 40'7" W) very close to the epicentre, following a 160 m long concrete fence oriented N 120° that completely crosses the fault line of the southern branch of the strike slip duplex structure described above (Fig 3.3). The wall is intact without rupture associated with a displacement of the fault. Similarly, we walked the area at coordinates (37 ° 41'42 "N 1 ° 40'49" W) to the west of the epicentre calculated by IGN, along several tracks, and the Las Canales Creek that crosses the faults forming the duplex structure. There has been observed clear evidences of surface deformations associated with the fault.

Also, we have measured temperatures in hot-springs associated to the FAM fault. Namely we have measured temperature of thermal water in the Carraclaca thermal baths. The average temperature of the water is 21 ºC and temperature obtained a thermocouple device was 21.5ºC. Taking into account the accuracy of the thermocouple (0.2ºC) and the resolution (0.1ºC) , we think that the variation is not relevant for a hot-water upwelling, even more if we consider that the thermal baths are located very close to the epicentre (1 km approximately) and the earthquake was very shallow.

Figure 3.3. Concrete fence basement used as a marker to look for deformation along the fault line of the FAM.

Finally, there has been a journey along the highway A-7 that located to the west of the epicenter and is crossed by the FAM. We observed some small NE-SW cracks on the road produced by the earthquake, but they do not present lateral continuity. Some observation was made in the tunnel and viaduct of the A-7 that passes through the FAM NW of Lorca, no tectonic deformations are observed in the infrastructure.

The preliminary observations and the field reconnaissance of the fault line of the Alhama de Murcia Fault, suggest that the low magnitude of the earthquake has no generated a surface rupture associated. However, if an aftershock relocation of epicenters points to a NW-SE fault plane as the possible seismic source, a new field reconnaissance along the Guadalentín valley would be necessary.

4. Ground instabilities produced by the 11th May 2011 Lorca earthquakes

Julián García Mayordomo (IGME)
Martín Jesús Rodríguez Peces (UCM)
Juan Miguel Insua Arévalo (UCM)

A summary of the field survey carried out from the evening of Thursday 12th to the afternoon of Saturday 14th May, 2011.

The 11 May 2011 seismic series has generated a number of slope instabilities. In general these are of a small size and distribute in a localized area. However, this assertion has yet to be contrasted with aerial imaginary taken after the main shocks.

The ground instabilities produced by the earthquakes are basically rock-falls of very different size (from mere bare patch to debris flows), single rock-falls and collapses of sections of the external wall of Lorca's castle.

Few of the instabilities produced by the earthquake can be referred as significative in the sense that they have produced some damage in buildings and temporal road-cuts.

In particular, at the easternmost point of Lorca's Castle cliff, a fallen rock-block has destroyed part of the wall enclosing the patio of a house. Alike, on the road up-the-hill to the castle few rock-falls have badly damaged the pavement. A similar situation has taken place on the road to the Pantano de Puentes, which was temporarily closed to traffic. It is remarkable that on Friday 13th (aprox 24 h after the earthquake) both situations were already solved and driving was possible with relative normality.

It is highlighted that the stability measures deployed on the southern slope of the castle cliff have performed adequately, avoiding what it would have been an aggravation of the damage produced by the earthquake and may be a larger number of casualties, particularly on the habitations located right under the cliff. A quick visual inspection suggested the perfect state of the measures, although this observation should be confirmed after a systematic and detailed inspection.

Finally, it is convenient to notice two important previous works done by IGME in Lorca:

- Seismic Hazard and Vulnerability of Lorca and its Municipal District (1992). *(In Spanish).*
- Rock-fall risks in the Castle cliff of Lorca (Murcia) (1988). *(In Spanish)*

It follows a brief photographic report of the instabilities mentioned above, classified by its location (viewpoints are shown in figure 4.1):

- North face of Lorca's castle cliff (Figure 4.2.0 and following).
- South face of Lorca's castle cliff (Figure 2.3.0 and following).
- North slope of the Pantano de Puentes road (Figure 4.4.0 and following).
- Additional pictures (Figure 4.5 and onwards).

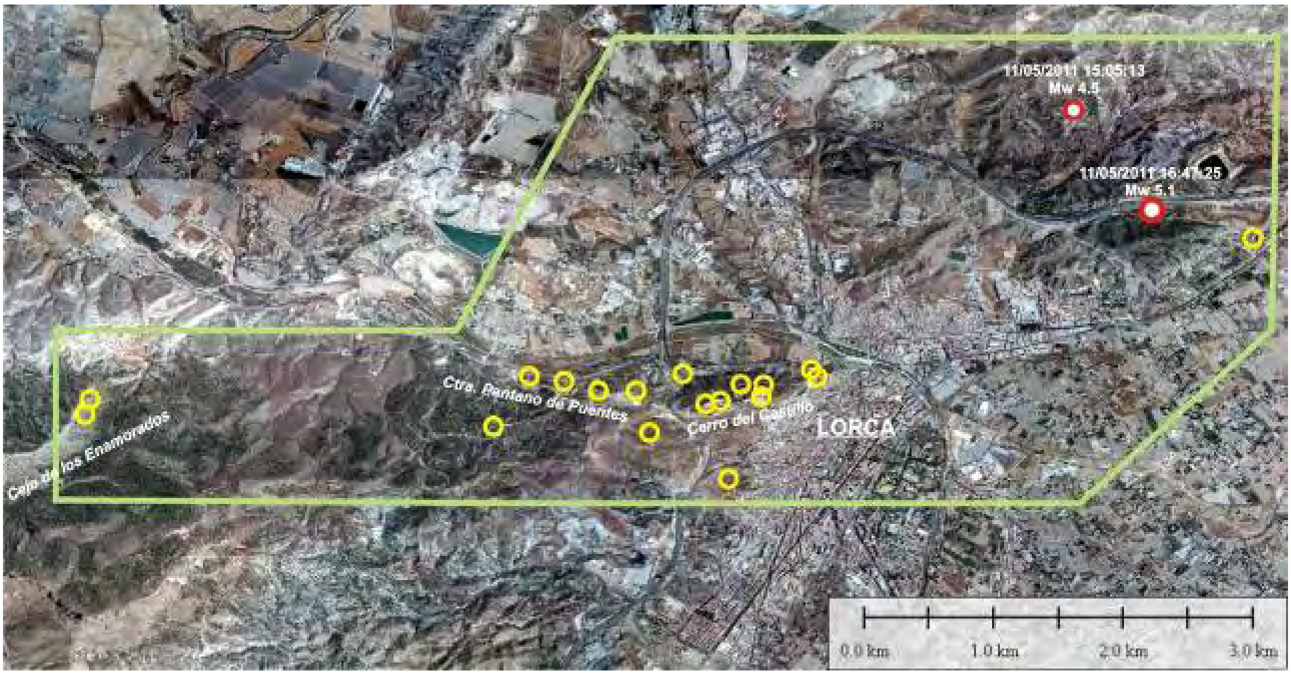

Figure 4.1: Situation of the main slope instabilities identified in the field survey.

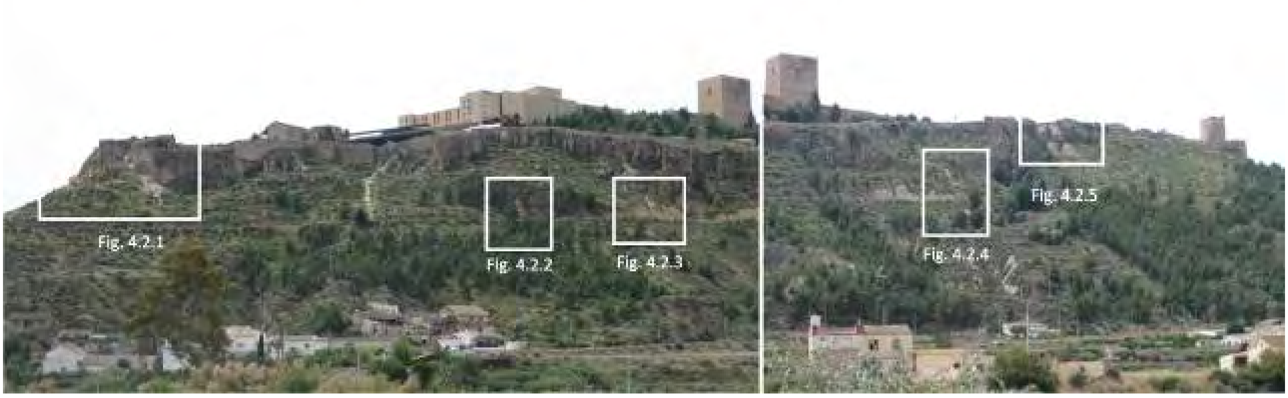

Figure 4.2.0: General view of the north slope of the Lorca's castle cliff. The most remarkable instabilities induced by the 11th May earthquake are identified.

Figure 4.2.1a: Partial collapse of the easternmost point of Lorca's castle cliff. A detached rock-block produced damage in a near house (see Fig. 4.2.1c). Picture on right corresponds to the same place few years back (taken from the IGME seismic hazard study of Lorca, 1992).

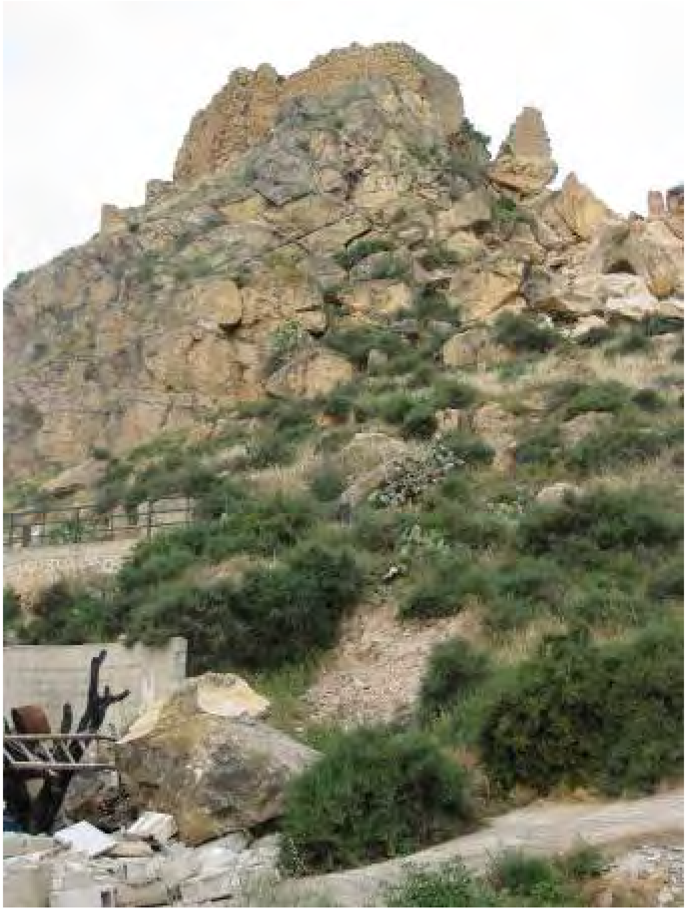

Figure 4.2.1b: View of south lateral of the easternmost point of the castle cliff and of the block that damaged a small wall of a house. The down-the-hill road pavement showed moderate damage at this point. It can be observed on the left the ending of the retaining wire mesh that stabilises the south face of the castle cliff.

Figure 4.2.1c: Result of the impact on a wall made of concrete blocks enclosing the patio of a house from a rock detached form the easternmost pint of the cliff.

Figura 4.2.1d: Moderate damage on the down-the-hill road caused by the rebound of the block detached from the easternmost point of the cliff (figure 1.b).

Figure 4.2.1e: Close-up of the collapse of the easternmost point of the castle cliff (looking South) and of the general conditions of the rock mass at this site. On the upper right corner it is observed part of a fallen wall (see figure 1.1f).

Figure 4.2.1f: Close up of the fall of part of an old retaining wall. It can be observed that the intrados filling remains meta-stable. This type of instability also appears on the south face of Lorca's castle cliff (see figure 2.1).

Figure 4.2.2: Small debris dragging a pine tree on the north talus of the up-the-hill road to the castle.

Figure 4.2.3: Rock-falls and debris on the up-the-hill road to the castle.

Figure 4.2.4a: Rock-fall of metric size that damaged badly the road (see figure 1.4b).

Figure 4.2.4b: Damage on the pavement of the up-the-hill road to the castle due to the fall and rebound of the block shown in figure 1.4a.

Figure 4.2.5: Collapse of the external wall of Lorca's castle (north face).

Figure 4.3.0: Partial views of the southern slope of Lorca's castle cliff. Photos are arranged from west to east, from left to right. Only two small size instabilities were identified: a small debris fall (photo number 2) and the collapse of the external wall of the castle (photo number 3 and fig. 4.3.1). On the last photo a visual of the easternmost point of the cliff is shown (figure 4.2.1). The stabilization measures of the rock mass performed adequately preventing the occurrence of more damage and personal losses. These consist in a double diameter wire mesh nailed to the rock mass by bolts and a dynamic barrier. These measures were put in place 3 years ago aprox. (pers. com. council).

Figura 4.3.1: Collapse of an old retaining wall attached to the external wall of the Lorca's castle on its south face. This instability warned the dwellers of the houses situated right under the cliff, which asked us whether it was safe to return back to their places.

Figure 4.4.1a: Rock-falls and debris on the summit of the north slopes of the Pantano de Puentes road. Their attribution to the earthquake is presumed. The westernmost one (on the right on the first photo) corresponds in part with a previous instability.

Figure 4.4.1b: Continuation of the Pantano de Puentes road towards the west. Along this road many instabilities were identified, although of a small size in general. Particularly remarkable are the rock blocks fallen from the ridge controlled by Las Viñas Fault (marked with an arrow). Picture on right shows a close-up of the damage produced by one of this rock blocks.

Figura 4.4.2: Rock-falls and rock-debris at the Cejo de los Enamorados.

Figure 4.5: Communications towers founded on a hill situated in front of the westernmost end of Lorca's castle cliff. Two recent instabilities are shown, which are attributed to the 11 May earthquakes.

Figure 4.6: View of the slope enclosing a butane-gas storage site on the Pantano de Puentes road. No slope instabilities that could be attributed to the earthquakes were identified here, although the collapse of the concrete-brick wall is attributed to them.

Figure 4.7: Irrigation pool situated nearby the epicentres of the 11 May earthquakes. Neither damage was observed in this area, nor instabilities on the talus on the background.

Figure 4.8: Rock falls on a dirt road that runs across the epicentral area (photo courtesy of J.J. Martínez-Díaz).

Figure 4.9: Shallow debris falls attributed to the May earthquakes on a service road of the Tajo-Segura canal.

5. 5. Study of the historical building damage within the village using structural geology techniques. Testing the Archaeoseismology methods

Jorge Luis Giner Robles (UAM)
Miguel Ángel Rodríguez Pascua (IGME)
Raúl Pérez López (IGME)
Fidel Martín-González (URJC)

The earthquake of Lorca (SE Spain) May 11th 2011 was responsible for a large amount of damage and seismic intensity on a wide range of buildings in the city of Lorca, including the historical buildings. The historical damaged buildings is observed not only in older buildings such as the portico of San Antonio, (whose origin is an ancient defensive wall of the XIIIth century), but in churches and monasteries around the cultural center Lorca. Aerial view shows a concentration of damage in the highest towers, mainly affecting the arches, buttresses canopies, bollards etc. Rotations also appear in decorative elements such as bollards and obelisks, like the obelisk in the San Francisco church.

According to the experience of ancient earthquakes happened worldwide, an earthquake of 5.1 magnitude should not have generated such a seismic intensity (VII EMS; www.ign.es). However, being shallow and the rupture spreads from the epicentral area to the southwest, we can assume that much of the rupture of the fault responsible of the earthquake was just below the village (assuming the FAM as the structure responsible). Moreover, alluvial continental deposits generated in the glacis of the Sierra de la Tercia and deposits of Guadalentín River have amplifying properties to for the seismic waves.

Lorca's earthquake has not produced widespread buildings collapses (only two buildings collapsed), during the inspection we have recognized, classified and described more than one hundred effects of the earthquake on buildings and structures described in the work of Giner-Robles et al., 2009 and 2011, Rodríguez-Pascua et al., 2011. These authors defined them as Archaeological Earthquake Effects, (commonly known as EAE). The analysis of these deformation structures in historic buildings is very important to identify and quantify historical earthquake damage in archaeological sites.

The EAE describe and quantify coseismic deformation in archaeological sites and historic buildings. After Giner-Robles et al., 2009 and 2011, Rodríguez-Pascua et al., 2011, they classify according to EAE: (1) permanent deformation of the surface (2) temporary deformation by the seismic ray during the earthquake.

The aim of this study is to correlate the different earthquakes damages in the historic town of Lorca described by EAEs type structures with the physical parameters of the earthquake and the geology and the seismotectonic models from previous chapters of this geological preliminary report. Moreover, in this preliminary work, we show deformations associated mainly to the anisotropy of the seismic ray. Thus, it is possible to determine the orientation of maximum horizontal compression (ey) that the city suffered during the main shock, which lasted about 5 seconds (Mw 5.1).

During the field work, carried out within the 72 hours after the main event, the deformation has been recognized mainly on the main historical buildings of the town of Lorca, such as churches, convents and cathedrals. The team was divided into two working groups in order to recognize all the damaged buildings and classified damages in a systematic way after Rodríguez-Pascua et al. 2011. Figure 5.1 shows the table of classification of EAE as proposed by these authors, with the keys used in the location map (Fig. 5.2).

The most relevant key of this archaeoseismic study is applied instrumental information of this earthquake to correlate the EAEs defined in historical earthquakes affecting archaeological sites with historical buildings and modern buildings. This information also can be correlated with seismic and geological parameters shown in this report, such as the magnitude and focal mechanism of earthquakes, the seismogenic fault and site effects due to the geology of Lorca.

The earthquake of Lorca is an ideal example to study deformation associated during an earthquake and to correlate the damages with the seismic intensity and parameters of the earthquake, such as magnitude, depth and geometry of the seismogenic fault. Hence, we can extrapolate these results of the Lorca earthquake (May 11th) to other studies of archaeological sites with near field effects. In this preliminary report we have collected and measured the main EAEs oriented in the convent of Clarisas (S. XVII), in the Church of San Juan (S. XV), in the Church of Santiago (S. XVIII), Santa Maria (S. XV), in the Church of San Francisco (S. XVII) and the Portico de San Antonio (S. XIII-S. XV). Moreover, similar structures have been described in modern buildings such as the collapse of the building in Las Viñas and other modern buildings. We also incorporate two new EAEs observed in field of buildings of Lorca.

All this preliminary information has been represented in a rose diagram (Figure 5.10), showing the main orientation in a NW-SE trend, N150º-160ºE. We interpret these direction NW-SE with azimuth from the SE. This suggests a direction of ey N150º-160º, which is coherent with the regional stress field, the focal mechanism of the earthquake (left lateral with reverse component) and the epicentral location in the *Sierra de la Tercia*.

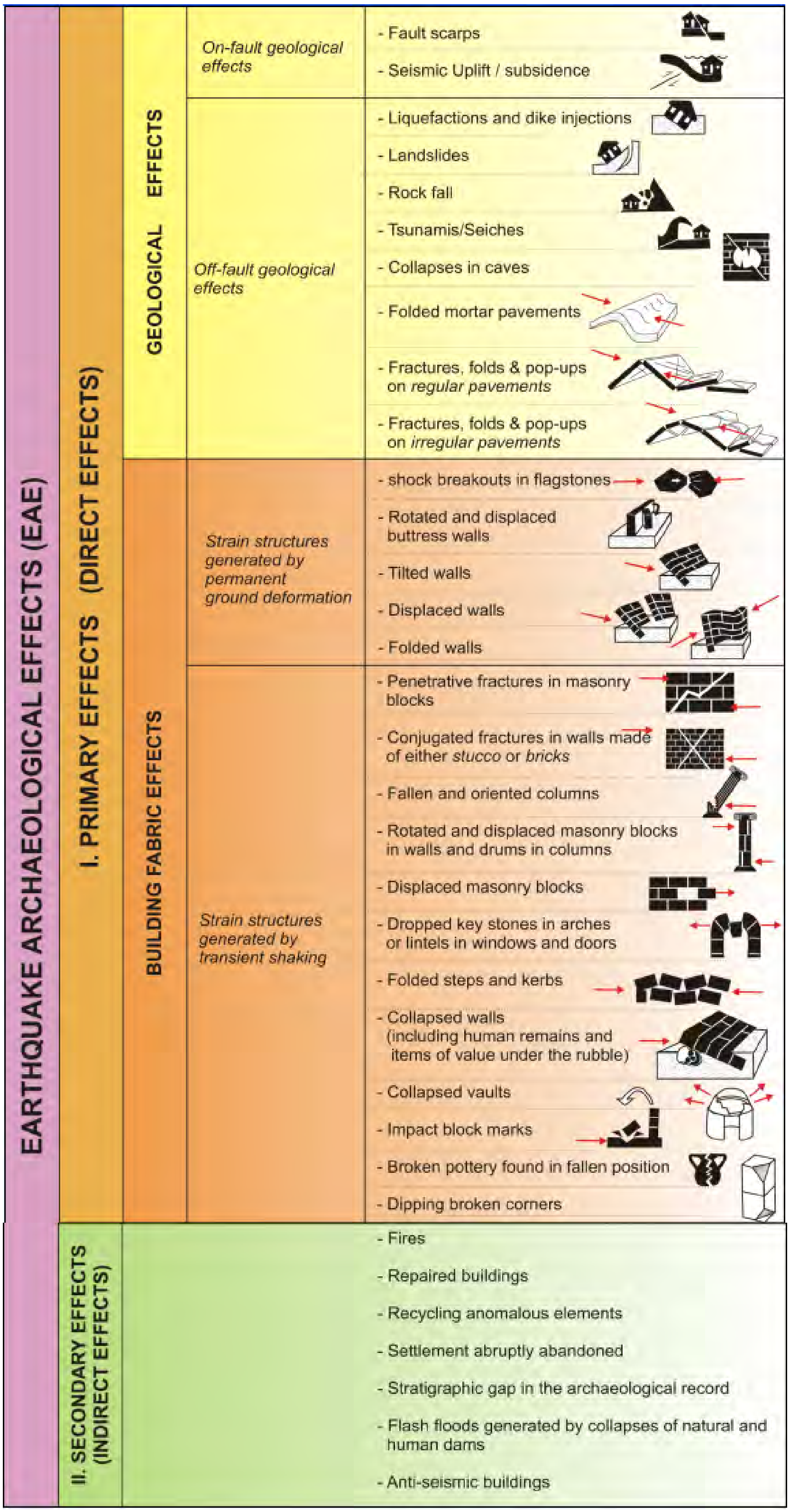

Figure 5.1: Classification table of the Earthquake Archaeological Effects (EAE) (Rodriguez-Pascua et al. 2011).

Figure 5.2 shows the map of the downtown area of Lorca, identifying the main EAEs recognized in this study. The symbols of the EAE are shown in Figure 5.1. The figures describe the main EAEs recognized and they have been created using the methodology of Giner-Robles et al., 2009.

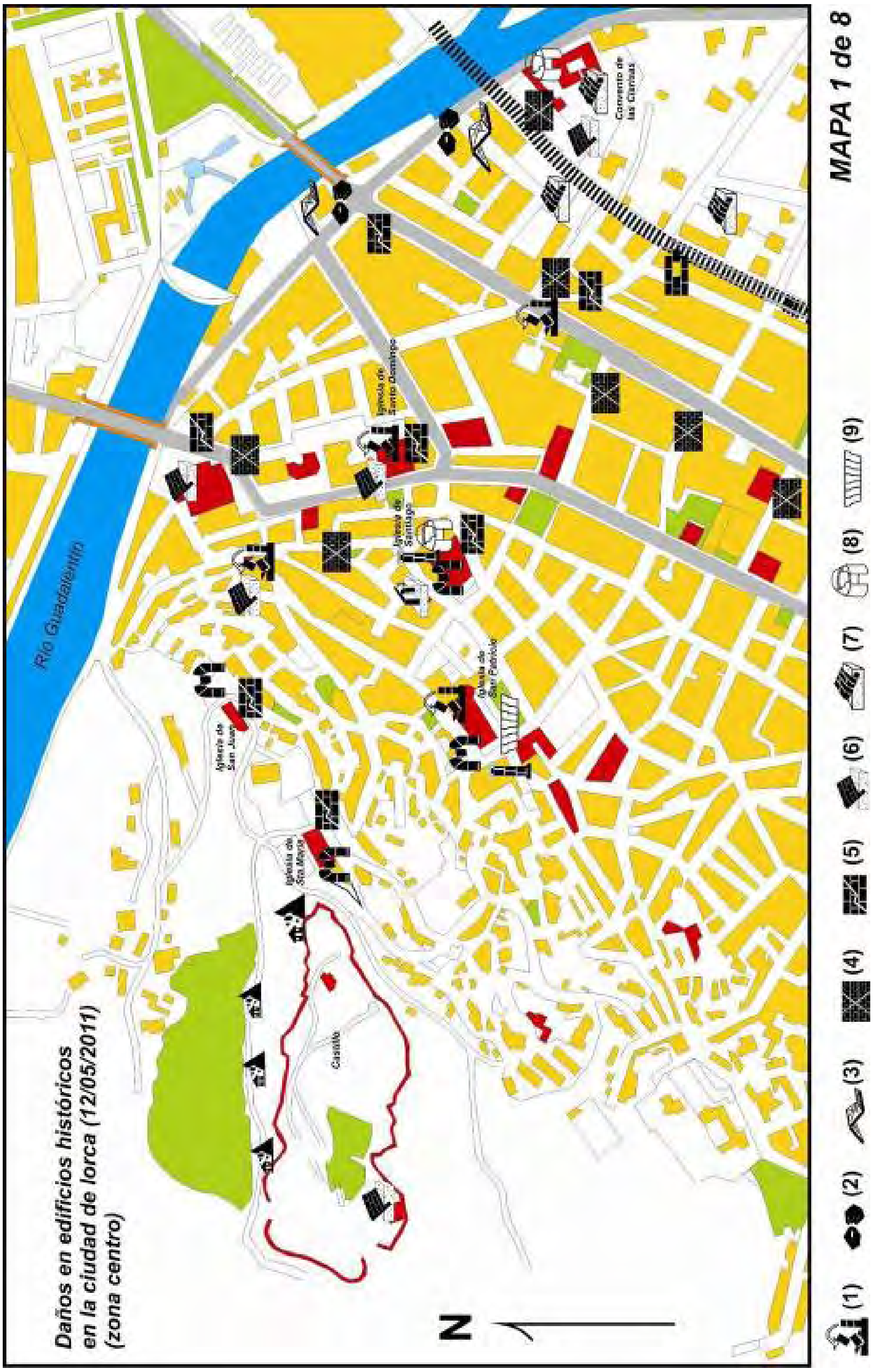

Figure 5.2: Map of downtown of Lorca, with the spatial distribution of the main EAEs classified during the field work after the earthquake. See figure 5.1 for further explanation of the symbols.

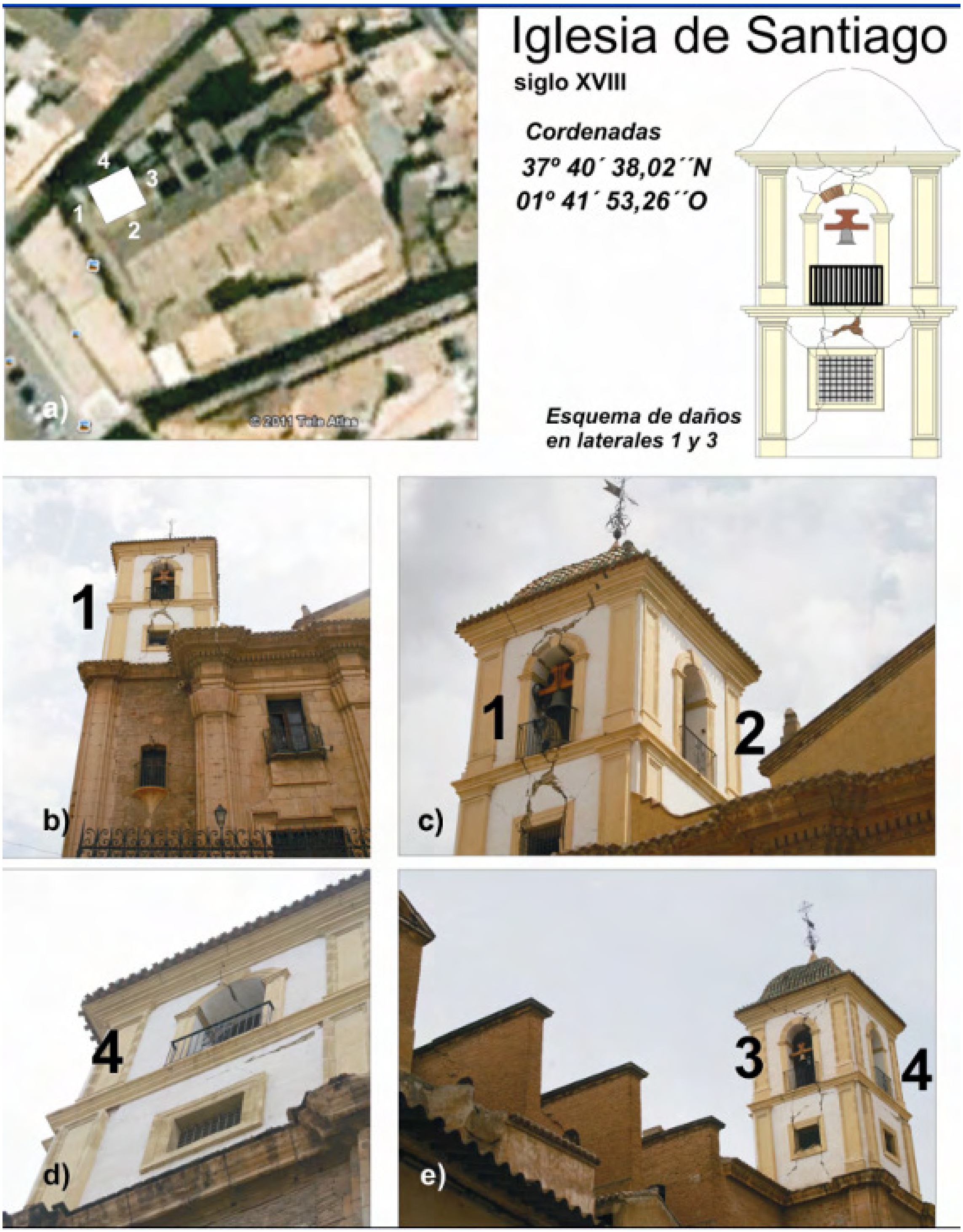

Figure 5.3: Damage in the church's tower of Santiago.

Figure 5.4: Damage in the battlements of the entrance of San Antonio (Tower of the old defensive wall of the Islamic Period).

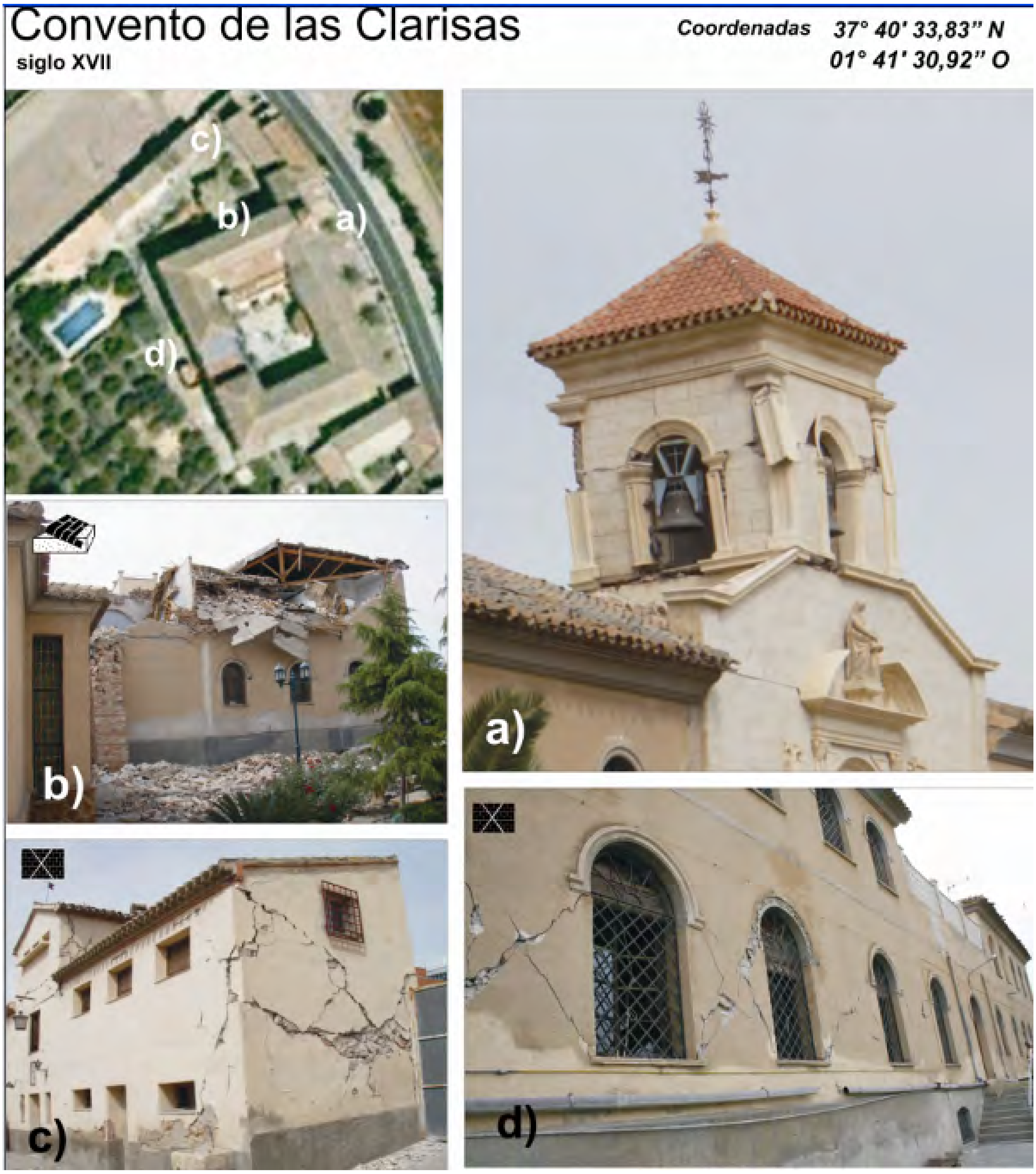

Figure 5.5: Damage in the tower and main buildings of the Clarisas´ Convent.

Figure 5.6: Damage in the San Francisco's Church.

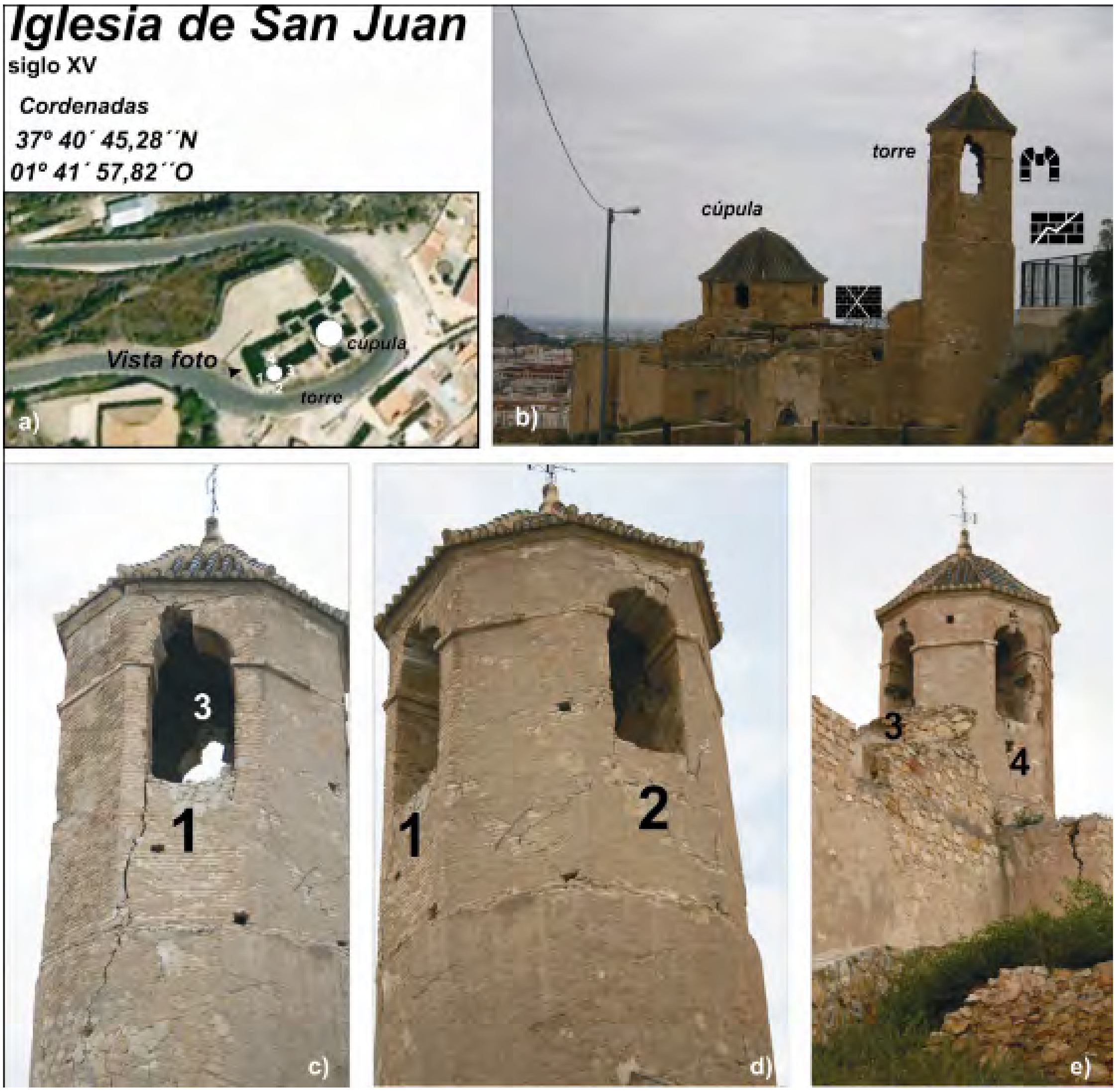

Figure 5.7: Damage in the San Juan's Church.

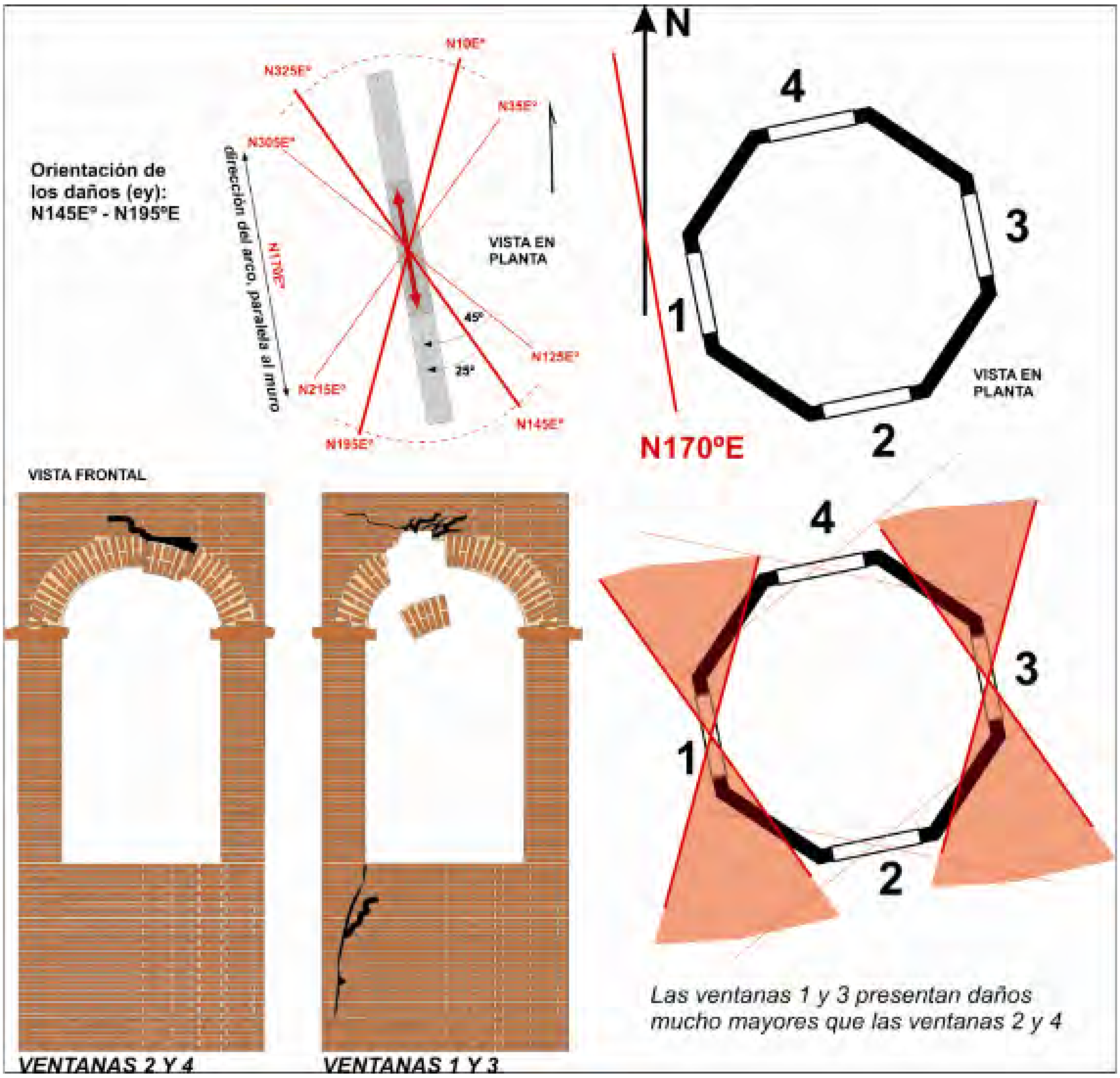

Figure 5.8: Example of analysis of deformation structures and the results of the orientation assessment of the strain (San Juan's Church).

Figure 5.9: Anthropic compacted substratum by seismic shock related to the Clarisas's Convent. New EAE structure.

Figure 5.10: Santa Maria's Church. Pop up of a clave stone.

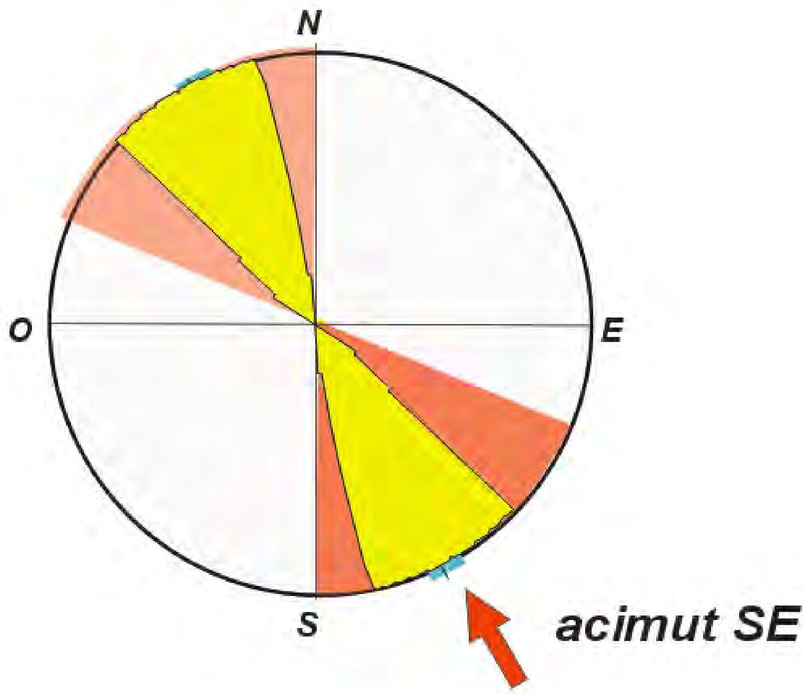

Figure 5.11: Rose diagram of the calculated main horizontal strain directions, using the EAEs. Preliminary results.

6. Preliminary Conclusions

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- Alhama-Murcia Fault (FAM) is the fault with greater evidence of Quaternary activity in the area, with evidence of paleoseismic activity (M > 6.0) over the last 1000 years, associated with thermal springs and a well-recognized surface trace. There was destructive historical seismicity located along the trace during the XVII, XVIII and XIX centuries. FAM has a clear geomorphological expression in this area and whose trace is parallel to one of the nodal planes of focal mechanisms obtained for the earthquakes of May 11, 2011. The sinistral strike-slip movement of the fault is consistent with the focal mechanism solution.

- The high seismic intensity experienced by the town of Lorca (intensity VII EMS-98 scale, data IGN) associated with a magnitude 5.1 Mw, may be due to the earthquake spread from the Sierra de la Tercia (epicentral area) to the SW. The lack of geological effects towards the east of the epicentre supports this possible directionality of propagation.

- The wave propagation supports the directionality of the FAM rupture spread from the epicentral area, crossing the city of Lorca. This reason associated with the shallowness of the earthquake, would explain the high seismic intensity and peak accelerations of 0.36 g (IGN data) recorded in the accelerometer of the old prison of Lorca (located in the downtown).

- The increasing in static stress (Coulomb Stress-Transfer Model) on the segments of the Alhama-Murcia Fault (FAM) generated by the main earthquake may have increased the likelihood of earthquake occurrence in these areas. However, it is not possible specify temporary occurrence of these earthquakes.

- The orientation of the principal axe of the strain ellipsoid (e_y), obtained from the archaeoseismological study is NW-SE, is consistent with the regional tectonic stress field and focal mechanism of the main earthquake and also with the epicentral location.

- the Archaeoseismological data (more than a hundred values) suggest an origin of the deformation associated with a nearby seismic field, implying that most of the main earthquake rupture occurred beneath the historic city of Lorca because the faulting subsurface rupturing runs below the Lorca village.

- With these data and their inclusion in the Environmental Seismic Intensity Scale ESI-07, this preliminary geological report will improve the information of historical earthquakes and epicentral location, improving the knowledge of the seismic process in Spain.

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ANEXO 1. Brief outline on the seismic hazard in the area

Translated literally by the author from the original report in Spanish

Julián García Mayordomo (IGME)

The seismic hazard at which the city of Lorca is subjected to (and, in general, the Murcia Region and Southeast Spain) has been analysed many times and by very different approaches. Not in vain the dwellers of Lorca municipality and nearby territories know that they lived under this natural risk.

Looking back to the past the last damaging earthquakes in Spain have located in Murcia Region (1999 Mula, 2002 Bullas, 2005 La Paca, and now 2011 Lorca). Likewise, the history of this territory is marked by the occasional occurrence of more or less strong earthquakes (see: www.ign.es/ign/layout/sismologiaEstadisticasCartografiaSismica.do). The municipality of Lorca itself have appointed studies on this topic several times, as for example the pioneer study carried out by the Institute of Geology and Mines of Spain (IGME, Instituto Geológico y Minero de España) in 1992. Furthermore, Civil Protection of Murcia Region counts on with a modern special emergency plan against seismic risk (Plan Especial de Protección Ante el Riesgo Sísmico, see: www.112rm.com/dgsce/planes/sismimur-home.php). On a national-scale legislative level, the construction or restoration of buildings in Lorca municipality is subjected to the obligatory accomplishment of the national seismic resistant code (Figure 1, see: www.fomento.es/MFOM/LANG_CASTELLANO/DIRECCIONES_GENERALES/INSTITUTO_GEOGRAFICO/Geofisica/sismologia/ingss/normageneral-pdf.htm).

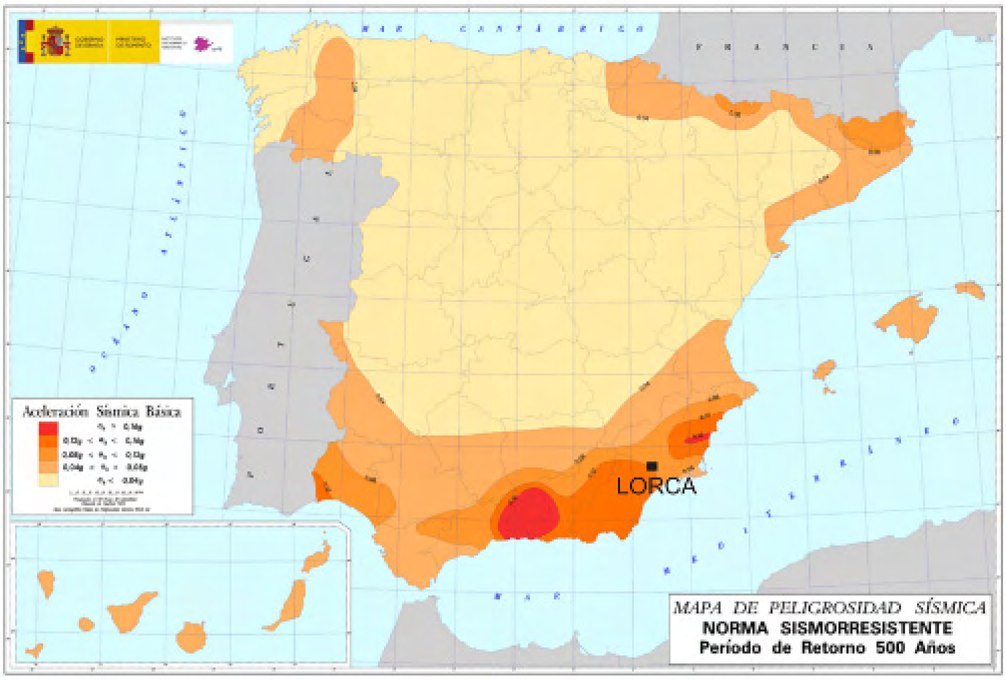

Figure 1: Location of Lorca city in the seismic hazard map included in the Spanish seismic code (NCSE-02).

In the Spanish context, Lorca is situated in a moderate seismic hazard zone in relation to other territories like Granada and the south of Alicante. This is because the calculation done to produce the map is strongly controlled by the knowledge we have of earthquakes happened in the historical past (in fact, two of the most destructive earthquakes in Spain in the last 100 years have taken place in these areas: 1884 Arenas del Rey and 1829 Torrevieja, respectively). However, from a geological point of view, Lorca is an area subject to a high seismic hazard.

Seismic hazard in Lorca city is controlled by two Basic types of sources capable of producing damaging earthquakes (García-Mayordomo, PhD Thesis UCM, 2005). (1) Known or unknown faults, which will presumably not produce earthquakes larger than 5.5-6.0, and (2) the Alhama de Murcia Fault. Concerning the first case, a recent scientific study (Gaspar-Escribano et al., 2008, BEE:6, 179-196) estimates that the most probable earthquake for a 500 years return period (which is the one considered legally for the construction of habitational buildings) would have a magnitude of the order of 5.0, very similar to the 11 May main shock). In this sense, it could be considered that Lorca has been put to the test with the strongest earthquake that conventional buildings should resist without collapse. However, there are still many questions to be explained, like the high acceleration recorded (0.37g) in relation to the basic design acceleration that the seismic code provides for building in Lorca (0.12g).

Regarding the possibility that really catastrophic earthquakes take place in Lorca, the most likely source is the Alhama de Murcia Fault itself, which delineates the contact between the ranges and the basin from approximately Puerto Lumbreras to nearby the city of Murcia, totalling a longitude of about 85 km. It is estimated that this fault is capable of producing earthquakes between 6.5-7.0 every 2000 years (information from Martínez-Díaz et al., 2010, in the *Quaternary Active Faults Database of Iberia*) (Figure 2). In the Region of Murcia exist other faults also capable of producing big earthquakes, likely with catastrophic consequences, with a high frequency in the geological sense (eg, once every few thousand years). An important shortcoming is that we do not know the date of the last big earthquake that these faults produced, which is a fundamental question for predicting the next one, and that it only can be solved through geological research.

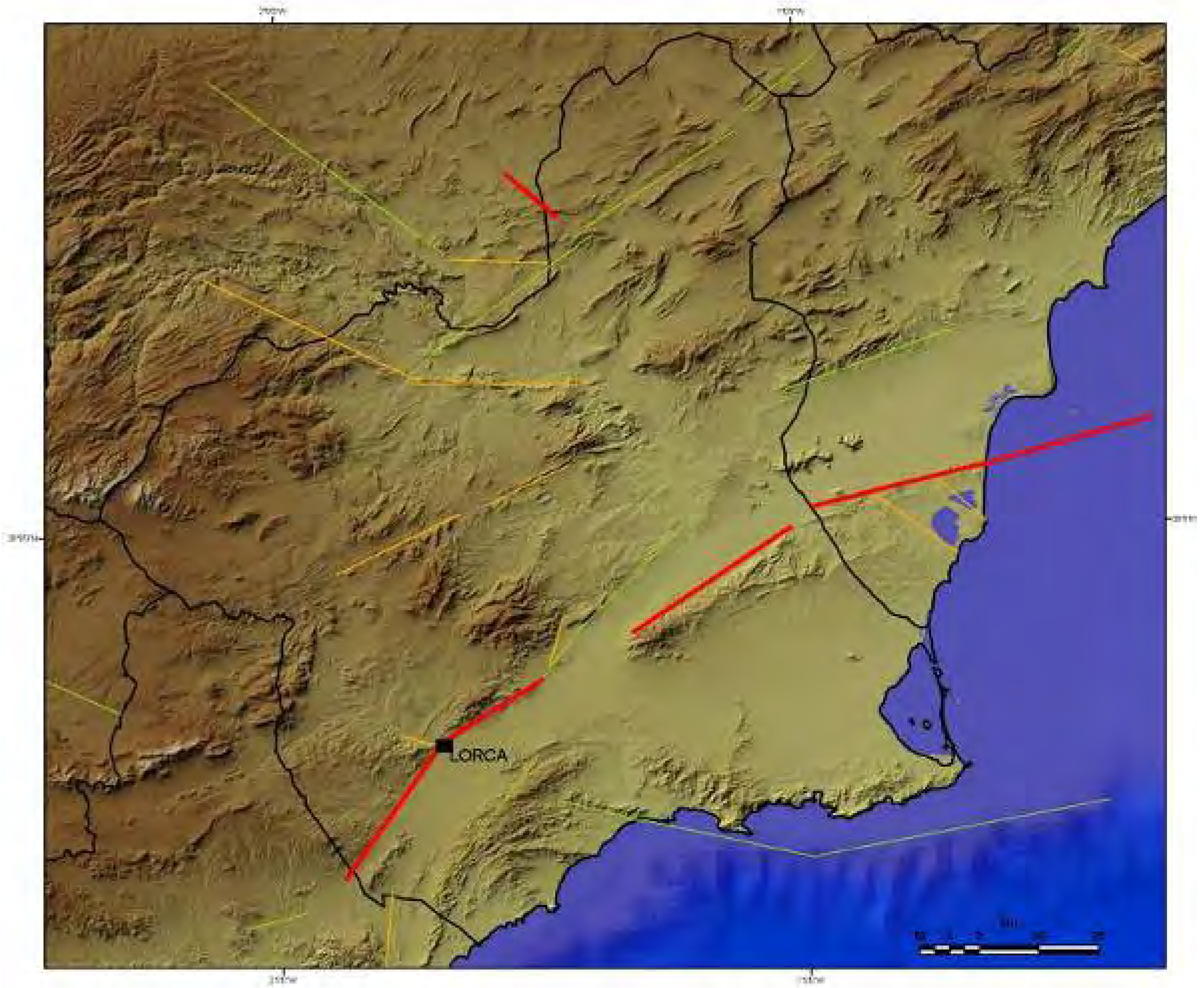

Figure 2: Situation of the main major active faults in the Region of Murcia. In red are marked faults capable of producing big earthquakes with relative frequency (every thousand years). Note that the Alhama de Murcia Fault crosses the town of Lorca. Source: Quaternary Active Faults Database of Iberia (a ongoing project by IGME in collaboration with earth science researchers from Spanish and Portuguese universities and research centres).

The 11th May 2011 earthquakes in Lorca are going to boost research and innovation in all the areas involved in preventing and mitigating seismic risk in Spain (geology, seismology, engineering, architecture, civil protection, citizen education, legislation). the lessons we learn today will serve to reduce losses and save lives tomorrow.