Geologica Acta, Vol.3, Nº3, 2005, 241-250
Available online at www.geologica-acta.com

From strike-slip to reverse reactivation: The Crevillente Fault System and seismicity in the Bullas-Mula area (Betic Cordillera, SE Spain)

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ABSTRACT

Several major N80ºE faults occur in the Bullas-Mula area (SE Spain). These faults and the numerous thrust slices of the Sierra de Ricote can be related to the movements of the Crevillente (or Cadiz-Alicante) fault system, which causes the westward displacement of the Betic Internal Zone and part of the External Zone. These faults moved with dextral strike-slip from Late Burdigalian to Early Tortonian. From this time on, the σ_1 position changed from a WNW-ESE direction to approximately N-S, giving rise to movements with a new reverse character. The focal mechanisms of the 1999 Mula earthquakes indicate a N80ºE nodal plane, and their pressure axes also coincide with the σ_1 direction existing from the Late Miocene and deduced from mesotectonic analysis at many points of the region. There is also good coincidence between their epicentral position and the fault traces. The Bullas earthquakes that occurred in 2002 are not directly related to the Crevillente faults, although their stress-pressure axes coincide with the σ_1 direction reported there.

KEYWORDS **Betic Cordillera. Crevillente Fault. Mula earthquakes. Neotectonics.**

INTRODUCTION

The area of Bullas-Mula (Figs. 1 and 2) has recently attracted attention because it has undergone several earthquakes (Figs. 3 and 4). The first seismic series was located in the Mula area, where the main event, which occurred in February 2nd 1999, reached a maximum intensity of VI (EMS-98) and caused damage in this town and villages located to the east. This event and its aftershocks had nodal planes oriented between N70ºE and E-W. Later, another seismic series occurred to the south of Bullas (June, 8th 2002), in the proximity of the village of Aviles (Fig. 4). In this case the maximum intensity was V (EMS98) with only minor damage in the epicentral area (for instance in the village of La Paca; Fig. 4). Given that some earthquakes have historically occurred in this zone, the area has been studied in order to provide better knowledge of the main structures, their kinematics and age of formation.

The distribution of earthquake epicenters in the Betic Cordillera and the Rif for the period 1980-2004 (with magnitude ≥ 3.0) and shallow focus (h<40 km) have been taken from the Instituto Geográfico Data File and plotted in Fig. 3. This figure shows three areas with a major concentration of epicenters: Almeria (ALM), the Granada Basin (GR) and the Alhoceima region (ALH), where the

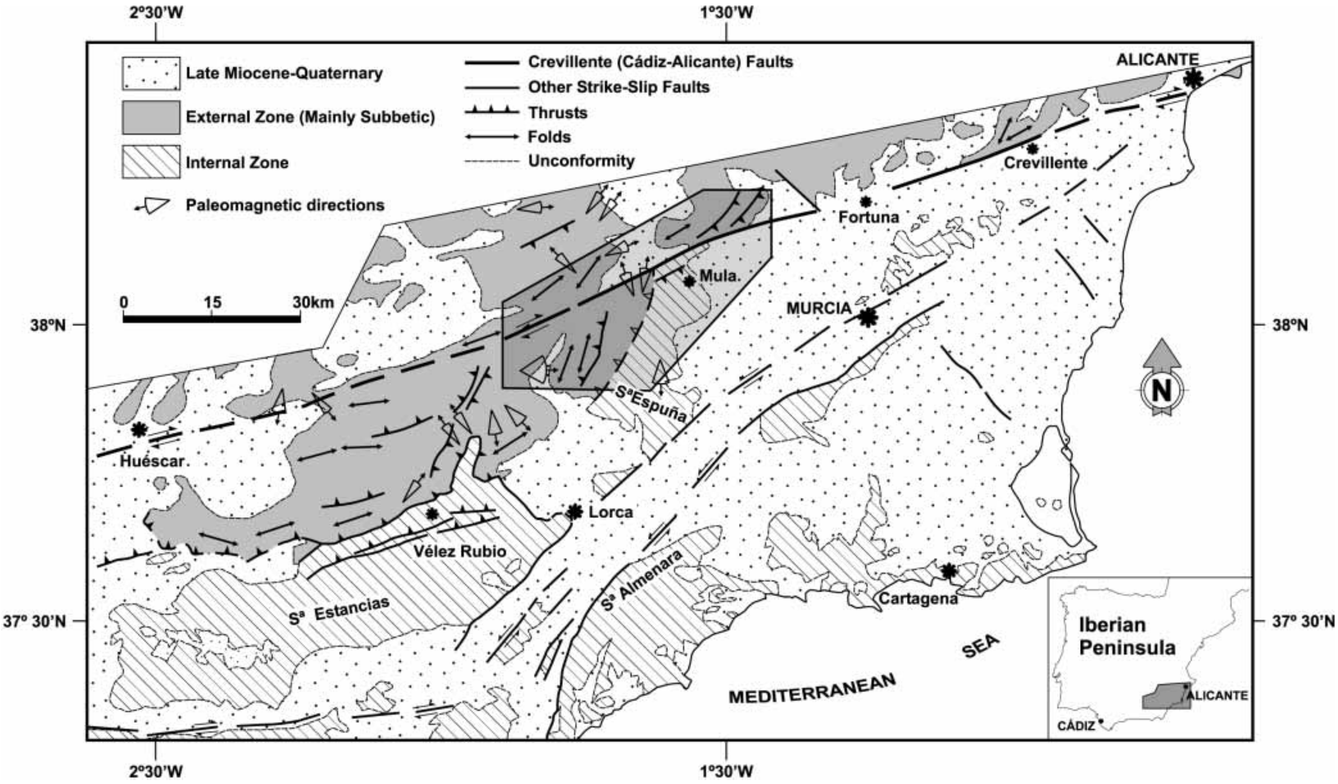

FIGURE 1 **Main geological domains and faults of the central-eastern sector of the Betic Cordillera. The Crevillente (Cadiz-Alicante) and Lorca-Murcia faults are emphasized. Paleomagnetic directions are taken from Allerton et al. (1992, 1993). Note the inset in the center for the location of Figs. 2 and 5.**

1994 (Mw=5.8) and 2004 (Mw=6.2) earthquakes occurred. Seismic events in the Mula and Bullas region (Fig. 4) had a moderate magnitude (in general less than 5.0). The Mw estimated for the Mula (MM) and Bullas (BM) main shocks was 5.1 and 4.6, respectively. For the Mula series, three shocks displayed magnitudes larger than 4.0: a foreshock occurred 23 minutes before the main shock (FM) and two aftershocks (M1 and M2). For the Bullas series the largest aftershocks displayed magnitudes ranging from 4.0 to 4.9. From historical seismicity, we know that the largest earthquake occurred in this region was the 1829 Torrevieja shock (I_{max}=X, Muñoz and Udías, 1991) located 50 km to the east of study area (Fig. 4). In 1911, the study area underwent two events with maximum intensities VIII (Buforn et al., 2005), which caused substantial damage.

This paper deals with the description of the Crevillente fault zone in the Bullas-Mula-Ricote area, its significance and kinematic evolution from the Early Miocene to Recent and its possible relationships with the current seismicity, particularly the Mula and Bullas earthquakes.

GEOLOGICAL SETTING

From a geological standpoint, this region is especially noteworthy because it contains part of the contact between the Internal and External zones of the Betic Cordillera, the so-called Crevillente Fault or Cadiz-Alicante Fault System (Sanz de Galdeano, 1983). The Internal Zone of the Betics is formed by three overthrusted complexes, which from bottom to top are the Nevado-Filabride, the Alpujarride, and the Malaguide, although in the study sector only the Malaguide occurs. The Malaguide Complex includes Paleozoic to Tertiary rocks that generally have not undergone metamorphism, with the exception of the lower Paleozoic rocks, which do not crop out in the Mula-Espuña area. The inclusion of Sierra Espuña into the Malaguide Complex has been accepted since the work of Paquet (1969), although the southern edge of this sierra reveals several intermediate units with the Alpujarride Complex. The area of Mula has been included in the Subbetic, although Martín-Martín (1996) demonstrated its relationship with the Malaguide Morrón de Totana Unit of Sierra Espuña. The External Zone, formed by the Subbetic and Prebetic domains, includes the Mesozoic to Tertiary sedimentary cover of the ancient S and SE continental margins of the Iberian Massif. Only the Subbetic domain is represented in the study area.

The structuring of the present contact between the Internal and External zones started at the end of the Early Burdigalian (Burdigalian paroxism of Hermes, 1985; Martín-Algarra, 1987). The Internal Zone was displaced

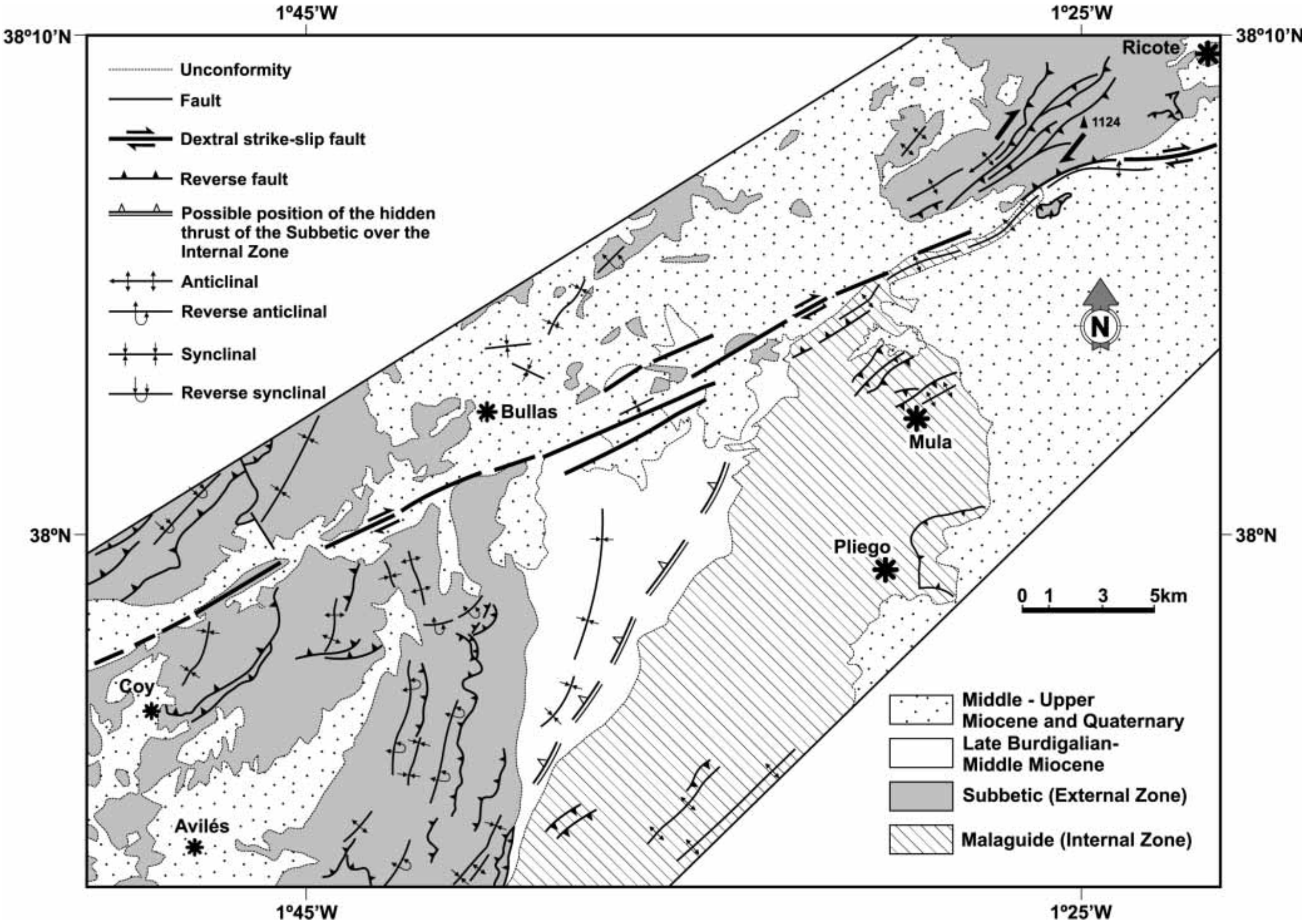

FIGURE 2 **Geological map of the study area. See Fig. 1 for location and Fig. 5 for additional tectonic characteristics of the zone.**

to the west (Andrieux et al., 1971; Durand-Delga, 1980; Durand-Delga and Fonboté, 1980) from an area close to the south of Sardinia (Sanz de Galdeano, 1990) in a process linked to the opening of the Algero-Provençal Basin (Boillot et al., 1984). The contact was formed in a right-lateral collision that strongly deformed the former sedimentary successions of the Subbetic Basin, which were integrated in several tectonic units.

During the late Burdigalian the dextral displacement of the Internal Zone took place progressively along the Crevillente fault zone. This fault zone is located in the southern External Zone near the Internal Zone and, in some places, is even in contact with it. This fault zone includes a set of parallel faults that stretches from Alicante to the western end of the Betic Cordillera (Cádiz area). It can be identified throughout most of the area, although it is locally covered by Upper Miocene or younger sediments or by the so-called Subbetic Olistostrome.

The contact between the Internal and External zone in the Ricote-Mula area has an approximately N70ºE direction, coinciding partially with the Crevillente faults (Figs. 1, 2 and 5). To the west of Mula, this contact changes to a NNE-SSW direction, where the Subbetic overthrusts the Malaguide. More to the SW, in the Velez-Rubio corridor the contact has again a N70ºE direction, but now in a southerly position in relation to the Crevillente fault zone.

MAIN FEATURES OF THE CREVILLENTE FAULT ZONE

Single faults in the Crevillente fault zone are rectilinear, with an average strike in the study area of N70º-75ºE (Figs. 1, 2 and 5). Between Bullas and Coy (Fig. 2), the Crevillente fault zone clearly affects the Subbetic and the Miocene sediments. A good morphologic expression occurs between Bullas and Mula, where several parallel fault segments affect the Middle to Upper Miocene (Tortonian) sediments (Velando and Paquet, 1974). Most of these sediments are poorly consolidated marls, silts and sands where fault surfaces are not preserved, although vertical fault contacts that juxtapose different sedimentary rocks crop out at many points. Elongated hills and small ranges, where the topography is controlled by individual faults are visible within the Crevillente fault zone. Single fault planes are only well exposed in the embankments flanking roads and in some quarries. Many of these outcrops are analyzed in this study. Numerous vertical joints, which parallel the Crevillente fault zone, occur locally in Middle-Upper Miocene bioclastic limestones that top some hills (Fig. 6A).

Near Mula, there are many N70E strike slip faults affecting Late Cretaceous to the Early Miocene and Early Burdigalian rocks (Jerez Mir et al., 1974; Martín-Martín, 1996). Several fault surfaces are very well exposed and show diverse striae that reveal dextral displacement.

To the NE, in the Sierra de Ricote, many NW verging thrust surfaces occur (Jerez Mir et al., 1974). These thrusts dip between 40º to 70º southwestwards (Figs. 2 and 5). Associated with these thrusts, there are folds of different scales, generally with horizontal axes that show roughly NE-SW trends with vergence to the NW (Fig. 4). The thrust vergence suggests a northwestward displacement, but widespread minor faults reveal that the displacements are practically westwardly, in agreement with the dextral displacement of the Crevillente fault zone, on the south border of Sierra de Ricote.

In the SW part of the study area, in the Aviles-Coy sector and near Aviles, at the epicenter of the earthquake of Bullas, the structures are not well exposed because of strong erosion. The observed folds and faults have a predominant N-S trend.

KINEMATIC ANALYSIS

The results of the meso-scale fault-data study are presented in Figs. 5 to 7. To the E of Bullas many minor dextral strike-slip faults occur with trends ranging between N70º and 110ºE, and horizontal or slightly plunging striae (Figs. 8A and 8B). Conjugate left lateral faults with trends between N145º and 180º are less developed. In the Mula sector, minor faults have similar orientations and kinematics.

Numerous right and left lateral meso-scale faults occur in the Sierra de Ricote, with the latter being less abundant but locally well represented. These faults have the same general orientation as that of the Bullas sector. The meso-scale structures are very well exposed owing to the existence of marlstone and marly red limestone beds (Late Liassic to Malm and even Late Cretaceous- Paleocene in age). Here, calcite fibers and striae are very well developed and enable the determination of displacement direction (Fig. 8C). Two less abundant sets of minor faults exist; the first set with a dextral displacement and a strike that ranges between N150ºE and N-S; and the second set with sinistral displacements and the strike of between N20º and 50ºE. There are also many sigmoidal structures that are consistent with the displacement of these faults. Finally, similar orientation faults occur also in the Aviles sector.

Data from minor faults were analyzed with the "Redes" program (Galindo-Zaldívar and González

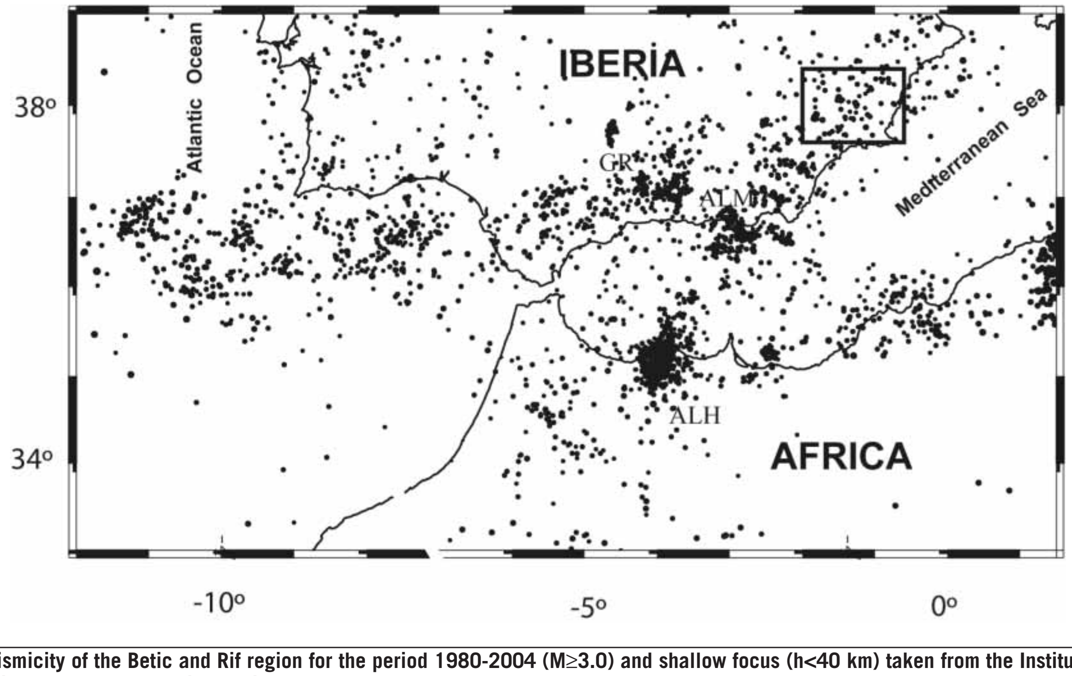

FIGURE 3 | **Seismicity of the Betic and Rif region for the period 1980-2004 (M≥3.0) and shallow focus (h<40 km) taken from the Instituto Geográfico Data File. The inset shows the location of Fig. 4.**

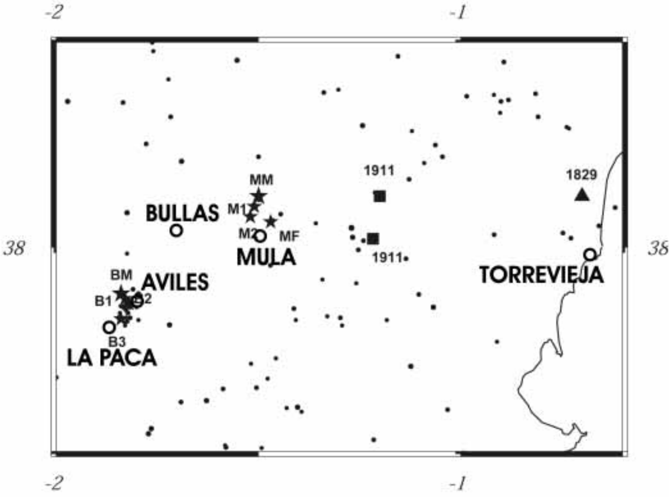

FIGURE 4 **Seismicity of the Bullas-Mula area. See location in Fig. 3.**

Lodeiro, 1988) to determine the stress ellipsoid at each point. These were subsequently plotted as stereographic projections (Figs. 5 and 7). Only the faults with clear displacement directions were considered.

The axial ratio $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ corresponds to prolate ellipsoids (Fig. 7), with one exception (Fig. 7M) from the eastern part of the Sierra de Ricote, where the axial ratio is approximately oblate (0.88; Fig. 6G).

To the east of Bullas (A to C in Figs. 5 and 7) the measurements were made in Early to Upper Miocene sediments. The results indicate directions of maximum compression σ_1 ranging from E-W to NW-SE, in accordance with the right-lateral displacements of the main faults.

In the Mula sector, (see D to F in Figs. 5 and 7) the results are similar to those in the previous sector and fully consistent with that of the large faults in the area.

In the Sierra de Ricote, the diagrams (G, I to L and N in Figs. 5 and 7) are very similar to the previous ones and the σ_1 directions also range from E-W to NW-SE. Diagram H corresponds to faults measured at the same location as in Fig. 5G, where the directions are nearer to N-S and the σ_1 direction is NNW-SSE. Figure 5M also corresponds to faults with nearer N-S directions in the point of

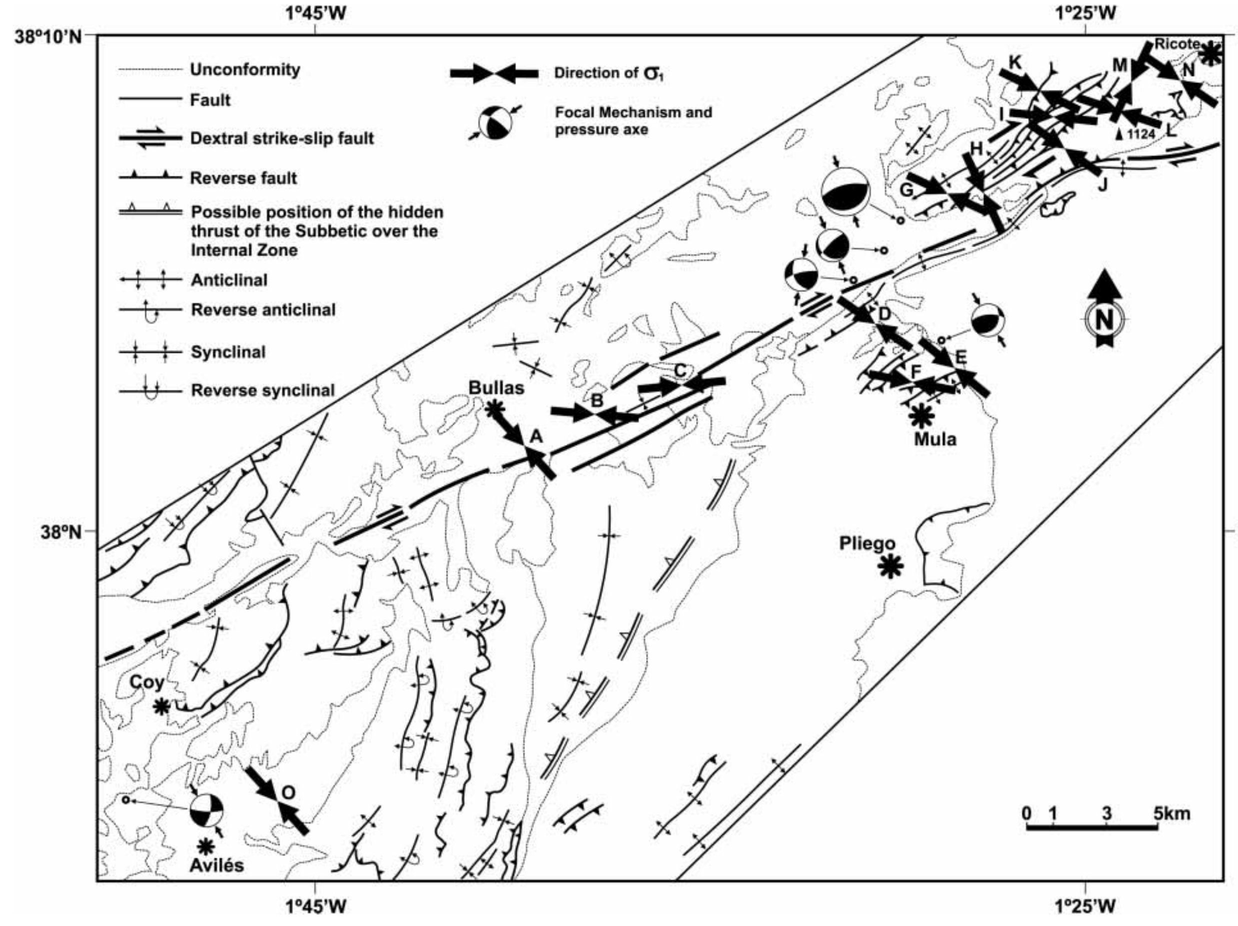

FIGURE 5 **Tectonic map of the study area (see location and overall geological characteristics in Figs. 1 and 2, respectively). The location of the diagrams of Fig. 7 is indicated by the corresponding lettering (A to O). The focal mechanisms of the Mula earthquakes are taken from Buforn et al. (2005).**

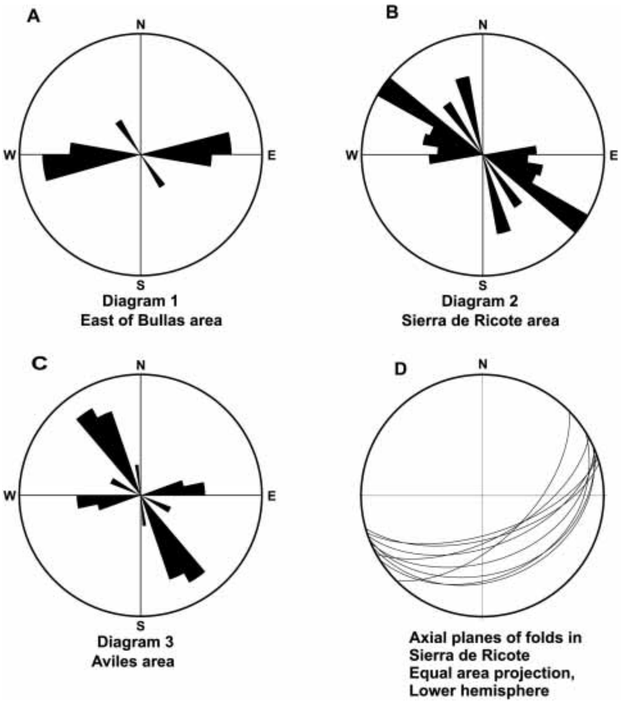

FIGURE 6 **A to C: Rose diagram of joints. A) To the East of Bullas, in the area of diagram B in Fig. 7. B) In the central part of Sierra de Ricote, in the area of diagrams G and H in Fig. 5C) In the Aviles sector, in the area of diagram O in Fig. 5 (some of the joints of this sector are not strictly vertical, but none dips less than 70º). D) Lower hemisphere projection of the axial planes of the minor folds measured in the central Sierra de Ricote.**

Fig. 5N and the σ_1 direction is NNE-SSW. In both cases, these points have been split into two groups because they correspond to clearly different fault systems.

Minor fold axes in Sierra de Ricote have clear NW vergences and trends that range between N45ºE and 72ºE, paralleling the surface trace of thrusts. These folds are overturned locally. The trend and vergence of minor folds (Fig. 6D) are consistent with the dextral displacements of the Crevillente fault system. The study of joints (Figs. 5B and 8D) indicates that many of them, which were filled by calcite, have a tensional character. Finally, to the SW, in the Aviles sector, the analysis of the faults (O in Fig. 5 and Fig. 7) indicates a N317E σ_1 direction similar to A in Fig. 7.

The results of the macro- and meso- scale structural analyses indicate that in the study area, faults belonging to the Crevillente fault zone had moved with approximately WNW-ESE σ_1 direction, ranging from E-W to NW-SE and with predominant dextral displacement. According to our interpretation, the westward displacement was progressively transferred to these N70 to E-W faults, after the collision between the Internal and External zones of the Betics. In the study area, these faults affected not only the contact between both zones but also part of the Internal Zone and especially the southern fringe of the Subbetic. These fault movements began during the Early Miocene and continued until the beginning of the Late Miocene.

During the Tortonian the σ_1 direction changed from WNW-ESE to NNW-SSE, N-S and even NNE-SSW (Ott d'Estevou and Montenat, 1985; Montenat et al., 1990; Sanz de Galdeano and Vera, 1992; Galindo Zaldívar et al., 1993). At this stage the minor faults of the Crevillente fault zone developed with trends close to N-S (Figs. 7H to 7M). In relation to this rotation of σ_1, Sylvester (1988) and Tearpock and Bischke (2003) have indicated that after the main movements of a strike-slip fault zone, the σ_1 direction must have changed to a nearly perpendicular trend in relation to the fault. This is certainly true in many cases in the proximities of the faults in the Crevillente fault zone, but in our case this phenomenon appears to be more general, affecting the whole Betic Cordillera as indicated by the previously cited authors. For this reason we support the interpretation of a regional rotation of σ_1.

RELATIONSHIP TO PRESENT SEISMICITY

The focal mechanisms of the earthquakes that occurred in Mula (1999) have been calculated by Buforn and Sanz de Galdeano (2001) and Buforn et al. (2005). Mancilla et al. (2002) and Stich et al. (2003) have studied the Mula main shock from the moment tensor inversion of surface waves at regional distances. According to Buforn et al. (2005), the main event location corresponds to the larger sphere in Fig. 5, and the foreshock and two aftershocks to the smaller ones. The focal mechanisms indicate a NNW-SSE pressure axis, with the exception of one of the aftershocks which is NNE-SSW. In all cases, except the aftershock situated directly to the south of the main event (Fig. 5), one of the two nodal planes has a N80ºE trend, the second plane being variable. In the case of the above-cited event, the direction of the more or less equivalent nodal plane is NE-SW. Nevertheless, with the exception of the main shock, these earthquakes have a lesser magnitude and the focal mechanism is not well determined.

The pressure axes of these focal mechanisms coincide with that of σ_1 deduced from Late Tortonian to present minor faults in the region (see H to M in Figs. 5 and 7). There is also a good coincidence with the N80ºE strike of the common nodal plane of the focal mechanism and the direction of the Crevillente fault zone. Moreover, the position of the epicenters clearly suggests a direct relationship between the Crevillente fault zone and the earthquakes.

This relationship with the previously existing faults and the present seismicity is reinforced by the coincidence of the earthquake epicenters with the fault locations

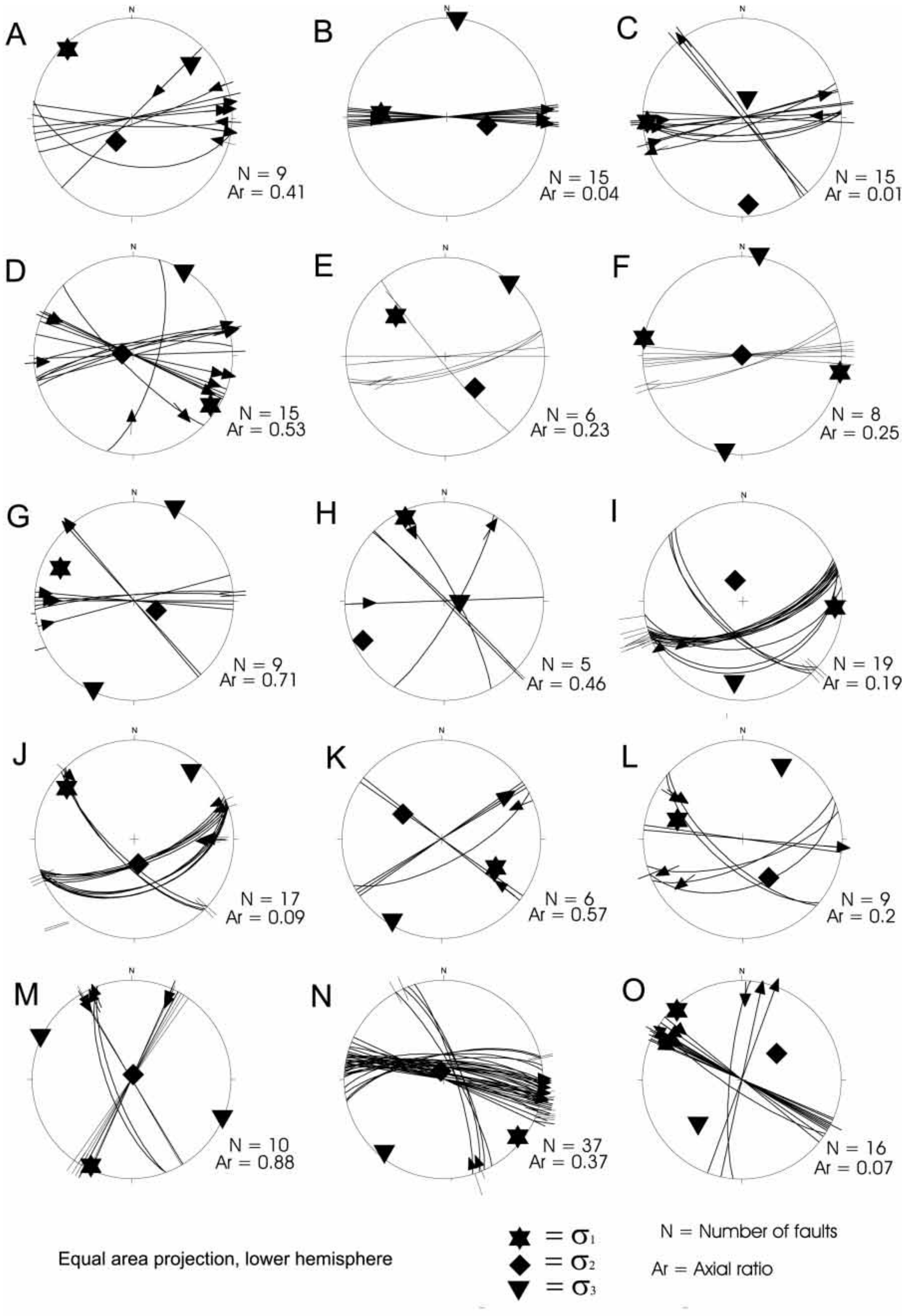

FIGURE 7 | **Diagrams with the results from the analysis of minor faults. See Fig. 5 for location. Lower hemisphere projection.**

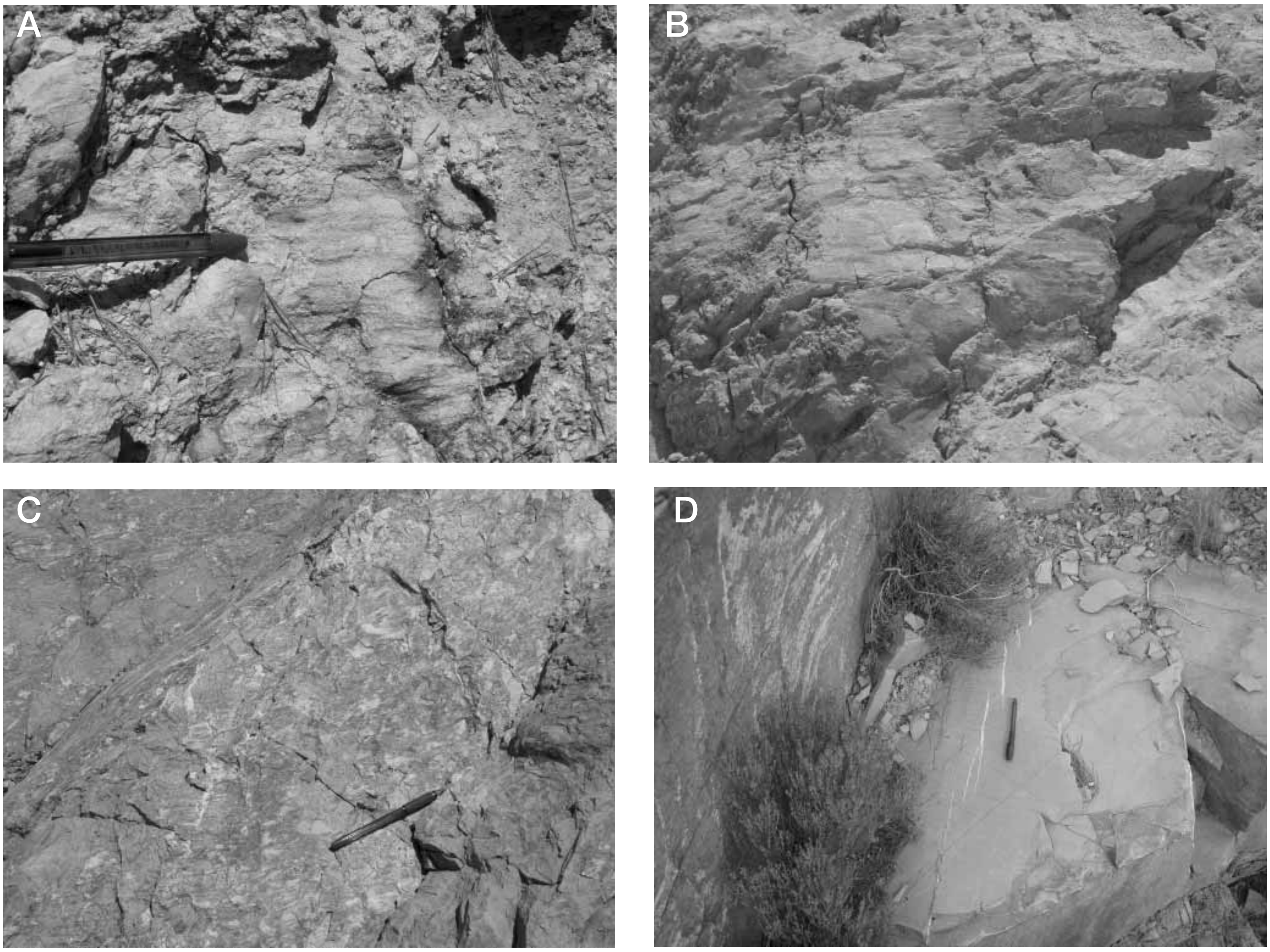

FIGURE 8 **A) Middle Miocene detritic marlstones affected by a minor N80ºE dextral strike-slip fault, showing horizontal striae. This outcrop is located several km to the East of Bullas. B) Middle Miocene limestones affected by N70ºE dextral strike slips faults, showing horizontal striae. This outcrop is located in a quarry several km to the East of Bullas. The horizontal length of the photo is approximately 4 meters. C) Upper Jurassic red limestones of the central part of Sierra de Ricote affected by minor dextral slip faults showing near horizontal striations (the pen is oblique to the striae). D) Upper Liassic marly limestones of the central part of Sierra de Ricote, showing several joints filled by calcite and approximately in the same direction as that of the σ1 established. There is a vertical dextral strike-slip on the left.**

and by the shallow depth of all these earthquakes (Buforn and Sanz de Galdeano, 2001; Martínez-Díaz et al., 2002a and b). Deeper hypocenters make it more difficult to correlate earthquakes with faults known on the surface. According to these authors, only one earthquake occurred at 7 km in depth, whereas the other took place at less at 5 km. Hence the relationship between faults and earthquakes has been established with confidence. Nevertheless, Mancilla et al. (2002) indicate the possibility of a depth ranging between 7.5 and 12.5 km; moreover Stich et al. (2003) have proposed a hypocenter at 8 km deep and very similar focal mechanisms, with strike-slip movement and a normal component. However, the damages caused by the Mula earthquake cast serious doubt on the validity of this depth, suggesting a shallower focus in agreement with the depth estimated by the Instituto Geográfico Nacional, and therefore we prefer the previous interpretations. With deeper earthquakes, for instance with hypocenters located more than 15 km in depth, it is more difficult to establish their relationship with the geological structures, which can vary very much in depth. These old N80ºE faults, when affected by a N-S to NNW-SSE compression, should move as reverse faults. With NNE-SSW compression, they could even present left lateral components, opposite to the right lateral movement previously recognized.

The focal mechanism of the main event of the Bullas series is situated in the SW part of Fig. 5. The nodal planes of this event and that of three of the principal aftershocks correspond to N-S and E-W directions, having a NW-SE pressure axis. This axis is more or less coincident with that of the Mula series and with the σ_1 direction reported from the Tortonian in this same sector (A, O, and H to M in Fig. 5; Figs. 7A, 7O, and 7H to 7M). In this case, however, we cannot confidently determine the relationship with the fault that moved during the earthquakes. These earthquakes took place between 5 and 10 km deep, and hence most of the faults are probably located in the basement. These depth values agree with the minor damage caused by this series (Buforn et al., 2005), and consequently it is much more difficult to ascertain the relationships with the surface structures. In the same way, it is not possible to relate these earthquakes with the Crevillente fault zone, as the faults are located far away from the earthquake foci.

CONCLUSIONS

In the Central-eastern Betic Cordillera, the Bullas-Mula-Ricote area is characterized by the presence of approximately N80ºE faults belonging to the Crevillente (or Cadiz-Alicante) fault zone, which is very well defined in this area. This fault zone gave rise to elongated fringes of Mesozoic to Miocene rocks that are conspicuous in the relief. In the Sierra de Ricote a large number of thrust slices can also be related to this fault zone. On the whole, these faults facilitated the westward displacement of the Betic Internal Zone and part of the External Zone.

The macro- and meso-scale structural analysis shows that these faults moved as dextral strike-slip faults during the Late Burdigalian and Early Tortonian, a time when σ_1 took a WNW-ESE direction. From Late Tortonian this direction changed to be approximately N-S, and ranged from NNW-SSE to NNE-SSW.

With only one exception, the focal mechanisms of the Mula earthquakes (1999) indicate a common nodal plane that coincides with the trend of the Crevillente fault zone. The pressure axes of these mechanisms also coincide with the direction of σ_1 that has existed since Late Miocene. There is also a clear relationship between the epicentral position of these earthquakes and the fault location. Moreover, these earthquakes are very shallow, enabling a better correlation with the faults. It is possible to relate these earthquakes and the faults, although the latter move today with a reverse mechanism and not as dextral strike-slip faults.

The Bullas earthquakes, for which the epicenters were located to the SW in the Aviles sector, are not related to the Crevillente fault zone, although the pressure axis of their focal mechanisms coincides with the σ_1 direction found there. Their correlation with known faults on the surface cannot be established. The stress pattern determined from focal mechanisms of the Mula and Bullas main shocks corresponds to local stresses due to the moderate magnitude of the earthquakes and they indicate motion only in a section of the Cadiz-Alicante fault, but not the general motion in this large fault system. However, the study of these earthquakes casts light on the active tectonics and assessment of the seismic hazard in this region.

ACKNOWLEDGEMENTS

This study corresponds to the project REN2003-05178-C03-01, the research group RNM217 (Junta de Andalucía) and the "Acción Especial BTE2001-5230-E". The figures have been drawn by A. Caballero. P. Ruano helped in the program of stress determinations. We are grateful for the accurate correction and the suggestions of Drs. González Lodeiro (Granada), Martínez Díaz (Madrid) and Santanach (Barcelona), together with the editor's corrections which have greatly improved the former version of the manuscript.

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Manuscript received July 2004;
Revision accepted February 2005.