THE CADIZ-ALICANTE FAULT: AN IMPORTANT DISCONTINUITY IN THE BETIC CORDILLERA

C. Sanz de Galdeano

Instituto Andaluz de Ciencias de la Tierra (CSIC- Universidad de Granada), Facultad de Ciencias, 18071 Granada (Spain). csanz@ugr.es

Abstract: During the Burdigalian and the middle Miocene the Cadiz-Alicante Fault facilitated the continuity of the westward displacement of the Betic Internal Zone, simultaneously dragging part of the Subbetic. Its position locally coincides with the contact between the Internal Zone and the External, but especially in the west part affects only the Subbetic. From the late Miocene the crustal discontinuity formed by this fault aided the subsidence of the depocentres controlled by NNW-SSE faults, acting as a backstop for the extension to the north. This fault constitutes an important discontinuity in the Betic Cordillera and, although there is no proof of earthquakes deeper than 7 km linked to the fault, a volcanoclastic emission occurred during the Burdigalian, apparently related to the fault. This implies that the fault cut deeply, a proposition easily assumed if it is considered that the subsidence of some of the depocentres limited by the fault is on the order of 3 km and even more, requiring a compensation depth greater than 10 km.

Key words: Cadiz-Alicante Fault, Betic Cordillera, strike-slip fault, depocentre.

Resumen: La falla de Cádiz-Alicante facilitó durante el Burdigaliense y el Mioceno medio la continuación de los desplazamientos hacia el oeste de la Zona Interna Bética, arrastrando al mismo tiempo parte del Subbético. Su posición coincide localmente con el contacto entre las zonas Interna y Externa, pero hacia el oeste solo afecta directamente al Subbético. Desde el Mioceno superior la discontinuidad cortical producida por esta falla facilitó la subsidencia de los depocentros controlados por fallas NNO-SSE, actuando como una barrera de la extensión hacia el norte. Constituye una importante discontinuidad en la Cordillera Bética y aunque no hay pruebas de terremotos más profundos de 7 km ligados a esta falla, una emisión volcanoclástica del Burdigaliense podría estar relacionada con ella. Esto indicaría que la falla es profunda, un hecho fácilmente asumible si se considera que la subsidencia de los depocentros limitados por la falla es del orden de 3 km e incluso más, requiriendo una profundidad de compensación superior a 10 km.

Palabras clave: Falla Cádiz-Alicante, Cordillera Bética, falla de desgarre, depocentro.

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Many cordilleras have faults cutting through them, creating major discontinuities, such as the North Anatolia Fault in Turkey, the North Pyrenaic Fault in France or the Insubric line in the Alps of Switzerland. In the Betics (Spain), the Cadiz-Alicante Fault is an important dislocation, although many of its features have gone practically unnoticed until now.

This fault extends from 550 km (Fig. 1) and, as its name indicates, goes from the proximities of Cadiz, in the SW of Spain, to Alicante in the E of the country. It passes over the Betic Cordillera, cutting through the External Zone, but in some places coincides with the contact between the External and the Internal zones.

Geological setting: There are two main domains in the Betic Cordillera, the Betic Internal Zone (or better, given that it is common with Internal Zone in the Rif, the Betic-Rif Internal Zone) and the Betic External Zone (Fig. 1). The Internal Zone is formed by four tectonic complexes. These are, from bottom to top, the Nevado-Filabride, the Alpujarride, the Malaguide, and the Dorsal, this last generally linked to the Malaguide. The two first complexes underwent Alpine metamorphism. The original position of the Internal Zone is debated, but nowadays most of the authors accept that it was situated to the east, in the western Mediterranean, forming the AlKaPeCa Domain (Bouillin *et al.*, 1986) (a name formed by its constituents: Alboran – in the Betics and Rif, Kabylias in Algeria, Peloritani Mountains in Sicily and Calabria, in southern Italy) or South Sardinian Domain (Sanz de Galdeano, 1990). This South Sardinian Domain was structured during the Tertiary (Palaeocene to Oligocene) and when the Algero-Provençal Basin opened (Boillot *et al.*, 1984) (during the early Miocene) began to be radially expelled (Fig. 2); in such a way that the Betic-Rif Internal Zone was progressively displaced westwards, thereby deforming the Betic External Zone as well as the Flysch Basin, a domain making the transition between AlKaPeCa and the Rifian External Zone. The main deformations occurred

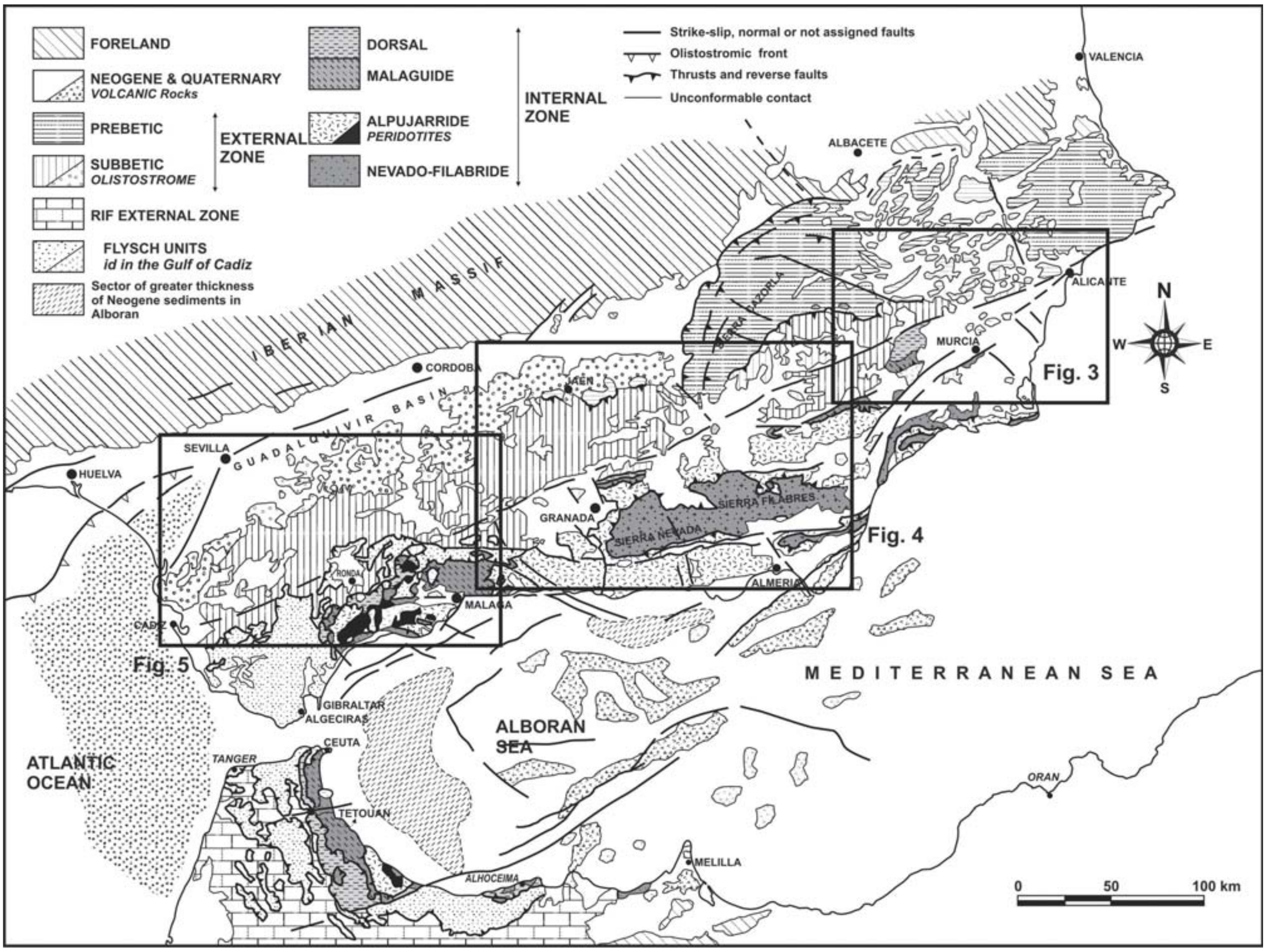

Figure 1.- Simplified geologic map of the Betic Cordillera and the Rif. The position of Figures 3 to 5 is indicated by the rectangles.

during the Burdigalian, the westward movement lasting during the middle Miocene, but with less intensity. As a result of this westward push, huge masses coming from the Flysch Basin and partially from the External Zones are presently accumulated in the gulf of Cadiz and even farther away from their origin (Iribarren *et al*., 2007).

The Betic External Zone is divided in Prebetic and Subbetic. Both domains formed the Mesozoic and Tertiary cover in the S and SE border of the Iberian Massif. During the Mesozoic, the Prebetic situated close to this massif, received continental or shallow marine sediments, while the Subbetic, in a more distant position, was formed by deeper marine facies and even volcanism. The Subbetic Basin was thus broken down by the effect of the collision of the Internal Zone, then forming many tectonic units. Notably among these units is the enormous olistostrome, the matrix of which is formed mainly by Triassic sediments, today outcropping from the central part of the Subbetic to the Cadiz Gulf. This olistostrome contains olistolites ranging in size from metres to tens of kilometres.

From the late Miocene, the westward displacement of the Internal Zone practically ceased and from this time the Betic Cordillera was affected by an approximately N-S to NNW-SSE compression and a perpendicular extension. At this time the present intramontane basins of the cordillera began to form (Sanz de Galdeano and Vera, 1992).

The Cadiz-Alicante Fault was called Crevillente Fault (Foucault, 1974) in the Alicante area. Later, Estévez *et al*. (1978) studying a Triassic outcrop in the Guadix-Baza Basin deduced the existence of a major fault that they called the Negratin Fault, situated in the western prolongation of the Crevillente Fault. Finally, Sanz de Galdeano (1983) compiled data of preceding authors and, together with the examination of large lateral displacements existing in various locations, roughly following a line going from Cadiz to Alicante, defined the Cadiz-Alicante Fault, a name used in later articles. Nevertheless, the very existence of the fault has not been accepted by all the authors.

This article contains further data, which, together with the information published previously, explain the existence of this fault more fully and sheds light on its importance as a great discontinuity of the cordillera.

The Cadiz-Alicante Fault along its path

Generally this fault is not expressed as a single line but usually by several parallel ones, making this a zone of parallel faults. Its strike is N70-75E and along its

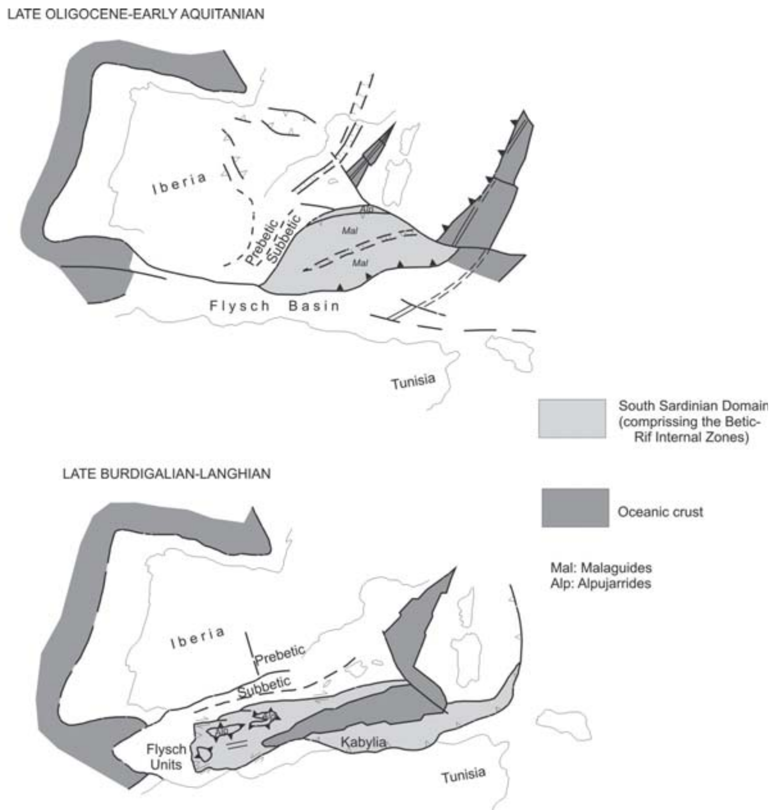

Figure 2.- Two moments in the evolution of the Betic and Rif Cordilleras with the opening of the Algero-Provençal Basin and the radial expulsion of the AlKaPeCa (South Sardinian) Domain. Note the pronounced dragging and the rotation undergone by the Subbetic, then forming the Cadiz-Alicante Fault.

path it cuts, at a slightly oblique angle, several domains of the Betics, particularly the Subbetic.

This fault separates the intramontane basin comprising the Alicante, Elche and Crevillente sectors, to the south, from the Prebetic, in the north (Fig. 3). Data published by Gauyau (1977), Gauyau *et al*. (1977), Montenat (1977), Alfaro (1995) and Delgado (1997) show that on the northern border of three sectors there is one depocentre, well marked in Elche, with a sedimentary infilling with a thickness of almost 2 km. The depocentre is a little less marked in Alicante but exists, although only a little more that 0.5 km of thickness in Crevillente. To the E and W the depocentres are bordered by NW-SE faults, as the Torrevieja Fault, but the Crevillente fault limits the depocentres on their north side, acting as a geological barrier. The subsidence occurred from the late Miocene, especially at this time, to the present.

North of the Crevillente Fault, the Prebetic forms a mountainous relief (De Ruig *et al*., 1987; De Ruig, 1992). There, several parallel lines of this fault show dextral displacements with associated drag folds. Nevertheless, some of the recent movements indicate sinistral displacements.

To the west, near the locality of Mula, Lukowski *et al*. (1988) describe the Fortuna basin and indicate pronounced transcurrent tectonics linked to the Crevillente fault zone. Poisson and Lukowski (1990) point out that the main depocentre of the Fortuna Basin, formed during the Tortonian and Messinian, is located on its NW border. This position is similar to that of the Elche-Alicante sector.

To the northeast of Mula, Van der Straaten (1990 and 1993) describes the Abaran Basin as a pull-apart basin controlled on its southern border by the Crevillente Fault. In this sector the fault zone is more than 10 km wide.

In the proximities of Mula, Paquet (1969) gave the name of Garobera Fault and later Mula-Archena Fault to the prolongation of the Crevillente fault. In the same area, Martín-Martín *et al*. (2006) and Martín-Rojas *et al*. (2007) indicate that the contact between the Internal and External zones (with the Subbetic) corresponds to a major dextral N70E fault. To the WSW the fault is located near Bullas, to the W of Mula, in the Median Subbetic. Throughout this sector, there are several lines of parallel faults, all at certain points showing horizontal striae in vertical or oblique planes, with dextral displacement. This fault zone affects middle Miocene sediments. The Mula earthquake (2nd February 1999) and its aftershocks, which can be related to this fault, present a reverse fault mechanism (Buforn and Sanz de Galdeano, 2001; Sanz de Galdeano and Buforn, 2005) with a hypocentre situated between 5 and 7 km.

Between Bullas and the Guadix-Baza Basin, the Crevillente Fault was studied by Hermes (1977, 1984 and 1985), Van de Fliert *et al*. (1980) and De Smet (1984 a and b). All of these authors refer marked wrenching tectonics and suggest that the structure of the Subbetic could correspond to a strike-slip orogen. Hermes (1977) even prolonged the Crevillente Fault to the proximities of Cadiz. De Smet (1984 a and b) describes an aggregate of large blocks formed by these

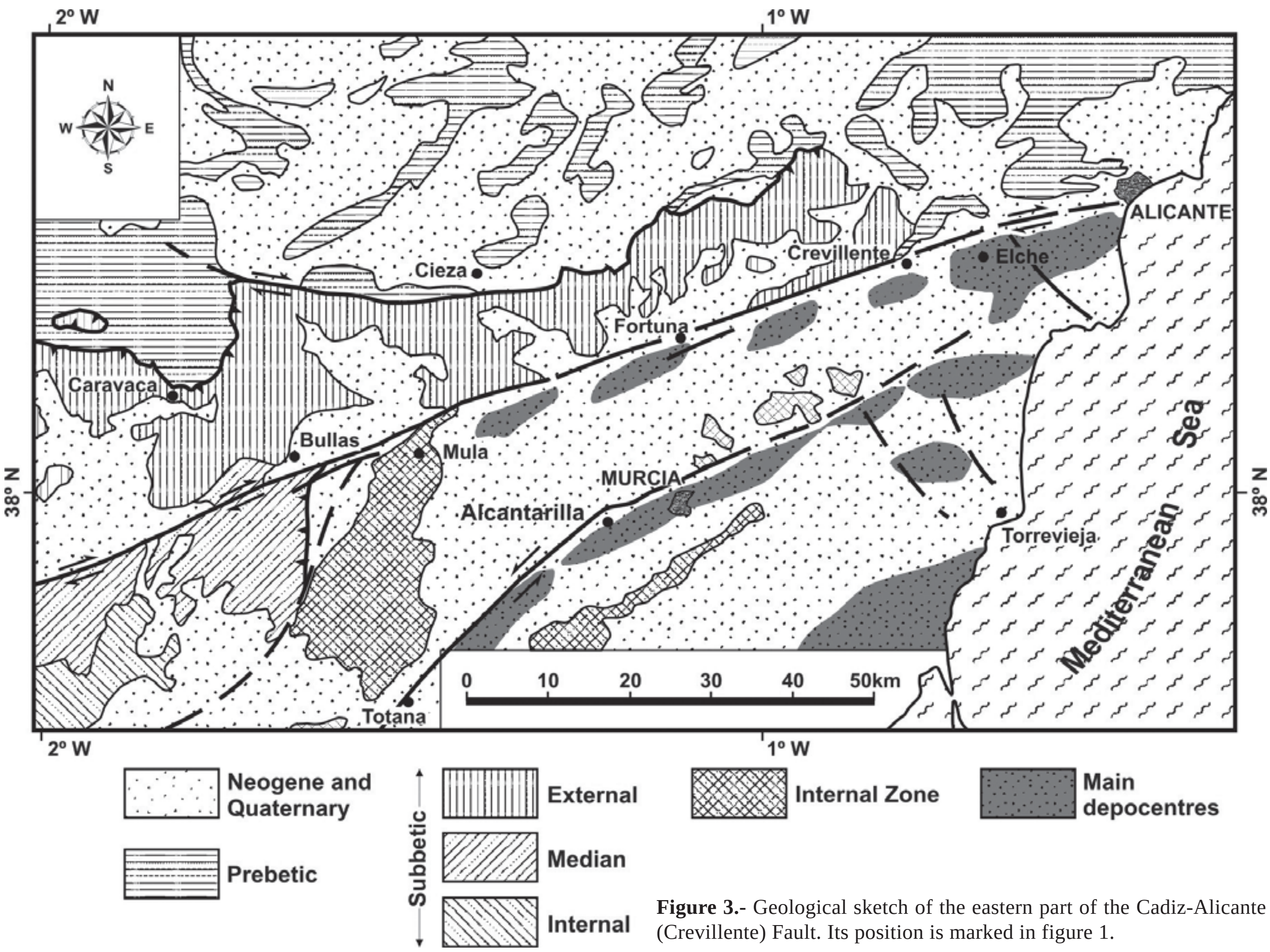

Figure 3.- Geological sketch of the eastern part of the Cadiz-Alicante (Crevillente) Fault. Its position is marked in figure 1.

wrenching tectonics, situated in the fault zone and indicates that to the north of the fault zone the vergence is northwards, while to the south it is southwards.

In the Guadix-Baza Basin, the Cadiz-Alicante Fault can be seen at only a few points. To the NE, on Botardo hill, near the locality of Huescar, there are Plio-Quaternary sediments affected by a N70-80E dextral fault. In the Negratin area, there is evidence a dextral fault that Estévez *et al*. (1978) named the Negratin Fault, also a prolongation of the Cadiz-Alicante Fault. Generally, the Plio-Quaternary sediments fossilized the fault, which is not visible in this case. Nevertheless, in this basin, there are three depocentres controlled by NW-SE and NNW-SSE faults (Fig. 4), limited on their northern border by the Cadiz-Alicante Fault (Sanz de Galdeano *et al*., 2007). These depocentres have been identified by gravimetric data showing that the subsidence was notable, especially in the Baza depocentre, sinking several kilometres from the late Miocene to the present.

Between the Guadix-Baza and Granada basins the Cadiz-Alicante Fault splits into several parallel lines, ranging from the contact between the Internal and External zones to the Median Subbetic. These lines have been described by Soria (1993 and 1994), Soria Mingorance *et al*. (1992) and Sanz de Galdeano (2004). They correspond to dextral strike-slip faults, locally with reverse components. Soria called them «Accidente Intrasubbético» and situates their main shifts during the early Burdigalian. This author describes volcanoclastic rocks, linked to the «Accidente Intrasubbético».

In the NE of the Granada Basin, Díaz Ucha (1988) described a zone of approximate E-O faults. These faults, detected using vertical electric wells, are in a prolongation of the Cadiz-Alicante Fault. To the north, several parallel faults situated in the Median Subbetic form a continuation of the aformentioned ones. Although the Granada Basin presents upper Miocene to Quaternary sediments that conceal the Cadiz-Alicante Fault, it is detected in some sectors, but its visible displacements sink the southern block, showing normal character. As in previous basins, the northern border of two depocentres of this basin is formed by the Cadiz-Alicante Fault (Fig. 4) and their age and control are the same. The throw is greater than 2 km in one depocentre (Rodríguez-Fernández and Sanz de Galdeano, 2006). Locally this fault displays silicifications originally linked to springs.

To the west the position of the Cadiz-Alicante Faults (Fig. 5) is difficult to discern because it crosses the Subbetic olistostrome, where the small competence of the Triassic sediments prevents the view of the faults. This olistostrome is totally disorganized, including huge olistolites of Mesozoic and Tertiary age with size, in some cases, exceeding ten kilometres. Peyre, (1974) called the olistostrome «Trías de

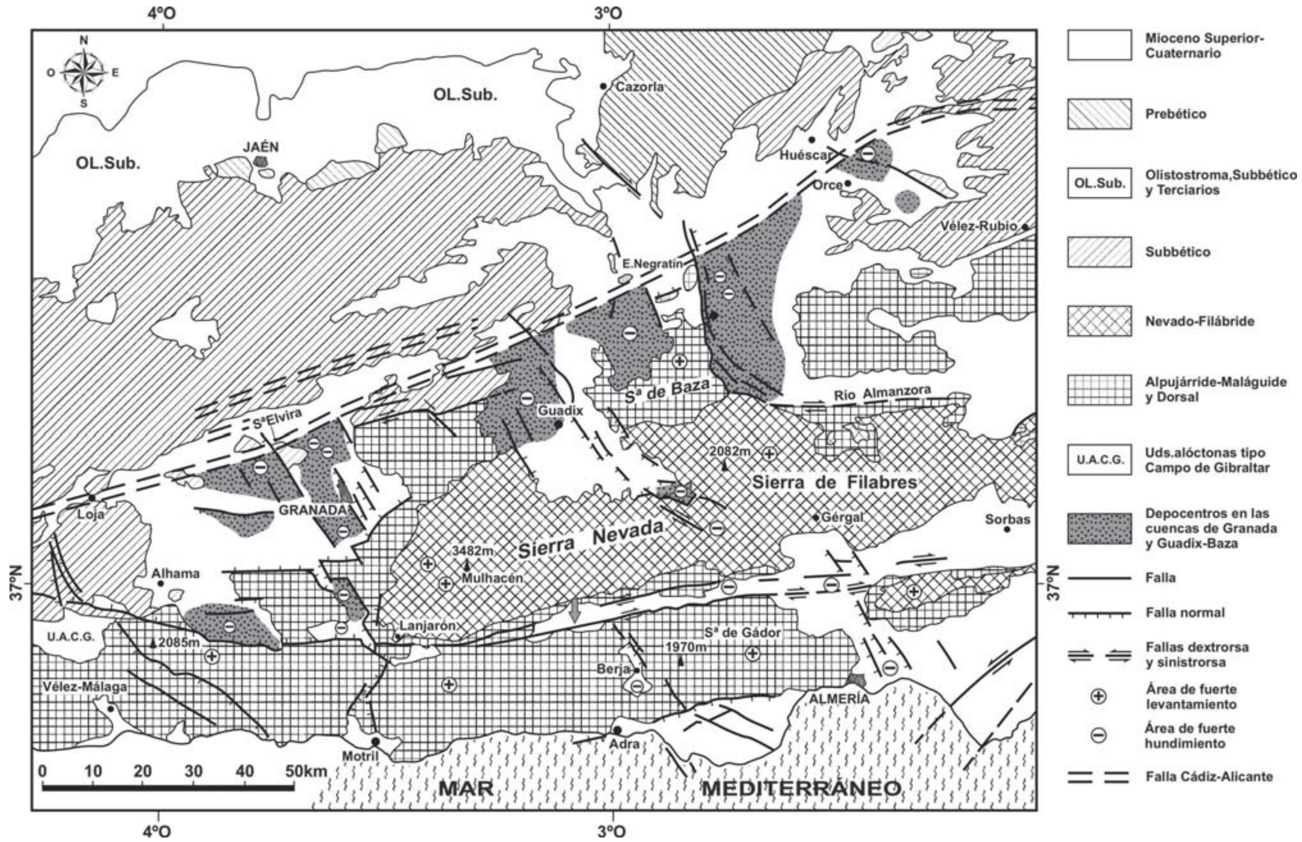

Figure 4.- Geological sketch of the central part of the Cadiz-Alicante zone of faults. Its position is marked in figure 1.

Antequera». Only on the south border of this olistostrome are N70E- to E-W tectonic bands visible, but they are probably related to southern faults, such as that of the Alpujarran Corridor (Sanz de Galdeano *et al*., 1985; Sanz de Galdeano, 1996).

The olistostroma extends to the west and only in the proximities of the town of Grazalema (in the Boyar Corridor) is there a dextral fault that places several different Subbetic units in contact with each other (Bourgois, 1978). In its prolongation, the La Sal and Cabra sierras, situated 10 km to the north of the locality of Alcala de los Gazules, constitute a megaolistolith. These sierras form a well-defined arc (Fig. 5) more than 25 km long (García de Domingo *et al*., 1990); its shape could be attributed to a drag effect of a fault. In this case, it should correspond to the Cadiz-Alicante fault zone.

Onshore, in the gulf of Cadiz, Malod and Didon (1975) and Malod and Mougenot (1979) indicate the existence of ENE to NE faults, some of which could be interpreted as belonging to the Cadiz-Alicante fault zone, but on the whole they cover a wider area. Maldonado *et al*. (1999) also describe faults in this region that could be considered the prolongation of the Cadiz-Alicante fault zone.

The relationships of the Cadiz-Alicante Fault to the geologic evolution of the Betic Cordillera

As indicated in the previous geological setting, when the Algero-Provençal Basin opened (Boillot *et al*., 1984), the Betic-Rif Internal Zone began to be pushed westwards (Durand-Delga, 1980; Durand-Delga and Fontboté, 1980; Wildi, 1983; Sanz de Galdeano, 1990; López Casado *et al*., 2001, etc.) and collided with other domains such as the Betic External Zone. Consequently, during the early Burdigalian, the Subbetic basin was destroyed at the same time the Internal Zone was practically inserted into it. Nevertheless, the westward pushing continued for the rest of the Burdigalian and the middle Miocene, provoking the formation of the Cadiz-Alicante fault zone. According to Sanz de Galdeano (1983), De Smet (1984 a and b), Soria *et al*. (1992) and Soria (1993 and 1994) the most important movements of this fault occurred at the end of the early Burdigalian.

These movements permitted the continuation of the westward displacement of the Internal Zone, simultaneously dragging part of the External Zone, especially the southerly sectors of the Subbetic. In fact, the Subbetic was completely cut off in the easternmost part of the cordillera, in such a way that the Prebetic is in contact with the Internal Zone. There the contact between the Internal and External zones and the Cadiz-Alicante Fault coincide. To the west, the Subbetic is progressively better conserved and the Cadiz-Alicante Fault locally coincides with the contact between the two zones. This is not a complete coincidence given that the contact between the Internal and External zones is irregular, while the Cadiz-Alicante Fault is practically rectilinear.

In the late Miocene, the westward displacements of the Internal Zone practically stopped because the

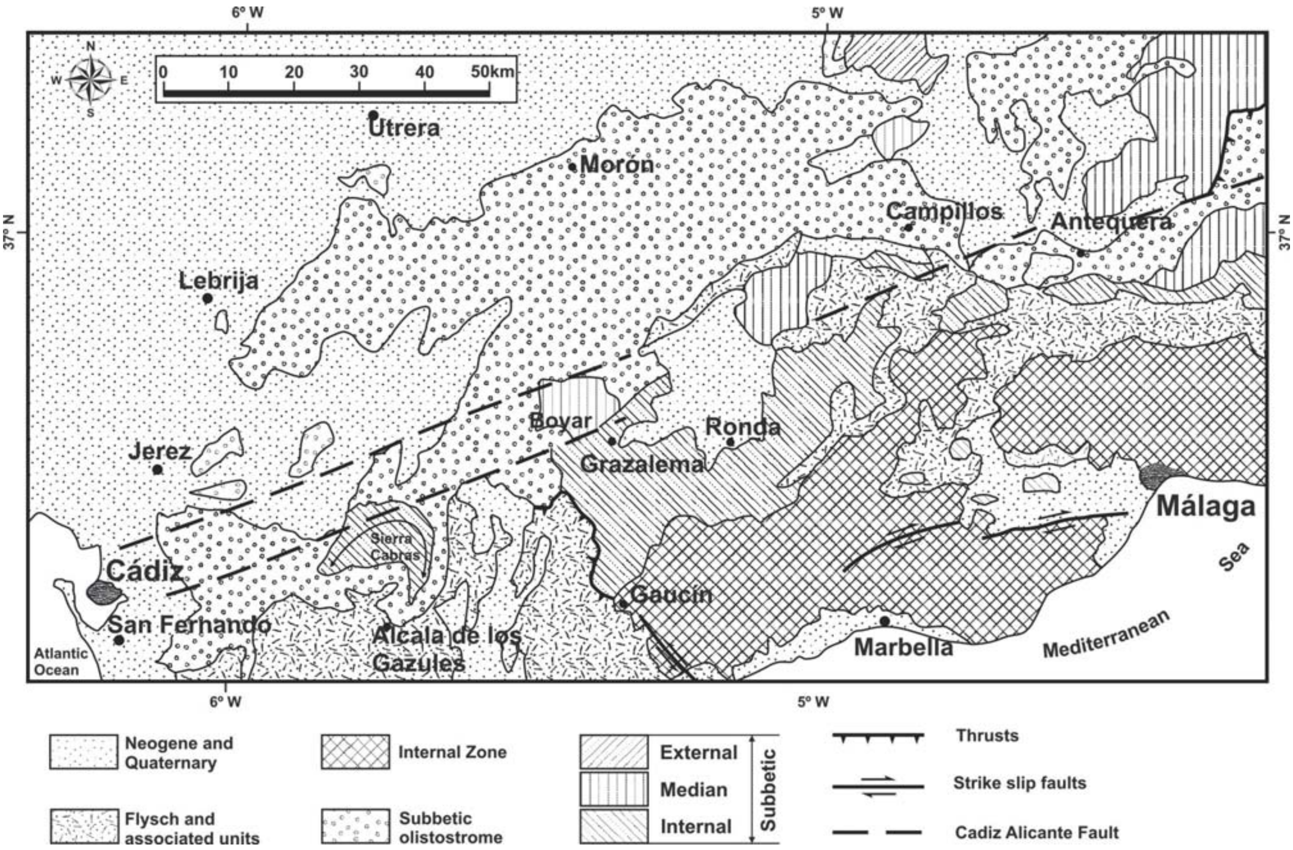

Figure 5.- Geological sketch of the western part of the Cadiz-Alicante zone of faults. Its position is marked in figure 1.

geodynamic situation changed in the Betic Cordillera, becoming dominated by a nearly N-S compression (with some oscillations to the NE and especially to the NW), combined with a roughly perpendicular extension (Galindo-Zaldívar *et al.*, 1993 and 1999). From this time to the present, the dextral displacement of the Cadiz-Alicante Fault practically ceased, but as it constituted a major crustal discontinuity in the Betic Cordillera, every segment of this fault could move independently, according the local conditions of each sector. That is, from the late Miocene the Cadiz-Alicante Fault really has been divided in different smaller faults, each with its own characteristics.

The coexistence of the compression and the perpendicular extension can be explained by changes in the position of $ó_1$ and $ó_2$, while the position of $ó_3$ remains constant, invariably in the ENE-WSW direction. When $ó_1$ is horizontal, in a more or less N-S direction, $ó_2$ is vertical, and the compression dominates. When the positions of the two axes are interchanged, the extension becomes dominant. This last feature has been more important in the intramontane basins formed from the Tortonian (Sanz de Galdeano and Vera, 1992) and was especially facilitated by NNW-SSE faults and to a lesser extent by other NNE-SSW faults (Sanz de Galdeano and López-Garrido, 2000; Rodríguez-Fernández and Sanz de Galdeano, 2006). The first faults controlled the formation of the cited depocentres in the Granada and Guadix-Baza basins (Sanz de Galdeano *et al.*, 2007) and, at least partially, in the Crevillente-Elche-Alicante sector.

It is worth emphasizing that practically the northern limit of these faults and especially that of the depocentres that they formed is constituted by crustal discontinuity formed by the Cadiz-Alicante Fault (Fig. 6). This discontinuity accommodated, from the late Miocene, the extension, which is especially evident in the Internal Zone. In some cases the depocentres are deep, more than 2 km in the Guadix-Baza basin (Alfaro *et al*, 2008) and even slightly more in the Granada Basin (Rodríguez-Fernández and Sanz de Galdeano, 2006).

To equilibrate in the depth the subsidence of these depocentres it is necessary that the NNW-SSE faults and the Cadiz-Alicante Fault reach depths greater than 10 or even 15 km. In fact, some earthquakes with these hypocentral depths or even deeper may be related to the first set of faults (Henares and López Casado, 2001). These features, together with the existence of the volcanoclastic rocks possibly linked to the Cadiz-Alicante Fault, appear to indicate that it may cut completely through the crust.

This control of the north border of the depocentres is, from the late Miocene, the most noteworthy feature of the discontinuity formed by Cadiz-Alicante Fault. At this time, some lateral movements occur, but they were much more limited than the previous ones. Some data indicate dextral displacement affecting Plio-Quaternary sediments at two points of the Guadix-Baza Basin and a

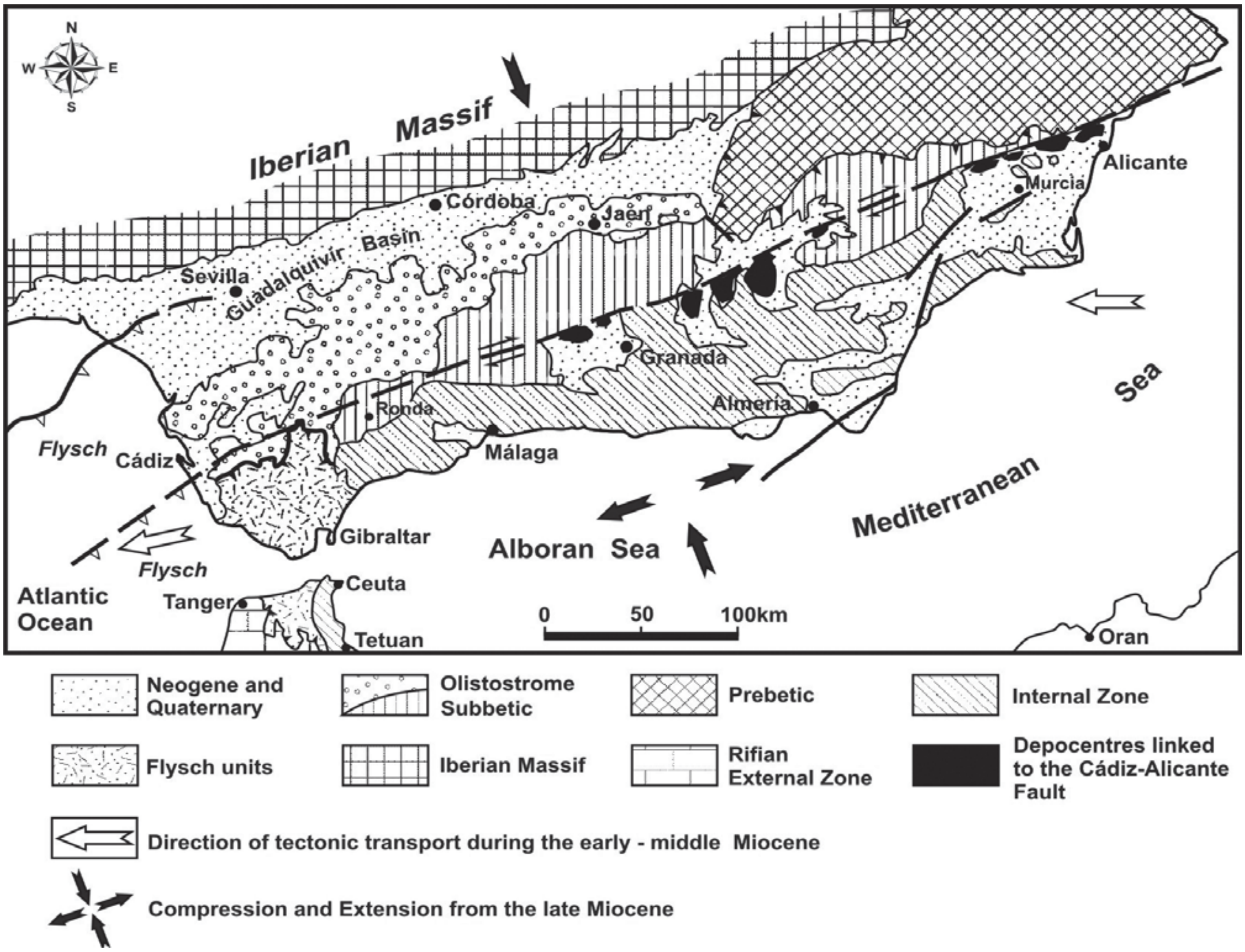

Figure 6.- Direction of tectonic transport during the early (Burdigalian)-middle Miocene and the later formation of depocentres limited by the Cadiz-Alicante Fault from the late Miocene and controlled by a near N-S compression and a major perpendicular extension.

sinistral displacement can be seen at one point. This latter type of movement has been cited in the Crevillente sector (Loiseau *et al*., 1990). This sinistral strike slip can be easily explained if the position of $ó_1$ has a NNE-SSW direction, as local and temporally occurred.

When the direction of $ó_1$ is situated near the horizontal (with a N-S to NNW-SSE direction) the discontinuity formed by Cadiz-Alicante Fault tends to remain immobilized or to move as a reverse fault. This is the case of the Mula (Murcia) earthquake, the focal mechanism of which corresponds to a reverse fault, and the same occurs with its aftershocks (Buforn and Sanz de Galdeano, 2001; Buforn *et al*., 2005). These earthquakes have been related with the Cadiz-Alicante Fault (Martínez-Díaz *et al*., 2002; Sanz de Galdeano and Buforn, 2005).

It is not easy to calculate the displacement of the Cadiz-Alicante Fault because of the lack of good references. Sanz de Galdeano (1983) estimated values of around 50-100 km, but this is a hypothesis. According to Nieto and Rey (2004) the movement could be about 75-100 km, comparing the current distribution of Subbetic facies at the two sides of the fault.

Finally, an indirect argument to demonstrate that the Cadiz-Alicante Fault constitutes a discontinuity in the Betic Cordillera is provided by examining the residual magnetic anomalies (Ardizone *et al*., 1989; Instituto Geográfico Nacional, 1992) that continue from the Iberia Massif in the basement under the External Zone. These anomalies are interrupted in the position of this fault (Fig. 7). For instance, this happens with the negative anomalies corresponding to granite plutons of the Iberian Massif. These anomalies are interrupted to the ENE of Granada. To the ESE of this interruption, there are other ones negative anomalies, but in this case they could be attributed to orthogneisses situated in the Nevado-Filabride, the former origin of which is situated many kilometres to the E.

Conclusions

a) The Cadiz-Alicante Fault facilitated the continuity of the westward displacement of the Internal Zone, simultaneously dragging part of the Subbetic. This happened during the collision of the Internal Zone with the External, which was heavily deformed, particularly the Subbetic. In many cases this fault is a fault

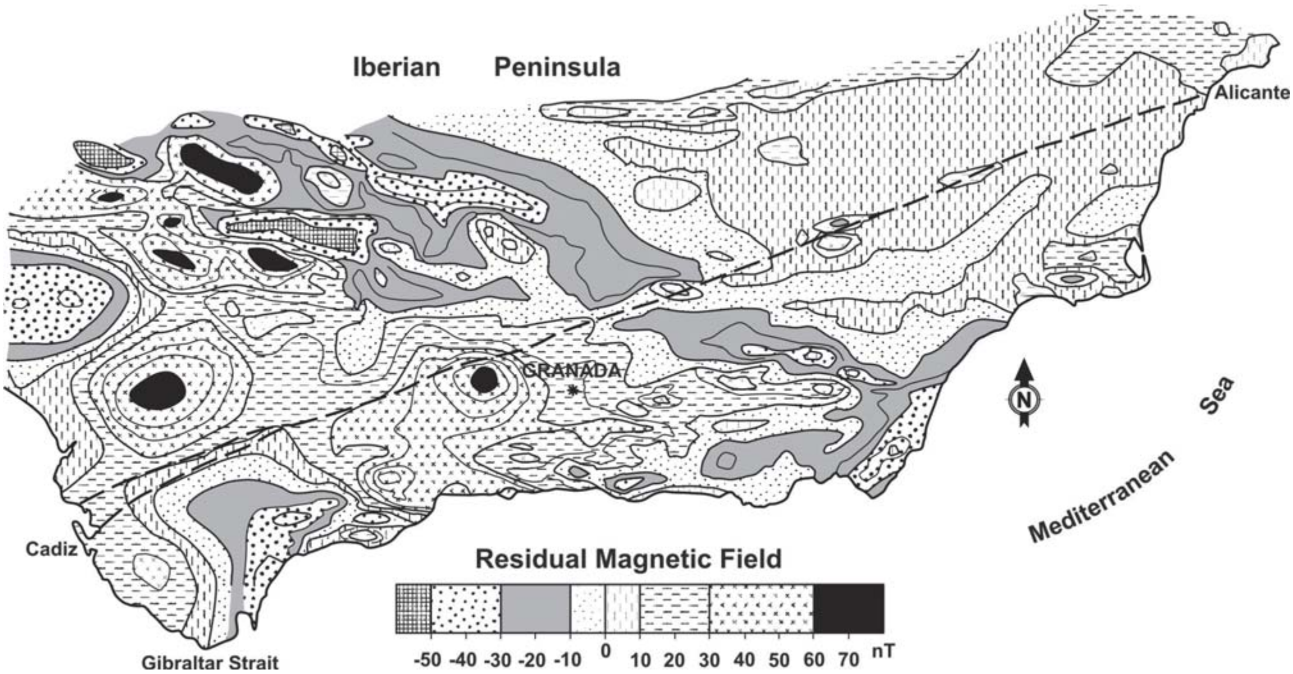

Figure 7.- Map of the magnetic residual anomalies of southern Spain. Extracted and simplified from the general map of the Mapa Aeromagnético de España Peninsular (Instituto Geográfico de España, 1992). Some isolines and plots are simplified to accommodate the small scale of the figure.

zone, expressed by several parallel surfaces. The displacements of this fault produced an important crustal discontinuity.

b) The Cadiz-Alicante Fault passes progressively from a partial coincidence with the contact between the Internal and External zones (in the eastern part) to be situated in middle of the Subbetic (in the western part). This happens because the insertion of the Internal Zone had an oblique wedge shape, in such a way that in the eastern sector the Subbetic was even completely cut through in some places.

c) The total displacement of the fault cannot be calculated because of the lack of clear references, though values of 50 to 100 km would be acceptable.

d) The crustal discontinuity formed by the Cadiz-Alicante Fault facilitates the sinking of the depocentres controlled by NNW-SSE fault, forming a barrier for the extension to the north. This happened when this fault was practically immobilized at the end of the middle Miocene and an approximate NNW-SSE compression and a perpendicular extension, strongly pronounced in the Granada, Guadix-Baza, Fortuna and Elche intramontane basins, was established in the Betic Cordillera. The extension is less notable to the north of this fault, that is, to the north of the crustal discontinuity, because from the late Miocene every segment of the discontinuity can move independently, not forming then a single fault, but different smaller ones.

e) There are no data indicating that the crustal discontinuity formed by the Cadiz-Alicante Fault had associated relatively deep earthquakes; moreover, the data available indicate that there is not great deal of linked seismicity and what is known at this moment shows reverse focal mechanisms, with a depth of as much as 7 km. In the Guadix-Baza Basin, in coincidence with this fault, there are some earthquakes with a hypocentre situated at 30 km, but it is not certain that this seismicity is be related to the fault. Earthquakes of this depth, but especially those of an approximate depth of 15 km, are linked to NNW-SSE faults in this latter basin. On the other hand, the presence of volcanoclastic rocks formed during the lower Burdigalian has been attributed to an eruption through the fractures of the Cadiz-Alicante zone of faults.

If this last hypothesis is correct, it would mean that the depth of the fault is notable, able to cut through the crust. This interpretation is aided by the fact that the subsidence of the north border of the aforementioned depocentres, on the order of 2-3 km in some cases, need to reach compensation depths at least of 10-15 km, if not more. Also the magnetic anomalies may indicate a cut in the crust.

Acknowledgments

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