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The Torcal de Antequera, an example of a structure formed by a large scale dextral transcurrent system

El Torcal de Antequera, un ejemplo de estructura formada por un importante sistema transcurrente dextrorso

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ABSTRACT

The Torcal de Antequera is situated in the Penibetic (part of the Betic External Zone) very near of the contact with the Internal Zone. It has an E-W fusiform shape and corresponds to a monocline structure, surrounded and uplifted by large scale dextral strike-slip faults. Its interior includes a large number of map-scale fractures, most of which can be explained by a mega dextral shear system. The minor structures measured, linked to the faults, are also consistent with this shear system and with its progressive evolution. The deduced predominant direction of σ_1 is NW-SE, congruent with the oblique displacements occurred between the Internal Zone and the Penibetic in this area; the Torcal area is one of the megastructures formed by it.

Keywords: Betic Cordillera, Penibetic, faults, wrench faulting, dextral shear system.

RESUMEN

El Torcal de Antequera está situado en el Penibético (parte de la Zona Externa Bética) cercano a la Zona Interna. Tiene una forma ahusada en la dirección E-O y corresponde a una estructura monoclinal, rodeada y levantada por grandes fallas de desgarre dextrorsas. En su interior existen innumerables fallas, la mayoría de las cuales pueden explicarse dentro de un sistema de desgarre dextrorso a gran escala. Las estructuras menores medidas, ligadas a las fallas, son consistentes con este sistema de cizalla y con su progresiva evolución. La dirección predominante de σ_1 deducida es NO-SE. En esta área, el sistema de cizalla está ligado a los desplazamientos de la Zona Interna en relación con el Penibético; el área del Torcal corresponde a una de las megaestructuras formadas en él.

Palabras clave: Cordillera Bética, Penibético, fallas, desgarres, cizallas dextrorsas.

Introduction

Many structures are formed under transcurrent tectonic systems. In many cases, they are small structures linked to strike-slip faults, metric to hectometric sized, but sometimes they correspond to large structures such as pull-apart basins (Harding, 1974; Sylvester, 1988), greater to tens and more kilometres. Such type of structures is now investigated in the Torcal de Antequera, which has a spindle-like form some 13km in length and is surrounded by important faults.

The Torcal de Antequera (Figs. 1 and 2), the first site in Andalusia (S of Spain) declared, in 1929, a place of national interest is a natural park. It has been widely studied in terms of hidrogeology, stratigraphy and even in the fracture analysis (at least in its general geometry). Nevertheless, many of the aspects linked to the fracture genesis and even to the structure of the Torcal, remained to be examined.

The Torcal forms part of the Betic Cordillera, which is divided in two main zones, the Internal and External. The Internal Zone is formed by four complexes, tectonically overthrusted, that from bottom to

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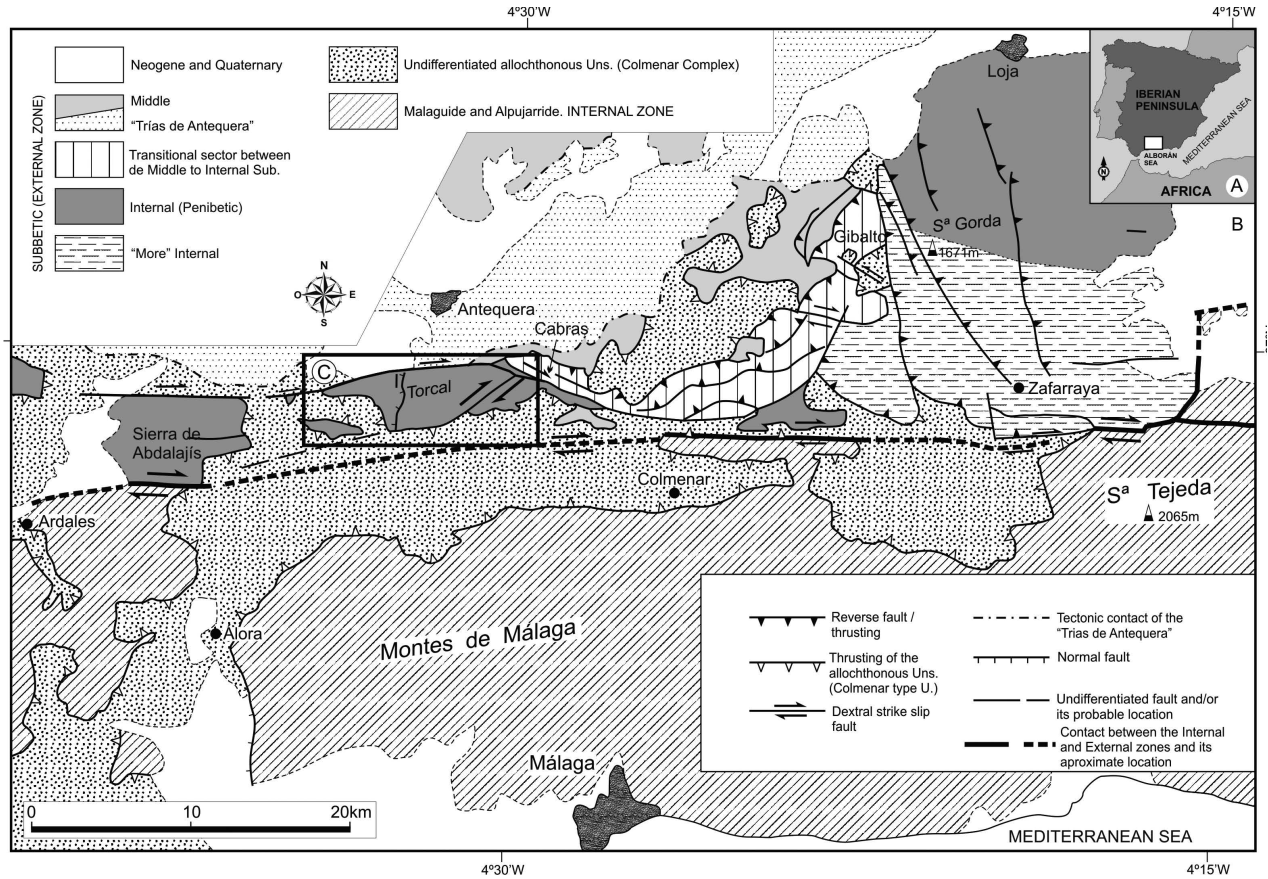

Figure 1.—Regional setting of the Torcal de Antequera. A: Location in the Betic Cordillera. The square corresponds to B. B: Position of the Torcal in the central part of the Betic Cordillera. The square marked with C corresponds to the Figure 2.

top are the Nevado-Filabride, the Alpujarride, the Malaguide, and the Dorsal. The first three complexes have rocks from the Precambrian to the Mesozoic and even to the Tertiary, while the Dorsal presents only Mesozoic and Tertiary rocks. The first two complexes have undergone major Alpine metamorphism.

The External Zone is divided in Subbetic and Prebetic domains, constituting the previous sedimentary paleomargin of the Iberian Massif. The series of both domains go from the Triassic to the Tertiary. The Subbetic usually is divided (García Dueñas, 1969) into the External, Middle, and Internal, with stratigraphic differences particularly in their Jurassic series. The Internal is at present situated more to the south, while its western part is usually called the Penibetic. The equivalence between these last two names is not complete, but both names can be applied to the Torcal.

Moreover these two zones, there are also in the Betics the Flyschs units and the Neogene basins, these latter formed above all the previous geologic domains.

The Subbetic, and particularly the Penibetic, underwent the push of the Internal Zone (Andrieux *et al.* 1971; Durand Delga and Fontboté, 1980; Wildi, 1983; Martín Algarra, 1987; Sanz de Galdeano 1990 and 1996, etc.) in a transpressional oblique collision, which brook-up its former sedimentary disposition. This happened during the early Miocene, particularly during the Burdigalian (Burdigalian paroxysm of Hermes, 1985), diminishing the deformations through the middle and late Miocene. This is the time when the tectonic units of the External Zone were formed, generally being displaced to the NW, WNW, and to the W, as happened in good part of the Penibetic.

State of the problem and aim of the paper

Many of the previous findings of the study in the Torcal area can be found in Peyre (1974), who describes its stratigraphic series and also the struc-

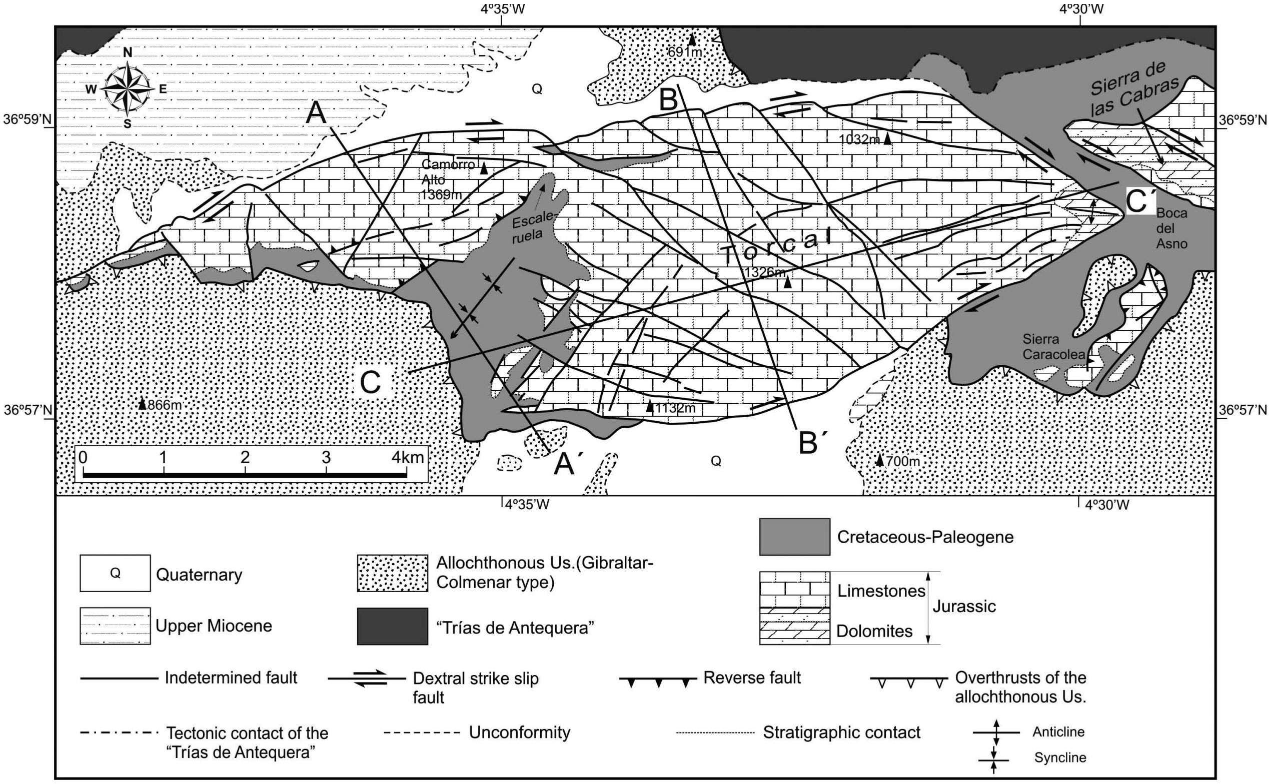

Figure 2.—Simplified geological map of the Torcal de Antequera. The positions of the cross-sections of Figure 4 are indicated. Its location is indicated in Figure 1.

ture, particularly the abundance of faults and the existence of knee folds in the borders of the Torcal. This agrees with the interpretation of Blumenthal (1930), who, according to Peyre, interpreted the structure of the Torcal as a mushroom fold, in which the upper part is tabular and the flanks vertical or even reversed. These flanks are bordered by faults.

The maps of the IGME, nº 1038 and nº 1039 (Barba Martín *et al.*, 1979 and Cano Medina, 1991) include the area of the Torcal, and also describe its stratigraphic and tectonic aspects. Barba Martín *et al.* (1979) seem to accept the existence of the mushroom fold, although they describe the structure as being a monocline.

Martín Algarra (1987) described the entire series of the Penibetic and also presents a general tectonic interpretation, summarized in its figure 179, indicating a synthesis of the transcurrent movements affecting it, whose first cause is the collision of the Internal Zone.

Sanz de Galdeano (1996) showed the importance of the transcurrent displacements to the south of the Torcal, which continued to the W and E, in this case as the prolongation of the Alpujarran Corridor. These displacements agree with those of the different segments into which the Internal Zone is divided. Later, Sanz de Galdeano *et al.* (2008), studying the “Trías de Antequera”, indicated an important dextral fault situated on the northern border of the Torcal. Sanz de Galdeano (2012) described the genesis of the Cabras-Gibalto arc, situated immediately to the east of the Torcal (Fig. 1) and indicated the importance of the transcurrent faults in the Subbetic, linked to the displacement of the Internal Zone. Also, Serrano and Guerra-Merchán (2004) described the main geological features of the Torcal, but without interpreting the genesis of the structure.

Balanyá *et al.* (2008) described the tectonics of the Alta Cadena (High Chain – a name taken from Peyre, 1974), but including a different area from that of the original name. In the case of the former authors includes the Sierra de Abdalajis — or Huma – towards the west, till the Sierra de las Cabras towards the east (Fig. 1). These authors indicated that the tectonics of this area can be considered to be a transpressive zone of deformation with a dextral sense of shear, although they offered no details for the Torcal area. There they cited open folds of N40-60 strike and the major dextral fault of the north of the Torcal. Crespo-Blanc (2008) studied a region situated to the east of the Torcal and compared it with an analogical model, emphasising the importance of the oblique collision of the Internal Zone. Díaz Azpíroz *et al*. (2009) and Barcos *et al*. (2011) consider the Torcal as a shear zone, although they not integrated all the sets of faults within it.

Fernández Rubio *et al*. (1981) described the geometry and density of the fractures of the Torcal for application in hydrogeology. Many authors have discussed the hydrogeology of the Torcal, including Burillo Panivino (1998), Pulido Bosch (1993), etc. Among the papers dealing with geomorphology, an important one was that of Lhénaff (1977).

From the antecedents, it can be deduced that part of the structure and particularly the aspects linked to the genesis of the fractures remain to be clarified. This clarification is the aim of the present article, particularly the integration of the structure within a major dextral transcurrent system. Great part of the new data correspond to the analysis of the characteristics linked to minor faults and also to the surfaces of the major faults, particularly those indicating the sense of the displacement.

Geological setting

The Torcal is situated about 25km to the NNW of Malaga (Fig. 1), very near to the contact with the Internal Zone, there represented by the Malaguide complex. To the north of the Torcal is the "Trías de Antequera", formed by Triassic rocks, but including other of Jurassic, Cretaceous and Tertiary ages (Sanz de Galdeano *et al*., 2008). It is a tectonic melange, passing to an olistostrome, covered in many places by sedimentary breccias. To the east, the Cabras-Gibalto arc is formed by Subbetic elements with intermediate characteristics among the Middle Subbetic and Penibetic; also several Penibetic units exist. The Penibetic continues westwards, in the Sierra de Abdalajis, and particularly to the south of Ronda.

The stratigraphic series of the Torcal is formed at the bottom by lower Liassic dolomites, outcropping only in its eastern end, in the sector of the Boca del Asno (Fig. 2). Regionally, these dolomites are several hundred metres thick, but in the Torcal only about 50m are visible (moreover, in the External Zone, under the dolomites, Triassic sediments formed by clays, silts, sands and carbonates exist, although they do not outcrop in the Torcal). The dolomites are overlain by limestones measuring more than 300m thick, going from the early Liassic to the transition from the Jurassic to the Cretaceous (Berriasian). Most of these limestones are oolitic and some are also of nodular character, in many cases red, alternating with the former and generally in the top of the series. In some places, separating the Jurassic limestones from the lower Cretaceous white marlstones, there is a hardground, but generally the first Cretaceous sediments correspond to salmon marlstones of the late Cretaceous-Palaeogene, with a conserved thickness at least 50m.

In this area, the Flysch units back-thrust the Malaguide and the Subbetic. These units are well represented more to the west, particularly in the Gibraltar area. The former basin where the sediments of the Flysch units were deposited was destroyed by the advance of the Internal Zone, pushing them to the west, but also part of the new units moved to the east, as happened here. The internal structure of these units is complex, but on the whole they can be considered as a uniform tectonic cover (Fig. 1) which in diverse points of the cordillera thrust lower Miocene sediments (Serrano *et al*., 2006). They are here called "Undifferentiated allochthonous Flysch units", or "Colmenar complex".

There are also upper Miocene to Quaternary sediments, deposited after the formation of the structure of the Torcal. Those of the late Miocene are of shallow marine character and today exceed 600m in height, clearly indicating a strong uplift.

The structure of the Torcal

The main topographic feature of the Torcal is its high relief, forming an immense wall along the northern border and good part of the southern one. In many places the wall height surpasses 400m. To the west, the relief progressively disappears.

The northern border comprises not only the Torcal mountain, but also its western prolongation, the Sierra de la Chimenea, the main peak of which is the Camorro Alto (it is necessary to include this latter area, in order to understand all the structure). Between these two sierras is the only depression of

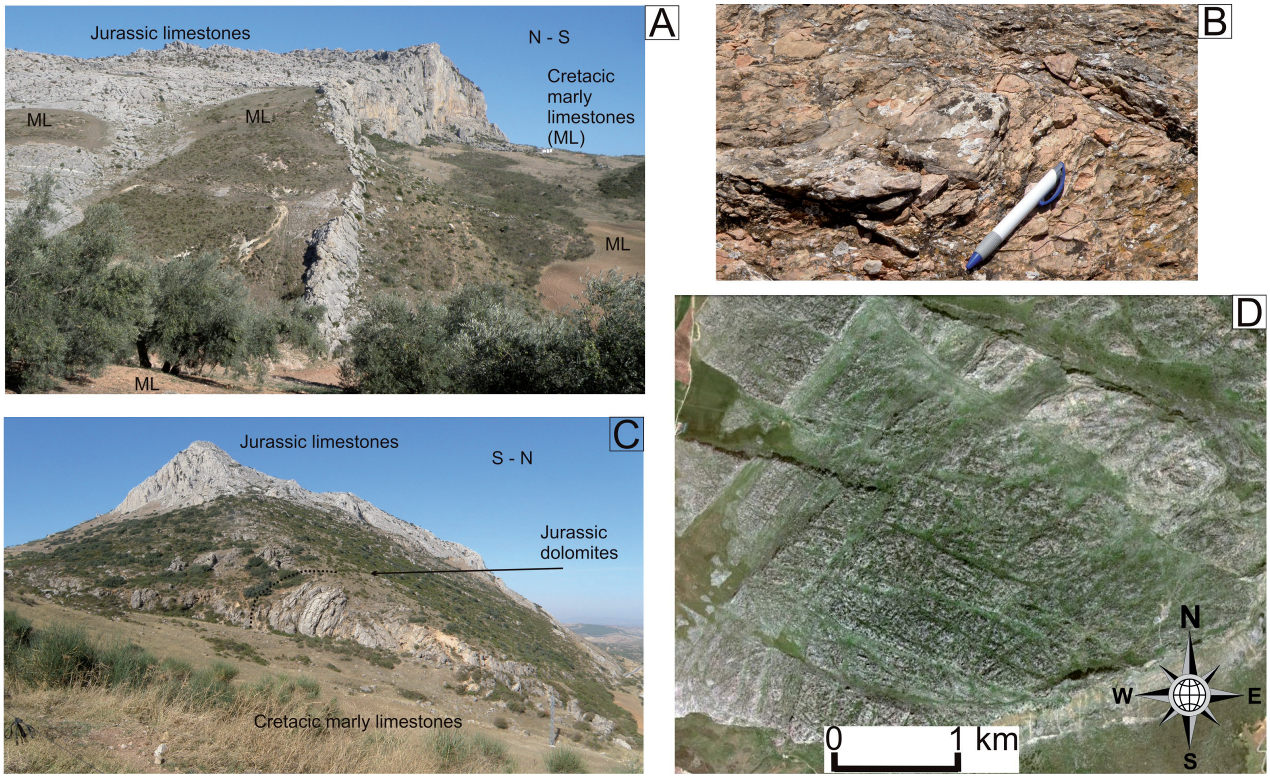

Figure 3.—A: view of the sharp western end of the fault of the southern border of the Torcal. Near the point of the limestones and also to the right, the minor structures of the station 3 were measured. B: example of one of the S-C structures examined in the sector shown in A. The rocks correspond to Cretacic marly limestones. The East is approximately to the right of the photo. C: eastern end of the Torcal, the only place where the dolomites outcrop. The roughly south vergence of the anticlinal is marked. D: view of part of the SE sector of the Torcal where the fracturing is very dense (taken from Google). Its position is marked in Figure 5.

the wall on the northern border, in the area called La Escaleruela. This is due to the presence there of late Cretaceous sediments, which are less resistant against the erosion.

The general strike of this border is E-W, although with several deviations, particularly on its eastern end, where its direction is NW-SE. Moreover, there are small breaks in the scarp at points where it is cut by oblique faults. This is indicated in Fig. 2. The erosion and the colluvial sediments have smoothed these breaks. On the whole, this border is a great dextral fault, with striae and grooves especially visible at its ends and in the Escaleruela area. To the west, the fault disappears, forming narrow, sharp relief and farther is covered by soft sediment of the Flysch units and thus cannot be seen, but in fact it continues more to the west, to the north of the Sierra de Abdalajís, as detected through two small tectonic windows where the Penibetic is visible.

The southern border is shorter and also is cut by some oblique faults. Its scarp disappears about 2.5km to the south of La Escaleruela, where it forms a sharp end (Fig. 3, A). The minor structures formed in the Cretacic marlstones situated near the scarp clearly indicate that the border corresponds to an important dextral fault (Fig. 3, B).

Both faults delimit the Torcal, except in the western part, where the structure is sunken. On the whole, the general shape of the Torcal is roughly a large spindle or a ship with the bow uplifted (to the east). There, the dolomites form an anticline with an approximately E-W axis, verging to the south (Fig. 2 and Fig. 3 C).

In the interior of the Torcal, although having wide and smooth big folds, the general structure is practically a monocline (Fig. 4). Nevertheless, in some places appear small folds (metric to decametric), generally drag folds, sometimes linked to the faults cutting the structure. To the west, the sinking

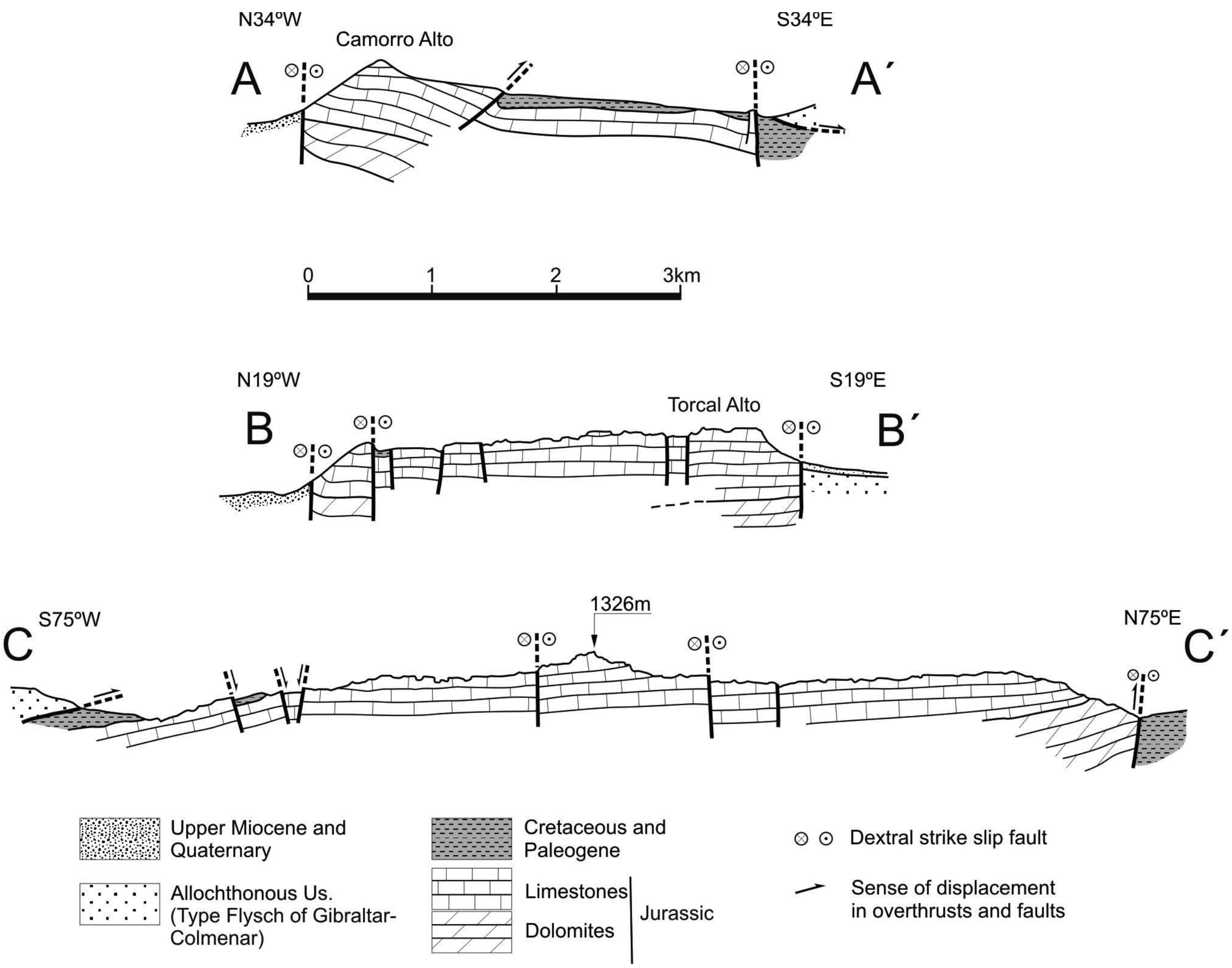

Figure 4.—Geologic cross-sections of the Torcal. Their positions are indicated in Figure 2.

of the structure, together with the more or less monoclinal structure of the Camorro Alto, dipping to the south (with some folds associated and many faults), would lead the sector of La Escaleruela to be interpreted as a syncline (Fig. 2), but in fact its flanks are no equivalents.

According to our data, the structure of the Torcal cannot be considered a great mushroom fold. We made a detailed examination of its borders, which generally show a sharp cut of the monoclinal structure (Fig. 4). At some points, the beds change more or less their dipping and strikes, but generally there is no vertical disposition of these beds in the borders. Only in a small sector of the south border do some beds strongly dip in this direction, but apparently corresponding to a local drag effect of the fault. Fig. 3 A shows this cut of the structure and the sharp end of the scarp, where the Jurassic limestones are cut.

The fractures within the Torcal

The famous karstic relief of the Torcal is facilitated by the near horizontal position of the beds and by its very intense fracturing (Fig. 5). Fig. 3 D shows one of the areas where the fracturing are more developed. There are several sets of fractures: set one, about E-W to N70ºE of strike; set two, NW-SE with some deviations; set three, NNW-SSE; and set four, approximately NE-SW.

In most of these fractures, it is not possible to distinguish whether they are faults or only joints, because only in recent sections are their surfaces

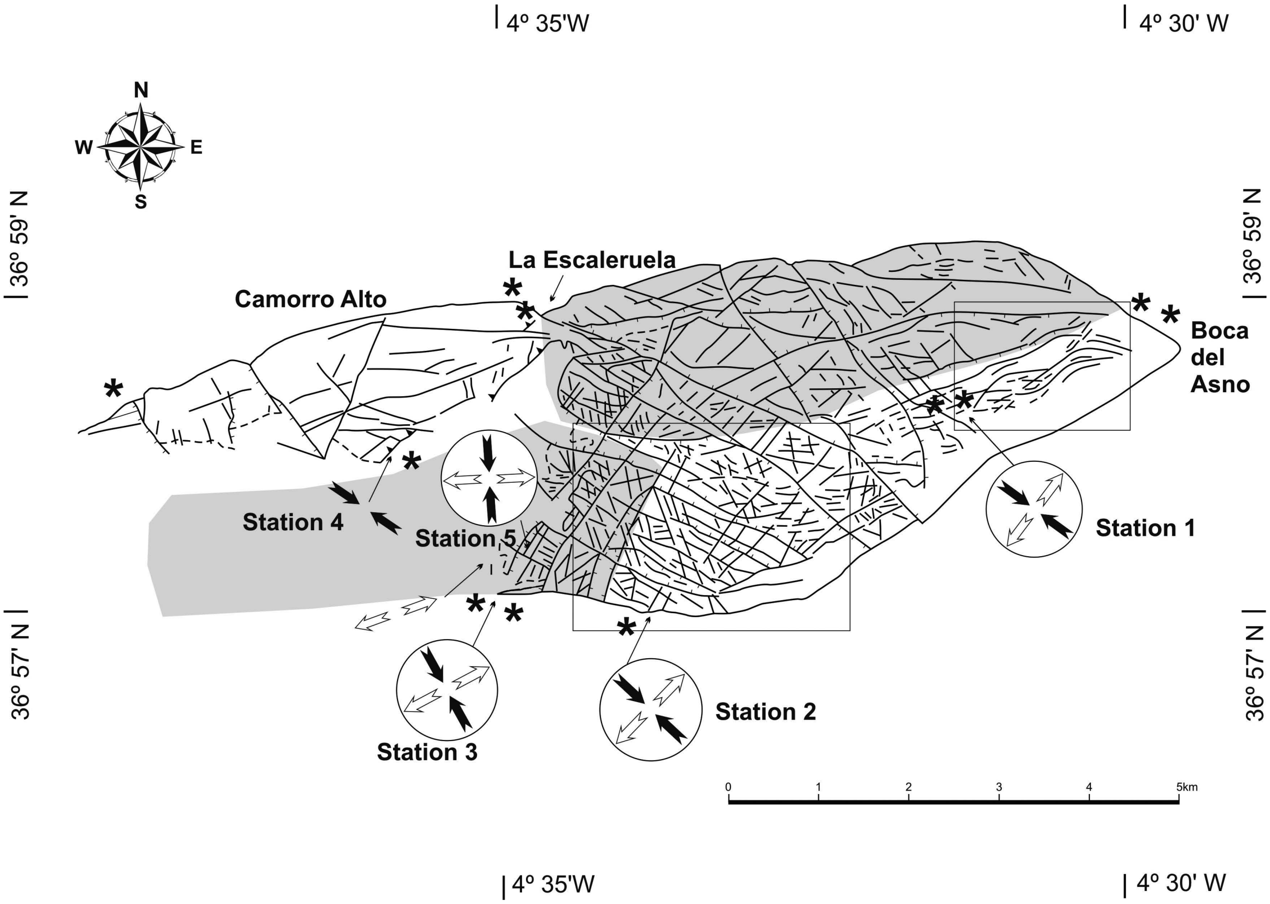

Figure 5.—Sketch of the fractures in the Torcal-Camorro Alto area. The position of the five stations of measures of minor structures (Fig. 7) is indicated. There, black arrows show the direction of compression, white arrows the direction of tension. Stars indicate other points where minor structures were measured. Grey colour differentiates the NE and SW sectors. The squares indicate the positions of D of the figure 3 and E of the figure 6.

with minor structures visible. In some cases, the faults, most of them vertical, have a clearly visible throw (greater than 100m in some cases).

The examination of recent sections indicates an overwhelming predominance of horizontal displacements. This is also corroborated by aerial photographs and satellite images revealing these types of displacements that some faults cause to others.

In the Torcal-Camorro Alto area, four sectors can be distinguished according to the topography and at the same time to the density and importance of the faults (Fig. 5). The NE sector bears the largest throws of the faults. This sector, although clearly uplifted comparing with the exterior, progressively sunk in this direction. That is, there are several steps that sunk the structure from the interior of the Torcal. In some cases, the throw of these faults can be calculated, comparing the displacement of the beds of the red nodular limestones. These faults are generally vertical or near vertical and, when minor structures are visible they indicate that the horizontal component of the displacements is the predominant.

The SE sector, the highest sector of the Torcal (although the highest peak is Camorro Alto), also presents abundant vertical faults (in many cases can be seen vertical displacements, but when it is possible to observe the striae, generally they are nearly horizontal). In any case, these faults produce less pronounced steps.

The NW sector is also highly fractured, where some reverse faults are easily detected when the Jurassic limestones thrust the Cretaceous marls and marlstones. This sector is uplifted compared with the adjacent ones. The last sector, the SW, is relatively sunk and is occupied by the allochthonous Gibraltar-Colmenar units (Fig. 2).

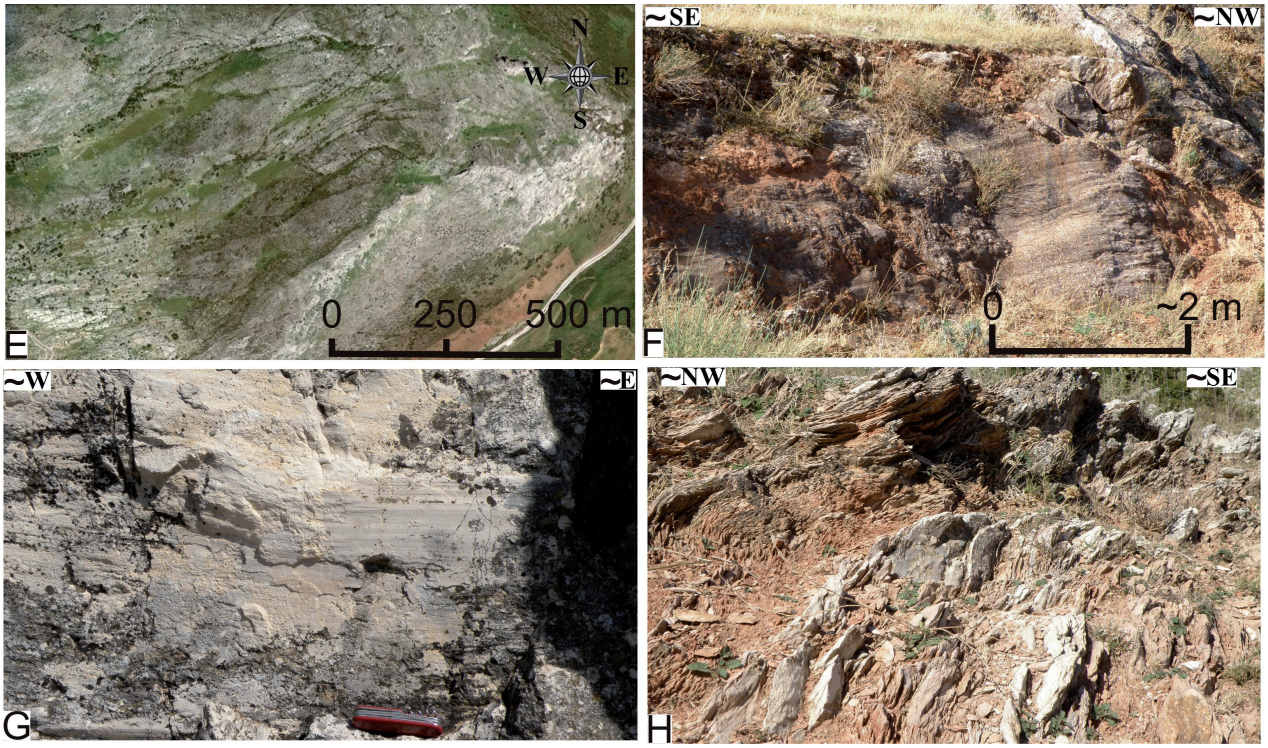

Figure 6.—A: area of the eastern of the Torcal where the curved fractures are visible (taken from Google). B: detail of the surface of the fault in the ENE border of the Torcal. The NW is to the right. C: detail of a surface of a minor fault. This is on the road to the booster station and has more or less an E-W direction. The W is to the left. D: detail of the drag produced in the Cretacic marly limestones by a reverse fault situated to the SE of Camorro Alto. At the top of most of these structures, there are calcite fibres, indicating the direction of the tectonic transport. Its position (station 4) is marked in Figure 5.

This differentiation in sectors cannot be taken in a rigid way, because the limits of the sectors can vary according to the geologic evolution, the position of each place, and the orientation of the structures at each site.

Finally, an unusual fracturing feature can be cited (Fig. 6 A). This is visible in the limestones of the eastern part of the Torcal. They correspond to sets of vertical joints forming acute angles, passing to eastern extreme of the Torcal to be warped, curved vertical fractures. The important superposed karstification does not permit to see displacements associated to them.

Minor structures linked to faults

These features have been examined in the great dextral faults of north and south borders, in fresh sections of roads, in an old quarry, and in upper Cretacic marlstones located near the main faults.

In the western end of the fault of the northern border of the Torcal, the grooves of its surface have a rake of about 20 degrees to the west. There are also parallel striae, indicating dextral displacements (and also some small and near-vertical striae, with a slight dextral component). In the area of La Escaleruela, there are many associated small faults presenting dextral movements, which affect Jurassic limestones and Cretacic marlstones. In the eastern part, the area of La Boca del Asno, where the fault has a NW-SE strike, a good exposure of striae and grooves is visible for more than 200m. Most of them dip about 20º to the SE and indicate dextral displacements, but others have greater rake and still others are horizontal (Fig. 6 B). On the whole, they clearly reflect the dextral character of the fault of the northern border, but also the vertical component of this fault, which contributed to the uplift of the Torcal.

In the vicinity, in the Sierra de las Cabras, as well as in the Boca del Asno, clear features show horizontal dextral displacements (Sanz de Galdeano, 2012) which indicate the eastward movement of the Cabras-Gibalto arc in relation to the Torcal.

Within the Torcal, minor structures were visible only in some very local places, the walls of two

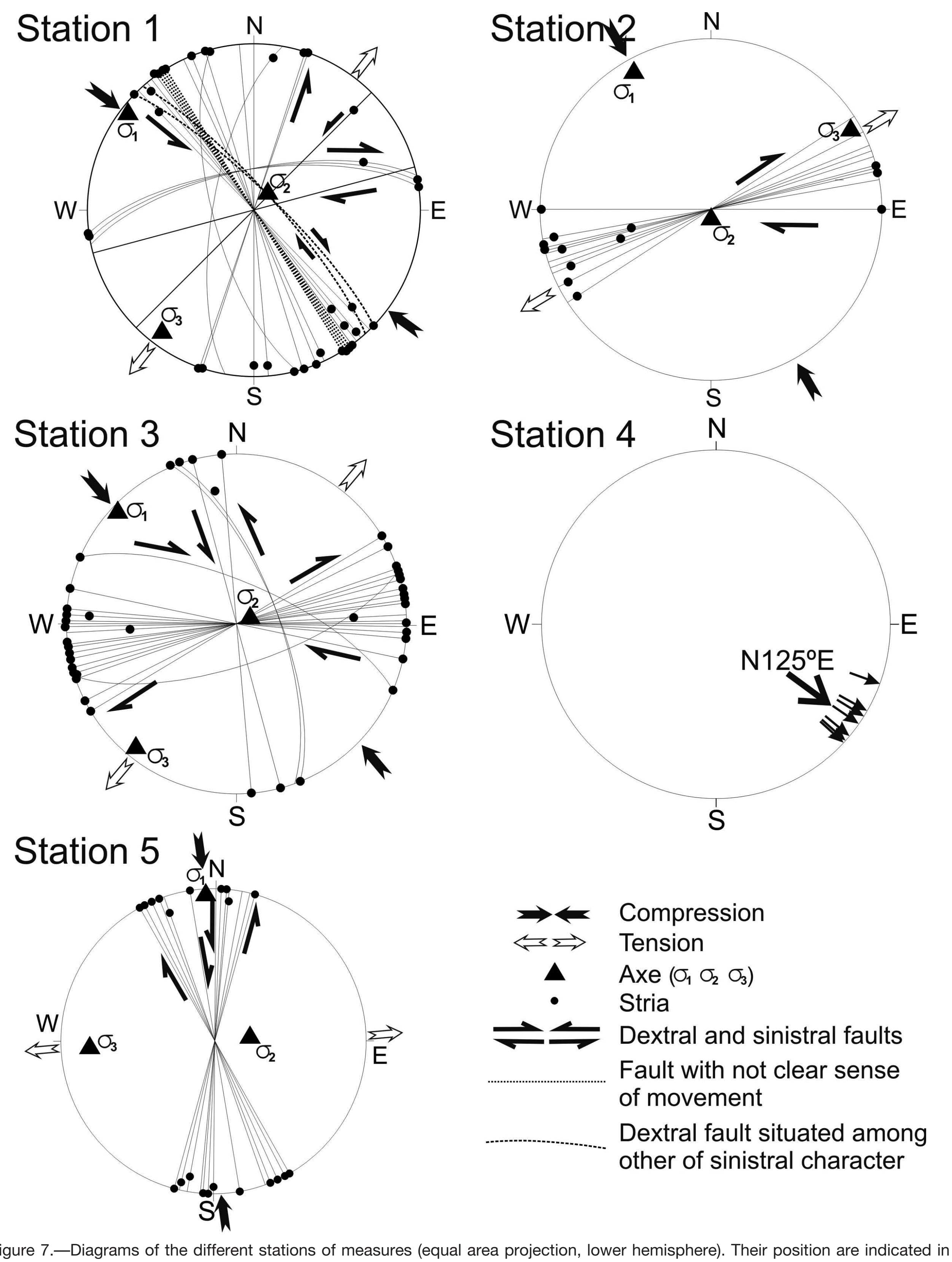

Figure 7.—Diagrams of the different stations of measures (equal area projection, lower hemisphere). Their position are indicated in Fig. 5.

small roads and in an abandoned quarry. In total, 25 faults (Fig. 7, 1) were measured, their striae indicating practically horizontal movements (Fig. 6, C). These measures have been treated by the method of Galindo-Zaldívar and González-Lodeiro (1988) and the result indicate the existence of one fracturing phase in which σ_1 has a direction of N127ºE with a slight dip of 3 degrees, i.e. practically horizontal (Fig. 7 and table 1). In this measures the NW-SE to NNW-SSE faults are predominantly sinistral but there are two exceptions and the sense of displacement of three of the faults is not clear. The reason of these exceptions can be found by two ways. One of them is that these faults have directions very proximal to that of the compression (σ_1) and it can fluctuate something along the time. The second possibility is to consider that they move after, when finally the compression passed to a nearer N-S direction (see data of station 5).

This result means that the compression is practically NW-SE and horizontal; the tension is perpendicular and also horizontal while the intermediate stress axis is nearly vertical. The axial ratio (0.26) indicates a clear difference among the values of the axes, corresponding to a prolate ellipsoid. This is characteristic of tectonic strike-slip faults.

On the southern border of the Torcal two stations of measures (stations 2 and 3) have been made in Cretacic marlstones (see Fig. 2). This type of rock develops minor structures much more easily, compared with the Jurassic limestones. Far from the major faults, these marlstones have relatively few fractures, although they have joints and minor faults, but in the sector strongly affected by the tectonics, many minor structures develop, particularly those related with S-C fragile shears.

The station 2 is located practically touching the fault of the southern border in a place where it has a strike of about N45. We used only 10 measures although many others had the same orientation. They were minor faults, many showing fragile S-C structures, where the calcite fibres indicate the sense of displacement. These fibres have dips oscillating between the horizontal and the vertical, but in most cases, their pitch is about 20º in both senses. The general direction of these minor faults varies from N50 to E-W. Their study indicates only one phase of fracturing, in which σ_1 is oriented in the N332ºE direction with a slight dip of 2º, i.e. practically horizontal (Fig. 7 and table 1). That is, the compression is roughly NW-SE, although a little more to the north than the previous station of the interior of the Torcal, and is horizontal; the tension is perpendicular and practically horizontal, and the intermediate axis more or less vertical. The axial ratio (0.44) indicates a prolate ellipsoid, although less marked than the previous one. This result is congruent with the direction of the fault on the south border at this site and indicates a slight rotation of the stress, which in the proximity of a great fault tends to be perpendicular to it (Anderson, 1951).

Tabla 1.—**Orientation of the axes and axial ratio of the ellipsoids of paleostress in the different stations of measures obtained**

Station number	σ_1 (direction & plunge)	σ_2 (direction & plunge)	σ_3 (direction & plunge)	Axial ratio (σ_2 - σ_3 /σ_1 - σ_3)
1	N127ºE/ 3º	N13ºE/ 82º	N217ºE/ 7º	0.26
2	N332ºE/ 2º	N215ºE/ 86º	N62ºE/ 4º	0.44
3	N314ºE/ 2º	N68ºE/ 86º	N332ºE/ 2º	0.42
4	N125ºE/ —	—	—	—
5	N358ºE/ 1º	N90ºE/ 70º	N268ºE/ 20º	0.01

The station 3 is located in the western, visible, end of the fault of the southern border. The structures also appear in the Cretacic marlstones, about 20m to the west of the end of the Jurassic limestones linked to the fault. Because many structures have the same orientation and characteristics, only 22 measures were used. The S-C fragile structures are abundant, indicating approximately dextral displacements. Moreover, some of the minor faults have a NNE-SSW strike and are sinistral. The analysis made indicated that all the measures are compatible with an ellipsoid in which σ_1 has a N314ºE strike, dipping 2º, practically horizontal (Fig. 7 and Table 1). The axial ratio is 0.42. These data are very similar to those of the previous stations.

Cretacic marlstones thrust by Jurassic limestones, in a reverse fault situated in the SE of the Camorro Alto, present abundant fragile S-C structures (Fig. 6, D) and striae. These latter have a mean direction of displacement of N125ºE. The measures obtained are represented in station 4 (Fig. 7).

South of the Escaleruela sector, the Cretacic marlstones show many minor vertical, straight, and long NNE-SSW faults with the appearance of joints, but the associated calcite fibres indicate sinistral displacements. There is another set of fractures, with NW-SE strikes, in some of which can be detected dextral movements. The measures obtained constitute the station 5 (Fig. 7 and Table 1) and there σ_1 has a N358ºE strike, dipping 1º, and the axial ratio (0.01) indicates a real prolate ellipsoid of stress. This direction of σ_1, N-S, is clearly different to the previous ones.

Dispersed measures of minor faults were made in many other places, in all cases consistent with the previous ones.

Finally, near the western end of the fault on the southern border, the marlstones situated over the Jurassic limestones are sliced in a N250ºE mean direction according to the striations measured on the surfaces of the beds. This caused a basal brecciation and a tectonic unconformity.

Discussion and interpretation of the meaning of the faults

The study of paleostress clearly indicates that the Torcal was affected by an approximately NW-SE compression, within a dextral transcurrent system. During the evolution and formation of the general structure, the direction of the stress would vary from one point to another through time. Figure 5 shows the directions identified in each sector analysed.

Figure 8 A provides a theoretical scheme indicating the different types of faults which can be associated to a dextral transcurrent system, as previously did Harding (1974). According to the orientation of each fault in relation to the ellipsoid of stress, the movements and other characteristics vary. This scheme can be applied directly to the fractures of the Torcal-Camorro Alto (Fig. 8 B). The mean faults or master faults (P), the synthetic or riedel (R) and other dextral faults, including those that also can present a reverse component, are indicated with thicker lines. Some of these faults have also a vertical component, as indicated in Figure 5, although they are generally vertical with a dextral dominant character.

The eastern part of the southern border of the Torcal (near Boca del Asno) has a nearly perpendicular orientation in relation to the σ_1 axis, and consequently its tendency is to have a strong reverse component, although the alluvial deposits do not allow it to be seen. In any case, the anticline existing on the eastern end presents a clear southward vergence, consistent with the aforementioned probable reverse component.

In the area of the Camorro Alto- La Escaruela, the σ_1 axis is more or less perpendicular to the N50ºE strike of the reverse faults existing there. The direction of the striae (N125ºE instead N140ºE, this last direction perpendicular to N50ºE) indicate a slight difference of orientation. All these faults have an SE vergence, although the existence of some reverse faults verging to the north cannot be ruled out.

Another type of fault corresponds to those faults which have an orientation practically parallel to the σ_1 axis (Fig. 5). These faults could move as normal faults (Fig. 8 B), although at the same time they can present dextral or sinistral component (as indicated in station 1). N-S to NNE-SSW faults are antithetic and present sinistral displacement.

The whole of these previous faults can be included within a dextral transcurrent shear system.

However, not all the faults can be interpreted within this system if it did not change in the time (this change is showed in the station 5; see there the direction of σ_1). Moreover, several normal N20ºE-40ºE faults are not directly compatible with this system, because with this direction they must have reverse and sinistral components. These faults are situated mainly to the south of La Escaleruela (Fig. 5).

Part of these different movements (in relation to the theoretical ones expected from the shear system) can be explained by the fact that the response to the stress was different according to the position of every sector of the Torcal area. The higher sectors of the Torcal-Camorro Alto area (those of the SE and NW) directly received the oblique compression due to the westward displacement of the Internal Zone, while those of the NE and SW tended to be stretched, as can be deduced from the Fig. 8 B and can be observed in the field. This stretch appears to be in the N250ºE direction in the SW sector, at least to the south of the La Escaleruela. With this direction of extension, previous N20-40E faults could move later, thus facilitating the stretching, all within the process of the evolution of the shear system.

The variation of the stress ellipsoid itself over time is noted in the Betic Cordillera, where the horizontal regional compression shifted in the early and middle Miocene from a WNW-ESE direction to NW-SE, NNW-SSE and even, in some places, to NNE-SSW, now from the late Miocene (Sanz de Galdeano and Vera, 1992; Sanz de Galdeano, 1990; Galindo-Zaldívar *et al.*, 1993).

The interpretation of the curved fractures at the eastern end of the Torcal can be referred to the beginnings of the formation of the dextral shear system. Presumably this was the time when the eastern end of the Torcal suffered the greatest compression. Then the south-verging anticline formed, and particularly the eastern area of the Torcal was

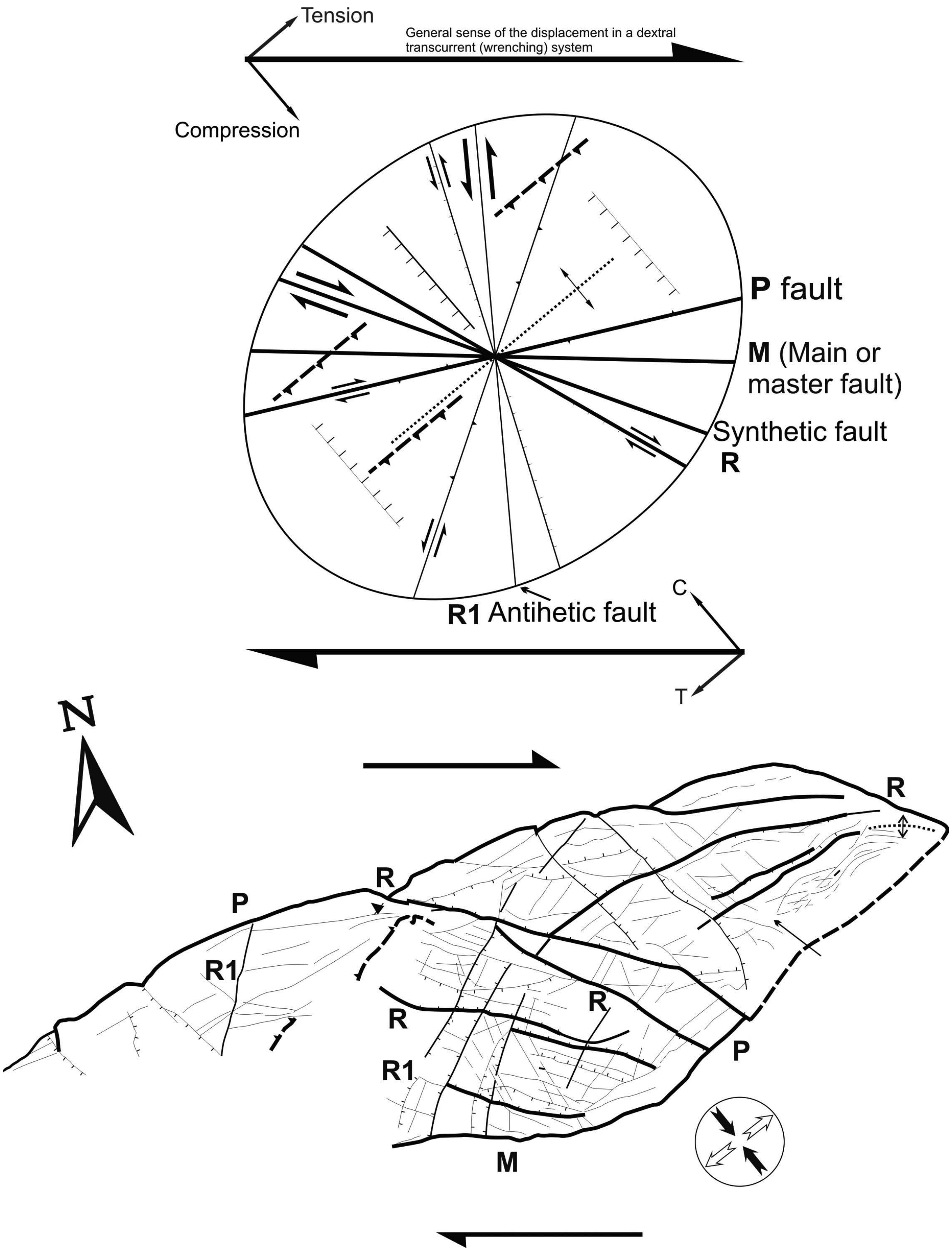

Figure 8.—A: Sketch of the distribution of faults within a dextral transcurrent (shear) system (modified from Harding, 1974). B: Simplified map of the faults in the Torcal where the main faults are compared with their equivalents in A. These equivalent faults are drown with the same thickness or other characteristics, and have the same general orientation. Other less important faults have been not differentiated in order to avoid a greater complexity in the figure, but they are equivalent to the main parallel ones. The Torcal is anticlockwise rotated 10º to facilitate the comparison between A and B. The directions of compression and tension indicated in B correspond to that of station 4, because probably it represents better the more general position of the paleostress.

greatly shortened. At present, we know of no other similar examples. These fractures lose their curvature towards the west, where they become sets of joints, which do not form 30º angles with the σ_1 axis but 50 to 80º. This orientation usually occurs in places submitted to a strong confining pressure, e.g. in metamorphic rocks. This is not the case, but mechanically it seems to present some affinity. Accordingly, we interpret these fractures as having been formed by the interaction of two sets of joints within a strong compression. The curved shape would represent the enveloping of two sets of fractures. It is clear that to be sure of this interpretation, we need more detailed observations.

General interpretation of the structure of the Torcal within its regional setting

On the whole, the Torcal-Camorro Alto area has an E-W elongated shape (Figs. 1 and 2). This form is consistent with the transcurrent movement of the dextral shear fault limiting it.

This transcurrence must be situated within the oblique collision that occurred between the Internal and External zones (Fig. 1), in which the southern part of the Subbetic were strongly deformed. The tectonic arc of Las Cabras-Gibalto (situated directly to the East of the Torcal) suffered the effect of this transcurrence as well (Sanz de Galdeano, 2012) and in fact was formed by the same process. To the west, the Sierra de Abdalajís also presents strongly transcurrent features, which can be interpreted in a similar context.

Regionally, the aforementioned oblique collision produced the westwards dragging of great part of the Penibetic now situated largely in the western border of the Internal Zone (Martín-Algarra, 1987). However, part of the Penibetic remained to the north (Abdalajís, Torcal and some units of the Cabras-Gibalto arc and Sierra Gorda de Loja), although these were very affected by the transcurrent tectonics described above.

Even in these latter units the westward transport was important, although lesser than that undergone by the units situated to the west of the Internal Zone. For this reason, in comparison with those units, the units such that of the Torcal, moved relatively to the east. These displacements form part of the dextral transcurrent system.

In this relative eastward displacement, the Torcal-Camorro area was also uplifted owing to the lack of space, particularly its eastern end and the SE and NW sectors.

Conclusions

The structure of the Torcal de Antequera is practically a monocline gently dipping westwards, surrounded by major dextral strike-slip faults on its northern and southern borders. These faults have uplifted the Torcal as much as several hundred of metres in some places, in relation to the neighbouring areas. This structure is completed with the Camorro Alto, its western prolongation, practically another monocline, dipping to the south and with greater dip.

The fracturing of the Torcal-Camorro area is extremely dense and most of the fractures can be explained within a dextral shear-zone system. Measures of minor structures linked to the these faults, such as fragile S-C deformations well developed in Cretacic marly limestones, and striae in the surface of the faults, are consistent with this shear system and also with its progressive evolution.

This shear system, responsible of the fusiform shape of the Torcal-Camorro area was formed by the oblique collision between the Betic Internal Zone and the External one, particularly with the Penibetic (or, generally considered, Internal Subbetic). A good part of the Penibetic was dragged westwards, but another part rested to the north of the Internal Zone and moved relatively to the east. This relative movement created the dextral shear system.

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