GEOMETRY OF FRACTURING LINKED TO EXTENSION AND BASIN FORMATION IN THE MAESTRAZGO BASIN (EASTERN IBERIAN CHAIN, SPAIN)

B. Antolín-Tomás[1], C.L. Liesa[1], A.M. Casas[1] and I. Gil-Peña [2]

[1] Departamento de Ciencias de la Tierra, Universidad de Zaragoza. Pedro Cerbuna 12, 50009, Zaragoza. borjanto@unizar.es
[2] Área de Estudios Geológicos, IGME. Ríos Rosas 23, 28003 Madrid.

Resumen: En este trabajo se caracterizan los procesos extensionales mesozoicos en la parte oriental de la Cuenca Ibérica (cuenca del Maestrazgo) a partir del estudio de la fracturación. A escala macroestructural (cartográfica) las fallas, muchas de ellas relacionadas con la formación de la cuenca durante el Cretácico inferior, muestran orientaciones preferentes N-S a NE-SW y E-W a NW-SE. Las orientaciones principales y su importancia relativa cambian desde la parte más occidental de la cuenca, donde dominan las fracturas NW-SE, hasta la parte oriental, donde dominan las fracturas NNE-SSW. En afloramiento las fallas y diaclasas desarrolladas sobre las capas del Jurásico y Cretácico inferior están organizadas en dos sistemas de fracturas, cada uno constituido por dos familias ortogonales principales: 1) un sistema primario formado por las familias de fracturas NW-SE y NE-SW y 2) otro secundario formado por las fracturas N-S y E-W. El origen de la fracturación en la región se relaciona con la formación de la cuenca durante el Cretácico inferior, la cual es coherente con un régimen de extensión radial caracterizado por dos direcciones de extensión principales: una ESE-WNW, dominante hacia el margen oriental de la cuenca, y otra NNE-SSW, más importante hacia el interior de la placa Ibérica.

Palabras clave: Extensión, cuenca sedimentaria, falla normal, fracturación, Cretácico inferior, Cordillera Ibérica.

Abstract: In this work we apply the study of fracturing to the characterisation of Mesozoic extensional processes in the easternmost part of the Iberian Basin (Maestrazgo basin). Faults at the macroestructural scale (many of them related with Early Cretaceous basin formation) show dominant N-S to NE-SW and E-W to NW-SE orientations. These main orientations and their relative importance change from the westernmost part of the basin *(NW-SE dominated fracturing*) toward the east *(NNE-SSW dominated fracturing)*. Joints and faults at the outcrop scale in the Jurassic and Lower Cretaceous beds are arranged in two systems each consisting of two orthogonal sets: 1) a primary system with NW-SE and NE-SW fractures and 2) a secondary with N-S and E-W fractures. The origin of fracturing in the studied area is related to basin formation during the Early Cretaceous, consistent with a radial extensional regime and two main extension orientations: ESE-WNW and NNE-SSW.

Key words: Extension, sedimentary basin, normal fault, fracturing, Early Cretaceous, Iberian Chain.

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To establish the extension direction is a necessary step to understand the dynamics of extensional sedimentary basins. Extension direction can be determined from the study of: tension gashes (see *e.g.*, Guiraud and Séguret, 1984; Mata *et al.*, 2001), joints (Lee and Angelier, 1994; Arlegui, 1996; Casas and Maestro, 1996; Maestro *et al.*, 1997), calcite twins (González Casado and García Cuevas, 2002), faults (Etchecopar *et al.*, 1981; Etchecopar, 1984; Galindo-Zaldívar and González-Lodeiro, 1988; Reches, 1987; Rivera and Cisternas, 1990; Reches *et al.*, 1992; Maestro and Casas, 1995), and lineations and foliations associated to crustal extension in lower crustal levels. In upper crustal levels, the study of fractures is crucial to unravel the extensional history of sedimentary basins. It usually includes the analysis of orientations of joints and faults, and of slickenside striations on fault planes.

The Iberian plate underwent extension during the Mesozoic, in a similar way to the western European rift system (Ziegler, 1988; Ziegler *et al.*, 1998). The Early Cretaceous Maestrazgo basin offers a good opportunity to study the fracturing processes associated with extension due to the good outcrop conditions of the pre-rift and syn-rift sequences, the thickness of the synrift deposits, and the relative abundance of brittle structures.

In spite of the importance of knowing the extension direction to unravel the Mesozoic history of Iberia, this topic has not received much attention in the geological literature. Works cover partial areas from different points of view: the Cameros basin (Guiraud and Séguret, 1984; Mata *et al.*, 2001; González Casado y García Cuevas, 2002), the Oliete sub-basin (Rodríguez-López *et al.*, 2006, 2007), the Desert de las Palmas (Roca *et al.*, 1994), and the Las Parras (Aranda and Simón, 1993) and Galve sub-basins (Simón *et al.*, 1998) of the Maestrazgo basin. In these works a NNE-SSW dominant extension is proposed for the northern part of the Iberian Basin and an ESE-WSW extension to multidirectional for its southern sector.

The aim of this work is to make a contribution for the characterisation of extensional features of the Early Cretaceous tectonic regime in the eastern part of the Mesozoic Iberian realm (the Maestrazgo basin). The novelty of this work lies in the integration of results from map and outcrop scale, by means of the study of fracturing in the pre-rift (mainly Jurassic) and the syn-rift (Lower Cretaceous) rocks. The methodology used includes determination of the orientation and geometry of fractures (joints and faults) at outcrop scale by means of field studies, and at macro and meso-scales from aerial photographs and satellite lineaments, and the quantitative analysis of fault orientation. The results obtained allow for this methodology to be proposed for the structural study of pre- and syn-rift sequences in other extensional sedimentary basins.

Geological setting

The Iberian Chain (Fig. 1A) is an intra-plate mountain range resulting from the inversion of the Mesozoic Iberian Basin and from basement-involved thrusts during the Tertiary shortening of the Iberian plate (Álvaro *et al*., 1979; Salas and Casas, 1993; Casas *et al*., 2000a, b; Casas and Faccenna, 2001). Tertiary positive basin inversion by means of northwards-directed thrusts (in the northern half of the Iberian Chain) and southwards-directed thrusts (in the southern half of the chain) was favoured by the presence of widespread detachment evaporitic levels (Middle-Upper Triassic) throughout the former Iberian Basin.

The formation of the Iberian Basin began during the Triassic, with localised subsidence and dominantly continental sedimentation in NW-SE trending troughs or sub-basins (Álvaro *et al.*, 1979; Salas and Casas, 1993, Capote *et al.*, 2002), associated in some places with calc-alkaline magmatism (Lago *et al.*, 2004). During the Jurassic, a major transgression took place, and shallow marine platforms developed, favouring the deposition of more than 500 m of marl and limestone series, widespread throughout the eastern part of the Iberian plate. During the Early Cretaceous the main rifting episode occurred (*e.g.*, Salas, 1987; Salas and Casas, 1993; Salas *et al.*, 2001; Capote *et al.*, 2002), with more than 2500 m of syn-rift continental and marine deposits in the easternmost part of the Iberian Basin (Maestrazgo basin) and up to 8000 m in the westernmost part of the realm, in the Cameros basin (Casas-Sainz and Gil-Imaz, 1998; Mata *et al.*, 2001). The Late Cretaceous was mainly shallow marine, and its deposition is related to thermal subsidence (Salas and Casas, 1993). Finally, during the Tertiary, convergence between Iberia, Europe, and Africa brought about the inversion of the whole Iberian Basin, that became a deformed and uplifted area (the Iberian Range) that was the source area for the terrestrial deposits filling the internally-drained Ebro (to the north), Almazán (to the west) and Tagus (to the south) foreland basins. Neogene extensional structures linked to the opening of the Valencia Trough superimposed to the compressional ones in the eastern margin of the Iberian Peninsula (Simón, 1984), partly reactivating some of the Cretaceous extensional features in the eastern part of the range.

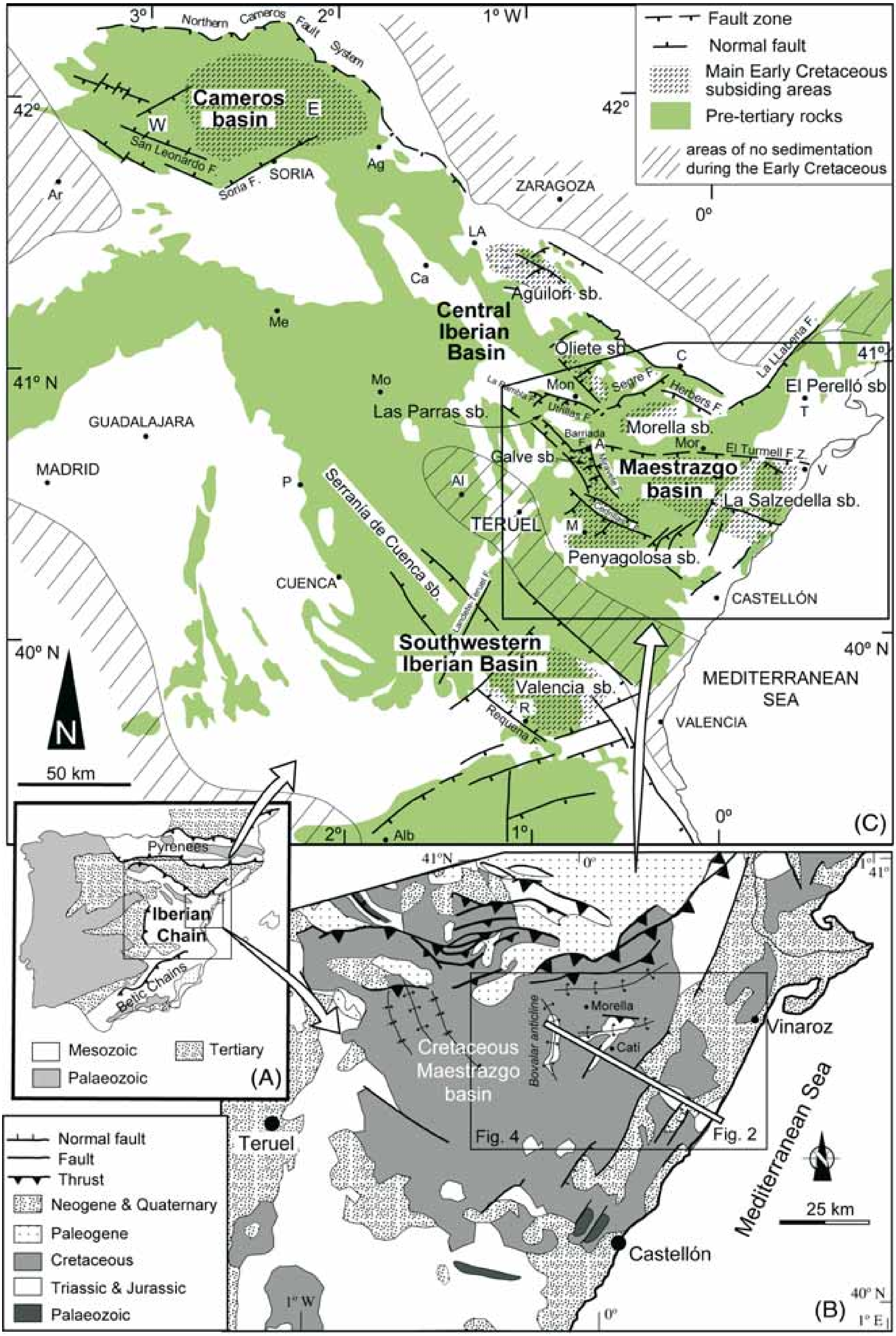
The main intra-plate Early Cretaceous basins within the Iberian realm are therefore the Cameros basin, located in the northwestern part of the Iberian Chain, and the Maestrazgo basin, located in the southeastern part of the chain. These two basins, characterized by an important thickness of Lower Cretaceous deposits, are separated by an area with no deposition or with much lower thickness of Cretaceous rocks (Fig. 1C). The thickness of the Lower Cretaceous, syn-rift sequences, changes gradually along the NW-SE trend, and much more abruptly along NE-SW direction. In an overall view, faults controlling the thickness of Lower Cretaceous deposits show NW-SE and NE-SW trends (Álvaro *et al.*, 1979; Salas *et al.*, 2001; Capote *et al.*, 2002; Liesa *et al.*, 2006), although in detailed inspections many other fault orientations can be found (Fig. 1C).

Stratigraphy

The basement of the Mesozoic sequences in the Iberian Chain is formed by Palaeozoic rocks, Cambrian to Carboniferous, mainly consisting of sandstones and shales, belonging to the European Variscan belt. The Maestrazgo area is located in the external part of the Iberian massif (Fig. 1), the Carboniferous Culm facies probably being the substratum to the Mesozoic sequence in this sector (Barnolas *et al.*, 1985).

The Permo-Triasic succession occurs in typical Germanic facies (Garrido and Villena, 1977). The lower terms consist of red beds, including Permian alluvial fans and fluvial systems in Buntsandstein

Figure 1.- Location of the Early Cretaceous Maestrazgo basin into the Iberian Basin. **A)** Location of the inverted Iberian Basin (the Iberian Chain) in the Eastern of Iberia. Rectangle marks the position of figure 6. **B)** Geological location and position of cross-section of figure 2 and map of figure 4. **C)** Main subsiding areas and sub-basins for the Early Cretaceous (modified from Capote *et al.*, 2002). A: Aliaga, Ag: Ágreda, Al: Albarracín, Alb: Albacete, Ar: Aranda de Duero, C: Calanda, Ca: Calatayud, LA: La Almunia de Doña Godina, M: Mora de Rubielos, Me: Medinaceli, Mo: Molina de Aragón, Mon: Montalbán, Mor: Morella, P: Priego, R: Requena, sb: sub-basin, T: Tortosa, V: Vinaroz.


Fault zone
Normal fault
Main Early Cretaceous subsiding areas
Pre-tertiary rocks
areas of no sedimentation during the Early Cretaceous
Northern Cameros Fault System
Cameros basin
W
E
San Leonardo F.
Soria F.
SORIA
Ag
Ar
ZARAGOZA
LA
Ca
Aguilón sb.
Me
Central Iberian Basin
Oliete sb.
C
La Llabena F.
El Perelló sb.
T
Mo
Mon
Segre F.
Herbers F.
Las Parras sb.
Morella sb.
Mor
El Turmell F.Z.
Barriada F.
A
Galve sb.
Maestrazgo basin
V
La Salzedella sb.
GUADALAJARA
MADRID
P
Al
TERUEL
M
Penyagolosa sb.
Serranía de Cuenca sb.
CUENCA
CASTELLÓN
Southwestern Iberian Basin
Valencia sb.
R
Requena F.
VALENCIA
MEDITERRANEAN SEA
50 km
Alb
(C)
Pyrenees
Iberian Chain
Betic Chains
Mesozoic
Tertiary
Palaeozoic
(A)
Normal fault
Fault
Thrust
Neogene & Quaternary
Paleogene
Cretaceous
Triassic & Jurassic
Palaeozoic
Teruel
Morella
Catí
Bovalar anticline
Cretaceous Maestrazgo basin
Fig. 4
Fig. 2
Vinaroz
Mediterranean Sea
25 km
Castellón
(B)

facies. The middle Triassic (Muschelkalk facies) consists of dolostones with an intermediate member of shales and evaporites. The Upper Triassic (Keuper facies, with gypsum and clays) acts, together with the evaporite beds of the Middle Triassic, as an important detachment level, both during extensional and compressional deformations.

The Jurassic consists mainly of marine limestones and marls ranging in thickness from several hundreds of meters to more than one kilometre (Salas, 1987; Salas *et al.*, 2001). Its thickness increases from west to east, reaching its maximum near the Mediterranean coastline. The Early and Middle Jurassic were characterised by sedimentation in large carbonate platforms. During the Late Jurassic, carbonate platforms also developed in subsiding areas as the Maestrazgo and Cameros basins. The thick series recorded in the Maestrazgo basin includes two Upper-Jurassic sequences, the Kimmeridgian and the Tithonian-Berriasian, which, together with the Lower Cretaceous succession, constitute the main syn-rift sequence (Salas and Casas, 1993; Salas *et al.*, 2001). The Kimmeridgian sequence includes distal facies consisting mainly of rhythmic marls and limestones (mudstones) with slumps and anoxic marls. The Tithonian-Berriasian sequence corresponds to shallower facies of bioclastic, oncolithic and oolitic limestones.

The Lower Cretaceous, constituting the main syn-rift sequence, shows a wide variety of facies. In the pre-Aptian, rock types range from red beds to evaporite-bearing sediments and lacustrine and marine limestones (Soria, 1997). The Aptian consists of shallow marine limestones containing *Toucasia*. In the Maestrazgo basin Salas *et al.* (2001) recognize a more subsiding sub-basin in the La Salzedella area, limited to the south by the Vistabella high (Canérot, 1974).

The Albian sands with coal measures (Escucha-Utrillas Fms.), widespread throughout the Iberian Chain, overlie a stratigraphic discontinuity. These deposits represent fluvial and lacustrine sedimentation that grades to deltaic in the Maestrazgo area. The final episode of the Mesozoic extensional stage is represented by marine platform limestones corresponding to the maximum transgressive period (Cenomanian to Maastrichtian), relatively homogeneous throughout the eastern part of the Iberian Peninsula.

Tertiary molasse sedimentation was linked to the tectonic inversion of the Mesozoic basins. Most part of the preserved Tertiary sediments reflects continental sedimentation with conglomerates, sandstones and shales originated in alluvial fan systems. Neogene extension and normal faulting also developed alluvial systems with terrestrial sedimentation. In the eastern Maestrazgo two main sequences of Tertiary deposits have been described (Anadón and Moissenet, 1996). The lower one, with a probable Oligocene-Lower Miocene age, consists of alluvial fan deposits followed by lacustrine limestones. This sequence was deformed during the Neogene by extensional tectonics associated to the eastern margin of Iberia (Simón, 1984), with a simultaneous deposition of the upper Tertiary sequence. It consists mainly of alluvial fan facies attributed to the Late Neogene-Early Pleistocene. Quaternary pediments also developed in the downthrown blocks of normal faults.

Macrostructure

The Maestrazgo basin is characterized by the presence of depocenters near the present-day coastline (La Salzedella sub-basin, Fig. 1C), where more than 2,500 m have been referred (Salas *et al.*, 2001). Towards the west, the thickness of Lower Cretaceous deposits diminishes gradually. Thickness changes are controlled by extensional faults striking NE-SW and NW-SE (Álvaro *et al.*, 1979; Salas and Guimerà, 1996; Soria, 1997; Salas *et al.*, 2001; Liesa *et al.*, 2004; Rodríguez-López *et al.*, 2007). N-S to NNW-SSE and E-W to ENE-WSW faults are also present in some areas, especially in the western marginal areas of the Maestrazgo basin (Liesa, 1992-1995, 2000), where they also control changes in thickness of the Cretaceous sequence (Liesa *et al.*, 2006).

At the map scale compressional structures in the central part of the Maestrazgo basin are rare. They are represented by N-S folds (Bovalar anticline, Fig. 1B), which can be interpreted as a detachment folds (Fig. 2). To the north, the Early Cretaceous Maestrazgo basin is bounded at present by the fold and thrust belt of the linking zone between the Iberian Chain and the Catalonian Coastal Ranges (Guimerà, 1988, 1996; Guimerà and Alvaro, 1990; Casas *et al.*, 2000a), that show NE-SW and NW-SE directions, coinciding with the directions of Cretaceous extensional faults (Liesa *et al.*, 1996, 2000, 2004). Compressional structures are rooted in the Middle and Upper Triassic marls and gypsiferous beds and in the upper Paleozoic.

Most part of the studied area (Fig. 1B) is characterized by horizontal bedding or large monoclines cut by large NE-SW to NNE-SSW striking normal faults, which can be followed up to 20 km along strike. Many of these faults can be identified from the topography (fault line scarps) and affect Neogene and Quaternary deposits, located in their hanging walls. According to our reconstruction (see cross-section of Fig. 2), in an overall view, the easternmost part of the Maestrazgo basin shows a horst-and-graben structure, with Jurassic and Cretaceous rocks cropping out in the footwalls and Neogene and Quaternary deposits in their hanging walls. Cenozoic deposits usually dip against the faults. The dips of Mesozoic beds, as can be identified in the horst areas, are between the horizontal and 20º, and the strike of beds usually follows the NE-SW direction. This reveals a process of Neogene extension that probably re-activated some of the Mesozoic extensional faults (*e.g.*, Simón, 1984, 1986; Guimerà, 1988; Roca and Guimerà, 1992). Neogene extension and faulting was linked to thinning of the

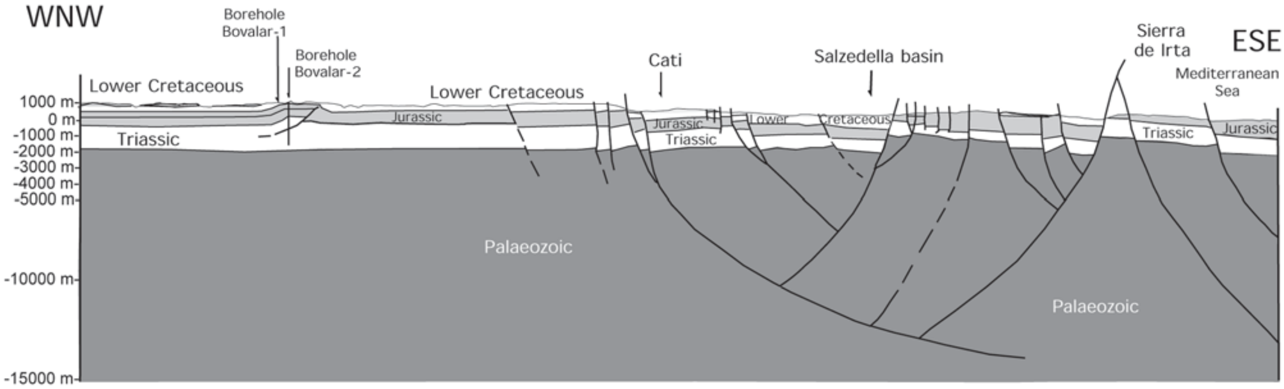


Figure 2.- WNW-ESE cross-section through the Maestrazgo basin showing the main normal faults, some of them re-activated during the Neogene extension. See location in figure 1b.

continental crust and to the opening of the Valencia Trough (Roca and Guimerà, 1992; Sàbat *et al.*, 1995). Limited tilting of blocks during faulting can be recognised in some areas. This re-activation of the NNE-SSW fault set, with fault throws up to 600 m as inferred from the separation of stratigraphic reference levels, precludes the direct observation of their role during the Cretaceous extension, because facies and thickness changes in the Cretaceous units are more difficult to observe.

The main faults with E-W to ESE-WNW strikes are more difficult to recognise, and can be inferred from thickness variations in the Late Jurassic and Early Cretaceous sequences (Salas *et al.*, 2001). The most important ones are, from north to south, the Herbers and Muela de Montalbán (also called Utrillas fault) fault, in the northern basin margin, the Turmell fault zone in the central part, and the Cedrillas fault in the southern part of the basin (Fig. 1C).

In spite of the bad quality of seismic-reflection profiles (*e.g.*, Fig. 3) along the main structural directions, they allow some of the main features of the different sets of faults to be inferred. Reconstruction of the deep structure can be done according to the following constraints:

- In seismic sections perpendicular to the E-W set of normal faults, rollover anticlines appearing in the hanging walls show relatively small wavelengths (see *e.g.*, Fig. 3A). In the vicinity of the fault of the seismic profile shown in figure 3A, a normal drag appears in the hanging wall, defining hanging wall syncline geometry. This can be interpreted as the result of a listric fault, flattening at about 3 km within the crust, probably in the upper levels of the Paleozoic rocks, coinciding with other interpretations of extensional systems in the Maestrazgo basin (Casas *et al.*, 2000a; Liesa *et al.*, 2000, 2006).
- In seismic sections with E-W to ESE-WNW directions no clear rollover anticlines can be distinguished, although tilting of beds near the surface can be recognised (Fig. 3B). Although horsts are apparently symmetrical, a dominance of westward-dipping faults can be inferred in some areas (Fig. 3B). Although these profiles do not allow clearly identify the geometry of the fault systems at depth, they are compatible with a deep detachment (between 10 and 15 km) as interpreted in figure 2, probably reaching the base of the crust in the Mediterranean basement. This geometry is consistent with the interpretations shown by Roca (1996) in cross-sections cutting across the Valencia Trough farther north.

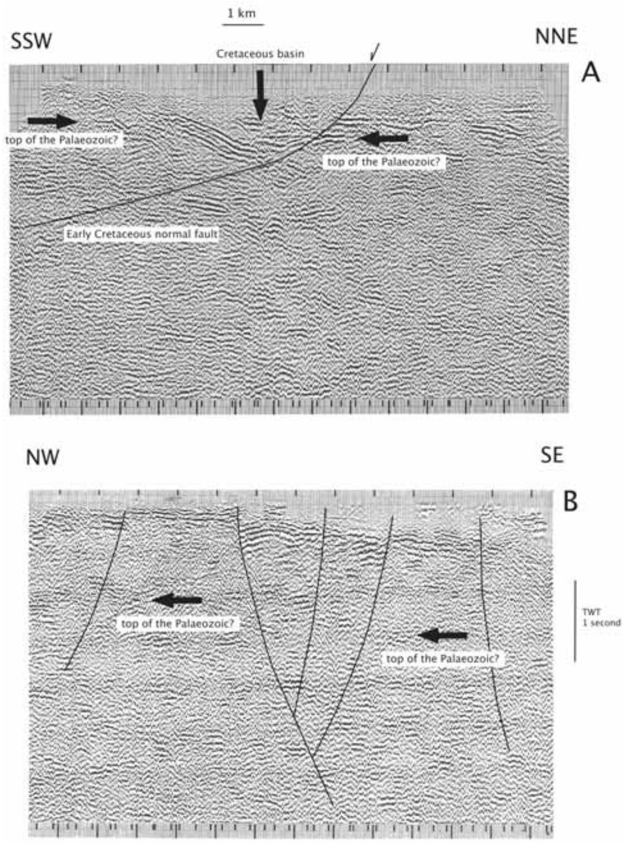


Figure 3.- Seismic sections along NNE-SSW (**A**) and NW-SE trends (**B**). In profile A a listric fault with shallow detachment can be interpreted. In profile B there are not clear rollover geometries, and probably the detachment level is at much deeper levels within the continental crust. See location in figure 6.

At surface the main difference between the two sets of faults is the above-mentioned landscape expression of the NNE-SSW set that cuts the E-W to NW-SE faults. The close interaction between the two sets of faults probably contributes for the bad quality of most of the seismic profiles cutting across the eastern part of the Maestrazgo basin.

Fracture orientation analysis

Observations at map scale

Statistical analysis of fault orientation at the map scale was done using published geological maps at the 1:50,000 scale (Canérot *et al.*, 1973a, b, c, and 1978; Martín Fernández *et al.*, 1973; Navarro Vázquez *et al.*, 1981; ITGE, 1990), and checking some of the faults by means of analysis of aerial photographs at the 1:30,000 scale. Faults were considered as rectilinear segments and the work area was divided using a 10x10 km grid. The results obtained show that several main sets of faults (mainly NW-SE, NE-SW and E-W) are represented throughout the studied area (Fig. 4). However, their relative frequency on the total population varies in different sectors. The NNE-SSW set is dominant in the easternmost part of the study area. Toward the inner part of the Iberian Chain, this directional maximum is not so clear and may be divided in two (NNE-SSW and ENE-WSW) and in some areas it is only represented by an ENE-WSW direction. The E-W direction is relatively well defined in the central part of the studied area, becoming WNW-ESE towards the

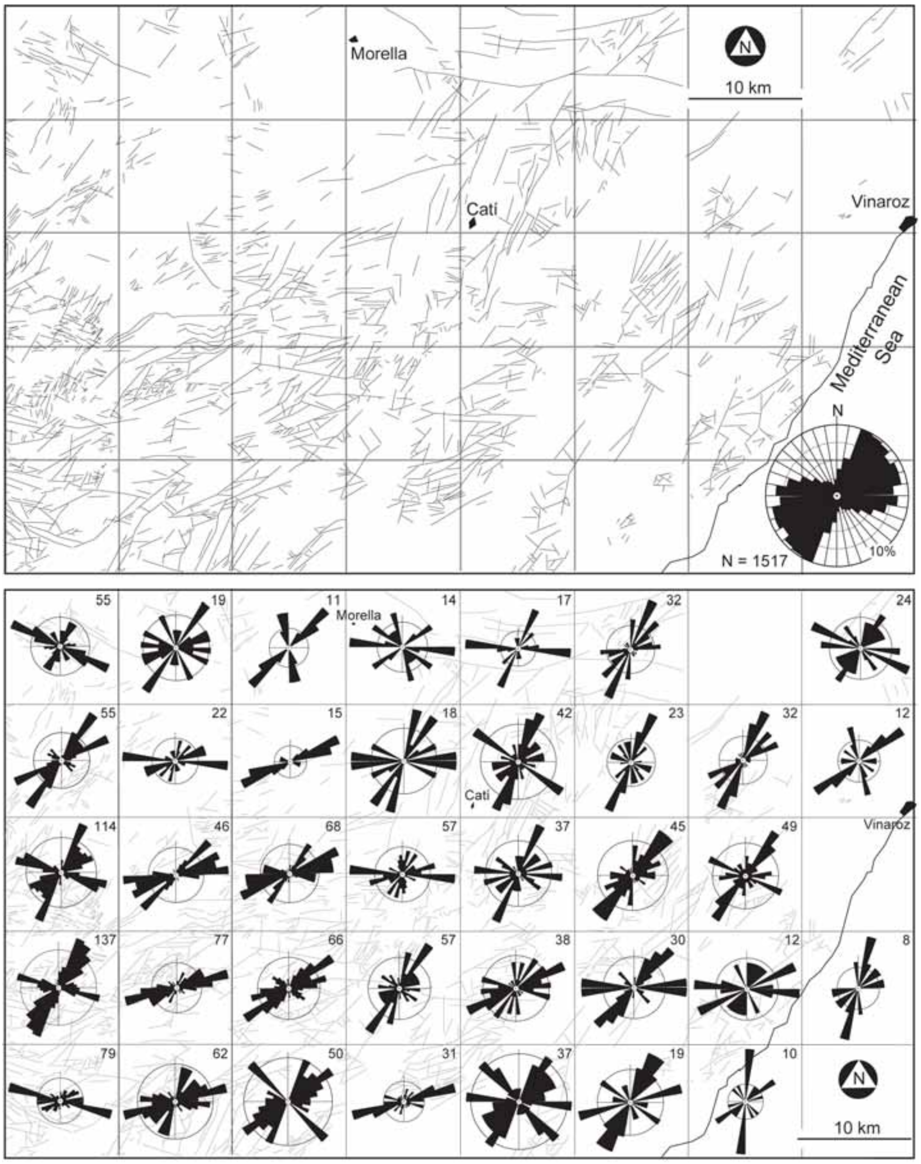


Figure 4.- Analysis of mapped faults in the studied area (see location in figure 1b). Fault data from Canérot *et al.* (1973a, b, c, and 1978), Martín Fernández *et al.* (1973), Navarro Vázquez *et al.* (1981), and ITGE (1990). Rose diagrams indicate statistics of faults in the 10 km x 10 km square grid. The total of faults is represented in the rose diagram of the upper map. Circle of rose diagrams in lower map indicates the 10% of faults. The number in each square indicates the number of faults.

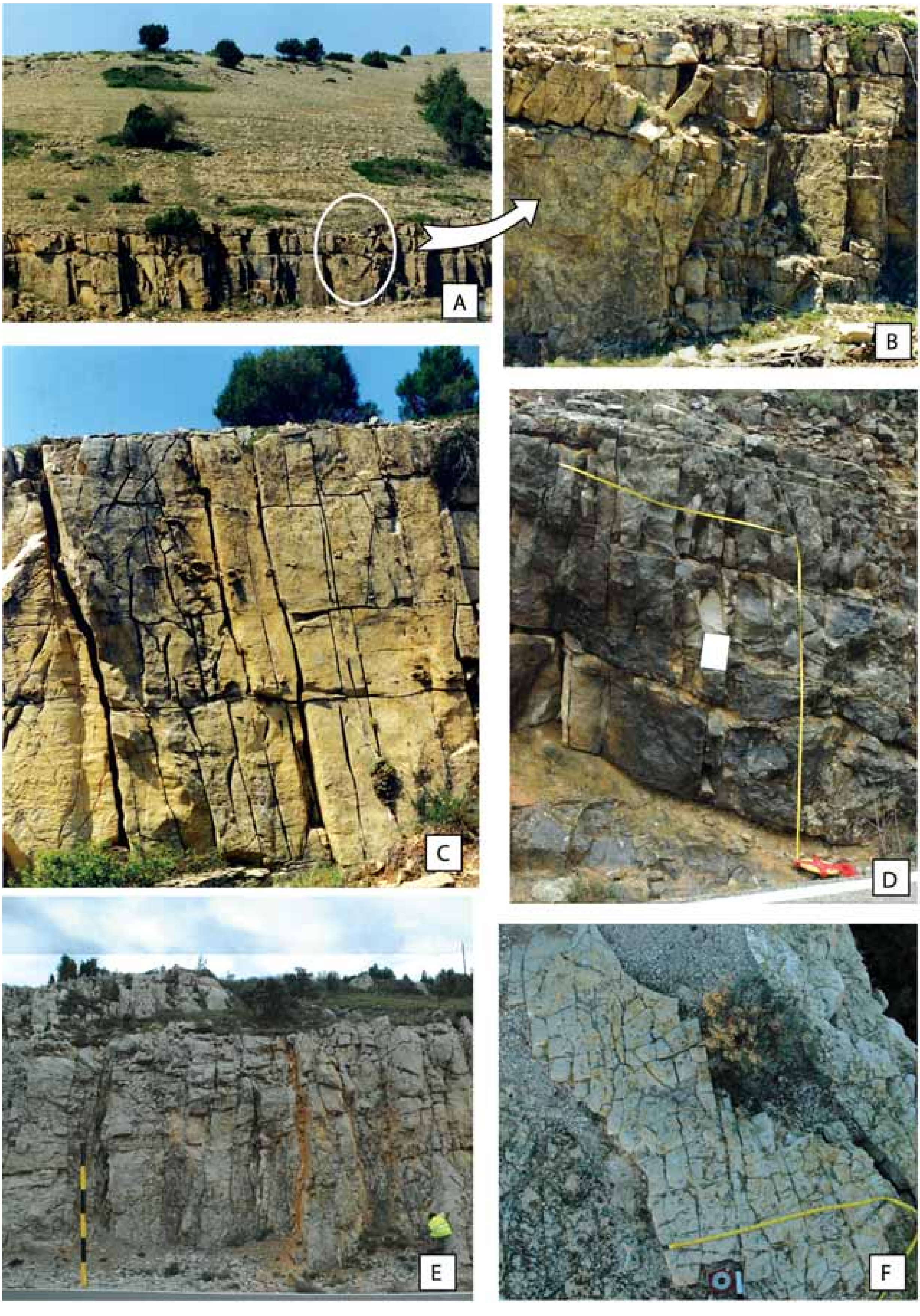


Figure 5.- Fractures at the outcrop scale. **A)** Photograph of closely-spaced NE-SW joints, also visible at surface, in the Camarena range (area 7 in figure 6). **B)** Close-up view of open joints and normal faults with small displacements shown in figure 5.A. **C)** Steeply-dipping normal faults with small displacement at the Camarena range. **D)** Photograph of vertical joints in horizontal beds, near Catí (area 3 in figure 6). **E)** A good exposure of the Jurassic units in Puerto de Querol with very penetrative set of vertical joints. **F)** Orthogonal joints near the Mediterranean coast (locality within area 5 shown in figure 6).

west. In the east, near the Mediterranean coast, this set is less important from the statistical point of view, being obscured by the dominant NNE-SSW set. The NW-SE set is well defined in the western and southern sectors of the Maestrazgo basin.

Observations at outcrop scale

The study of fractures at the outcrop scale was carried out by measuring the attitude and by considering the features of more than 2,500 faults and fractures throughout the studied area (Fig. 5). We

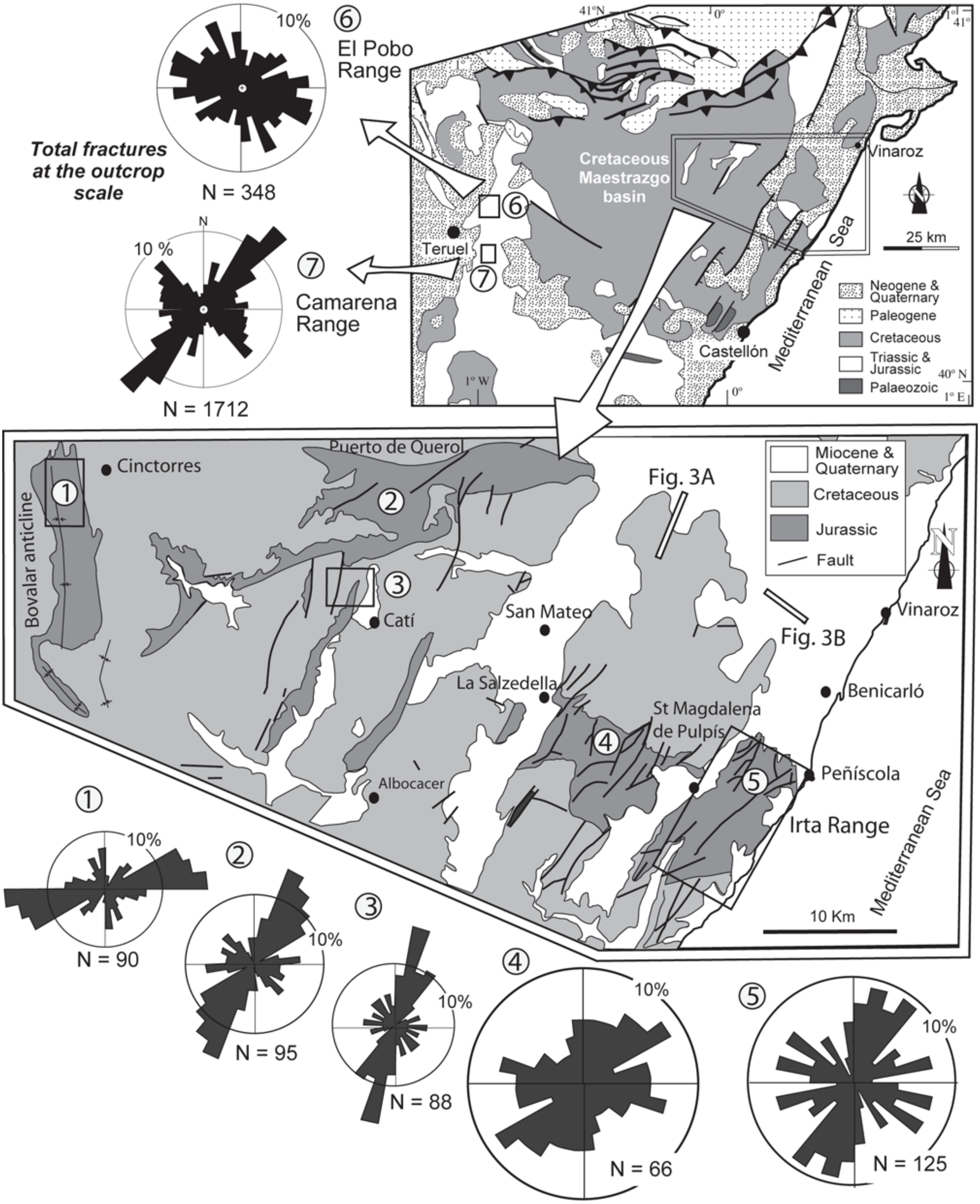


Figure 6.- Orientation of fractures at the outcrop scale in the different studied sectors. Fractures have been measured in near-horizontal beds, which allow their further comparison between outcrops and with fracture results on map scale.

Area	Fracture sets at outcrop scale			
	N-S	NE-SW	E-W	NW-SE
1. Bovalar Anticline	175º E	45º E	**75º E**	155º E
2. Puerto de Querol horst		**35º E**	85º E	125º E
3. Catí horst		**20º E**		120º E
4. La Salzedella horst	0º E	**50º E**	98º E	
5. Irta Range		**25º E**	75º E	105º E and 125º E
6. El Pobo Range	175º E	50º E	85º E	**110º E** and 155º E
7. Camarena Range	15º E	**45º E**	85º E	**135º E**

Table I.- Mean orientation (strike) of fracture sets at the outcrop scale in the different sectors. The dominant fracture sets are shown in bold.

focused the study in several areas with good outcrop conditions (Fig. 6): the Bovalar anticline, the Puerto de Querol, Catí, La Salzedella-St. Magdalena de Pulpís horsts, and the Irta, El Pobo and Camarena ranges. Studies were completed by means of aerial photographs analysis (using the 1:30,000 to 1:5,000 scales and comparing the results with outcrop orientation).

Most structures were measured from rocks located near the top of the pre-rift sequence (i.e., Upper Jurassic, Tithonian-Berriasian depositional sequence), consisting of a section, several hundreds of metres thick, of marine limestones. At the El Pobo and Camarena areas structures were also measured in the lowermost Jurassic units, consisting in well-bedded platform marine limestones. Data were taken in good exposures, where possible, to determine their vertical variations along the stratigraphic sequence and their relationships (Fig. 7). The width of the covered area allows for a representative sample of fracturing in the Maestrazgo basin to be determined.

In an overall view the dominant fracture directions (Fig. 6 and table I) are NE-SW (ranging from N020E to N050E), E-W (average about N090E), and NW-SE (ranging from N105E to N155E, sometimes displaying two subsets, as in the Irta and El Pobo ranges). In several areas a poorly developed N-S fracture set is also present (Table I). In general, the main fracture directions appear throughout the investigated area, but some differences arise if the relative importance of the different sets is taken into account. The NE-SW set is more developed than the E-W and NW-SE sets throughout the study area, but in the Bovalar anticline (central area of the Maestrazgo basin) the E-W set is dominant. In the western areas (El Pobo and Camarena ranges) the NW-SE set shows a higher frequency, becoming the main set in the Camarena area.

Fracturing at the outcrop scale corresponds mainly with joints, although normal and strike-slip faults are also developed (Fig. 5A, B, C). As a general rule, rocks are intensively fractured, although spacing of fractures depends on the fracture set orientation. In several outcrops spacing of joint sets have been analysed in relation to bed thickness. In the Camarena range outcrops the *Fracture Spacing Ratio* (*FSR*; Becker and Gross, 1996) is in average 1.98 (standard deviation of ± 0.3) for the NE-SW joint set, 0.98 (± 0.1) for the E-W set, and 0.72 (± 0.24) for the NW-SE set (Liesa, 2000). In the Irta range (Fig. 5F) the *FSR* is in average 1.00 (± 0.14) for the NE-SW joint set, and 0.69 (±0.07) for the E-W set.

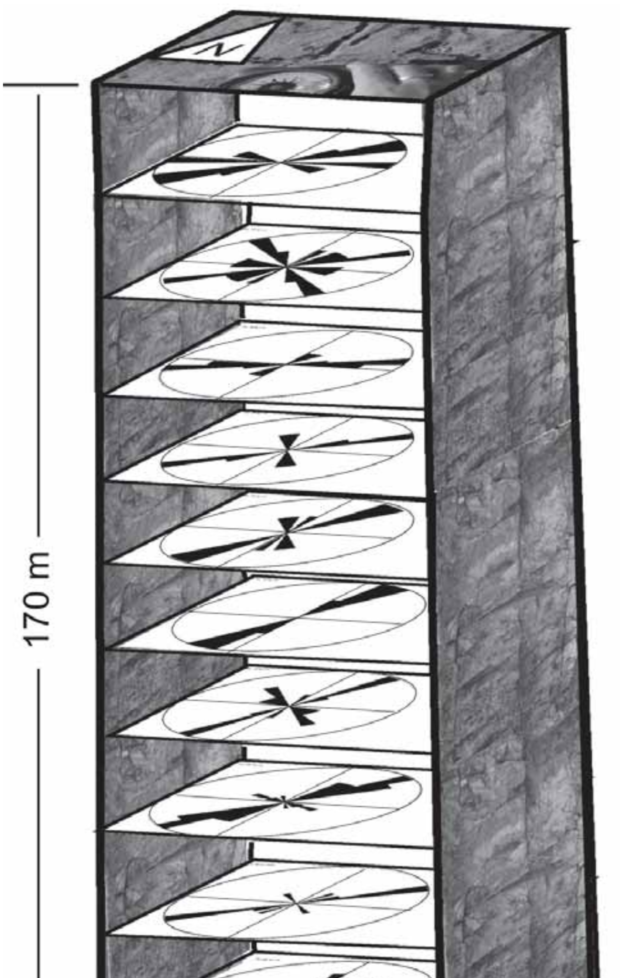


Figure 7.- Variations in fracture orientation along a section of the lower part of the syn-rift sequence in Puerto de Querol. A constant attitude of fractures and maxima can be observed through the whole section.

The dip of fractures, on horizontal beds, is between 70º and 90º (see Fig.5A, D), that points to the formation of faults as joints (Angelier and Colleta, 1983). This implies that a good correlation between the orientation of mapped fractures and faulting and fracturing at the outcrop scale should be expected, as previous results also suggest (Liesa, 1992-1995, 2000).

In the westernmost part of the studied area (Camarena and El Pobo ranges) there are very good quality outcrops that allow for a more detailed study. In these outcrops, horizontal Jurassic beds are exposed for some hundreds of m^2, and fractures of different size are also well displayed on the aerial photograph (Fig. 8B). In both areas, fracturing analysed from detailed mapping on 1:30,000 scale (Fig. 8B and table II) shows the N-S, NE-SW, E-W, and NW-SE sets observed at outcrop scale. According to Liesa (2000), who analysed the fracturing from 1:30,000 scale to the outcrop scale through an intermediate-scale aerial photograph at 1:4,300, major fractures correspond with normal faults and the pervasive fracture network displayed between them in the aerial photographs (Fig. 8B) corresponds to the master joints observed at the outcrop scale (Fig. 5A). This fact, together with the extraordinary good correlation between the fracture sets distinguished at both the mapping and the outcrop scales, suggest that fracturing at the outcrop scale could be considered as representative for the major fracturing throughout the basin.

Chronological constraints for the development of fractures (joints and faults) can be obtained from analysis of fracturing in dipping beds. In most sites fractures are perpendicular to bedding, independently of the dip of strata (Fig. 5F). This means that, since fracturing may post-date lithification, and folding can be related either with the Cretaceous extensional stage (rollover anticlines linked to listric faults) or the Tertiary compressional stage, time for fracture development occurred during the basin formation stage. The constant attitude of fractures throughout thickness of more than one hundred meters along the section of the upper Jurassic sequence (Fig. 7) also supports a common origin for all extensional fractures. Furthermore, Liesa and Simón (1994) and Liesa (2000) have shown how fracturing in the Upper Cretaceous limestones in central Maestrazgo is much less pervasive than in the Upper Jurassic and Lower Cretaceous beds and it is characterized by a very different fracture network, associated to the Tertiary compressional stage. These results also support the Early Cretaceous origin for most fractures of the syn-rift sequences. Other chronological criteria are the parallelism between hectometric-scale faults linked to Lower Cretaceous syn-extensional deposits and outcrop scale fractures (Liesa, 1992-1995, 2000). In the Camarena area this relationship is clearly observed in outcrops of the pre-rift and syn-rift sequences linked to NW-SE faults (see Fig. 8). This relationship allows for a common origin for the two scales of fractures to be proposed. In other areas, however, this kind of relationship cannot be so clearly established.

Interpretation and discussion

From the data exposed above, a close relationship between the orientations of macro- and meso-structures can be inferred. Study of fracturing at the outcrop scale indicates the close spacing of joints and faults in the Jurassic (pre-rift) sequence. The orientation of these closely-spaced set of faults coincides with the main trends of map scale faults linked to thickness changes in the Lower Cretaceous (syn-rift sequence, Salas and Guimerà, 1996; Capote *et al.*, 2002). The fault-to-basin-formation relationship is also evident from field data in different sectors of the Maestrazgo basin (*e.g.*, Salas and Guimerà, 1996; Soria, 1997; Liesa *et al.*, 1996, 2004, 2006; Rodriguez-López *et al.*, 2007). Some of the features of seismic reflection profiles seem to confirm this relationship. Correlation between macro- and outcrop structures can help to constrain the age of fractures at the outcrop scale about the Early Cretaceous rifting stage. Two fracture mechanisms responsible for basin formation, which could co-exist to some extend within the whole basin, appears as plausible end-members. They are: (1) the formation in first instance of a dense grid of fractures in the pre-rift rocks (and later activation of these fractures as faults during bed tilting) was the mechanism resulting in extension and basin formation, as proposed, for example by Angelier and Colletta (1983); and (2) large-scale normal faulting predating the formation of subsequent outcrop scale joints in the faulted strata.

Detailed mapping and outcrop studies of fractures also provide some information about how the fracturing process took place. Analyses must include fracture length, statistics of fracture set orientation, and cross-cut and abutting relationships between fractures of different sets. In and overall view the fracture network is constituted by two fracture systems formed each one by two orthogonal sets of joints and normal faults

Area	**Measured Fractures**	**Fracture sets at map (1:30,000) scale**			
		N-S	**NE-SW**	**E-W**	**NW-SE**
6. El Pobo Range	All	15º E	**50º E**	90º E	**160º E**
7. Camarena Range	Macrofractures		**35º E**	85º E	**130º E**
	Mesofractures	15º E	**55º E**	95º E	**135º E**

Table II.- Mean orientation of fracture sets obtained from analysis of aerial photographs at the 1:30,000 scale. The dominant fracture sets are shown in bold.

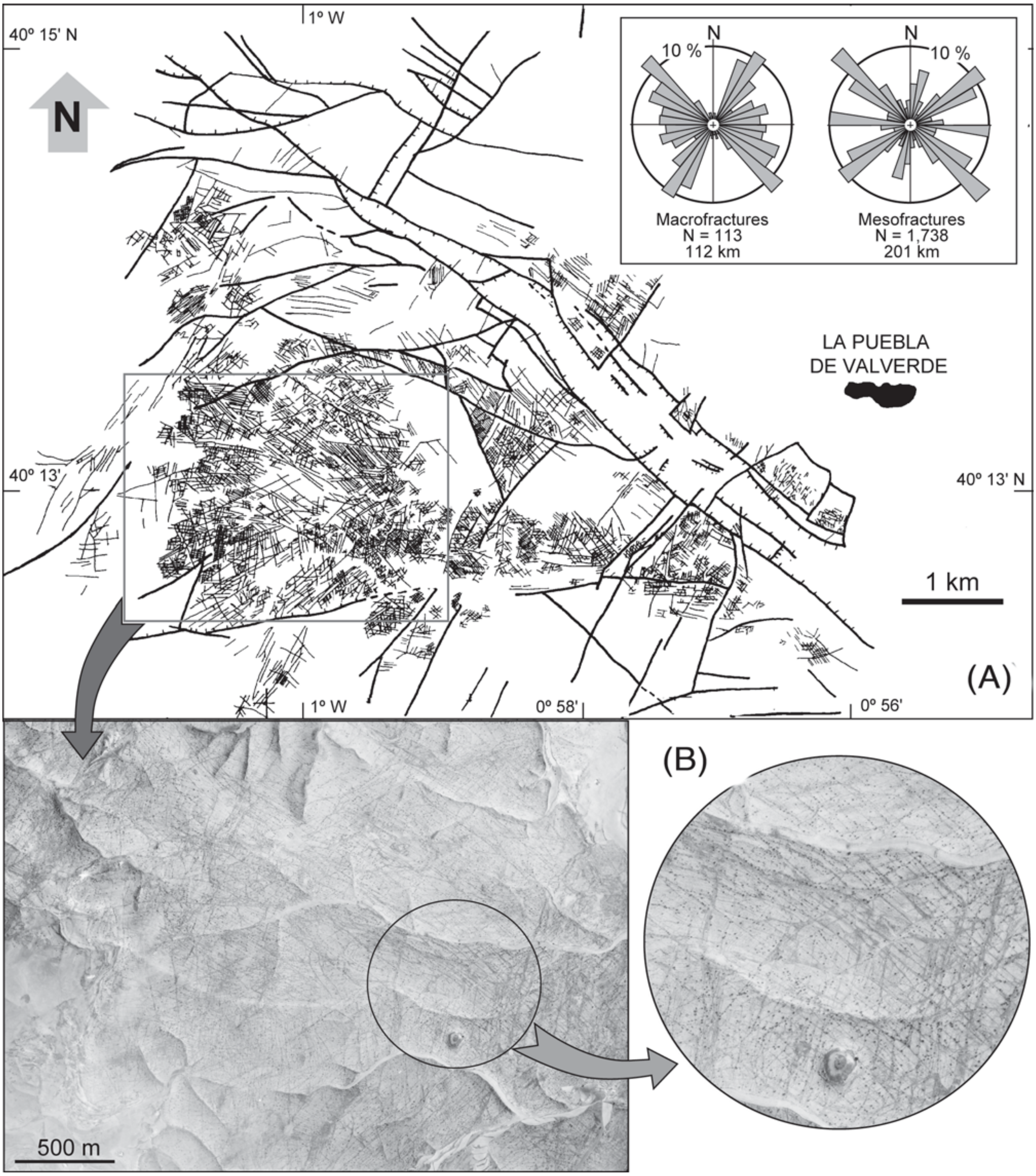


Figure 8.- Fracture network at the Camarena range (area 7 in figure 6). **A)** Fracture mapping elaborated from 1:33,000 scale aerial photographs. Inset shows frequency diagram of fracture orientation according to their accumulative length (macrofracture: thick line on map; mesofracture: thin line on map). **B)** Aerial photograph (1:18,000 scale) and detailed view showing a complex fracture network.

(Liesa, 2000; see Fig. 8). The first one, constituted by the NW-SE and NE-SW sets, is the most important in this region and controlled the Late Jurassic-Early Cretaceous major extensional structure (see for example the La Puebla de Valverde graben in Fig. 8A). The other system is constituted by the E-W and N-S to NNE-SSW sets, the latter consisting mainly in joints. Both systems pre-date the tilting of beds according to their geometrical relationships with bed orientation. Which one of the two systems is the primary with respect to the Cretaceous extensional stress field? The data about joint spacing indicate that the NE-SW fracture set, the dominant in most sectors, is the closest spaced one considering the whole basin, with *FSR* values close to 2.00 or higher. This fact could be interpreted according to a fracture set oriented perpendicular to the main extension direction. However, the influence of basement faults in the

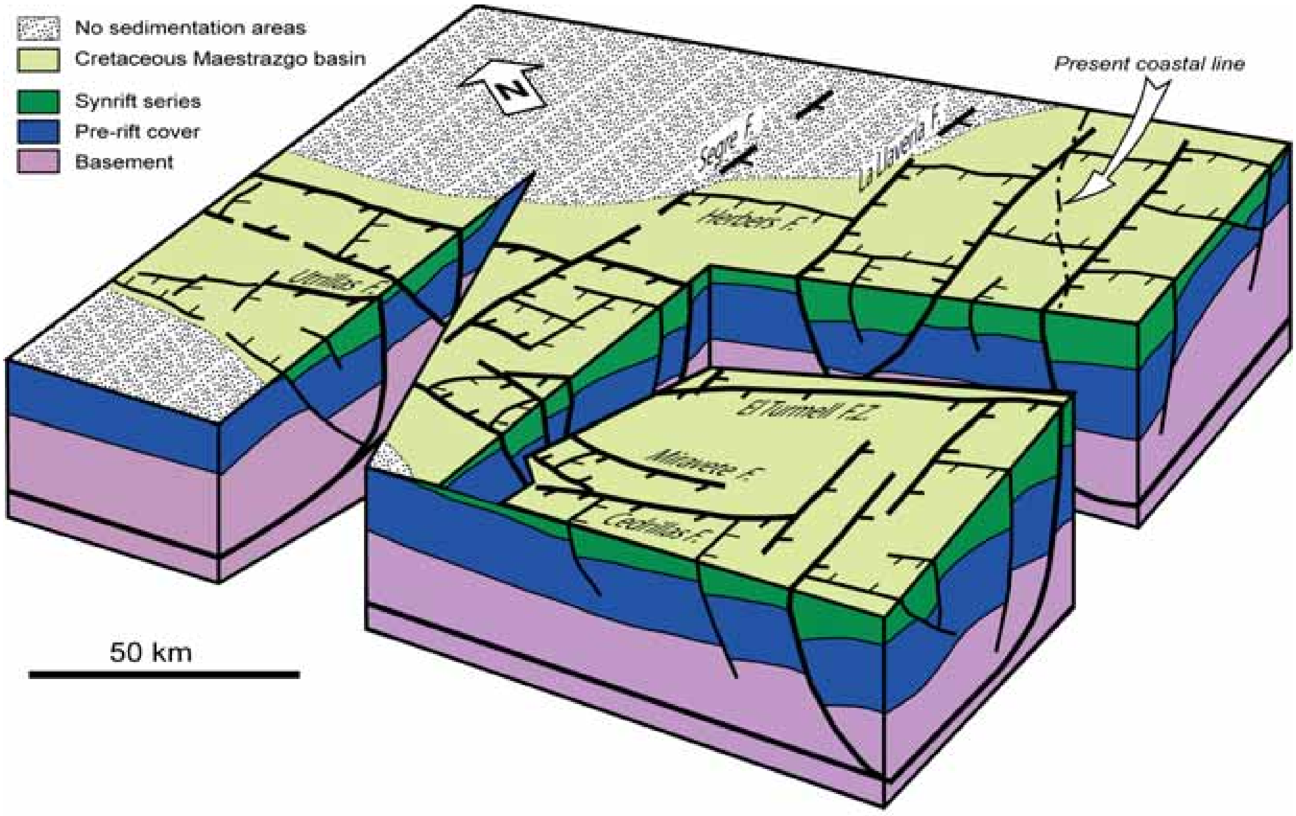


Figure 9.- Tectonic sketch showing the geometry proposed to explain fracturing during basin formation. In the western Maestrazgo basin (see location in figure 1) WNW-ESE to NW-SE normal faults are dominant, with secondary NE-SW faults. In the eastern Maestrazgo the dominant structures are NNE-SSW deep-rooted normal faults.

development of fracture systems is one constrain (see below) that must be taken into account when interpreting the fracture-stress relationships (see, for example, Casas *et al*., 2000b, c; Cortés *et al.*, 2003), because small-scale fractures can mimic the attitude of large-scale fauls.

Therefore, throughout the study area there is a pervasive pattern of orthogonal fault sets. This is revealed as WNW-ESE to NW-SE and NNE-SSW to NE-SW fracture systems, as N-S and E-W fracture systems, or, in some places combination of the two systems. The orthogonal pattern of fractures is common in extensional regimes without a strongly dominant extension direction ($s_1 >> s_2 \sim s_3$, *e.g.*, Simón *et al.*, 1988). This is in accordance with palaeostress results inferred by Aranda and Simón (1993) and Rodríguez-López *et al.* (2006), who characterized an extensional regime in Early Cretaceous syn-rift units, probably with a radial tendency, with an extension direction between ENE and SE.

Since large-scale faults are conditioned by Late-Variscan fracturing of the Palaeozoic basement (with main NE-SW and NW-SE orientations, Arthaud and Matte, 1977; Álvaro *et al.*, 1979; Capote *et al.*, 2002), orientation of extensional mesostructures could be therefore strongly controlled by previous structures. In the Maestrazgo basin, the dominant fracture directions can be interpreted as controlled by previous basement fault directions. However, as stated before, the occurrence of perpendicular patterns is probably linked to the radial extensional regime. These conditionings preclude the straightforward determination of extension directions, as proposed in other areas of the Iberian Chain (Guiraud and Séguret, 1984; Mata *et al.*, 2001; González Casado and García Cuevas, 2002).

Independently on the scale of observation, the NE-SW (or NNE-SSW) fracture set is mainly dominant in the eastern part of the Maestrazgo basin, close to the present-day coastline (*e.g.*, Roca *et al.*, 1994), although it is also important in the western parts of the studied area. In central parts of the basin, the E-W fracture set is sometimes the dominant, and conversely, in the westernmost part of the basin, the NW-SE fracture set acquires a relevant role. We think that this regional distribution of fractures on the basin (see Fig. 9) could be a consequence of the extensional process of the Iberian plate. Following Álvaro *et al.* (1979), we propose that during the Early Cretaceous rifting stage an expansion centre (RRR triple junction type) was located in the western Tethys, in the present-day offshore of the studied area. One of the arms of this triple junction was the Iberian Basin, the other two would be more or less parallel to the Betic Chain and the present-day coastline. In such a situation the Maestrazgo basin was approximately located in a central position between these three arms. This can explain the higher density of NE-SW fractures near the coast, because this fracture set represents the orientation of the main fault system, linked to the opening of the western Tethys in this area, probably related with a WSW-ESE extension direction. It also explains the higher importance of the NW-SE fault set in the western part of the Maestrazgo basin, which was located on the NW-SE arm of the triple rift junction.

Finally, the close relationship between Early Cretaceous extension and jointing in Jurassic strata is witnessed by the relationship between bed thickness and joint spacing. The late faulting/fracturing processes, during the Neogene extension, did not result in new fracture formation but in the reactivation of the Early Cretaceous faults. Since thickness changes in the Lower Cretaceous units are not clearly controlled by this set of faults, at least onshore, we can suppose that the NNE-SSW set, secondary during the Mesozoic extension, acted as primary during the Neogene extension, probably conditioned by the WNW-ESE extension direction in the Valencia Trough, and lithospheric stretching along this same trend.

Conclusions

The Maestrazgo basin is one of the most important Early Cretaceous basins within the Iberian plate. This basin was inverted during the Tertiary compression, allowing for the pre-rift and the syn-rift sequences to be exposed at surface. Analysis of fracturing at the macro- and meso-structural scales in these sequences (Jurassic and Lower Cretaceous) indicates the existence of two pervasive fracture systems, each one consisting of two orthogonal sets: 1) a primary system consisting of an WNW-ESE to NW-SE set and a NNE-SSW to NE-SW set, and 2) a secondary system consisting of sets oriented along N-S and E-W directions. Both systems are well represented throughout the studied area, their relative importance changing mainly along an E-W trend, especially in the primary system. Whereas NNE-SSW large-scale faults dominated in the eastern Maestrazgo basin, the WNW-ESE- to NW-SE ones dominated in the western of the basin. At the macro-structural scale the primary system faults seem to control the main changes in thickness of the Early Cretaceous syn-rift sequence in the Maestrazgo basin (Fig. 9).

Analysed fractures in both fracture systems comprise normal faults and joints formed during the Early Cretaceous extensional stage. Fracture orientation allows to charasterise the Early Cretaceous tectonic regime as radial extensional (vertical $s_1 >> s_2 \sim s_3$) with two main extension directions: NNE-SSW in the western sector of the Maestrazgo basin and ESE-WNW in its eastern sector. Both extensional directions and spatial differences in the development of the primary fracture system are compatible with basin formation related with a triple R junction below the depocenter of the Maestrazgo basin.

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