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# Neotectonic features of the Catalan Coastal Ranges, Northeastern Spain

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## RESUMEN

**Rasgos neotectónicos de las Cadenas Costeras Catalanas, NE de España.**

Las Cadenas Costeras Catalanas constituyen el sector emergido del dominio Catalano-Valenciano del surco de Valencia. Este sector del surco de Valencia ha estado sometido desde el Oligoceno superior a un proceso extensivo que se ha atenuado a partir del Mioceno superior. Aunque la evolución tectónica durante el Mioceno es bien conocida no ha sido estudiada durante el Plioceno-Cuaternario. La sismicidad de la zona es moderada y constante pero no suficientemente intensa para caracterizar y localizar la tectónica reciente. El análisis geológico aporta información al respecto. Se presenta el análisis morfotectónico y de la deformación de las Cadenas Costeras Catalanas. Se describen tres grandes frentes montañosos que muestran indicios de actividad neotectónica: los de El Camp, El Baix Ebre y El Montseny. Estos frentes presentan facetas triangulares, con más de una generación en El Camp y El Montseny, sinuosidad moderada a baja (1.30-1.50), drenaje ortogonal al frente, cuencas de drenaje en forma de *"wine glass"* con un índice Se/L moderado (0.52 en el frente de El Baix Ebre) y perfiles topográficos convexos perpendiculares al frente. Varios escarpes de falla se disponen paralelos a las fallas principales en la mitad sur de la zona estudiada. Se describen anomalías en la red de drenaje, como asimetrías en las cuencas que indican basculamientos. Se analiza la segmentación del abanico de St. Jordi (El Baix Ebre) debido seguramente a una falla que lo afecta. La deformación frágil en los sedimentos pliocenos y cuaternarios es escasa. En el afloramiento de St. Onofre (El Baix Ebre) se describen fallas normales con $\sigma_1$ vertical y $\sigma_3$ NNW-SSE en los sedimentos pliocenos y fallas normales con dirección NNW-SSE en el Cuaternario. Se describen sedimentos afectados por liquefacción posiblemente relacionados con paleosismicidad. Se deduce un salto predominantemente vertical y normal en las fallas recientes, con una mayor concentración de la deformación en la parte meridional de la zona estudiada. La actividad tectónica actual es caracterizada como muy baja.

*Palabras clave:* Plioceno-Cuaternario. Cadenas Costeras Catalanas. Neotectónica. Geomorfología. Fracturación. Liquefacción.

## ABSTRACT

The Catalan Coastal Ranges constitute the northwestern emerged sector of the Catalan-Valencian domain of the Valencia trough. Since late Oligocene this domain of the Valencia trough was subjected to extension wich gradually attenuated during later periods. The Miocene tectonic evolution of the Catalan Coastal Ranges is relativelly well known while the Pliocene to-Quaternary stages have not been studied in detail. The recorded seismicity of the area is moderate and constant but not sufficiently intense to characterize and locate recent tectonics. However, geological analysis provides further information. A morphotectonic and deformational analysis of the Catalan Coastal Ranges is presented in this paper.

Three main mountain fronts which show characteristic neotectonic features are examined: El Camp, El Baix Ebre and El Montseny mountain fronts. These fronts have faceted spurs, -with more than one generation in El Camp and El Montseny fronts-, moderate to low sinuosity (1.30-1.50), orthogonal drainage across the fault, "wine glass" drainage basins with moderate Se/L index -0.52 in El Baix Ebre front- and convexity in the topographic profiles orthogonal to the front. Several fault scarps are aligned parallel to the main faults in the southern half of the studied zone. Morphological anomalies are also apparent in the fluvial network, for example: asymmetrical drainage basins indicating tilting. Segmentation is noticeable in St. Jordi alluvial fan located near the Baix Ebre basin. Brittle deformation in Pliocene and Quaternary sediments is sparse, but is evident in St. Onofre outcrop (Baix Ebre) with normal faulting with vertical $\sigma 1$ and NNW-SSE $\sigma 3$ in Pliocene sediments and NNW-SSE normal faults in Quaternary sediments. Liquefaction deformational features are described and may be related to paleoseismology. Vertical normal slip is inferred for the main neotectonic mountain fronts with more activity concentrated in the southern Catalan Coastal Ranges. Present-day tectonic activity is characterized as very small.

*Keywords:* Pliocene-Quaternary. Catalan Coastal Ranges. Neotectonics. Geomorphology. Fracturation. Liquefaction.

## INTRODUCTION

The Catalan Coastal Ranges are a NE-SW system of low ridges (the highest point is 1,700 m above sea level) and depressions occurring in the SE edge of the Ebro Basin, parallel to the Catalan coast (Fig. 1). They are the emerged sector of the Catalan-Valencian domain of the Valencia trough (Fontboté *et al.;* 1990), and constitute its northwestern edge. Its structure is characterized by an echelon fault system, subparallel to the coast, that affected the Hercynian basement and the Mesozoic overlying sediments. These basement faults had strike and reverse slip component during the Paleocene (Guimerà 1984, Anadón *et al.,* 1985) and acted later as normal faults to accommodate the extension that took place from the Late Oligocene to the present. The Neogene extension in the Valencia trough was intense during the early Miocene and decreased during middle and upper Miocene and in the Pliocene. In the latest periods the deformation was concentrated mainly in the edges of the trough and concentrated in the major marginal faults (Roca and Desegaulx 1992; Bartrina *et al.,* 1992).

The normal faults have created a *"horst and graben"* system with Miocene to Quaternary basin infilling. From SW to NE the basins studied in the area are el Baix Ebre, el Camp and Vallès-Penedès (Fig. 1).

Some recent tectonic activity features in outcrops of the Catalan Coastal Ranges have been described by other authors (Llopis 1942; Solé Sabarís *et al.,* 1957; Julià and Santanach 1980; Gallart 1981; De Mas 1983; Arasa 1985; Masana 1991). As the seismicity of the area is low but constant (Susagna, 1990) -several M<4 earthquakes recorded annually - there is a need for a global neotectonic study in the zone to determine the amount, kind and situation of the recent tectonic activity. The present tectonic activity in the Catalan Coastal Ranges is not intense enough to localize the more active zones by means of seismicity information only. In order to overcome this problem we have done a morphological analysis of the whole zone and a structural analysis of the deformations observed in recent sediments.

After a synthesis of the seismic data we present the results of the morphoneotectonic analysis, -that is, the analysis of the mountain fronts, the fault scarps, the fluvial network and the arrangement and possible anomalies of the alluvial fans that lie at the foot of the fronts, followed by a description and analysis of the recent deformational structures and possible paleoseismic indicators.

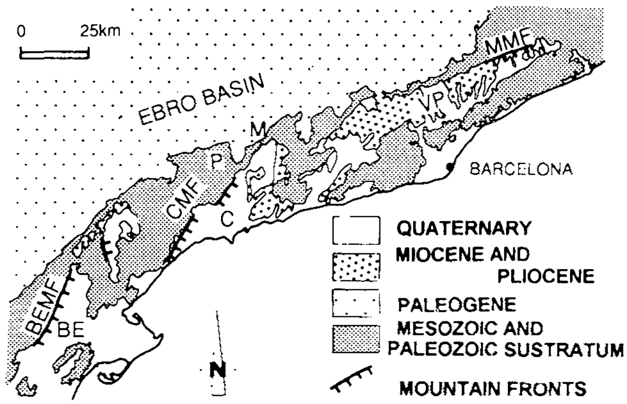



Figure 1. Mountain fronts in the Catalan Coastal Ranges with neotectonic morphological features similar to those described in known active mountain fronts. MMF, Montseny Mountain Front. CMF, El Camp Mountain Front. BEMF, Baix Ebre Mountain Front. BE, Baix Ebre basin. C, El Camp basin. VP, Vallès-Penedès basin. P, Prades range. M, Miramar range.

Figura 1. Frentes montañosos de las Cadenas costeras Catalanas que muestran características morfológicas similares a las de frentes montañosos activos. MMF, Frente montañoso del Montseny. CMF, Frente montañoso de El Camp. BEMF, Frente montañoso del Baix Ebre. BE, fosa de El Baix Ebre. C, fosa de El Camp. VP, fosa de El Vallès-Penedès. P, Sierra de Prades. M, Sierra de Miramar.

## SEISMICITY

The Valencia trough seismicity is considered moderate. The macroseismic and instrumental data of the northeastern Iberian Peninsula show three concentrations of epicenters, the Eastern Pyrenees, the Catalan Coastal Ranges and the Betic range, with almost total absence of earthquakes between the last two zones (Olivera *et al.,* 1992).

The northern and southern half of the Catalan Coastal Ranges have different seismic behaviour (Fig. 2). In the northern half there is a higher concentration of epicenters that range from very low magnitude to M=4. In the southern half there are fewer epicenters but the M=4 is more abundant and there are not many low magnitude earthquakes (Susagna, 1990). The hypocenters are no deeper than 15 km.

The Tivissa earthquake (1845) -Intensity VI (MSK)-, which produced landslides (Jardí and Brú, 1921) and the Montseny one (1927) -Intensity VII (MM)- are the more important historical earthquakes in the macroseismic catalogue.

Figure 2 shows the location of the epicenters recorded by the "Servei Geòlogic de la Generalitat de Catalunya" bulletin between 1986 and 1991 and the focal mechanisms determined by Susagna (1990) and Olivera *et al.,* (1991 and 1992). The absence of epicenters in the Baix

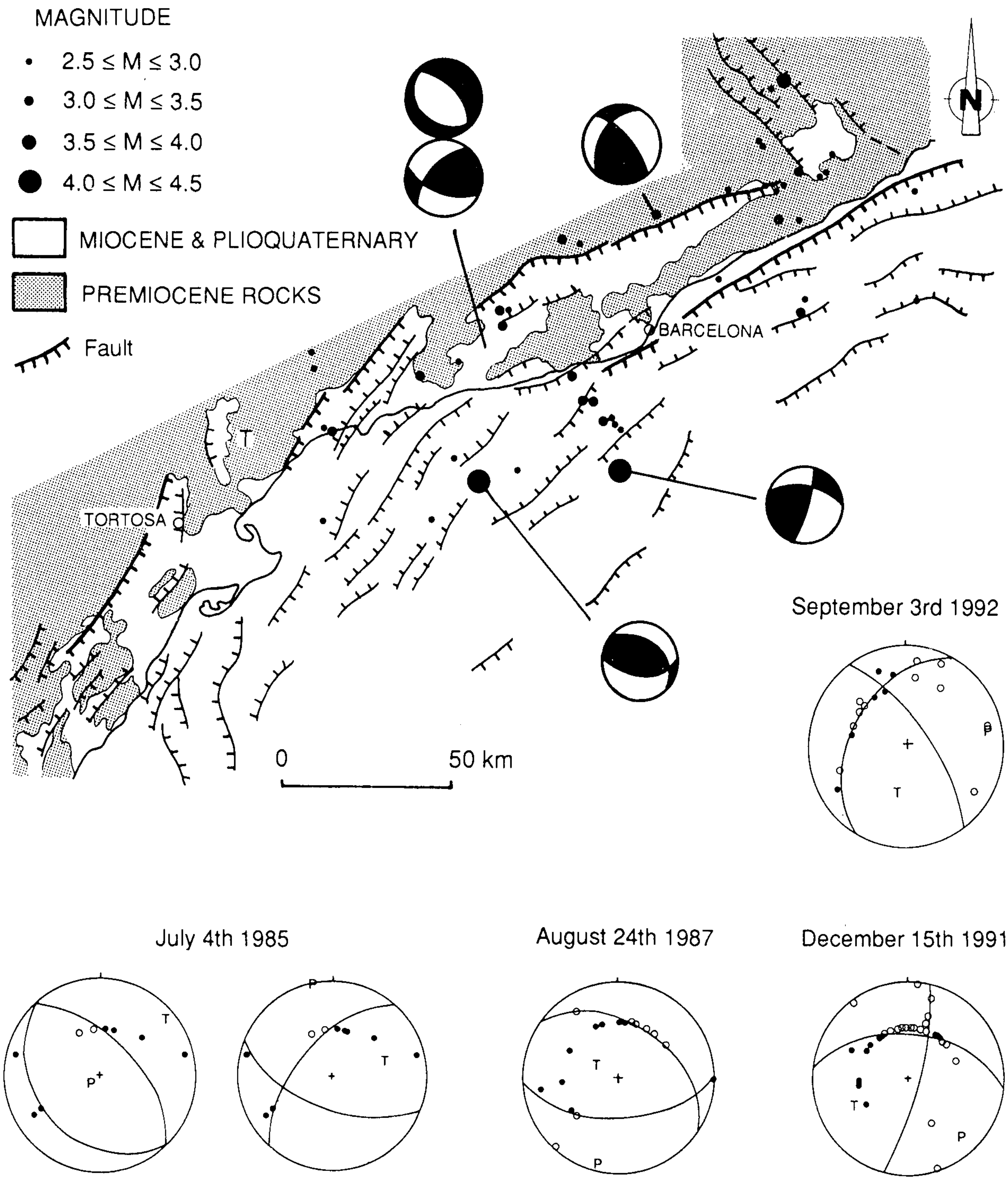



Figure 2. Epicenter map (instrumental data) of the earthquakes occurring between 1987 and 1992 in the Catalan Coastal Ranges containing the calculated focal mechanisms (note that the earthquake with two focal solutions is older than the time span represented on the figure). The situation of the main faults is also shown. (Olivera *et al.*, 1987, 1988, 1989, 1990, 1991, 1992, Roca and Guimerà 1992).

Figura 2. Mapa de epicentros (datos instrumentales) de los terremotos ocurridos entre 1987 y 1992 en las Cordilleras Costeras Catalanas con los mecanismos focales de algunos de ellos (nótese que existe un terremoto con dos soluciones focales que es anterior al periodo representado en la figura). Se representa también la situación de las fallas principales (Olivera *et al.*, 1987, 1988, 1989, 1990, 1991, 1992, Roca and Guimerà 1992).

Ebre zone may be due to a bias caused by the lower density of the seismic network. As the magnitude of the earthquakes of the zone is not high some focal mechanism solutions have also been calculated using the aftershocks. In one case there are four possible nodal planes to explain the mechanism (1985 earthquake). Most of the solutions indicate a directional and reverse slip but the amount of data is not enough to form a definitive conclusion.

## MORPHONEOTECTONIC FEATURES

A geomorphological analysis has been carried out mainly along the principal normal faults which limit the neogene basins. This analysis has pointed out some neotectonic features also described in active zones by other authors. In large active normal faults when the slip is faster than erosion, mountain fronts can form and segmented alluvial fans can be generated next to them (Bull, 1964). The movement along the fault can also produce anomalies in the fluvial network. A very recent slip along a fault can generate a fault scarp if it reaches the surface. The observance of such a scarp may indicate its recent formation because they degrade quickly. These are the main morphoneotectonic features observed in the studied zone that are analysed in this chapter.

### Mountain Fronts

The mountain fronts observed in the Catalan Coastal Ranges are much more degraded than the fronts in active zones (Hamblin 1976; Wallace 1978; Armijo *et al.*, 1988). Figure 1 locates the mountain fronts in the studied zone which show some similarities with active fronts described in the literature. The Baix Ebre mountain front is the most preserved, followed by the Montseny front and the El Camp front (Fig. 3a).

#### *The Baix Ebre Mountain Front*

The slip along the Baix Ebre fault since Lower Miocene has built a NNE-SSW mountain front that limits the Ports de Tortosa range (El Mont Caro 1,434 m), mainly made on massive and stratified Mesozoic dolomites, with the Baix Ebre basin, filled with 400 m of sediment (Arasa, 1992).

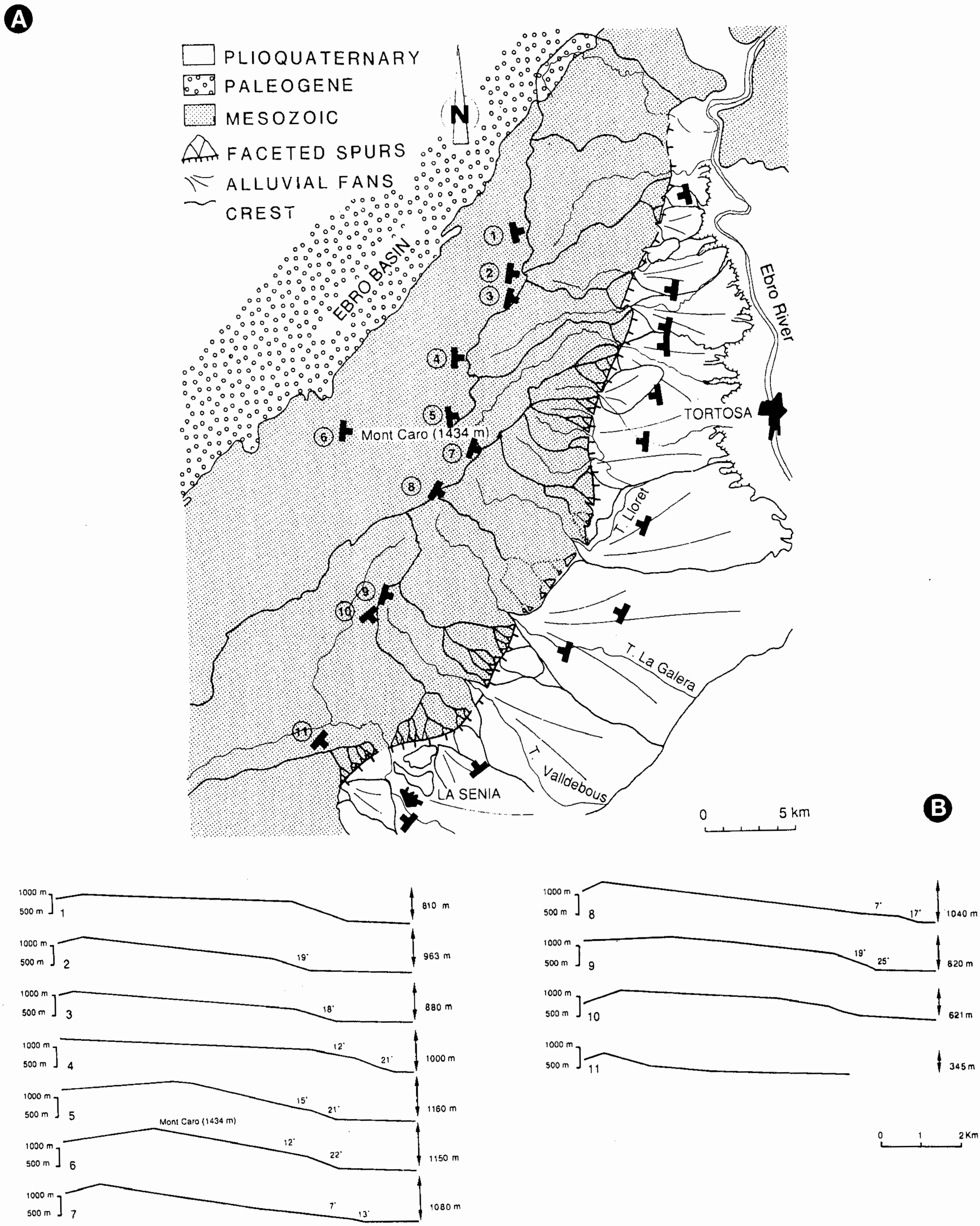
Three fault segments have been pointed out by the morphological analysis of the mountain front (Fig 3A): a) a northern one which is very eroded, perhaps because of the proximity of the incised Ebro river which may cause upward erosion in its tributaries; b) a central segment, W of Tortosa and at the foot of Mont Caro, which better preserves the features of an active mountain front faceted spurs, low sinuosity, creeks crossing the front orthogonally-. The northern half of this central segment has a N-S trend while between the Lloret and Valldebous creeks, in the south, the segment has a NNE-SSW trend, with an intermediate zone where the front is more eroded, possibly due to a lithologic difference -zone of marls and limestones-. And c) a small segment near La Sènia, with NE-SW trend and a fresh morphology.

The sinuosity of the front (S) has been measured as defined by Bull and McFadden (1977): S=Lmf/Ls, where Lmf is the length of the front along the irregularities (buoyances) caused by erosion and Ls is the length of the front along a straight line, without taking into account the buoyances. The sinuosity for the whole Baix Ebre front is 1.46. The segment with lowest sinuosity is in the zone of La Sènia (1.12) and the highest is between la Galera and Lloret creeks (2.30) where the footwall is made of marls and limestones while the rest of the front is mainly composed of massive and stratified dolomites. Although the sinuosity values (S=1.01 to 1.14) proposed by Keller (1986) for active mountain fronts -uplift greater than 0.4 mm/y- are slightly lower than those observed in the Baix Ebre front, the sinuosity in the latter indicates a recent uplift of the front.

The Baix Ebre front has preserved triangular facets. In the central segment the facets have altitudinal differences of 230 to 550 m with a slope angle between 11° and 18°. In la Sènia segment the altitudinal differences are 270 to 360 m and the slope angle 15° to 17°. These slope angles

Figure 3. **A)** Major morphological features of the Baix Ebre Mountain Front. The highest point in Ports de Tortosa range is Mont Caro (1434 m). **B)** Topographic profiles orthogonal to the Baix Ebre Mountain Front. The profiles are situated in Fig 3A. Some profiles show different segments with uniform slope angle along each one as indicated. The arrows at the end of the profiles are from top to bottom of the front indicating the minimum vertical slip of the fault.

Figura 3. **A)** Caracteres morfológicos del frente montañoso de El Baix Ebre. El punto más alto en la sierra de los puertos de Tortosa es el Mont Caro (1434 m). **B)** Perfiles topográficos perpendiculares al frente montañoso de El Baix Ebre. Situación de los perfiles en 3A. Los perfiles muestran en su mayoría segmentos con una pendiente uniforme que se indica en cada caso. Las flechas al final de cada perfil indican el salto vertical mínimo de la falla desde el inicio de su actividad.


A
PLIOQUATERNARY
PALEOGENE
MESOZOIC
FACETED SPURS
ALLUVIAL FANS
CREST
N
EBRO BASIN
Ebro River
Mont Caro (1434 m)
TORTOSA
T. Lloret
T. La Galera
T. Valldebous
LA SENIA
0 5 km
B
1000 m
500 m
1
810 m
2
19°
963 m
3
18°
880 m
4
12°
21°
1000 m
5
15°
21°
1160 m
Mont Caro (1434 m)
6
12°
22°
1150 m
7
7°
13°
1080 m
8
7°
17°
1040 m
9
19°
25°
820 m
10
621 m
11
345 m
0 1 2 Km

are comparable to the slopes described by Wallace (1978) for a second or third stage of degradation -stage B and C of the faceted spurs (20 and 12) for a fault dipping 60°.

Taking into account the whole history of the normal fault, the greatest vertical slip took place in the central segment (Fig. 3B) where the topographic difference between the highest point in the range (Mont Caro) and the foot of the front (200 m), is maximum (1,234 m). Of course this is a minimum slip on that profile because it does not take into account the thickness of the sediment in the basin.

The basin Mesozoic substratum is near the surface (400 m of maximum depth; Arasa ,1992) as it is deduced through well data (Junta d'Aigües de Tortosa, internal reports), so that some even higher blocks outcrop in the middle of the basin. These data also show a pediment at the foot of the front, now overlapped by the quaternary alluvial fans. The pediment may be the consequence of a recent period of low front uplift which caused a retreat of the front.

Creek arrangement is influenced by tectonics. Creeks cross the Baix Ebre front orthogonally, indicating the maximum slope gradient, coherently with an uplift of the mountain front. In the uplifted block, far from the front, some of the creeks set according to the alpine structure, in this case oblique to the front (NE-SW). The mean relation (Se/L) between the interbasin spacing (Se) and basin length (L) is 0.52. This is a higher value than that calculated for the active zones (0.30-0.40, Wallace, 1978; Briais *et al.,* 1990) but lower than that calculated for non active zones (0.87, Wallace, 1978). The geometry of the drainage basins of the Baix Ebre mountain front are "*wine glass*" shaped, similar to those described in active fronts (Wallace, 1978). The geometry of the fluvial net is consistent with the other kind of information for that front, indicating that the activity has been low but existent.

*El Camp Mountain Front*

The El Camp fault defines the limits of the El Camp basin (Fig. 1), filled by Neogene and Quaternary sediments (2,000 m of maximum thickness), with the Prades Range in the southern half and the Miramar Range in the northern half (La Mussara 1,005 m). The slip along the El Camp fault originated a mountain front in the zone where the basin limits with the Prades range. Although it is quite eroded, this front preserves some characteristic features of active mountain fronts (Masana *et al.,* 1991). These features are not visible in the Miramar segment of the fault.

A characteristic neotectonic feature of the front is the drainage network that crosses it orthogonally and the *"wine glass"* valley shapes (Wallace, 1978) of the drainage basins in the uplifted block although these basins are not constant in area. The channels are separated by spurs which end, in the front side, as very eroded faceted spurs that are aligned defining segments along the fault (segments of Hospitalet on Jurasic limestones and Vilavella and les Borges del Camp on Paleozoic shales and arcoses; Masana, 1991). These segments, with the exception of the les Borges del Camp in the north of the mountain front, with S=1.56, generally have high sinuosity.

The triangular facets show 2 to 3 generations depending on the segment, which means that there have been several alternating periods of uplift and quiescence of the front (Hamblin, 1976). At least two generations of alluvial fans have been deposited beneath the front, and may be related to different periods of uplift (Masana, 1991).

*El Montseny Mountain Front*

Since at least Early Miocene, the activity of the Vallès-Penedès fault has originated the Vallès-Penedès basin (Fig. 1), filled with Neogene sediments -locally Quaternary- (2,500 m of maximum thickness, Bartrina *et al.,* 1992). This is the studied basin with minimum extension and thickness of Quaternary sediments and maximum thickness of Neogene sediments in the litoral Neogene basins.

The morphological analysis of this fault shows some recent tectonic features on the El Montseny mountain front in the northern part of the el Vallès-Penedès fault, where the seismicity is most outstandingly numerous. With the exception of that zone, the Vallès-Penedès fault does not display clear morphological features of neotectonic origin.

In the El Montseny front the uplifted block is basically made of slates, limestones and granitoids. The maximum topographic difference is 1,340 m (Turó de l'Home 1,709 m). Transversal topographic profiles show a convexity to the foot of the front indicating a high ratio between uplift and retreat of the front (Wallace, 1978). Three faceted spur generations have been identified, the younger showing a slightly more pronounced slope at the base of the front (12° to 20°) than the higher and older facets (8° to 19°). The fluvial network is orthogonal to the front. The sinuosity of the front is 1.31. Similarly to the fronts described before, the morphological features indicate that the front is not active today but has shown recent activity.

## Fault Scarps

A direct result of an earthquake is the surficial generation of fault scarps. In the studied zone there are some lineations (Fig. 4) in quaternary sediments where there is a topographic step between the two sides of the lineation. After a detailed study of each of the scarps we have interpreted them as eroded fault scarps as no other process can explain their morphology (Fig 4a). The Mont-roig scarp (Fig. 4B), located in the southern half of the el Camp basin and limited to the NW by the el Camp mountain front (Masana, 1991), is the better preserved. Its length is 10 km, and its maximum altitude is 2 m. No kinematic indicators have been found in the front of the scarp. Several creeks cross orthogonally through the scarp; they are incised in the uplifted block to the level they flow in the downthrown block, indicating that the uplift velocity is low compared with the incision velocity of the creeks. The alluvial fans affected by the scarp have been correlated morphologically with the Castellvell fan, where interstratified Musterian lithic industry (coeval to the last pleistocene glaciation) have been described (Masana, 1991; Masana and Guimerà, 1992). The existence of preserved fault scarps indicates recent activity of the fault on that trace.

## Fluvial Network

Two principal conclusions have come out from the fluvial network analysis 1) the presence of some anomalies possibly indicating tilting toward the recent faults. and 2) the absence of anomalies indicating strike slip along the recent faults.

The Gaià river shows a good example of assymetry in its fluvial network that may be produced by a tilting towards the el Camp fault (Fig. 5). Its drainage basin looses its natural symmetry when the river comes into the el Camp basin where the creeks in the western bank of the Gaià river flow towards the Francolí river, that is towards the el Camp fault.

Although the directional slip is usually well recorded by the network in active strike slip faults, in the studied zone the analysis did not reveal any of the anomalies caused by it, so it is not probable that in recent times the studied faults have had significant directional slip.

## Alluvial fans

Pliocene-Quaternary alluvial fans are extensive in the southern half of the Catalan Coastal Ranges. Their drai-

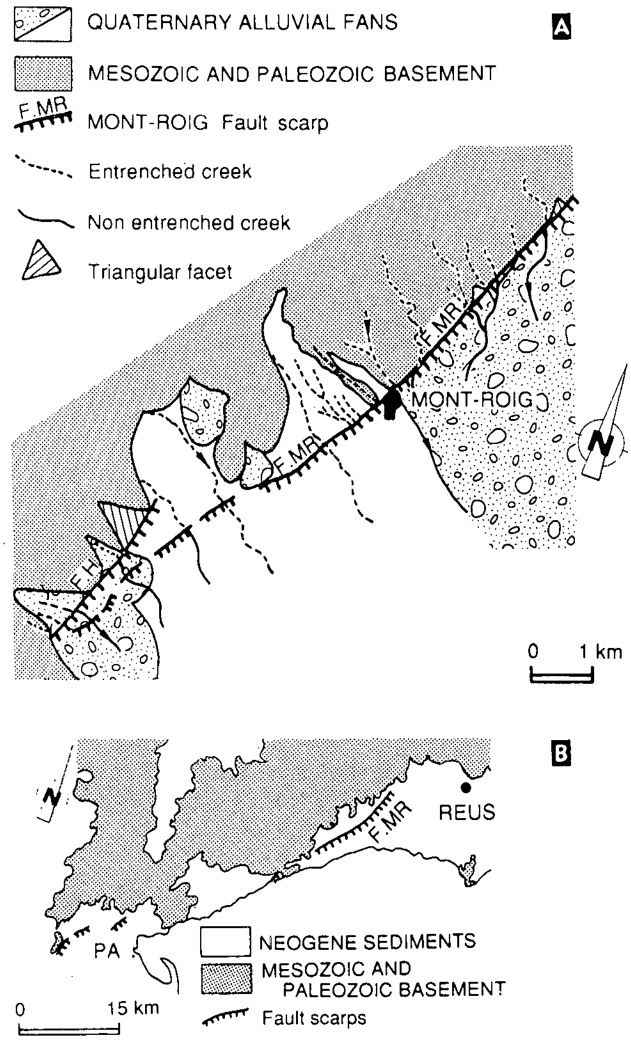



Figure 4. **A.** The Mont-roig scarp cutting through two generations of alluvial fans. The drainage is entrenched in the upthrown block of the fault and it is not in the downthrown block. FH Hospitalet fault. FMR Mont-roig scarp. **B.** Situation of the scarps localized in the studied area. PA, Pla de l'Ampolla.

Figura 4. **A.** El escarpe de Mont-roig afecta a dos generaciones diferentes de abanicos aluviales. La red de drenaje está encajada en el bloque levantado y no lo está en el hundido. FH Falla de Hospitalet. FMR Escarpe de falla de Mont-roig. **B.** Situación de los escarpes de falla localizados en la zona estudiada. PA, Pla de l'Ampolla.

nage basins are on Mesozoic sediments, basically on carbonates and in some fans in the El Camp basin in Paleozoic limestones and graywackes.

Segmented alluvial fans are described by Bull (1964) in fans that developed at the foot of uplifting or subsiding mountain fronts. The longitudinal topographical profiles of those fans show several segments with decreasing or increasing slopes respectively. Thus, seg-

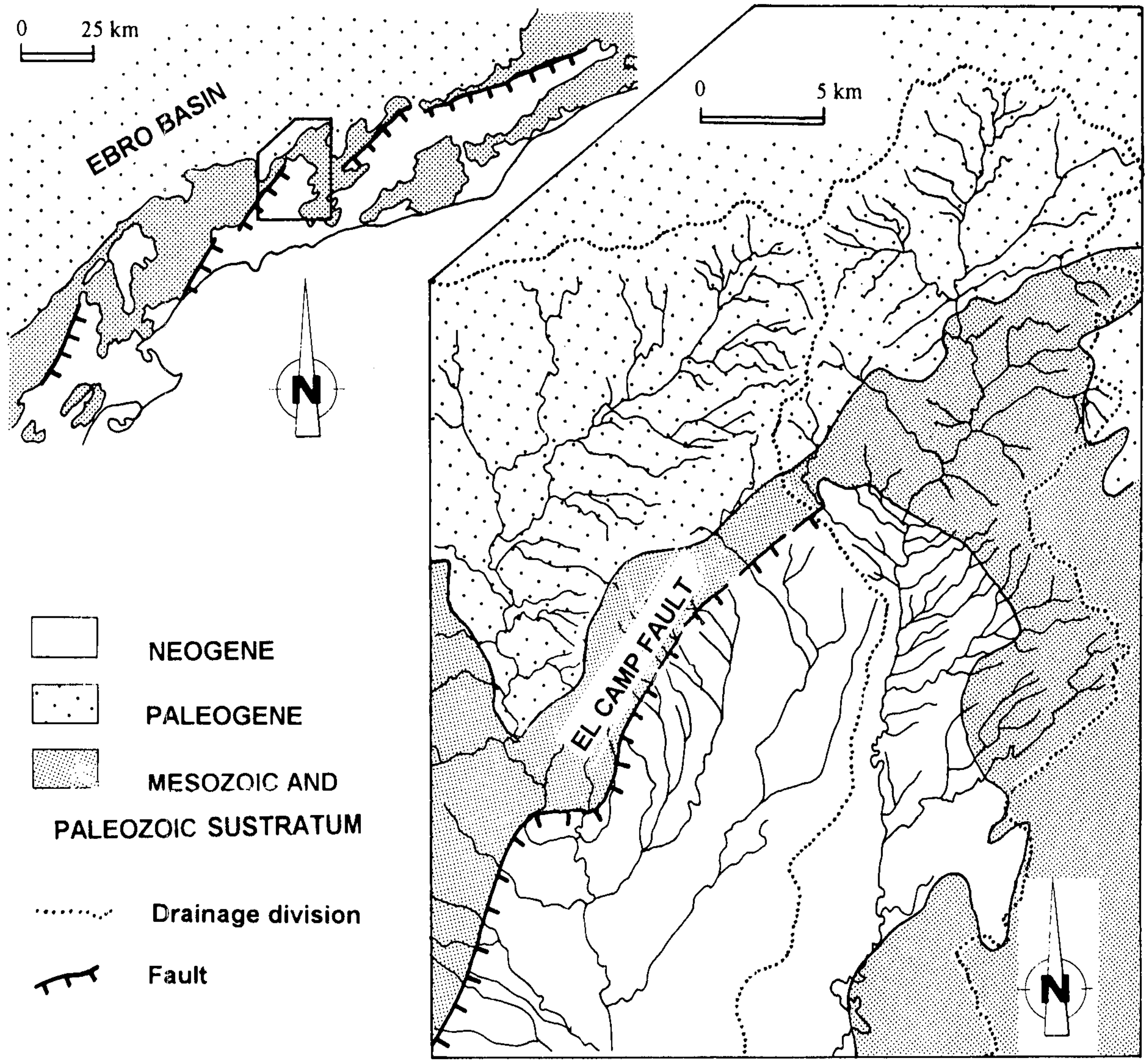



Figure 5. Drainage network of the Francolí and Gaià rivers and its relation to the el Camp normal fault. Note that the drainage basin of the Gaià river becomes assymetric when the river goes into the el Camp Basin; the creeks flow towards the Francolí river possibly due to a tilting of the basin towards the El Camp fault, that is towards the ENE.

Figura 5. Cuencas de drenaje de los ríos Gaià y Francolí y su relación con la falla normal de El Camp. Nótese que la cuenca de drenaje del río Gaià pierde su simetría al entrar el río en la fosa del Camp; los torrentes vierten sus aguas hacia el río Francolí, posiblemente debido a un basculamiento de la fosa hacia la falla del Camp, esto es hacia el ENE.

mentation on alluvial fans may be an indicator of recent tectonic activity.

Although alluvial fans are abundant in the southern half of the Catalan Coastal Ranges, their morphological analysis shows no good examples of segmentation (Bull, 1964). Coarse lithology (fanglomerate) may hide the segmentation effect, but the low presence of segmentation may also be caused by a lower uplift velocity compared with the entrenchement velocity of the principal channel, which makes the uplift effects immune to the fault building processes. The entrenchement of the channels in most fans makes the last possibility more convincing.

Julià and Marquès (unpublished) name a segmentation in the Sant Jordi alluvial fan (Tarragona), which is, as revealed by the morphological analysis presented here, the best example of segmentation in the Catalan Coastal Ranges. However, its morphology is not typical of a segmented fan. Radial profiles (Fig. 6) show an upper seg-

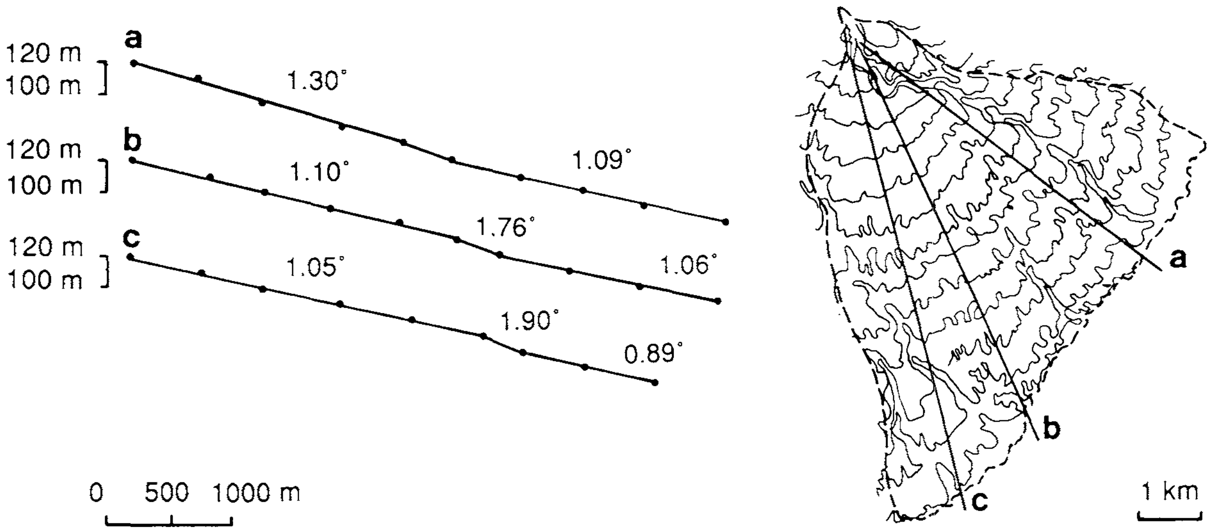



Figure 6. Altitudinal features of St. Jordi alluvial fan. The radial profiles show a well correlated step. It also shows that the upper segments are steeper than the lower.

Figura 6. Topografía del abanico aluvial de St. Jordi. Los perfiles radiales muestran un escalón correlacionable en todo el abanico. Los segmentos superiores tienen más pendiente que los inferiores.

ment with 1.05° to 1.30° of slope and a lower one with slope between 0.89° and 1.09° separated by a small step with 1.90° of slope. This morphology may be the consequence of the activation of a fault scarp, which in this case would have a NNE trend similar to the others described in the zone, while the fan was active. The available data are insufficient to corroborate this interpretation. The little difference in slope between the two long segments together with the lack of geochronology data of the fan makes it difficult to interpret it in the way of Bull (1964).

## DEFORMATIONAL STRUCTURES

There are very few deformation structures affecting recent sediments in the studied zone. Most of these structures are in the Baix Ebre Basin and some of them in a zone between it and the El Camp Basin. The more complete outcrop is the Sant Onofre (Baix Ebre), which is the only pre-quaternary outcrop of the Baix Ebre basin as alluvial fans cover almost the whole basin. Some normal faults and tiltings in Pliocene-Quaternary sediments of the zone are mentioned by Julià and Santanach (1980). The lithostratigraphic units are described by Arasa (1992) as follows. The prepliocene successions are formed by La Venta del Ranxero conglomerates (carbonatic pebbles alternating with red clays, and by the siliciceous conglomerates of Anguera. (polygenic conglomerates with silicic pebbles) which overly erosively the Venta del Ranxero unit. The Anguera unit is attributed to the Turolian by Arasa (1990). The Pliocene, erosive on the last unit, is formed by three units; the lower is formed by gravel and sands containing ostreids; it is followed by the blue marls of Campredó and the Sant Onofre carbonates on the top. Although the Pliocene fossil record has been studied by different authors there is no coincidence on the age of the units. Some authors (Agustí *et al.,* 1983) attribute the top Pliocene carbonates to the Ruscinian, while others (Aguirre 1982; Magné, 1978; Martinell and Domènech, 1984) date the lower units in Middle to Upper Pliocene. Arasa (1990) describes an upper conglomerate unit, Roca Corba conglomerates, which lies conformably over the carbonates and which he dates as Villafranquian.

The Quaternary sediments, which are very extensive, are separated from the older sediments by an unconformity the following units: the Ford conglomerates, formed by polygenic pebbles and attributed to the Low Quaternary; and the Mas de la Palma gravels also with polygenic pebbles which form the upper Ebre terrace. These polygenic gravels and conglomerates are laterally interfingered with the alluvial fan monogenic gravels (carbonate pebbles) that overlay most of the basins.

The La Venta del Ranxero prepliocene conglomerates are tilted 30° to the NW and show normal faults with NE-SW trend. Once the stratification is restored to the

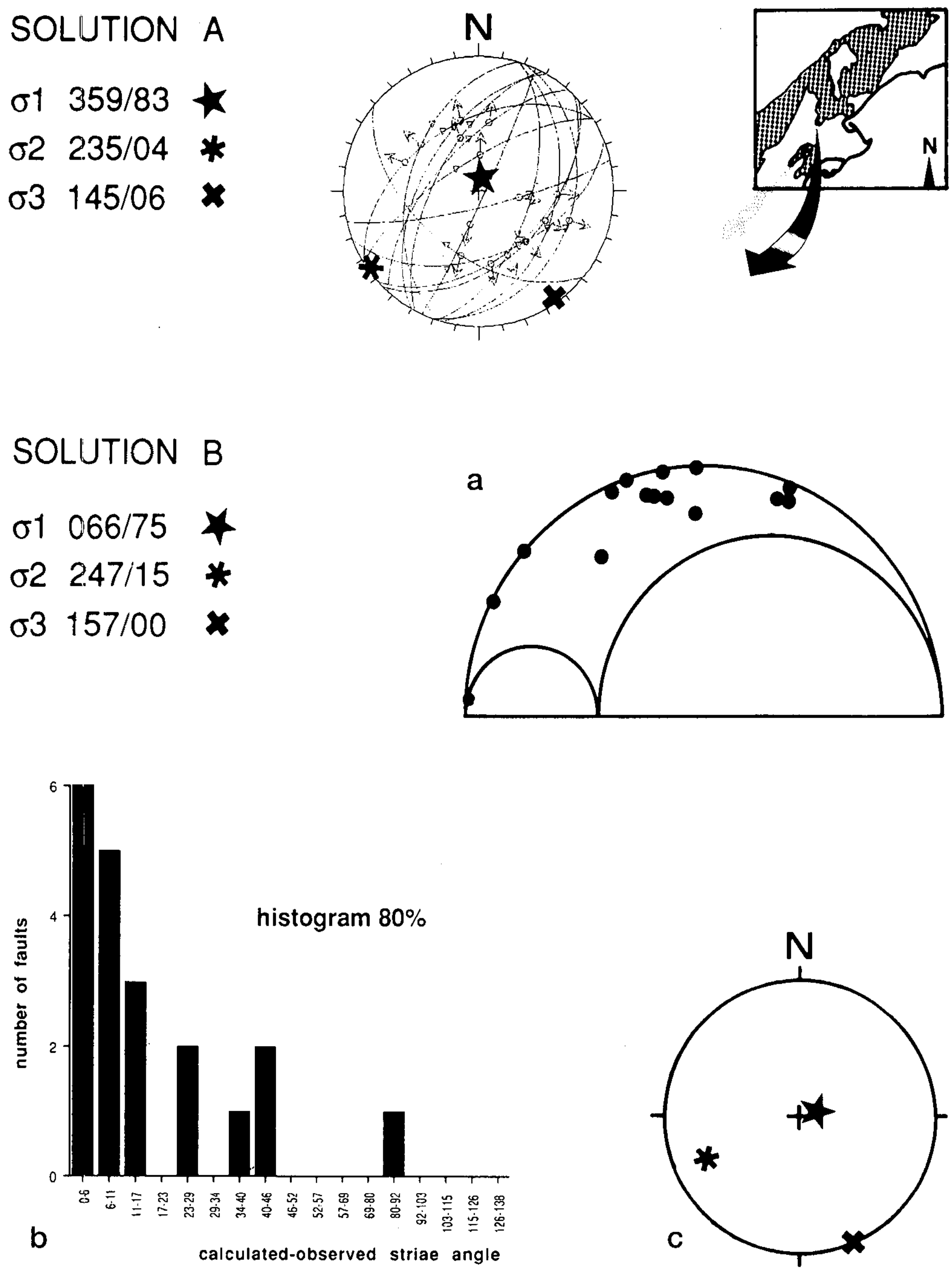



Figure 7. Two different solutions for the deformation field affecting the Pliocene marls of St Onofre (Tarragona) inferred from striated normal fault planes. Solution A has been calculated by the T.Villemin's program (Stress, unpublished) and solution B by the method of Etchecopar *et al.* (1981). In solution A a lower hemisphere projection of the faults and the striae is represented as well as the principal stress axes. Solution B shows the Mhor circle (a) and the histogram for the analysed faults (b) as well as the representation of the lower hemisphere of the principal stress axes (c). Both solutions show a vertical $\sigma_1$ and a NNW-SSE $\sigma_3$ for the Pliocene sediments of the Baix Ebre basin.

Figura 7. Dos soluciones diferentes del cálculo del campo de deformación que afecta a las margas Pliocenas de St Onofre (Tarragona) realizado a partir de planos de falla estriados. La solución A se ha calculado mediante el programa de T.Villemin (Stress, no publicado) y la solución B con el método de Etchecopar *et al.* (1981). En la solución A se representa la proyección estereográfica en hemisferio inferior de las fallas y estrías analizadas así como los ejes de los esfuerzos principales. En la solución B se muestra el diagrama de Mhor (a) y el histograma de las fallas analizadas (b) así como la proyección estereográfica en hemisferio inferior de los ejes principales de esfuerzo (c). Las dos soluciones muestran $\sigma_1$ vertical y $\sigma_3$ NNW-SSE para los sedimentos pliocenos de la fosa del Baix Ebre.

horizontal, and taking into account the limitations of the method using little data, the optimum stress method (Etchecopar 1984) shows a vertical $\sigma_1$ and a NW-SE $\sigma_3$.

The Pliocene sediments are affected by normal faults (Fig. 7) more abundant in the lower part of the unit. We established a measuring station of the striated fault planes in the marls and analysed them with the Etchecopar *et al.* (1981) method and with the program Stress from T. Villemin. The results are very similar, as is shown in Fig 6: $\sigma_3$ is NNW-SSE and $\sigma_1$ is vertical. The slip along the faults is synpliocene because some of the faults are overlapped by the same marls.

In some Pliocene conglomerate outcrops the carbonate pebbles are dissolved showing a vertical trend of maximum dissolution which is difficult to interpret as the conglomerates are not believed to have been overburdened by a thick layer of sediments.

The Pleistocene Ford gravels, deposited by the Ebre river, are tilted 25° NW (Fig. 8) and are affected by a conjugate normal fault set with a NNW-SSE trend that produce 1-2 m of slip in the outcrop.

## PALEOSEISMICITY FEATURES

Paleoseismicity is the study of prehistoric earthquakes based on the geological record they produced, which are called seismites. In the Catalan Coastal Ranges the possible paleoseismicity features are basically liquefaction indicators in Quaternary sediments and fault scarps which have previously been described in this paper. Liquefaction is a process by which water saturated sediments may flow under overpressure conditions. The ground acceleration produced by the seismic waves during an earthquake, if strong enough, raises liquefaction in a prone sediment, that is: recent sediments, well sorted, fine grain sized, with low density, deposited quickly and under phreatic level but usually less deep than 3 m from the surface (Vittori *et al.*, 1981). Many descriptions of actual earthquake effects show liquefaction in some sediments (Sims, 1973 and 1975; Seilaher, 1969 and 1984). There are other elements able to produce liquefaction such as instability produced by density differences in saturated fine grained sediments or sudden overloads. It is difficult to differentiate the origin of the liquefaction and so to identify it as of paleoseismicity genesis but as some fault scarps have been described in the zone as well as historical big earthquakes, the relation between liquefaction and the earthquakes is possible.

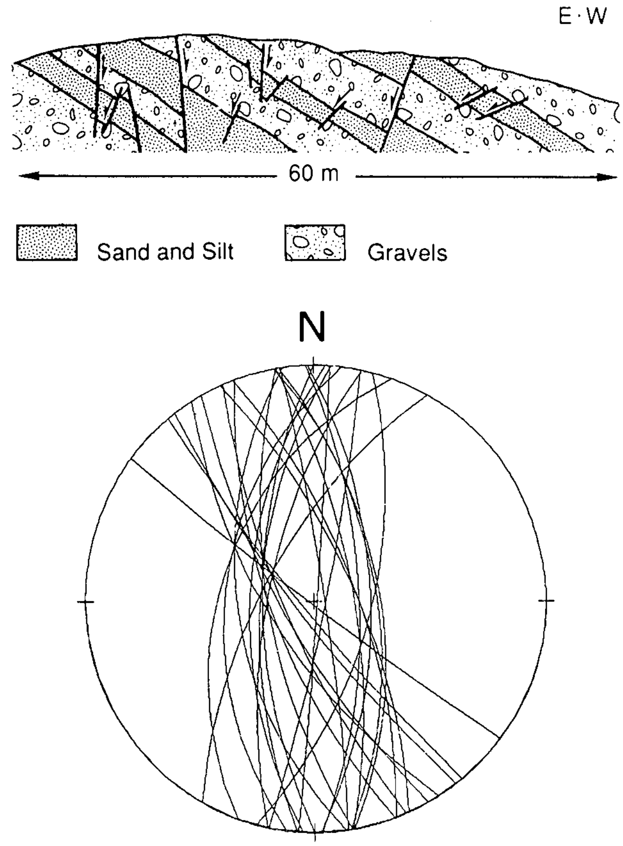



Figure 8. E-W profile of the quaternary Ford gravels and a projection on stereographic net (lower hemisphere) of the fault planes in the gravels. A vertical $\sigma_1$ is inferred.

Figura 8. Perfil E-W de las gravas cuaternarias de Ford y proyección en plantilla estereográfica (hemisferio inferior) de los planos de falla que afectan dichas gravas. Se deduce una posición vertical de $\sigma_1$.

In the studied area, most liquefaction features are localized in the Morro del Gos area (Fig. 9), between the Baix Ebre Basin and el Camp Basin, where the sediments are more susceptible to liquefaction. The surrounding zones are covered by Quaternary carbonate clast alluvial fans wich have caliche soils over them, while the sediments observed in the Morro del Gos area are the following ones, from bottom to top:

- Non cemented gravels with poligenic and well rounded pebbles alternating with silts. The lithology of the pebbles and the stratigraphy of the sediments indicate a fluvial origin. The maximum observed thickness of the fluvial sediments is 10 m.

- Conglomerates with limestone pebbles and with caliches in the upper zone. They have alluvial fan morphology and they overlay pliocene sediments in St. Onofre (Arasa, 1992). They have regional extension, covering the Baix Ebre basin. They have been inter-

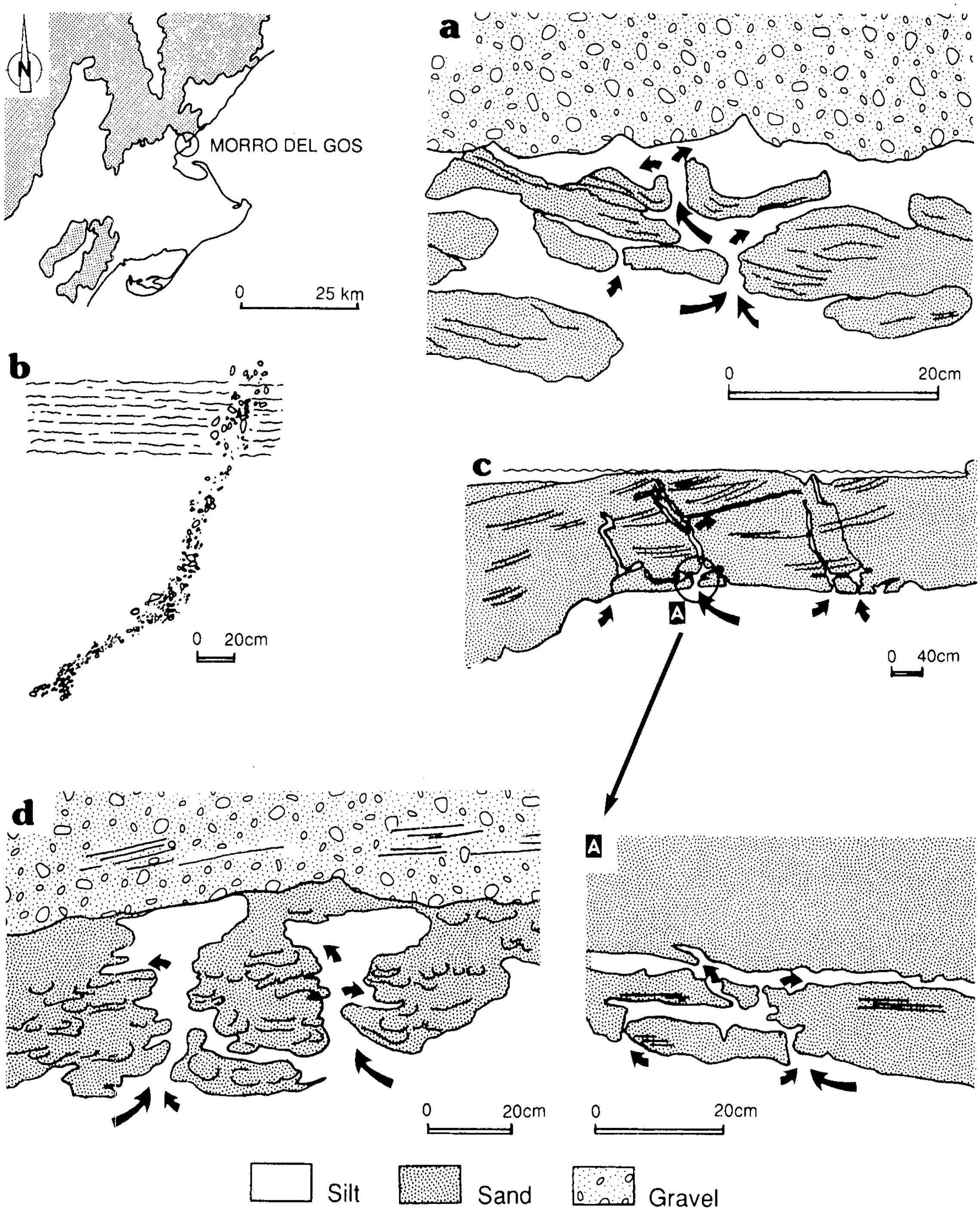



Figure 9. Some liquefaction features observed in the Morro del Gos area. **a**, Silt injection in a sandy layer which is also deformed plastically as shown by the upwards bending of the layers. **b**, Gravel and silt dike injected in a non cemented silt layer. **c**, Underlaying silts injected through joints and cross-bedding planes of an overlaying sand layer, with a detail (A) of the liquefaction of silts and their transport through the sands. **d**, Example of plastic deformation caused by the intrusion of a silt underlaying mass towards a sandy overlaying level.

Figura 9. Afloramientos con indicios de licuefacción en los sedimentos pliocenos-cuaternarios de Morro del Gos. **a**, Inyección de limos en un nivel arenoso que está a su vez deformado plásticamente **b**, Dique clástico compuesto de gravas y arenas inyectado en un nivel superior de limos no cementados. **c**, Limos inyectados en diaclasas y planos de estratificación cruzada de un nivel de arenas cementado con un detalle (A) de la liquefacción de los limos y su transporte a través de las arenas. **d**, Ejemplo de deformación plástica producida por la intrusión de un nivel inferior limoso en un nivel superior arenoso.

preted as Pleistocene alluvial fanglomerates. In some outcrops they are interfingered with the fluvial sediments and in some others they overlay them. The maximum observed thickness of the alluvial sediments in the zone is 15 m.

- 40-100 cm of eolic sandstones with high angle cross lamination interpreted as sand-dunes. These sandstones are observed usually over the fluvial sediments and also in the higher levels of the alluvial fanglomerates.

- 60-100 cm of cemented sand layer that contains *Strombus* and other marine fauna (Maldonado, 1972,; Porta *et al.,* 1981). It has been interpreted as a marine terrace of Neotyrrhenian age.

- 25 cm layer of sand containing banal fauna. Interpreted as a recent marine terrace.

There are several deformation patterns affecting the Morro del Gos sediments. Two main joint sets affect the tyrrhenian cemented sands, a more dominant one with EW trend and a second one with N10-20E trend. The two sets do not show clear structures by which to deduce the chronology between them. As there is no evidence on whether they are extension or shear joints no interpretation of the deformation field can be achieved. Several 2 m slip normal faults with average 005/80W orientation affect the polygenic gravels and sands. The pebbles near the fractures show slight dissolution with a subvertical maximum dissolution axis.

Liquefaction induced structures are often observed in the zone mostly in silt fluvial outcrops. Two main structures have been observed: distortion in the sediments and sand dikes (Fig. 9).

The observed sediment distortion show typical liquefaction structures like those produced in laboratory (Sims, 1975; Ringrose, 1989) and like those observed after big earthquakes (Sims, 1973 and 1975; Ben-Menahem, 1976; Anand and Jain, 1987): small vertical columns through which sediment has gone upward (pillars), subsiding zones over the empty spaces formed by the upwards migration of sediment, small fractures, and convoluted laminations and bedding. Those structures affect either thin or thick levels. In some cases silts intrude the upper levels as a mass, without following any previous structure. In fine flat laminated beds convolution is often observed unless it is developed in a low degree.

Plenty of clastic dikes are observed in the zone. In the Morro del Gos island with a basal silt layer overlain by cross-bedded sandstones, two kinds of dikes are observed: silts and sands intruding the sandstones through joints forming vertical clastic dikes, and silts and sands intruding through discontinuities of cross bed lamination forming subhorizontal sills.

Some examples of gravel clastic dikes have been described in the zone. They usually intrude through silt layers and contain pebbles, sand and silt coming from underlaying gravels. As the gravels are difficult to liquefy the pebbles may go into the dike due to a suction effect.

## DISCUSSION AND CONCLUSIONS

No indicators of high recent tectonic activity have been found in the Catalan Coastal Ranges. Most Pliocene and Quaternary sediments are not deformed and the geomorphological analysis done in the zone do not show typical features of high neotectonic activity. On the other hand several signals of recent low activity have been described in this paper.

Three mountain fronts with neotectonic morphological features -faceted spurs, low sinuosity, orthogonal drainage to the front, *"wine glass"* drainage basins, moderate Se/L index and convexity in the topographical profiles across the fronts- are pointed out from the morphological analysis, from N to S: El Montseny front, El Camp front and Baix Ebre front.

The morphology of these mountain fronts as well as the anomalies observed in the fluvial network show a prevailing vertical slip along the faults that originated them. Any morphological indicator of strike slip along the recently active faults have been detected. Even though possible local or temporal variations of the slip are not excluded. For example, in the Vallès-Penedès basin small deformations have been described in Miocene sediments that show reverse and strike slip, which may be a consequence of local variations of deformational field (Fontboté *et al.,* 1985; Bartrina *et al.,* 1992; Amigó, 1986).

A pediment in the Baix Ebre front may indicate a recent erosion and retreat of the front caused by the uplift velocity decrease. So the fault is either non active or its actual fault trace is some hundred meters away from the actual front, under the alluvial fans. As no deformational features have been observed in the alluvial fans of the zone, the last possibility is less probable. In the other two recently uplifted fronts no scarp has been described at the foot of the fronts, indicating, as well as in the Baix Ebre front, that the uplift is not active now.

Although it has a lower number of earthquakes, more neotectonic features have been described in the southern half of the studied zone than in the northern half: less eroded morphological features, deformation in Quaternary and Pliocene sediments, fault scarps, and liquefacction features possibly caused by earthquakes. The better preservation of the southern morphological features may be influenced by a lightly dryer weather in the zone. The sedimentation of Quaternary sediments is more extensive in the El Camp basin and Baix Ebre basin while in the Vallès-Penedès basin the erosion predominates on the Quaternary sediments. The mentioned Quaternary sediment distribution is in agreement with the more intense recent uplift of the southern mountain fronts, but the data is too little to make any definitive conclusion in that direction.

The infilling sediments in the Catalan Coastal Ranges Neogene basins are less deformed during Quaternary than in earlier times. Faults and striae in pebbles in Miocene and Pliocene sediments show an SE-NW extension direction while in Quaternary sediments extension is E-W. These results are not relevant to characterization of the regional deformation field as data is not very extensive and is obtained from mesostructures.

The evidence of active tectonics in the zone is little. The seismicity is sparse and of low magnitude, but the historical data shows that the zone can suffer moderate earthquakes -Intensity VI and VII for Tivissa and Montseny earthquakes respectively-. Several structures have been interpreted as paleoseismological indicators: fault scarps and deformational features in soft sediments.

The observed fault scarps break up alluvial fans with Neothirrenian beaches entrenched at their distal zones (Pla de Sant Jordi, Plà de l'Ampolla) and alluvial fans correlated with other fans containing lithic Musterian industry (Mont-roig). The orientation of the scarplets is similar in all cases, NNE-SSW, parallel to the whole range orientation. The described scarps still have morphological expression and, although they are in carbonated soils which are more difficult to erode than uncemented gravels, can be interpreted as of very recent formation. Wallace (1978) considers that the maximum time span during which a normal fault scarp is still preserved from erosion is about 100,000 years, as an order of magnitude (reverse fault scarps erode much more quickly).

The step observed in Sant Jordi alluvial fan is probably an eroded or fossilized fault scarp. The two segments observed in the fan may show a variation in uplift velocity. The lack of information about the age of distal and proximal sediments of the fan makes it impossible to determine whether the slight difference in slope angle of the two segments is due to an increase or a decrease in the uplift velocity of the alluvial drainage area.

From what has been discussed above, it can be deduced that Miocene extension in the Catalan Coastal Ranges has decreased in intensity but has continued during Pliocene and early Quaternary. However the deformation in recent times has been low and especially concentrated along the Baix Ebre, El Camp and Montseny mountain fronts with mainly normal slip, being more intense in the southern half of the Catalan Coastal Ranges.

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