Evidence for past earthquakes in an area of low historical seismicity: the Catalan coastal ranges, NE Spain

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Abstract
The Catalan coastal ranges are situated far away from a plate margin and thus are characterized by low rates of deformation and low seismicity. Nevertheless, up to six morphological scarps in quaternary alluvial fans, large landslides and liquefaction features were detected in the southern half of these ranges and motivated a more detailed geomorphologic and palaeoseismologic study. In the Baix Ebre Fault zone, the morphological analysis of the mountain front and the fluvial network showed evidence of alternative periods of uplift and quiescence and suggested a sub-actual reactivation of the fault after a recent stable period. In El Camp zone the Almadrava and Mont-roig scarps were analysed in detail. The first shows evidence of fault control and of two probably seismic deformation events. A normal semi-hidden fault that folds the surface was suggested to explain the deformation observed in this scarp. The second is also considered to be controlled by a fault which was active between 100000 and 4490-4790 year B.C. If creep deformation could be rejected the Mont-roig scarp fault may be considered an active fault able to generate large earthquakes ($M > 6.5$). In summary, although the zone shows low historical seismicity, evidence that can be referred to past earthquakes was detected. Further palaeoseismologic studies should be carried out in these structures in order to better constrain the active behaviour of the faults.

Key words *fault scarps – geomorphology – Quaternary – palaeoseismicity – Catalan coastal ranges*

1. Introduction

In the Catalan coastal ranges (fig. 1), the instrumental data shows low seismicity with magnitudes up to 4.5 in a period of about 50 years, and the historical seismicity reports the occurrence of two intensity VI-VII earthquakes that caused damage in the zone in a period of 1000 years. Nevertheless, in other regions of low seismicity considered (the Meers fault, U.S.A.; Crone and Luza, 1990), geological and palaeoseismological investigation evidenced the existence of high seismic potential. In these zones the time span covered by the historical record is shorter than the recurrence period, which may be of more than 100000 years (Crone and Luza, 1990). Recently, some seismic events occurred in zones with low historical seismicity such as in 1986 in Marryat Creek, Australia, or in 1989 in Ungava, Canada (Machete *et al.*, 1993; Adams *et al.*, 1992). These considerations, together with the high population of the Catalan coast that constrains its high vulnerability, motivated a detailed study of the active tectonics of the area.

The principal aim of this study was to detect and analyse the geologic and geomorphologic elements that can be related to the recent tectonic activity of the Catalan coastal ranges to determine whether this zone contains active structures or not. This analysis involved structural and geomorphic investigation and showed the existence of several features – fault scarps,

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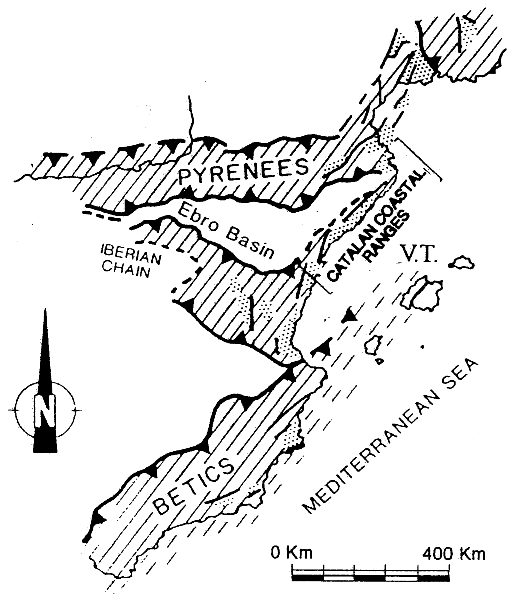

Fig. 1. Map of the oriental half of the Iberian Peninsula where the zones deformed under compression during the Paleogene are represented with stripes and the main rifts created during the Neogene extension are represented with dots. The rectangle indicates the Catalan coastal ranges, the studied area. V.T. = Valencia trough (from Fontboté *et al.*, 1992).

liquefaction features, mass movements – that could be related to palaeoseismicity in the area. Moreover, a palaeoseismological study was performed in some of these structures.

2. The seismicity of the Catalan coastal ranges

The north-eastern part of the Iberian Peninsula exhibits a moderate to low seismic activity. The instrumental record shows earthquakes up to *M* 4.5 located mostly in the Pyrenees and also in the Catalan coastal ranges, with the Ebre basin zone in between with no seismicity. The historical seismicity points out two catastrophic events, up to intensity X, that occurred in the Pyrenees (several hundred kilometers north of the Catalan coastal ranges). South of the studied area there is a concentration of earthquakes in the Betic Cordillera, separated from the Catalan coastal ranges by a zone without seismicity (Olivera *et al.*, 1992a).

The instrumental seismicity of the Catalan coastal ranges shows several earthquakes concentrated mostly in the northern half of the ranges, with maximum magnitudes of 4.5 (fig. 2). By contrast, in the southern half of the ranges, earthquakes with magnitudes between 3 and 4 are more abundant although the total number of events is lower than in the northern half (Susagna, 1990).

The historical catalogue, which begins in the XI century, does not show any catastrophic earthquake in the zone. Two of the seismic events described in the catalogue caused damage in the surrounding areas: the Tivissa (1845) and the Montseny (1927) earthquakes. The epicentre of the first was situated near the town of Tivissa, Northeast of Tortosa (fig. 2). It had an intensity of VI and some landslides were triggered by the earthquake (Jardí and Bru, 1921; Correig, 1982). The seismic event in the Montseny had an intensity of VII (Fontserè, 1927; Comas, 1927).

Four focal mechanisms (fig. 2) have been obtained for this zone (Susagna, 1990; Olivera, *et al.*, 1991; 1992a,b). These determinations have only been possible for the largest earthquakes, and as these earthquakes show low values in magnitude ($M < 4.5$) in some cases the solutions are poorly constrained (see, *e.g.*, two solutions for the 1985 earthquake in fig. 2). This suggests the data may not be significant for tectonic interpretations. Nevertheless, it should be pointed out that N-S compression axes come out on some solutions, contrasting with evidence of E-W extension tectonics inferred from structural and geomorphologic data.

3. General geological setting

The Catalan coastal ranges are formed by a system of ranges and depressions with NE-SW to NNE-SSW stike, sub-parallel to the coast, bounding to the NW with the Ebre basin, a very weakly deformed unit.

During the N-S convergence of the African and Euroasiatic plates which took place from

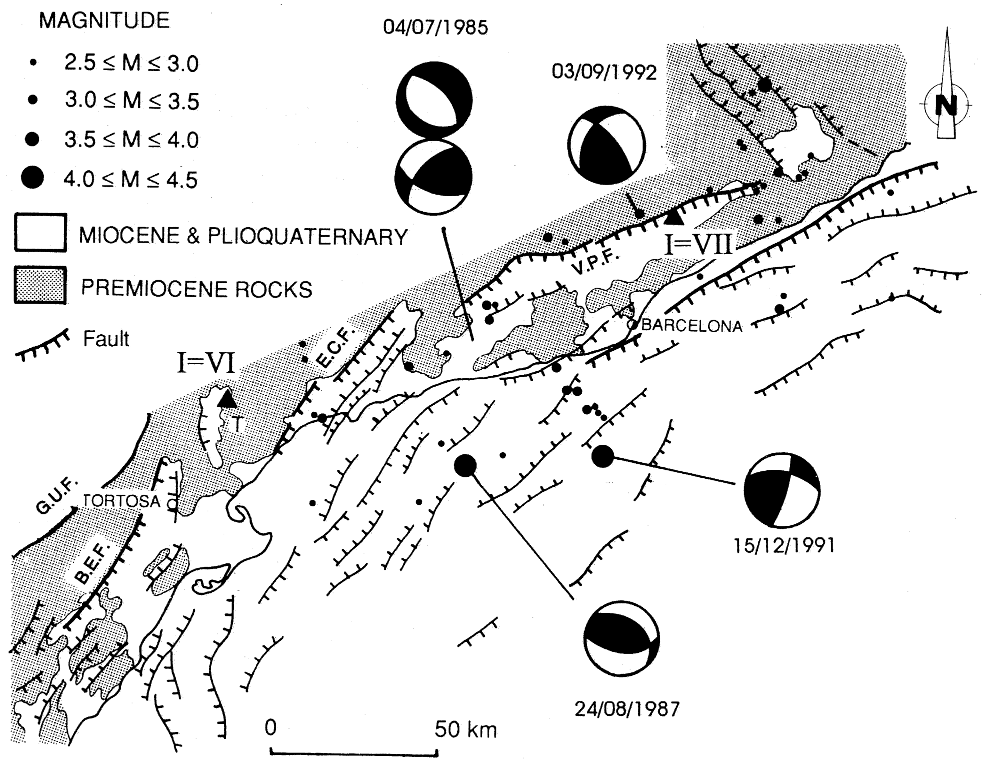

Fig. 2. Seismicity map for the period 1987-1991 in the Catalan coastal ranges ($M > 2$) and focal solution for the main earthquakes in the zone (data from Servei Geologic de Catalunya). Thick lines with fault symbol indicate main faults. T = Tivissa; V.P.F. = Vallès-Penedès Fault; E.C.F. = El Camp Fault; G.U.F. = Gandesa-Ulldemolins Fault; B.E.F. = Baix Ebre Fault.

the Aptian to the Present (Dewey *et al.*, 1973; Biju-Duval, 1977; Dewey *et al.*, 1989), in the Catalan coastal ranges the deformation was mainly absorbed by several basement faults with NNE-SSW strike: Vallès-Penedès, El Camp and Gandesa-Ulldemolins faults (Anadón *et al.*, 1985; Guimerà, 1988). The behaviour of these faults changed with time depending on changing tectonic regimes. During the Paleogene the Catalan coastal ranges area was under N-S compression and was part of the Iberian chain (fig. 1) (Anadón *et al.*, 1979, 1985). The main faults displayed reversal and sinistral strike-slip movement (Fontboté, 1954; Guimerà, 1984). The Neogene extension that took place in the Valencia trough, related to the rotation of Corsica and Sardinia, led to the inversion of the compressive Paleogene faults (fig. 1). From the early Miocene, in the Catalan coastal ranges, the major faults had a normal slip and several asymmetrical grabens with Neogene sedimentary infilling formed next to those faults (Fontboté, 1954). In the mainland the main Neogene basins included in the Catalan coastal ranges are the Baix Ebre, El Camp and Vallès-Penedès basins (figs. 2 and 3). The maximum thickness of the sediment infill reaches up to 4000 m in the Vallès-Penedès basin (Bartrina *et al.*, 1992).

While Miocene tectonic evolution of the Catalan coastal ranges has been well studied (Cabrera, 1981; Bartrina *et al.*, 1992; Roca, 1992), little information is available on its Pliocene and Quaternary evolution. The main extension period in that region took place during the early Miocene but some recent works show that this zone has also been under extension up to the Present (Masana, 1994a, 1995). The deformation that took place from the late Miocene is not intense but is recognised from structural and geomorphologic analysis (Masana, 1995). The indicators of this deformation are mainly located in the southern half of the Catalan coastal ranges, in the area where fewer historical earthquakes were recorded (figs. 2 and 3).

Structural analysis of structures involving Pliocene and Quaternary sediments was based on the study of minor faults (method from Etchecopar, 1984; Angelier and Bergerat, 1983), strike of joint sets, deformation on striated pebbles (method from Schrader, 1988) and tilting of bedding. These structures are scarce and concentrated mostly in the southern half of the Catalan coastal ranges. All the observed faults are normal and only in a few cases did the amount of faults per site allow fault population analysis. The results for the

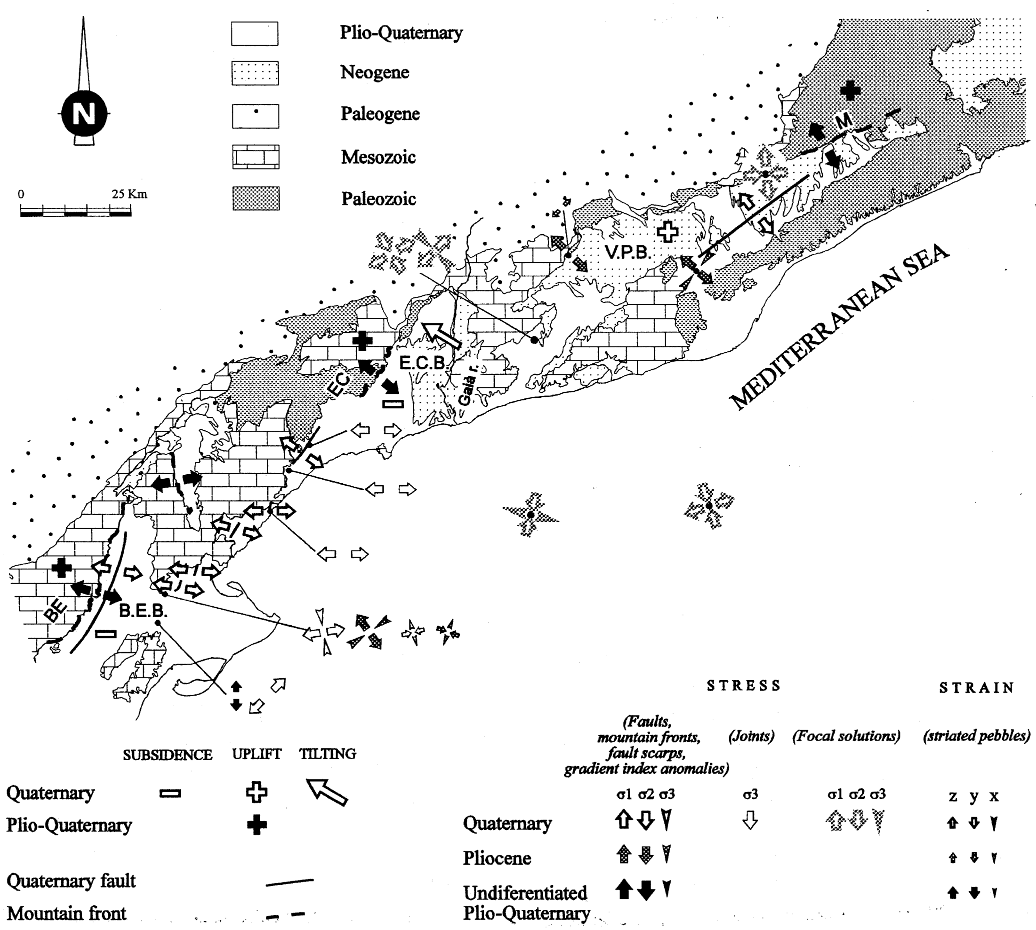

Fig. 3. Map of the recent tectonic features detected in the Catalan coastal ranges. V.P.B. = Vallès-Penedès Basin; E.C.B. = El Camp Basin; B.E.B. = Baix Ebre Basin; M = Montseny front; EC = El Camp front; BE = Baix Ebre front.

Quaternary outcrops indicate a vertical $\sigma 1$ and an E-W $\sigma 3$ while for the Pliocene sediments $\sigma 1$ was vertical and $\sigma 3$ was SE-NW (fig. 3).

4. Recognition of palaeoseismicity indicators

A detailed geomorphologic analysis was performed in the Catalan coastal ranges – using aerial photographs, topographical analysis and field survey – in order to recognise recent deformation and possible palaeoseismological features. It was mainly based on the study of mountain fronts, fluvial network and alluvial fans. Some information on the tectonic behaviour of the area during the Pliocene and the Quaternary was obtained from this analysis. The mountain fronts of Baix Ebre, El Camp and Montseny, if compared with the other fronts of the area which are highly eroded, show evidence of Quaternary uplift: low sinuosity, faceted spurs, wineglass valleys, convex topographical profiles and high vertical incision (Masana, 1995) (descriptions of the methods can be found in Hamblin, 1976; Wallace, 1978; Bull and MacFadden, 1977; Briais *et al.*, 1990). In the Neogene basins other evidence of vertical movements were described. The Valles-Penedes basin shows vertical incision and sparse and highly degraded Quaternary deposits. This suggests that the basin was uplifted in respect to its base level during the Quaternary. On the other hand, the El Camp and Baix Ebre Basins show both well preserved and extensive Quaternary sedimentation as well as slight incision, features which were interpreted as the consequence of Quaternary subsidence. In the El Camp Basin the asymmetry of the drainage pattern of the Gaia river indicates the tilting of the basin towards the El Camp Fault. No systematic deflection in the fluvial network was detected (Masana, 1994b), suggesting the absence of recent strike slip movements, while several anomalies in the longitudinal profile of the rivers – gradient index versus equilibrium profile: SL/K (Sebeer and Gornitz, 1983) – were pointed out, indicating recent vertical movements. Some of these SL/K anomalies are aligned parallel to Neogene faults bounding the Vallès-Penedès and Baix Ebre Basins indicating recent vertical movements parallel to the actual edges of those basins. In summary, all this morphological data show deformation caused by vertical motion mainly concentrated along some of the basement faults that had normal slip during the Miocene. It results that the blocks that were uplifted during the Neogene extension show evidence of recent uplift, and the blocks that were thrown down during the Neogene extension show evidence of recent subsidence. This, together with the structural data that show SE-NW to E-W extension during the Pliocene and Quaternary, suggest that the recent deformation of the area was in continuity with the Miocene extension (Masana, 1995).

Three possible palaeoseismic indicators were detected in the Catalan coastal ranges (fig. 4): fault scarps, liquefaction structures and land-

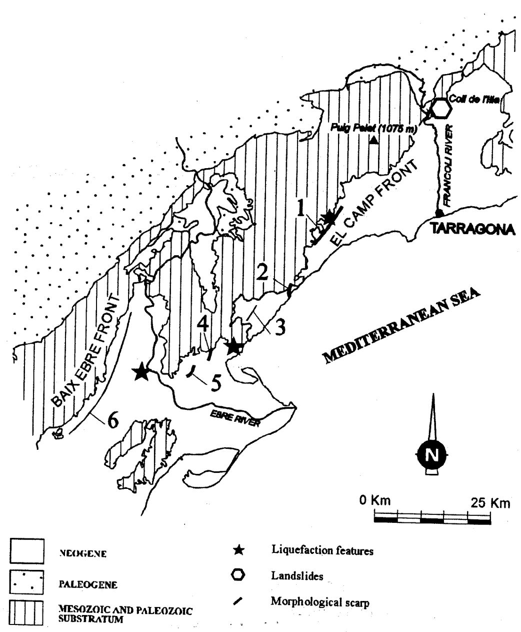

Fig. 4. Map of the detected elements that could indicate palaeoseismicity in the Catalan coastal ranges. Numbers represent: 1 = Mont-roig scarp; 2 = Almadrava scarp; 3 = Sant Jordi scarp; 4 = Camarles scarp; 5 = Aldea scarp; 6 = Baix Ebre scarp. Thick lines represent the scarps observed by the aerial photograph, and thin lines represent the scarps interpreted by the morphological analysis.

slides. Between these, the most reliable are the fault scarps, since they are the surface expression of the latest movements of a fault, although palaeoseismic character cannot be confirmed if aseismic deformation behaviour is not rejected for the fault. Liquefaction structures may be triggered by seismic waves but also by other phenomena (Vittori *et al.*, 1991) so they are not palaeoseismological indicators in themselves. This also applies to the landslides because although they can be triggered by earthquakes, there are other possible causes for their triggering.

The fault scarps, liquefaction features and landslides observed in the Catalan coastal ranges are all located in the southern half of the ranges (fig. 4). Broadly, this distribution is the same observed for the other recent tectonic structural and geomorphologic features that are also mainly concentrated in the south, and, in detail, the possible palaeoseismic indicators are mostly associated with two of the zones where neotectonic indicators were also clustered: the Baix Ebre mountain front and the El Camp Fault zones.

4.1. *The zone of Baix Ebre front*

Several morphological indicators show uplift of the Baix Ebre mountain front situated at the western to north-western edge of the Baix Ebre Basin. The Baix Ebre Basin is infilled with Miocene sediments and thick (up to 400 m) and poorly entrenched Plio-Quaternary deposits. The front is 40 km long, has a NNE-SSW strike, and cuts the NE-SW trending Paleogene compression structures. It is mostly built up on Jurassic limestones although in its northern part some Triassic dolomites and marls show up, and in the southern part some Cretaceous limestones and marls crop out (Esteban and Robles Orozco, 1976; Salas, 1983). The highest point of the range is Mont Caro (1434 m) and the bottom of the front is 200 m high in the North and 500 m high in the South, so the topographic difference in this front is up to 1200 m. This front (fig. 5) is eroded but still shows: low sinuosity – 1.69, and locally 1.02 (Masana, 1995) –, faceted spurs, wineglass valleys, convex topographic profiles and a moderate to low basin separation index – between 0.48 and 0.52 – (Masana, 1995). The vertical incision (rate between lateral and vertical incision) of the valleys crossing the front is high – values ranging from 3 to 4 – if compared with the incision in the other valleys of the Catalan coastal ranges which entrenched in fronts where recent tectonic indicators are lacking – 6 to 13.

In the central and southern sectors of the front, the faceted spurs show two and three generations of facets respectively (fig. 5). So this front has experienced at least two or three uplift periods separated by quiescence periods according to Hamblin (1976). The bottom of the front does not show any evidence of very recent movement like a well preserved and continuous scarp, or knick points in the creeks crossing the front. This means that the uplift period that caused the last generation of triangular faceted spurs is finished. Data from water wells show, however, the existence of a pediment at the foot of the front, under up to 10 m of Quaternary alluvial sediments. With a very low uplift rate the erosion could produce the retreat of the front. In this case, the pediment and the sediments observed at the base of the front can be related to a period of quiescence of the fault. Furthermore, the bottom of the mountain front is not in the same position as the fault that caused the front.

The study of SL/K anomalies, in the longitudinal profiles of the creeks, discloses some segments with a higher slope compared to the equilibrium slope of the creek. A broad lineation of these anomalies is observed parallel to the front, several hundreds of meters away from it (fig. 5). As SL/K anomalies could reflect lithological contrasts, we took into account only the features located in areas of homogeneous substratum. In this light these anomalies can be considered tectonically induced. This kind of anomalies are easily eroded (Mackin, 1948) and are considered to be a recent feature. The situation of the anomalies relative to the front suggests that they can represent deformation due to the very recent reactivation of the Baix Ebre Fault after its quiescence period. If this is confirmed, the described alignments could be interpreted as an incipient fault scarp.

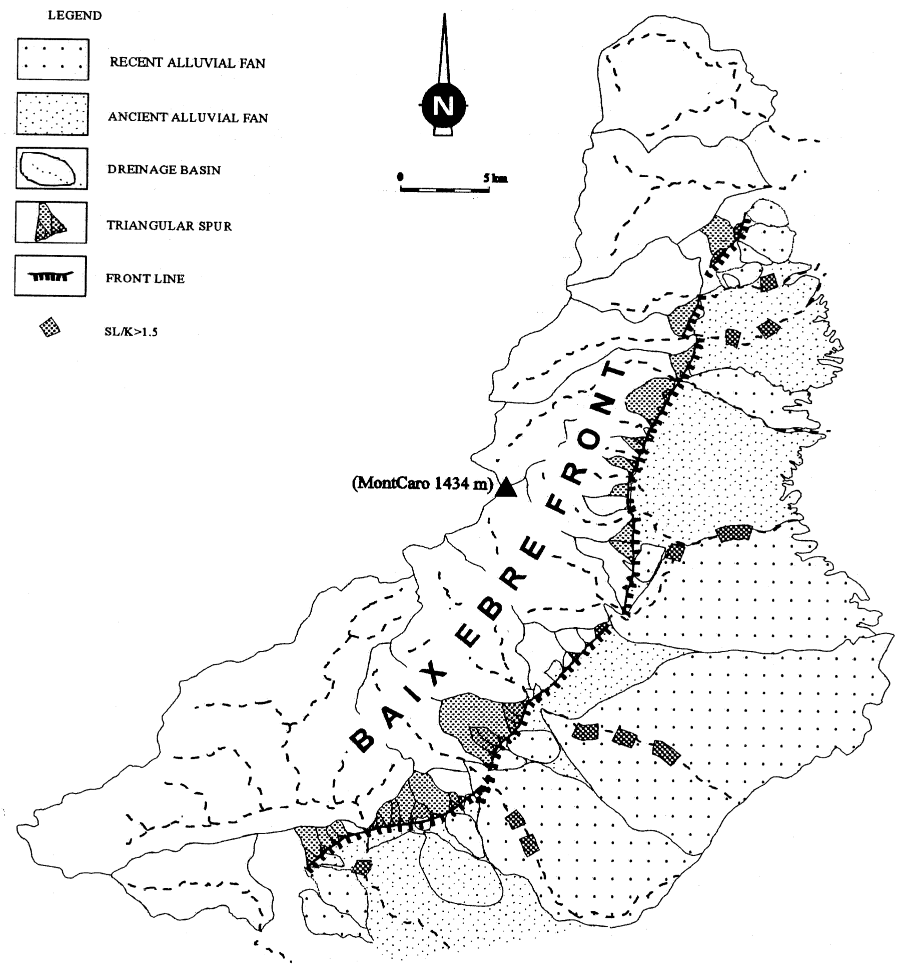

Fig. 5. Geomorphologic map of the Baix Ebre mountain front zone.

4.2. *The zone of El Camp Fault*

The north-western edge of the El Camp Basin shows a mountain front that is 60 km long and has a NNE-SSW strike. It is formed by two steep sectors, the northern sector also being the eastern one. The highest point of the range is Puig Pelat (1075 m) and the bottom of the front lies between 20 and 200 m high (fig. 4). The lithology of the front is heterogeneous: in the southern and northern extremities it is made of Mesozoic limestones while in its central part it is built up by Variscan granites and shales.

The El Camp front shows, from the Francoli river to the southwest, evidence of recent tectonic uplift in the geomorphologic record: up to three generations of faceted spurs, moderate sinuosity values (1.25), wineglass valleys, moderate to low basin separation rates (0.53), as well as convex topographic profiles. Alluvial fans of two generations lay at the foot of the front. One of the fans belonging to the youngest generation (Masana and Guimerà, 1992), near Reus, yielded Musterian industry (Lumley, 1971) which means that this generation of fans is younger by at least 100000 years.

Five morphological scarps on the alluvial fans were detected along the El Camp Fault zone, one near the foot of the El Camp mountain front and the others south of it. Four of them were detected using aerial photograph analysis (Mont-roig, Almadrava, Camarles and Aldea scarps) and one using topographical analysis on the fan surface (Sant Jordi). They are between 1 and 10 km long, have NNE-SSW strike, broadly parallel to the main fronts of the Southwest Catalan coastal ranges. All of them are on Quaternary calcareous alluvial fans which show usually cemented surfaces.

Moreover, liquefaction structures and landslides were identified in the El Camp area. Liquefaction features are mostly concentrated in Cap Roig, E of the Camarles scarp (fig. 4). In this site fluvial siliciclastic sediments – non cemented polygenic gravels, sands and limes – crop out interfingered with Quaternary alluvial fans of the Neogene basins. Two marine terraces lie over the fluvial sediments: the oldest one is Tyrrhenian in age and the youngest contains non characteristic fauna (Maldonado, 1972; Porta *et al.*, 1981). The nature of the described sediments possibly favoured the formation of liquefaction structures. Several sand and gravel dikes cut the bedding and show evidence of transport of sediment towards higher layers. Some sand sheets are highly disturbed displaying pillar and pillow structures. Minor normal faults with up to one meter separation are sparse in the zone. This kind of liquefaction structures, although fewer in number, have also been observed around the Mont-roig scarp and in some fluvial terraces of the Ebre river. As the lithological control is evident in all the liquefaction structures detected, and sites with those structures are not abundant, the higher concentration of them in Cap Roig cannot be considered caused by its proximity to any epicentre.

Twenty Quaternary landslides have been detected in Coll de l'Illa (fig. 4), north of Tarragona. They are located in a small zone (10 km^2) and range from under 50 m to 2 km in diameter. They consist of Triassic limestones glided on Triassic lutites and Paleozoic shales. As several alluvial fans of the recent generation have been sedimented over them, the landslides are older than 30000 to 100000 years (Musterian range). In all the Catalan coastal ranges, only this site shows such a concentration of landslides, but their seismic origin cannot be proved.

The Mont-roig scarp and the Almadrava scarp are described in more detail in this paper due to their better exposure.

4.2.1. The Almadrava scarp

This scarp, which runs as far as 500 m from Vandellós Nuclear Power Plant (fig. 6a), is 1 km long, with N-S strike and 7 m of maximum vertical separation, measured in a topographical profile performed orthogonaly to the scarp. Its southern extremity goes into the sea across a smooth cliff and brings natural outcrops where the structure of the scarp can be analysed in more detail than in the other scarps of El Camp Fault zone; in addition, some artificial outcrops exist in the zone, one of them dug across the fault scarp. In this trench the relation between deformation structures and sedimentation was studied in order to recognise structures related to palaeoseismic events (Pantosti and Yeats, 1993). Three stratigraphic units were defined in the trench and were correlated to the other outcrops of the area (fig. 6b).

The trench cuts mostly across the up-thrown bloc and therefore gives poor information about the total deformation of the scarp zone that could extend further east. However, deformation is clearly visible in the three stratigraphical units described and some information can be extracted from the trench.

Several fractures die out against the topographical surface, and the top of unit B, and sparse fractures die out at the top of unit A. Between those, three main fractures stand out (1, 2 and 3 of fig. 6a,b). Fault 1 produces one meter of vertical separation at unit A and 90 cm at unit B – which is partly eroded near the

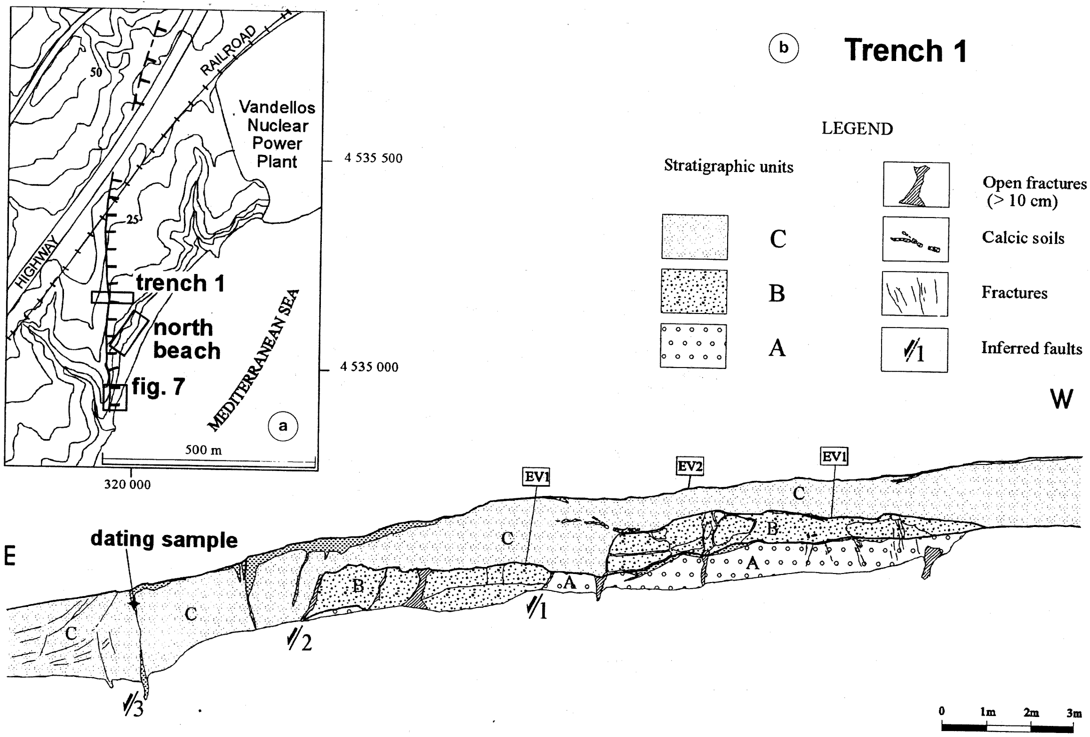

Fig. 6a,b. a) Map of the Almadrava Fault scarp and the principal outcrops of the scarp. Note the proximity of the Nuclear Power Plant. b) Log of the trench from a detailed 1:20 profile. The units observed have the following characteristics: A = heterometric (0.5 to 20 cm in diameter), well cemented, calcareous conglomerate with angular pebbles. On the top, caliche levels up to 8 cm thick developed. The lack of lamination means that this caliche was formed in a buried state; B = red clays containing caliche clasts and caliche concretions. Locally it contains well cemented calcareous conglomerates. The top of this layer shows a caliche horizon, up to 6 cm thick, with plenty of pisoids and laminated internal structure, meaning that it was formed on an exposed surface; C = calcareous gravels slightly cemented and with a large amount of muddy and sandy matrix. Pebbles are calcareous, angular and from 3 to 5 cm in diameter. The top of this layer coincides with the current topographic surface and is formed by a caliche horizon which also developed in the sub vertical fractures that reach the surface. Surfaces EV1 and EV2 were interpreted as the topographical surface when earthquakes occurred (see text for discussion).

fault – while unit C overlays it with no evidence of faulting. This suggests that this fault was active before the sedimentation of unit C. The small difference on vertical separation observed between units A and B is not significant – the top of the units is not sharply defined – to demonstrate the occurrence of two separate movements at this fault. Fault 2 cuts units A and B. Only a minimum vertical dislocation – 3 m – can be established for these faults in the trench because these units are not visible in the down thrown block east of this fault. Unit C overlays the fault with no evidence of movement. Fracture 3 reaches the surface but it cuts only through unit C so dislocations are not visible. However, the eastern block of that fracture – in the lower topographical side of the scarp – displays a smooth synclinal fold that could be the consequence of down throwing of that side. In this case, fracture 3 could be considered a fault. Moreover, south of this trench site, this fracture displays up to 0.5 m of topographical vertical dislocation, therefore, it can be considered a fault (figs. 7 and 8). Fault 3, as well as the other fractures that reach the surface between this and fault 2, contain a thick caliche soil that was dated by U/Th. The results indicate that the sample is older than 350000 years – older than the time span covered by the method. Because of the possibile contamination of the dated caliche by older lutites (Tertiary and even Mesozoic in age), and taking into account the good preservation of the scarp, it seems reasonable to doubt on the obtained radiometric age. A much younger age should not to be disregarded.

In summary, the trench shows evidence of two deformation events: 1) an older one characterised by faults with vertical displacement of up to 3 m that cut units A and B and are overlaid by unit C, and 2) a younger one characterised by fractures that cut unit C and reach the surface. The first event shows signs of sudden deformation – sharp truncation of the stratification – while the youngest cannot be confirmed as seismically induced by the data available at the trench. Further information can be obtained from other outcrops along the scarp. The beach outcrop in fig. 7 shows normal faulting that reaches the surface and cuts units A and B. In the north beach outcrop this same fault also cuts through unit C with the same amount of surface vertical displacement, 0.5 m. One of these faults can be correlated with fault 3 – defined at the trench – and, as it sharply breaks stratification, it suggests that also the second event was a sudden deformation event (fig. 8).

The alluvial stratification near the scarp describes a gentle fold with the axe following the scarp line. Wedge-like fractures that strike parallel to the scarp and are oriented perpendicular to bedding, crop out at beach sites (fig. 7). These fractures are coherent with the extension that takes place in the outer hinge of the flexure and may be a consequence of it. Besides folding, faulting was described in the trench and is also observed in beach outcrops and in the topography (figs. 7 and 8). Tilting of the down-thrown block towards the scarp was observed in the north beach outcrop and also detected by means of topographical profiling sug-

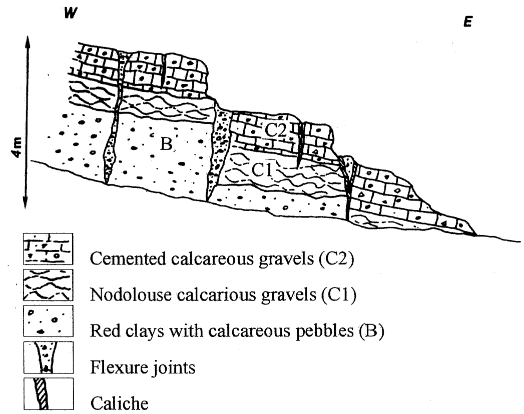

Fig. 7. Log of an outcrop that intersects the fault scarp (location in fig. 6a). It shows several wedge-like fractures orthogonal to the tilted stratification. The extension that takes place in the outer side of a hinge, in a fold, is considered to be the cause for the structures observed in the profile. Fault slip up to 0.5 m is also visible in the outcrop.

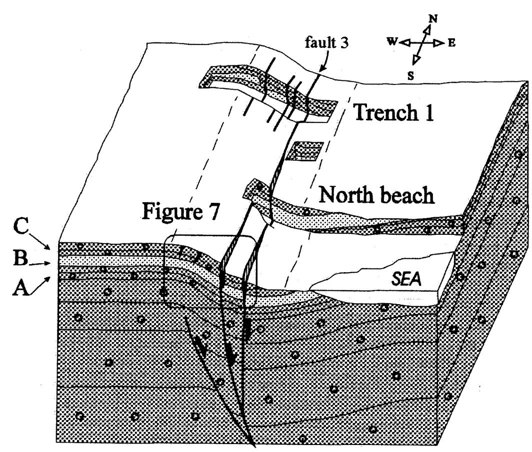

Fig. 8. Sketch without scale of the structures observed in the Almadrava scarp zone. Principal outcrops are indicated: trench 1, north beach and fig. 7. Correlation of the principal structures between those outcrops is shown. Fault 3 in the trench 1 shows surface breaking in north beach and in fig. 7 outcrops. Letters A, B and C indicate stratigraphical units described in the trench 1.

gesting normal slip of the fault. Folding could account for part of the vertical displacement observed in topographical profiles for the hole scarp – 7 m – which is larger than the vertical displacement observed in the outcropping faults – although the trench does not cut along the whole deformation zone. This suggests that the structure responsible for the surface deformation could be a semi-hidden normal fault that would bend the topographic surface, with some small faults reaching the surface (fig. 8).

4.2.2. The Mont-roig scarp

The Mont-roig scarp is 10 km long, has a NNE-SSW strike and a maximum vertical topographical separation of 17 m south of Mont-roig (fig. 9). North of this town, the scarp separates Variscan granites, on the up-thrown block, from cemented Quaternary conglomerates on the down thrown one, while south of Mont-roig, it cuts Quaternary alluvial fans (fig. 9). As it cuts fans belonging to the youngest generation, this scarp is considered to be younger than 100000 years. It looks very fresh, and some fractures, dipping as much as 80° towards the up thrown block, are present.

In order to date the most recent movements of the fault, one trench was dug perpendicular to the scarp. The trench is located south of Mont-roig, in a zone where Holocene sediments were deposited in a creek that crosses the scarp (fig. 9). This is a favourable situation for detecting the most recent movements of the fault because the sediments are very young.

The stratigraphy exposed in the 4 m deep trench shows three thinning upward sequences (from A to D facies each sequence) with tops clearly visible because of the dark colour of the silts and sands at the top of the sequences (fig. 10).

Unfortunately the trench does not show any fault. Nevertheless the bedding displays a gentle dip of about 4° towards WNW, that is on the opposite sense of the general slope of the fan. If the depositional slope of bedding was flat or similar to the general slope of the fan the present dip should be considered of tectonic origin. Nevertheless, a small water fall or a sudden widening of the creek channel can produce a turbulent environment in which sediments may be originally deposited in such a slope. As both situations – water fall and widening – are reasonable on the site, the tectonic origin of the dipping sheeds is not considered here. Radiocarbon dating of coal samples (see fig. 10 for location) give an age of 4490-4790 years B.C. (2 σ, dendrochronologically calibrated, after Stuiver and Becker, 1993).

Several topographic profiles across the scarp show a back-tilting of the alluvial fan surface on the down thrown block (fig. 11 shows one of this profiles). This suggests that a normal fault controls the scarp.

No fault was directly observed along this scarp but several features suggest it is a fault scarp:

1) *independence from topography*: the scarp crosses through the topographical isolines rejecting a possible shore-line origin;

2) *independence from lithology*: the scarp is not following a lithological contrast;

3) *higher deformation in older deposits*: in the older fans the vertical displacement is higher than in the younger suggesting a longer period of deformation in the first;

4) *back tilting of the fan*: the topographical profiles show that the surface of the lower block is tilted towards the scarp, on the opposite direction of the fan surface slope;

5) *fractures parallel to the scarp*: although the joint set that crops out all along the scarp does not show slip, it implies some brittle tectonics.

Moreover, this scarp is parallel and only 10 km away from the Almadrava scarp, where faults where observed in outcrop unless the main deformation was considered to be produced by a semi-hidden fault. A similar structure in the Mont-roig scarp would explain the dip towards the upthrown block of the joint sets that could correspond to the extension joints that take place in the outer hinge of a flexion, as in the Almadrava scarp. Taking into account that the scarp has not moved at least since 4490-4790 B.C., the fresh front it shows cannot be a free face but may have been

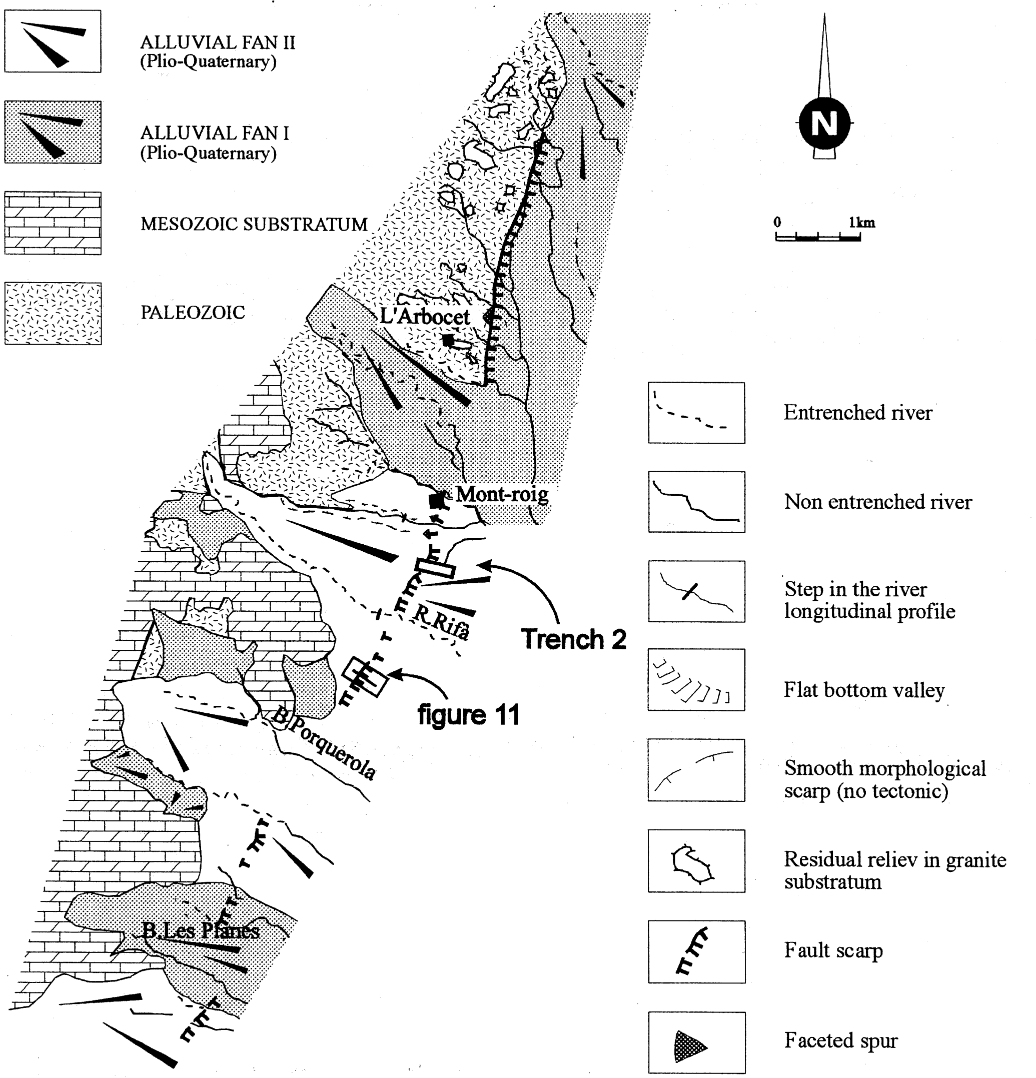

Fig. 9. Geomorphologic map of the Mont-roig scarp where it is shown how the scarp cuts through two generations of alluvial fans. Figures 10 and 11 are situated and indicated.

caused by the collapse of some of the mentioned joints at the front of the flexion. All the elements exposed suggest that the Mont-roig scarp is controlled by a fault and imply the same kind of structure considered in the Almadrava scarp, that is, a semi-hidden normal fault that causes a fold in surface.

Therefore, considering it as a fault scarp, and taking into account the radiocarbon dating of the undeformed sediments of the trench and the age constraints for the youngest alluvial fans deformed, the Mont-roig scarp would have been active between 100000 years and 4490-4790 years BC.

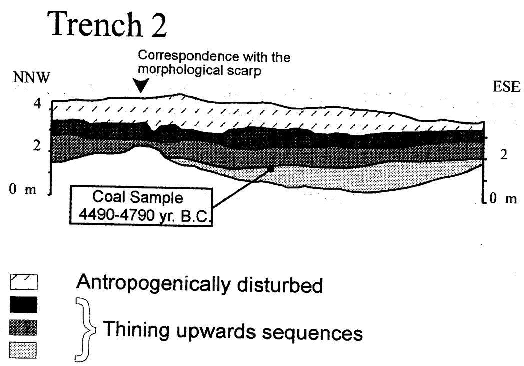

Fig. 10. Log of the trench along the Mont-roig Fault scarp. No tectonic deformation can be distinguished in the trench (see text for discussion). Every unit represented in the log is formed by a thinning upwards sequence that contains, from bottom to top, the following facies: A = clast supported gravels with a low amount of sandy matrix. Heterometric pebbles with diameters varying between 1 and 7 cm. Usually these gravels lie on an erosion surface. The direction of transport is also towards the ESE; B = polygenic gravels with sandy matrix and pebbles ranging from 2 to 4 cm in diameter. Although they show low classification, thinning upwards sequences can be distinguished. Some levels contain coal. Imbricated clasts show an ESE direction of transport; C = thin levels of coarse sands with high angle cross lamination and horizontal lamination; D = silt and fine sand with some poorly classified pebbles. Locally they show horizontal lamination. Some levels contain coal.

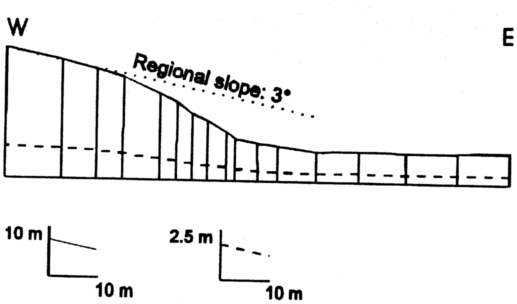

Fig. 11. Topographical profile perpendicular to the Mont-roig Fault scarp (location in fig. 9). The regional dip of the surface of the alluvial fans (three degrees in this particular case) is not maintained in the down thrown block, on the contrary, a flat surface is observed in this block.

There is no direct evidence of the seismic behaviour of the fault in the Mont-roig scarp although the morphological similarity and the proximity of the Almadrava scarp has to be considered. Taking this into account, and keeping in mind that only indirect indicators where used to suggest a fault control for the Mont-roig scarp, an estimation of the order of magnitude of the recurrence period interval for that fault was carried out in order to constrain further studies in the zone. A minimum and a maximum length measurement of the scarp were taken into account: the minimum is considered to be the morphologically preserved length of the scarp, that is 10 km, and the maximum is considered to be the length of the El Camp Fault segment to which the Mont-roig scarp belongs, that is 25 km. Considering the relations between length of surface rupture and slip per event proposed for normal faults by Wells and Coppersmith (1994), with a maximum vertical displacement of 17 m, the Mont-roig fault would have experienced between 19 and 40 events in at least 100000 years. The estimated recurrence period for that fault is therefore between 2500 and 5200 years. This implies that the order of magnitude of the recurrence period for the Mont-roig Fault is of some thousands of years. Therefore, if aseismic slip could be rejected, this fault should be considered potentially a seismogenic fault. Empirical relations established by Wells and Coppersmith (1994) based on current seismicity, assign M 6,5 earthquakes to a 10 km length of surface ruptures. Hence, considering that the 10 km length is the morphologically preserved scarp but that the length of this El Camp Fault segment is up to 25 km, larger earthquakes could be expected.

5. Synthesis and conclusions

The detailed geomorphologic analysis carried out in the Catalan coastal ranges, together with the data obtained from structural analysis of the deformation structures observed in the area (Masana, 1995), disclosed that the extensional tectonics that took part in that area during the Miocene is still active during the

Pliocene and Quaternary. A SE-NW and E-W σ 3 orientation, during the Pliocene and Quaternary respectively, was inferred from structural data and was confirmed by the orientation and interpretation of geomorphologic features. By means of this geomorphologic study, three kinds of possible evidence of past earthquakes were detected: six morphological scarps, concentration of big landslides and liquefaction features. The landslides and liquefaction features were rejected as direct and unequivocal earthquake indicators because other origins for them cannot be excluded. On the contrary, fault control was discussed for three of the scarps, where better exposure or more data were available, and evidence of past earthquakes was considered in some of them. In more detail, these scarps can be associated, due to their situation and orientation, to two of the main Neogene normal faults: the El Camp (Almadrava and Mont-roig scarps) and the Baix Ebre Faults.

In the Almadrava scarp, topographic, trench, and outcrop data show a fault control of the observed structures and, hence, the morphological step is interpreted to be a fault scarp. The observed geological relations suggest that the main fault is normal and does not reach the surface; instead, it flexes the upper stratigraphical units, while small normal faults break the surface and extension joints form at the outer hinges of the flexion. Evidence for two sudden deformation events were inferred from trench structures and outcrop data in this scarp, the most recent of which reaches the topographical surface. Therefore, aseismic deformation was considered improbable and the observed deformational events were interpreted as evidence of past earthquakes. Dating of the younger event was performed by the U/Th technique and provided that the faults are older than the range of time covered by the method, that is 350000 years, but, as the samples where on caliche, the possibility that they could contain older particles cannot be rejected, and therefore a younger age cannot be excluded with these data alone. Further dating also with other techniques should be carried out in this trench in order to avoid uncertainty.

In the Mont-roig morphological scarp, neither surface nor trench geology provided direct observation of a fault. Nevertheless geological and topographical data – independence of the scarp from topography and from lithology, higher deformation in older deposits, back tilting of the fan surface, parallel fractures to the scarp – indirectly suggest a fault control for the observed surface deformation. The morphological similarities with the Almadrava Fault scarp, together with the proximity of both scarps, implies that also in the Mont-roig scarp a semi-hidden normal fault could control the deformation. Further studies should be done to shed light on that hypothesis. No tectonic deformation was interpreted in the trench dug on sediments younger than 4490-4790 years B.C. (radiometric dating), while the scarp cuts the alluvial fans of the younger generation (younger than 100000 years). Therefore, the morphological scarp was active between 100000 and 4490-4790 years B.C. No evidence of the seismic or aseismic behaviour of the scarp was provided by the available data. However, an estimation of the order of magnitude of the recurrence period that such a scarp would have if it was seismic was carried out in order to constrain further studies. A recurrence period of several thousands of years resulted from this estimation indicating that, in this case, the Mont-roig scarp would be controlled by an active fault. With the same aim, although the seismic behaviour of that scarp was not proved, an estimation of the possible magnitude that such a scarp could provide was performed based on the data compiled by Wells and Coppersmith (1994). A magnitude $M > 6.5$ was estimated indicating that, under these assumptions, that fault could produce large earthquakes. These estimations evidence the need for further studies in this scarp – the longest of the scarps detected – in order to determine the seismic or aseismic behaviour of the fault and to better constrain the dating of its latest movements.

At the Baix Ebre Fault zone, alternating uplift and quiescence tectonic periods was interpreted by means of the morphology of the mountain front. A recent quiescence period and a sub-actual reactivation of the uplifting was suggested by the presence of a pediment at the foot of the front and the observation of a lineation of SL/K anomalies at the edge of the pediment respectively. In this case, a new fault scarp should form following the SL/K anomalies, if the deformation continues.

In summary, the data outlined in this paper reveal that although the Catalan coastal ranges do not show large earthquakes in the historical record, they show evidence of past large earthquakes. Further work should be done in order to better constrain the detected evidence and signs, that is, determine: 1) the possible fault control for the rest of the detected morphological scarps; 2) the seismic or aseismic behaviour of the faults in each scarp, and 3) the exact dating and amount of slip of the last movements of this structures. With all these data a general model for the role of the El Camp and El Baix Ebre Faults in each case could be provided to constrain the seismic hazard of that highly populated zone.

Many studies have been published on the paleoseismicity or the active tectonics around the Mediterranean region. Reasonably, those studies were carried out in areas with most evidence of active tectonics, that is: a) near the plate or sub-plate edges, and b) in areas with high historical seismicity or where one or several large historical earthquakes occurred. On the contrary, in this paper, evidence and signs of past earthquakes were described in an area situated far away from the plate edges and with no large earthquake in its historical seismic record. In more detail, all the signs described in the studied zone are situated in the southern half of the Catalan coastal ranges, where less historical seismicity is known. This shows that, in the Mediterranean region, large earthquakes can also take place in areas where the historical seismicity or the plate tectonic context does not evidence it. This paper, therefore, shows the usefulness of carrying out similar studies in areas considered stable but with high vulnerability, in order to determine their real level of tectonic stability.

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