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Plio-Quaternary extensional seismotectonics and drainage network development in the central sector of the Iberian Chain (NE Spain)

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ABSTRACT

Westward propagation of postorogenic rifting in the central sector of the Iberian Chain generated the Teruel and Calatayud Mio-Pliocene grabens and the Jiloca, Daroca and Munébrega Plio-Quaternary half-grabens, partially superimposed on the western margins of the pre-existing basins. The progressive capture and transformation from endorheic (aggradational) to exorheic (incisional) drainage of the active grabens resulted in the development of a drainage network dominated by axial streams controlled by neotectonic activity and the distribution of basin fill lithofacies. This paper reviews the geomorphic and stratigraphic evidence of Plio-Quaternary extensional tectonics and provides new chronological data (radiocarbon and OSL dating) on offset deposits and the associated paleoseismic record. The Daroca Fault offsets mantled pediment deposits dated at 113–119 ka. Based on a radiocarbon age of the colluvial sequence (43 ka) affected by the Rubielos de la Cérida Fault, a vertical slip rate of 0.05–0.07 mm/yr has been estimated for this fault. Four paleoearthquakes subsequent to 72 ka have been inferred from the classic exposure of the Concud Fault indicating a recurrence interval of less than 18 ka. A gravitational origin related to the dissolution of subjacent evaporites is attributed to two faults affecting an Upper Pleistocene terrace (15 ka) in the Alfambra Valley, close to the Concud Fault. These structures have recently been interpreted as evidence of coseismic deformation on the Concud Fault. Although the faults have a low slip rate and a long seismic cycle, their length (<25 km) suggest that earthquakes with moment magnitudes of around 6.5–7 might be expected in the study area.

1. Introduction to the geomorphology and geology of the Iberian Chain

The Iberian Chain, with a dominant NW–SE structural and topographic grain, is located in the NE of the Iberian Peninsula. It stretches for about 400 km from its northwestern end down to the Mediterranean Sea, and is up to 200 km in width (Fig. 1). Its topography is dominated by extensive planation surfaces, commonly above 1000 m in elevation and largely developed on Jurassic and Cretaceous carbonate rocks. This plateau-like topography is locally interrupted by neotectonic grabens and uplifted blocks, fluvial valleys, poljes and areas of residual relief (monadnocks) that may reach more than 2000 m above sea level (Gutiérrez and Peña, 1994).

The Iberian Chain is an intraplate orogene located within the Iberian plate. The northern and southern margins of this plate are formed by the Pyrenees and the Betic Ranges, which resulted from the collision of the Iberian plate with the European and African plates, respectively. The Iberian Chain is located to the west of the NE–SW trending offshore Valencia Trough, an extensional structure generated in late Oligocene–Miocene times that is part of the western Mediterranean rift system (Alvaro et al., 1979; Vegas et al., 1979; Roca and Guimerà, 1992; Anadón and Roca, 1996).

In the Iberian Chain the Alpine cycle, which lasted from the Upper Permian to the Lower–Middle Miocene, is divided into two major stages: the sedimentary stage and the orogenic stage. During the sedimentary stage, from the Upper Permian to the late Cretaceous, extensional tectonics created sedimentary basins with shallow marine and continental deposition (Sopeña et al., 2004). The orogenic stage began in the late Cretaceous, when the tectonic regime within the Iberian basins switched from extensional to compressional due to the convergence and collision of the Iberian and European plates. The consequent shortening caused the tectonic inversion of the Mesozoic basins, largely through the positive reactivation of the normal faults that had been active during the sedimentary stage.

From the Lower–Middle Miocene onwards an extensional stress field dominated the eastern and central sectors of the Iberian Range generating NW–SE, NNE–SSW and NNW–SSE-trending grabens

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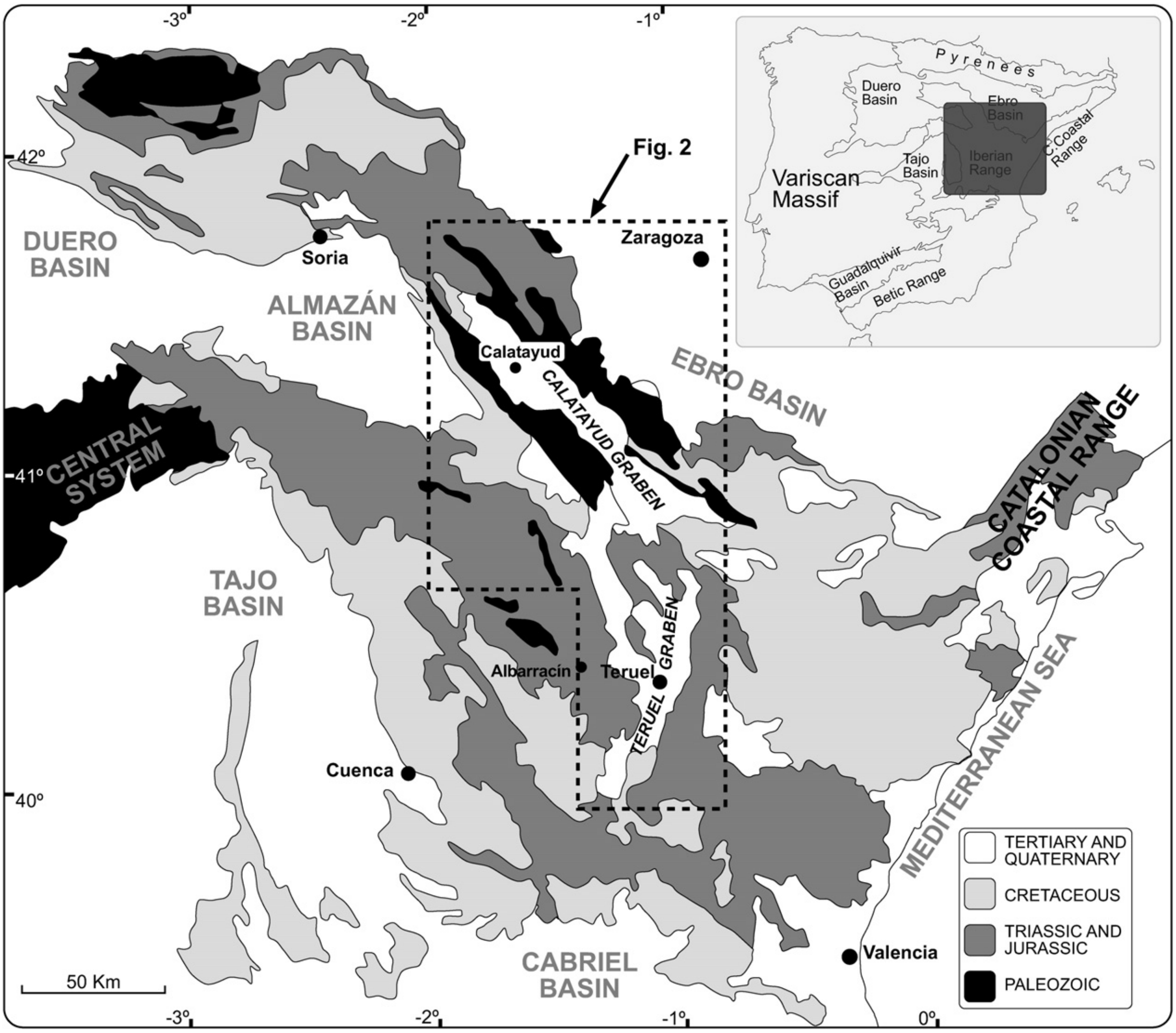

Fig. 1. Location and simplified geological map of the Iberian Range (based on IGME, 2004).

superimposed on the previous shortening structures (postorogenic rifting) (Fig. 2). The normal faults that control these extensional basins result to a great extent from the negative inversion of inherited basement faults that moved as reverse faults during the Palaeogene compression. These postorogenic basins become progressively younger toward the interior of the Iberian Peninsula reflecting the westward propagation of the rifting that formed the offshore Valencia Trough in the late Oligocene (Anadón and Moissenet, 1996; Anadón and Roca, 1996; Capote et al., 2002) (Fig. 2). The formation of the NE–SW trending Maestrazgo grabens in the eastern sector of the Iberian Chain started in the Lower Miocene (Anadón and Moissenet, 1996). The oldest sediments of the Teruel and Calatayud grabens are Lower–Middle Miocene in age (Alcalá et al., 2000; Sanz-Rubio et al., 2003). The Jiloca, Daroca and Munébrega half-grabens, partially superimposed on the western margins of the Teruel and Calatayud grabens, formed in Upper Pliocene–Quaternary times (Fig. 2).

Although an extensional stress field has prevailed in the central sector of the Iberian Chain from the Middle Miocene up to the present-day, two main phases of deformation can be differentiated (Capote et al., 2002). The first extensional phase started in the Lower–Middle Miocene and generated the two largest intramontane basins of the Iberian Chain; the NW–SE trending Calatayud Graben and the NNE–SSW Teruel Graben, both about 100 km long (Fig. 2). These grabens were filled by alluvial fans that graded to lacustrine and fluvial environments in the depocentral sectors. Traditionally it has been considered that by the end of the first extensional episode, a great part of the Iberian Chain was dominated by flat planation surfaces cut across folded pre-Neogene sediments. Several stepped planation levels have been recognised in some areas (Gracia et al., 1988). There is a particularly extensive planation surface, named the Main Planation Surface of the Iberian Chain, that records a period of relative tectonic quiescence (Peña et al., 1984; Simón, 1984; Gracia et al., 1988; Gutiérrez and Gracia, 1997). Although this erosional surface is not considered to represent an isochron (Gutiérrez et al., 1996), its age has been locally constrained on the basis of its topographic connection with the top of Pliocene limestone units in Calatayud and Teruel grabens (Peña et al., 1984; Gracia et al., 1988; Gracia, 1990; Gutiérrez, 1998a). This surface and the uppermost Pliocene calcareous sediments of Calatayud and Teruel grabens have been widely used as a marker to characterise the geometry of the neotectonic deformations developed subsequent to their formation (Peña et al., 1984; Simón, 1984; Gutiérrez and Gracia, 1997). Recently, some authors have proposed that most of the planation surfaces of the Iberian Chain could have been developed during the compressive uplift (orogenic stage) of the orogen (Guimerà and González, 1998; Casas-Sainz and Cortés-Gracia, 2002).

The second extensional phase developed in Pliocene and Quaternary times and produced some of the most outstanding morphotectonic features of the central sector of the Iberian Chain (Peña et al., 1984; Simón, 1989; Gracia, 1990; Gutiérrez and Peña, 1994; Gracia and

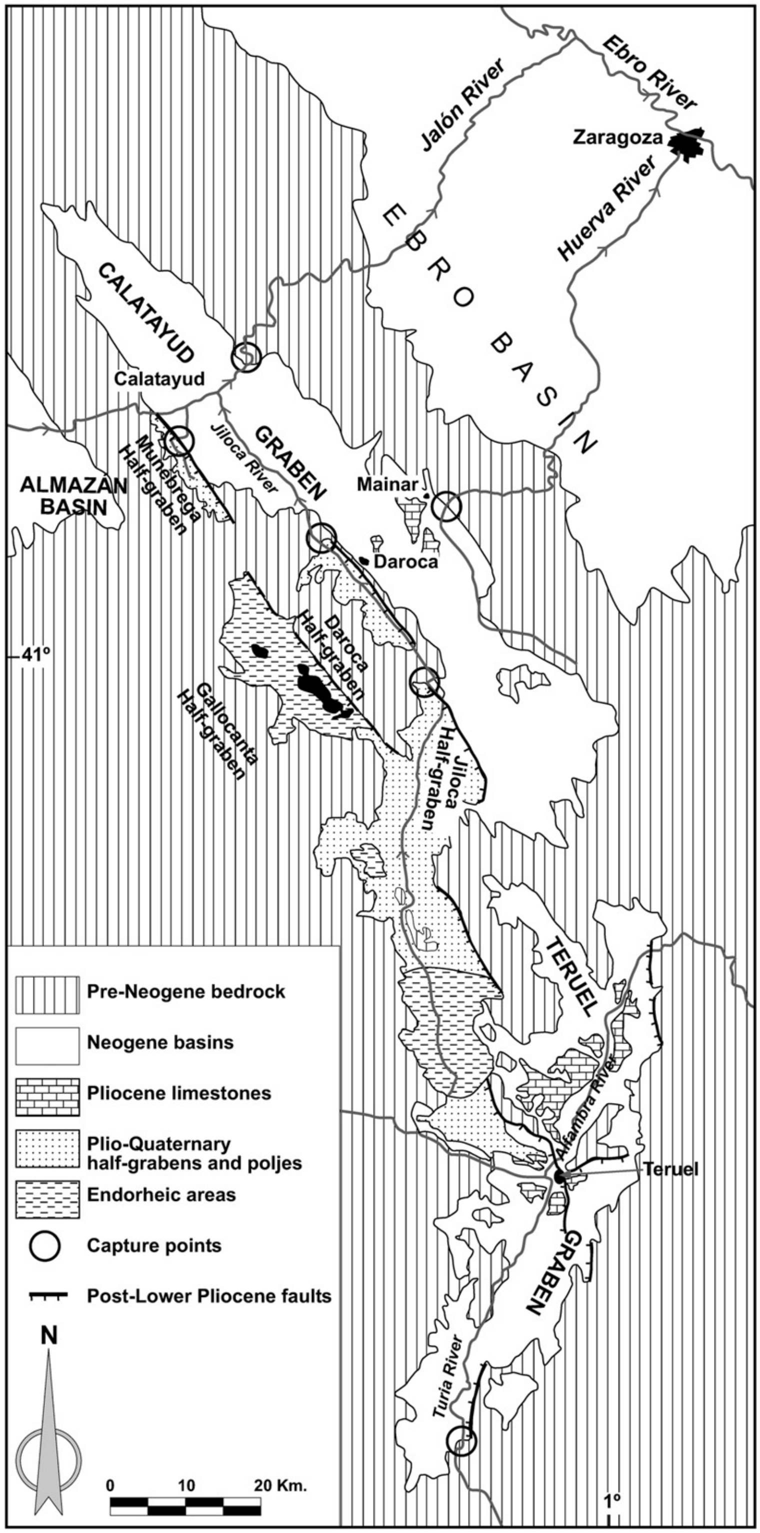

Fig. 2. Geological sketch showing the distribution of the Neogene and Plio-Quaternary grabens in the central sector of the Iberian Range.

Gutiérrez, 1996; Gutiérrez and Gracia, 1997; Gutiérrez, 1998a). The onset of this phase took place once the Calatayud and Teruel grabens had been captured by external drainage and the basins were changing progressively from endorheic to exorheic conditions (Gutiérrez et al., 1996; Gutiérrez, 1998a). Extensional block tectonics during this episode deformed the Main Planation Surface, reactivated the Calatayud and Teruel grabens, tilted and faulted Pliocene formations, induced deposition of alluvial fan units, and generated new half-grabens located to the west of the pre-existing Neogene grabens. These new Plio-Quaternary structural depressions, controlled by NW–SE faults along their eastern margins, include, from north to south: the Munébrega Half-graben (Gutiérrez, 1998a), the Daroca Half-graben (Gracia, 1990, 1992a), the Gallocanta Polje-Graben (Gracia et al., 2002) and the Jiloca Polje-Graben (Gracia et al., 2003) (Fig. 2). The Gallocanta

Depression (Gracia et al., 2002) and the central sector of the Jiloca Depression (Gracia et al., 2003) have been interpreted as karst poljes developed in neotectonic grabens, whose topographic relief is largely due to corrosional lowering rather than to tectonic subsidence. The bottom of the Jiloca and Gallocanta depressions is occupied by alluvial fans, mantled pediments and extensive lacustrine systems. The Munébrega and Daroca half-grabens are filled by alluvial fan sediments capped by mantled pediments.

The dominant recent regional stress field (Upper Miocene–Quaternary) in the eastern and central sector of the Iberian Chain, inferred from the analysis of outcrop-scale brittle structures, is characterised by extension with NW–SE and NE–SW σ_3 trajectories (Cortés, 1999; Herraiz et al., 2000). Concerning the present-day stress field, from the focal mechanisms of 161 earthquakes distributed throughout the Iberian Peninsula ($M \geq 3$; focal depths ≤ 30 km; 1980–1995 record period), Herraiz et al. (2000) indicate that most of the Iberian Peninsula is undergoing NW–SE to NE–SW compression related to the Africa–Iberia–Europe plate convergence. However, the average stress ellipsoid inferred for the eastern and central sector of the Iberian Chain from 15 focal mechanisms indicates a vertical σ_1 axis and an ENE–WSW-trending σ_3.

Extensional neotectonics have had a great impact on morphogenesis in the Iberian Chain as revealed by the normal faults that affect Pliocene and Quaternary deposits and landforms. According to Burbank and Anderson (2001), the best geomorphic markers to study recent tectonic deformation are readily recognizable landforms that display the following three characteristics: (1) a known pre-deformational geometry, (2) a known age, and (3) high preservation potential with respect to the time scale of the analysed tectonic processes. The main limitation of the planation surfaces, despite their high preservation potential, is that the age and initial undeformed geometry are in many cases difficult to ascertain. Numerous studies have reported stratigraphic and geomorphic evidence of Plio-Quaternary extensional tectonics in the Iberian Range. However, in the majority of the cases, only a relative chronology based on morphostratigraphic, stratigraphic, and archaeological criteria has been proposed for the deformation. The one exception is the Concud Fault, whose neotectonic and paleoseismological characterization has been based on questionable geochronological data and erroneous morphostratigraphical sequences, as discussed below (Simón and Soriano, 1993; Simón et al., 2005). The lack of geochronological information has limited the possibilities of gaining insight into some relevant and practical aspects from the geomorphologic and seismic hazard perspective, such as the slip rate of the faults or the associated paleoseismic record (coseismic displacement events, chronology, recurrence).

The main objectives of the paper are: (1) to analyse how the episodic migration of a postorogenic rifting process may control the development of the drainage network in an orogene, (2) to illustrate how an understanding of the landforms and morphostratigraphic sequences is crucial to identify, characterise and assess extensional neotectonic deformations, and (3) to present an analysis and absolute dating of deformed deposits and landforms in order to draw conclusions on the seismic hazard potential of active normal faults with long seismic cycles.

2. The progressive capture of the endorheic grabens and drainage network development

The episodic development of grabens related to the westward migration of the rifting process, and their fluvial capture have played an instrumental role in the development of the drainage network in the central Iberian Chain. The transformation of the grabens from endorheic to exorheic drainage begins with the fluvial capture of the depressions by the external drainage network. This event constitutes a crucial landmark in the geomorphological, sedimentary and hydrological evolution of the basins (Martín-Serrano, 1991; Mather, 1993; Gutiérrez et al., 1996; Calvache and Viseras, 1997). The subsiding endorheic basins behave as closed sediment collectors dominated by the stacking of sedimentary units that rarely display morphological expression. In these aggradational basins the internal drainage network commonly consist of transverse and centripetal alluvial fan systems that feed lakes and fluvial systems located along the depoaxis of the basin (Leeder and Jackson, 1993). Once the tectonic depressions are captured, the local base-level drop produced by the piracy stimulates development of an aggressive drainage network that tends to excavate the endorheic infill of the basin by headward erosion (Harvey and Wells, 1987). The change from endorheic to exorheic conditions transforms the structural depressions into areas of net erosion unless the incision trend is counterbalanced or surpassed by tectonic subsidence. The new exorheic incisional drainage developed within the basin may inherit its path from the previous endorheic drainage, controlled by the most rapidly subsiding areas (Mather, 1993; Calvache and Viseras, 1997), and may also adapt its course to the more easily erodable facies of the basin fill due to differential excavation (Gutiérrez et al., 1996). In contrast to the sedimentary units deposited under endorheic conditions, aggradational episodes in the exorheic basins are generally represented by stepped sequences of alluvial deposits with morphological expression inset into the endorheic basin fill (Gutiérrez et al., 1996).

Piracy of endorheic grabens usually results from headward expansion of the external drainage network across the margins of the depressions. Capture takes place preferentially via topographically lower areas of the basin margins which commonly coincide with the location of drainages that feed marginal alluvial fans (Martín-Serrano, 1991; Stokes and Mather, 2003). Major topographic gaps (wind and water gaps) are usually associated with the transfer zones (step overs) of the main basin-bounding faults where large oblique drainage basins tend to develop (Leeder and Jackson, 1993; Burbank and Anderson, 2001; Trudgill, 2002). The drainage responsible for the capture tends to adapt its course to any of the valleys excavated in the basin margins that formerly drained into the endorheic depression, involving a flow reversal (Stokes and Mather, 2003). Once the grabens are captured, the change from endorheic to exorheic conditions occurs in a gradual way as the new drainage expands by headward erosion toward areas located progressively further away from the capture point (Martín-Serrano, 1991; Gutiérrez et al., 1996); thus, following capture, there may coexist within a basin exorheic areas subjected to net erosion and endorheic areas dominated by aggradation. From the morphostratigrahic point of view, a post-capture time interval may be represented in different sectors of a basin by endorheic sedimentary units, erosional hiatuses, or landforms and morphosedimentary units inset into the basin fill (Gutiérrez et al., 1996; Gutiérrez, 1998a).

Teruel Graben was captured by an ancestral Turia River through the southern edge of the basin. It is very likely that the piracy occurred in the Lower Pliocene because the youngest endorheic sediments in this sector of the basin are limestones of Upper Miocene or probable early Lower Pliocene age (Adrover et al., 1978) (Fig. 3A and B). The headward erosion and consequent change to exorheic conditions advanced progressively toward the northern sector of the graben. The Turia River in the southern sector roughly follows the axis of an open synformal structure that folded the Mio-Pliocene sediments in the basin fill. During the Lower Pliocene, lacustrine environments with carbonate and evaporite deposition covered an extensive area in the central and northern sectors of the graben (Hernández and Anadón, 1985; Alonso-Zarza and Calvo, 2000) (Fig. 3B). In the Upper Pliocene the carbonate lacustrine systems were restricted to two residual basins located in the hangingwall blocks of Concud–Teruel Fault (central sector) and El Pobo Fault (northern sector) (Mein et al., 1989-1990) (Fig. 3C). These Upper Pliocene endorheic limestone units are unconformably overlain by Upper Pliocene alluvial deposits (Hernández and Anadón, 1985; Mein et al., 1989–1990). The fact that these

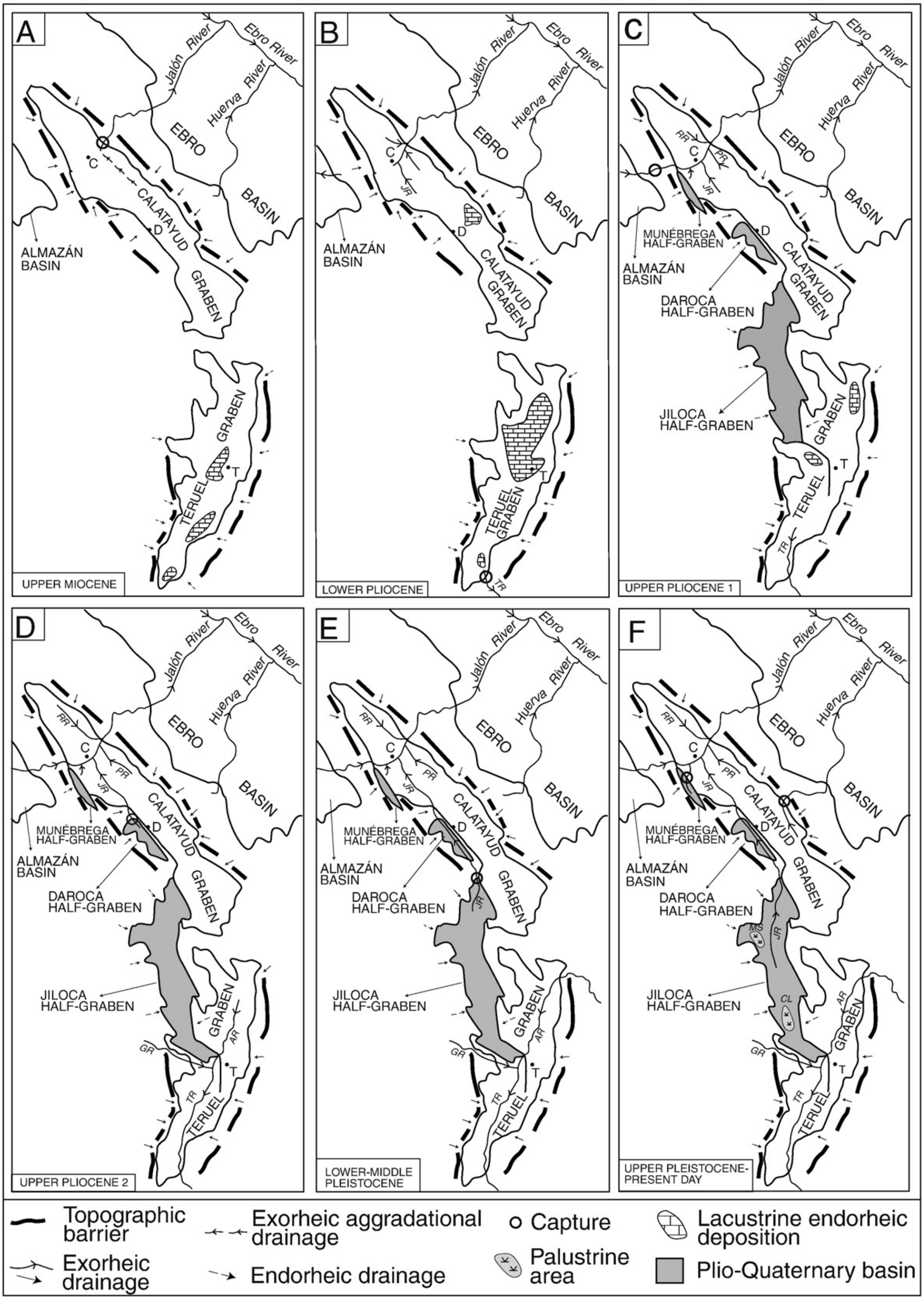

Fig. 3. Proposed evolutionary model for the progressive capture and transformation from endorheic (aggradational) to exorheic (incisional) conditions of the Neogene and Plio-Quaternary grabens in the central sector of the Iberian Chain. RR: Ribota River, PR: Perejiles River, JR: Jiloca River, MS: Mierla Swamp, CL: El Cañizar Lake, AR: Alfambra River, GR: Guadalaviar River, TR: Turia River, C: Calatayud, D: Daroca, T: Teruel.

alluvial units are inset in the basin fill and are capped by mantled pediments inclined toward the current drainage indicates that the change to exorheic conditions in the central and northern sectors of the graben took place during the Upper Pliocene (Gutiérrez, 1998a). In the central sector of the basin the Alfambra River crosses the Concud Fault transversely and the Guadalaviar and Alfambra–Turia Rivers run along the drownthrown block controlled by the active Concud–Teruel fault system. In the northern sector the Alfambra River flows longitudinally along the axis of the open and asymmetric synform that affects the Mio-Pliocene basin fill. The concordance between the tectonic structures affecting the Pliocene lacustrine sediments of the basin fill, and the distribution of the fluvial systems in the Teruel Graben, reveals that the post-capture configuration of the drainage was largely controlled by neotectonic activity (Gutiérrez, 1998a). This explains why the fluvial valleys have been excavated along the areas where the more resistant carbonate formations are thicker.

The Calatayud Graben was captured through the Huérmeda topographic gap by an ancestral Jalón River, a tributary of the Ebro River (Fig. 3A). The landscape and drainage evolution models of the Ebro Basin developed by García-Castellanos et al. (2003) suggest that this basin was open through external drainage toward the Mediterranean between 13 and 8.5 Ma (Middle–Upper Miocene). Magnetochronological studies of the youngest sediments of the endorheic fill in the central portion of the Ebro Basin also indicate that this sector became exorheic sometime in Middle–Upper Miocene (Pérez-Rivarés et al., 2002, 2004; Salazar Rincón, 2003). From detailed sedimentological and stable isotope study of the tufaceous fluvio-lacustrine carbonates and alluvial-fluvial clastic unit that caps La Muela de Borja, Vázquez-Urbez et al. (2002) proposed that it constitutes the oldest preserved record of exorheic sedimentation in the central sector of the Ebro Basin (Pardo et al., 2004). Unfortunately, its chronostratigraphy is not precisely constrained (late Vallesian–Turolian?). The progressive base-level drop caused by the excavation of the Ebro Basin fill induced an incisional wave, which propagated toward the margins of the depression favouring the headward expansion of tributary streams such as the ancestral Jalón River. This stream captured the Calatayud Basin in the Huérmeda area, a major topographic gap located in the transfer zone between the en echelon fault systems that bound the La Virgen and Vicort ranges. According to Sanz-Rubio et al. (2003), the Upper Unit of the basin fill in the Calatayud area, of Upper Vallesian–Lower Ruscinian age and composed of fluvial–alluvial detrital facies and fluvio–lacustrine tufaceous sediments, was deposited by an axial exorheic drainage that presumably had its outlet in the eastern margin of the basin (Fig. 3A). The boundary between the Intermediate Unit (Middle Aragonian–Vallesian) and the Upper Unit constitutes a basin-scale stratigraphic discontinuity that represents a hiatus covering up to 4 Ma and shows paleokarstic features affecting the endorheic lacustrine carbonates on the Intermediate Unit (Sanz-Rubio et al., 2003). Although these data indicate that the Calatayud Graben was probably captured by the ancestral Jalón River and became exorheic in the late Vallesian (Upper Miocene), the incision of the basin fill that led to the development of the present-day fluvial valleys did not start until the Lower Pliocene. Probably Lower Pliocene lacustrine calcareous sediments situated further to the SE in the Mainar area (Adrover et al., 1982; Villena et al., 1991) are partially coeval with an excavation period in the Calatayud sector (Fig. 3B). The new drainage expanded transversally to the SW and longitudinally to the NW and SE. The development of an important transverse stream was favoured by the basin structure (centripetal dips) of the Neogene sediments around Calatayud city and possibly by the presence of another important transverse stream in the opposite flank of the basin controlled by a transfer zone (Gutiérrez, 1998a). This transverse stream eventually linked with the adjacent Almazán Basin generating the discordant Jalón fluvial system that crosses transversely the Calatayud Graben. The preferential excavation of clay facies between the more resistant coarse-grained marginal detrital sediments and the distal carbonate facies explains the development of NW–SE trending axial drainages like the Ribota, Perejiles and Jiloca fluvial valleys (Bomer, 1960; Gutiérrez, 1998a). The shallow entrenchment of the Huerva River into the basin fill in the Mainar area (around 20 m, in contrast to 400 m of excavation in the Calatayud sector), indicates that capture by the Huerva River took place in recent times, probably in the Upper Pleistocene (Fig. 3F). The capture point of the Huerva River is also controlled by a transfer zone.

Excavation of the Daroca Half-graben started once the Jiloca River captured the depression through its northern edge, possibly in Upper Pliocene–Lower Pleistocene times (Fig. 3D). This active fault-angle depression shows a stepped sequence of four alluvial levels inset into the basin fill (Gracia, 1990) and the river runs longitudinally close to the master Daroca Fault. Subsequently, the Jiloca River captured the northern sector of the half-graben (Fig. 3E). The presence of a tufaceous terrace in this portion of the basin dated by U/Th at 312 ka (Gracia and Cuchí, 1993) suggests that the capture and change to exorheic conditions probably occurred in the Lower–Middle Pleistocene. The entrenchment of the axial Jiloca River diminishes toward the south (Gracia, 1993). From Santa Eulalia to Cella the Jiloca Polje-graben remained as an endorheic area until historical times hosting Cañizar Lake (11.3 km^2) in the Villarquemado area and the Mierla Swamp to the SW of Monreal del Campo (Fig. 3F). The Cañizar Lake was drained in the 18th century by an artificial channel that is erroneously designated as the Jiloca River on topographical maps (Deler, 1995; Gracia et al., 2003; Rubio and Coloma, 2004). The Gallocanta Polje-graben, which hosts the Gallocanta Lake (14.4 km^2), remains as a large endorheic depression situated around 100 m above the Jiloca River (Fig. 2). The local morphostratigraphic sequence suggest that the capture of the Munébrega Depression by the El Molino Stream, a tributary of the Jalón River, occurred in the Upper Pleistocene (Fig. 3F). The longitudinal profile of this stream is entrenched up to 30 m into the basin fill up to a conspicuous knick point 3 km upstream of the capture point; above it stream incision is negligible and aggradational processes predominate (Gutiérrez, 1998a).

3. Geomorphic and stratigraphic evidence of Plio-Quaternary extensional tectonics

The most reliable geomorphic markers used to identify and quantify Plio-Quaternary tectonic deformation in the study area include: (1) planation surfaces developed at the margins of the Neogene basins that can be correlated with Pliocene calcareous formations in the basins by means of their physical and/or topographical connection (the age of the planation surfaces found in distant areas from the basins may be difficult to determine); and (2) the morphogenetic surfaces of alluvial and fluvial levels such as terraces, pediments and alluvial fans. The position of these landforms in the morphostratigraphical sequence helps to bracket the relative deformation chronology. Young normal faults are also inferred from the presence of linear mountain fronts that may show truncated bedrock spurs and fault scarps (Table 1).

Stratigraphic markers used for the detection of recent tectonic activity include: (1) Upper Miocene and Pliocene calcareous formations of the basin fill that typically cap mesas; (2) Plio-Quaternary alluvial, fluvial and colluvial deposits. The tectonic rejuvenation of the margins of the Neogene basins has been also deduced from the presence of relatively thick alluvial fan deposits with pediment morphology associated with linear range fronts. Commonly, these detrital alluvial units overlie unconformably and are inset into the endorheic basin fills and the morphogenetic surfaces are inclined towards the present-day drainage. Internal angular unconformities and cumulative wedge outs are found in some of these tectonically-induced sedimentary units.

3.1. Calatayud Neogene Graben

The Calatayud Graben is a NW–SE trending intramontane basin around 110 km long and up to 25 km wide (Fig. 4). The age of the post-orogenic sedimentary infill ranges from Middle Miocene to Lower Pliocene and the thickness of the Tertiary sequence exceeds 1 km according to a 600 m-deep borehole drilled close to the Jiloca valley bottom in the Calatayud area (Marín, 1932). This graben is superimposed on a synformal Palaeogene basin developed between two major NW–SE antiformal structures with Palaeozoic rocks in their cores (Cortés, 1999).

Table 1

Summary reviewed extensional structures indicating the main morphological and stratigraphic evidence of Plio-Quaternary deformation, orientation, length and estimated vertical offset and slip rate

	Trend	Length (km)	Geomorphic and stratigraphic evidence of Plio-Quaternary deformation	Vertical slip (*) slip rate	References
Calatayud Neogene Graben					
La Virgen Range front	NW–SE	11	Tectonically-induced Plio-Quaternary alluvial fan deposits inset into the basin fill.		Gutiérrez (1998a)
Vicort Range front	NW–SE	24	Tectonically-induced Plio-Quaternary alluvial fan deposits inset into the basin fill.		Gutiérrez (1998a)
Paniza Range Front	NW–SE	22	NE-tilted Lower Pliocene limestones and Plio-Quaternary alluvial fan deposits.		Olivé et al. (1980); Gracia (1990)
Munébrega E Fault	NW–SE to E–W	15	Tectonically-induced Plio-Quaternary alluvial fan (Valgalindo Fan) inset into the basin fill.		Hoyos et al. (1977); Gutiérrez (1998a)
Teruel Neogene Graben					
El Pobo Range Fault	NNW–SSE	11	Tectonically-controlled deposition of Upper Pliocene limestones and alluvial fan units. Eastward tilting of Lower Pliocene limestones and the Plio-Quaternary Perales mantled pediment.	500 m (P) >0.12 mm/yr	Moissenet (1982, 1983); Olivé et al. (1983); Simón (1983); Gutiérrez (1998a)
Alfambra Fault	NNE–SSW	8	Tilted Lower Pliocene limestones in the downthrown block and uplifted correlative planation surface in the footwall.	200 m (P) >0.05 mm/yr	Gutiérrez (1998a)
Valdecebro Fault	E–W and NW–SE	4	Uplifted Lower Pliocene planation surface and faulted Pleistocene pediment deposits.	150 m (P) >0.03 mm/yr	Godoy et al. (1983a); Gutiérrez (1998a)
Aldehuela Fault	N–S	4	Faulted alluvial fan deposits with cumulative wedge outs and angular unconformities.	>10s of m (PQ)	Adrover et al. (1978); Moissenet (1982, 1983, 1989a); Simón (1983)
Cascante del Río Graben	ESE–WNW	7	Upper Miocene limestones offset more than 200 m. Tectonic valley with conspicuous geomorphic expression	>200 m (UM)	Godoy et al. (1983b); Moissenet (1983, 1989b)
Val de la Sabina Fault	NNE–SSW	10	Upper Miocene units displaced vertically more than 300 m. Tectonically-controlled deposition of Upper Pliocene limestones in the hangingwall.	>300 m (UM)	Abril and Rubio (1978); Moissenet (1983)
Munébrega Plio-Quat. Half-graben					
Munébrega W Fault	NW–SE	19	Pleistocene terrace-pediment offset more than 7 m. Linear range front with triangular and trapezoidal fault facets.	>35 m	Gutiérrez (1998a)
Daroca Plio-Quat. Half-graben					
Daroca Fault system	NW–SE	20	>100 m thick Upper Pliocene-Pleistocene sequence deposited in the hangingwall basin. Faulted Upper Pleistocene mantled pediment deposits. Triangular facets. Anomalously large fans.	>100 m (P) >0.02 mm/yr	Colomer (1987); Gracia (1990, 1992a)
Jiloca Plio-Quat. Half-graben					
Calamocha Fault	NW–SE	17	Lower Pliocene limestone sediments displaced vertically more than 250 m. Faulted Quaternary alluvial deposits. Thick Plio-Quaternary sequence beneath the valley bottom. Triangular facets.	>250 m (P) >0.05 mm/yr	Hernández (1983); Simón, (1983); Colomer (1987); Gracia (1990)
Bañón Fault	NE–SE	4	Faulted Quaternary alluvial deposits.		Gracia (1990); Gracia and Gutiérrez (1996)
Palomera Range Fault	NW–SE	16	Faulted Upper Pliocene–Quaternary alluvial deposits with angular unconformities and cumulative wedge outs. Anomalously steep fans. Triangular and trapezoidal fault facets.	10s to 400 m	Cortés (1999); Casas-Sainz and Cortés-Gracia (2002); Arlegui et al. (2005)
Concud-Teruel Fault	NW–SE to N–S	23.5	Tectonically-controlled deposition of Upper Pliocene limestones in the downthrown block. Tilted and faulted Pliocene limestone units with vertical offset of more than 250 m. Tilting and faulting of Pleistocene alluvial and fluvial deposits. Linear range front with truncated bedrock spurs associated to Concud Fault.	>250 m (P) >0.06 mm/yr	Moissenet (1983); Simón and Soriano (1993); Gutiérrez (1998a); this study
Villar del Salz Fault	E–W	5	Faulted Quaternary alluvial deposits.		Gracia (1990); Gracia et al. (2003)
Aguatón Fault	NW–SE	¿	Offset Holocene colluvium and fault scarp 0.5 m high	2.5 m (Q)	Burillo et al. (1985)
Rubielos de la Cérida Fault	N–S	2.5	Faulted Upper Pleistoce and Holocene? colluvial deposits	>9.3 m (Q) 0.05–0.07 mm/yr	Capote et al. (1981); Gutiérrez et al. (1983a,b); this study

(*) the age of the morphological or stratigraphic marker is indicated. UM: Upper Miocene, P: Pliocene, PQ: Plio-Quaternary, Q: Quaternary.

The graben is controlled by en echelon normal fault systems that are commonly onlapped by Plio-Quaternary piedmont deposits, although examples of such faults juxtaposing Palaeozoic and Neogene sediments are found in the valleys carved by the Jalón and Manubles rivers (Julivert, 1954; Gutiérrez, 1998a). The higher elevation of the NE flank of the graben (>300 m) and the proximity of the evaporite and carbonate facies to this margin reflects its asymmetric structure with a more active northeastern margin (Gutiérrez, 1998a). In the SW margin, from the village of Daroca to Burbágena, Cambrian rocks override Aragonian detrital sediments along the NW–SE-trending and NE-verging Daroca Thrust, which is in turn unconformably overlain by Middle–Upper Miocene sediments (Julivert, 1954; Colomer and Santanach, 1988). This reverse fault with a dextral strike-slip component reveals that a compressional stress regime operated in the area until Middle Miocene times (Colomer and Santanach, 1988).

The sediments of the basin fill show a general subhorizontal structure with the most conspicuous tectonic deformations being found in the vicinity of the margins. Nonetheless, the carbonate and detrital sediments overlying evaporitic rocks in the Calatayud and Barrachina–Torre los Negros areas show spectacular gravitational

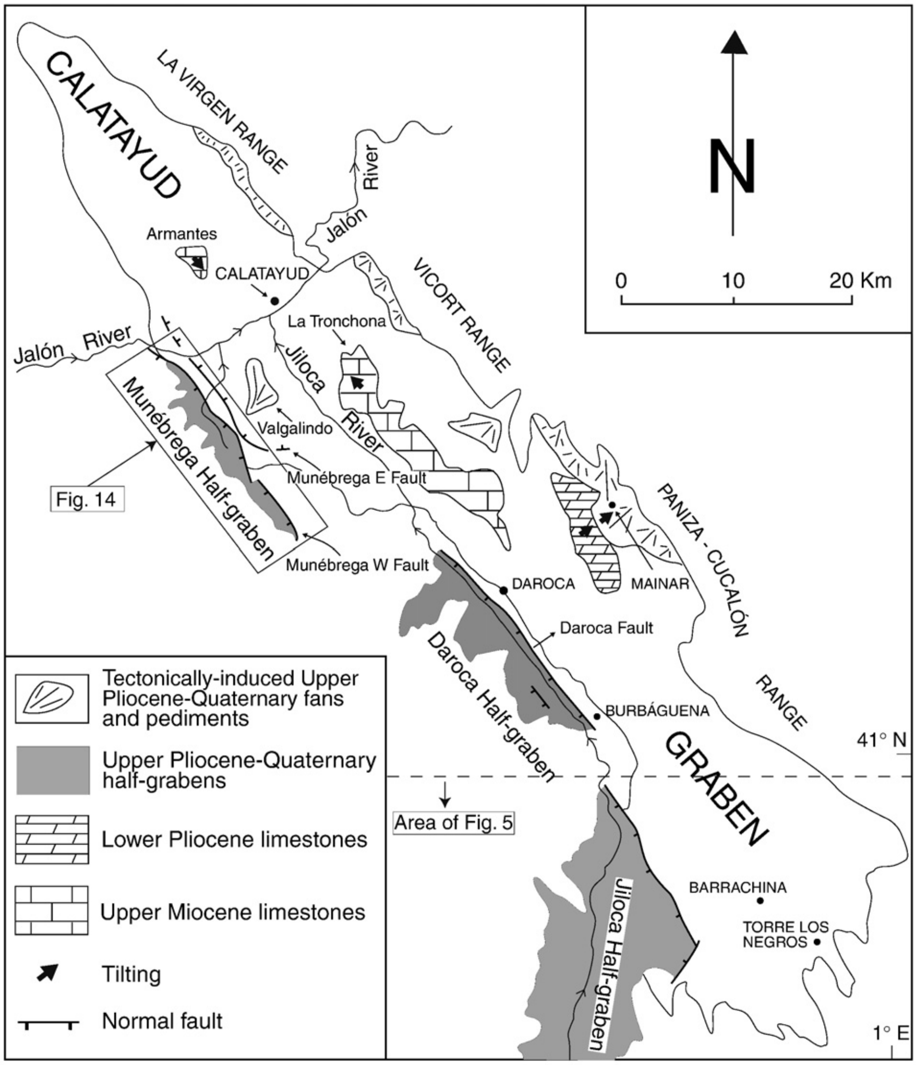

Fig. 4. Map of Calatayud Neogene graben and Munébrega and Daroca Plio-Quaternary half-grabens showing some of the stratigraphical and geomorphic evidence of neotectonic activity and the location of structures mentioned in the text.

deformation caused by interstratal karstification of the halite-bearing evaporites (Gutiérrez, 1996, 1998a; Sanz-Rubio et al., 2003; Gutiérrez et al., 2004) (Fig. 6). In the Calatayud area, the Miocene sediments display centripetal dips directed toward the sector where the more soluble evaporitic facies were deposited (Ortí and Rosell, 2000). This recent deformation, including anomalous tilting of the Upper Miocene carbonate sediments of Armantes and La Tronchona toward the Jalón valley (Fig. 4), may be due to differential interstratal karstification processes, whose activity was favoured by the enhanced hydraulic gradient induced by excavation of the basin fill (Gutiérrez, 1998a). The most significant Plio-Quaternary deformations associated with the Calatayud Graben correspond to the Munébrega, Daroca and Jiloca half-grabens superimposed and/or inset into the Calatayud Graben. The tectonic activity associated with these morphostructures is reviewed below in separate sections.

Evidence indicates that the NE margin of the Calatayud Graben has undergone reactivation in Plio-Quaternary times. In the Mainar area, Lower Pliocene calcareous sediments and the overlying alluvial fan deposits show a clear thickening and post-depositional dip towards the NE (Olivé et al., 1980; Gracia, 1990). Additionally, relatively thick alluvial fan-pediment deposits are frequently found along the linear range fronts of the NE margin (Fig. 4). In the Calatayud area these alluvial deposits (La Virgen and Vicort range fronts) are inset more than 300 m into the uppermost sediments of the basin fill, indicating that they were deposited after a long period of excavation (Gutiérrez, 1998a) (Fig. 6). In the SW margin of the Calatayud Basin, the Miocene sediments are affected by a NW–SE trending normal fault (Munébrega E Fault) that changes to an E–W direction towards its southern termination. This fault and the adjacent master fault of the Plio-Quaternary Munébrega Half-graben (Munébrega W Fault) define the horst that constitutes the active margin of Munébrega fault-angle depression (Gutiérrez, 1996, 1998a) (Fig. 6). The tectonically-induced Valgalindo alluvial fan (Hoyos et al., 1977), inset into the basin fill, records the recent activity of this structure (Gutiérrez, 1998a) (Figs. 4 and 6).

3.2. Teruel Neogene Graben

The Teruel Graben is a NNE–SSW-trending depression transverse to and superimposed on the previous compressional structures that have a prevalent NW–SE grain. This sedimentary basin, around 100 km long and 15–20 km in wide, is filled with more than 300 m of sediments ranging in age from Upper Miocene to Upper Pliocene in the northern and central sectors, and from Lower Miocene to Pliocene in the southern sector (Adrover et al., 1978; Anadón and Moissenet, 1996; Alcalá et al., 2000). The northern and central sectors of the basin constitute a half-graben controlled by normal faults along the eastern margin. These master faults juxtapose the Neogene sediments of the basin fill against

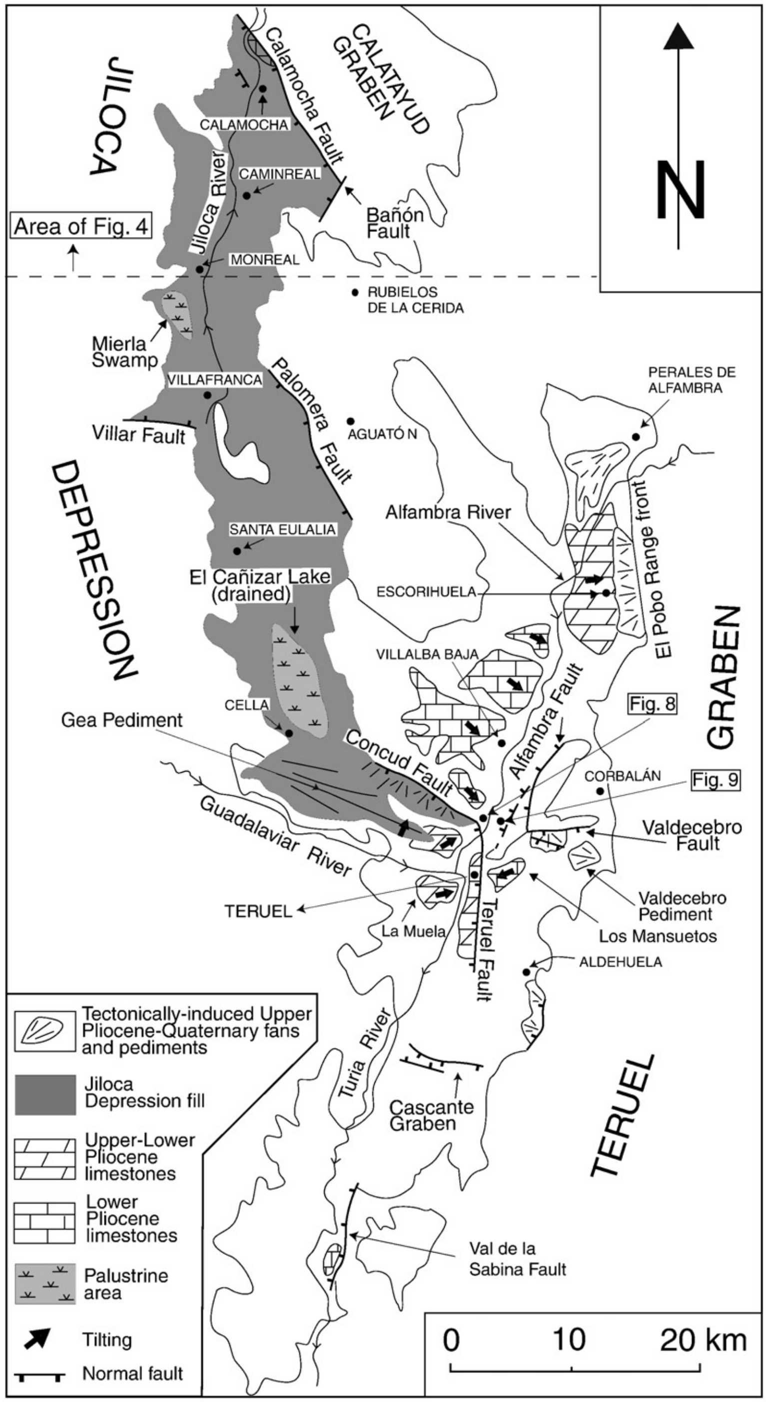

Fig. 5. Map of Teruel Neogene graben and Jiloca Plio-Quaternary depression showing location of the normal faults that are discussed, and the stratigraphic and geomorphic evidence of neotectonic activity documented in the text.

the Mesozoic rocks that form the prominent El Pobo Range (Moissenet, 1983; Simón, 1983; Gutiérrez, 1998a) (Figs. 5 and 6). In the western margin, to the north of the Concud Fault, the Neogene formations unconformably onlap Palaeogene and Mesozoic rocks truncated by a planation surface that is linked topographically and physically with Lower Pliocene calcareous sediments of the basin fill (Palomera Range and Cerro Gordo) (Fig. 6). These Lower Pliocene erosional and aggradational surfaces, correlative in age, show conspicuous tilting toward the ESE indicating that the eastern margin of the graben extended its activity into Upper Pliocene and Quaternary times (Sánchez-Fabre, 1989; Gutiérrez, 1998a) (Fig. 5). The tilted sediments correspond to the western limb of the gentle and asymmetric synclinal structure that affects the basin fill, whose axis, displaced toward the eastern active margin of the graben, controls the position of the Alfambra River valley (Moissenet, 1984) (Fig. 6). To the north of Teruel City, Neogene sediments are interrupted by an inlier of Triassic and Jurassic rocks of an uplifted intrabasinal block (Fig. 5). In this area, the Neogene sediments overlying Triassic evaporitic formations show abundant and chaotic synsedimentary and postsedimentary deformation generated by interestratal karstification of the bedrock (e.g. basin structures with cumulative wedge outs, synforms and periclines, graben structures, sackung) (Gutiérrez, 1998a; Calvo et al., 1999).

The general synformal structure of the basin fill is complicated in the central sector (Teruel City area), where the southern termination

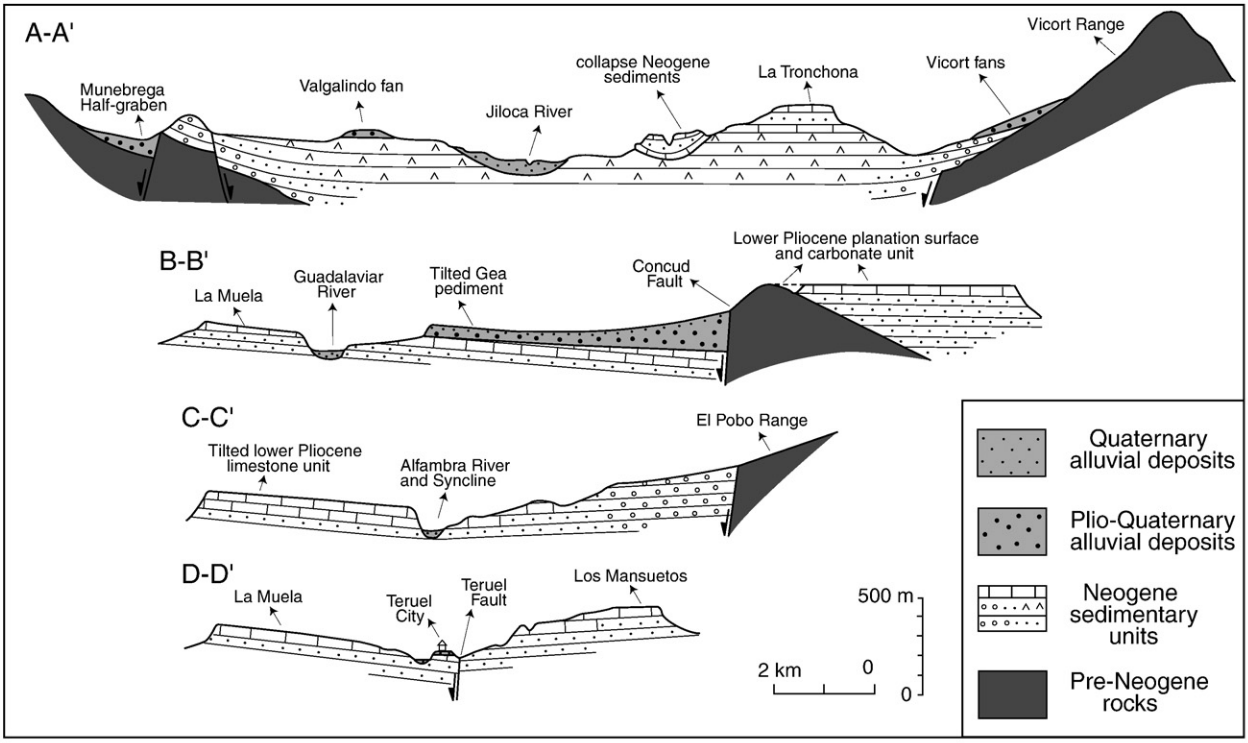

Fig. 6. Geological cross-sections of the Neogene and Plio-Quaternary grabens. The trace of the sections is indicated in Figs. 4 and 5.

of the Jiloca Plio-Quaternary Half-graben, defined by the Concud–Teruel Faults, is superimposed on the Teruel Neogene Graben (Figs. 5 and 6). The Concud Fault, with a dominant NW–SE strike, changes to a N–S trend along the western margin of the Alfambra River valley, cropping out further south on the opposite side of the valley with a N–S trend where it is named the Teruel Fault. This fault system vertically displaces Lower Pliocene calcareous formations more than 250 m and has generated the Concud Depression, a neotectonic depression (southern sector of Jiloca Half-graben) within the prior Teruel Graben (Fig. 6). In the southern sector of Teruel Basin, although the faults with major structural throw are located along the eastern flank, the graben shows a more symmetrical geometry. In addition, there are several important extensional structures, some of which are oriented subperpendicular to the graben (Valdecebro and Concud faults and Cascante Graben) (Fig. 5).

In the Teruel Graben, the chief geomorphic and stratigraphic markers used to detect Plio-Quaternary tectonic movements are the Lower Pliocene calcareous formations and the correlative planation surface, plus the alluvial–fluvial exorheic morphosedimentary units inset into the basin fill. These deposits are clearly Plio-Quaternary in age since the onset of the excavation cycle in the whole basin took place in Pliocene times as revealed by the available chronostratigraphic information (Gutiérrez, 1998a). The presence of Upper Pliocene lacustrine–palustrine calcareous sediments deposited in tectonically-controlled residual basins is also indicative of Pliocene tectonics. Some deformation that affects the terrace and pediment deposits overlying the Neogene and Triassic evaporites in the Orrios–Escorihuela and Teruel areas was initially attributed to extensional tectonics (Peña et al., 1981; Peña, 1983; Simón, 1983, 1984), but has been latterly ascribed to dissolution-induced subsidence phenomena (Moissenet, 1983, 1985, 1989a; Gutiérrez, 1998a,b) similar to that found in the Villaba Baja area (Gutiérrez et al., 1985; Moissenet, 1989a; Gutiérrez, 1998a,b).

In the northernmost sector of the graben, the eastern active margin is defined by the linear NNW–SSE trending El Pobo Range front, which is 11 km in length (Figs. 5 and 6A). Olivé et al. (1983) estimate a postorogenic vertical throw of more than 600 m on this fault. Based on the position of the Lower Pliocene calcareous formations (biozone MN 15) and the correlative planation surface in El Pobo Range, Gutiérrez (1998a) calculates 500 m of vertical Plio-Quaternary offset. Considering a maximum time interval of 4.2 million years for the deformation (base of the MN15 biozone; Mein et al., 1989–1990; Opdyke et al., 1997; Agustí et al., 2001), a minimum slip rate of 0.12 mm/yr can be computed for this fault. Evidence of Plio-Quaternary activity includes: (1) conspicuous eastward tilting of the Lower Pliocene calcareous and gypsiferous formations and the presence of Upper Pliocene lacustrine sediments deposited in a residual basin controlled by the El Pobo Fault (Mein et al., 1989–1990); (2) deposition of the anomalously thick Perales de Alfambra alluvial fan unit. This unit, dated biostratigraphically as Upper Pliocene (Mein et al., 1989–1990), unconformably overlies the endorheic sediments of the basin and is capped by a mantled pediment which constitutes the oldest alluvial level of the area. The alluvial fan deposits display synsedimentary tectonic deformation (Moissenet, 1982, 1983) and the pediment surface is anomalously tilted towards the El Pobo Range (Simón, 1983); (3) The deposits of the mantled pediment correlative to the highest terrace of the Alfambra River (70–80 m above the channel, Gutiérrez and Peña, 1976) in the El Pobo piedmont show an anomalously large thickness (>10 m; the alluvial units deposited on insoluble bedrock are typically less than 5 m thick) including aeolian–alluvial deposits with paleoseismites (fluid escape structures and convolute bedding; J.L. Simón, pers. comm.).

Farther to the south, the NNE trending Alfambra Fault juxtaposes Neogene and Triassic sediments against Jurassic carbonate rocks bevelled by the Lower Pliocene planation surface. The Triassic and Neogene sediments clearly show an unconformable contact although the sharp upward flexure of the Miocene formations suggests the presence of a blind normal fault that could be linked to the Alfambra Fault (Fig. 5). The movement on the Alfambra Fault has caused the back-tilting of the intrabasinal block creating the Corbalán Depression. Gutiérrez (1998a), based on extrapolation of the tilted Lower Pliocene calcareous formations of the basin and the position of the correlative planation surface, estimated a cumulative vertical offset of 200 m on the Alfambra Fault and a minimum slip rate of 0.05 mm/yr. This intrabasinal uplifted block is bounded to the south by the Valdecebro Fault, whose trace is defined by a very straight E–W trending mountain front. From altitudinal difference between the top of the Lower Pliocene calcareous sediments of Los Mansuetos mesa (1150 m) and the correlative planation surface developed on the Jurassic sediments of the uplifted block (1280 m), Godoy et al. (1983a) estimated a vertical Plio-Quaternary displacement of around 150 m on this fault. This offset yields a minimum slip rate of 0.03 mm/yr. At some distance from the mountain front, both the deposits and the surface of the mantled pediments developed in the footwall depression are affected by a N125E trending and SW dipping fault. The pediment surface shows a degraded fault scarp and the deposits, partially stripped from the footwall, attain more than 7 m in the hangingwall indicating a cumulative vertical displacement in excess of 10 m, considering both the topographic and stratigraphic throws (Fig. 7B). Unfortunately, the age of these pediment deposits is unknown. The Valdecebro covered pediment, although older than the pediments associated with the Valdecebro Fault, is clearly inset into the basin fill (Upper Pliocene–Quaternary). The origin of this relatively thick alluvial unit is attributed to the neotectonic rejuvenation of the eastern margin of the graben (Fig. 5). Normal faults up to 2 km long and affecting both the pediment deposits and surface have been reported (Peña et al., 1981; Moissenet, 1983). Peña et al. (1981) identify three sets of normal faults with SSE, ESE and ENE azimuths that form basins and elevated areas in the pediment surface.

To the south of Aldehuela, there is a Plio-Quaternary alluvial sequence juxtaposed by normal faults against the Jurassic rocks of the basin margin (Fig. 5). This alluvial sequence shows clear thickening towards the fault and internal angular unconformities indicative of episodic synsedimentary tectonic subsidence. Based on the thickness of the alluvial deposits the minimum Plio-Quaternary vertical displacement on this fault exceeds several tens of meters (Adrover et al., 1978; Moissenet, 1982, 1983; Simón, 1983). In an aggregate pit (Moissenet (1989a) described a faulted fluvio-deltaic unit inset into the previously mentioned deposits that showed spectacular slumps and concluded that these sediments record the presence of a small

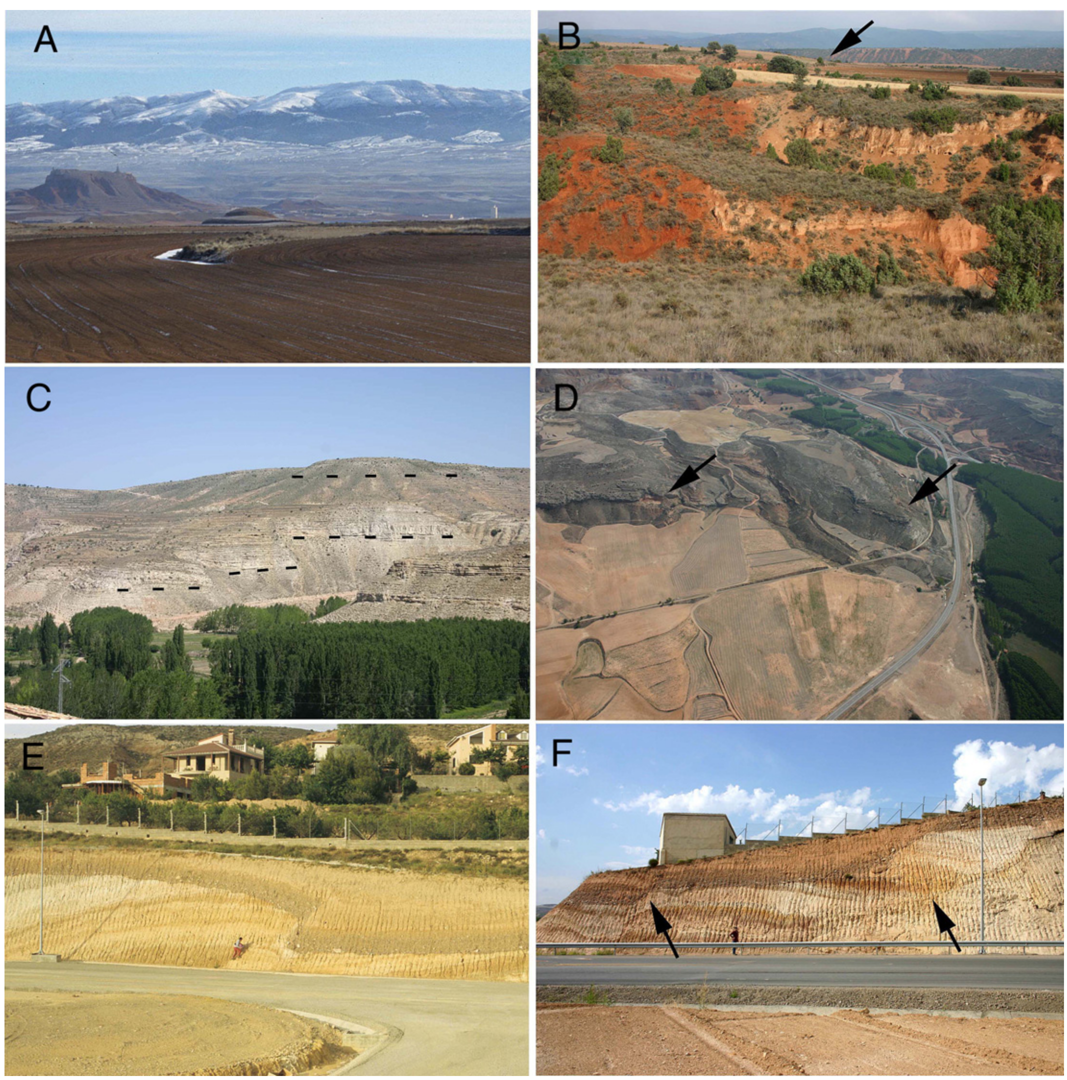

Fig. 7. A: El Pobo Range front in the eastern active margin of Teruel Graben. B: normal fault in Valdecebro piedmont juxtaposing red Miocene shales against a Pleistocene pediment deposit around 7.5 m thick. The trace of the fault is defined by a degraded fault scarp (arrow). C: Miocene sediments offset in Cascante del Río Graben. The dashed lines indicate the base of an Upper Miocene limestone unit in the different fault blocks. D: Oblique aerial view of Concud Fault. Left arrow points to an aggregate pit excavated in a mantled pediment that yielded an age of 56 ka. Right arrow points to the conglomeratic and tufaceous terrace preserved in the upthrown block. E: Flexure and N140E trending reverse fault affecting an Upper Pleistocene terrace of the Valdecebro Creek. F: Faults in Miocene sediments overlain by terrace deposits of the Valdecebro Creek. Left arrow points to a N000E striking normal fault displacing the Upper Pleistocene terrace of the Valdecebro Creek. Right arrow indicates a listric fault truncated by the terrace deposit. This failure could correspond to an old rotational landslide.

lacustrine depression generated by the Plio-Quaternary tectonic activity of the basin-bounding normal faults. Unfortunately these outcrops have disappeared. The Cascante del Río fault system has formed an ESE-trending and 7 km-long graben that controls the location of the Camarena Stream (Fig. 5). This structure displaces Upper Miocene limestones around 200 m (Godoy et al., 1983b) (Fig. 7C). Moissenet (1983, 1989b) proposes a gravitational origin for the structure related to the presence of thick Triassic evaporites in the subsurface. Similar graben valleys generated by salt dissolution have been studied in the Canyonlands section of the Colorado Plateau (Cater, 1970; Gutiérrez, 2004). The most important neotectonic structure in the southern sector of the graben corresponds to the 10 km-long NNE–SSW Val de la Sabina fault system (Fig. 5). This has displaced Upper Miocene units more than 300 m vertically and controlled the deposition of Pliocene carbonate sediments in the hangingwall (Abril and Rubio, 1978; Moissenet, 1983).

3.2.1. Concud–Teruel fault system

Although the Concud and Teruel Faults are the master faults that control the southeastern termination of the Jiloca Plio-Quaternary Half-graben, they are analysed in this section because the markers used to assess their recent activity are the Pliocene calcareous sediments of Teruel Graben and the terrace deposits of the Alfambra and Turia river systems. The fault-angle depression produced by these extensional structures hosts the Concud Piedmont and has determined the position of the Alfambra, Guadalaviar and Turia River valleys and their related Quaternary alluvial deposits. The Alfambra River crosses the Concud Fault transversally to the north of Teruel city (Fig. 5). Gutiérrez (1998a) has differentiated a stepped sequence of 11 alluvial levels in the Alfambra valley upstream of the Concud Fault and 10 levels in the Alfambra, Guadalaviar, Turia valleys downstream of it. The terraces deposited in the upthrown and downthrown blocks cannot be correlated using altitudinal criteria.

In the footwall to the north of Concud Fault and the east of Teruel Fault, the Lower Pliocene calcareous formations form prominent mesas (Alto de Celadas, La Losilla, Los Mansuetos) at around 1150–1200 m asl. In the hanging wall, the Lower and Upper Pliocene calcareous sediments, tilted towards the Concud and Teruel faults, crop out at around 900 m asl close to the faults (Fig. 6). Consequently, the Lower Pliocene calcareous formations have been offset vertically more than 250 m along these two faults. Considering this structural throw and a maximum time span for the deformation of 4.2 Ma, which is the base of the MN15 Mein biozone (age of the youngest sediments dated biostratigraphically in the upthrown and downthrown blocks; Mein et al., 1989–1990; Opdyke et al., 1997; Agustí et al., 2001), a minimum vertical slip rate of 0.06 mm/yr can be estimated for these faults during Plio-Quaternary times (Gutiérrez, 1998a).

Several authors have inferred a Quaternary displacement of 40–50 m on the N–S trending Teruel Fault, based on correlation of alluvial deposits at different altitudes on both sides of the fault (Peña et al., 1981; Peña, 1983; Moissenet, 1983, 1989a). However, this correlation was based on an incomplete morphostratigraphical sequence of three terrace levels. Subsequently, Gutiérrez (1998a) has ascribed the deposits used to quantify the tectonic deformation to two different and non correlative alluvial levels. South of Teruel, in a gravel pit located 300 m west of Teruel Fault, terrace deposits of the Turia–Valdelobos streams overlying unsoluble bedrock and at 70–75 m above the channel show an open synform and normal faults with decimetric throws that very likely correspond to subsidiary ruptures associated with the Teruel Fault (Gutiérrez, 1998a). Unfortunately, no correlatable Quaternary deposits have been found on both sides of the main fault strand.

The 13 km-long Concud Fault is a NW–SE trending structure that changes to a N–S orientation in the western margin of the Alfambra River valley. This fault must connect with the 10.5 km-long N–S Teruel Fault at the other margin of the Alfambra valley (Fig. 5). The Concud Fault creates a very straight mountain front with a local relief of 120 m (Fig. 7D). The upthrown block consists of folded Triassic and Jurassic rocks unconformably overlain by Mio-Pliocene formations of the Teruel Graben fill. The Concud Piedmont hosts a stepped sequence of three Quaternary mantled pediments. The oldest level corresponds to two coalescing and interdigitated pediments: the Gea Pediment, rooted in Albarracín Range 18 km to the west and with a general gradient toward the Alfambra valley, and the highest pediment developed at the foot of the Concud range front. The Gea Pediment lies about 90 m above the Guadalaviar and Alfambra River channels and its alluvial deposits record prevalent SE paleocurrents (Godoy et al., 1983a). The original inclination toward the Alfambra River has been altered by postdepositional tilting toward the Concud Fault (Moissenet, 1982, Gutiérrez, 1998a) (Figs. 5 and 6). The two youngest pediment levels are located in the eastern sector of the piedmont where the morphostratigraphic units become younger toward the Alfambra River valley (Gutiérrez, 1998a).

Evidence and indicators of recent deformation associated with the Concud Fault include: (1) low sinuosity of the mountain front where

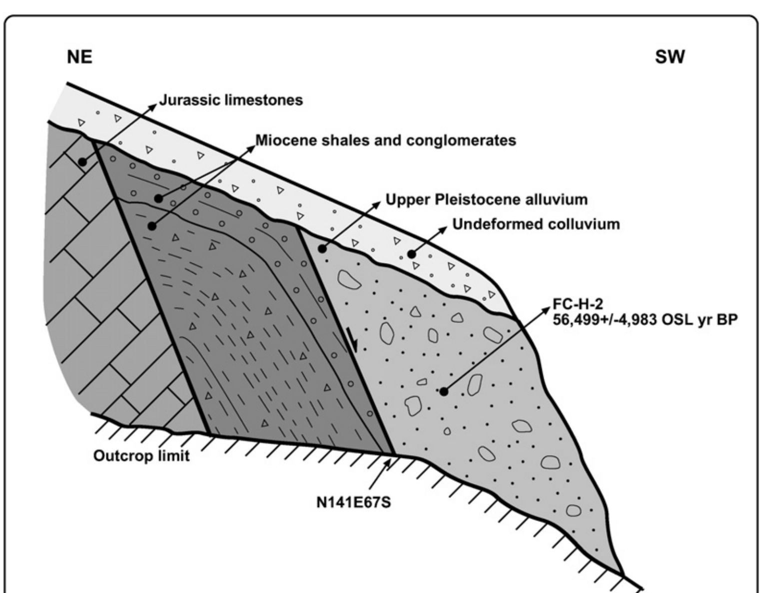

Fig. 8. Cross-section of an outcrop where two faults associated with the Concud Fault strand juxtaposes Jurassic limestones, red Miocene sediments and recent Quaternary deposits.

embayments and alluvial backfilling are almost absent; (2) conspicuous composite triangular fault facets developed on Jurassic carbonate rocks. These landforms are not well displayed in the more easily erodable Neogene sediments; (3) postdepositional tilting of the Gea Pediment toward the NE caused by the rotation (rollover) of the hangingwall (Moissenet, 1982, Gutiérrez, 1998a) (Fig. 6); (4) knick points close to the fault trace in the longitudinal profiles of the creeks that dissect the Mesozoic and Neogene sediments of the upthrown block; (5) the deposits of the youngest pediment level are truncated by the fault. A sample collected from these faulted deposits yields an age of 56,499±4983 OSL yr BP predating the last coseismic deformation event (Figs. 7D and 8); (6) locally, in the eastern sector of the mountain front, there are striking fault scarps up to 2 m high on Jurassic carbonate rocks with subvertical striations and slickensides. These geomorphic features have been explained as tectonic scarps resulting from recent displacement on the Concud Fault (Simón, 1983; Simón and Soriano, 1993) and as exhumed fault planes generated by the differential erosion of the Miocene shales and Quaternary alluvium in the hangingwall (Birot, 1959; Moissenet, 1983; Gutiérrez, 1998a). The latter interpretation is the most reasonable, in our opinion, because these scarps are only observable in a small portion of the fault strand.

Cuts excavated for an old railway in the western margin of the Alfambra valley show an interesting and controversial exposure of the Concud Fault (Figs. 6D and 8). The fault has a N–S azimuth, dips 80–90° to the W, and juxtaposes white Upper Miocene limestones and marls against Quaternary colluvial and alluvial deposits. The stratigraphic units exposed in the footwall along the Alfambra Valley include folded Jurassic formations unconformably overlain by an Upper Miocene sequence composed of a lower unit of red shales with conglomeratic beds and an upper unit of white limestones and marls. Adjacent to the fault, this upper unit (Uml) shows a downward flexure (fault drag) consistent with the fault movement (Fig. 9). The Upper Miocene sediments are unconformably overlapped by a conglomerate 9–17 m thick capped by, and locally interfingered with, a tufaceous deposit 2–7 m thick (QU1). The fact that this sedimentary unit is inset into the Neogene sequence and located at the margin of the Alfambra River valley indicates that it corresponds to a Quaternary terrace of the Alfambra fluvial system (Fig. 7D). It is anomalously thick, reaching 17 m next to the Concud Fault. This characteristic seems to be incongruent for a terrace deposited on the footwall of an active normal fault. The large thickness could be related to a synsedimentary subsidence caused by the downward flexure that affects the underlying formations (Fig. 9). The terrace flight is located 60–66 m above the Alfambra River channel and shows a slight downstream inclination towards the south (Fig. 9). Based on a morphostratigraphical sequence of three levels above the floodplain, several authors have attributed this terrace to the intermediate "Riss terrace level" (Moissenet, 1979, 1983; Simón and Soriano, 1993; Arlegui et al., 2004; Simón et al., 2005). However, in a detailed geomorphological study, Gutiérrez (1998a) has identified a stepped sequence of 11 alluvial levels above the floodplain of the Alfambra River upstream of the Concud Fault. Two tufa samples were dated by U/Th at 169 and 116 ka (Arlegui et al., 2004, 2006). The large discrepancy between both ages raises questions about the reliability of these geochronological data. In order to shed light on this issue, three samples were collected for 230U/234Th dating. Two subsamples from each original sample were extracted and analysed by TIMS U series McMaster University. The subsamples derived from two of the samples (wackestone with gastropods and charophytes) were not suitable for dating due to high detrital 232Th. The two remaining subsamples (mudstone with gastropods), with significantly lower detrital Th content, yielded ages of 250+32/−25 and 213+33/−26 ka, which could be considered as an approximate estimate of the age of the tufa unit. These data

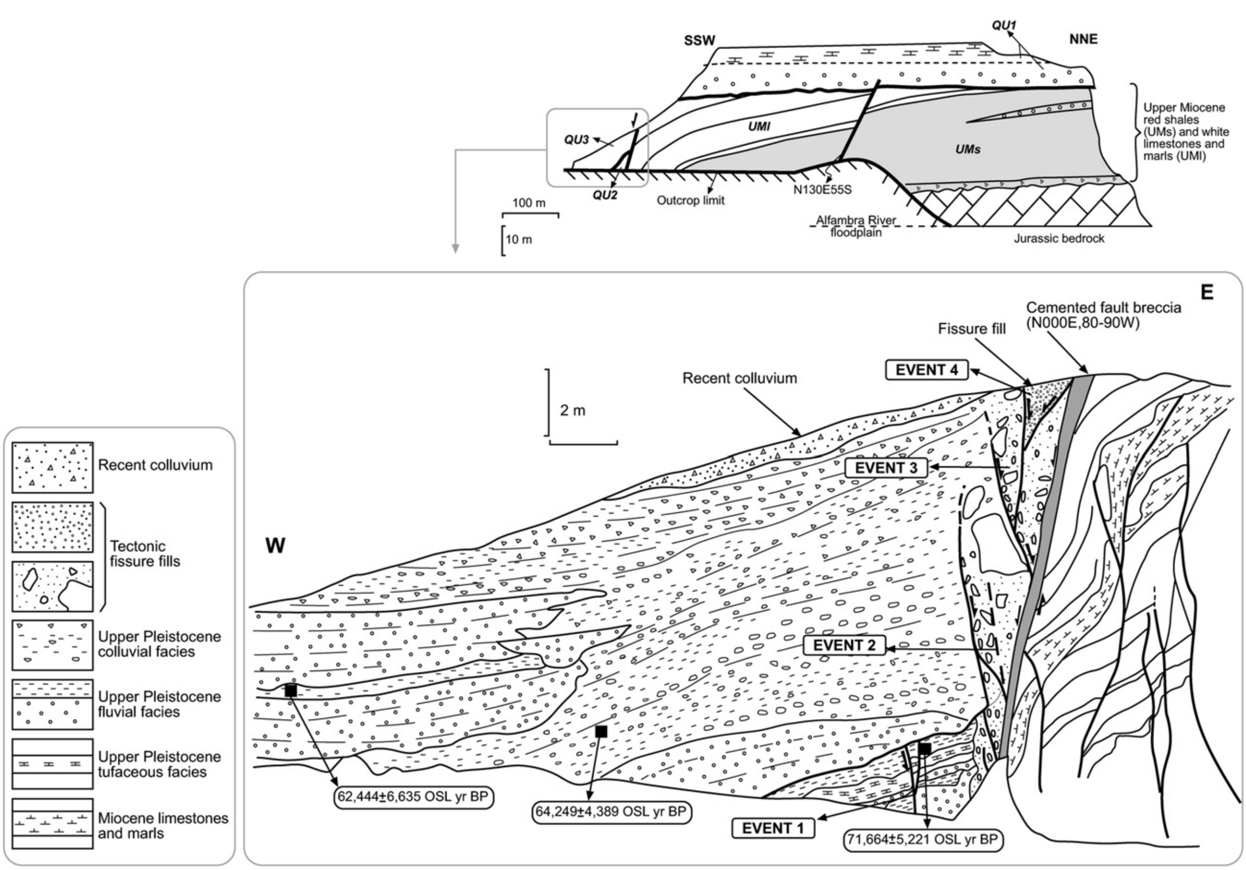

Fig. 9. Cross-section of the Concud Fault in the Los Baños Station area and paleoseismic interpretation of the Pleistocene sediments of the hangingwall.

strongly suggest that the terrace deposit is older than the ages obtained in previous work.

Two sedimentary units bounded by an angular unconformity and cut by the fault can be differentiated in the Pleistocene sediments of the hangingwall (Fig. 9). The lower unit (QU2) corresponds to strongly deformed and cemented deposits made up of conglomerates, silts and a thin tufaceous bed. This unit, like some other detrital deposits located further to the south, has been attributed to the terrace deposits preserved in the footwall (Simón and Soriano, 1993; Arlegui et al., 2004, 2006). Based on this correlation, a vertical throw subsequent to terrace formation of 40 to 63 m has been estimated for this fault (Moissenet, 1979, 1983; Simón and Soriano, 1993; Simón et al., 2005). Nonetheless, an OSL dating carried out in this unit has yielded an age of 71,664±5221 yr BP. This date indicates that this lower unit is younger than the terrace deposit (QU1) preserved in the footwall.

The upper unit (QU3) lies on an erosional surface that clearly truncates the deformation affecting the lower unit (Fig. 9). It consists of colluvial deposits that grade distally into fluvial facies. The colluvial facies are formed by pale orange silts with scattered clasts and beds of angular clasts with a silt matrix (sheet flow and debris flow deposits). The fluvial deposits are made up of a stacked sequence of sheet- and ribbon-shaped channels filled with well-sorted and subrounded gravels and overbank light orange fines. Linear erosional grooves exposed at the base of some channels indicate a N145E paleocurrent towards the Alfambra valley. Two samples collected from this unit have yielded ages of 64,249±4389 and 62,444±6635 OSL yr BP. These dates indicate a sedimentation rate between deposition of the two sampled layers of 1.5 mm/yr (Fig. 9).

The absence of sediments on the downthrown block correlative with the terrace sediments preserved in the footwall admits two possible interpretations: 1) the terrace may have been eroded by incisional channel networks controlled by the progressive entrenchment of the adjacent base level. In this case it would not be possible to estimate the vertical offset of the terrace. 2) The terrace deposits are located below the exposure. In this case the vertical throw would be greater than 44 m, which is the vertical distance between the top of the terrace deposits and the base of the exposure. This would indicate a vertical slip rate higher than 0.18 mm/y on the fault, considering a minimum vertical displacement of 44 m and an age of 250 ka for the terrace deposit.

The exposed Quaternary sediments of the downthrown block record multiple coseismic displacement events (Fig. 9). The oldest event (Event 1) is indicated by faults that displace unit QU2 but not the overlying unit QU3. This coseismic deformation occurred between ca. 64 and 72 ka. Several (as many as three) younger events (Events 2, 3 and 4) are required to form the three "nested" fissure fills that extend through unit QU3. These fissure fills are bounded by well-defined surfaces and show quite obvious differences in texture and colour. The two oldest ones incorporate large blocks derived from the terrace deposit of the footwall (rock falls). These events must be younger than 64 ka. If at least 4 large paleoearthquakes have occurred from 72 ka, the recurrence interval on this fault has been lower than 18 ky. The scarcity of chronological information on the paleoseismic history of the Concud Fault does not allow us to infer the precise frequency of large earthquakes, but the associated morphostratigraphic record indicates that it constitutes a potential seismogenic source. This is an important interpretation from the seismic hazard perspective since Teruel city is partially built upon the Teruel Fault. Assuming that the Concud–Teruel Fault ruptures seismically in its whole length (about 23 km) and using the empirical relations of Wells and Coppersmith (1994) and Stirling et al. (2002), earthquakes with moment magnitudes of around 6.6–7 might be expected on this structure.

Two faults affecting Upper Quaternary terrace deposits have been recently exposed in two orthogonal cuts in the opposite flank of the Alfambra Valley and in the northwestern margin of the Valdecebro Creek (N-420 and A-226 roads junction) (Figs. 6E, F and 9). The bedrock consist of gently folded Miocene orange shales and white marls underlain at shallow depth by Triassic evaporites that crop out around 100 m to the east. In this sector the Neogene and Quaternary sediments overlying the soluble Triassic formations show numerous dissolution-induced deformation features, whereas the Cenozoic sediments overlying Triassic and Jurassic carbonates hardly display any evidence of disturbance (Gutiérrez, 1998a; Calvo et al., 1999). The Miocene sediments are overlain unconformably by a terrace deposit of Valdecebro Creek. This terrace, at around 19 m above the current channel, probably correlates with the youngest preserved terrace above the floodplain of the sequence established by Gutiérrez (1998a). The terrace deposit is made up of a lower 2 m thick gravel unit and an upper 2.5 m thick fine-grained unit with clasts. A sample collected from the base of the upper terrace unit has provided an age of 15,034±959 OSL yr BP (Fig. 10). In the cut parallel to the Alfambra Valley, the terrace deposit and the underlying Miocene sediments are affected by a well-defined reverse fault and some subsidiary steeper faults (Figs. 6E and 9). The

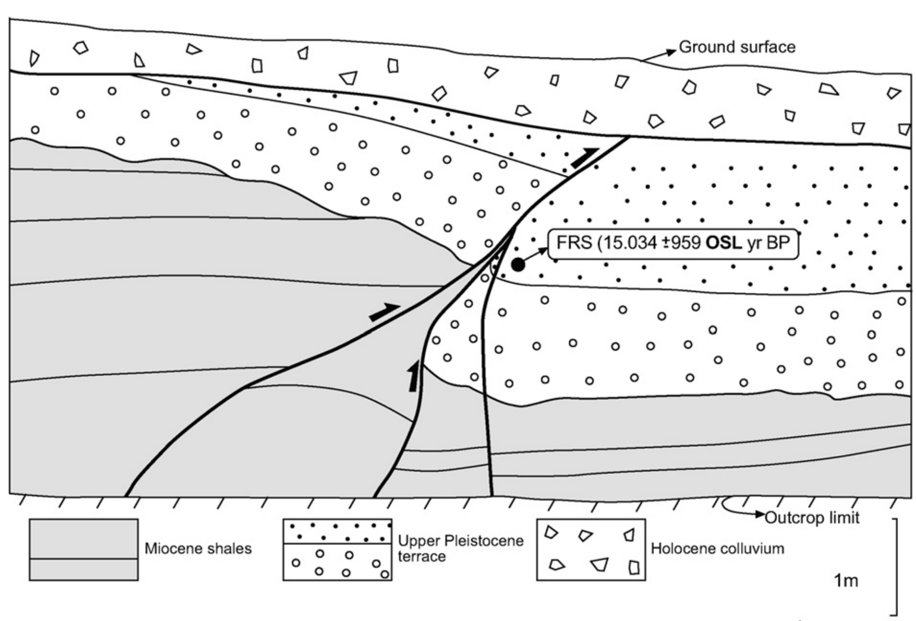

Fig. 10. Cross-section of the reverse fault cutting an Upper Pleistocene terrace of the Valdecebro Creek in the eastern margin of the Alfambra River valley.

main reverse fault has a N140E azimuth and a dip ranging from 30 to 45° to the NE. This brittle deformation is accompanied by the downward flexure of the terrace deposit in the hangingwall. Both the flexure and the antithetic reverse fault have produced a cumulative vertical displacement of around 3 m in the terrace deposits. A vertical offset of 1.7 m (2.4 m of dip slip displacement) has been measured in the reverse fault. The terrace deposit and its deformation are overlapped by an undeformed colluvial deposit. Consequently the deformations affecting the terrace deposit have taken place between 15 ka and the time when the deposition of the colluvium started. The adjacent cut, parallel to Valdecebro Creek, exposes a vertical N000E normal fault slightly refracted in the terrace deposits with a vertical throw of 1.4 m. This cut also shows a circular mass of terrace gravels within the Miocene shales and marls and a listric failure surface in the Miocene sediments fossilised by the terrace (Fig. 7F). Very likely the gravel mass corresponds to a conduit generated by the upward propagation of a solution cavity and its subsequent fill by alluvium derived from the overlying terrace. The subcircular failure may be interpreted as a rotational landslide prior to the terrace. Simón et al. (2005) propose that the two faults affecting the terrace are the same normal fault, which could be rooted in the Concud–Teruel Fault. This interpretation cannot be valid because the two structures have markedly different orientations. These authors also suggest that the offset of the terrace could record the two most recent coseismic ruptures on the fault. In our opinion, gravitational deformation caused by subjacent dissolution of Triassic evaporites is the most reasonable interpretation for the structures in the terrace and the gentle folding of the underlying Miocene sediments. Laboratory physical models show that the bending of sediments due to the lack of basal support (karstification) may produce contractional structures like antithetic reverse faults (bending-moment faults) and buckle folds (Ge and Jackson, 1998). Reverse faults due to karstic subsidence have also been reported from paleokarst exposures in the south of Portugal (Pereira and Cabral, 2002).

3.3. Northern and central sectors of the Jiloca Depression

The NNW–SSE-striking Jiloca Depression, 70 km long and around 10 km in width, is controlled on its eastern margin by three major NW–SE trending normal faults with a right-stepping en echelon arrangement: Calamocha, Palomera and Concud Faults (Fig. 5). The association of these faults with parallel NE-verging thrusts and anticlines (Daroca Thrust and Palomera and Cella anticlines, respectively) suggest they may result from the inversion of contractional structures at depth (Cortés, 1999). These structures define three half-graben sectors, each displaying particular morphostructural characteristics and a different tectonosedimentary evolution. The southern sector, controlled by the Concud–Teruel Fault and superimposed on the Teruel Graben has been described in the Teruel Graben section above. The northern and central sectors show asymmetric topography flanked on the eastern active margins by prominent escarpments controlled by the Calamocha and Palomera faults. The Plio-Quaternary basin fill in these sectors is composed dominantly of alluvial fan deposits several tens of meters thick.

The northern sector of the Jiloca Half-graben is partially superimposed on the Calatayud Neogene Graben along the Calamocha and Bañón faults, 17 and 4 km long, respectively. The Calamocha Fault in its northern sector (Venta de los Céntimos area) juxtaposes Paleozoic and Miocene rocks against Lower Pliocene limestones of the Calatayud Basin fill (Fig. 5). Hernández (1983), based on the elevation of Pliocene limestones in Calatayud Basin (footwall) and the Jiloca Depression (hangingwall), estimate a vertical Plio-Quaternary offset of more than 250 m on this fault. Considering a maximum time span of 5.3 Ma for the deformation (base of the Pliocene), a minimum slip rate of 0.05 mm/y can be estimated on this fault.

To the east of Calamocha village the fault cuts Upper Pliocene–Quaternary alluvial fan deposits (Gutiérrez et al., 1983a; Simón, 1983; Colomer, 1987; Gracia, 1990; Gracia and Gutiérrez, 1996). A good example is seen in cuts along the Zaragoza–Teruel railway (Fig. 11A). Further to the south the fault gives way to a monoclinal flexure (Hernández, 1983) and in its southeastern termination is cut by the NE–SW-trending Bañón Fault (Fig. 5). In the southern cut of the Caminreal–Bañón road this oblique fault juxtaposes Miocene sediments of the Calatayud Graben against Upper Pliocene–Quaternary deposits (Gracia, 1990) (Fig. 11B). Unfortunately, it is not possible to obtain information on the recent displacement of these faults (Late

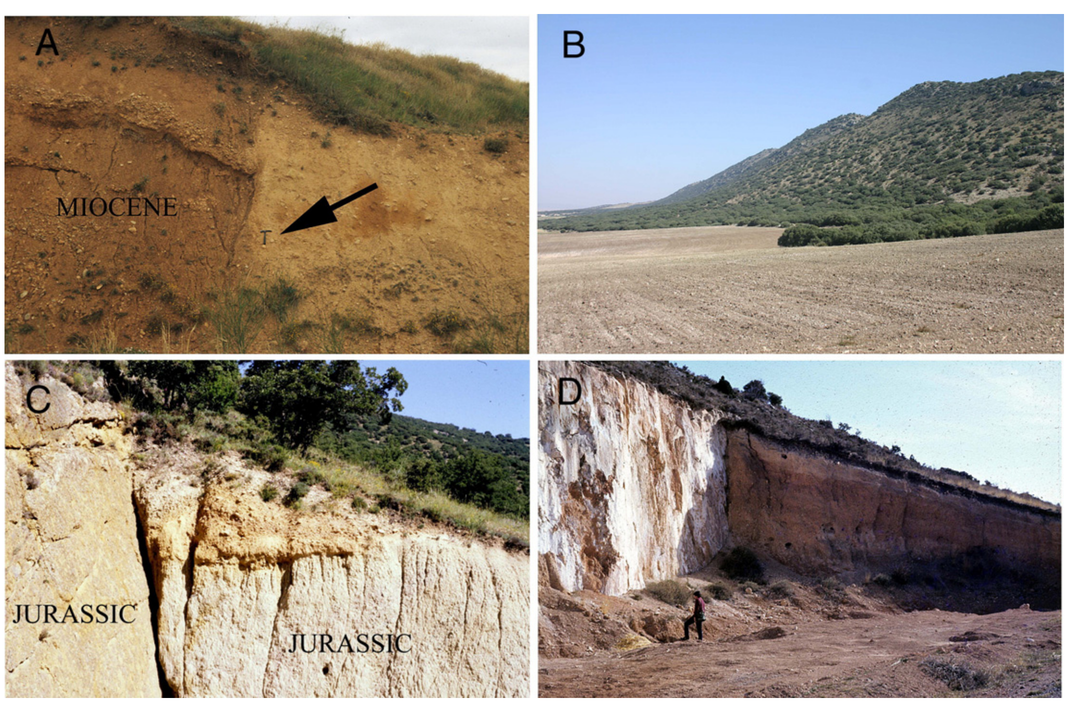

Fig. 11. A: Outcrop of Bañón Fault in the N-211 road juxtaposing Miocene red shales againts Pleistocene alluvial deposits. Arrow points to a hammer for scale. B: General view of the Palomera Range front. C: Fault affecting two unconformable units of colluvial deposits close to Aguatón village. D: Colluvial deposit 8.4 m thick affected by the Rubielos de la Cérida Fault.

Quaternary–Holocene) due to the limited exposures and the lack of geochronological data. To the west of Calamocha village, Upper Pliocene–Quaternary mantled pediments show a NW–SE trending and 3.5 km long uphill-facing fault scarp 5 m high (Gracia, 1990) (Fig. 5). In the central sector of the depression borehole data reveal the presence of tufaceous terrace deposits more than 25 m thick. U/Th dating of a tufa sample taken 4 m under the ground surface yielded an age of 312 ka (Gracia, 1990, 1993; Gracia and Cuchí, 1993). Drillholes record a 50 m thick unit of organic-rich lacustrine sediments between the tufa sequence and a red detrital facies of supposed Upper Pliocene age. All these data indicate that this sector of the Jiloca Half-graben has undergone sustained tectonic subsidence in Upper Pliocene and Quaternary times (Gracia, 1990, 1993).

The central sector of the Jiloca Depression, traditionally considered to be a neotectonic graben, has been recently reinterpreted as a karst polje developed within an active half-graben (Gracia et al., 2003).

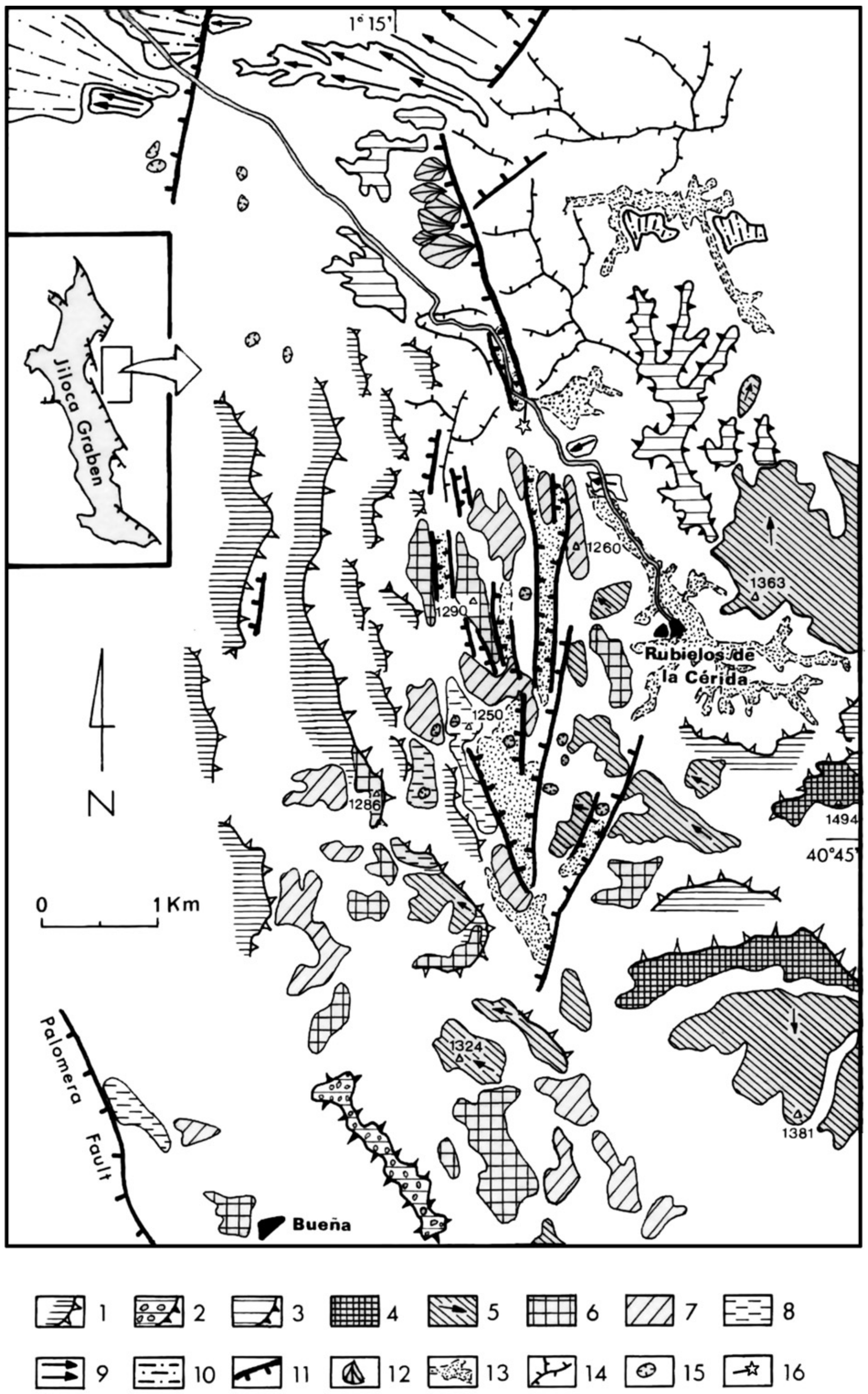

Fig. 12. Geomorphological sketch of the Rubielos de la Cérida "graben valleys" located in the northeastern margin of the Jiloca Half-graben. 1: Cuesta fronts on Mesozoic carbonates; 2: Mesas on Paleogene conglomerates; 3: Mesas on Miocene sands and gravels; 4: Miocene planation surface; 5: Main Planation Surface of the Iberian Range; 6, 7 and 8: Upper, Middle and Lower corrosion surfaces; 9 and 10: Upper and Lower pediment levels; 11: Fault scarp; 12: Alluvial fan; 13: Valley bottom; 14: Drainage divide; 15: Doline; 16: Gravel pit (Figs. 10D and 12).

Detailed geomorphological mapping reveals the presence of eight stepped corrosion surfaces cut in Jurassic limestones with a slight inclination toward the bottom of the basin in the western margin of the depression (Gracia et al., 2003). This sequence of corrosion surfaces corresponds to the remains of previous polje floors. The bottom of the depression is flanked by alluvial fans and is very flat. Here, the carbonate bedrock is mantled by a thin cover of alluvium (<40 m) locally interrupted by protruding inliers (hums) of Jurassic and Triassic rocks. The shallow water table in two sectors has given rise to two large palustrine areas, the Mierla Swamp SW of Monreal and the Cañizar Lake S of Caminreal (Fig. 5). The eastern flank of the depression is formed by the Palomera range front which has 400 m of local relief (Fig. 11B). Evidence of neotectonic activity along this margin of the depression includes: (1) faulted Upper Pliocene–Quaternary alluvial fan deposits that locally show angular unconformities and cumulative wedge outs; (2) anomalously steep alluvial fans; (3) triangular and trapezoidal fault facets and hanging canyons (Moissenet, 1980; Gracia and Gutiérrez, 1996; Gracia et al., 2003). Some authors consider that the prominent relief of the Palomera Range front is largely due to structurally controlled differential erosion rather than to tectonic subsidence (Cortés, 1999; Cortés and Casas, 2000; Casas-Sainz and Cortés-Gracia, 2002; Gracia et al., 2003). Cortés and Casas (2000) indicate a vertical throw of a few tens of meters. However, in the absence of unequivocal stratigraphic markers, a probable vertical offset of 400 m is estimated from morphostructural reconstructions by Arlegui et al. (2005). Several lines of evidence suggest limited Plio-Quaternary deformation on Palomera Fault: (1) Pediments cut on Jurassic limestones at the foot of the range front; (2) Reduced thickness of the basin fill (<40 m); a vertical throw of 400 m on Palomera Fault would produce an asymmetric fault-angle depression with a thick sedimentary sequence adjoining the active margin; (3) The presence of large inliers of Mesozoic rocks in the centre of the basin. In the western margin of the depression, the linear E–W trending Villar Fault, 5 km in length, affects Pleistocene mantled pediment deposits (Gracia et al., 1987, 2003; Gracia, 1990).

Some of the most interesting exposures of normal faults affecting recent deposits have been found in the eastern margin of the Jiloca Depression. Around 1.5 km east of the Palomera Fault, a down-to-the-east normal fault affecting two unconformable colluvial units 2 m thick was exposed in a cut of the Torrelacárcel–Aguatón road close to Aguatón village (Burillo et al., 1985) (Figs. 5 and 10C). In the footwall, the displacement of the N155E-trending fault has generated a relatively fresh 0.5 m high scarp on Jurassic limestones. In the downthrown block, the lower colluvial unit 1.5 m thick was affected by a subsidiary antithetic normal fault unconformably overlain by a younger colluvial unit with a calcareous regosol clearly cut by the fault. Burillo et al. (1985) assigned an age range of 1200–500 yr B.C. to the upper colluvial unit based on geoarcheological remains found within it. Thus, the exposure records two coseismic deformation events that occurred before and after 1200 yr B.C. This is the youngest documented geological record of paleoearthquakes in the central sector of the Iberian Range.

3.3.1. Rubielos de la Cérida tectonic valleys

In the vicinity of Rubielos de la Cérida village, the outcrops of Jurassic rocks, dominantly carbonates, are interrupted by N–S linear infilled valleys (Figs. 10D, 11, 12). These depressions have been interpreted as "tectonic valleys" generated by the Quaternary activity of normal faults with a dominant N–S trend (Capote et al., 1981; Gutiérrez et al., 1983a,b). These narrow graben valleys are less than 4 km long and their width ranges from less than 100 m to around 0.8 km (Fig. 12). Commonly, the profile of the rock hillslopes on the

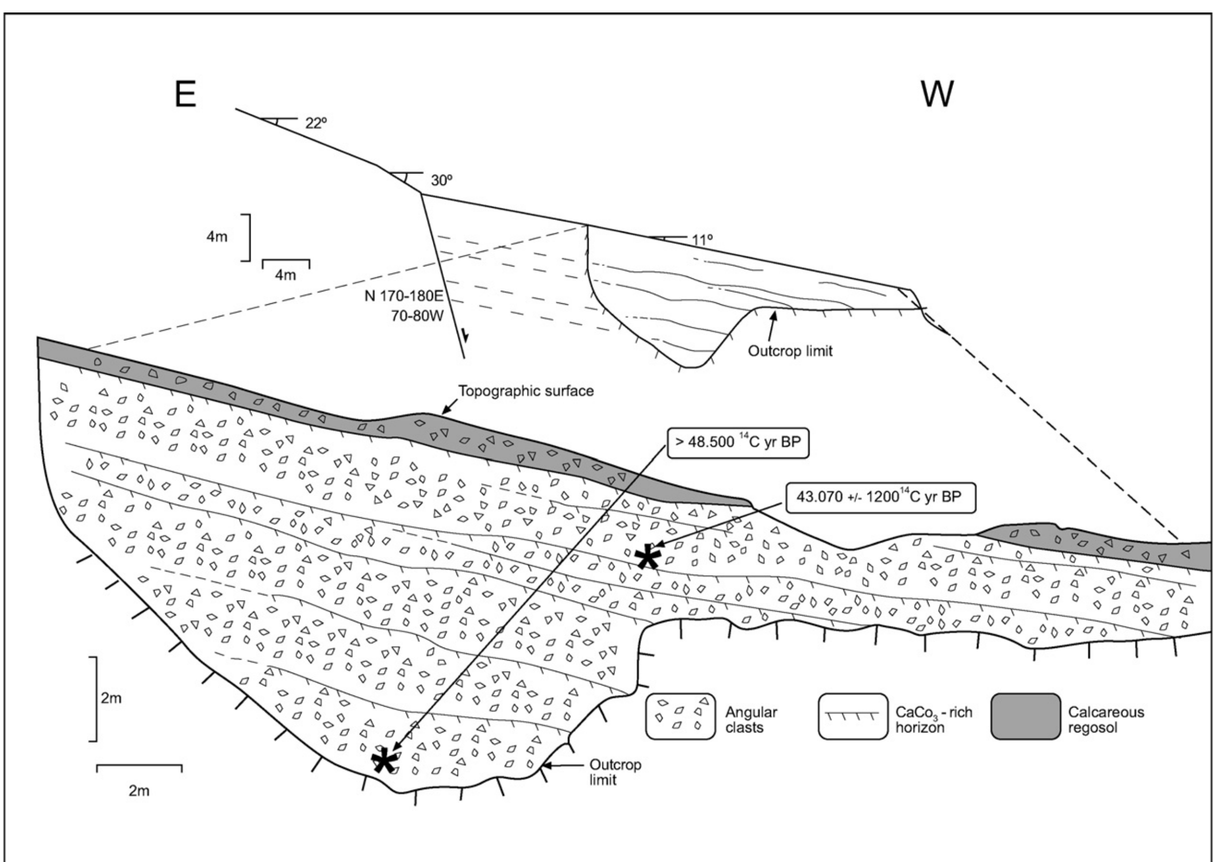

Fig. 13. Cross-section across the Rubielos de la Cérida fault affecting a Pleistocene–Holocene? colluvial sequence.

valley margins (upthrown blocks) show a conspicuous break or scarp at the foot next to the detrital infill of the valleys. Degraded truncated bedrock spurs with triangular facets are also found at some locations.

In a gravel pit located at the margin of one of the graben valleys, around 2 km NW of Rubielos de la Cérida, a spectacular exposure of a fault plane affecting a thick colluvial deposit was found more than 25 years ago (Figs. 10D and 12). This outcrop was originally studied by Capote et al. (1981). The structure corresponds to a down-to-the-west 2.5 km long normal fault with a N170–180E strike and a dip of 75–80 W. A very smoothly polished plane has been developed on a strongly cemented fault breccia of Jurassic carbonates. This surface shows several types of slickensides such as striations, grooves, steps and vertical undulations with relatively large wavelengths. A 82 N pitch has been measured in the striations. The plane is also irregularly coated with calcium carbonate. The whole colluvial deposit on the hangingwall, 8.4 m thick in the exposed outcrop, has been displaced by the fault movement, including the calcareous regosol developed at the top of the sequence (Capote et al., 1981). In the exposure all colluvial beds can be traced to the fault (Fig. 13). A detailed examination of the topography reveals that the morphological expression of the fault is not a fresh scarp but an increase in the gradient of the hillslope in the footwall from 22 to approximately 30° (Fig. 13). This break in the slope profile reflects a cumulative vertical displacement of around 0.9 m on the fault.

The colluvial sequence has parallel bedding with a general dip towards the valley of around 10° that is roughly concordant with the topographic surface. The stratification becomes less obvious towards the proximal sector and the deposit located next to the fault, although not very well exposed, has coarser-grained texture and stronger cementation. The entire deposit is considerably indurated by cementation. The colluvial accumulation comprises layers from 0.3 to 1.5 m thick showing a thinning upwards sequence composed of clast-supported angular pebbles and cobbles of the Jurassic carbonates with a pale orange-light brown fine-grained clayey silt matrix. Although the fabric is dominantly subparallel to the bedding, some gravel particles show primary subvertical orientations. A significant number of the layers have a thin horizon less than 5 cm thick of secondary calcium carbonate at the top. Some beds contain clasts of Jurassic rocks coated with secondary carbonate and granule and pebble-sized calcrete fragments at their base. These sediments are interpreted as sheetflow, sheetwash and occasionally low cohesion debris-flow deposits derived from the hillslope of the footwall. The large size of some of the clasts indicates sporadic deposition by high competence flow events generated by storms. The thin horizons of calcium carbonate developed at the top of the beds may record periods with little or no sedimentation. Alternatively, the detrital particles of pedogenic carbonate and the coated clasts found at the base of some units may correspond to high energy flow events that caused the erosion and reworking of colluvium deposits with a Bk horizon developed under semiarid conditions.

No colluvial wedges or unconformities indicative of discrete episodes of coseismic slip have been found in the detrital sequence. This may be explained by two hypotheses. The first is that colluvial wedges cannot develop in this geomorphological context from fault scarps on hard and soluble carbonate rocks. An explanation is that the slip on the studied fault has been achieved by continuous creep deformation. Pieces of charcoal have been collected from two beds located at 2.1 and 7.9 m below the surface (Fig. 13). In both cases the charcoal corresponds to detrital particles incorporated in the gravel deposits. The youngest sample has provided a conventional radiocarbon age of 43,070 ± 1200 ^{14}C yr BP, whereas the lower one is older than the ^{14}C range (>48,500 ^{14}C yr BP). The age of the upper sample provides a rate of deposition for the upper 2.1 m of the sequence of 0.05 mm/yr and a rate of vertical slip between 0.05 and 0.07 mm/yr. If we assume that the rates of deposition and slip have been relatively constant, an age range of 132,850–168,000 yr BP can be estimated by extrapolation for the base of the exposed colluvial deposit located at 8.4 m below the surface. Alternatively, the estimated slip rate, although derived from only one date, suggests that the studied fault has a slow movement.

The presence of a cemented and polished fault breccia next to the colluvial deposit indicates that the Jurassic rocks of the footwall were initially brecciated by friction with competent rocks of the downthrown block. This fault breccia was later cemented and polished. The available exposure indicates that the amount of Quaternary (Middle Pleistocene–Holocene) vertical displacement exceeds 9.3 m (9.5 m of dip slip displacement). If this structure is seismogenic, then, the slow slip rate and short length (2.5 km) suggest that the recurrence interval of large earthquakes on this fault is very long (>10,000 yr) and that earthquakes with magnitudes higher than 5.6–6.2 might not be expected (Wells and Coppersmith, 1994; Anderson et al., 1996; Villamor and Berryman, 1999; Stirling et al., 2002; González et al., 2003). However, the short length of the mapped fault suggests that it is unlikely that this structure could be an independent seismic source. There is also the possibility that the subsidence undergone by the graben fill deposits would be partially due to karstic subsidence caused by suballuvial corrosion of the carbonate bedrock in the downthrown block. If this were the case, these morphostructural depressions would have a mixed tectonic and karstic origin like that of the adjacent Jiloca Polje-Graben (Gracia et al., 2003).

3.4. Daroca Plio-Quaternary Half-graben

The Daroca Half-graben, 20 km long and about 5 km wide, is a NW–SE trending depression controlled along its NE active margin by the Daroca Fault (Gracia, 1992a) (Fig. 4). This fault system partially results from the negative inversion of the parallel and adjacent NE-verging Daroca Thrust on which Cambrian rocks override Aragonian detrital sediments of the Calatayud Neogene Graben (Julivert, 1954; Colomer, 1987; Colomer and Santanach, 1988). A similar structural configuration has been described in the Neogene half-grabens of the northern Rio Grande Rift system in the Rocky Mountains of Colorado, which result from the inversion of Laramide and older thrusts (Kellog, 1999). Topographically, the Daroca Depression is inset in relation to the Calatayud Neogene Graben, thus its generation occurred in Plio-Quaternary times. Along the NE margin of the depression, the Daroca fault system defines a rectilinear range front of Palaeozoic rocks that display truncated bedrock spurs. The sedimentary fill of the basin is more than 100 m of red detrital sediments consisting of angular Palaeozoic clasts embedded in a clayish matrix. An Upper Pliocene–Quaternary age has been attributed to this formation, known as the Daroca Detrital Unit (Gracia, 1990, 1992a). In the SW flank of the basin the top of this sedimentary unit shows a pediment topography inclined toward the active margin of the graben. This red detrital unit is overlain unconformably by a stepped sequence of four aggradation terrace and pediments of the Jiloca River (Gracia, 1990). This morphostratigraphical sequence inset into the basin fill records the evolution of the Jiloca fluvial system subsequent to the capture of the depression.

Clear evidence of Quaternary activity on the Daroca Fault is found in an aggregate pit located close to the village of Daroca and next to the N-234 road (Fig. 14). Here, the fault juxtaposes Paleozoic argillites in the footwall against two detrital units (U1 and U2) bounded by an angular unconformity in the hangingwall. These units and the fault are truncated and unconformably overlain by an undeformed Holocene cone deposit (U3). A N140E azimuth and a 50SW dip have been measured on the fault plane. The footwall rocks are of bluish grey and intensively crushed Cambrian argillites. The argillites associated with the fault plane show a dark grey shear zone up to 30 cm thick with foliation parallel to the failure surface and secondary calcite crystals. The older unit affected by the fault is the Upper Pliocene–Quaternary Daroca Detrital Unit (U1) made up of a crudely bedded deposit of angular Palaeozoic clasts up to 25 cm in size embedded in a red clayish

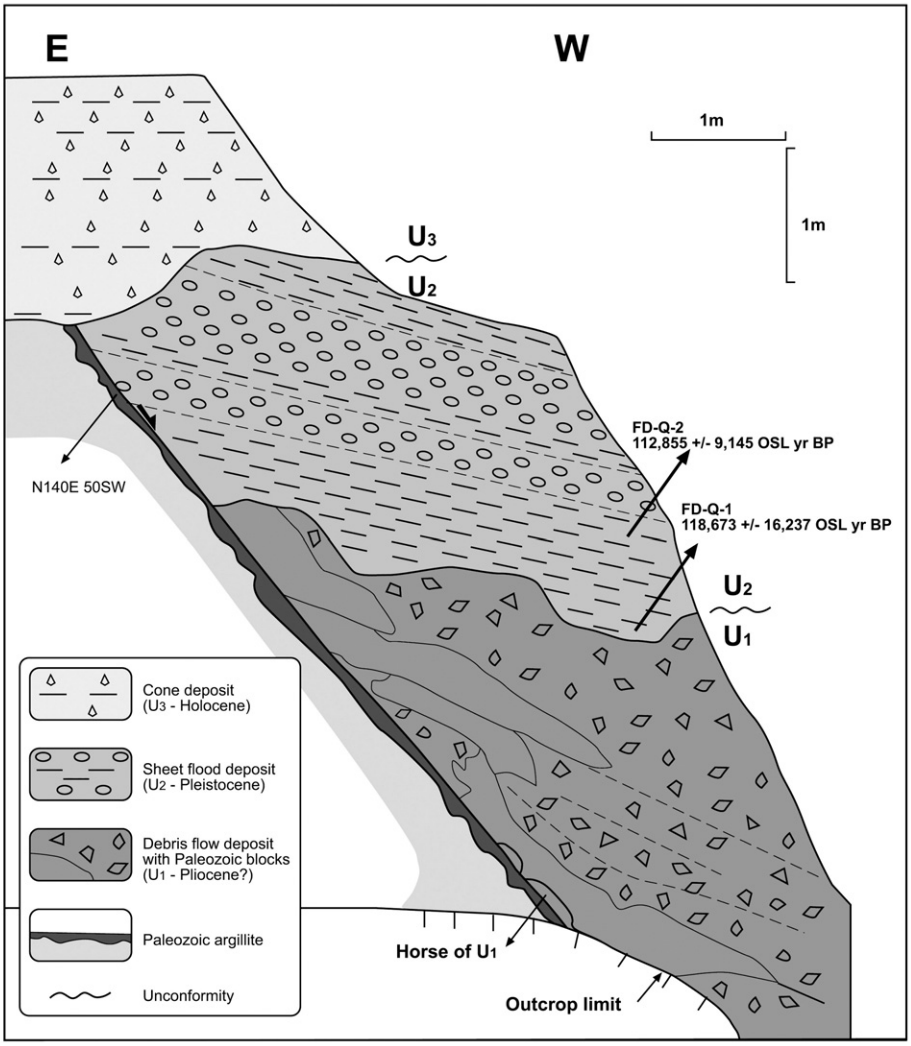

Fig. 14. Sketch of the Daroca normal fault juxtaposing Paleozoic argillites against two detrital Plio-Quaternary units bounded by an angular unconformity. The fault is truncated by an undeformed Holocene deposit.

matrix. This unit has a dip of 25 W. Next to the fault, these debris-flow deposits contain several overlapped lenticular blocks of greenish Paleozoic rocks, up to 3 m long that are concordant with the stratification. This suggests that they were deposited by recurrent gravitational movements (seismically-induced planar slides?) or that they formed part of the debris-flow deposits. Locally, the red detrital facies juxtaposed against the Palaeozoic blocks has acquired a purplish colour with a higher degree of cementation. Additionally, some horses of this unit with high carbonate content occur associated with the fault plane.

The red Upper Pliocene U1 unit is unconformably overlain by a pale orange unit (U2) that dips 13° to the SW and is also affected by the fault (Fig. 14). This deposit corresponds to the oldest alluvial unit inset in the basin fill located at around 35–40 m above the Jiloca River in its distal sector. It consists of alternating beds of clast-supported angular gravels and fine-grained sediments with a dominant tabular geometry (sheet-flood deposits). Some channel-shaped erosional troughs indicate paleo-currents oriented toward the present Jiloca River valley. The thickness of this unit in the gravel pit reaches 10 m. Two samples of fine-grained facies collected from it for OSL dating yielded ages of 119 and 113 ka (118,673 ± 16,237 and 112,855 ± yr BP). In previous works, when the exposure was very limited, this Upper Pleistocene unit was not considered to have been affected by the Daroca Fault (Gracia, 1990, 1992a).

The faulted footwall and hangingwall sediments are overlain by an undeformed Holocene cone deposit (U3) related to the gully systems that dissect the adjacent outcrops of Cambrian rocks (Fig. 14). This unit is a poorly bedded and loose greyish brown gravel and silt deposit. Unfortunately, the chronology of the latest fault movement cannot be constrained due to the lack of any absolute dates from it. Some other indicators of recent tectonic movements in the Daroca Half-graben include an uphill-facing scarp 10 m high on a Plio-Quaternary mantled pediment inset in the basin fill produced by a synthetic fault within the basin (Gracia, 1990, 1992a), and the anomalous morphometry of the debris cones that feed the drainage basins excavated in the Daroca Fault hangingwall (Gracia, 1992b).

3.5. Munébrega Plio-Quaternary Half-graben

The Munébrega Plio-Quaternary Half-graben, with a NW–SE trend, is superimposed to the southwestern margin of the Neogene Calatayud Graben (Gutiérrez, 1998a) (Figs. 4, 6, 14). This neotectonic depression is 19 km long and up to 3 km in width. The poorly exposed basin fill includes more than 30 m of fine-grained and gravel sheetflood alluvial fan facies capped by a mantled pediment with a petrocalcic horizon that displays the stage V of the evolutionary sequence proposed by Machette (1985). The NE active margin of the depression is a prominent horst, between the Munébraga E and Munébrega W faults, composed Miocene conglomerates of the Calatayud Graben and pre-Neogene rocks that are deeply incised (Figs. 6 and 15). The linear Munébrega E Fault juxtaposes Miocene

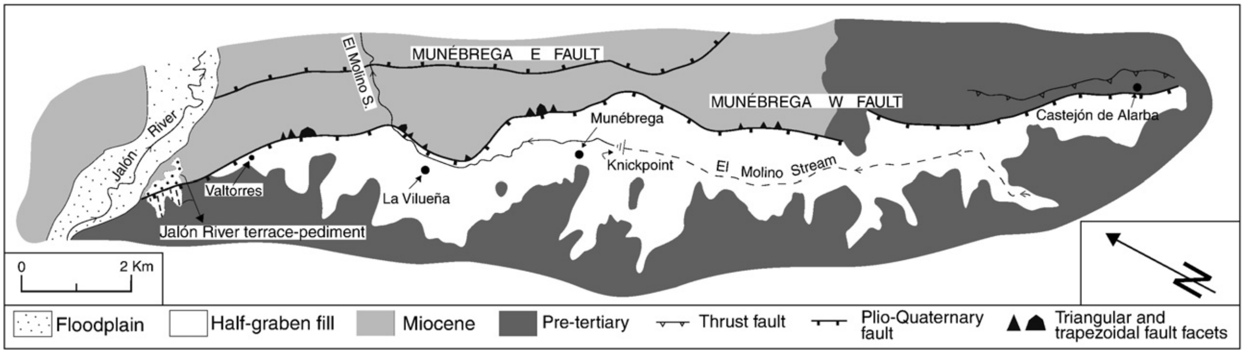

Fig. 15. Sketch of the Munébrega Half-graben.

conglomerates against fine-grained and gypsum Miocene facies and has controlled deposition of the Valgalindo alluvial fan (Figs. 4 and 6). The Munébrega W Fault consists of several SW-facing concave segments and shows a clear step over. Conspicuous triangular and trapezoidal facets on conglomerates are associated with the fault trace. In the southern sector, this fault runs parallel to a thrust that overrides Palaeozoic rocks on Triassic formations and in the northern sector some slivers of Palaeozoic rocks are thrust over and intercalated within the Miocene conglomeratic sequence. These features suggest that, as in the Daroca Half-graben, the Munébrega W Fault may result from the negative inversion of a pre-existing thrust system (Gutiérrez, 1998a). In the southern margin of the Jalón valley, this master fault offsets a pediment some 7 m vertically. This pediment is linked to a terrace of the Jalón River located at 45 m above the current channel (Gutiérrez, 1998a) (Fig. 15). This fault scarp, very degraded by human activity, may represent the cumulative throw produced by more than one coseismic deformation event. Deposits and extensional structures exposed in a trench dug across the fault are being analysed for information on the paleoseismic activity.

4. Discussion and conclusions

Westard-migrating postorogenic rifting in the central sector of the Iberian Chain generated the Mio-Pliocene Teruel and Calatayud grabens and the Plio-Quaternary Jiloca, Daroca and Munébrega Half-grabens, inset and partially superimposed on the western margin of the pre-existing Neogene basins. The evolutionary model proposed for the configuration of the drainage network in this sector of the Iberian Chain involves a progressive capture and transformation of the active grabens from endorheic to exorheic conditions by development of incisional axial fluvial systems controlled by neotectonic activity and the distribution of the basins fill lithofacies. Capture of the basins took place preferentially through topographic gaps controlled, in some cases, by transfer zones. The Teruel Graben was probably captured by an ancestral Turia River in the Lower Pliocene and the entire basin became exorheic at the Upper Pliocene. The trajectory of the longitudinal Alfambra and Turia rivers, roughly coincident with the axis of the NNE–SSW-striking synformal structure of the Mio-Pliocene basin fill, was controlled by tectonic subsidence. Stratigraphic and sedimentological studies suggest that the Calatayud Graben became exorheic in the Upper Miocene (Sanz-Rubio et al., 2003). Nonetheless, the incision cycle and entrenchment of the drainage network in the basin fill started in the Lower Pliocene. The preferential excavation of less resistant facies of the basin fill favoured the development of axial streams such as the Jiloca River. The headward expansion of this subsequent drainage led to the sucessive capture of the Daroca and Jiloca Half-grabens, possibly in the Upper Pliocene–Lower Pleistocene and in the Lower–Middle Pleistocene, respectively. The southern sector of the Jiloca Depression remained as an internally drained area until its artificial canalisation. In the future this evolutionary model could be improved substantially by: (1) obtaining additional data on the chronostratigraphy-geochronology of the basin fills and the exorheic morphosedimentary units, particularly the youngest endorheic units and the oldest alluvial levels, respectively; (2) analysing the sediments and landforms that record the paleogeographic evolution of the capture areas, as carried out satisfactorily in some Neogene–Pleistocene basins subjected to recent tectonic inversion in the Betics (SE of Spain) (Harvey and Wells, 1987; Mather, 1993; Calvache and Viseras, 1997; Stokes and Mather, 2003).

Most of the evidence for Plio-Quaternary neotectonic activiy is associated with the eastern margin of the Neogene grabens and the NE-tilted Plio-Quaternary half-grabens. From the empirical relations of Wells and Coppersmith (1994) and Stirling et al. (2002), the lengths of the faults and fault-controlled mountain fronts (<25 km) suggest that, earthquakes with moment magnitude larger than 6.7–7 might not be expected in the area. Plio-Quaternary hectometric vertical thows have been attributed to some of the main faults. Although offsets attained in Quaternary times are difficult to appraise due to the lack of correlative recent sediments on both sides of the faults and reliable geochronological data, they may attain several tens of meters. The Plio-Quaternary vertical offset of some major faults in the Teruel Neogene Graben has been estimated using Lower Pliocene calcareous sediments and correlative planation surfaces. The largest throw reaches 500 m on the basin-bounding El Pobo Fault. Throws of 200 and 150 m have been calculated for the intrabasinal Alfambra and Valdecebro faults, respectively. Minimum slip rates between 0.12 and 0.03 mm/yr have been derived from these values. The vertical displacement on two of the master faults of the Jiloca Plio–Quaternary Half-graben (Calamocha and Concud–Teruel faults), inferred from the offset of Lower Pliocene calcareous formations, exceeds 250 m, yielding a minimum slip rate of 0.05 mm/yr. These values of deformation are similar to the 0.02–0.08 mm/yr slip rates calculated for the southern segment of the El Camp normal fault in the Catalan Coastal Range (Masana et al., 2001; Santanach et al., 2001). The expected low slip rates in an intraplate setting (Giardini, 1995) suggest that the structures investigated here have a long seismic cycle (>1,000 yr) (Villamor and Berryman, 1999; González et al., 2003). Evidence of four paleoearthquakes after 71 ka have been identified in an outcrop of the Concud Fault indicating that the recurrence interval of large earthquakes on this seismogenic structure is less than 18 ky. Due to the low recurrence interval of the seismogenic structures, the brief instrumental and historical record needs to be supplemented with paleoearthquake data to predict reliably the probability of future earthquakes with destructive magnitude (Wallace, 1987; McCalpin and Nelson, 1996; Santanach and Masana, 2001). Seismic hazard assesments based solely on the limited historical and instrumental earthquake catalogue may underestimate the probability of future earthquakes such as has been demonstrated in a paleoseismic study of the El Camp normal fault (Catalan Coastal Range) located in the vicinity of a nuclear power station (Santanach et al., 2001; Masana et al., 2001). Consequently, to avoid misleading interpretations, it would be of great interest to conduct future paleoseismological investigations supported by improved understanding of morphostratigraphic sequences. These studies would also provide important data on the influence of tectonic activity on the geomorphological evolution of the area and its impact on the fluvial systems. Special care should be taken when studying deformation affecting sediments underlain by evaporitic rocks, as this is likely to result from dissolution subsidence (Gutiérrez, 1996, Gutiérrez et al., 2001).

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