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# Neogene-Quaternary onshore record in the lower Ebro river incised palaeovalley (Ebro margin, Catalan Coastal Range, NE Iberia)

**A. ARASA-TULIESA[1] and L. CABRERA[2]**

**[1]Grup EbreRecerca**
C/ Rosa Molas 25A, 2B, 43500 Tortosa, Catalonia, Spain. E-mail: arasa44@gmail.com

**[2]Universitat de Barcelona. Facultat de Ciències de la Terra. Departament de Dinàmica de la Terra i de l'Oceà.**
**Institut de recerca Geomodels. Grup de Recerca Consolidat de Geodinàmica i Anàlisi de Conques**
C/ Martí Franquès s/n 08028 Barcelona, Catalonia, Spain. E-mail: lluis.cabrera@ub.edu

**ABSTRACT**

The lower Ebro is a bedrock-alluvial mixed incised valley with a persistent degradational stacking architecture developed from latest Serravallian(?) to Holocene. This degradational pattern was probably controlled by isostatic rebound in NE Iberia and punctuated by major relative sea level changes that temporally accentuated or attenuated the palaeovalley entrenchment and sediment retention. Six allostratigraphic units in the palaeovalley constitute the onshore record of its evolution and the opening and connection of the Ebro Basin with the Mediterranean. This paper deals with the analysis and reinterpretation of these units in order to precise the sequence of events that took place on the onshore part of the Catalan continental margin during the Ebro River drainage entrenchment. Plausible chronology and palaeogeographic evolution of the Neogene-Quaternary drainage incision in the lower Ebro are also proposed. The early evolutionary stages of the incised palaeovalley (Latest Serravallian?-Tortonian-Early Messinian, from 11.63–9? to near 5.6Ma) were dominated by entrenchment and intense sediment transfer from the onshore to the offshore zones (erosion surface S2). These processes were only punctuated by the sedimentation of the alluvial palaeovalley unit M2 (late Messinian). The polygenetic onshore erosion surfaces S2 and S3 are linked here with the onshore erosive processes that fed the sedimentation of the terrigenous shelf-slope system of the offshore Castellón group and considered coeval with the offshore Messinian erosion surfaces (reflectors M and m). During a further evolutionary stage (Pliocene to Early Pleistocene from 5.3 to approximately 2Ma) the Early Pliocene major Mediterranean reflooding caused some sediment retention in the incised palaeovalley (sedimentation of unit P) but sediment transfer into the offshore remained very effective. In the last evolutionary stage (Early Pleistocene-Holocene, from 2Ma to present) the palaeovalley became again mainly degradational (generation of erosion surfaces S4 to S6 and sedimentation of stepped alluvial terraces Q1-2 to Q4). The onshore stratigraphic record, including the allostratigraphic units P and Q1-2 to Q4 and the related bounding surfaces S3 to S6, is correlated with the sedimentation of the terrigenous shelf-slope system of the offshore Ebro group.

***KEYWORDS*** **NW Mediterranean. Ebro Basin opening. Onshore erosion surfaces. Late Miocene (Tortonian and Messinian).**

## INTRODUCTION

The opening of the Ebro Basin to the Mediterranean has been a matter of debate in regard to both the involved processes and their timing. Lake overflow, sediment overfill, capture of the basin and drainage piracy by headward erosion of a coastal river catchment developed in the Catalan Coastal Range (CCR) or a combination of some of these mechanisms have been considered as possible leading processes for this endorheic-exorheic transition of the Ebro Basin (Riba *et al*., 1983; Serrat, 1992; García-Castellanos *et al*., 2003; Arche *et al*., 2010). There is no complete agreement about the age of the downcutting of the earliest lower Ebro palaeovalley and of the opening of the Ebro basin into the Mediterranean Basin. The diverse proposals range from 13Ma to 5.5Ma (Alonso *et al*., 1990; Arasa-Tuliesa, 1990; Coney *et al*., 1996; Evans and Arche, 2002; García-Castellanos *et al*., 2003; Nichols, 2004; Babault *et al*., 2006; Arche *et al*., 2010). However, the chronostratigraphic dating and sedimentological characteristics of the youngest depositional units in the central sectors of the Ebro Basin (Azanza, 1986; Barberà *et al*., 2001; Pérez-Rivarés *et al*., 2002, 2004; Vázquez-Úrbez *et al*., 2002, 2012; Larrasoaña *et al*., 2006; Vázquez-Úrbez, 2008; Valero *et al*., 2014; Pérez-Rivarés, 2016), the Serravallian-Early Messinian age of the first progradational shelf-slope system developed in the Ebro Delta Shelf (Evans and Arche, 2002; Arche *et al*., 2010; Urgelés *et al*., 2011) and recent modelling scenarios (García-Castellanos and Larrasoaña, 2015) suggest that the basin capture and opening could have occurred between 11.63Ma (Serravallian-Tortonian transition) and 7.2Ma (Messinian), although some are inclined towards the younger age, *i.e*. late Tortonian between 10 and 8Ma. This last range of ages accords well with the time when the rapid exhumation of basement rocks in the eastern Pyrenees took place, which was calculated based on fission tracks as younger than 10Ma and that has been linked to the opening of the Ebro River towards the Mediterranean (Beamud *et al*., 2011; Fillon and van der Beek, 2012; Fillon *et al*., 2013; Rushlow 2013).

Most of the above mentioned recent proposals on the timing and the processes that ruled the opening of the Ebro Basin and more in general its Neogene and Quaternary evolution have been based on the advances in the knowledge of the Neogene record in the offshore (Urgeles *et al*., 2011 and references therein) or in the Neogene-Quaternary stratigraphic record in the eastern and central sectors of the Ebro Basin. However, the onshore stratigraphic record developed in the lower Ebro River valley, although fragmentary, deserves to be considered since it developed across the CCR, the mountain range between the Ebro Basin and its Mediterranean outlet.

This study of the Cenozoic-Quaternary stratigraphic record of the lower Ebro provides new data on the valley incision-filling and the opening of the Ebro Basin drainage to the Mediterranean. The previous geological studies carried out in the area at both regional and local scale have neither recognized some of the existing units nor established their correlation between the isolated and often poorly outcropping sequences that occur in the Tortosa Graben, the Móra Basin and the Flix area of the Ebro Basin (Colodrón and Orche, 1979; Maldonado *et al*., 1979; Orche *et al*., 1980, 1981; López and García, 1985).

## GEOLOGICAL SETTING

The lower Ebro is integrated in the CCR, which forms part of the Catalan continental margin (NE Iberian margin) and constitutes the northwestern edge of the NW Mediterranean and the Valencia Trough domain (Stoekinger, 1971, 1976; Mauffret, 1976; Durand-Delga and Fontboté, 1980; Fontboté *et al*., 1990; Roca and Guimerà, 1992; Roca, 1994; Roca *et al*., 1999) (Fig. 1). The NW Mediterranean Basin resulted from the Oligocene–Miocene rifting related with the back-arc extension associated with the rollback of the retreating Calabrian–Tethys subduction zone (Roca, 1994; Granado *et al*., 2016).

Palaeozoic Variscan rocks constitute the basement of this part of the CCR onshore, including major slates and sandstones, and plutonic rocks (granitoids) that resulted in metamorphic aureoles and quartz porphyritic dykes (Colodrón *et al*., 1978; Melgarejo, 1987; Sáez and Anadón, 1989; Valenzuela, 2016). Major carbonate and minor siliciclastic Mesozoic sequences mainly deposited under rifting and post-rift conditions, unconformably overlie the Variscan basement and constitute its cover (Anadón *et al*., 1979, 1985; Salas *et al*., 2001).

Compressive folding and thrusting took place in the area from the Eocene to the late Oligocene, during the upbuilding of the intraplate CCR Orogen (Anadón *et al*., 1979; Guimerà, 1983, 1984; Lawton *et al*., 1999; López-Blanco, 2002; Merren *et al*., 2004). The SE Ebro Basin constituted the foreland of this orogen and its basin infill includes a variety of non-marine silicilastic and carbonate units ranging in age from Palaeocene to Oligocene (Colombo, 1980, 1986; Cabrera, 1983; Cabrera and Sáez, 1987; Lawton *et al*., 1999; Barberà *et al*., 2001; López-Blanco, 2002; Merren *et al*., 2004; Costa *et al*., 2006; Valero *et al*., 2014). The latest Oligocene-Miocene Móra Basin developed paralleling the Ebro Basin margin resulting initially from its late compressive structuration and its lower basin fill includes Palaeogene deposits (Anadón *et al*., 1979, 1983; Teixell, 1985, 1988).

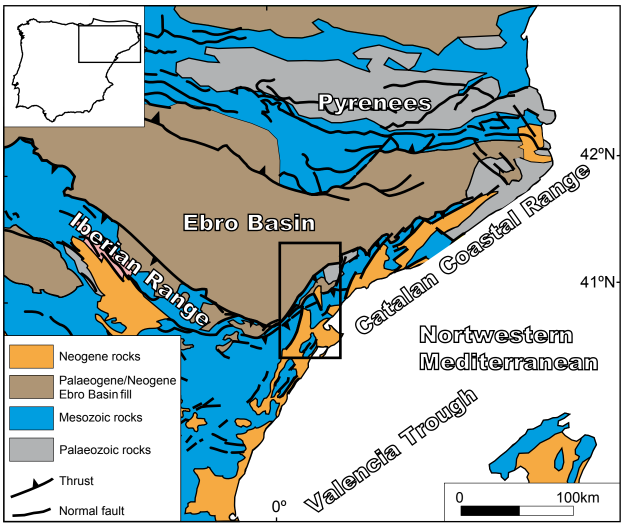


**FIGURE 1.** Location of the study area (black-framed inset) in the framework of the NE Iberian Peninsula, the Catalan Coastal Range (CCR) and the Catalan part of the NE Iberian continental Margin that makes up the NW margin of the Northwestern Mediterranean Basin.

This region was subsequently affected by Neogene extension both in the onshore (Móra Basin, Tortosa Graben) and offshore (Ebro Shelf) areas (Anadón *et al.*, 1979, 1983; Simón *et al.*, 1983; Guimerà and Álvaro, 1990; Roca and Guimerà, 1992; Urgeles *et al.*, 2011). The rifting took place by hyperextension of the Iberian-European lithosphere. (Granado *et al.*, 2016) and started at the latest Oligocene (Biju-Duval *et al.*, 1978; Fontboté *et al.*, 1990) giving rise to the eastern Iberian continental margin and to its characteristic Neogene horst, graben and tilted block structure (Anadón *et al.*, 1979; Santanach *et al.*, 1980; Fontboté *et al.*, 1990). Some regional faults experienced slow and minor activity during the Quaternary until Recent (Masana, 1995; Perea, 2006; Perea *et al.*, 2006)

A Late Miocene to Recent flexural isostatic uplifting affecting the major structures in NE Iberia (Pyrenees, Ebro Basin and Catalan continental margin, including the CCR) has been proposed. This overall uplifting would be caused mainly by erosive unloading of the region and its intensity would decrease from the Ebro Basin centre to its margins (García-Castellanos and Larrasoaña, 2015). Moreover, the CCR and the SE Ebro Basin margin would have experienced also a gentle isostatic rebound resulting from a rift shoulder effect triggered by the rifting that originated the NW Mediterranean and its NW continental margin (Gaspar-Escribano *et al.*, 2001, 2004).

A variety of depositional units make up the infill of the extensional basins resulting from the above-mentioned rifting. In the onshore zones (*e.g.* Móra Basin, Tortosa Graben), alluvial-fan clastic sedimentation was widespread. On the Ebro Shelf, the offshore extensional basins were infilled by a variety of continental and marine deposits (Alcanar group; Urgeles *et al.*, 2011; Granado *et al.*, 2016 and references therein), although marine deposits were dominant. From the Middle Miocene until the present, two prograding shelf-slope siliciclastic systems, which developed in the post-faulting stage of the Ebro Shelf, dominated the deposition in the offshore area (Castellon and Ebro Groups; García-Siñeriz *et al.*, 1978; Riba, 1981; Soler *et al.*, 1983; Maldonado, 1985; Maldonado *et al.*, 1986; Nelson and Maldonado, 1990; Urgeles *et al.*, 2011; Granado *et al.*, 2016).

The Serravallian to Holocene sedimentation at the Ebro palaeovalley and on the Ebro Shelf was not continuous and the marine and transitional systems were affected both by the above-mentioned tectonic evolution and the sea level changes that affected the region. The most important that affected the evolution of the lower Ebro palaeovalley were two major sea level drops (Late Serravallian-Early Tortonian, Late Messinian) and the dramatic sea level rise that resulted from the Early Pliocene Mediterranean reflooding (Dañobeitia *et al.*, 1990; Escutia y Maldonado, 1992; Álvarez-de-Buergo and Meléndez-Hevia, 1994; Urgeles *et al.*, 2011; Granado *et al.*, 2016). Extensional faulting, although with moderate to low intensity, was still active during the Pliocene and the Quaternary, and influenced locally on sedimentation.

## METHODOLOGY

This work was based on the hypothesis that the external drainage of the Ebro Basin into the Mediterranean should be recorded by the existence in the lower Ebro onshore record of incised fluvial deposits formed downstream from the NW margin of the CCR and including an increasing variety of clasts derived from the erosion of Mesozoic and Palaeozoic rocks of the CCR, the Cenozoic fill of the Ebro foreland basin and finally the Pyrenean Orogen.

Considering that the studied units are bounded by unconformities, they are defined as allostratigraphic units (I.S.G., 1994; N.A.C.S.N., 2005) and both the erosion surfaces and the depositional units have been named with alphanumeric references. This approach was preferred instead of sequence stratigraphy criteria (Dalrymple *et al.*, 1994, 2006; Zaitlin *et al.*, 1994; van Wagoner, 1995; Boyd *et al.*, 2006) considering both the difficulty of a precise correlation between the onshore and offshore records and the ongoing debate on the sequential meaning of the incision surfaces that define the lower palaeovalley boundaries and its correlation with the deltaic and shelf successions (Blum *et al.*, 2013).

A new mapping and inventory of both outcrop and subsurface data have been carried out to better understand the extension, development and correlation of these Neogene-Quaternary units and the distribution of clasts from different source areas. The recent carrying out of extensive civil works and the increasing open-pit extraction of alluvial materials have enabled a thorough and detailed review of these Neogene-Quaternary units from the Ebro foreland basin to the Tortosa Graben and the intermediate Móra Basin. Because of the often poor, restricted and scattered outcrop conditions of these units, detailed mapping has been carried out at 1:25,000 and 1:5,000 scale. Geological sections have been made on the basis of the digital terrain model, which allows observation of significant geomorphological characteristics that could not be analysed formerly. Moreover, an inventory of more than 800 hydrogeological surveys is now available and has improved subsurface knowledge and enabled establishing a correlation with the outcropping units. The consulted databases were the borehole inventories by Arasa-Tuliesa (1994a, 75%), the Hydrographic Confederation of the Ebro (HCE, 23%), Lanaja (1987, 1%), and P.L. Bermejo (personal communication, 2015; 1%). The resulting data base is of major importance for the geological knowledge of the subsurface materials in this study, considering that more than 80% of the materials of the studied units occur in the subsurface. The graphic information provided in Figures. 1–6 is complemented in the Electronic Appendix (available at www.geologica-acta.com) with detailed supplementary mapped information, geological cross sections and stratigraphic columns, and details of the most outstanding outcrops (Figs. I–XII in Electronic Appendix). The Ebro River level and the height of the terrace levels is provided in metres above mean sea level (a.s.l.) given that the dams and water reservoirs of Flix and Riba-roja, as well as other civil works that channelized the river changed the natural river levels.

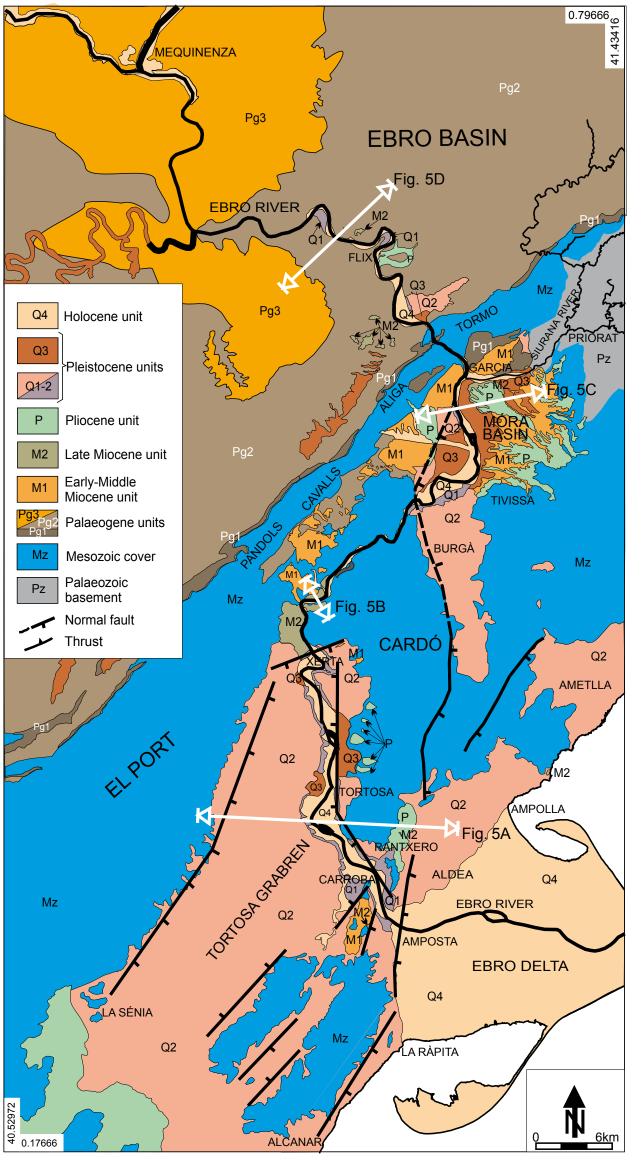


**FIGURE 2.** Geological sketch of the study area indicating the location of the geological cross sections A to D in Figure 5. More detailed mapping of the allostratigraphic units is provided in the Electronic Appendix, figures I to XII.

## CENOZOIC-QUATERNARY STRATIGRAPHY

On the SE Ebro Basin margin zone and in the Móra Basin sectors, before the compressive deformation reached the area and the present margin of the basin was structured, the Cenozoic sedimentation started with the Palaeocene-Eocene Cornudella group (Pg1), which includes 180 to 200m-thick sequences made of mudstones, evaporites, sandstones and lacustrine limestones (Figs. 2; 3). The facies distribution and the palaeocurrent data indicate the development in this area, of distal alluvial plains and evaporitic mud-flats fed from source areas located in the inner zones of the CCR Orogen (Colombo, 1980, 1986).

The late Eocene to latest Oligocene-earliest Miocene Scala Dei group (Colombo, 1980, 1986; Pg2a) unconformably overlies the Cornudella group in the marginal zones of the Ebro Basin. It consists of carbonate and siliceous clast–dominated alluvial conglomerates, sands and mudstones (Figs. 2; 3) and pass basinward into carbonate, mudstone- and sandstone-bearing sequences of the lacustrine Los Monegros group (Pg3), which in this area is mainly late Oligocene in age (Cabrera, 1983; Cabrera and Sáez, 1987; Arenas and Pardo, 1999; Barberà *et al.*, 2001; Cabrera *et al.*, 2002; Valero *et al.*, 2014). These syntectonic alluvial sequences were folded and some growth strata occur (Lawton *et al.*, 1999). The uppermost syntectonic alluvial conglomerates in the area (Rocas del Benet outccrops) are probably Earliest Miocene

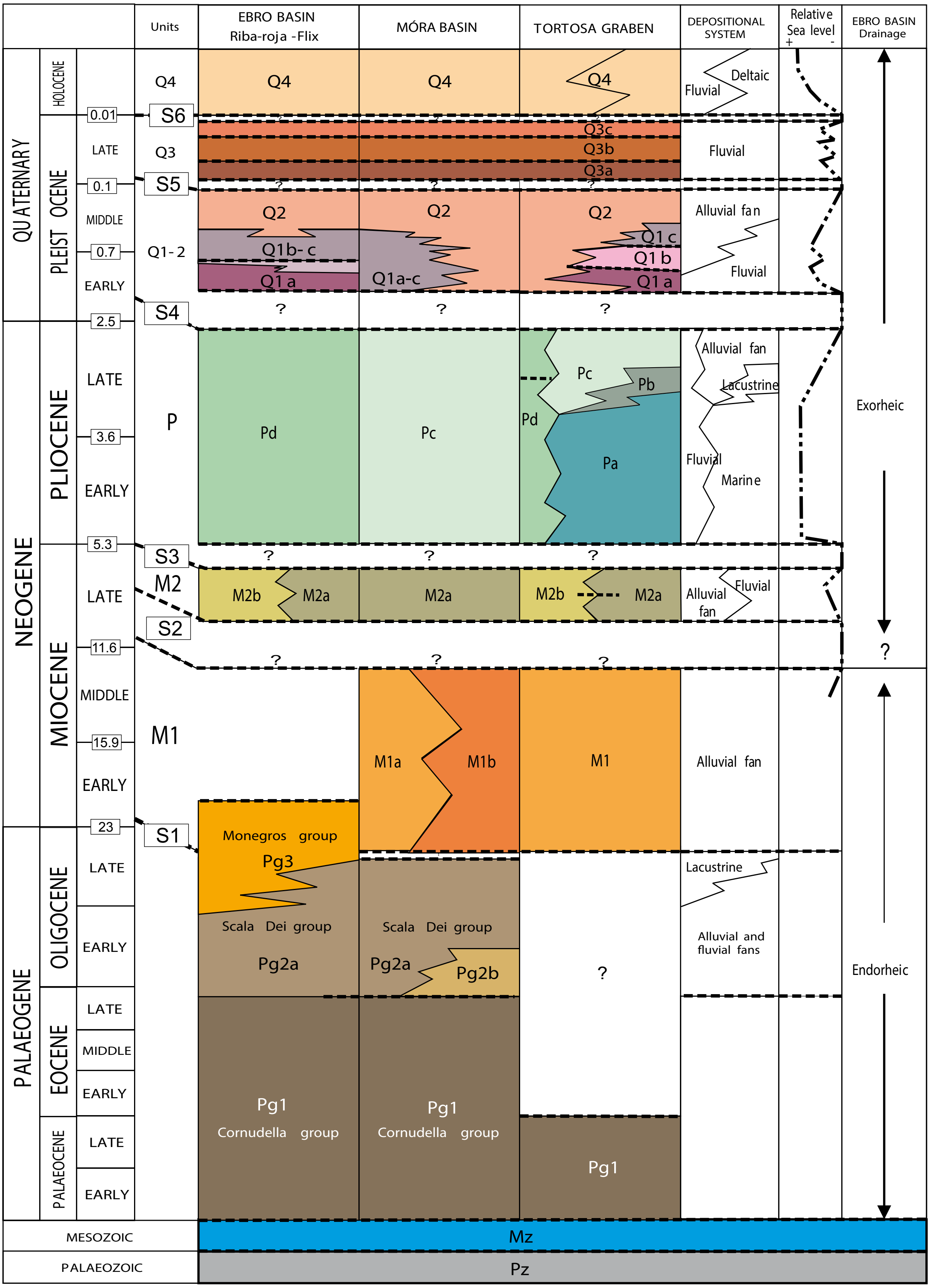


**FIGURE 3.** Stratigraphic chart showing the correlation of the allostratigraphic units, depositional systems recorded in each unit, the relative sea level changes, and the change of the Ebro Basin drainage system from closed to open basin conditions. See further explanation in the text.

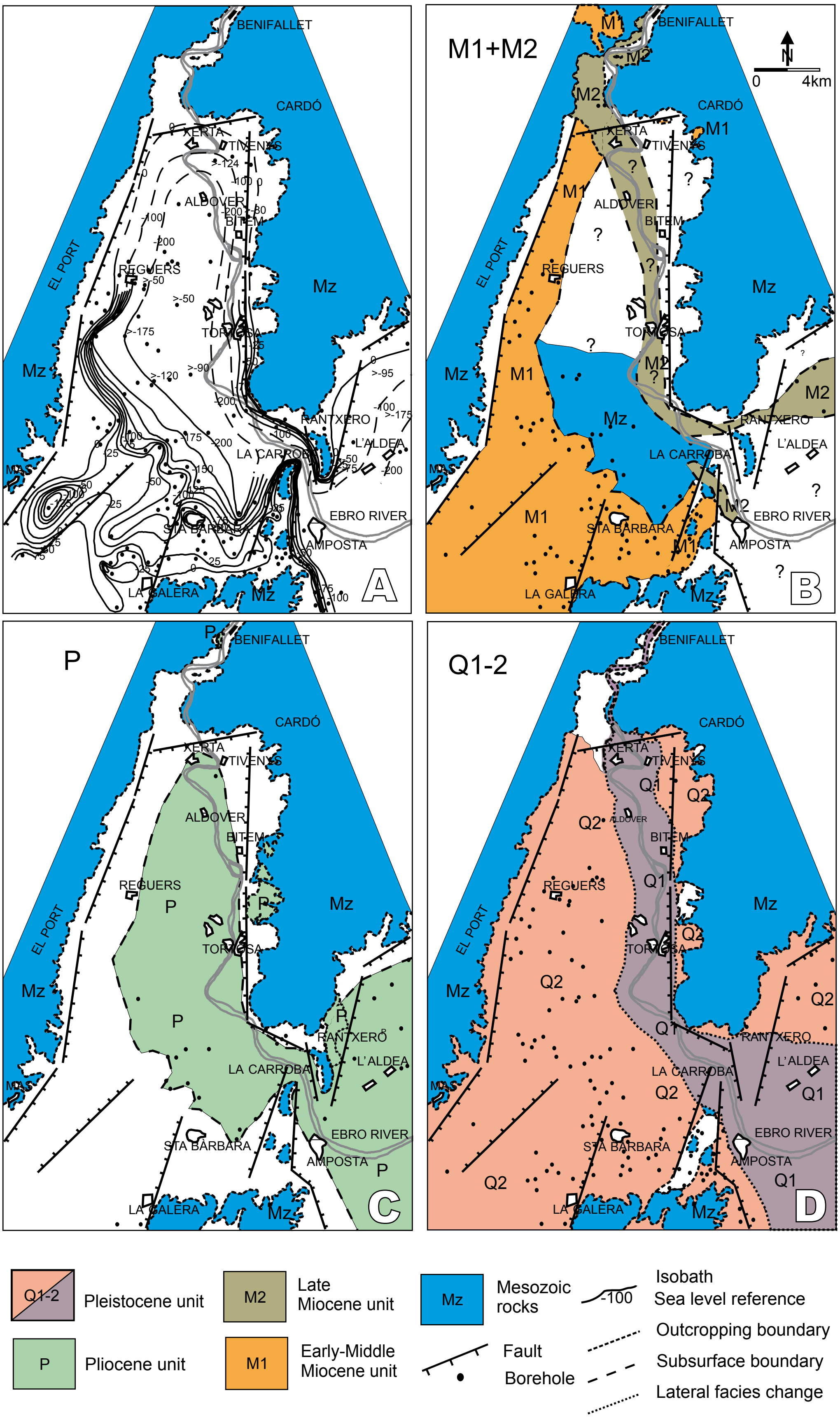


**FIGURE 4.** See figure caption in the next page.

in age. These conglomerates unconformability overlie the Mesozoic substratum infilling a paleorelief and showing a sub-horizontal or very slightly titled arrangement. These late-postorogenic conglomeratic deposits currently occur between 700 and 1000m of altitude.

In the Móra Basin, the alluvial deposits of the Scala Dei group unconformably overlie an erosion surface developed on the Cornudella group (Figs. 2; 3). The Scala Dei alluvial facies in this basin (Pg2b) mainly consist of Palaeozoic siliceous clast, Lower Triassic and Mesozoic carbonate clastics from source areas located in the Priorat. Unit Pg2a is also represented by carbonate clast–bearing conglomerates (Figs 2; 3; García Boada, 1974; Anadón *et al.*, 1979, 1983; Colombo, 1980, 1986; Guimerà, 1984; Teixell, 1985, 1988; Guimerà and Alvaro, 1990).

Further South, in the Tortosa Graben area, the Palaeogene record only includes a thin, *Vidaliella gerundensis*-bearing breccia and a pisolite bearing mudstone unit that is attributed to the Thanetian (Figs. 3; IVA; Canerot, 1974; Fonollosa, 1976; Santanach *et al.*, 1980; Arasa-Tuliesa, 1990).

The latest Oligocene-Neogene and Quaternary sequences in the lower Ebro occur unconformably overlying the Palaeozoic basement and the Mesozoic and lower Palaeogene cover in the Ebro Basin (Flix area), the Móra Basin and Tortosa Graben (Figs. 2; 3; Arasa-Tuliesa, 1990). This record is not continuous and was largely influenced by the development of six major erosion surfaces (S1 to S6) that were deeply eroded into the pre-existing stratigraphic successions.

The outcrop distribution of the mainly latest Oligocene-Neogene and Quaternary allostratigraphic units is shown in a geological sketch (Fig. 2) and a stratigraphic chart (Fig. 3). This information is complemented with a map showing the Mesozoic isobaths and the subsurface distribution of some of the units described in the Tortosa Graben and the sector located immediately to the North (Fig. 4). The synthetic geological sketches show the main stratigraphic and morphological relationships between the various depositional units and erosion surfaces (Figs. 5 and 6). This synthetic information is enlarged and completed with the maps, cross sections and related data description of the stratigraphic units contributed in the Electronic Appendix (see Figs. I to XII).

## Late Oligocene-Quaternary erosion-bounding surfaces

### *Surface S1*

The erosion surface S1 is overlaid by the unit M1. This surface affects both the Mesozoic and the eroded Palaeogene cover, including the deposits of the Cornudella (Pg1) and Scala Dei groups (Pg2a-b), which are affected by extensional tectonics in the Móra Basin and the Tortosa Graben (Figs. 3–6). S1 is time transgressive since it was generated in relation to diverse structural processes in the CCR. In the Móra Basin S1 was generated before the basin split away from the Ebro foreland Basin. S1 has been also recognized in the Tortosa Graben where it records the pre-rift Palaeogene erosive processes (Figs. 3; 6).

### *Surface S2*

The erosion surface S2 is the most deeply entrenched in the lower Ebro and it was cut downwards through its bed into the Mesozoic cover (Mz), the Palaeogene successions (Pg) and the unit M1 (Figs. 2; 3). This surface is the earliest preserved palaeovalley incision and it impinged at least 70km upstream of the present coast line as far as the Flix area, in the SE Ebro Basin marginal zone (Fig. 6). It crops out also in the Móra Basin, Benifallet zone and Tortosa Graben. In the lower river tract (at Xerta) S2 is entrenched down to 0m-a.s.l. into Mesozoic materials (Figs. 3; 5B; 6).

**FIGURE 4.** Overall major structures and Miocene to Early Pleistocene stratigraphic record of the Tortosa Graben. A) Isobaths of the Mesozoic in relation to sea level. Although lower resolution of the isobath traces occurs in the northern and eastern marginal graben zones they show the existence of an incised palaeovalley whose bottom erosion surfaces reached the lower Miocene sequence (unit M1) and the underlying Palaeogene and Mesozoic cover rocks. Notice the threshold developed at the SW of the study zone at La Carroba-Rantxero sector. B) Distribution of unit M1 (Early-Middle Miocene) and M2 (Late Miocene). Unit M1 was mainly syntectonic and infilled the graben. Unit M2 is made of marginal alluvial-fan and fluvial deposits that infilled a bedrock-alluvial mixed palaeovalley deeply incised in the Mesozoic-Palaeogene cover and in the Early-Middle Miocene deposits of unit M1, as can be observed at the northern end of the Tortosa Graben (Fig. 5A). To the North of Xerta, the palaeovalley is perfectly traceable since it erodes Mesozoic substratum and unit M1 rocks (Fig. 5B). The trace of the palaeovalley could have been conditioned by the activity of El Port normal fault. The depth of the palaeovalley, which cuts the Mesozoic basement, is entrenched down to 0m msl. In the southern part of the Tortosa Graben (Rantxero area) Unit M2a filled the palaeovalley excavated in both Mesozoic materials and unit M1 (Fig. IIID in Electronic Appendix,). To the North of l'Aldea, in borehole 522-2-19, unit M2a underlies the blue marine mudstones of the early Pliocene Pa marine assemblage (see Figs. 5A; IXC, D in Electronic Appendix). The palaeo-Ebro shows in this sector a North-eastward trend near the present coast line, as evidenced by the outcrops of Capelo North of l'Ampolla (Figs. 2; V in Electronic Appendix). C) Distribution of unit P (Pliocene-Early Pleistocene?). During the Pliocene and perhaps the Early Pleistocene the lower part of the palaeovalley as far as 45km from the present coast line became a depositional sink (transitional-marine embayment) where a transgressive-regressive sequence developed. An estuarine-deltaic depositional framework topped by the development of marginal alluvial fans deposits gave rise to up to a few hundred m-thick palaeovalley infill. Notice the persistence of the threshold at the SW of the study zone at La Carroba-Rantxero sector. D) Distribution of subunits Q1 and 2 (Early-Middle Pleistocene). These subunits consist of interfingering fluvial (Q1), and alluvial fan facies assemblages (Q2) and makes up a well-established terrace level. The Q1 fluvial assemblage overlies the S4 erosive Surface that is often entrenched into the Pliocene blue-grey mudstones (Pa). The alluvial fan facies (Q2) coalesced and spread from the surrounding reliefs.

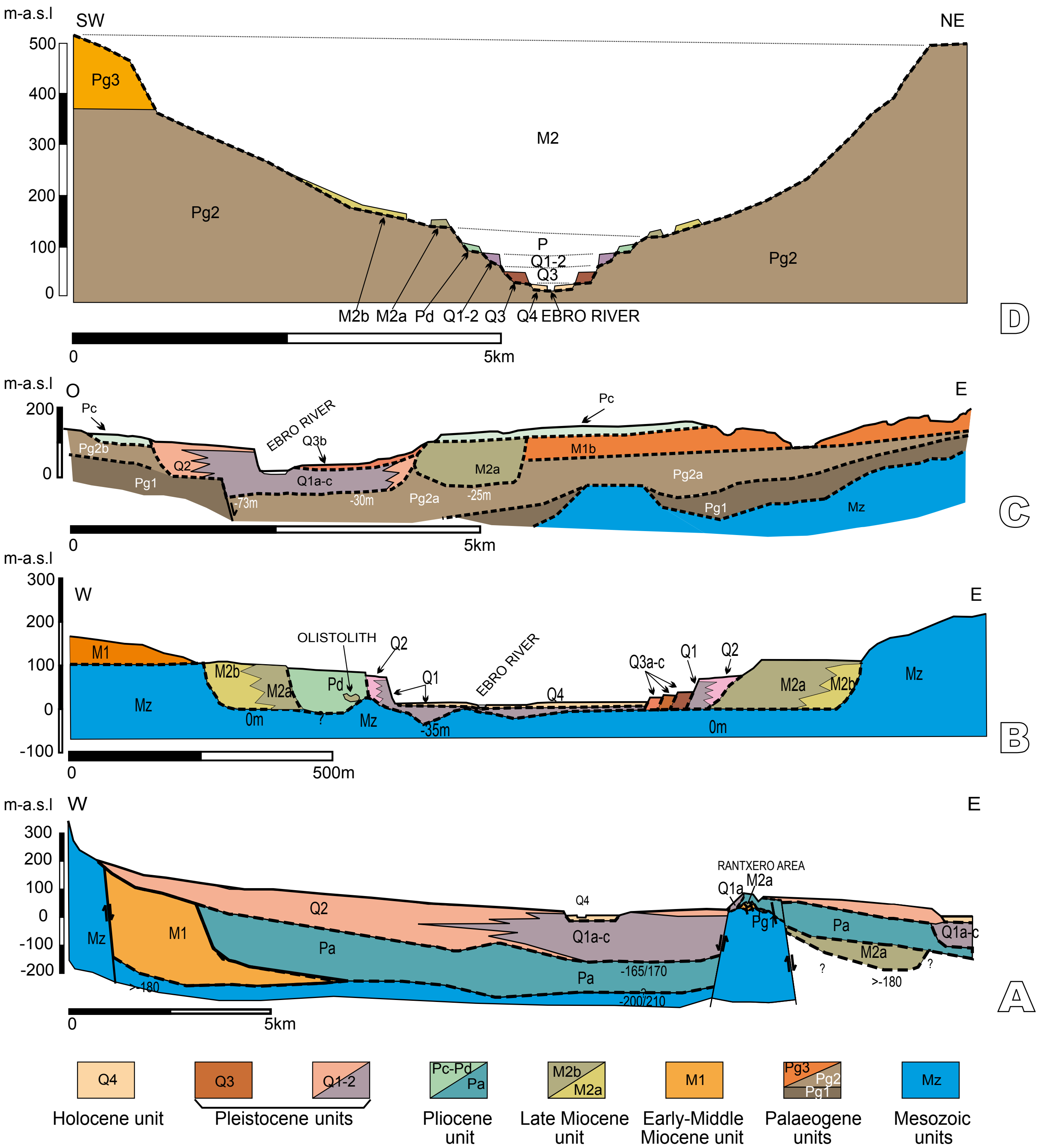


**FIGURE 5.** Synthetic geological cross sections showing the geometric relations and relative chronology of the described allostratigraphic units. See Figure 2 for location of the cross sections and Figure 6 for further information on the eroded surfaces S1 to S6. A) Tortosa Graben: In the Rantxero area the Late Miocene fluvial assemblage of unit M2 (M2a) fille the palaeovalley excavated in the rocks of both Mesozoic and Early-Middle Miocene unit M1 (see Figs. I; II; IIID; IX in Electronic Appendix). B) To the North of Xerta: The palaeovalley eroded the Mesozoic substratum and the Early-Middle Miocene rocks of unit M1 (Figs. I; VI; VIIC in Electronic Appendix). Depth of the eroded? bottom paleovalley is up to 0m-a.s.l. In Benifallet, M2a olistoliths occur at the bottom of the Pliocene unit Pd and were eroded, after this the subunits were sedimented Q1-2, there are attributed to the Early-Middle Pleistocene (Figs. VI; VIIB in Electronic Appendix). C) Móra Basin: Unit M2a fills palaeovalley incised into units M1 and Pg2 and with its deposits ranging from -25 to 115m-a.s.l. Units Pg2 and M1 reach absolute altitude levels of around 200m-a.s.l. and 300m-a.s.l., respectively, and the valley shows a maximum recognized incision of around 450m in the CCR (see Figs. I; X; XI in Electronic Appendix). D) Flix area: The Ebro Basin shows a maximum recognized incision of around 500m. The deposits of unit M2a ranges from 105 to 150m-a.s.l. and the equivalent alluvial fans (M2b) are recorded from 250m-a.s.l. up.

### *Surface S3*

The erosion surface S3 developed on the top of unit M2 and also affected the Mesozoic cover (Mz), the Palaeogene successions (Pg) and the mainly Miocene units M1 and M2. S3 has been recognized from the SE sector of the Tortosa Graben as far as the SE marginal zones of the Ebro Basin (Figs. 2 and 3). Thus, this erosion surface also impinged at least 70km upstream of the present coast line as far as the Flix area, in the SE Ebro Basin marginal zone. In spite of this wide areal extent it did not reach an entrenchment as significant as S2 (Fig. 6).

### *Surface S4*

Erosion surface S4 underlies the Pleistocene Ebro terrace materials incised mainly in the older Miocene and Pliocene units and has been correlated with the "G" reflector on the continental shelf (Farran *et al.*, 1984; Maldonado *et al.*, 1986). In the lower river tract (at Benifallet) S4 is entrenched down to -35m-a.s.l. into Mesozoic materials. Considering the available data, it is deduced that the onshore surface S4 resulted from the river incision during the Early Pleistocene into the unit P deposits (Fig. 6).

### *Surface S5*

This erosion surface underlies the Q3 Ebro terraces incised mainly into the older Miocene, Pliocene and Q1-2 units (Fig. 3). In the upper river tracts (at the Flix sector in the Ebro Basin) S5 is entrenched down into Q1-2 and the erosive bottom of unit Q3 is located between minimum 30 and maximum 60m-a.s.l., although the maximum incision has not been well established. In the Móra Basin sector S5 is entrenched down to 29m into Q1-2 and the erosive bottom of unit Q3 is located between minimum 24 and maximum 55m-a.s.l. In the lower river tract (at Vinallop between Aldover and Amposta) S5 is entrenched down to 35m into Q1-2 and the erosive bottom of Q3b is located between minimum 8 and maximum 10m-a.s.l. (Fig. 6). Considering the available data, it is proposed that the onshore surface S5 was incised during the Middle-Late Pleistocene.

### *Surface S6*

This erosion surface affected the youngest Ebro terrace materials incised mainly into the older Quaternary terrace deposits (Figs. 3; 6). Considering the available data, it is proposed that the onshore surface S6 was eroded during the Early Holocene (Arasa-Tuliesa, 1994a; Somoza *et al.*, 1998; Pérez-Obiol *et al.*, 2011). In the Tortosa Graben S6 is entrenched between -10 (at Tortosa) and -15m (at Amposta) bmsl and at -51m bmsl at the mouth of the Ebro River (Somoza *et al.*, 1998).

## Allostratigraphic units

### *Unit M1*

The unit M1 was deposited on top of the late Oligocene-Early Miocene unconformity (S1) and its top was affected by the deeply entrenched erosion surface S2 (Fig. 3). This unit encompasses carbonate clast conglomerates and red mudstones organized in fining-upward sequences. In the study area, M1 unconformably overlies both the eroded Mesozoic and Palaeogene cover, including the deposits of the Cornudella (Pg1) and Scala Dei groups (Pg2a-b). Also, its top was affected by the erosive processes that resulted in the erosion surfaces S2 and S3 and is unconformably overlain by deposits of units M2 and/or Pa (Figs. 2–5; IVB).

In the Tortosa Graben, unit M1 is deposited on Mesozoic and Palaeogene materials affected by the early phase of rifting in the western Mediterranean, and these materials are tilted in the subsequent activity of extensional faults. The sequences of M1 attain in this graben their maximum reported thickness (300m, borehole 521-7-3; Figs. 2; 4A; 5A; I; II; IVC and cross sections A to C in Fig. IX in Electronic Appendix).

In the Móra Basin, the M1 sequences are arranged mainly sub-horizontally. The sequences that encompasses carbonate clast conglomerates in unit M1a attain up to 100m in thickness and pass laterally basinward into red mudstones (M1b assemblage) (Teixell, 1985, 1988; Arasa-Tuliesa, 1994a; Figs. X; XI in Electronic Appendix). The top of these sequences currently occur up to 250m-a.s.l.

The M1 deposits record deposition on proximal-middle to distal alluvial-fan zones fed by relatively local drainages with local source areas in the CCR. The middle-distal alluvial fan deposits can be split into channelized flood plain and distal-marginal mud-flat palaeoenvironments. The unit M1 records the latest Oligocene and Early to Middle Miocene intramontane alluvial fan sedimentation in the CCR, previous to any major regional drainage entrenchment.

### *Unit M2*

The unit M2 was deposited overlying the major erosion surface (S2). In turn, its top was affected by the erosion surface S3 (Fig. 3). It consists of two main terrigenous facies assemblages (M2a and M2b) that show a close interfingering in the areas where extensive outcrops can be analysed (Figs. 2; 3; 5; VI–VIII in Electronic Appendix).

The lateral extent and preserved thickness of the outcrops attributed to this unit are sometimes limited and their correlation may be difficult. However, they occur

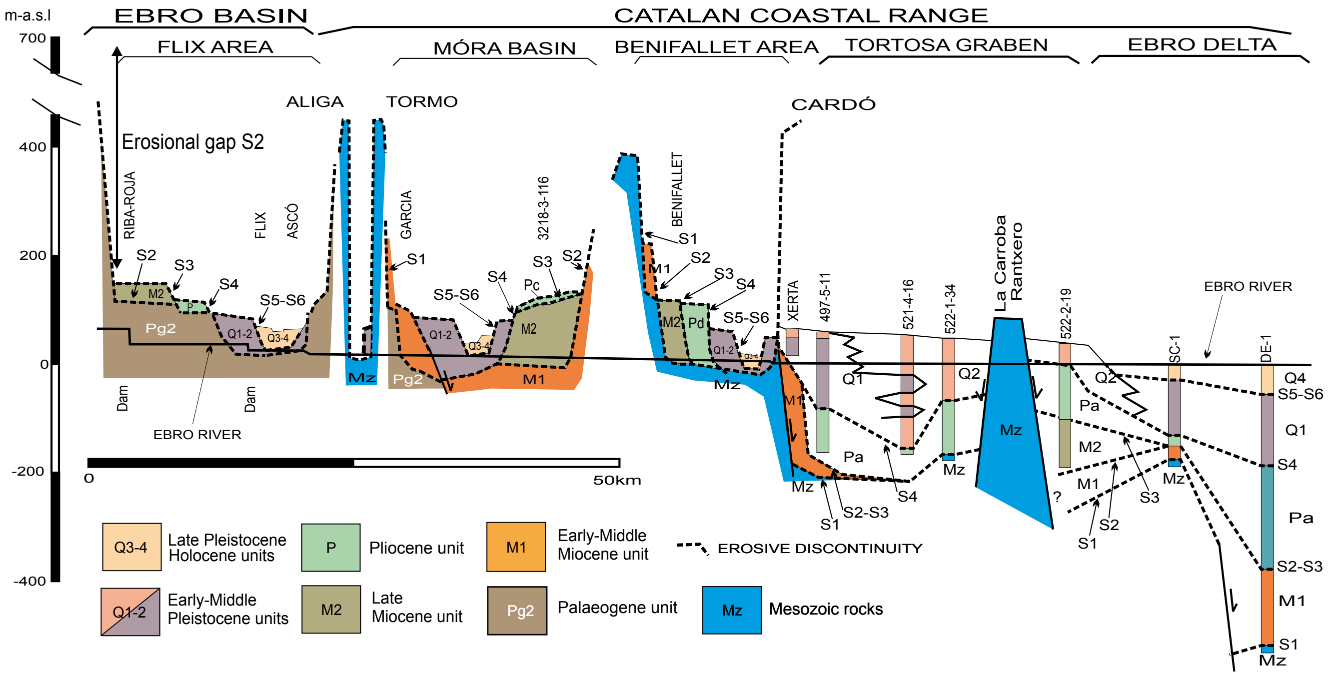


**FIGURE 6.** Synthetic cross section showing the current arrangement of the eroded surfaces and the allostratigraphic units in the study area. The sectors shown in this figure have experienced differential isostatic uplift that has modified the original altitudinal position of the diverse elements. Surface S1: This erosion surface affects both the Mesozoic and the Palaeogene cover from the Móra Basin to the Ebro Delta and can be traced as far as the offshore zones. Surface S2. Flix area: The erosion surface S2 ranges from 105 to 140m-a.s.l. and the alluvial fan deposits of M2b are recorded from 250m-a.s.l. Considering the altitude of the surrounding tablelands excavated in the Oligocene successions (565m-a.s.l.) and the missing eroded sequences equivalent to those that can be recorded in inner basin zones, (*i.e.* Mequinenza area; with some additional 100m (Cabrera and Sáez, 1987), this could mean a valley incision from the basin fill top of about 560m. The further incision of the erosion surface S3 into unit M2 would mean 15 to 20m of additional entrenchment that would reach near 600m. Móra Basin: Unit M2a filled a palaeovalley incised into units M1 and Pg2 and with its deposits ranging from -25m-a.s.l. (surface S2) to 115m-a.s.l. (unit M2 top). Considering the altitude of the top of the basin fill sequences of M1 (between 260 and 300m-a.s.l.) this would mean a valley incision ranging at least from 290 to 325m. Benifallet area: The palaeovalley eroded the M1 unit and the Mesozoic basement that cuts to 0m-a.s.l. (Figs. 4B; 5B). Considering the altitude of 250m of the preserved top of unit M1 this could mean a valley incision of at least 300m. The further observed incision of the erosion surface S3 into unit M2 would be close to 100m and was followed by the sedimentation of up to 100m-thick sequences of unit P. Tortosa Graben (Rantxero area): The unit M2a filled the palaeovalley excavated in both Mesozoic materials and unit M1 (Fig. IIID in Electronic Appendix). Moreover, to the North of Aldea, up to 80m of siliceous clast bearing fluvial deposits that underlay the marine deposits of unit Pa were recorded at the well 522-2-19 from -100 to -180m-a.s.l. (Fig. IXD in Electronic Appendix) This would be the maximum depth recorded in subsurface, although it must be considered that this area was affected by extensional tectonic subsidence. See location of boreholes in Figures IX and XI in Electronic Appendix. Surface S3: The erosive processes related to the fluvial valley entrenchment would have dominated the development of S3 in the upper parts of the palaeovalley, while the later ravinement erosive reworking related to the Early Pliocene transgression could be more significant at the lower palaeovalley tracts in the Tortosa Graben (Fig. IVB, E in Electronic Appendix). Flix area: The incision of S3 into unit M2 reached up to 20m. Móra Basin: S3 is affecting some thin alluvial fan deposits directly derived from the erosion of the CCR relieves. Benifallet area: S3 shows an incision into unit M2 close to 100m. In this zone the Pliocene marine sedimentation did not develop, but M2a olistoliths occur at the bottom of the Pliocene unit Pd pointing to the existence of a significant erosion surface. This assemblage is in turn eroded by the unit Q1-2 attributed to the Early-Middle Pleistocene (Arasa-Tuliesa, 1994a; Arasa and Colombo, 1995; Figs. 5B; VI; VII in Electronic Appendix). Tortosa Graben: The S3 surface has been recorded in some wells in the between -190 and -210m depth recording a minimum entrenchment of 200m. S3 is overlain by the Pliocene transgressive-regressive sequence (unit P) that includes transitional (Figs. IV B, E in Electronic Appendix), marine alluvial and lacustrine deposits whose upper levels could attain the Lower Pleistocene. Surfaces S4 to S6: Are Pleistocene to Holocene in age and record the younger incision processes of the lower Ebro. Surface S4 is the most incised of these recent erosion surfaces and is correlated with the offshore "G" reflector (Farran *et al.*, 1984; Maldonado *et al.*, 1986). Surface S5 is less entrenched than the former one. Flix area, S5 is entrenched into Q1-2 and the erosive bottom of the overlying unit Q3 is located between minimum 30 and maximum 60m-a.s.l., although the maximum incision has not been well established. Móra Basin sector, S5 is entrenched down to 29m into Q1-2 and the erosive bottom of unit Q3 is located between minimum 24 and maximum 55m-a.s.l. Tortosa Graben (Vinallop between Aldover and Amposta) S5 is entrenched down to 35m into Q1-2 and the erosive bottom of Q3b is located between minimum 8 and maximum 10m-a.s.l. Surface (S6) is incised mainly into the older Quaternary terrace deposits. In the Tortosa Graben S6 is entrenched between -10 (at Tortosa) and -15m (at Amposta) bmsl and at -51m-bmsl at the mouth of the Ebro River (Somoza *et al.*, 1988).

throughout the three sectors of the study area (Tortosa Graben, Móra Basin and Flix area of the Ebro Basin). Despite the dispersal of these outcrops, most of them display some characteristics that help to gather them into a single unit and to distinguish them from other units with similar lithology:

i) The eroded bottom of this unit (S2) often affected the Mesozoic and Palaeogene cover as well as unit M1, considering the whole area (Fig. 5B).

ii) The clast composition with widespread occurrence of siliceous and/or carbonate clasts is very similar in all the reported outcrops (60% of brown quartzite, quartzite with quartz veins, and milky quartz; 15% of slates and schists; 5% of granitoids; 5% of Lower Triassic conglomerate (Buntsandstein facies), 10% of Mesozoic carbonate; 4% of Ilerdian Alveolina limestone; 1% of sedimentary cherts). The lithology of the siliceous and carbonate clasts indicates the Pyrenean provenance of a significant percentage. In the CCR, quartzites are scarce and only occur thinly interbedded with slates and cherts (Colodrón *et al*., 1978; Sáez and Anadón, 1989), and their facies appearance is totally different from those that were fed from the Pyrenees. Therefore, the clasts of massive quartzite with quartz veins reported in unit M2 have been described in the Cambro-Ordovician of the axial zone (García-Sansegundo, 1991) and are good evidence to establish the Pyrenean provenance from either the orogen or the foreland alluvial conglomerates that bear them.

iii) The top of the unit is affected by an erosion surface (S3) overlain by marine (Pa) or non-marine deposits attributed to unit P, although the superposition of successive younger erosion surfaces caused the top of M2 to be also overlain by younger Pleistocene units (Q1-2) (Fig. VIII in Electronic Appendix).

In the northern part of the Tortosa Graben, to the North of Xerta, M2b consists of interbedded red mudstones and coarse-grained conglomerate and breccious conglomerates dominated by carbonate pebble, cobble and boulder clasts. Some reddened palaeosoils occur in the mudstone facies. These coarse-grain-dominated sequences resulted from the sedimentation on alluvial fans fed from close, local CCR source areas. These alluvial fan systems show eastward and westward palaeocurrents depending on their catchment location at one of the valley sides. In this zone the fluvial assemblage M2a is made up of an assemblage of siliceous and carbonate clast-bearing conglomerate, sandstone and mudstone, which are up to 80m-thick (522-2-19 borehole) and attain up to 118m-a.s.l. The recorded palaeocurrents show southward sedimentary transport for these facies that are interpreted as fluvial valley infill deposits. The top of the M2a and M2b assemblage in Xerta is unconformably overlain by siliciclastic deposits of allostratigraphic units P and Q1-2. Minor extensional faults affected these deposits (Figs. IIIE; IVD, E in Electronic Appendix).

The interrelationship between M2a and M2b, their depositional characteristics and the morphological relationships shown with the surrounding substratum rocks suggest that M2a deposits record the existence of an Ebro palaeovalley entrenched into Mesozoic carbonates and M1 conglomerates (Bomer, 1976; Arasa-Tuliesa; 1994a) (Figs. 2, 4, 5B, VI and VII in Electronic Appendix).

In the southern Tortosa Graben the M2 unit occurs affected by the surface S3 and by minor extensional faults (Arasa-Tuliesa, 1990, 1994a; Figs. I; II; IIIA, D, E; IVD–F; IX in Electronic Appendix). The relatively thick accumulation of fluvial M2 facies suggests a significant subsidence and/or the generation of accommodation space related with the deeply incised erosion surface S2 (Figs. 5A; 6; IX in Electronic Appendix).

In the Móra Basin (Figs. 2; 3) the unit M2 includes siliceous clast–bearing conglomerates and gravels contributed both by the Ebro and the Siurana rivers. In the higher terraces (110m-a.s.l.) of the Siurana River, Palaeozoic and Mesozoic clasts from the El Priorat CCR basement occur (Figs. 2; X; XI in Electronic Appendix). The top of these deposits is affected by the erosion surface S3 and overlain by alluvial fan deposits attributed to unit Pc (Figs. 2; 3).

In the Ebro Basin (Flix area) a variety of siliceous and carbonate clast–dominated gravels, conglomerates and breccias occur (Fig. 5D). Considering that these aluvial fan and equivalent fluvial sediments were deposited on the erosion surface S2 they are attributed to the M2a-M2b unit.

### *Unit P*

The unit P was deposited overlying the erosion surface (S3). In turn, the top of this unit was affected by successive Quaternary erosion surfaces (S4 to S6) that preceded the deposition of the successive Quaternary valley-fill terraces (Arasa-Tuliesa, 1990, 1994a) (Figs. 3; 4; 5A; II; IIID–E; IVE–G in Electronic Appendix).

Unit P was mainly recorded in the Tortosa Graben, where the main outcrop and subsurface data indicate its extensive development (Figs. 2–4). However, it is proposed here, on the basis of geomorphological criteria, that the non-marine Pliocene record can be extended to some upper tracts of the lower Ebro valley, the Móra Basin and the closer sectors of the Ebro Basin (Flix area).

In the Tortosa Graben, between Xerta and l'Aldea in the La Carroba-Rantxero area (Figs. 2; II; IIID–E; IVB, E–G in Electronic Appendix), a transgressive-regressive sequence constitutes this unit. The transgressive assemblage includes bottom-lying, 3m-thick bioeroded gravels affected by normal synsedimentary faulting, which are overlain by 40m-thick blue marls with sandy interbeds, widespread benthic microfauna and malacofauna (Magné, 1978; Martinell and Domènech, 1984; Arasa-Tuliesa, 1990; Masana, 1995). The regressive assemblage encompasses 35m-thick palustrine carbonate (Pb) with rodent microfauna (Agustí et al, 1983) and 55m-thick carbonate clast–dominated red conglomerates with "Microcodium" and carbonated crusts (Pc). The Pliocene marine assemblage (Pa) was recorded in several boreholes making up the filling of a major Ebro palaeovalley. At the axis of this main palaeovalley, the Pliocene sediments overlie mainly Mesozoic carbonates affected by a palaeokarst. Some deep boreholes (*i.e.* 497-5-11 near Tivenys; Fig. 4C) allowed us to establish the northernmost record of the Pliocene marine facies in the graben. At the palaeovalley margins the Pliocene deposits overly M1 conglomerates (Figs. 4C; 5A; IX in Electronic Appendix). The whole transgressive-regressive sequence records early Pliocene transitional and marine sedimentation in a deeply incised palaeovalley that became a marine embayment which was later gradually infilled by progradational-aggradational delta, fan-delta and alluvial fan systems.

In Benifallet, on the right bank of the Ebro River (Figs. 2–4), there is a 75m-thick alluvial assemblage (Pd). These deposits unconformably overly Mesozoic and M1 and M2 unit rocks and are affected by an intraformational erosive discontinuity associated with minor extensional faults that tilted the sequence and include olistoliths derived from unit M2a. (Figs. 5B; VI; VIIB in Electronic Appendix) and is interpreted as incised valley fluvial deposits with probable lateral alluvial fan contribution.

In the Móra Basin, the mapping review enabled us to carry out geological cross sections based on the digital terrain model and to establish some relative chronology for the distinguished deposits and geomorphological units. As a result, it is worth mentioning the ancient alluvial fan deposits (Pc) that unconformably overly the M1b and M2a assemblages and could be attributed to the Pliocene (Figs. 2; 5C; X; XI in Electronic Appendix).

In the Flix area has been reported a fluvial episode recorded by fluvial incision and the sedimentation of silts and sands in a fluvial meander. This structure is affected by an erosion surface (S4) that is in turn overlain by Pleistocene Q1-2 deposits (Figs. 2; 5D; XII in Electronic Appendix). Therefore, a Pliocene age is here proposed for it.

### Unit Q1-2

This unit was deposited overlying the erosion surface (S4). In turn, its top was affected by the erosion surfaces S5 and S6 (Fig. 3). It consists of terrace deposits incised mainly in the older Miocene and Pliocene units. In several sectors of the study zone, this unit is constituted by two interfingering main facies assemblages, Q1, a fluvial assemblage, and Q2, an alluvial fan assemblage (Figs. 2; 3; 4D; 5; VIII–XI in Electronic Appendix). Considering the clast composition of this unit in percentage, it appears to be very similar to those described on the higher, middle and lower terraces of the Segre and especially the Cinca rivers (Peña, 1988; Peña and Sancho, 1988). Meanwhile, Q2 records the development of local coalescing alluvial fans fed from the surrounding reliefs that linked morphologically with the fluvial terrace levels.

Q1-2 is well developed in the Tortosa Graben and also occurs in the Móra Basin and the Flix area of the Ebro Basin. The outcrop data of the fluvial assemblage Q1 together with the borehole data confirm its lateral-longitudinal extent and thickness along the valley.

In the Tortosa Graben, unit Q1-2 occurs on both Ebro River margins and constitutes a well-developed terrace level. In the Aldover sector (Figs. 2–5; VIIIC in Electronic Appendix), the deposits of this unit are widespread, crop out extensively and have been well recorded in the boreholes drilled in the area. In this area the Q1 assemblage encompasses siliceous and carbonate clast–bearing fluvial deposits that include granitoid, quartzite with quartz veins, chert, slate and Alveolina limestone clasts, among others. These deposits are interbedded with carbonate clast–dominated alluvial fan conglomerates that include major Mesozoic limestone clasts affected by calcareous crusts (Q2 assemblage; Solé *et al.*, 1965; Maldonado, 1972; Orche *et al.*, 1980; Arasa-Tuliesa, 1985, 1994a, 1994b).

In the southern Tortosa Graben, at the La Carroba-Rantxero uplifted block, the siliceous clast–dominated fluvial deposit Q1 was affected by minor extensional faults (Santanach *et al.*, 1980; Arasa-Tuliesa, 1992; Masana, 1995) that record the reactivation of the La Carroba-Rantxero threshold faults. In the rest of the Tortosa Graben, small normal faults with a slip of less than 1m affected the upper part of the alluvial fan facies Q2 (Arasa-Tuliesa, 1994b, 1996; Masana, 1995; Fig. IX in Electronic Appendix).

In the Móra Basin and in the Flix area, Q1-2 equivalent levels of terraces are recognized (Figs. 6; 7D). In the Móra Basin, a single unit of siliceous clast–bearing conglomerates, gravels and sands (Q1a-c) is recognized both at outcrops and boreholes. Between Móra d'Ebre and Benissanet the borehole data allow recognizing the siliceous clast-bearing fluvial conglomerates down to -70m-bmsl.

In the area of Flix two levels of siliceous clast–bearing fluvial units Q1a and Q1b-c configure two terrace levels at 75 and 50m-a.s.l., respectively. These terraces have been correlated to equivalent levels described in the Móra Basin and recorded in Tortosa Graben (Figs. 5D; XII in Electronic Appendix).

### Unit Q3

This unit Q3 was deposited overlying the erosion surface (S5). In turn, its top was affected by the erosion

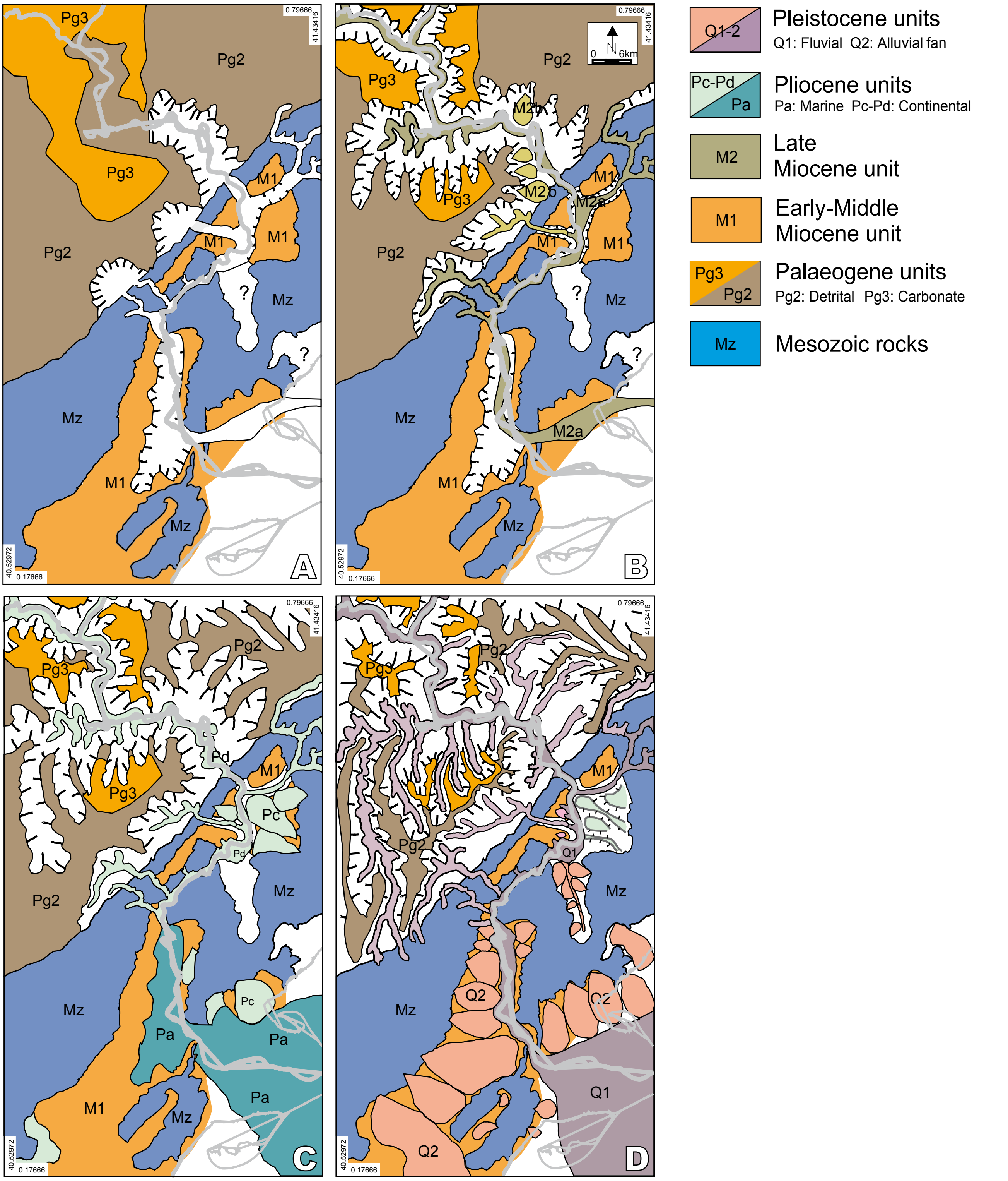


**FIGURE 7.** Palaeogeographic sketches of the Neogene-Pleistocene evolution of the drainage in the lower Ebro valley. The current Ebro River and coastline traces are shown as reference. A) Early stage of headward erosion during the Late Miocene with erosion of the Mesozoic, Palaeogene and early Miocene rocks of Unit M1; B) Development of the alluvial fans and fluvial valley infill of unit M2 (probably Late Messinian) that make up the first preserved depoitional onshore record of the opening of the Ebro Basin. C) Sedimentation of the Pliocene-Early Pleistocene? Unit P. D) Development of the Early-Middle Pleistocene alluvial fans and fluvial valley infill of unit Q1-2. See further explanation in the text.

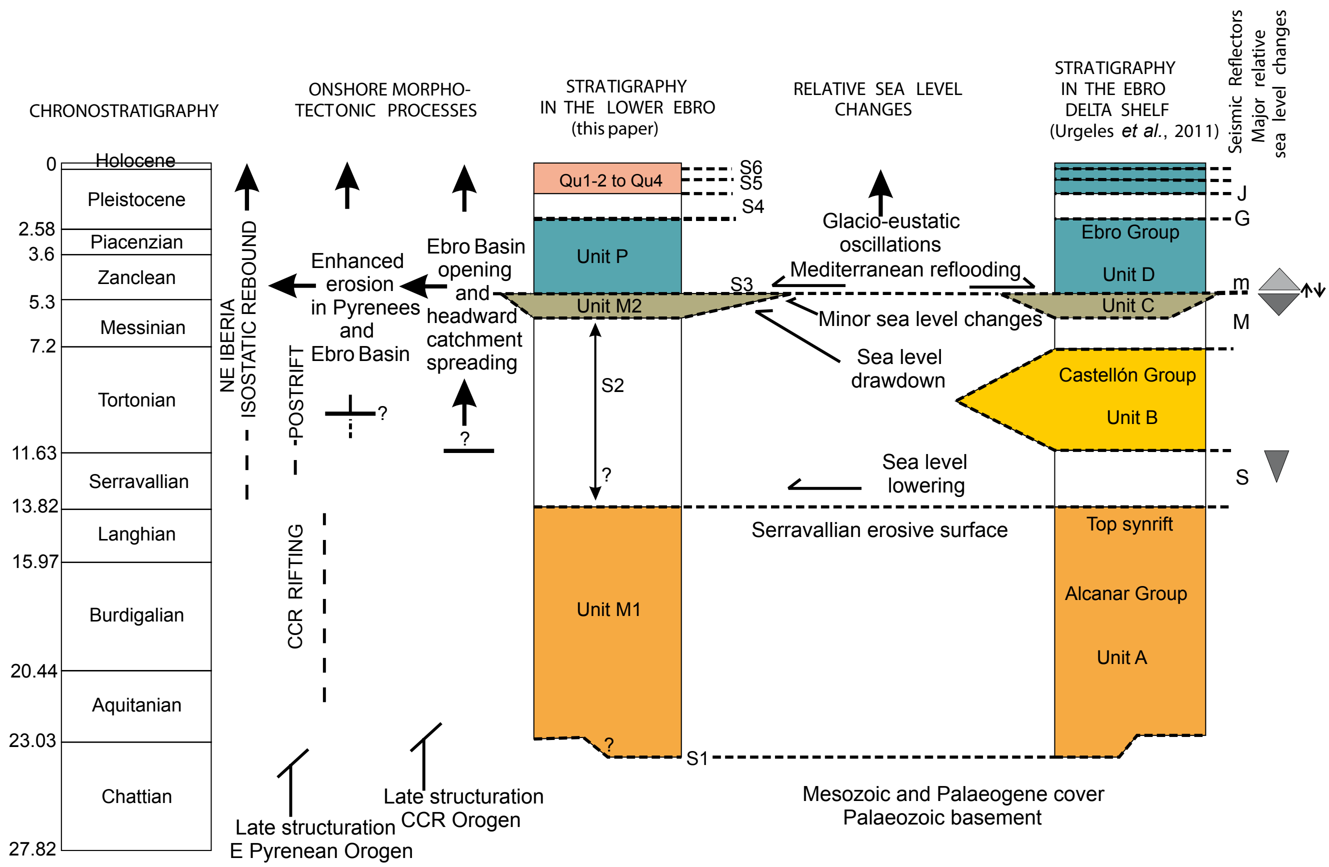


**FIGURE 8.** Correlation between the stratigraphic records of the onshore lower Ebro palaeovalley and the offshore Ebro Delta Shelf in the frame of the main evolutionary processes that affected the region. Onshore morphotectonic processes after Anadón *et al.* (1979); Riba (1983); Gaspar Escribano *et al.* (2001, 2004); García-Castellanos *et al.* (2003); Arche *et al.* (2010); Beamud *et al.* (2011); García-Castellanos and Larrasoaña (2015); Stange *et al.* (2016). Sea level changes after Rouchy and Caruso (2006); Urgelés *et al.* (2011); Bache *et al.* (2012). Offshore stratigraphic record after Soler *et al.* (1983); Farran *et al.* (1984); Maldonado *et al.* (1986); Alonso *et al.* (1990); Alvarez de Buergo and Meléndez-Hevia (1994); Urgelés *et al.* (2011). S, Serravallian erosion surface described in the literature on the onshore stratigraphy. M, G and J some of the major reflectors (erosion surfaces) recorded in the offshore. The reflector "m" corresponds to the minor erosion surfaces described by Urgelés *et al.* (2011) developed on top of their Unit C.

surface S6 (Fig. 3). It is made up of several stepped fluvial terraces incised into the older units. Q3 is well developed in the Tortosa Graben and also occurs in the Móra Basin and the Flix area of the Ebro Basin. The lateral extent and preserved thickness of the deposits attributed to this unit are good enough to enable their correlation along the river valley.

In the Tortosa Graben, three carbonate clast–dominated terrace levees occur (Q3a, b and c). Each terrace level is dominated by clasts of diverse size, and thus Q3a shows a clear predominance of cobble-size clasts, Q3b deposits are mainly pebble-size clasts, and Q3c deposits are mainly sandy (Arasa-Tuliesa, 1992; Figs. 2; 5B; VI in Electronic Appendix). These terrace levels have been correlated with the Late Pleistocene offshore units on the continental shelf affected by extensional tectonics (Farran *et al.*, 1984; Maldonado *et al.*, 1986).

### *Unit Q4*

This unit Q4 was deposited overlying the erosion surface S6 (Fig.3) and integrates the fluvial deposits that fill the present Ebro River valley and form the currently evolving delta where compaction and growth faulting take place (Somoza *et al.*, 1998). Gravel and sand predominate in the river tract between Flix and Xerta, while silt predominates up to the Ebro River mouth (Maldonado, 1972; Colodrón *et al.*, 1979; Orche *et al.*, 1981; Arasa-Tuliesa, 1994b). The incision of this unit reached up to 30m in relation to Q3 and must correspond to the sea level drop related to the last glacial maximum (Würm).

The slope of these deposits corresponds to the present base level of the Ebro River conditioned by the existing dam-water reservoirs. At Riba-roja this level is located at 42m-a.s.l. and 29m-a.s.l. at Ascó. In the Móra Basin, the altitude of Q4 is 20±2m-a.s.l. In the Tortosa Graben, from Xerta to Amposta, the base level descends from 12 to 3m-a.s.l. (Fig. 2).

## Chronology

The dating of the Neogene-Quaternary allostratigraphic units and their bounding surfaces is not always well established due to the absence of direct dating criteria. Consequently, the dating of some of these units will be tentative although supported by evidences such as the overall global-regional sea level trends (Haq *et al.*, 1987; Dañobeitia *et al.*, 1990; Hardenbol *et al.*, 1998; Zachos *et al.*, 2001; Miller *et al.*, 2005), the stratigraphic information derived from onshore and offshore studies in the neighbouring zones of the Catalan continental margin (Bartrina *et al.*, 1992; Corregidor *et al.*, 1997; Roca *et al.*, 1999; Urgeles *et al.*, 2011 and references therein) and the improved knowledge on the complex evolution of the Mediterranean Basin during the Messinian (Clauzon *et al.*, 1996; Gargani, 2004; Rouchy and Caruso, 2006; Maillard *et al.*, 2006; Gargani and Rigollet, 2007; Bache *et al.*, 2009, 2012, 2015; Gargani *et al.*, 2010; Urgeles *et al.*, 2011; Pérez Asensio *et al.*, 2013; Lancis *et al.*, 2015).

### *Unit M1*

On the basis of the age of the youngest deposits affected by compressive deformation in the Ebro Basin and the neighbouring CCR zone (*i.e.* latest Chattian–earliest Aquitanian), in the Móra Basin M1 is considered to be latest Oligocene–early Miocene in age, without ruling out the possibility of a Middle Miocene age for its uppermost deposits (Anadón *et al.*, 1979; Guimerà, 1984; Teixell, 1985, 1988; Arasa-Tuliesa, 1990, 1992, 1996; Arasa-Tuliesa and Colombo, 1995; Masana, 1995). The attribution to the latest Oligocene and Early Miocene of the alluvial-fan dominated Unit M1 is supported by the regional stratigraphic and structural data that constrain the end of compression and the beginning of the extension to that time (Barberà *et al.*, 2001; Merren *et al.*, 2004). The continuation of sedimentation in the Móra Basin during the Middle Miocene is debatable although it is suggested as a plausible possibility considering the tectono-geomorphic characteristics of the CCR by that time.

In the Tortosa Graben, where M1 sedimentation was related to the rifting processes that affected the region, it is mainly attributed to the Early Miocene considering also the possibility of a Middle Miocene age for its uppermost deposits (Arasa-Tuliesa, 1990, 1992, 1996; Arasa-Tuliesa and Colombo, 1995; Masana, 1995). The deposits of the unit M1 in the Tortosa Graben are here correlated with most of the offshore Units A and B (lower part) defined by Urgeles *et al.* (2011).

### *Unit M2 and associated erosion surfaces (S2 and S3)*

No direct chronostratigraphic data are available for unit M2. The deposits here attributed to this unit are incised through S2 in the Mesozoic carbonate cover and in the Palaeogene and the unit M1 sequences (latest Oligocene–Early to Middle? Miocene). The top of the unit was affected by the erosion surface S3 and onlapped by marine and non-marine early Pliocene deposits in theTortosa Graben (Figs. 5A, B; IIID, E in Electronic Appendix).

A chronology proposal for the depositional unit M2 and the related erosion surfaces can be based on the comparison to other onshore records that suggest that the fluvial valley deposits can be attributed to the latest Messinian-Earliest Pliocene time span (Corregidor *et al.*, 1997; Lancis *et al.*, 2015). However, this chronological analysis needs to consider also the Middle and Late Miocene (Tortonian and Messinian) stratigraphic evolution provided from the offshore record in the mediterranean regions and especially from the neighbouring Ebro Delta Shelf (Urgeles *et al.*, 2011).

The Messinian erosion surfaces in the Mediterranean Basin margins resulted from a major sea level lowering followed by several sea level oscillations of diverse range that took place between the first Late Messinian major sea level lowering and the Early Pliocene reflooding. As a result, several erosion surfaces (usually preserved only in the inner Mediterranean Basin zones where Messinian sequences are thicker) developed tending to merge into a single major, erosion surface in the onshore and the marginal offshore zones (Clauzon *et al.*, 1996; Gargani, 2004; Maillard *et al.*, 2006; Rouchy and Caruso, 2006; Bache *et al.*, 2009, 2012, 2015; Pérez Asensio *et al.*, 2013; Lancis *et al.*, 2015).

The existence of successive sea oscillations during the Late Messinian in the Gulf of Lion was emphasized by Bache *et al.* (2009, 2012) and it was also evidenced in the Ebro Shelf by Urgeles *et al.* (2011). These authors describe a major erosive unconformity (reflector M), the development of some Messinian fluvial terraces and the deposition of a thin overlying unit (Unit C), the development of minor erosion surfaces on top of C and finally the sedimentation of Early Pliocene transgressive deposits. The major unconformity M records the Late Messinian sea level major lowering while the overlying deposits of unit C and the erosion surfaces on its top would correspond to later sea level oscillations that immediately preceded the major Early Pliocene flooding. Considering this offshore information the onshore surface S2 is here mainly correlated with the reflector M and a Late Messinian age is tentatively proposed for its latest evolution. The erosion surface S3, which overlies the unit M2 and is directly overlain by the Early Pliocene transgressive deposits, is correlated to the erosion surfaces on top of unit C that resulted from the latest Messinian sea level oscillations that immediately preceded the Early Pliocene reflooding. Consequently, the unit M2 is correlated with the offshore unit C and attributed to the Late Messinian (Figs. 3–8).

The proposed correlation of the preserved surface S2 with the Messinian surface M does not disregard the earlier development (Tortonian or even slightly earlier) of erosion surfaces in the onshore. Several authors (Dañobeitia *et al.*, 1990; Álvarez-de-Buergo and Meléndez-Hevia, 1994) pointed out that significant erosion surfaces developed in the offshore in the Serravallian-Tortonian transition and this process could have been extended later to the onshore as suggested by the unroofing episodes in the Pyrenees dated as mainly younger than 10Ma (Beamud *et al.*, 2011; Fillon and van der Beek, 2012; Fillon *et al.*, 2013). These earlier erosion surfaces would have been related with the earlier sediment transfer from NE Iberia area into the Valencia trough and the sedimentation of the first significant shelf-talus terrigeous progradation system along the Catalan continental margin (Castellón group, Unit B of Urgeles *et al.*, 2011). The surface S2 would be polygenic and its earlier evolutionary Tortonian stages would have been concealed by the later Late Messinian and post-Messinian erosive processes.

### *Unit P*

The lower transgressive and high stand marine assemblages in the Tortosa Graben have been clearly attributed to the Pliocene, likely to the Zanclian (Martinell and Domènech, 1984; Fleta *et al.*, 1991). In turn, the upper regressive transitional and non-marine assemblage is late Pliocene in age, although it might reach the earliest Pleistocene (Riba, 1981; Simón *et al.*, 1983; Agustí *et al.*, 1983; Arasa-Tuliesa, 1990). On the basis of their geomorphological features, the alluvial equivalent assemblages described in the Benifallet, Móra Basin and Flix area are also considered Pliocene in age, although they were formerly considered as Quaternary (Colodrón and Orche, 1979; Orche *et al.*, 1981; I.G.C., 2006). Considering these data, it is proposed that the sedimentation of unit P developed mainly during the Pliocene although it could last until the Earliest Pleistocene. This unit is correlated mainly with the Pliocene part of the Ebro group equivalent to the unit D defined by Urgelés *et al.* (2011).

### *Unit Q1-2*

The dating of unit Q1-2 in the Tortosa Graben has been controversial since no conclusive chronostratigraphic data have been reported for the whole unit. After an early attribution to the Pliocene (Solé *et al.*, 1965), it was later attributed to the interglacial Riss-Würm or Euthyrrenian (Maldonado, 1972). This unit has been correlated with marine sediments that overly the "G" reflector on the continental shelf and were attributed to the Early-Middle Pleistocene (Farran *et al.*, 1984; Maldonado *et al.*, 1986). Electronic spin resonance dating applied on the upper carbonate crust levels in the alluvial fan assemblage (Q2) in the Tortosa Graben provided values ranging from 436 to 351ka BP ±15% (Brüchner and Radtke, 1986; Radtke *et al.*, 1988). These ages correspond to the Middle Pleistocene, *i.e.* the Mindel-Riss interglacial or Palaeotyrrhenian (Arasa-Tuliesa, 1990, 1992). The two terrace levels in the area of Flix, correlated with equivalent terraces in the Móra Basin and Tortosa Graben, would have the same age (Figs. 5D and XII in Electronic Appendix). Moreover, the unit Q1-2 would be approximately of the same age than the assemblage of the upper fluvial terrace levels reported in the Cinca and Segre rivers (Early-Middle Pleistocene; Sancho *et al.*, 2007; Stange *et al.*, 2013a).Considering these data, it is proposed that the erosion surface entrenched into the unit P deposits and unit Q1-2 were eroded and deposited, respectively, between 1Ma and 400ka approximately (late Early and Middle Pleistocene).

### *Unit Q3*

The S5 erosion surface that underlies the unit Q3 probably correlates with the seismic reflector "J" recorded in the shelf and overlain by three Thyrrenian marine levels (Farrán *et al.*, 1984; Maldonado *et al.*, 1986; Farrán and Maldonado, 1990). Considering the available data, it is proposed that the onshore surface S5 was incised during the Middle and/or Late Pleistocene. In its turn, the Q3 terrace levels have been correlated with the Late Pleistocene offshore units on the continental shelf (Arasa-Tuliesa, 1994b). Moreover, some fluvial terrace levels of Q3 have also been recognized in the Móra Basin and the Flix area of the Ebro Basin, where they encompass carbonate and siliceous clasts that were reworked from older terrace levels. Similar upper Pleistocene fluvial terraces have been described in the rivers Cinca and Segre (Sancho *et al.*, 2007; Stange *et al.*, 2013a, b).

### *Unit Q4*

This unit is attributed to the Holocene. At Amposta, samples from the borehole 522-6-17, at 18.5m-depth, provided an average 14C age of 8,819a BP (Arasa-Tuliesa, 1994a; Somoza *et al.*, 1998; Pérez-Obiol *et al.*, 2011).

## DEPOSITIONAL FRAMEWORK AND DRAINAGE EVOLUTION

The analysis of the stratigraphic record of the palaeovalley and neighbouring Ebro Basin sectors allows disclosing the evolution of the regional drainage. This analysis considers regional distribution, thickness, palaeocurrent trends and clast composition of the depositional units and their geometric relations with the substratum through the erosion surfaces. The analysis focuses on the evolutionay stages previous to the development of the exorheism of the Ebro Basin and on the successive palaeovalley downcutting episodes.

### Eocene-Early Oligocene: sedimentation in the Ebro foreland Basin fed from the Catalan Coastal Range Paleogene Orogen

The record of this evolutionary stage includes the Paleogene units that are part of the basin fill of the present marginal zone of the SE Ebro Basin and/or have been incorporated in the frontal thrusts and folds of the CCR (Figs. 1–3).

The palaeocurrent data reported from the Cornudella and Scala Dei groups (Colombo, 1980, 1986), indicate a prevailing Eocene to Oligocene northwestward alluvial sediment transport from the inner zones of the CCR Paleogene Orogen into the Ebro Basin (Lawton *et al*., 1999; Merren *et al*., 2004). The Oligocene sedimentation took place mainly on distributive alluvial systems that spread from the Ebro Basin margins under the influence of the late compressional structuration and the overall uplifting of the CCR orogen that resulted in a relief higher than 1500m in average (López-Blanco *et al*., 2002; Gaspar-Escribano *et al*., 2004). Lacustrine depositional systems (Los Monegros lacustrine system) developed in the inner Ebro Basin zones although they spread southwards the basin margins in some evolutionary stages (Cabrera and Sáez, 1987; Lawton *et al*., 1999; Barberà *et al*., 2001; López-Blanco, 2002; Merren *et al*., 2004; Valero *et al*., 2014).

### Late Oligocene-Early and Middle Miocene: sedimentation in the Ebro foreland and CCR intramontane basins

The record of this evolutionary stage includes the Late Oligocene-Early Miocene units that form the uppermost basin fill of the present marginal zone of the SE Ebro Basin. In the present basin margins these units were deformed by the folds and thrusts that make up the orogenic front of the CCR (Lawton *et al*., 1999; Merren *et al*., 2004). It also encompasses the erosion surface S1 and the overlying unit M1 (Figs. 1–3).

Although some axial NNE-SSW palaeocurrent orientations occur along the CCR, the facies distribution and palaeocurrent data reported from the upper Scala Dei alluvial sequences indicate the persistence of prevailing basinward oriented alluvial sediment transport from the inner zones of the CCR Paleogene Orogen into the Ebro Basin (Colombo, 1986; Cabrera and Sáez, 1987; Lawton *et al*., 1999; Merren *et al*., 2004). Moreover, during the late Oligocene, the uplifting of the compressive structures along the NW margin of the CCR led to the split of the Móra Basin from the larger Ebro foreland Basin (Anadón *et al*., 1979, 1983; Teixell, 1985, 1988). This basin paralleled the Ebro Basin margin and its filling started with the sedimentation on latest Oligocene-Early Miocene alluvial fans fed from the surrounding CCR compressive reliefs.

In the Early Miocene the setting on of the extensional fault activity in the CCR near the present shoreline and the neighbouring offshore zones resulted in the generation of the onshore Tortosa Graben where alluvial-fan sedimentation supplied from the surrounding CCR extensional culminations also started. The Móra Basin could also have been affected by extensional faulting. The clastics from the CCR reliefs were deposited in the Móra Basin and Tortosa Graben from the Early to Middle (?) Miocene. The red bed alluvial fan deposits of unit M1 shape the depositional record of this evolutionary stage (García-Boada, 1974; Teixell, 1985, 1988; Guimerà, 1988; Arasa-Tuliesa, 1994a) There is neither evidence of contribution from the Ebro Basin nor of internal drainage conditions (lacustrine or playa-lake carbonate or evaporite deposits) in the Móra Basin and Tortosa Graben.

### End of Middle Miocene and Late Miocene: CCR drainage upward erosion, lower Ebro incision and opening and headward spreading of the Ebro Basin catchment

The onshore record of this evolutionary stage is fragmentary and discontinuous and includes the unit M2 and their bounding erosion surfaces S2 and S3. From the Flix area in the Ebro Basin to the Benifallet area the fluvial deposits of the unit M2 were deposited in a quite deeply incised palaeovalley whose minimum entrenchment has been roughly estimated on the basis of the distribution of the unit M2 bottom. This minimum entrenchment ranged from 560m in the Ebro Basin marginal zone, to about 300m in the Móra Basin and the Benifallet zone and 250 to 300m in the Tortosa Graben (Fig. 6). The palaeo-Ebro must have shown a North-eastward trend near the present coast line, as evidenced by the outcrops of Capelo North of l'Ampolla (Figs. 2; 3; 4B; 6; V in Electronic Appendix).

In the Tortosa Graben the palaeovalley erosion surfaces S2 and S3 were locally affected by the extensional faults that modified their original arrangement (Fig. 5A; IIID, E; IVE in Electronic Appendix). However, it is possible to establish that large scale erosion resulted in a deeply entrenched trough. The erosion surface S2, overlain by the unit P, affected both the Mesozoic substratum and the syntectonic unit M1 with a minimum preserved entrenchment of 250m and could probably attain more than 300m in the Benifallet zone. This surface was affected by the activity of the Port and other minor faults with minimal 100m-slip (Figs. 5A; 6).

Although it has been a matter of debate, the development of older than Messinian (mainly Tortonian) significant erosion surfaces and drainage entrenchment in the lower Ebro sector of the Catalan margin onshore has received renewed support due to the confirmed development of a very significant volume of Middle-Late Miocene shelf-slope progradational deposits (Castellón group) that overlie a Serravallian erosive unconformity (Dañobeitia *et al.*, 1990; Álvarez de Buergo and Meléndez-Hevia 1994). These deposits could not have been contributed by fluvial systems with their catchments limited to the CCR domain (Evans and Arche 2002; Arche *et al.*, 2010; Urgeles *et al.*, 2011), although these contributions could be locally significant at other parts of the Catalan continental margin (Bartrina *et al.*, 1992, Roca *et al.*, 1999). The beginning and further development of the erosion in the CCR and the Ebro Basin could be loosely constricted between the Serravallian-Tortonian transition (11.63Ma) and the late Tortonian (9-8.5Ma; Arche *et al.*, 2010; García-Castellanos and Larrasoaña, 2015; Figs. 3; 8).

Considering these offshore data and its comparison to the more fragmentary onshore record, a period of headward erosion of the CCR drainage could began in the Latest Serravallian(?)-Tortonianand finally resulted in the entrenchment of the lower Ebro palaeovalley and the carving of significant early erosion surfaces across the CCR and SE Ebro Basin during Tortonian and Messinian times (Figs. 7A and 8). This onshore headward erosional stage had a significant depositional effect in the offshore with the sedimentation of the terrigenous shelf-slope system of the Castellon group (Dañobeitia *et al.*, 1990; Arche *et al.*, 2010) that is equivalent to the unit B defined by Urgeles *et al.* (2011) (Fig. 8). The headward erosion of this onshore drainage system would have progressed and been influenced by the maximum of the Messinian sea level lowering in the Mediterranean and that in the Ebro Shelf resulted in the generation of a deeply entrenched canyon and a well-developed drainage (Urgeles *et al.*, 2011).

These plausible Tortonian-Messinian erosive stages in the onshore zones are here related with the development of the erosion surfaces S2 and S3 and the deposition in the lower Ebro palaeovalley (overlying S2 and topped by S3) of the unit M2 (Figs. 4B; 7B; 8). This unit was in part deposited in alluvial fan systems fed by the local contribution of carbonate clasts from both margins of the palaeovalley. The drainage of the alluvial fan systems in this part of the lower Ebro was mainly perpendicular to the valley axis where fluvial deposits accumulated. The interrelationship between the fluvial and alluvial-fan assemblages, their depositional characteristics and their morphological relationships with the substratum rocks indicate the existence of a well-developed bedrock-alluvial mixed valley, entrenched into the unit M1 (Early-Middle? Miocene), the Palaeogene units and even the Mesozoic carbonate substratum. This unit is the first preserved depositional record of this situation at the lower Ebro.

The clast composition of the fluvial deposits of unit M2 points to the fact they were fed from the Pyrenees or its proximal southern foreland and it suggests the existence of a relatively mature and significantly headward spread drainage in the Ebro Basin. This fact means that the sedimentation of unit M2 probably did not take place during the earliest stages of the drainage entrenchment but after it had experienced a relatively long evolution, suggesting a more probable Messinian age for M2 and for the late evolution of the underlying S2 (Figs. 7B; 8).

A mainly Late Messinian age has been proposed here for the generation and evolution of the preserved parts of the S2 surface and the deposition of unit M2, while a very late Messinian age is attributed to the erosion surface S3 that overlies the unit M2 and in turn is directly overlain by the Early Pliocene transgressive deposits resulting from the reflooding of the Mediterranean Sea. This sequence of at least two Late Miocene onshore erosive episodes punctuated by a single preserved alluvial unit (M2) constitute the only available early onshore record of the entrenchment of the lower Ebro palaeovalley and the closer sectors of the Ebro Basin during the Miocene. The erosion/sedimentation balance in the palaeovalley onshore zones resulted in minor alluvial-fan and fluvial valley infill. It also could cause a widespread degradation and even destruction of the older (mainly Tortonian? and early Messinian) onshore erosion surfaces (Figs. 7B, C; 8).

### Pliocene-Early Pleistocene: depositional infill at the lower palaeovalley tract

The record of this evolutionary stage includes the unit P (Figs. 2; 3; 4C; 6; 7C; 8). At the end of the Messinian the lower Ebro palaeovalley had been downcut by the successive erosive episodes developed through the Late Miocene. The marine and continental Pliocene deposits of unit P overlie the S3 erosion surface.

The Pliocene transitional and marine sedimentation (Pa) was limited to the Tortosa Graben (Fig. 7C). Alluvial fan system deposits developed in the Móra Basin (Pc; Figs. 2; 5C; 7C), while in the Flix area fluvial sedimentation (Pd) was recorded (Fig. XII in Electronic Appendix).

The depositional characteristics and the arrangement of the Pliocene transitional and marine facies in the graben and their onlap relationships with the substratum rocks indicate the existence of a depositional sink in a marine embayment established in the bedrock-alluvial mixed lower palaeovalley that was entrenched in many places into unit M1 and also in the Palaeogene and Mesozoic cover rocks. According to subsurface and outcrop data (*e.g.* in Rantxero and l'Aldea; Figs. 2; 5A; 6; III; IX in Electronic Appendix) the Pliocene sediments overlay the unit M2 where it occurs. The incised palaeovalley must have reached the Móra Basin at a present minimum altitude of 65m-a.s.l. and the Flix area at 80–90m-a.s.l. (Figs. 4; 5A; 6; II; IIID, E; IV in Electronic Appendix; Arasa-Tuliesa, 1990, 1994a).

The valley tracts stretching from the Ebro Basin to the northern end of the Tortosa Graben were well defined and the available record allows tracing them with relative precision. In the lower river tract (Tortosa Graben) the isobath map of Mesozoic substratum and the distribution of the Pliocene marine facies (Fig. 4A, C) enable to establish the probable location of the former incised fluvial valley. The Mesozoic isobaths, that reflect in part the erosion associated with the erosion surfaces S2 and S3, are only approximate in some areas due to the limited information on the substratum depth provided by the boreholes (Fig. 4A). The depths of the contact between the Pliocene sequences and the substratum (observed mainly in boreholes) were partially modified by the subsidence that still affected the Tortosa Graben zone from the Pliocene to Holocene times (Figs. 6; 7C). Some of lowermost deposits of this unit show evidence of synsedimentary faulting in the La Carroba-Rantxero threshold and some tectonic subsidence in the Tortosa Graben (Figs. 5A; IXB, C in Electronic Appendix). Although the isobaths contours of the Mesozoic substratum resulted from several processes (*i.e.* tectonic subsidence and successive Miocene erosive episodes) they show that the main Ebro paleovalley probably adopted changing orientations in the Tortosa Graben ranging from N-S to NW-SE (Fig. 4A–C). In the SW graben marginal zones the isobaths also trace the contours of smaller, probably tectonically and erosively controlled lateral transverse palaeovalleys, which can be related to ancient drainage systems (Fig. 4A). Other minor transverse drainages that probably existed along the N-S oriented segment of Tortosa Graben have not been recognized probably due to the low resolution of the subsurface data.

### Quaternary: Renewed incision and degraded palaeovalley infill

The record of this evolutionary stage includes the erosion surfaces S4 to S6 that were overlain respectively by the units Q1-2 to Q4 (Figs. 2; 3; 4D; 5; 6; 7D; VII; IX; XI in Electronic Appendix). The successive erosion surfaces and deposits related to these terraces re-excavated and concealed the previous record of the palaeovalley infill.

The terrace units Q1-2 to Q4 unconformably overlie the Neogene deposits and other underlying cover units in the valley. The deposition of these terraces took place when the palaeovalley trace of the lower Ebro valley was close to its present location. During this stage the valley evolution was influenced by climatic and glacioeustatic changes, the overall isostatic rebound in NE Iberia (García-Castellanos and Larrasoaña, 2015; Stange *et al.*, 2016) and in some sectors (Tortosa Graben) by the low to moderate tectonic activity reported at some extensional faults (Masana, 1995; Perea, 2006; Perea *et al.*, 2006). These extensional tectonics also occurs in some areas located upstream causing the local increase in thickness of unit Q1-2 (*e.g.* Burgà fault; Figs. 2; 6; 7D).

The sedimentation of the Early and Middle Pleistocene Q1-2 unit took place after the development of a significant entrenchment surface (Arasa Tuliesa 1994b) that has been correlated with a conspicuous erosion surface (reflector G) in the offshore (Farran *et al.*, 1984; Maldonado *et al.*, 1986). The depositional interrelationship between Q1, a fluvial assemblage, and Q2, an alluvial fan assemblage, their depositional characteristics and their morphological relationships with the substratum rocks indicate the existence of a well-developed Ebro palaeovalley. The widespread development of alluvial fans fed from the reliefs that surrounded the river constrained its evolution.

## DISCUSSION

The Neogene-Quaternary stratigraphic record of the lower Ebro palaeovalley resulted from an overall situation of scarce deposition and dominant incision, sediment transport and by-pass into the Ebro Shelf and the Valencia Trough during most of its evolution. When considering the long term (>1Ma) average, the lower Ebro palaeovalley played a major role in the source-to-sink sediment transfer from the Pyrenees and the southern Pyrenean foreland region into the Valencia Trough and was a very efficient bypass system where erosion, sediment transport and transference into the offshore prevailed (Farran *et al.*, 1984; Nelson and Maldonado, 1990; Dañobeitia *et al.*, 1990; Urgeles *et al.*, 2011; García-Castellanos and Larrasoaña, 2015 and references therein). Consequently, the successive incision valley episodes gave rise to a mainly compound erosion and fill discontinuous record (Figs. 6–8).

The lower Ebro valley is a bedrock-alluvial mixed valley with a long-lived, mainly Late Miocene to Quaternary, palaeovalley history. The very early antecedents of the erosion of the precursor of the lower Ebro palaeovalley could start from nearly 11.63Ma (Serravallian-Tortonian transition) or more probably around 8-9Ma (Tortonian; García-Castellanos *et al*., 2003; Arche *et al*., 2010; García-Castellanos and Larrasoaña, 2015).

Given the still low resolution of the stratigraphic dating in the lower Ebro our analysis will be restricted to considering long term evolutionary trends of the erosion/sedimentation balance during the main evolutionary stages of the palaeovalley. Therefore, it will focus mainly on the major and most significant factors for long term evolution, *i.e*. the regional to local isostatic rebound and the base level changes at the lower river transect close to its outlet into the Mediterranean. These base level changes were in turn mainly related to relative sea level changes and perhaps local tectonic activity. The analysis of other significant factors (*e.g*. climatic and sediment contribution changes from the Pyrenees and the related foreland) is beyond the scope of this paper.

## Influence of tectonics and major sea level changes on the palaeovalley evolution and its stratigraphic record

River incision and sedimentation is controlled at diverse space and time scales by a variety of factors whose relative influence and mutual interplay can change, making more complex and difficult its comprehension (Martin *et al*., 2011). In the case of the lower Ebro isostatic uplift in NE Iberia and the CCR, regional to local tectonics in the CCR, climatic changes influencing water and sediment inputs from the catchment and base level changes in the outlet zone (*e.g*. relative sea level changes, regional base level changes in the CCR) have been considered. Also changing sea level and the sediment contribution and redistribution during the Messinian and the Early Pliocene resulted in isostatic crustal re-equilibrium (Gaspar-Escribano *et al*., 2001, 2004; García-Castellanos *et al*., 2003; Gargani, 2004; Gargani *et al*., 2010; Arche *et al*., 2010; Urgeles *et al*., 2011; García-Castellanos and Larrasoaña, 2015; Stange *et al*., 2016 and references therein).

The Neogene and Quaternary evolution of the lower Ebro has been largely influenced by the active isostatic and/or tectonic uplift of NE Iberia and some segments of the CCR (Fig. 8). The overall flexural isostatic rebound that affected the whole NE Iberian and CCR region favoured the long term river entrenchment and made easier the sediment erosion and transport from the Ebro Basin into the NW CCR fringe and finally into the Ebro Shelf and the deeper Valencia Trough. This isostatic rebound has affected the lower Ebro zone and the neighbouring Ebro Basin at least since the Late Miocene. In the case of the Ebro Basin this rebound has been mainly attributed to the erosion and the resulting lithologic unloading of the Pyrenean Orogen and its southern foreland (Beamud *et al*., 2011; Fillon *et al*., 2012, 2013; García-Castellanos and Larrasoaña, 2015 and cites therein). In the CCR and the SE marginal zones of the Ebro Basin this rebound should be considered together with the general isostatic readjustment after the rifting processes that affected the NW Mediterranean during the Miocene and the activity of the faults that bounded the Miocene grabens (Gaspar-Escribano *et al*., 2001, 2004; García-Castellanos *et al*., 2003). Since the isostatic rebound in the Ebro Basin was larger in comparison to that finally resulting in the CCR and the Ebro Shelf this fact probably resulted in a topographic gradient that favoured the long term (Late Miocene to Holocene) sediment erosion and transference through the lower Ebro into the offshore zones that has been approximately quantified at a maximum ranging from 25,000 to 45,000km$^3$ (García-Castellanos and Larrasoaña, 2015).

The clearly negative sedimentation balance in the valley through most of its history was reinforced or weakened depending on the base level changes in the river outlet to the Mediterranean. Once the lower Ebro was open to the Mediterranean the long-term evolution of the palaeovalley and its erosion/transport/depositional balance could be modified by the major sea level changes that deeply changed the river base level. The Late Messinian sea level downdrawn between 1000 and 1200m at around 5.6Ma (Urgeles *et al*., 2011; Bache *et al*., 2012) would have largely enhanced the capacity of sediment transfer through the valley into the Ebro Shelf and the Valencia Trough. On the contrary, the Early Pliocene reflooding at 5.3Ma, of similar magnitude, impinged into the palaeovalley, largely modified the river base level and resulted in the sedimentary infilling of its lower transect that was incised in the Tortosa Graben (Figs. 4C; 5A; 6; 8; IX in Electronic Appendix). Considering the proposed dynamics and timing for the development of the Mediterranean reflooding these changes should take place rapidly, in a time span of tens to hundred ka (Bache *et al*., 2009, 2012, 2015; García-Castellanos *et al*., 2009).

The Late Miocene history (lasting a minimum of 3 and up to a maximum of 7Ma) of the lower Ebro is characterized by prevailing erosion and sediment transfer into the Ebro Shelf and the Valencia Trough sink. The depositional balance in the palaeovalley became positive only during the Pliocene-earliest Pleistocene (?) when a fast and major sea level rise drowned the lower valley tract and triggered a significant sedimentation in it during 3.5Ma although this fact did not prevent the sediment contribution into the offshore (Fig. 8). The subsequent short-term Quaternary more moderated glacioeustatic sea level and climatic changes, which developed in the same scenario of overall isostatic rebound of the region (Stange *et al*., 2016), resulted in the sedimentation during the last

2Ma of terraces characterized by a mainly degradational stacking architecture (units Q1-2 to Q4).

The influence of the local tectonic activity on the base level and drainage evolution in the lower Ebro has not been precisely established, but it was not homogeneous. The analysis of the stratigraphic record from the Flix area of the Ebro Basin to the Móra Basin and the closer surrounding CCR sectors show the existence of local faults with very low slip and minor related subsidence. In the Móra Basin, the larger thickness of the unit Q1-2 at the western bank of the Ebro River in comparison to that reported in the eastern bank suggests a differential subsidence related with the Burgà fault activity (Figs. 2; 5C). On the other hand, in the Tortosa Graben tectonic control could be noticeable due to the activity of the graben faults. These faults undoubtedly controlled the sedimentation of the unit M1 in the graben (300m-thick preserved red-bed deposits). Later affected at least a part of the Pliocene and Quaternary deposits. Therefore, some influence was exerted by the Tortosa Graben faults on the Late Miocene-Holocene evolution of the lower Ebro valley sectors that were closer to the river outlet. However, this influence cannot be specified in detail beyond the fact that the successive traces of the main fluvial valleys along the graben should be favoured by the easier erosion of the mudstone-dominated graben infill and/or forced by the topographic gradient that resulted from the tectonic-sedimentation-erosion balance in the graben. Also, must be considered the development of tectonic thresholds that modified the valley evolution in its lowermost tracts (La Carroba, Figs. 4–6 IX in Electronic Appendix). The differential isostatic rebound between the Ebro Basin and the CCR, the extensional faulting and the subsequent locally changing subsidence in the Móra Basin and the Tortosa Graben must have affected the equilibrium profile of the lower Ebro. Therefore, although the available data did not enable to trace paleoriver profiles, it is suggested that knickpoints could develop from the marginal zones of the Ebro Basin through the CCR, (including the Móra Basin) and the Tortosa Graben during the Late Miocene-Quaternary time.

## Late Miocene erosion surfaces in the Ebro catchment

The absence of a deeply entrenched canyon in the Ebro valley that does not accord well with the deeply incised canyons observed in the offshore has been considered a paradox and matter of debate (Babault *et al.*, 2006; Arche *et al.*, 2010 and references therein; Urgeles *et al.*, 2011; García-Castellanos and Larrasoaña, 2015). Urgeles *et al.* (2011) described in detail the characteristics of the Messinian erosion surface (reflector M) in the Ebro Shelf showing the existence of deeply entrenched subaerial valley morphology under the Plio-Quaternary progradational cover (Ebro group, Unit D) in the shelf-slope zone. These authors attributed the observed valley morphology to a fast exposure and incision during the proposed lowering of the Mediterranean Sea by ~1.2km. According to this, the large water discharge of the Ebro River and its pronounced slope in its way downstream from the Ebro Basin to the sea should have quickly caused its upstream propagation and the excavation of a valley deeply impinged into the CCR-Ebro Basin region as far as in other Mediterranean rivers like the Rhone and the Nilo (Gargani, 2004; Gargani *et al.*, 2010). Arche *et al.* (2010) and Urgeles *et al.* (2011) suggested several factors that could prevent the deep valley excavation in the CCR and the Ebro Basin including, among others, lesser volume of the river discharge in comparison to other larger Mediterranean rivers, smaller catchment than the present of the palaeo-Ebro during the Late Miocene, CCR structural-lithological barrier effect and transport-limited incision due to very high sediment current load. García-Castellanos and Larrasoaña (2015) suggested that the isostatic rebound in NE Iberia could be larger enough to cause the exposition and obliteration of a possible Messinian canyon in the onshore.

The Neogene-Quaternary onshore record in the lower Ebro shows poor or no preservation of the earlier erosion surfaces and of the fluvial deposits related to the evolution of a Tortonian to Messinian drainage, including the palaeo-Ebro. The record is fragmentary and makes difficult to precise their original depositional arrangement due to the differential isostatic rebound and local tectonic modification affecting the region. However, wether estimation is made in sectors affected by similar isostatic rebound (as the Ebro Basin marginal zone in the study area; García-Castellanos and Larrasoaña, 2015) a rough estimation of incision can be made based considering that neither major extensional faulting nor tilting affected the erosion surface S2 and the unit M2 deposits (Fig. 6).

The onshore record constituted by the alluvial unit M2 and its associated erosion surfaces S2 and S3 suggests the existence of Late Miocene incisions that could reach nearly 600m in this marginal zone of the Ebro Basin. This level of entrenchment does not attain the larger values reported from the offshore Messinian canyon in the Ebro Shelf (Urgeles *et al.*, 2011) but suggests a quite significant entrenchment mainly favoured by the isostatic rebound in the region and enhanced by the Late Miocene Mediterranean Sea level drops.

Other additional considerations can be proposed to explain the relatively low onshore entrenchment of the catchment observed in the Ebro foreland basin. It is commonly accepted that substrate resistant lithology and tectonic uplift often tend to narrow the valley width and to increase its entrenchment (Salisbury *et al.*, 1968; Ardies *et al.*, 2002). Most of the Ebro River catchment is incised mainly into easily erodible rocks, this fact contributing to a lesser entrenchment due to the strong efficacy of the side wall erosion resulting from the lithology weakness. Moreover, deep entrenchment of an incised valley could be prevented if the sea level fall was (independently of its magnitude) short lasting (Martin *et al.*, 2011 and cites therein). Both factors can be considered as contributors to a lesser than expected late Miocene Ebro River incision in the onshore.

## CONCLUSIONS

The deposition of three Miocene to Pleistocene (M1, M2 and P) and three Pleistocene-Holocene (Q1-2 to Q4) allostratigraphic units and their bounding erosive unconformities (S1 to S6) constitute the onshore record of the downcutting and infill cycles of the lower Ebro palaeovalley. This compound erosion and fill record characterizes the lower Ebro as a bedrock-alluvial mixed incised valley with a mainly degradational stacking architecture developed during its Late Miocene to Holocene history (Fig. 8).

Three main evolutionary stages can be distinguished:

i) Latest Serravallian (?)-Tortonian and Messinian (11,63 (?)- 9 to 5,3Ma)

Headward erosion, drainage entrenchment and source to sink sediment transport and transference were prevalent and the river incision in the lower Ebro reached the Early-Middle Miocene alluvial basin infill (unit M1) as well as the Palaeogene and Mesozoic cover rocks of the CCR and the SE marginal zone of the Ebro Basin.

The polygenetic erosion surface S2 (most probably Tortonian to Late Messinian in age) constitutes the oldest preserved onshore record of the drainage entrenchment related to the opening of the Ebro Basin to the Mediterranean and of the further headward erosion of the Ebro catchment. The development of this erosion surface was coeval to the earlier sediment transfer from the Pyrenees and its southern foreland into the shelf-slope offshore system. This sediment transfer resulted in the development of the first major progradational shelf-slope terrigenous system of the Catalan continental margin during the Tortonian and Early Messinian (Castellón group). This fact corresponds well with the enhancement of the erosion in the Pyrenees linked to the opening of the Ebro Basin to the Mediterranean and calculated as younger than 10Ma. Consequently, widespread onshore drainage entrenchment and sediment transfer into the Valencia trough basin could take place intensively during Tortonian and Early Messinian (Fig. 8).

The overlying alluvial-fan and fluvial unit M2 (Late Messinian) is bounded by the surfaces S2 and S3 and includes clasts of Pyrenean provenance showing that it was deposited when the upstream erosion of the Ebro catchment had spread significantly as far as the Pyrenean Orogen or at least its proximal foreland basin. This unit is correlated with the offshore C unit defined by Urgeles *et al.* (2011). The analysis of the arrangement of the erosion surfaces S2 (Tortonian-Late Messinian) and S3 (Latest Messinian) and of the related alluvial-fan and fluvial deposits of the unit M2 (most probably Late Messinian) suggests the development of a significant Late Miocene (most probably Tortonian to late Messinian) entrenchment in the neighbouring SE Ebro Basin sectors and in the CCR segment crossed by the upper lower Ebro (more than 500 and up to 600m). This entrenchment was not précised in the CCR intramontane basins (Móra Basin, Tortosa Graben) although it reached at least a few hundred meters.

ii) Pliocene-Early Pleistocene? (5.3 to 2Ma)

The lower part of the the river valley close to its marine outlet became a sediment sink due to the Early Pliocene reflooding in the Mediterranean that led to the drowning of the lower part of the incised Ebro palaeovalley. A transgressive-regressive marine to non-marine sequence (unit P) was deposited in the accommodation derived mainly from the eroded surfaces S2 and S3 but also by the extensional tectonic subsidence in the Tortosa Graben (Fig. 8).

This evolutionary stage was the only with a clear positive balance of sediment accumulation (up to several hundred m) in the lower Ebro paleovalley. The erosion surface S3 and the overlying unit P are considered coeval to the latest Messinian erosion surfaces recorded in the Ebro Shelf and the overlying onshore Pliocene deposits that constitute the lower part of the second major progradational shelf-slope complex (Ebro group, unit D defined by Urgeles *et al.*, 2011) that fringes the continental margin.

iii) Early Pleistocene-Holocene (2Ma to Present)

During this late evolutionay stage the valley became again mainly degradational (development of the erosion surfaces S4 to S6) and several stepped units (Q1-2, Q3 and Q4) record successive incisions when the valley had reached a shape similar to the present. The assemblage constituted by the erosion surfaces S4 to S6 and the overlying units Q1-2 to Q4 is coeval to the Pleistocene-Holocene offshore deposits that overlie the reflectors G and J and that make up the upper part of the Ebro group shelf-slope complex. The S5 and S6 erosion surfaces respectively related to the Late Pleistocene unit Q3 and the Holocene unit Q4 were less incised than the previous ones (Fig. 8).

Considered as a whole, the scarce sediment volume preserved in the incised valley (units M2, P and Q1-2 to Q4) and the poor stratigraphic continuity contrast with the larger estimated accumulation of sediment in the progradational shelf-slope terrigenous systems that developed in the Ebro Shelf (late Serravallian-Tortonian and early Messinian Castellón group; Pliocene-Holocene Ebro group). This fact characterizes the lower Ebro palaeovalley as a very efficient axis for the source to sink sediment transfer from the Pyrenean Orogen and its southern foreland into the Valencia Trough-Menorca and Provenzal basins.

The persistent topographic gradient caused by the larger isostatic rebound in the Ebro Basin in comparison to that in the CCR and the Ebro Shelf favoured the long-term sediment erosion and transference into the offshore zones. The major regional sea level lowering episodes in the Mediterranean (*e.g.* the late Messinian sea level drawdown) would have accentuated this trend in a punctuated way. On the other hand, only the Early Pliocene reflooding gently altered this long-term erosion-dominated evolution in the lower palaeovalley transect during 3.3Ma. However, the intense sediment contribution into the Valencia Trough was recovered and persisted during this episode of palaeovalley infilling.

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# ELECTRONIC APPENDIX I

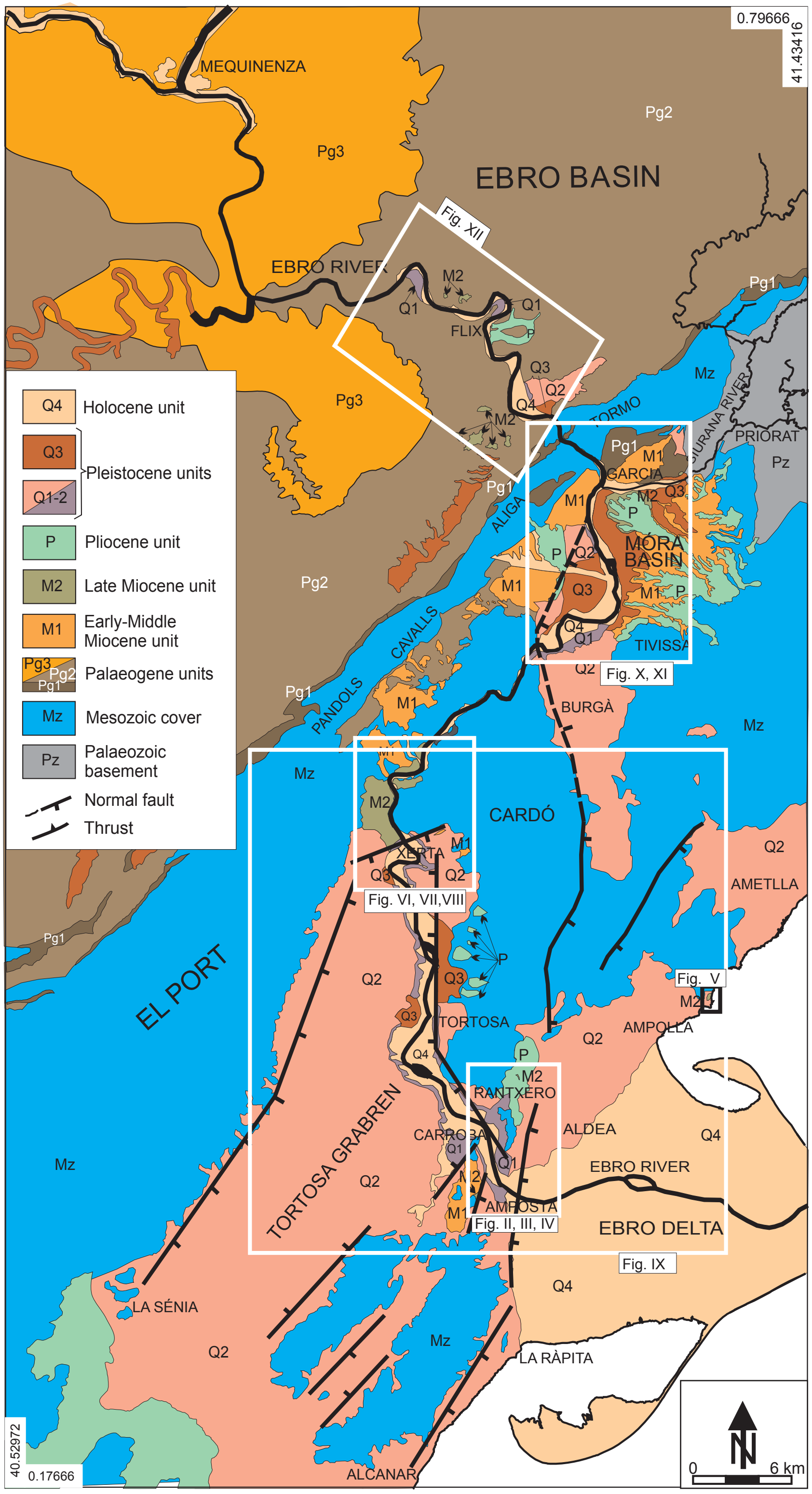



**FIGURE I.** Geological sketch of the study area frame with indication of the location of Figures II–XII.

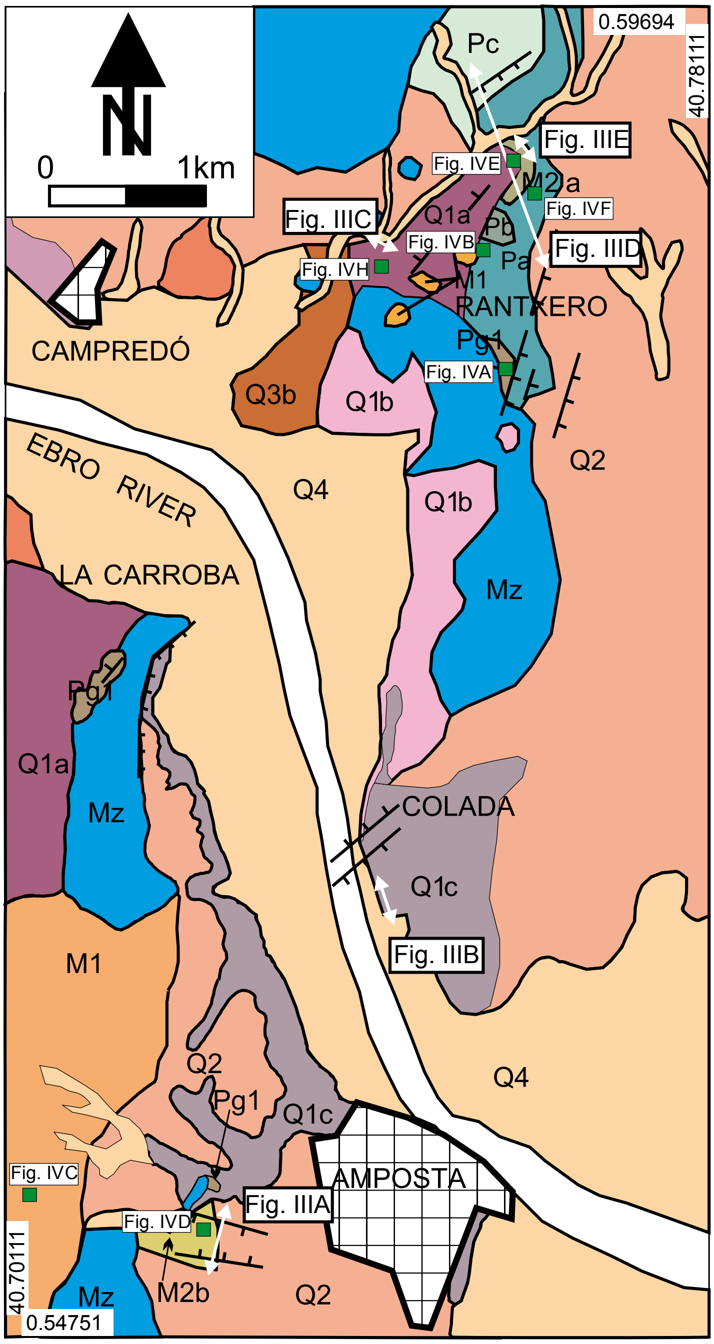



**FIGURE II.** Geological sketch of the La Carroba-Rantxero area in the Tortosa Graben showing the location of the geological cross sections of Figure III. (see legend in Fig. 3 in the main text). Green box indicates location of outcrop pictures provided in Figure IV. The mapping of the Miocene (M1 and M2), Pliocene-Early Pleistocene unit (P) and Quaternary units (Q1-2 to Q4) is also shown. In the Tortosa Graben the sequences of unit M1 attain their maximum reported thickness (300m, borehole 521-7-3; see Figs. 4A; 5A). To the South-West of Amposta, up to 40m-thick red mudstones and lenticular conglomerates attributed to this unit occur. They unconformably overlie (surface S1) the carbonate Mesozoic cover of the La Carroba-Rantxero uplifted block (see Figs. 2; 5A in the main text). See also cross sections A to C of Figure IX.

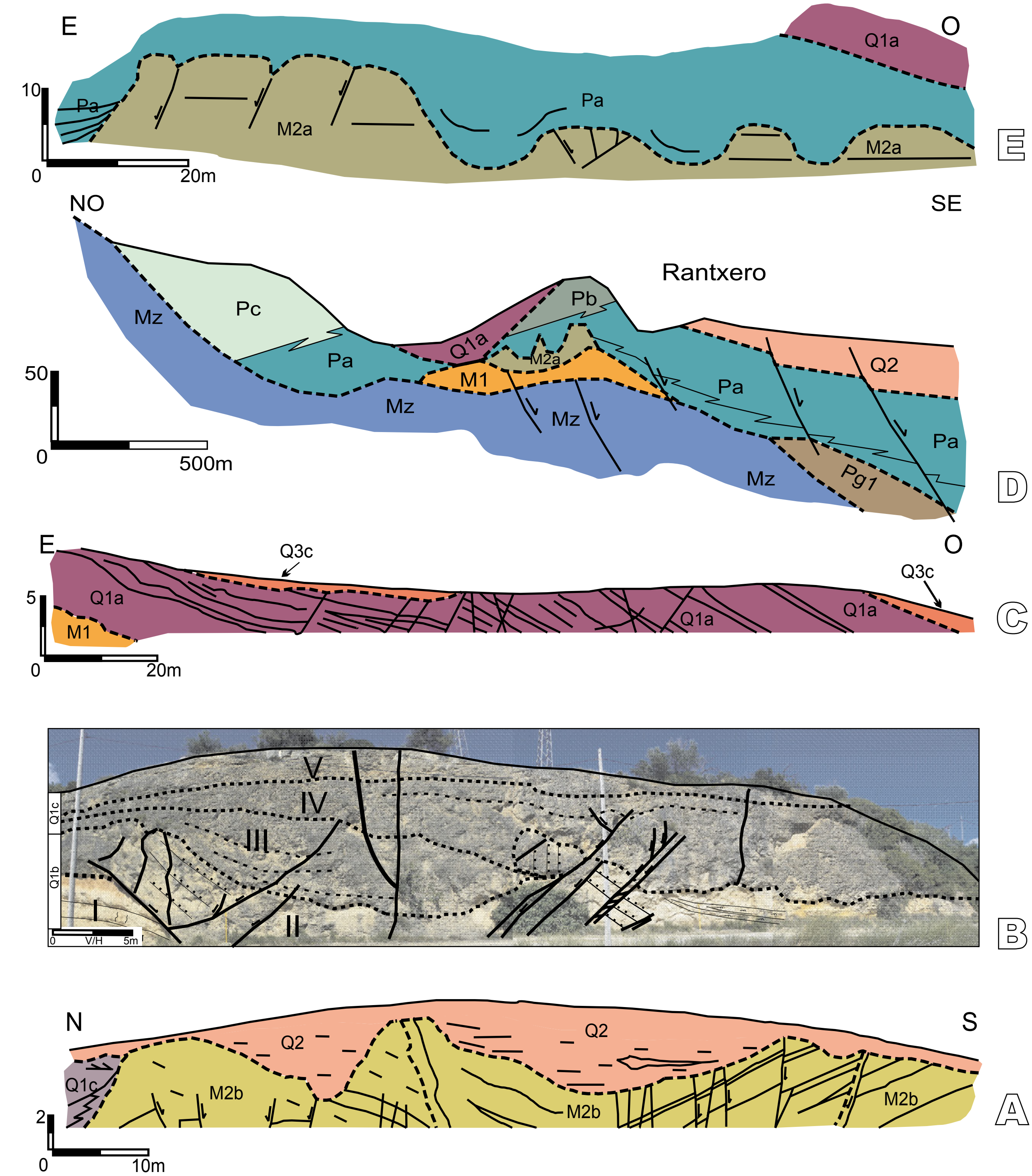



**FIGURE III.** Geological cross sections in the southern Tortosa Graben in the Rantxero-La Carroba sector (see location in Fig. II and legend in Fig. 3 in the main text): A) Late Miocene allostratigraphic unit M2 affected by minor extensional faults; B) Erosive discontinuities in Pleistocene unit Q1b-c; C) Tilted deposits of Pleistocene unit Q1a; D) General geological section, Rantxero area. See Figure 5A in the main text and Figure IVE–G for further detail; E) S3 erosion surface between unit M2 (affected by minor faults) and the marine Pliocene deposits in the Rantxero area. The Late Miocene M2a fluvial facies assemblage in the Tortosa Graben was fractured by minor extensional faults and affected by the last Messinian minor erosion surfaces (see Figs. I; II; IIIA, D, E; IVD–F; IX).

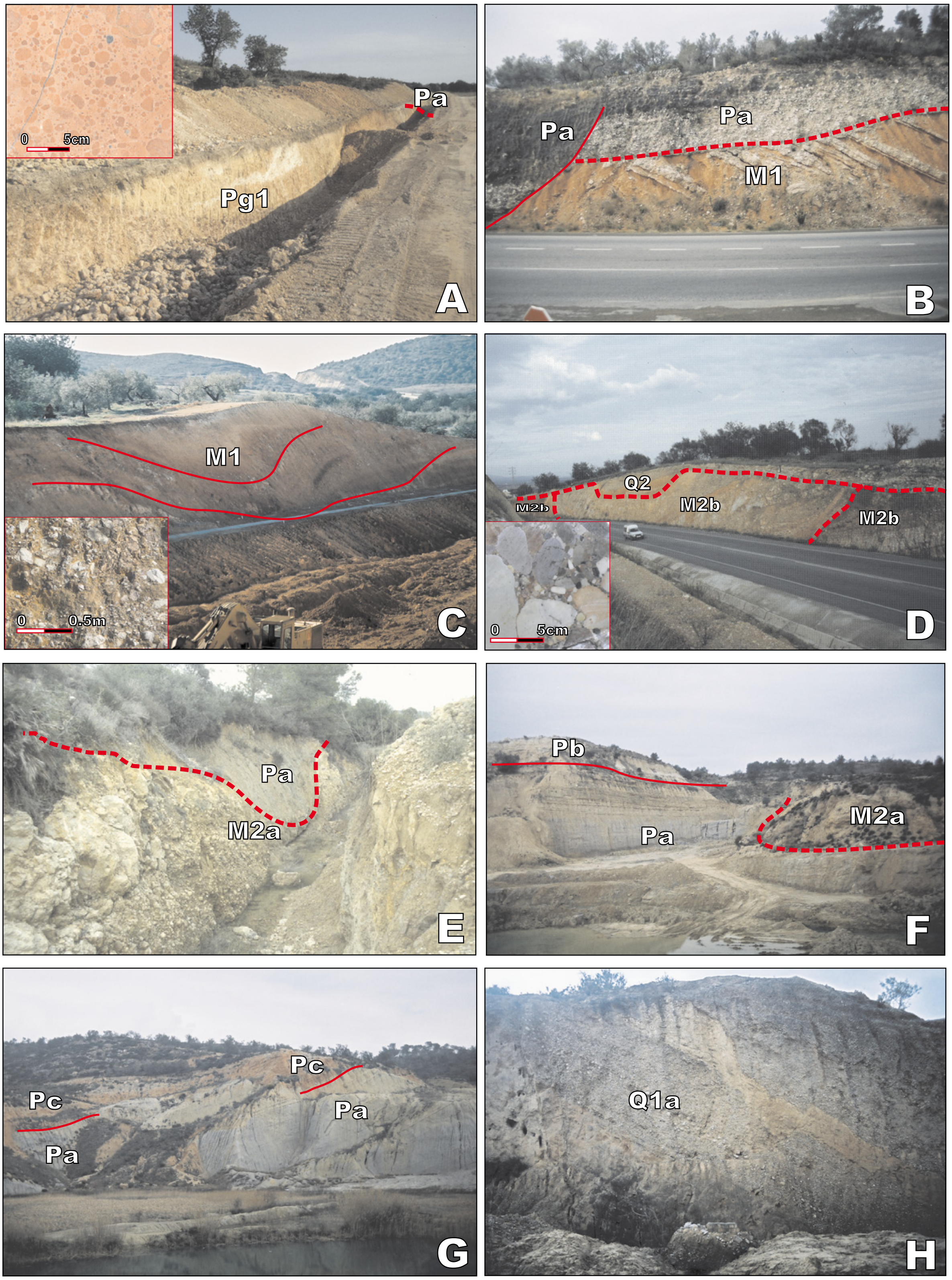



**FIGURE IV.** Field pictures of some of the described units. See location in Figure II. A) Paleogene Unit Pg1: Outcrop and detail of the pisolitic clay facies. B) Erosive transgressive surface between units M1 (Early-Middle Miocene alluvial red beds) and P (Pa marine assemblage including bored clast bearing beach facies). C) Early-Middle Miocene alluvial red bed facies of unit M1. D) Outcrop of unit M2b affected by faults and showing an erosive intraformational discontinuity. E and F) Erosion surface S3 between the Late Miocene fluvial assemblage M2a and the transgressive deposits of the marine Pliocene assemblage (Pa). G) Sedimentary continuity between the marine (Pa) and continental (Pc) assemblages in the Pliocene-Early Pleistocene unit P. H) Tilted siliceous clast-bearing conglomerates of the fluvial valley-infill assemblage Q1a.

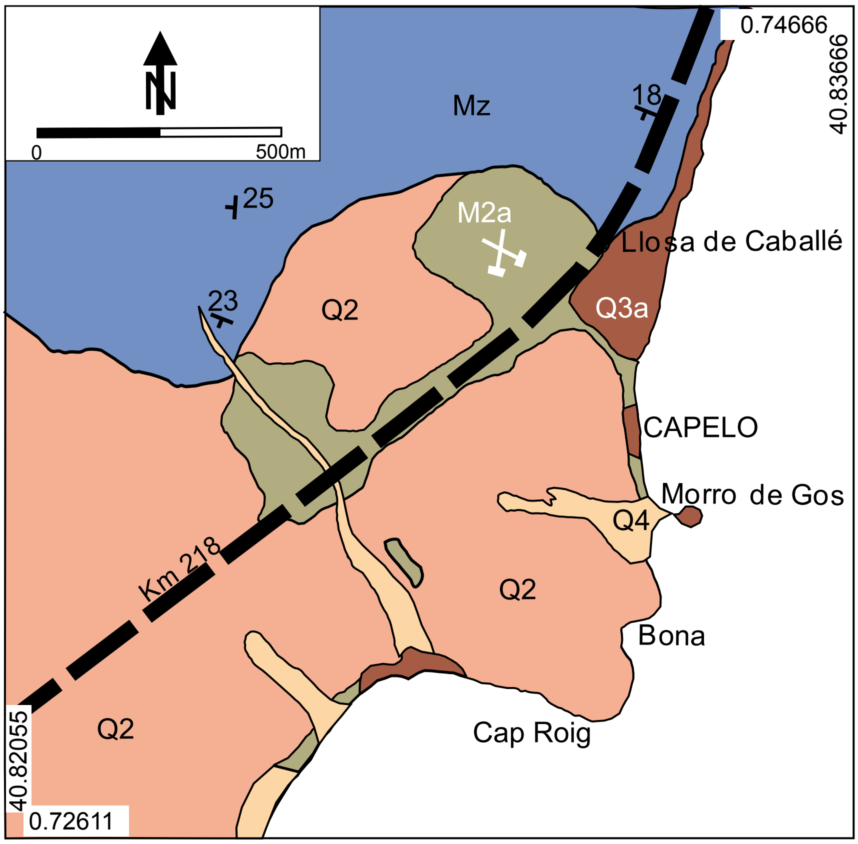



**FIGURE V.** Geological sketch of the Capelo area to the NE of l'Ampolla (see legend in Fig. 3 in the main text). Mesozoic carbonates (Mz), Late Miocene unit M2 and Quaternary units Q1-2 (facies assemblage Q2), Q3a (marine terraces) and Q4. The outcrops of the M2a fluvial assemblage suggest that the palaeo-Ebro had a North-eastward trend near the present coast line (see also Figs. 2; 4B in the main text).

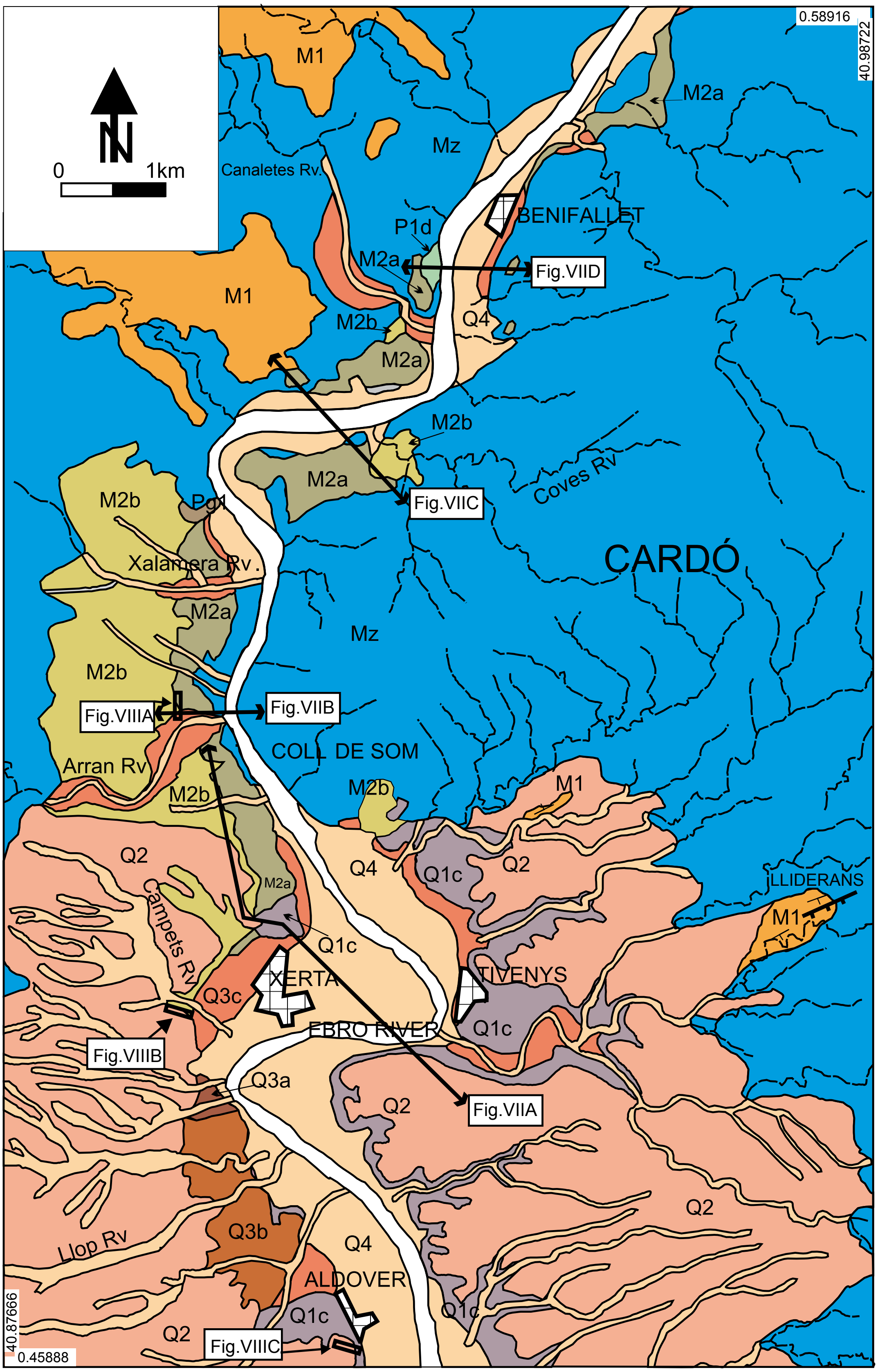



**FIGURE VI.** Geological sketch of the Aldover-Xerta-Benifallet area in the northern Tortosa Graben showing the location of the geological cross sections of Figure VII and the stratigraphic logs of Figure VIII (see legend in Fig. 3 in the main text).

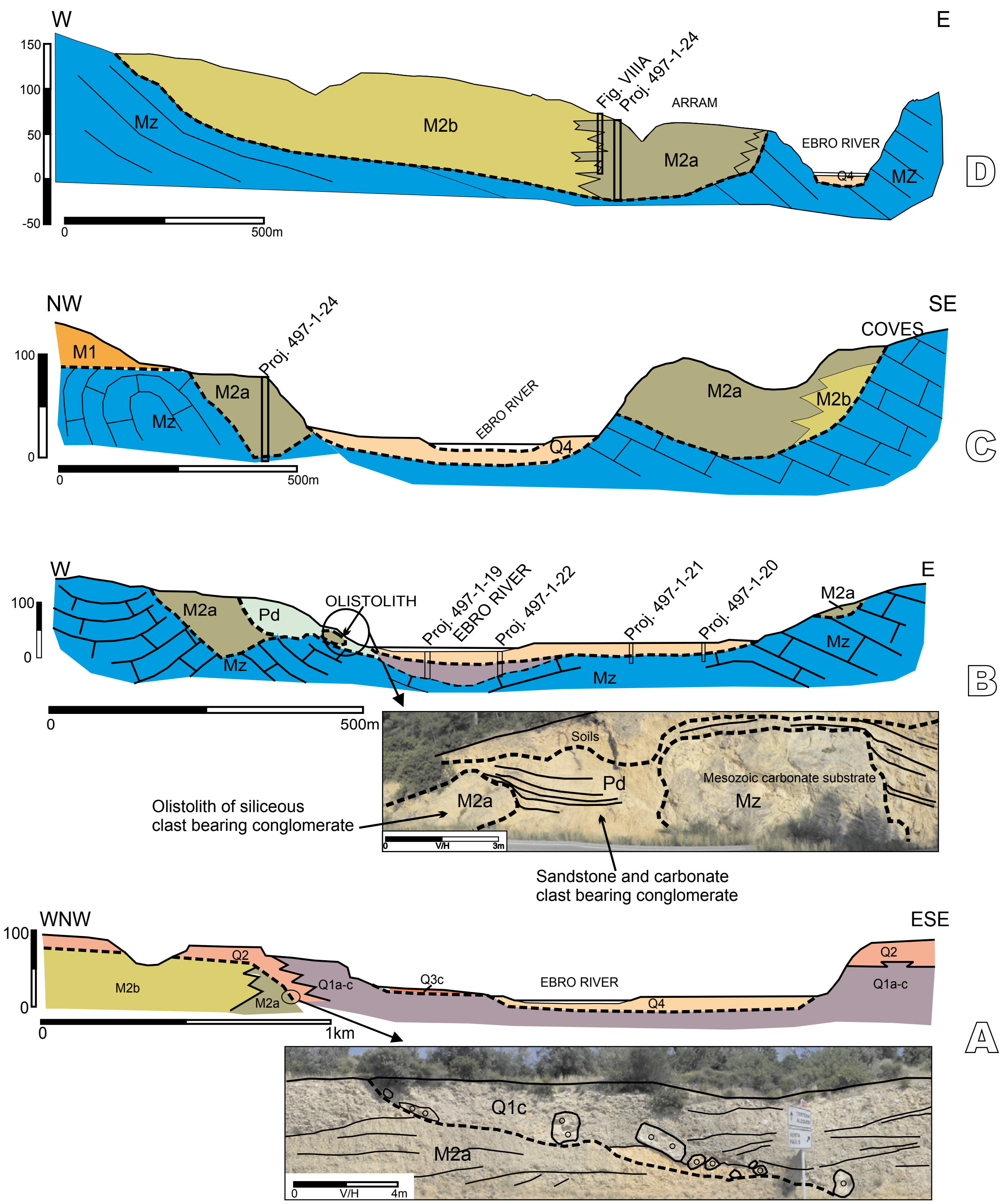



**FIGURE VII.** Geological cross sections between Xerta and Benifallet (see location in Fig. VI and legend in Fig. 3 of the main text). The sections B to D show the Late Miocene M2a-b unit overlying the erosion surface S2 developed indistinctly either on the Mesozoic or on the M1 unit. A) Relationship between unit M2 and the stepped terrace deposits of units Q1-2 to Q4. B) Outcrop that includes up to 75m in thickness of fluvial sands overlain by carbonate clast-bearing conglomerates (unit Pd). These deposits unconformably overlie Mesozoic rocks and sequences of the Miocene units M1 and M2. They are also affected by an intraformational erosive discontinuity associated with minor extensional faults that tilted the sequence. This alluvial succession includes olistoliths of siliceous clast–dominated conglomerate derived from unit M2a. This assemblage attains an altitude of 100m-a.s.l. and resulted from an incised valley fluvial sedimentation associated with probable lateral alluvial-fan contributions. The occurrence of an M2 olistolith demonstrates that this Pd assemblage must be younger than this unit and may represent the lateral alluvial-fluvial equivalent to the Pa marine facies of the unit P. This succession occurs as laterally eroded by the surfaces S4 to S6 and overlain by units Q1-2 to Q4. C) The Late Miocene M2a-b unit erodes indistinctly the Mesozoic substratum and the Early-Middle M1 unit. D) Lateral relationship of the M2a (fluvial) and M2b (alluvial-fan) assemblages overlying the Mesozoic substratum and evidencing the ancient layout of the palaeo-Ebro.

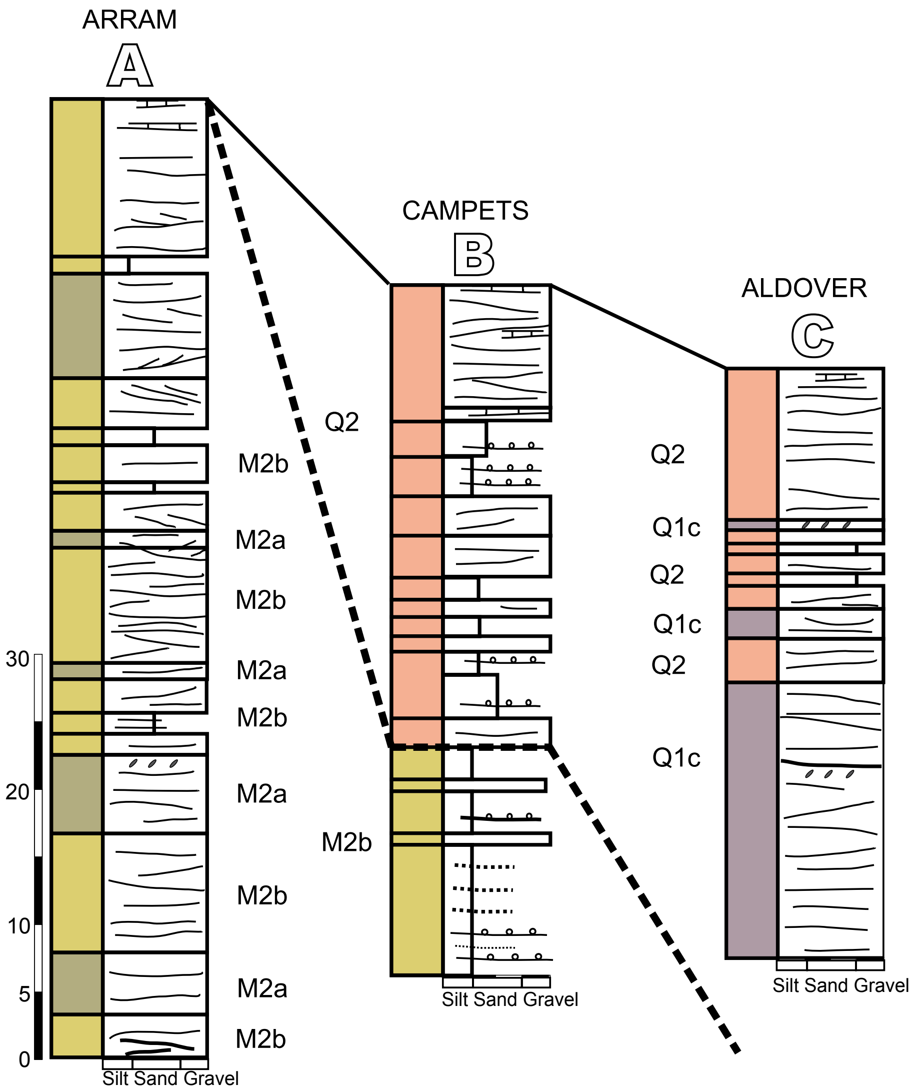
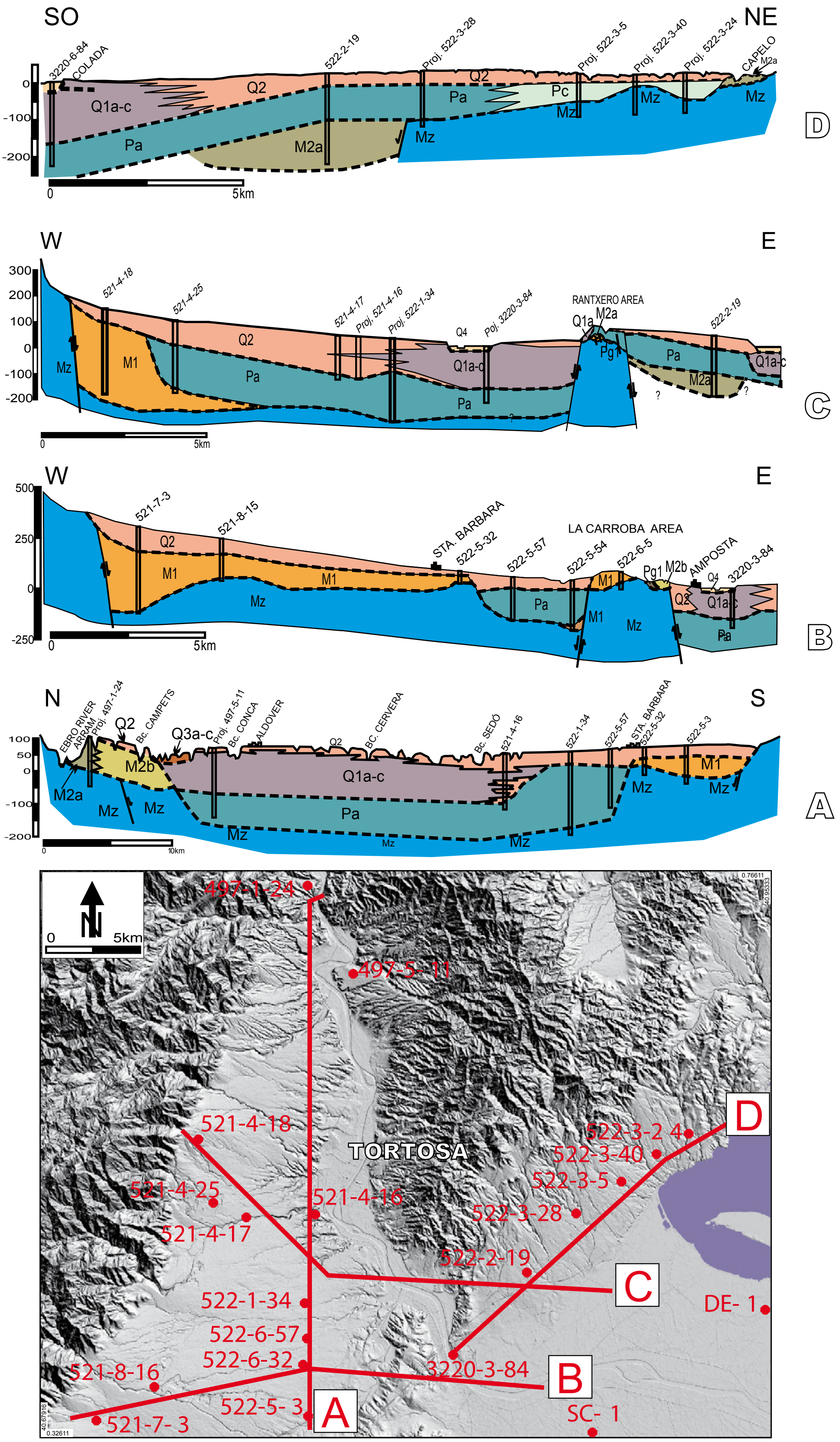



**FIGURE VIII.** Correlation of the stratigraphic columns in Figure VI, showing the interbedding of the fluvial (M2a) and alluvial–fan facies (M2b) in unit M2 and the erosion surface S4 between units M2 and Q1-2. The position of the columns refers to the topographic altitude.

**FIGURE IX.** Location of boreholes and geological cross sections of the Tortosa Graben (see legend in Fig. 3 of the main text). The Late Miocene M2 unit has been recorded at the top of La Carroba-Ranxero tectonic threshold (see also Figs. III; V) where it unconformably overlies the Mesozoic substratum and reaches a preserved thickness of up to 15m. Moreover, more than 80m of siliceous clast–bearing conglomerates have been recorded to the North of l'Aldea (borehole 522-2-19) where the fluvial deposits of the facies assemblage M2a are overlain by the blue marine mudstones of the lower Pliocene Pa assemblage (see cross sections C, D; see also Fig. IVE–G). The relatively thick accumulation of fluvial M2a facies suggests a significant subsidence and/or the generation of accommodation space related with the deeply incised erosion surface S2 (see also Figs. 5A and 6). The Quaternary Q1 fluvial assemblage often overlies an erosion surface (S4) deeply entrenched into the Pliocene blue-gray mudstones (Pa) and occurs on both sides of the Ebro River, reaching up to 165m in thickness (cross sections A to D). The alluvial fan facies (Q2), which spread from the surrounding reliefs, reach up to 200m in thickness, recorded at the boreholes near the El Port fault. These alluvial fan deposits thin towards the Ebro valley axis, where the outcrops show up to 5–10m-thick sequences, although up to 190m-thick sections that interfinger with the fluvial deposits have been reported (borehole 521-4-16; cross-section IXA). At La Carroba-Rantxero uplifted block, the siliceous clast–dominated fluvial assemblage Q1 was affected by minor extensional faults that record the reactivation of the faults in the topographic threshold that tilted the lower Q1a deposits 25º-35º North-westward. Subunits Q1b and Q1c were only affected by discontinuities and fractures associated with the extensional faults of the La Carroba-Rantxero zone (see also Fig. III, cross-sections A to D).



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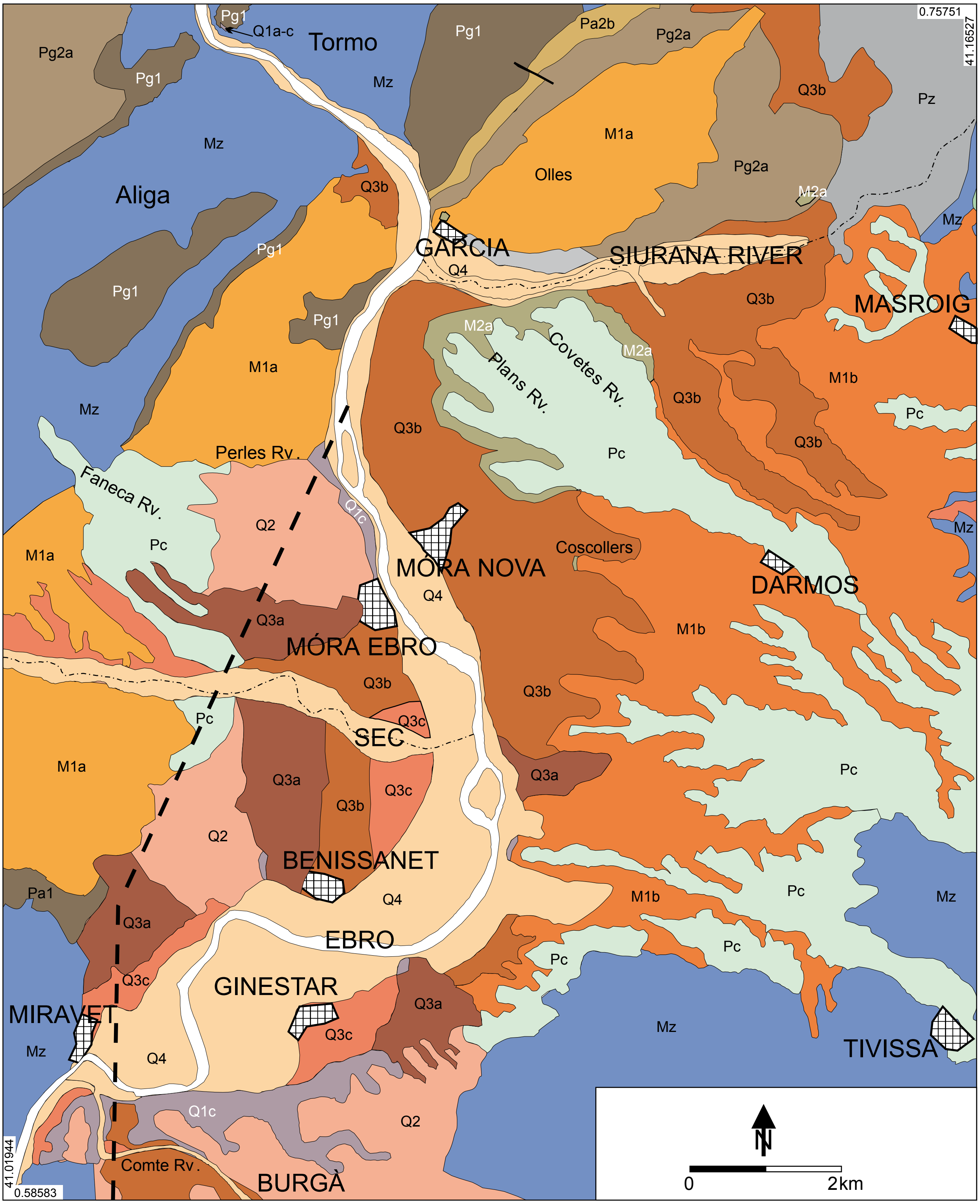
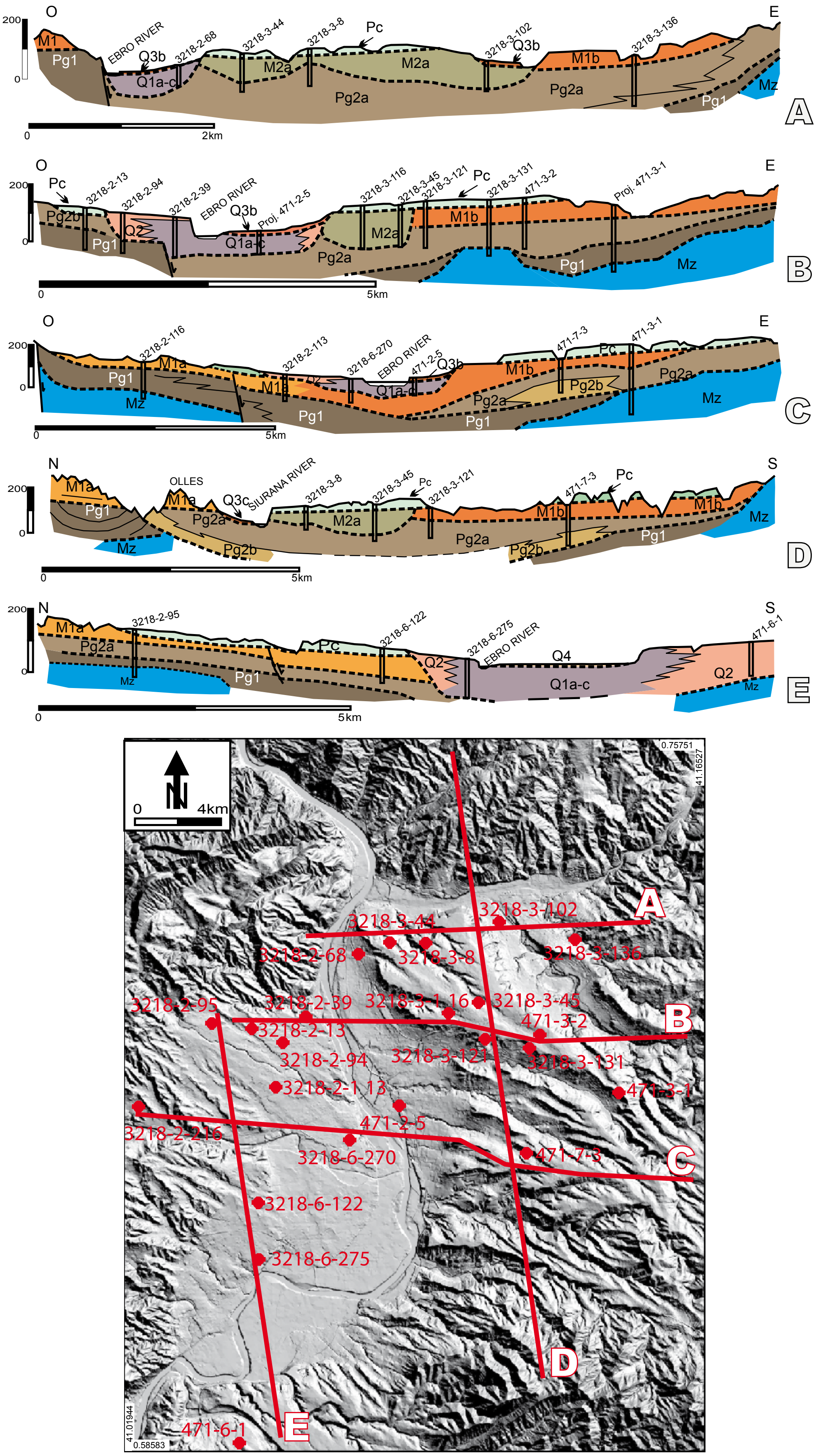



**FIGURE X.** Geological sketch of the central zones of the Móra Basin (see legend in Fig. 3 of the main text). See cross sections in Figure XI.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M1
Pg1
EBRO RIVER
Q3b
Q1a-c
3218-2-68
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3218-3-8
Pc
M2a
3218-3-102
M1b
3218-3-136
Pg2a
Mz
A
2km
Pg2b
Q2
3218-2-13
3218-2-94
3218-2-39
Proj. 471-2-5
3218-3-116
3218-3-45
3218-3-121
3218-3-131
471-3-2
Proj. 471-3-1
B
5km
3218-2-116
M1a
3218-2-113
3218-6-270
471-2-5
471-7-3
471-3-1
C
N
S
OLLES
Q3c
SIURANA RIVER
D
3218-2-95
3218-6-122
3218-6-275
Q4
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E
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0.75751
41.16527
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3218-2-68
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471-3-1
471-2-5
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471-7-3
3218-6-122
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471-6-1

**FIGURE XI.** Location of boreholes and geological cross sections in the Móra Basin showing the Miocene to Quaternary sequences overlying the Mesozoic and Palaeogene units (see legend in Fig. 3 in the main text). Early-Middle Miocene Unit M1: The sequences of the M1a assemblage made up by carbonate clast-bearing conglomerates attain up to 100m in thickness and pass basinward into the red mudstone dominated M1b assemblage. The top of these sequences currently occurs up to 250m-a.s.l. Late Miocene Unit M2: This unit includes outcrops of 70m-thick siliceous clast–bearing conglomerates and gravels. In the Siurana River valley, the higher terraces (110m-a.s.l.) contain slate, chert, granitoid and Mesozoic clasts and are considered equivalent to M2. Most of these Palaeozoic clasts were here mainly contributed from the Palaeozoic basement of the CCR (El Priorat, see Fig. 2 in the main text). The available borehole data points to the existence of a palaeovalley incised into the M1b red mudstones and conglomerates and filled by these deposits whose top was affected by the erosion surface S3 and overlain by alluvial fan deposits attributed to unit Pc (Figs. 2; 3; 5C in the main text). Quaternary: The Quaternary unit Q1-2 is recorded both at outcrops and boreholes as a single unit of siliceous clast–bearing conglomerates, gravels and sands (Q1a-c). Between Móra d'Ebre and Benissanet, the borehole data allow recognizing the siliceous clast-bearing fluvial conglomerates down to -70m-a.s.l. This thick conglomerate accumulation is here correlated with the subsidence resulting from the Burgà fault activity (Figs. 2; 5 in the main text). These fluvial deposits pass laterally and are overlain by thin (up to 5m-thick), carbonate clast–dominated conglomerate (Q2) deposited on a local alluvial fan system. The outcrops in Móra d'Ebre and those in Benissanet are especially significant (see also Fig. 5C in the main text).

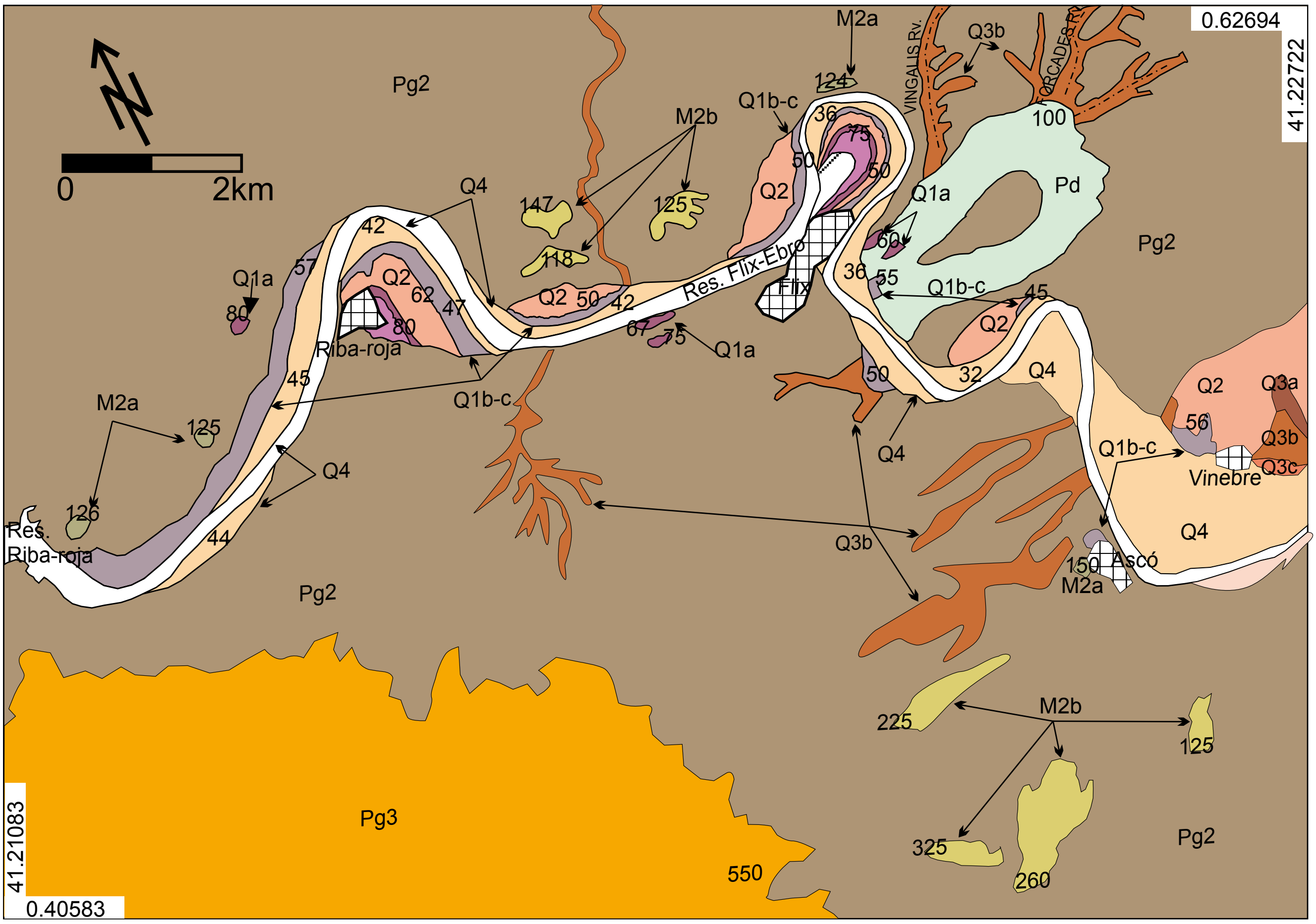


**FIGURE XII.** A) Geological sketch of the Flix-Riba-roja area showing the preserved record and distribution of diverse Late Miocene to Quaternary down-stepped units (see legend in Figure 3 of the main text). Numbers indicate the altitude above mean sea level (a.s.l.). Late Miocene (M2a and M2b). A variety of siliceous and carbonate clast–dominated gravels, conglomerates and breccias occur (see also Fig 5D). The siliceous clast–dominated deposits range from 2 to 20m in thickness and are locally topped by carbonate crusts. These deposits are fluvial in origin and make up stepped terraces incised into the Palaeogene rocks (Colombo, 1980). They include granitoid, Cambro-Ordovician quartzite with quartz veins (García-Sansegundo, 1991) and Ilerdian Alveolina limestone clasts. These fluvial deposits range from 105 to 150m-a.s.l. and pass laterally into much degraded carbonate clast–dominated alluvial fan breccias that resulted from the erosion of the surrounding Oligocene alluvial mudstones and lacustrine carbonates (Pg3; see Fig. 5D). These alluvial fan and fluvial assemblages have been correlated with the M2 deposits in the Xerta zone and considered Late Miocene in age. Pliocene Unit (Pd): A meander body incised into the Oligocene materials (Pg2) consists of 12m-thick sandy silt deposits, including some cobbles and pebbles derived from the Oligocene substratum. This deposit is located at 100m-a.s.l. and currently makes a part of a degraded glacis with contributions from the adjacent ravines. This structure is affected by an erosion surface (S4) that is in turn overlain by Pleistocene Q1-2 deposits (Fig. 5D). Therefore, a Pliocene age is here proposed for it. Quaternary (Q1-2 to Q4). Two highest terrace leves (Q1a and Q1b-c) occur at 75 and 50m-a.s.l., respectively. Other lower terrace levels (Q3 and Q4) also occur. All these terraces are topographically correlated with equivalent terraces in the Móra Basin and the Tortosa Graben (see also Figs. 5D; 6 in the main text).