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Tectonic and climatic controls on the development of foreland fan deltas: Montserrat and Sant Llorenç del Munt systems (Middle Eocene, Ebro Basin, NE Spain)

M. López-Blanco[a,*], M. Marzo[a], D.W. Burbank[b], J. Vergés[c], E. Roca[d], P. Anadón[c], J. Piña[a]

[a]Department d'Estratigrafia i Paleontologia, Facultat de Geologia, Universitat de Barcelona, 08028 Barcelona, Spain
[b]Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, USA
[c]Institut de Ciències de la Terra "Jaume Almera," CSIC, L. Solé Sabaris s/n, 08028 Barcelona, Spain
[d]Department de Geodinàmica i Geofísica, Facultat de Geologia, Universitat de Barcelona, 08028 Barcelona, Spain

Abstract

Along an early Cenozoic foreland–hinterland boundary in northeastern Spain, we synthesize the depositional environment, climatic conditions, structural evolution, age, catchment geometry, and altitudinal characteristics from sedimentologic, palynologic, stratigraphic, structural, and paleomagnetic data. As the transpressional Catalan Coastal Ranges rose during the Paleogene, two large fan deltas prograded into the Ebro foreland basin adjacent to the northeastern part of the range. The apices of the fans likely were localized by lateral ramps or tear faults along which rivers from hinterland catchments debouched into the foreland. Beginning in the late Lutetian, proximal debris-flow, sheetflood, and distal fluvial deposits maintained the fan surface at or above sea level, despite rapid basin subsidence during the succeeding 4.4 my. Palynological data suggest that a warm, humid climate prevailed throughout this interval. The mapped extent of the two fans permits an estimation of their volumes, whereas the spatial distribution of distinctive lithologies within the ancestral Catalan Coastal Ranges serves to delimit the approximate catchment areas for each of the fans. We estimate mean hinterland denudation rates to range from 100 to 180 m/my and mean catchment elevation to range from 700 to 1250 m. The steep gradients between these catchments and the low-lying fan deltas is attributed to the tectonic style of the ancestral Catalan Coastal Ranges, which are characterized by an uplifted basement block along a steep frontal thrust accompanied by folding of cover rocks. The considerable topographic relief of these catchments is inferred to have combined with co-seismic shaking to produce landslides and rockfalls, which were reworked as debris- and fluid-gravity deposits on the fan surfaces.

Keywords: Foreland basin; Fan delta; Eocene paleoclimatology; Magnetostratigraphy; Subsidence analysis; Tectonosedimentology; Tectono-geomorphology; Relief denudation

1. Introduction

This paper aims to reconstruct the tectono-sedimentary, tectono-geomorphic, and paleoclimatic setting of Eocene fan-delta complexes located at a foreland basin margin adjacent to the Paleogene Catalan Coastal Ranges, which comprise a transpressive chain that was subsequently modified by a Neogene extensional fault system (Figs. 1 and 2). These reconstructions provide the basis for a semiquantitative estimate of the rates of some key geological processes (denudation, sedimentation, and subsidence) controlling the long-term (~4.5 my) development of the fan deltas.

* Corresponding author.
E-mail address: miguel@geo.ub.es (M. López-Blanco).

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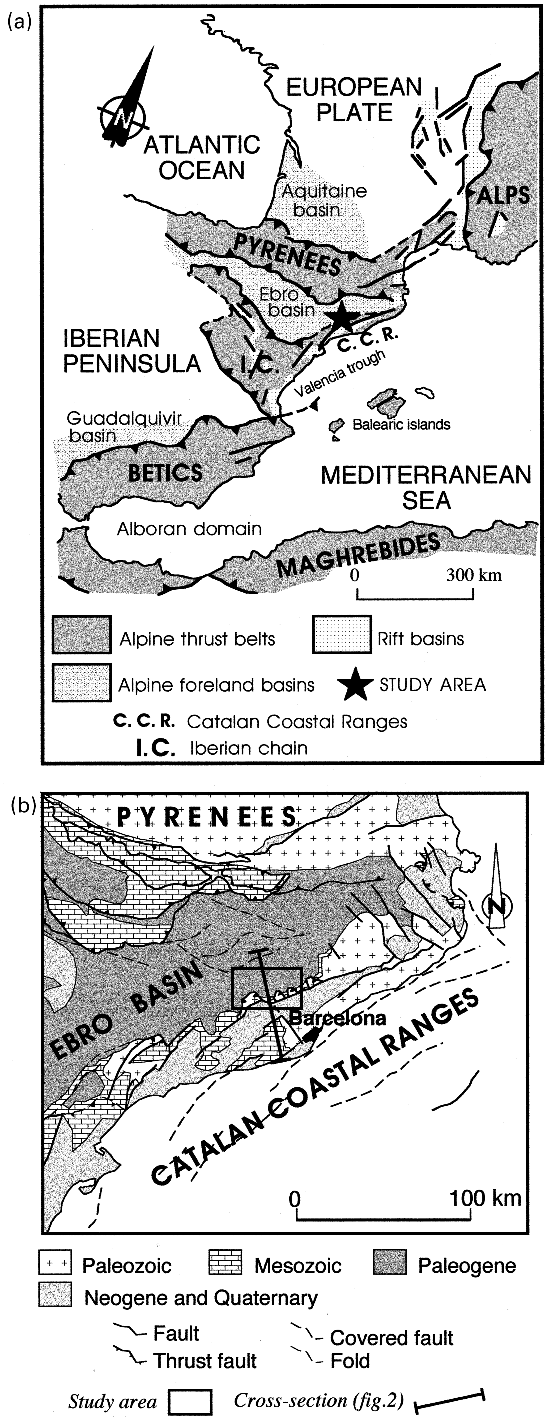


Fig. 1. Main geological units: (a) in the western Mediterranean; (b) in the northeastern part of the Iberian peninsula.

We have taken an interactive, multidisciplinary approach involving the following steps.

- Sedimentological and stratigraphical analysis of the syntectonic, Paleogene foreland basin-margin deposits with particular emphasis on reconstructing (semiquantitatively) the fan-delta depositional surfaces and on dating the Montserrat section using combined biostratigraphic and magnetic polarity studies.
- Paleoclimatic analysis based on palynological, sedimentological, paleontological, geochemical and mineralogical evidence.
- Structural studies along the preserved segments of the compressive Catalan Coastal Ranges, which allow us to determine the general structure of the chain and the sequence of deformation.
- Integration of structural, stratigraphic, and sedimentological data in order to establish the timing of basin-margin deformation and its related unroofing sequence.
- Calculation of subsidence and sedimentation rates and evaluation of their relationships to the previously established tectono-sedimentary basin-margin evolution;
- Reconstruction of the fan-delta catchment areas from fan-delta clast-composition analysis and outcrop–subcrop mapping; this allowed us to estimate (a) denudation rates (by restoring depositional volumes to their related catchment-basin surfaces) and (b) mean topographic elevation of drainage basins (by using empirical formulae); and
- Determination of the relationships among tectonics–topography, topography–climate–denudation rates, and tectonics–subsidence–sedimentation rates in order to constrain the controls on the development of the studied clastic wedges.

It is largely the synthesis of diverse data sets that provides new insights into the relationships among basinal deposition, hinterland deformation, and denudation (cf. DeCelles et al., 1991; Burbank and Vergés, 1994; Burbank et al., 1996). In isolation, each data set may permit a reconstruction of a limited aspect of the complete erosional–depositional system. When considered together, feedbacks and linkages between climate, topography, erosion, structure, geomorphology, and sedimentation can be examined and an

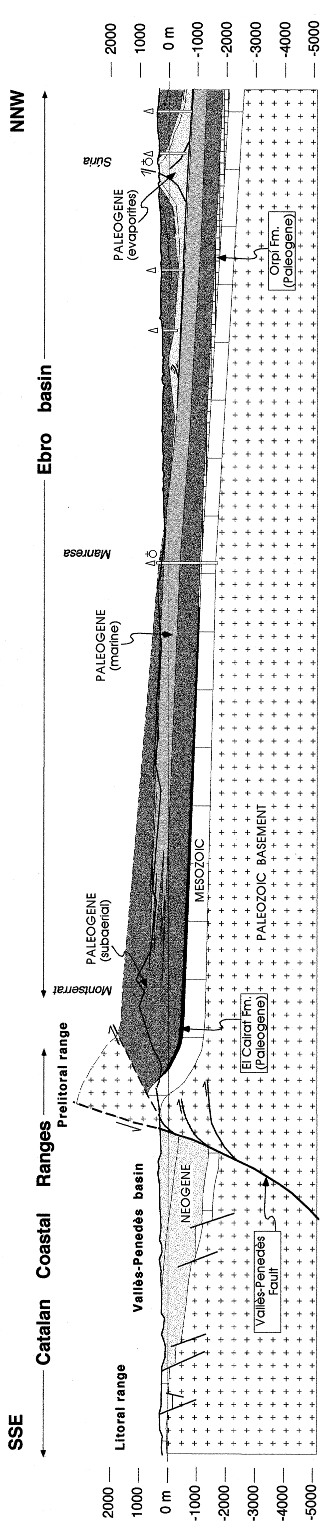


Fig. 2. Cross section through the Catalan Coastal Ranges and the southeastern margin of the Ebro Basin showing the superposition of compressive (Paleogene) and extensive (Neogene) structures (based on Vergés, 1993). The Paleogene subaerial and marine deposits refer to the Montserrat alluvial fan and fan-delta system and the Paleogene evaporites to the Cardona Fm. (see Fig. 3 for additional stratigraphic information).

improved understanding of the complex responses of these integrated systems can be attained.

2. Geological setting

The studied fan deltas are located along the southeastern margin of the Ebro foreland basin adjacent to the Catalan Coastal Ranges, an Alpine structural unit running parallel to the Mediterranean coast in the northeastern part of the Iberian Peninsula (Fig. 1).

2.1. Alpine tectonic history of the NE margin of Iberia

The structure of the northeastern margin of Iberia resulted from two Alpine processes: the convergence between Iberia and Eurasia and the displacement of the Alboran domain towards the west relative to Iberia.

The first process, Late Cretaceous–Early Miocene in age, led to a N–S compressive regime that built the Pyrenean orogen along the northern margin of the Iberian plate and, during the Paleogene, caused the development of thrust belts in the interior of the Iberian plate (i.e., Iberian Chain and Catalan Coastal Ranges). Synchronously, foreland basins developed atop the northern Iberian plate. Bounded by the Pyrenees, the Iberian Chain, and the Catalan Coastal Ranges, the Ebro foreland basin formed primarily as a flexural response of the lithosphere to the Pyrenean thrust belt (Brunet, 1986; Millán et al., 1995), although some flexure was induced by the tectonic loads of the Catalan Coastal Ranges and the Iberian Chain on the southern and eastern margins of the basin (Zoetemeijer et al., 1990).

After the welding of the Iberian and Eurasian plates during the Oligocene (Vergés et al., 1995), the structural evolution of eastern Iberia was controlled by the western displacement of the Alboran domain relative to Iberia. This process initiated the development of both contractive and extensional structures. The contractive structures were concentrated in the collision area between Iberia and the Alboran domain and led to the growth of the Betic–Balearic thrust-and-fold belt. The extensional structures developed mainly in the inner parts of Iberia, although they also belatedly affected the Betic–Balearic orogen. Widespread extensional basins often formed from the tectonic inversion of old Paleogene compressive structures.

Outstanding among these basins, the Valencia Trough is located between the Iberian Peninsula and the Betic–Balearic thrust-and-fold-belt.

2.2. The Catalan Coastal Ranges

The Catalan Coastal Ranges trend NE–SW between the Ebro Basin and the Valencia Trough (Ashauer and Teichmüller, 1935; Llopis Lladó, 1947). These ranges have a complex structure that reflects the superposition of compressive and extensional structures (Figs. 1B and 2) resulting from the growth of a Paleogene transpressive intraplate chain (Anadón et al., 1985a; Guimerà, 1988). From the Late Oligocene, this chain became the western passive margin of the extensional Valencia Trough (Roca and Guimerà, 1992).

The structure of the Paleogene intraplate chain has resulted from a NW-directed thrust system whose hanging-wall is cut by sinistral NE–SW strike-slip faults (Roca, 1992). This thrust system crops out mainly in a narrow ENE–WSW to NE–SW-oriented zone between the Catalan Coastal Ranges and the Ebro Basin, and has two detachment levels. The lower detachment, now located at a depth of 12 km, is related to the formation of large-scale, basement-involved structures (Roca and Guimerà, 1992; Colombo and Vergés, 1992; López-Blanco, 1993). The upper detachment is located in Triassic rocks and forms a décollement between basement and cover rocks. Although there is apparent tectonic transport normal to the direction of the chain, the oblique direction of the Catalan Coastal Ranges with respect to the convergence vector and the existence of strike-slip faults strongly suggests that there was a Paleogene precursor to the Catalan Coastal Ranges. This likely took the form of a transpressive chain with sinistral motion along segments of its front (Guimerà, 1984; Anadón et al., 1985a). In addition to the syntectonic Paleogene sediments located along the Ebro Basin margin, this Paleogene structure involves Paleozoic basement and Mesozoic (Triassic, Jurassic, and Cretaceous) cover.

Although the Paleogene deformation is well recorded, the main features of the present structure of the Catalan Coastal Ranges were acquired during the late Oligocene–Miocene opening of the Valencia Trough, and show a typical continental margin structure with a relatively thin crust (22–32 km; Gallart et al., 1994) and a well-developed horst-and-graben structure. Resulting from the tectonic inversion of the major Paleogene basement faults, this extensional structure is parallel to the present-day coastline and compartmentalizes the previous Paleogene structure of the Catalan Coastal Ranges into several ENE–WSW to NE–SW-striking blocks, generally tilted to the NW (Figs. 1B and 2). The grabens are filled by as much as 4000 m of Neogene sediments (Bartrina et al., 1992) and are bounded to the northwest by major ENE–WSW to NE–SW, listric normal faults.

Where preserved in the footwall of these major faults, the Catalan Coastal Ranges and the southeastern margin of the Ebro Basin are not affected by extensional structures. Instead, they display striking topographic relief, which reveals the regional tilt of the Paleogene beds of the Ebro Basin (Fig. 2). The post-Oligocene formation of this relief is synchronous with the development of the extensional structures of the Valencia Trough. Consequently, the origin of this relief has been attributed to an edge effect (rift shoulder) of the crustal thinning that generated the Valencia Trough during the late Oligocene–Miocene (Morgan and Fernández, 1992; Janssen et al., 1993).

3. Stratigraphy and sedimentology

The Ebro foreland basin-fill includes marine and continental deposits that are Paleocene to Middle Miocene in age. The Paleocene to Eocene Ebro Basin was connected to open Atlantic waters to the northwest and to Tethyan waters to the northeast (Fig. 1A). Restriction of these marine connections during the late Bartonian led to the deposition of evaporites (Cardona Formation). Subsequently, the Late Eocene (Priabonian) to Late Miocene Ebro foreland basin became an endorheic sedimentary trough filled exclusively with continental deposits. The studied fan-delta deposits, mostly Middle Eocene in age, belong to the first, marine, basin-fill hemicycle.

3.1. The Paleogene succession at Montserrat and Sant Llorenç del Munt

Paleogene sedimentation along the central part of the southeastern margin of the Ebro Basin produced both shallow marine and continental deposits whose lithostratigraphic relationships, chronostratigraphy, and inferred depositional environments are summarized in Fig. 3.

Two sectors with markedly different facies associations are apparent (Fig. 3): the Igualada area to the WSW and the Montserrat–St. Llorenç del Munt area to the northeast. The facies association in the Igualada region, dominated by fine-grained clastics, carbonates, and evaporites, is representative of those areas located several kilometers away from the basin margin. The Montserrat–Sant Llorenç del Munt facies association, characterized by thick accumulations of conglomerates and breccias, typifies basin-margin settings. In this marginal setting, only Bartonian (late Middle Eocene) marine deposits crop out, contrasting with the Igualada area, where two marine depositional episodes, early Ypresian and Bartonian in age, respectively, are recorded.

In addition to the Montserrat and Sant Llorenç del Munt Conglomerates (see below), the main lithostratigraphic units integrated within the Montserrat–Sant Llorenç del Munt facies association are as follows (Anadón, 1978; Anadón et al., 1985b, 1986, 1989; Marzo and Anadón, 1988):

1. Mediona Formation (50-m thick), consisting of red sandstones and mudstones with frequent paleosols developed on alluvial mudflats and palustrine–lacustrine environments.
2. Cairat Formation (up to 200-m thick), consisting of monogenic (Triassic-derived) carbonate breccias interbedded with red sandy mudstones, interpreted as debris- and mud-flow deposits, accumulated on small, coalescing alluvial fans and screes.
3. La Salut Formation (up to 300-m thick), consisting of distal alluvial, red mudstones and sandstones enclosing channeled to sheetlike bodies of polygenic conglomerates with Mesozoic and Paleozoic clasts.
4. La Torre, Can Ferrés, Les Morelles, and Can Sabater Formations, consisting of monogenic breccias of Paleozoic-derived clasts, which represent scree deposits abutting basement thrust sheets.

3.2. The Montserrat and Sant Llorenç del Munt Conglomerates

During the Lutetian (early Middle Eocene), tectonic activity in the Catalan Coastal Ranges led to the development of coalescing alluvial fan systems along the southeastern Ebro Basin margin. After a regionally widespread Bartonian relative sea-level rise (the so-called "Bartonian transgression"), these alluvial fan systems evolved to fan deltas (Anadón, 1978; Anadón et al., 1985b; Marzo and Anadón, 1988). Among these, the Montserrat and Sant Llorenç del Munt fan-delta complexes stand out because of their thickness and the radial geometry of their deposits.

The most proximal, conglomeratic deposits of the Montserrat fan complex (Montserrat Conglomerate Formation) overlie the finer-grained La Salut Formation (Fig. 3). According to Anadón et al. (1985b) and Marzo and Anadón (1988), these conglomerates show a maximum radial extent of about six km and constitute a coarsening-upward megasequence more than 1400 m thick. They include eight component conglomeratic units (75–250 m thick) bounded by thin sand-rich intervals that have crude to well-defined, coarsening or coarsening-fining upward trends. Although debris-flow conglomerates are commonly found near the fan apex (Anadón et al., 1985b), the proximal subaerial reaches of the Montserrat fan are characterized by a dominance of fluid-gravity flow (sheetflood) and channeled flow deposits (Marzo and Anadón, 1988). Almost all Montserrat conglomerates consist of moderately to well-rounded clasts of Triassic carbonates, with minor amounts of Cretaceous carbonates, Triassic sandstones, and Paleozoic rocks derived from the erosion of the ancestral Catalan Coastal Ranges during the Paleogene. This clast composition denotes a dominance of mostly Triassic-cover outcrops in the catchment area of the Montserrat fan.

Detailed mapping (López-Blanco, 1996) reveals that the proximal facies of the Sant Llorenç del Munt fan consists of a thick succession (up to 1500 m) of massive conglomerates (Sant Llorenç del Munt Conglomerate Formation; Fig. 3) with a maximum observed radial extent of about 13 km. The Sant Llorenç del Munt fan includes sheetflood, streamflood channels, and debris-flow deposits (López-Blanco, 1993, 1996). The latter are more common than in the Montserrat fan and sometimes spread 10 km away from the fan apex. In contrast with the Montserrat Conglomerate, Paleozoic-derived clasts are generally dominant, Cretaceous-derived clasts are

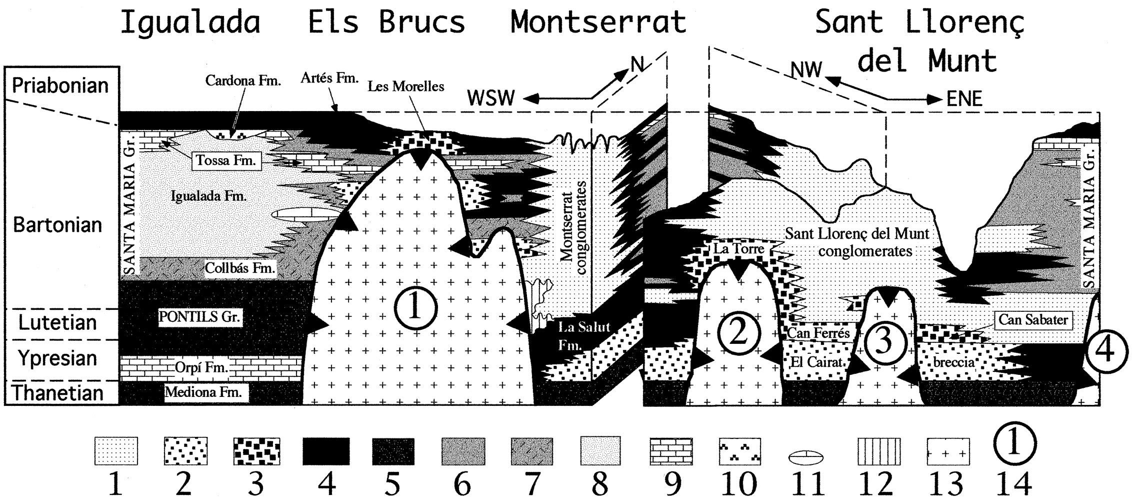


Fig. 3. Lithostratigraphy, chronostratigraphy, and depositional environments of the Paleogene of the central part of the eastern margin of the Ebro Basin (see inset in Fig. 1B) along a section parallel to the basin margin (no vertical scale). Modified from Anadón et al. (1985b). 1: Polygenic, alluvial-fan conglomerates. 2: Monogenic, Triassic-derived breccias. 3: Monogenic, Paleozoic-derived breccias. 4: Distal alluvial-fan/fan-delta plain, red sandstones, mudstones, and conglomerates. 5: Alluvial, red mudstones and sandstones. 6: Fan-delta front, sandstones and conglomerates. 7: Nearshore, sandstones, calcarenites, and calcareous mudstones. 8: Offshore and prodelta calcareous mudstones. 9: Reef and platform carbonates. 10: Gypsum. 11: Triassic-derived olistostromes. 12: Erosional gaps related to syntectonic unconformities. 13: Covered by thrust sheets. 14: Paleozoic thrust sheets (1: Els Brucs, 2: Les Pedritxes, 3: Can Sallent, 4, Bigues).

very rare, and the clasts are generally more angular. Triassic-derived clasts are also common and locally dominant, so that the stratigraphic subdivision of the proximal facies in the Sant Llorenç del Munt Conglomerate is based on the presence of four main marker beds of monogenic conglomerates, 0.5–25-m thick, traceable over most of the fan system and consisting mostly (up to 80%) of Triassic-derived carbonate clasts (López-Blanco, 1996; López-Blanco et al., 2000).

Basinward, the proximal massive conglomerates of the Montserrat and Sant Llorenç del Munt fans thin rapidly and merge into distal alluvial fan and marine facies associations (Marzo and Anadón, 1988; López-Blanco, 1993). The distal alluvial facies are characterized by scoured, channel-fill conglomerates embedded in red sandstones and mudstones (Fig. 3). Based on the lateral extent of this distal alluvial facies belt, a mean radial extent of about nine and 16 km can be deduced for the subaerial reaches of the Montserrat and the Sant Llorenç del Munt fan systems, respectively. From these values, the related fan areas have been estimated at 100–150 km^2 (Montserrat) and 350–450 km^2 (Sant Llorenç del Munt). When compared with other values of fan-areas compiled by Blair and McPherson (1994, their Fig. 14.22), the studied examples can be typified as large fan systems.

The transitional to marine facies association comprises alternating clastic (mostly sandy) fan-delta and carbonate platform deposits (López-Blanco, 1993). Seven, 50 to 250-m thick, transgressive–regressive, composite sequences have been identified in the transitional areas of the Montserrat and Sant Llorenç del Munt systems (López-Blanco, 1993; López-Blanco, 1996; López-Blanco et al., 2000). Several exploration wells (Castellfollit 1 and Sant-pedor), drilled 20–30 km away from the Catalan Coastal Ranges, show clearly the basinward passage of the shallow marine transitional facies belt into a thick succession of prodeltaic and shelf mudstones.

3.3. Montserrat magnetic polarity stratigraphy

In order to develop improved time control on the depositional history of the Montserrat fan delta, an analysis of the magnetic polarity stratigraphy of the Eocene marine and terrestrial strata was undertaken. The Class I and II data (see Appendix for more details on the sampling and analytical procedures) define a magnetic polarity stratigraphy (MPS) comprising 11 magnetozones, each of which includes two or more sites of similar polarity (Fig. 4). The a_{95}-error envelope indicates that these polarities are generally unambiguous. Correlation of the MPS with the global magnetic polarity time scale (Cande and Kent, 1992) is aided by fauna associated with strata that define the so-called "Bartonian transgression" (~650 m, Fig. 4). In addition, regional mapping indicates that the Cardona evaporites (Fig. 3) stratigraphically overlie the entire dated sequence at Montserrat. Biostratigraphic studies indicate that the Cardona evaporites are late Bartonian in age (Serra-Kiel and Travé, 1995), whereas magnetic studies in the southern Pyrenees indicate that the Cardona strata were mostly deposited during the latter half of chron 17.1 (Burbank et al., 1992; Vergés and Burbank, 1996). Given these constraints, the most reasonable correlation with the magnetic time scale assigns the base of the Montserrat Conglomerate to the base of chron 19n and places the top of the dated section in the lower half of chron 17.1 (Fig. 4). Accordingly, the Montserrat Conglomerate section spans as much as ~4.4 my, from ~37.2 to 41.6 Ma.

The lack of outcrops of pre-Bartonian marine rocks and the paucity of fossil remains in the continental La Salut and Cairat Formations make it difficult to determine their chronostratigraphic position (Anadón, 1978). Despite the magnetic sampling, no reliable correlation was obtained of the La Salut Formation (Fig. 4) with the global magnetic polarity time scale. Such a correlation would require a closer sampling (see Appendix) in order to check the possible occurrence of significant stratigraphic gaps and their duration.

4. Paleoclimate

Palynological data, supplemented by sedimentological, mineralogical, and isotopic observations, provide the key to a Bartonian paleoclimatic reconstruction for the study area. Cavagnetto and Anadón (1996) have described variations in pollen spectra in some stratigraphical intervals from the Middle Bartonian to the Lower Oligocene in the Igualada area.

During the Middle Bartonian (Collbas Formation, Fig. 3), the majority of the taxa identified correspond to present-day taxa confined to tropical or subtropical climates; thus, the assemblage is characteristic of a warm climate. In addition, several taxa suggest warm and humid vegetation. Taxa that are representative of extant temperate regions are absent. Complex mangrove swamp vegetation grew along the coast. Further inland, a plain with *Nypa* possibly covered a large area (Cavagnetto and Anadón, 1995). The Middle Bartonian pollen assemblage shows a greater diversity of taxa than in the Upper Bartonian and Priabonian.

During the Upper Bartonian (Igualada Formation, Fig. 3), the mangrove vegetation is represented only by *Nypa* (less than 1% of pollen grains). However, the presence of Rubiaceae pollen *Psychotria*-type (genus unknown) and Bombacaceae indicate the persistence of warm conditions. Reworking of Mesozoic pollen from the sedimentary cover of the Catalan Coastal Ranges is indicated by the presence of *Classopollis*, *Normapolles*, and different spores: *Classopollis* is abundant in Jurassic, Lower Cretaceous, and Cenomanian fossil pollen floras.

The pollen data from the Priabonian nonmarine deposits (Artés Formation, Fig. 3) indicate that the flora no longer included a large number of thermophilous angiosperms, although 17 megathermal genera are still present, and some of them apparently appeared during the Priabonian. Several genera grow at present in tropical or subtropical regions and others may indicate a change to more open vegetation (some taxa are today typical of savannah) and the development of a dry season. The presence of a group of six taxa interpreted as indicators of a dry climate and the disappearance of those indicating humid climatic conditions distinguish the flora of the Priabonian from that of the Middle Bartonian. Dry climatic conditions characterize the Lower Oligocene.

Based on these palynological data, the most likely climatic setting for the studied depositional areas during the Bartonian was one of warm and relatively humid conditions. These conditions accord with other observations indicating the presence of mangrove swamp paleofloras (Alvarez Ramis, 1982; Biosca and Via, 1988), as well as with the extensive development of scleractinian reefs (Salas, 1995; Santisteban and Taberner, 1988; Serra-Kiel and Travé, 1995)

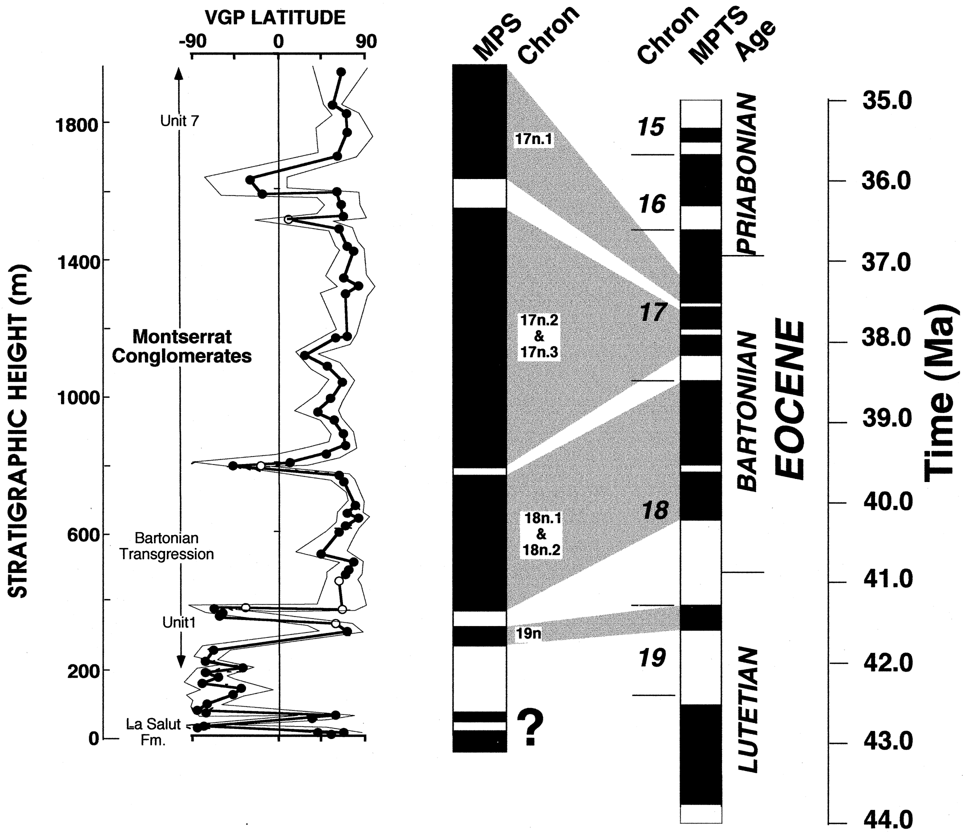


Fig. 4. Magnetic polarity stratigraphy for the Montserrat section and correlation with the magnetic polarity time scale (Cande and Kent, 1992). The VGP latitudes of Class I and II sites are plotted with their associated 95% confidence intervals. The normal and reversed data define 11 magnetozones, each of which contains two or more sites and includes at least one Class I site. Chronological tie points, consisting of the Cardona evaporites that overlie the dated succession (see Figs. 2 and 3) and the marine strata of the Bartonian transgression, constrain the correlation. This correlation indicates that the deposition of the Montserrat Conglomerate Formation commenced in late Lutetian times (~41.6 Ma) and that the upper part of the Montserrat Conglomerate dates from ~37.2 Ma.

synchronous with the development of the Montserrat and Sant Llorenç del Munt fan deltas. The occurrence of marked, sporadic, or episodic (seasonal or plurannual?) fluvial discharge and water-table fluctuations are deduced from: (1) sedimentological and isotopic analyses of microbialites found in distal alluvial fan, channel-fill deposits (Anadón and Zamarreño, 1981; Zamarreño et al., 1997); (2) the dominance of palygorskite in alluvial flood plain, lacustrine, and lagoonal sediments (Inglés and Anadón, 1991); (3) the abundance of hydromorphic paleosols in overbank alluvial deposits (Anadón, 1978; Anadón et al., 1985b); and (4) the occurrence of sedimentological features in shallow lacustrine to paludal limestones (Anadón, 1978) pointing to a seasonal wetland regime (Platt and Wright, 1992; Wright and Platt, 1995).

5. Tectonics

Due to the superposition of the Neogene extensional fault system in the study area, only the frontal structure of the contractive Paleogene Catalan Coastal Ranges is preserved along a narrow ENE–WSW strip (called Prelitoral Range) bounded by the Vallès–Penedès fault (Figs. 1B, 2, and 5). In this strip, the Hercynian basement, the Triassic cover, and the lower part of the Ebro basin-fill (Lower Paleogene in age) are involved in a contractive structure characterized

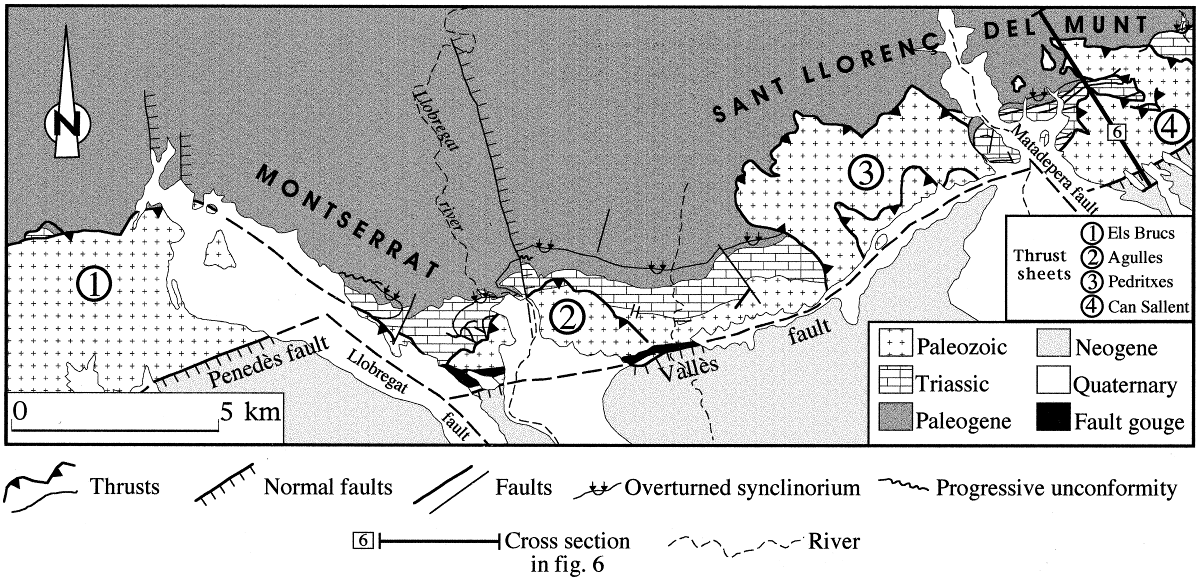


Fig. 5. Geological map of the preserved segment of the compressive, Paleogene Catalan Coastal Ranges (Prelitoral Range) and the Ebro foreland margin in the study area. Map is based on data from the present study and from Peón et al. (1975a,b) and Ubach (1990). The Hercynian basement, the Triassic cover, and the lower part of the Ebro basin-fill are involved in a compressive structure characterized by a syncline–anticline pair that forms a homoclinal NW-verging flexure in the basin-chain boundary. A large out-of-sequence thrust (Prelitoral thrust) cut the forelimb of the anticline–syncline pair and carried Paleozoic basement rocks on top of the Mesozoic and foreland Tertiary rocks deformed on its footwall (see Fig. 6).

by a syncline–anticline pair that forms a homoclinal NW-verging flexure in the basin-chain boundary (Fig. 2). Southwest of the study area, where the above-mentioned flexure is completely preserved, the width of the anticline–syncline couplet is ~2 km (Colombo and Vergés, 1992) giving an idea of the folding amplitude.

According to López-Blanco (1994), two main sets of thrusts deformed both basement and cover in the study area (Fig. 6). The first set of thrusts is mostly foreland-directed (with subordinated backthrusts), intersects bedding at a low angle, and repeats the Triassic section. Basement rocks are involved, implying that this thrust system takes root within the basement. These thrusts were subsequently folded and tilted during the development of the anticlinal–synclinal flexure.

The second set of thrusts, involving a greater amount of shortening, is northwest-directed and southeast-dipping. They are interpreted as out-of-sequence thrusts because they are located towards the hinterland of the previous system of thrusts and they displace the older thrusts. This younger set of thrusts cut the forelimb of the anticline–syncline pair and carried Paleozoic basement rocks over the Mesozoic and foreland Tertiary rocks deformed on its footwall (Figs. 5 and 6).

Considering the crosscutting relationships between the different structures, we can establish a clear sequence of deformation, involving three partly synchronous stages.

1. Emplacement of a first set of low-angle thrusts deforming both the cover and the basement.
2. Development of an anticline–syncline flexure, which is interpreted as a response to tip migration of a deep-seated thrust (fault-propagation anticline). This anticline folds the previous set of thrust faults.
3. Development of a large "out-of-sequence" thrust across the vertical and overturned anticline–syncline limb, carrying basement rocks to the surface.

The frontal structure of the Catalan Coastal Range,

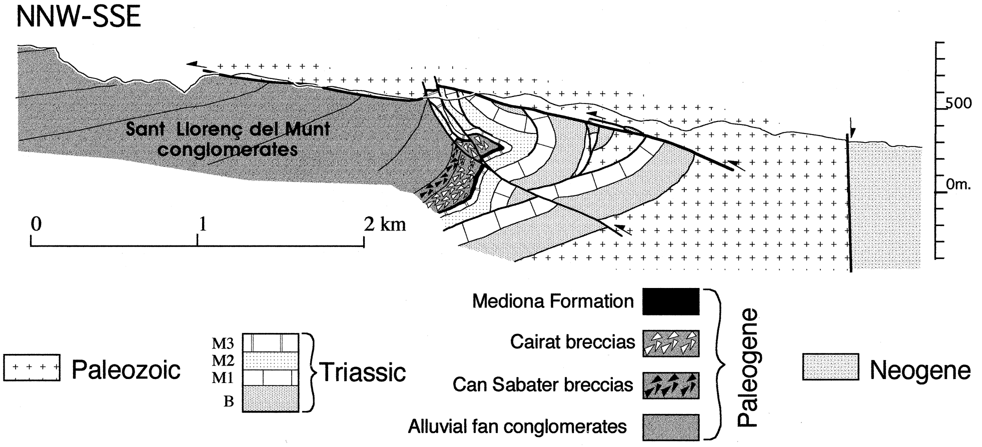


Fig. 6. Cross section of the compressive Catalan Coastal Ranges at Matadepera (see Fig. 5 for location). A. The sequence of deformation involves three partly synchronous stages: (1) emplacement of a first set of low-angle thrusts deforming both the cover and the basement; (2) development of an anticline–syncline flexure interpreted as the tip-point of a deep-seated thrust (fault-propagation anticline; the anticline folds the previous set of thrust-faults); and (3) development of a large, out-of-sequence thrust (Prelitoral thrust) across the vertical and overturned anticline–syncline limb, which carried basement rocks to the surface. B. Buntsandstein facies (Lower Triassic) and M1, M2, and M3 (Lower, Middle, and Upper Muschelkalk facies, Middle Triassic), respectively. See Fig. 3 for further stratigraphic information on the Paleogene deposits.

therefore, roughly corresponds to the propagation of a large out-of-sequence thrust (called the Prelitoral thrust) through the forelimb of a syncline–anticline pair. This thrust has an irregular map trace that can be explained as frontal and lateral ramps (Fig. 5). It is important to note that both Montserrat and Sant Llorenç del Munt fans are located at the intersection between frontal and lateral segments of the thrust, corresponding with the SE–NW-oriented Llobregat and Matadepera dextral tear faults (Figs. 5 and 7). These lateral segments created SE–NW-trending uplifts that influenced the location and geometry of the drainage basins during thrusting (Section 8.1).

The hanging wall of the Prelitoral thrust is also affected by an ENE–WSW strike-slip fault zone that does not cut the overthrusted Ebro Basin basement and infill. Located near the Neogene Vallès–Penedès fault, this broad, nearly vertical fault–gouge zone formed mainly in Paleozoic rocks (Fig. 5). The inhomogeneous deformation in this fault gouge indicates an important strike-slip component (Julià and Santanach, 1984), which is presumed to be related to the coalescence of different relative movements along the same zone during the formation of the range.

All the previously described contractive deformation disappears rather quickly towards the interior of the Ebro Basin. As a result, some 6 km to the NW of the Vallès–Penedès fault, the Ebro basin-fill and its Paleozoic–Mesozoic substratum are only slightly tilted to the NW and affected by a few N–S to NNW–SSE faults. The latter also cut the previously developed syncline–anticline pair and its related folded thrusts (Fig. 5).

These structures reveal that the Paleogene deformation of this sector of the Catalan Coastal Ranges involved a major emergent or buried thrust, which is presently oriented ENE–WSW. The related thrust slice was emplaced roughly northwards at about the same time as the strike-slip motion on ENE–WSW subvertical faults in its hanging wall. This complex structure is consistent with the development of an ENE–WSW transpressive chain, which was related to the Paleogene N–S convergent deformation of the northeastern part of Iberia.

The amount of sinistral displacement produced along the ENE–WSW faults is unknown due to the present lack of appropriate piercing points in Mesozoic and Paleogene rocks cut by these faults. In contrast, the amount of NNW–SSE horizontal shortening related to the ENE–WSW oriented folds and thrusts can be more easily estimated. We calculate, from cross sections, a NNW–SSE horizontal

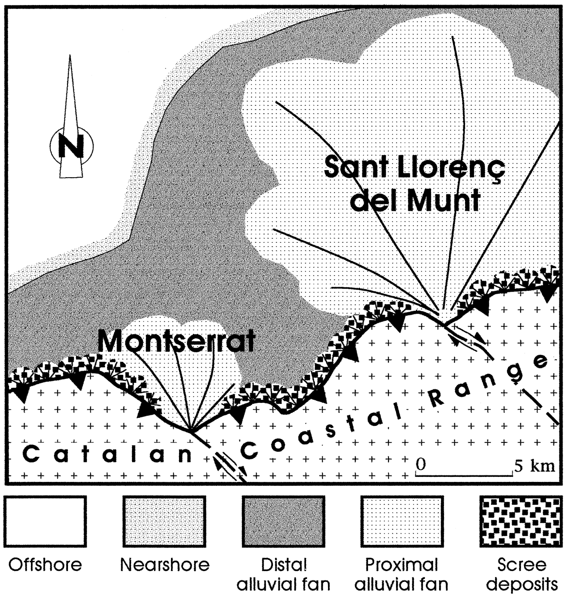


Fig. 7. Location of the Montserrat and Sant Llorenç del Munt fans at the intersection between frontal and lateral segments of the Prelitoral thrust. The lateral segments correspond to the SE–NW oriented Llobregat and Matadepera dextral tear faults (see Fig. 5).

component of shortening of about 8 km for this sector of the Catalan Coastal Ranges. Of this shortening, about 3.7 km is attributable to the Prelitoral thrust, 2.5 km to the folded thrusts and 1.8 km to the syncline–anticline pair.

6. Tectonics and sedimentation

The Paleogene basin-margin deposits in the Montserrat and Sant Llorenç del Munt areas (Fig. 3) record clearly the shortening and uplift of the Catalan Coastal Ranges and contain an unroofing succession related to the structural evolution of these ranges (Fig. 8). The Paleogene succession starts with fine-grained, alluvial and palustrine–lacustrine deposits (Mediona Formation), which probably accumulated in a tectonically quiescent setting during the Thanetian.

The Mediona beds are sharply overlain by the El Cairat breccias. These Triassic-derived breccias, deposited in small, short-headed, coalescing alluvial fans and screes during the Ypresian, record the onset of tectonic activity along the basin margin and the dismantling of the Triassic cover of the Catalan Coastal Ranges. They are related to an early system of thrusts and backthrusts involving cover materials (Figs. 8A and B). The top of El Cairat breccia marks an abrupt change in the tectono-sedimentary regime in both the Montserrat and Sant Llorenç del Munt areas.

In the Montserrat area, above the El Cairat breccias, alluvial red mudstones and sandstones of La Salut Formation (Lutetian) were deposited. This alluvium shows a coarsening-upward trend accompanied by an increase in the percentage of polygenic conglomerates derived from basement and Triassic-cover materials. These conglomerates grade upward into the uppermost Lutetian–Bartonian, alluvial fan, and fan-delta deposits forming the Montserrat Conglomerate Formation.

The whole Paleogene succession up to the second conglomeratic unit of the Montserrat (lowermost Bartonian in age) is affected by syncline–anticline pair folding. Progressive unconformities related to the synsedimentary growth of the syncline and involving the lowermost units of the Montserrat Conglomerates (and probably also La Salut Formation) are clearly exposed (Anadón, 1978; Anadón et al., 1985b; Marzo and Anadón, 1988). It is likely that this fold pair developed during the Late Lutetian to the Early Bartonian.

The out-of-sequence thrusts cut the syncline and the Montserrat Conglomerates up to the uppermost Bartonian units. The time equivalence of the sedimentation of most of the Montserrat fan-delta conglomerates and the emplacement of the Prelitoral thrust has been deduced from the presence of monogenic, basement-derived, sedimentary breccias that abut against the thrusts and are laterally equivalent to the Montserrat Conglomerates (Fig. 3).

In the Sant Llorenç del Munt area, the top of El Cairat Triassic-derived breccias is marked by a very abrupt change to breccias almost exclusively formed by Paleozoic-derived clasts (Can Sabater levels; Fig. 3). This indicates that Paleozoic basement rocks emerged and were eroded during the Late Ypresian-(?) Early Lutetian, and points to a more-developed stage of the first thrust system and/ or a significantly thinned and eroded Mesozoic cover (Fig. 8C). Above the Can Sabater levels, the Paleogene succession is characterized mainly by the poligenic, alluvial-fan, and fan-delta conglomerates of the Sant Llorenç del Munt (Upper Lutetian–Bartonian).

The syncline–anticline pair involves El Cairat breccia, Can Sabater levels, and the basal part of the Sant Llorenç del Munt Conglomerates (Fig. 6). The syncline grew primarily during the very early stages of deposition of Sant Llorenç del Munt Conglomerates (Lutetian–Early Bartonian), although it could have partially developed earlier due to the stacking of different thrust slices during the initial interval of thrusting.

An out-of-sequence thrust cuts the first thrust system, the Cairat breccia, the Can Sabater levels, the Sant Llorenç del Munt Conglomerates, and the syncline (Fig. 6). Most of the Sant Llorenç del Munt fan-delta conglomerates (except perhaps the lowermost levels) clearly can be regarded as syntectonic deposits related to the Prelitoral thrust activity, because they grade toward the basin margin and merge into Paleozoic-derived breccias interpreted as scree deposits directly abutting this thrust (Figs. 3 and 8E and F).

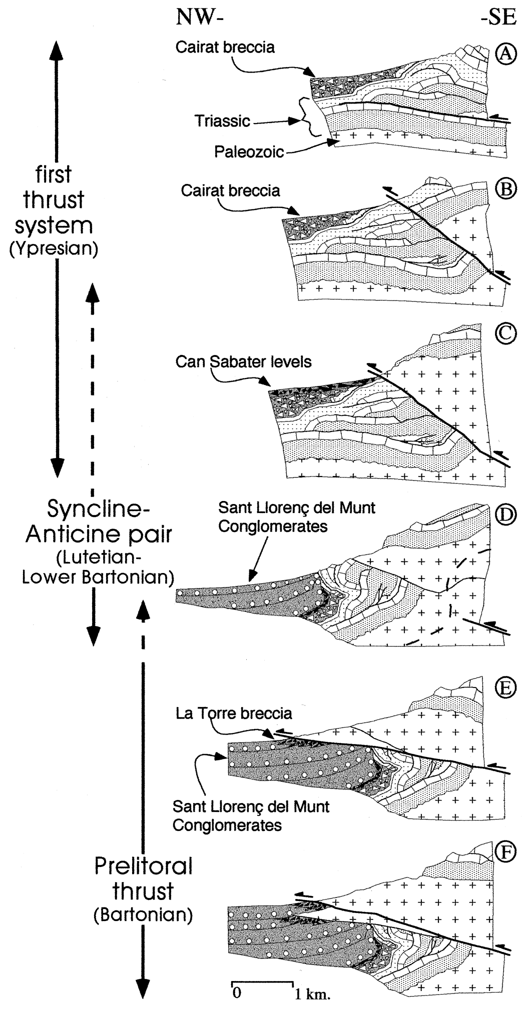


Fig. 8. Simplified model for the basin-margin tectono-sedimentary evolution and unroofing sequence. Three main episodes are differentiated: (1) The first thrust system (Ypresian–Early Lutetian?) records the onset of deformation and the development of a series of small alluvial fans or screes (A–C). The unroofing sequence records the erosion of the Triassic-cover (Cairat breccia) and the later emergence of Paleozoic-basement rocks (Can Sabater breccia); (2) The syncline–anticline pair folding (C–D) (Lutetian–Early Bartonian) originated in response to the antiformal piling up of thrust units and/or to a fault-propagation-fold mechanism. This episode is near synchronous with the deposition of the lowermost conglomeratic units of the Sant Llorenç del Munt and Montserrat alluvial-fan systems, leading to the development of progressive unconformities. The polygenic nature of the Montserrat and Sant Llorenç del Munt Conglomerates, as well as of those found in the underlying La Salut Formation, point to an unroofing of both the Paleozoic basement and the Mesozoic cover. This indicates that there was an enlargement of the alluvial-fan catchment areas in relation to those that developed during the Ypresian to Early Lutetian. The out-of-sequence (Prelitoral) thrust emplacement (Early to at least Late Bartonian) (D–F) was essentially coeval with the regionally widespread “Bartonian transgression” and the subsequent development of the Montserrat and Sant Llorenç del Munt fan deltas.

7. Basin-margin subsidence and sedimentation rates

The subsidence history of the Ebro Basin margin at Montserrat is shown in Fig. 9a. Due to the lack of a precise dating on the continental deposits (Mediona, El Cairat, and La Salut Formations) lying below the first Bartonian transition to marine, fan-delta deposits (Section 3.3), the reliability of the subsidence curve for the Ypresian and most of the Lutetian is poorly constrained. Despite this uncertainty, however, deposition of the Montserrat Conglomerate corresponds to an interval of high rate of tectonic subsidence (Fig. 9). This accelerating subsidence correlates with the latter stages of the syncline–anticline pair folding and with the emplacement of the Prelitoral thrust (Section 6). In addition, both the compacted sedimentation and the total subsidence rates tended to increase through time (Fig. 9), the latter reflecting the progressive sedimentary loading induced by the accumulation of the Montserrat fan-delta wedge. The proximal deposits of this wedge exhibit a long-term (~4.4 my) mean, compacted sedimentation rate of ~330 m/my. However, short-term sedimentation rates are very unsteady (Fig. 9b). Whereas apparent rate variations associated with relatively thin (<50 m) magnetozones could be attributable to the irregular sampling array and to the stochastic variability of sediment accumulation on fan surfaces (McRae, 1990), the rate variations represented by contrasts between the extensive normal or reversed magnetozones are likely to represent reproducible, long-term changes in sedimentation rates.

8. Reconstruction of the fan-delta catchment basins and denudation rates

The Montserrat and Sant Llorenç del Munt fan deltas developed in a warm and relatively humid climate at the foot of a tectonically active transpressive mountain front. Following is a semiquantitative evaluation of the physiography (extent, elevation, and slope gradients) and denudation rates of the fan-delta catchment areas.

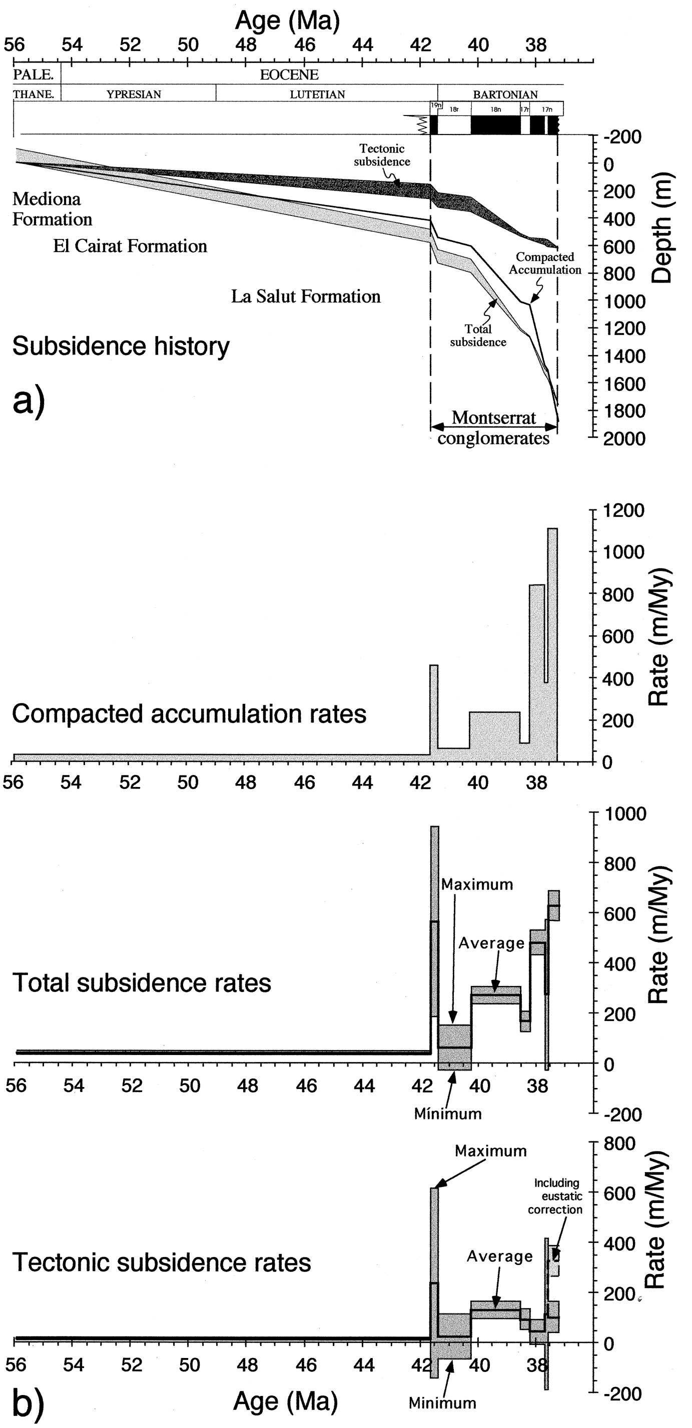
8.1. Extent

The different clast populations of the proximal conglomerates of the Montserrat (characterized by a subordinate amount of Cretaceous-derived clasts) and Sant Llorenç del Munt (characterized by the near absence of Cretaceous clasts) provide a reasonable basis for the reconstruction of the catchment areas of both fan systems. These catchment areas now lie below the sedimentary infill of the Neogene grabens (Figs. 1b, 2, and 10a). However, surface and subsurface data (Fig. 10) allow the reconstruction of the most likely distribution of Cretaceous outcrops in the Paleogene Catalan Coastal Ranges before Neogene extension. The subsurface data come from two onshore oil-wells (drilled in the Vallès–Penedès graben) and several offshore oil-wells (distributed parallel to the Mediterranean coast). These data (Fig. 10b) indicate that the Cretaceous cover was mostly restricted to a southwestern and a southeastern domain located adjacent to the present coastline. The rest of the Paleogene Catalan Coastal Ranges was occupied largely by Paleozoic-basement and Triassic-cover rocks. From this reconstruction, and taking into account the differences in clast-composition mentioned above, we can deduce the extent of the contributing catchment basin for each of the two fan systems and a likely location for the NNW–SSE water shed separating both basins (Fig. 10c). Because Cretaceous clasts are absent, the southern boundary of the Sant Llorenç del Munt drainage basin is inferred to have been limited by the northern edge of the Cretaceous rocks located NNE of Barcelona. The northeastern boundary remains unknown. For the Montserrat fan, the drainage basin is limited to the southwest by the thick and complete Mesozoic sections located WNW of Barcelona, whereas the southeastern boundary remains uncertain. The minimum area calculated for the drainage basins varied between 200–300 km^2 for the Montserrat and 700–800 km^2 for the Sant Llorenç del Munt (Fig. 10c). On a log–log plot of drainage basin area versus fan area, the above-mentioned values and the mean fan areas estimated for Montserrat (100–150 km^2) and Sant Llorenç del Munt (350–450 km^2) are consistent with the ensemble of fan data compiled by Bull (1964) and Blair and McPherson (1994, their Fig. 14.22).

It should be noted that the reconstructions of both catchment areas (Fig. 10c) show a remarkable asymmetry in relation to the axes defined by the SE–NW oriented Llobregat and Matadepera faults (Fig. 5), whose intersection with the Prelitoral thrust probably controlled the location of the fans (Fig. 7). This asymmetry, characterized by mostly eastward development of the drainage basin in relation to the above-mentioned axes, is consistent with the presence of SE–NW uplifted trends westwards of the Llobregat and Matadepera tear faults (Section 5).

8.2. Denudation rates

Chemical and mechanical denudation rates can be evaluated either from present-day river loads or from the volume of sediment accumulated in sedimentary basins during a certain time period. In the latter case, in addition to accurate time control, the extent of the distributive drainage and depositional areas must be known. For that reason the method is more appropriate for studying closed or semi-closed basins as a


Age (Ma)
56 54 52 50 48 46 44 42 40 38
PALE.
EOCENE
THANE.
YPRESIAN
LUTETIAN
BARTONIAN
Tectonic subsidence
Mediona Formation
El Cairat Formation
La Salut Formation
Compacted Accumulation
Total subsidence
Subsidence history
a)
Montserrat conglomerates
-200 0 200 400 600 800 1000 1200 1400 1600 1800 2000
Depth (m)
Compacted accumulation rates
1200 1000 800 600 400 200 0
Rate (m/My)
Total subsidence rates
Maximum
Average
Minimum
1000 800 600 400 200 0 -200
Rate (m/My)
Tectonic subsidence rates
Maximum
Including eustatic correction
Average
Minimum
800 600 400 200 0 -200
Rate (m/My)
b)
Age (Ma)

whole and is hardly applicable to our case study, given that the extent of the submarine depositional areas of the fan-delta systems, located in an open basin, are unknown.

Our approach to evaluate a minimum, mean mechanical denudation rate for the Montserrat and Sant Llorenç del Munt drainage areas is based on a rough estimate of the volume of sediment accumulated during a time span of ~4.4 my on the subaerial reaches of both fans. Considering the maximum depositional thicknesses reported for the Montserrat (1400 m) and Sant Llorenç del Munt (1500 m), as well as other depositional, geometric parameters summarized in Fig. 11, the minimum volumes of sediment accumulated during the above-mentioned time span are estimated to be 130–160 and 470–540 km^3, respectively. Taking into account the minimum areas calculated for the Montserrat (200–300 km^2) and Sant Llorenç del Munt (700–800 km^2) catchment basins, mean, minimum mechanical denudation rates of 100–140 and 130–180 m/my, respectively, are inferred. The calculated sediment volumes ignore both the dissolved load and the solid load that escaped beyond the fan. These minimum values of 100–140 and 130–180 m/my are similar to those measured for "upland" rivers in southern Europe with similarly sized catchments (Milliman and Syvitski, 1992) and lower than those reported for mountain rivers in a tropical climatic setting where a mean mechanical denudation rate of 200–500 m/my and a mean chemical denudation rate of ~30 m/my have been suggested (Einsele, 1992). It must be stressed, however, that these proposed values (Einsele, 1992) are suggested as valid for moderate to large drainage areas with mixed lithologies. In small drainage basins, denudation may be largely controlled by specific rock types, and considerable deviation from the average values given above is possible.

8.3. Mean elevation

Using the empirical formula proposed by Pinet and Souriau (1988), correlating mean mechanical denudation rates with the mean drainage basin elevation for "young orogens" ($Ds = 419 \times 10^{-6}\ H - 0.245$) and using the minimum value for Ds obtained above for the Sant Llorenç del Munt (130–180 m/my = 0.13–0.18 m/ky), we calculate a mean elevation for the drainage basin of 900 − 1000 ± 300 m. If we take into account the correction proposed by Leeder (1991) to the data set provided by Pinet and Souriau (1988) in order to include dissolved load and apply the Ahnert (1970) regression line ($Ds = 1.54 \times 10^{-4}\ H - 1.09 \times 10^{-2}$), a value of 900–1250 m is obtained. Similar calculations for the Montserrat (with a minimum value of Ds in the order of 100–140 m/my = 0.10 − 0.14 m/ky) give a mean drainage basin elevation ranging from 800–900 m ±250 m (see Pinet and Souriau, 1988) to 700–1000 m (see Ahnert, 1970). These approaches must be regarded as rough first approximations with associated uncertainties in the calculated mean altitude of 30% or more due to the formal uncertainties in the regressions. Moreover, some authors have claimed that the denudation rate is governed by the slope gradients (Summerfield, 1991) or topographic relief, rather than by the absolute elevation of a region.

In fact, a mean elevation of 700–1250 m for the catchment basins of the Montserrat and Sant Llorenç del Munt fan deltas seems high, in view of the relatively small catchment area (200–800 km^2) and would imply high topography close to the shoreline where the fan deltas developed (Fig. 12). Nevertheless, the value is consistent with the observation reported by Busquets et al. (1994) from the Vic region (50 km to the northeast of the studied area) where the existence of Bartonian topographic relief high enough

Fig. 9. (a) Subsidence history for the Montserrat region. The subsidence curve for the Ypresian and most of the Lutetian is poorly constrained, due to the lack of dating of the continental deposits (Mediona, El Cairat, and La Salut Formations). The onset of deposition of the Montserrat Conglomerate corresponds to an increase in the rate of tectonic subsidence that correlates with the latter stages of the syncline–anticline pair folding and with the emplacement of the Prelitoral thrust (see Fig. 8). Compacted sedimentation and total subsidence rates increased through time, the latter reflecting the progressive sedimentary loading induced by the accumulation of the Montserrat fan-delta wedge. The proximal deposits of this wedge exhibit a long-term (~4.4 my) mean, minimum compacted sedimentation rate of ~330 m/my. (b) Sedimentation, total subsidence, and tectonic subsidence rates showing marked short-term variations (steadiness between 56 and 41.6 Ma is due to the lack of precise chronostratigraphic control).

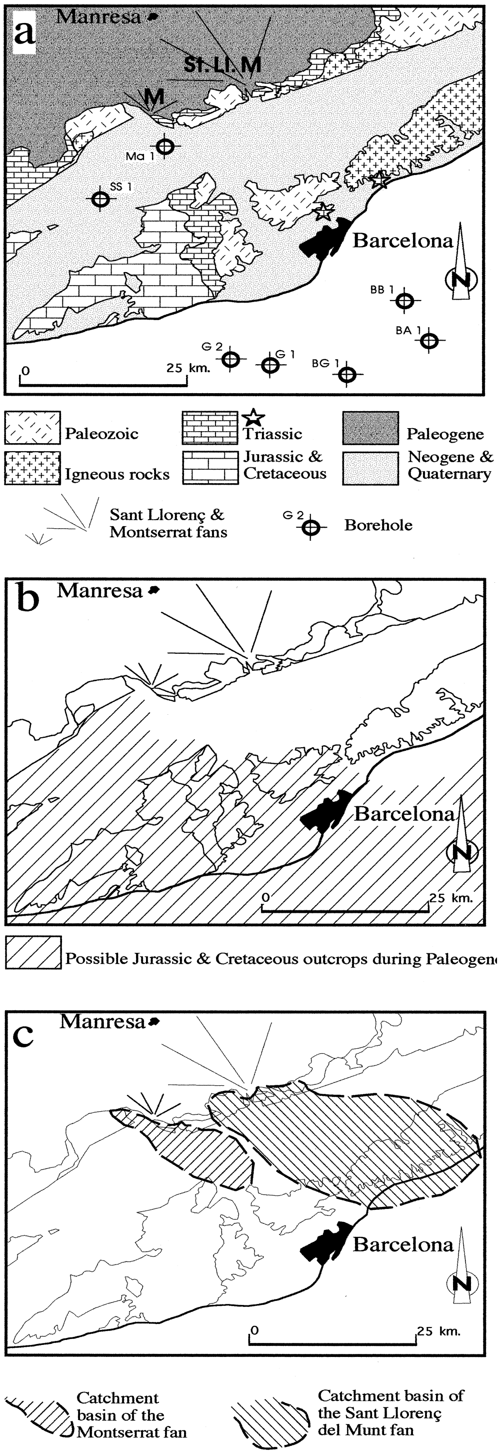
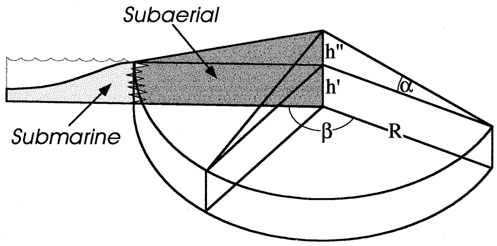


Fig. 10. Reconstruction of the catchment areas of the Montserrat and Sant Llorenç del Munt fan-deltas (c), based on the comparative analysis of the clast-composition of the proximal conglomerates of Montserrat (with a small percentage of Cretaceous clasts) and Sant Llorenç del Munt (with Cretaceous clasts practically absent) and surface and subsurface mapping of the most likely distribution of Cretaceous outcrops in the Paleogene Catalan Coastal Ranges (b), before the Neogene extensional event (see present day geological map in (a)). The minimum area calculated averages 200–300 km^2 (Montserrat) and 700–800 km^2 (Sant Llorenç del Munt). The marked E–NE asymmetry of both basins is probably related to SE–NW uplifted trends associated with the lateral ramps of the Prelitoral thrust (see Fig. 7).



	Montserrat	St. Llorenç del Munt
R	9 km	16 km
h'	1000 m	1000 m
h"	400 m	500 m
α	2'5°	1'8°
β	150°	150°

Fig. 11. Main geometrical depositional parameters used to calculate sedimentary volumes for the subaerial realms of the deltas: (A) Montserrat fan delta; (B) Sant Llorenç del Munt fan delta. The derived volumes are minimum values because they ignore the contribution of the marine facies.

to develop a stratified vegetation cover, with a pine forest overlying a lower-topography area dominated by ferns, has been deduced from the study of pollen assemblages. However, as the strata sampled by these authors are located near the center of the Bartonian marine basin, the provenance of the pollen assemblages, whether from the relief to the north (Pyrenean orogen) or to the south (Catalan Coastal Ranges) (Fig. 1) or from mixing of floras distributed over a wide geographic region, is unknown.

The high calculated values of topography can be justified from the structural style of the compressive, Paleogene Catalan Coastal Ranges in the studied

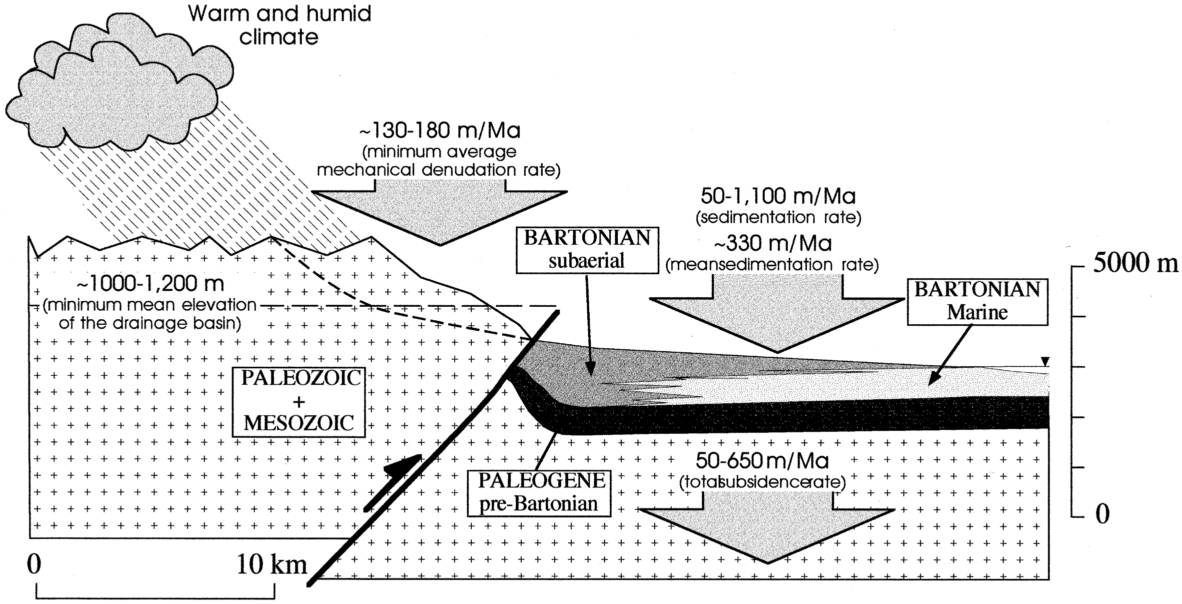


Fig. 12. Conceptual model summarizing the tectono-sedimentary and tectono-geomorphic settings of the studied fan deltas, as well as the rates of geological processes controlling their development during the Bartonian (~4.4 my).

region. In this area, the frontal structure is characterized by a broad syncline–anticline pair cored by Paleozoic, basement rocks. Remnants of the forelimb of this anticline show vertical to overturned Triassic-cover rocks, indicating a rather high amplitude fold. Furthermore, the Paleozoic core extruded across the forelimb of the anticline. This kind of frontal structure would define a basement-involved uplifted region with a relatively flat upper portion. If so, the Paleogene Catalan Coastal Ranges would have comprised a relatively flat and elevated basement-cover block with a relatively steep and complex frontal region, involving only modest shortening (c.f. Fig. 2). This geometry is similar to the presently preserved topography of the Serra de la Llena in the Catalan Coastal Ranges, southwest of the study area.

Dependent on the densities applied to the model of local isostasy, 700–1250 m of local relief would correspond to crustal thicknesses of about 35–37 km. This amount is higher than the present-day 32 km of crustal thickness reported for the region. However, it should be noted that the present thickness was acquired during Neogene normal faulting as a consequence of crustal tectonic denudation.

8.4. Slope gradients

After the initial onset of subsidence at the basin margin at ~41.6 Ma (Fig. 9a), a rapid development of topographic relief is inferred, implying a relatively low value of shortening in comparison to an important vertical component of bedrock uplift. This rapid uplift seems to have been reflected in the development of steep stream gradients in the catchment areas, favoring the transport of very coarse, bed-load material during peak flows. These steep gradients are inferred from the common occurrence of large cobbles and boulders (up to 1–1.5 m in diameter) in the debris-flow, sheetflood, and streamflood conglomerates that characterize the proximal, subaerial realms of the Montserrat and Sant Llorenç del Munt fan deltas. Note that even if a relatively modest slope of two degrees is assumed, the large radius of the Sant Llorenç fan necessitates an altitude of ~500 m near the fan apex. A minimum altitude > 500 m for the catchment above the fan apex thus can be established.

In addition, the existence of steep valley slopes in the studied fan-delta catchment basins can be deduced from the evidence of catastrophic slope mass-movements, as an important sediment-supply mechanism, as follows:

1. Intact tetrads of Upper Triassic-derived, reworked pollen grains are relatively common in the essentially muddy, prodeltaic facies of the Sant Llorenç del Munt fan delta. This suggests a direct gravity mass-flow transfer from the mud-rich Triassic materials cropping out in the catchment areas into the subaqueous, fan-delta slope (López-Blanco and Solé de Porta, 1993).
2. The monogenic conglomerate beds are traceable throughout the subaerial realms of the Sant Llorenç del Munt fan delta and consist mainly of poorly rounded to angular, Triassic-derived carbonate clasts. They are probably linked to (earthquake-triggered?) landslides involving highly unstable alternating sequences of red mudstones, evaporites, and carbonates of the Triassic cover in catchment areas. These episodes of instability could have induced a series of processes affecting the whole fan surface, such as catastrophic, landslide-dam failures or temporary landslide-blocking of the main feeder valley, both of which would lead to the rearrangement of the drainage network and subsequent changes in clast composition.

Gravitational mass-movements are particularly important in present-day, tectonically or volcanically active, high-relief, warm and wet regions (Brabb and Harrod, 1989). This is due to the combination of ubiquitous steep slopes, rapid weathering under humid conditions, and the abundance of running water resulting from a more or less seasonal pattern of rainfall punctuated with intense storms.

9. Conclusions

The Sant Llorenç del Munt and Montserrat fan-delta systems are large fans whose subaerial portions cover a mean, minimum area of 350–450 and 100–150 km^2, respectively. The minimum surface area of their catchment-basins has been estimated to be 700–800 km^2 (Sant Llorenç del Munt) and 200–300 km^2 (Montserrat). Both fans developed during a 4.4 my time-span, from 41.6 to 37.2 Ma (Bartonian, Middle Eocene) under prevailing warm and relatively humid climatic conditions.

The formation and evolution of the Montserrat and Sant Llorenç del Munt fans, at the southeastern margin of the Ebro foreland basin is closely related to the tectonic evolution of the adjoining Paleogene Catalan Coastal Ranges, a transpressive chain characterized by a frontal structure roughly corresponding to the propagation of a large out-of-sequence thrust through the forelimb of a syncline–anticline pair. Tectonosedimentary relationships along the foreland margin show clearly that the creation and development of the studied fan deltas took place during the late stages of anticline–syncline folding and the emplacement of a thrust. The intersection between frontal and lateral segments of this thrust controlled the location of the fan-delta apices.

The subsidence history of the basin margin and the syntectonic development of both fans indicate that the onset of the development of the Montserrat fan coincides with a clear increase of the tectonic subsidence. The subsidence analysis shows that long-term (4.4 my) sedimentation and total subsidence rates increase through time, the latter recording the progressive loading induced by the accumulated deposits and by the growing thrust load. The proximal deposits of the Montserrat fan-delta wedge show a long-term mean, minimum compacted sedimentation rate of ~330 m/my (Fig. 12); shorter-term sedimentation rates are very unsteady.

A mean, minimum mechanical denudation rate of 100–180 m/my has been calculated for the catchment basins of both fan deltas. This denudation rate implies a minimum mean elevation for the catchment basins of 700–1250 m (Fig. 12). The development of this high topography close to the shoreline is attributed to the compressive structural style of the Paleogene Catalan Coastal Ranges. This structure involved an uplifted and comparatively flat basement-cover block (with a complex detached structure of the cover unit) bounded seawards by a relatively steep and complex frontal region.

The sudden onset of subsidence at the basin margin was accompanied by rapid growth of the topographic relief, in response to modest shortening and considerable vertical bedrock uplift. Increasing rates of sedimentation and total subsidence, recorded by progressively younger fan-delta deposits, also point to rapid uplift. This, in combination with the prevailing warm and humid climate, resulted in increased denudation rates and increased sediment supply to the shoreline. The progressive increase in sediment supply, mostly accomplished through sediment- and fluid-gravity (sometimes catastrophic) processes, initially compensated and eventually exceeded the increasing accommodation space created by both tectonic and sediment loading. Throughout nearly the entire interval of fan deposition, the sediment supply rate was sufficient to fill all the available accommodation space and consequently maintain the surface of the fan at or above sea level. Given this condition of oversupply, it appears that eustatic variations had little impact on the long-term (~4.4 my) evolution of these fans.

Acknowledgements

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Appendix A. Montserrat magnetic polarity stratigraphy

A.1. Sampling procedure

Commencing in La Salut Formation and extending into conglomeratic unit 7, ~100 magnetic sampling sites were established through a section ~1800-m thick (Fig. 13). Samples were collected until no additional fine-grained interbeds could be attained among the increasingly coarse grained conglomeratic facies. Sites typically were spaced 15–20 m apart and each produced four oriented specimens of siltstone, marl, mudstone, or uncommonly very fine-grained sandstone.

A.2. Analytical procedure

Paired specimens of representative rock types throughout the section were subjected to thermal demagnetization at 9–14 temperature steps up to 640°C in order to characterize their magnetic behavior and to determine the optimal demagnetization procedures for the remaining samples. The results from these pilot studies indicate that most of the normally magnetized specimens lost 50–70% of their initial intensity during heating to 250°C (Fig. 14), and many lost >40% of their remanence by only 100°C. This decrease in intensity is interpreted to result from progressive reduction of a normally polarized, viscous overprint. Removal of this overprint at temperatures below ~240–300°C sometimes increased the measured intensity in reversely magnetized specimens (Fig. 14b). Most pilot samples displayed stable directions and a steady decrease in intensity between ~250 and 400°C. We used these directions to define the characteristic remanence. At temperatures ≥450°C, many of the pilot samples displayed an increase in intensity and magnetic susceptibility, and their magnetic directions became considerably less stable. This suggests that oxidation during heating at higher temperatures overprinted the depositional remanence. Only reversely magnetized samples commonly displayed an increase in intensity during heating to 250°C.

Based on the demagnetization results, all of the remaining specimens were thermally demagnetized at 240, 280, 310, and 340°C. A characteristic remanence direction was defined for each specimen based on these successive measurements. The validity of the specimen directions was further assessed using Fisher (1953) statistics on the multiple specimens at each temperature level at each site. Sites were then classified as "Class I," if Fisher $k \geq 10$ (implying that these directions were nonrandom at >95% confidence level; Irving, 1964); "Class II" when the polarity of the site was unambiguous, but $k \leq 10$; and "Class III," when no reliable polarity could be determined for a site. The mean site directions were used to determine a Paleolatitude for the virtual geomagnetic pole (VGP), which in turn formed the basis for classifying sites as of either normal or reversed polarity. An α_{95}-error envelope was calculated on the VGP latitude to assess further the reliability of each site. Polarity

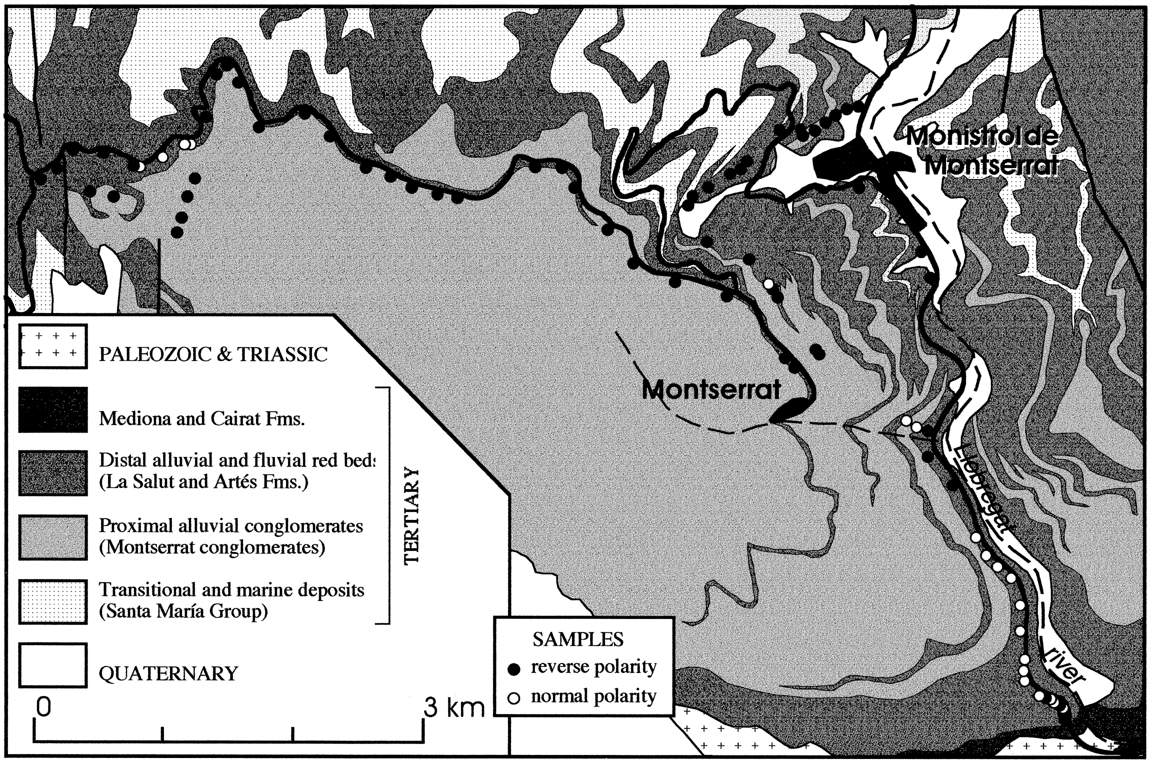

Fig. 13. Location map of the magnetic sampling sites at Montserrat. Filled circles are normally magnetized sites, and open circles are reversely magnetized sites.

determinations are considered reliable when the 95% error envelope does not overlap 0° of paleolatitude; that is, all likely polarity calculations for that site are either normal or reversed.

The Class I data do not pass a reversal test (Fig. 15), because the error envelopes on the mean directions fail to overlap at the 95% confidence level. Whereas the reversed data display ~24° of clockwise rotation

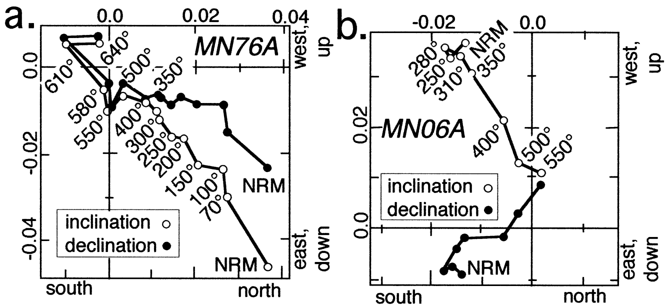

Fig. 14. Ziderveldt diagrams of typical behavior during thermal demagnetization. (a) Normally magnetized sample, MN76A; 50% of the initial remanence is lost by 200°C. The nearly linear decrease in intensity between 250 and 500°C defines the characteristic remanence direction. Above 500°C, the magnetic susceptibility increases and directions become less stable, probably due to the oxidation of minerals during thermal demagnetization at these higher temperatures. (b) Example of a reversely magnetized sample, MN06A, displaying a characteristic remanence between 240 and 400°C. Large increases in susceptibility occur above 400°C.

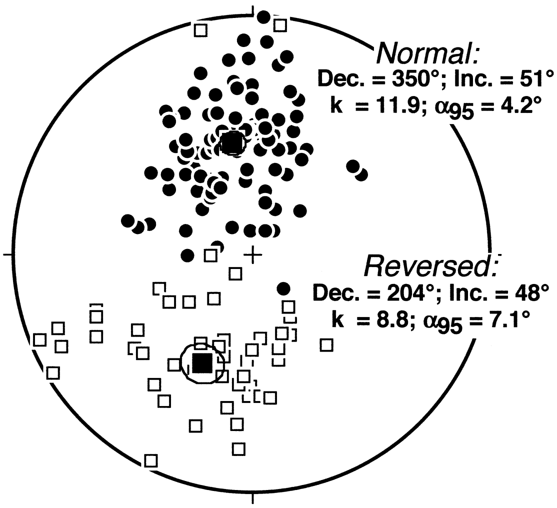

Fig. 15. Stereoplot of Class I normal and reversed sites. Filled circles represent lower hemisphere data; open squares represent upper hemisphere data. The mean normal and reversed directions and associated α_{95} errors are also shown. The data do not pass a reversal test.

about a vertical axis, the normal data show ~4° of counterclockwise rotation. This discrepancy could have resulted from the incomplete removal of a normal overprint, which biased directions toward the northwest, or from a rotation that occurred during deposition. Because >75% of the reversed data come from the basal 400 m of the section, the rotation displayed by the reversed data could have occurred prior to deposition of the top half of the section. High-temperature (>550°C) magnetic data from sandstones in the lower part of the section (Parés et al., 1988) also displayed ~20° of clockwise rotation. At present, we cannot determine whether it is overprinting or syndepositional rotation that has caused the data to fail the reversal test.

References

Ahnert, F., 1970. Functional relationships between denudation, relief and uplift in large mid-latitude drainage basins. Am. J. Sci. 268, 243–263.

Alvarez Ramis, C., 1982. Sobre la presencia de una flora de Paleomanglar en el Paleógeno de la depresión central catalana (curso medio del Llobregat). Acta Geol. Hisp. 17, 5–9.

Anadón, P., 1978. El Paleógeno continental anterior a la transgresión Biarritziense (Eoceno medio) entre los ríos Gaià y Ripoll (prov. de Tarragona y Barcelona). Est. Geol. 34, 341–440.

Anadón, P., Zamarreño, I., 1981. Paleogene nonmarine algal deposits of the Ebro Basin, northeast Spain. In: Monty, C. (Ed.), Phanerozoic Stromatolites. Springer, Berlin, pp. 140–154.

Anadón, P., Cabrera, L., Guimerà, J., Santanach, P., 1985a. Paleogene strike-slip deformation and sedimentation along the southeastern margin of the Ebro Basin. In: Biddle, K.T., Christie-Blick, N. (Eds.), Strike-Slip Deformation, Basin Formation and Sedimentation. Soc. Econ. Paleont. Mineral. Spec. Publ., vol. 37, pp. 303–318.

Anadón, P., Marzo, M., Puigdefàbregas, C., 1985b. The Eocene Fan-Delta of Montserrat (Southeastern Ebro Basin, Spain). In: Milá, M.D., Rosell, J. (Eds.), Sixth European Regional Meeting Excursion Guidebook. Institut d'Estudis Ilerdencs, Lleida, pp. 108–146.

Anadón, P., Cabrera, L., Colombo, F., Marzo, M., Riba, O., 1986. Syntectonic intraformational unconformities in alluvial fan deposits, eastern Ebro Basin margins (NE Spain). In: Allen, P., Homewood, P. (Eds.). Foreland Basins. Spec. Publ. Int. Ass. Sediment., vol. 8, pp. 259–271.

Anadón, P., Marzo, M., Riba, O., Sáez, A., Vergés, J., 1989. Fan-delta deposits and syntectonic unconformities in alluvial fan conglomerates of the Ebro basin. , Fourth International Conference on Fluvial Sedimentology Excursion Guidebook. Publicacions del Servei Geològic de Catalunya, Barcelona (100 pp).

Ashauer, H., Teichmüller, R., 1935. Die variscische und alpidische Gebirgs bildung Kataloniens. Abh. Gessell, Göttingen. Math. Phys. 16, 16–98.

Bartrina, M.T., Cabrera, L., Jurado, M.J., Guimerà, J., Roca, E., 1992. Evolution of the central Catalan margin of the Valencia trough (western Mediterranean). Tectonophysics 203, 219–247.

Biosca, J., Vía, L., 1988. El género Nypa (Palmae) en el Eoceno de la Depresión Central Catalana. Batalleria 1, 7–23.

Blair, T., McPherson, J.G., 1994. Alluvial fan processes and forms. In: Abrahams, A.D., Parsons, A.J. (Eds.), Geomorphology of Desert Environments. Chapman and Hall, London, pp. 354–402.

Brabb, E.E., Harrod, B.L., 1989. Landslides, Extent and Economic Significance. Symposium on Landslides. Proceedings of the 28th International Geological Congress, Washington, 385 pp.

Brunet, M.F., 1986. The influence of the evolution of the Pyrenees on adjacent basins. Tectonophysics 129, 345–354.

Bull, W.B., 1964. Geomorphology of segmented alluvial fans in western Fresno County, California. US Geological-Survey Professional Paper, 352-E, 128 pp.

Burbank, D.W., Vergés, J., Muñoz, J.A., Bentham, P.A., 1992. Coeval hindward- and forward-imbricating thrusting in the central southern Pyrenees: timing and rates of shortening and deposition. Geol. Soc. Am. Bull. 104, 1–18.

Burbank, D.W., Vergés, J., 1994. Reconstruction of topography and related depositional systems during active thrusting. J. Geophys. Res. 99 (B10), 20 281–20 297.

Burbank, D.W., Meigs, A., Brozovic, N., 1996. Interactions of growing folds and coeval depositional systems. Basin Res. 8, 199–223.

Busquets, P., Alvarez, G., Solé de Porta, N., Urquiola, M.M., 1994. Low sedimentation rate aphotic shelves with Dendrophyllia and sponges- Bartonian of the easternmost sector of the Ebro

Basin. In: Oekentorp-Küster, P. (Ed.), Proceedings of the VI International Symposium on Fossil Cnidaria and Porifera, vol. 172(2). Cour. Forsch-Inst. Senckenberg, Münster, pp. 265–273.

Cande, S.C., Kent, D.V., 1992. A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. J. Geophys. Res. 97 (B10), 13 917–13 951.

Cavagnetto, C., Anadón, P., 1995. Une mangrove complexe dans le Bartonien du Bassin de l'Ebre (NE de l'Espagne). Paleontogr. Abt. B 236, 147–165.

Cavagnetto, C., Anadón, P., 1996. Preliminary palynological data on floristic and climatic changes during the Middle Eocene–Early Oligocene of the eastern Ebro Basin, northeast Spain. Rev. Paleobot. Palynol. 92, 281–305.

Colombo, F., Vergés, J., 1992. Geometría del margen SE de la Cuenca del Ebro: discordancias progresivas en el Grupo Scala Dei. Serra de la Llena (Tarragona). Acta. Geol. Hisp. 27, 33–53.

DeCelles, P.G., Gray, M.B., Ridgway, K.D., Cole, R.B., Srivastava, P., Pequera, N., Pivnik, D.A., 1991. Kinematic history of a foreland uplift from Paleocene synorogenic conglomerate, Beartooth Range, Wyoming and Montana. Geol. Soc. Am. Bull. 103, 1458–1475.

Einsele, G., 1992. Sedimentary Basins: Evolution, Facies and Sediment Budget. Springer, Berlin, 628 pp.

Fisher, R.A., 1953. Dispersion on a sphere. R. Soc. London Proc. Ser. A 217, 295–305.

Gallart, J., Vidal, N., Dañobeitia, J.J., Group, T.E.-V.T.W., 1994. Lateral variations in the deep crustal structure at the Iberian margin of the Valencia trough imaged from seismic reflection methods. Tectonophysics 232, 59–75.

Guimerà, J., 1984. Paleogene evolution of deformation in the northeastern Iberian Peninsula. Geol. Mag. 121, 413–420.

Guimerà, J., 1988. Estudi estructural de l'enllaç entre la Serralada Ibérica i la Serralada Costanera Catalana. PhD thesis, Universitat de Barcelona, 600 pp.

Inglès, M., Anadón, P., 1991. Relationship of clay minerals to depositional environments in the non-marine Eocene Pontils Group, SE Ebro Basin (Spain). J. Sediment. Petrol. 61, 926–939.

Irving, E., 1964. Paleomagnetism and its Application to Geological and Geophysical Problems. Wiley, New York, 399 pp.

Janssen, M.E., Torné, M., Cloething, S., Banda, E., 1993. Pliocene uplift of the eastern Iberian margin: Inferences from quantitative modelling of the Valencia trough. Earth Planet. Sci. Lett. 119, 585–597.

Julià, R., Santanach, P., 1984. Estructuras en la salbanda de falla paleógena de la falla del Vallés–Penedés (Cadenas Costeras Catalanas): su relación con el deslizamiento de la falla. I Congreso Español de Geología, Segovia Tomo III, pp. 47–59.

Leeder, M.R., 1991. Denudation, vertical crustal movements and sedimentary basin infill. Geol. Rundschau 80 (2), 441–458.

Llopis Lladó, N., 1947. Contribución al Conocimiento de la Morfoestructura de los Catalánides. Inst. Lucas Mallada, C.S.I.C., Barcelona, 372 pp.

López-Blanco, M., 1993. Stratigraphy and sedimentary development of the Sant Llorenç del Munt fan-delta complex (Eocene, southern pyrenean foreland basin, northeast Spain). In: Frostick, L., Steel, R.J. (Eds.), Tectonic Controls and Signatures in Sedimentary Successions. Spec. Publs Int. Ass. Sediment., vol. 20. pp. 67–88.

López-Blanco, M., 1994. Estructuras contractivas de la Cordillera Prelitoral Catalana entre la sierra de Les Pedritxes y el río Ripoll, evolución y relación con los depósitos del margen de la cuenca del Ebro. Geogaceta 16, 3–5.

López-Blanco, M., 1996. Estratigrafía secuencial de sistemas deltaicos en cuencas de antepaís: ejemplos de Sant Llorenç del Munt, Montserrat y Roda (Paleógeno, cuenca de antepaís surpirenaica). PhD thesis, Universitat de Barcelona, 238 pp.

López-Blanco, M., Solé de Porta, N., 1993. Palinomorfos del Triásico Superior resedimentados en los materiales marinos eocenos de Sant Llorenç del Munt (cuenca del Ebro, NE de España). Acta Geol. Hisp. 28 (4), 5–13.

López-Blanco, M., Marzo, M., Piña, J., 2000. Transgressive–regressive sequence hierarchy of foreland, fan-delta clastic wedges (Montserrat and Sant Llorenç del Munt, Middle Eocene, Ebro Basin, NE Spain). Sediment. Geol. 138 (2000), 41–69.

Marzo, M., Anadón, P., 1988. Anatomy of a conglomeratic fan-delta complex: the Eocene Montserrat Conglomerate, Ebro Basin, northeastern Spain. In: Nemec, W., Steel, R.J. (Eds.), Fan Deltas and Related Systems. Sedimentology and Tectonic Settings. Blackie, London, pp. 318–340.

McRae, L.E., 1990. Paleomagnetic isochrons, unsteadiness, and non-uniformity of sedimentation in Miocene fluvial strata of the Siwalik Group, northern Pakistan. J. Geol. 98, 433–456.

Millán, H., Den Bezemer, T., Vergés, J., Marzo, M., Muñoz, J.A., Roca, E., Cirés, J., Zoetemeijer, R., Cloething, S., Puigdefàbregas, C., 1995. Paleo-elevation and effective elastic thickness evolution at mountain ranges: inferences from flexural modelling in the Eastern Pyrenees and Ebro Basin. Mar. Petrol. Geol. 12, 917–928.

Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. J. Geol. 100, 525–544.

Morgan, P., Fernandez, M., 1992. Neogene vertical movements and constraints on extension in the Catalan Coastal Ranges, Iberian Peninsula and the Valencia trough (western Mediterranean). Tectonophysics 203, 219–248.

Parés, J.M., Banda, E., Santanach, P., 1988. Paleomagnetic results from the southern margin of the Ebro Basin (NE Spain): evidence for a Tertiary clockwise rotation. Phys. Earth Planet. Int. 52, 267–282.

Peón, A., Alonso, F., Ramírez del Pozo, J., 1975. Mapa Geológico de España, E. 1:50.000. Hoja de Igualada (391). Instituto Geológico y Minero de España. Servicio de Publicaciones del Ministerio de Industria.

Peón, A., Rosell, J., Trilla, J., Obrador, A., Alonso, F., Ramírez del Pozo, J., Cabañas, J., 1975. Mapa Geológico de España, E. 1:50.000. Hoja de Sabadell (392). Instituto Geológico y Minero de España. Servicio de Publicaciones del Ministerio de Industria.

Pinet, P., Soriau, M., 1988. Continental erosion and large-scale relief. Tectonics 7, 563–582.

Platt, N.H., Wright, V.P., 1992. Palustrine carbonates and the Florida Everglades: towards an exposure index for the freshwater environment. J. Sediment. Petrol. 52, 1058–1071.

Roca, E., Guimerà, J., 1992. The Neogene structure of the eastern Iberian margin: structural constraints on the crustal evolution of the Valencia trough (western Mediterranean). Tectonophysics 203, 203–218.

Roca, E., 1992. L'estructura de la conca catalano-balear: paper de la compressió i de la distensió en la seva gènesi. PhD Thesis, Universitat de Barcelona, 330 pp.

Salas, R., 1995. The basin margin in the Igualada area. In: A. Perejón, P. Busquets (Editors), Field trip C: Bioconstructions of the Eocene South Pyrenean Foreland Basin (Vic and Igualada areas) and the Upper Cretaceous South Central Pyrenees (Tremp area). VII International Symposium on Fossil Cnidaria and Porifera, Madrid, pp. 30–35.

Santisteban, C., Taberner, C., 1988. Sedimentary models of siliciclastic deposits and coral reefs interrelation. In: Doyle, L.J., Roberts, H.H. (Eds.), Carbonate-Clastics Transitions. Developments in Sedimentology, vol. 42, pp. 35–76.

Serra-Kiel, J., Travé, A., 1995. Lithostratigraphic and chronostratigraphic framework of the Bartonian sediments in the Vic and Igualada areas. In: A. Perejón, P. Busquets (Eds.), Field trip C: Bioconstructions of the Eocene South Pyrenean Foreland Basin (Vic and Igualada areas) and the Upper Cretaceous South Central Pyrenees (Tremp area). VII International Symposium on Fossil Cnidaria and Porifera, Madrid, pp. 11–14.

Summerfield, M.A., 1991. Subaerial denudation of passive margins: regional elevation versus local relief models. Earth Planet. Sci. Lett. 102, 460–469.

Ubach, J., 1990. Geología de los materiales Paleozoicos de las Escamas de la Cordillera prelitoral catalana al Este del río Llobregat. Acta Geol. Hisp. 25 (1/2), 113–121.

Vergés, J., 1993. Estudi tectònic del vessant sud del Pirineu oriental i central. Evolució cinemàtica en 3-D. PhD, Universitat de Barcelona, 203 pp.

Vergés, J., Millán, H., Roca, E., Muñoz, J.A., Marzo, M., Cirés, J., Den Bezemer, T., Zoetemeijer, R., Cloething, S., 1995. Eastern Pyrenees and related foreland basins: pre-, syn- and post-collisional crustal-scale cross sections. Mar. Petrol. Geol. 12, 893–915.

Vergés, J., Burbank, D.W., 1996. Eocene–Oligocene thrusting and basin configuration in the eastern and central Pyrenees (Spain). In: Friend, P.F., Dabrio, C.J. (Eds.), Tertiary Basins of Spain: The Stratigraphic Record of Crustal Kinematics. Cambridge University Press, New York, pp. 120–133.

Wright, V.P., Platt, N.H., 1995. Seasonal wetland sequences and dynamic catenas: a re-apprisal of palustrine limestones. Sediment. Geol. 99, 65–71.

Zamarreño, I., Anadón, P., Utrilla, R., 1997. Sedimentology and isotopic composition of Upper Paleocene to Eocene non-marine stromatolites, eastern Ebro Basin, NE Spain. Sedimentology 44, 159–176.

Zoetemeijer, R., 1990. Lithospheric dynamics and tectonic–stratigraphic evolution of the Ebro Basin. J. Geophys. Res. 95 (3), 2701–2711.