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Stratigraphic and tectonosedimentary development of the Eocene Sant Llorenç del Munt and Montserrat fan-delta complexes (Southeast Ebro basin margin, Northeast Spain)

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Resum

En aquest article es volen sintetitzar els ambients deposicionals, la paleoclimatologia, l'evolució estructural, l'edat, les característiques de l'àrea font i l'organització seqüencial d'un marge de conca del nord-est espanyol a partir de dades sedimentològiques, pal·linològiques, estratigràfiques, estructurals i paleomagnètiques.

Durant el creixement al Paleogen de les cadenes costaneres catalanes (caracteritzades per plecs i encavalcaments vergents al nord-nord-oest), dos ventalls costaners (Sant Llorenç del Munt i Montserrat) van progradar cap a la conca de l'Ebre. La condició sintectònica d'aquests dipòsits s'evidencia per la presència de fàcies i geometries directament relacionades amb el creixement d'estructures específiques i l'activitat tectònica de l'àrea font. S'ha deduït una evolució tectonosedimentària al llarg del marge de conca i s'ha mostrat una migració de la deformació cap al sud-oest.

Els efectes de les elevades taxes de subsidència i aportaments sedimentaris associades amb l'elevació de l'orogen van influenciar directament l'organització seqüencial dels dos ventalls costaners. S'aprofundeix en la importància de les diferents superfícies clau relacionades amb els cicles bàsics, el model d'apilament de les seqüències d'alta freqüència i la formació de seqüències compostes de menor ordre, la duració i periodicitat associada amb cada jerarquia seqüencial, la continuïtat de les seqüències costaneres en zones continentals, i la importància relativa de la relació entre acomodació i variacions d'aportament sedimentari en el control de la jerarquia seqüencial.

Paraules clau: Ventall costaner, sedimentologia, estratigrafia seqüèncial, evolució tectonosedimentària, conca de l'Ebre.

Abstract

The depositional environment, climatic conditions, structural evolution, age, catchment area characteristics, and sequence stratigraphic arrangement along an early Cenozoic foreland-hinterland boundary in northeastern Spain were determined from sedimentologic, palynologic, stratigraphic, structural, and paleomagnetic data. As the transpressional Catalan Coastal Ranges (characterized by NNW-verging folds and thrusts) rose during the Paleogene, two fan-deltas prograded into the Ebro basin. The syntectonic condition of the Paleogene deposits is evidenced by facies and geometries directly related to the growth of specific structures and tectonic activity in the catchment area. A tectonosedimentary evolution was deduced along the basin margin, clearly indicating a NE to SW migration of the deformation.

In the present study, the effects of high rates of subsidence and sediment supply, associated with orogenic uplift and loading, on the sequence-stratigraphic organization of two fan-delta clastic wedges are highlighted. Specific topics addressed are the relevance of different key stratigraphic surfaces to the development of basic depositional cycles; the stacking pattern of high-order sequences, and the formation of lower-order composite sequences; the time span and periodicity recorded by the sequence hierarchy; the traceability of coastal sequences into the alluvial realm; and the relative importance of accommodation vs. sediment supply changes in controlling sequence hierarchy.

Keywords: Fan-delta, sedimentology, sequence stratigraphy, tectonosedimentary evolution, Ebro basin.

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Montserrat and Sant Llorenç del Munt are two conglomeratic massifs located on the SE margin of the Ebro basin, 30 km NW from Barcelona. Those significant mountains, which became national parks in 1987, are emblematic and treasured sites for Catalan culture and history. Local geologists have studied this area, mostly during the second half of the 20th century. During the last two decades, following the creation of new outcrops due to forest fires in the 1980s, more detailed studies as well as collaborations among different universities (Universitat de Barcelona, Universitet i Bergen, University of Wyoming, Uppsala University) have led to an enormous increase in our knowledge and understanding of the area.

Montserrat and Sant Llorenç del Munt are geologically exceptional areas, ideal for teaching, training, and research purposes, due to the erosive processes that took place during the quaternary, which resulted in a series of long and deeply incised valleys where the Eocene sediments crop out. The excellent and abundant (mostly continuous) outcrops provide a three-dimensional ensemble of two fan-delta systems covering a surface of about 5000 km^2 and a thickness of approximately 1000 m.

The lateral continuity of outcrops allows scientists to see the main facies belts (alluvial fan, near-shore, off-shore, carbonate platform) and to study the rapid lateral facies changes among them along sections that are 1–2 km long. Whereas in other basins, geologists must travel long distances to observe different facies belts or paleoenvironments, in Montserrat and Sant Llorenç del Munt it is possible to walk from one to the other and to see their relationships from the landscape. This "pocket model" facilitates study of the source area until the turbidites (crossing the subaerial, coastal, and shallow marine environments).

The excellent and continuous outcrops also allow appreciation of the architectural arrangement of the different facies belts, thus providing an exceptional natural laboratory to study sequence stratigraphy and to experience both the elements and a wide range of different surfaces that can actually be touched, rather than merely read about.

Montserrat and Sant Llorenç del Munt are the basinal response of the Palaeogene uplift and the erosion of a source area located SE of the two massifs. Part of the tectonic structures responsible for the uplift of the source area is present in a narrow strip attached to the Ebro basin margin. Thus, the tectonosedimentary evolution of the fan-delta complexes can also be understood by studying the relationships among the tectonic structures and the Eocene sediments.

This article aims to be an integration, summary, and compendium of the knowledge derived from research carried out by the team at Barcelona University during the last 15 years. The focus of this research has included sedimentology, sequence stratigraphy, in addition to tectonics, basin analysis, and tectonosedimentary evolution of the area.

Regional setting

Montserrat and Sant Llorenç del Munt fan-delta complexes are located at the SE margin of the Ebro foreland basin adjacent to the Catalan Coastal Ranges, which are an Alpine structural unit that runs parallel to the Mediterranean coast in the NE of the Iberian Peninsula (Fig. 1).

Alpine tectonic history of the NE margin of Iberia

The structure of the NE margin of Iberia resulted from two alpine processes: the convergence between Iberia and Eurasia and the displacement towards the west of the Alboran domain in relation to Iberia.

The first process, which occurred during the Late Cretaceous-Early Miocene, led to a N-S compressive regime that built the Pyrenean orogen along the northern margin of the Iberian plate and caused the development of thrust belts in the interior of the Iberian plate (i.e., the 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 [13, 54]. However, some flexure was also induced by the tectonic loads of the Catalan Coastal Ranges and the Iberian Chain on the southern and eastern margins of the basin [96] (Fig. 1).

After welding of the Iberian and Eurasian plates in the Oligocene [91], the structural evolution of eastern Iberia was controlled by the western displacement of the Alboran domain in relation to Iberia. This process initiated the development of both contractive and extensional structures. The compressive 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, although also affecting belatedly the Betic-Balearic orogen, developed mainly in the interior of Iberia. 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 (Fig. 1).

The Catalan Coastal Ranges

The southeastern margin of the Ebro foreland basin is formed by the Catalan Coastal Ranges (Fig. 1). The NE-SW Catalan Coastal Ranges are located between the Ebro basin and the Valencia trough [9, 38]. Their complex structure reflects the superposition of compressive and extensional structures resulting from the growth of a Paleogene transpressive intraplate chain [4, 27], that during the Late Oligocene, became the western passive margin of the extensional Valencia trough [74].

The structure of the Paleocene intraplate chain results from a NW-directed basement-thrust system related to sinistral NE-SW strike-slip faults [26, 4]. The thrust system crops out mainly in a narrow ENE-WSW to NE-SW-oriented zone (Prelitoral Range) between the Vallès-Penedès basin and the Ebro basin (Figs. 2, 3). Although there is apparent tectonic transport normal to the direction of the chain, the oblique direction of the

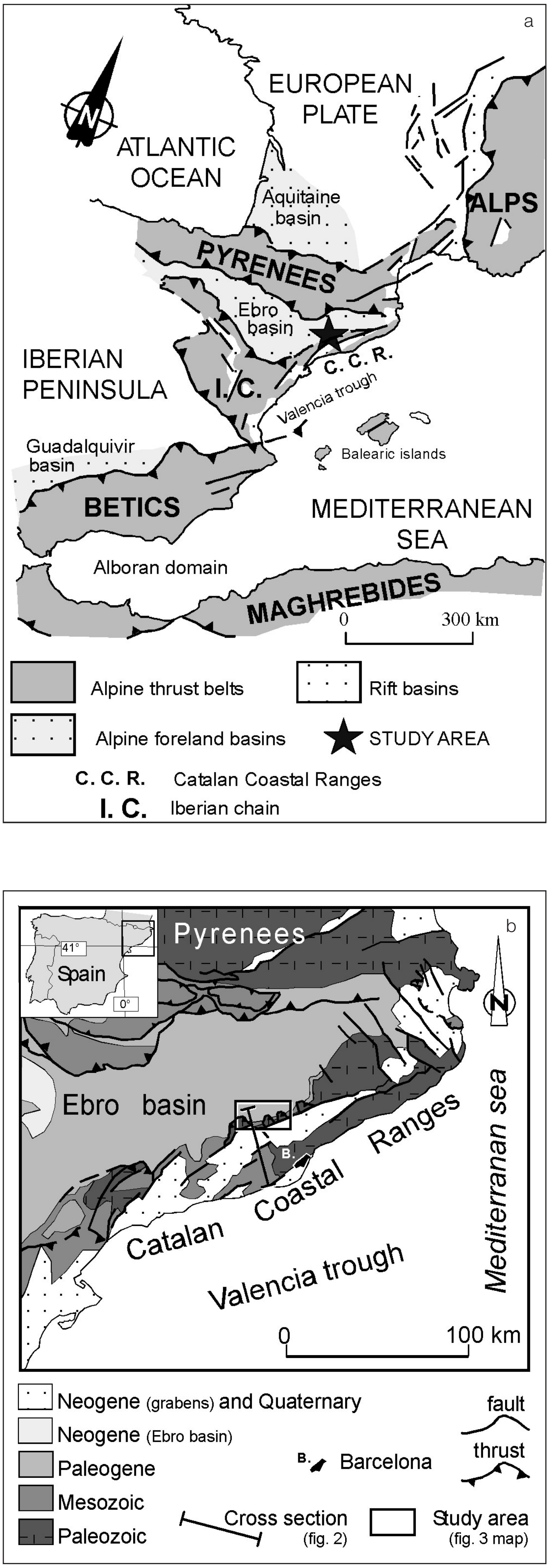

Figure 1. Main geologic units (a) in the western Mediterranean and (b) in the northeast of the Iberian Peninsula (From [45]).

Catalan Coastal Ranges with respect to the Iberia-Europe convergence vector and the presence of major basement strike-slip faults suggests that there was a Paleogene precursor to the Catalan Coastal Ranges. This precursor was a transpressive chain with sinistral motion along segments of its front [26, 4]. This Paleogene structure involves the syntectonic Paleogene sediments located along the Ebro basin margin, the Paleozoic basement, and the Mesozoic cover.

Although the Paleogene deformation has been well-documented, 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 well-developed horst and graben structure [73] (Fig. 2). As a result of the tectonic inversion of the major Paleogene basement faults, this extensional structure is parallel to the present-day coastline and divides the previous Paleogene structure of the Catalan Coastal Ranges into several ENE-WSW to NE-SW-striking blocks (Fig. 1), generally tilted to the NW. The grabens are bounded to the NW by major ENE-WSW to NE-SW, listric normal faults (Figs. 2, 3).

Where preserved in the footwall of these major faults, the Catalan Coastal Ranges and the SE 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). Post-Oligocene in age, the 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 [58, 32].

The central SE Ebro basin margin succession

The basin-margin Paleogene succession consists of continental units, that may have passed laterally (basinwards) to coastal and marine deposits during the Bartonian (Fig. 4).

Paleocene, Ilerdian, Cuisian, and Lutetian stratigraphic units cropping out in the area (Mediona formation, El Cairat formation, La Salut formation, and Montserrat and Sant Llorenç del Munt Conglomerates) are continental. Their lateral marine equivalents can be found in the Pyrenean margin of the Ebro basin (60 km northwards), and, for the Ilerdian deposits, also 20 km SW in the same SE Ebro basin margin (Igualada area).

Bartonian continental units (Sant Llorenç del Munt and Montserrat Conglomerates), after a basal Bartonian transgressive event, passed laterally to the marine and transitional deposits of the Santa Maria Group (Milany sequence). The end of the marine conditions in the Ebro basin is evidenced by evaporitic deposition of the Odena and Cardona formations.

Priabonian and Oligocene sediments are not represented along the studied basin margin, but can be inferred the presence of marginal conglomeratic units (Montserrat and Sant Llorenç del Munt Conglomerates) that represent the proximal equivalents of alluvial and lacustrine formations of the Ebro basin (Artés and Castelltallat formations).

Tectonic structure of the prelitoral range

The Prelitoral Range represents the northwesternmost part of the Paleogene Catalan Coastal Ranges, bounding the Ebro basin (Fig. 2). This part of the Catalan Coastal Ranges was not involved in the Neogene extensional structuration because it is located on the footwall of the most external normal fault of the system.

The Paleogene frontal structure of the Catalan Coastal Ranges (Prelitoral Range) in this area is basically characterized by contractional fold-and-thrust structures. A general simplified cross-section of the Paleogene structure in this area is summarized in Fig 5. Figure 6 shows three selected cross-sections across the range and the Ebro basin margin. The structure of the area basically consists of a series of foreland-directed intercutaneous thrust wedges [68, 50], with their related foreland syncline cut by a large-scale out-of-sequence foreland-directed thrust (Prelitoral thrust of [45]) (Figs, 5, 6).

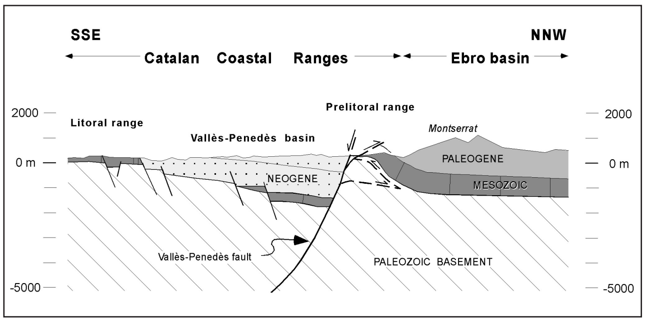

Figure 2. Cross section through the Catalan Coastal Ranges and Ebro basin margin, showing the main structural units of the area and the superposition of compressive (Paleogene) and extensive (Neogene) structures. Notice the relationship between the normal Vallès-Penedès fault (Neogene) and the Paleogene reverse faults of the Prelitoral range (From [43]).

As pointed out in [43], there are deep intercutaneous thrust wedges involving Paleozoic rocks (basement) and shallow intercutaneous thrust wedges affecting Mesozoic cover rocks (Triassic) (Figs. 5, 6). As a result, the footwall of the out-of-sequence frontal thrust is highly deformed and so displays a foreland syncline cut by both foreland– and hinterland-dipping thrusts related to the thrust wedges. The syncline has been interpreted as a complex foreland syncline or foreland frontal monocline (Figs. 5, 6) mainly related to the emplacement of deep intercutaneous thrust wedges. The large-scale out-of-sequence foreland-directed thrust results in large basement thrust sheets formed by several foreland-verging thrust sheets [85, 40, 41, 11].

A series of syntectonic unconformities affect Paleogene deposits from the El Cairat formation up to Montserrat Conglomerates (Figs. 4, 6, 7), which are associated with the emplacement of thrusts (intercutaneous thrust wedges and backthrusts) and fold growth [45, 43].

A major structure in the area is a large strike-slip fault represented by a broad ENE-WSW to ESE-NNW oriented, nearly vertical fault gouge zone (Figs. 3, 5) mainly involving Paleozoic basement and local Triassic cover rocks. Its inhomogeneous deformation indicates an important strike-slip component [35]. This fault gouge affects both the hanging wall and the footwall of the major thrusts. The rooting of the major thrust sheets in the fault gouge, described in [35], indicates that movement of the strike-slip fault and the major thrusts were relatively simultaneous (Eocene in age). This major strike-slip fault is thought to be the "root" of the thrusts and faults [45, 43].

In the studied portion of the Prelitoral Range, a series of transverse faults affecting both the Prelitoral Range and the Paleogene deposits (Fig. 3) have been observed. These faults are

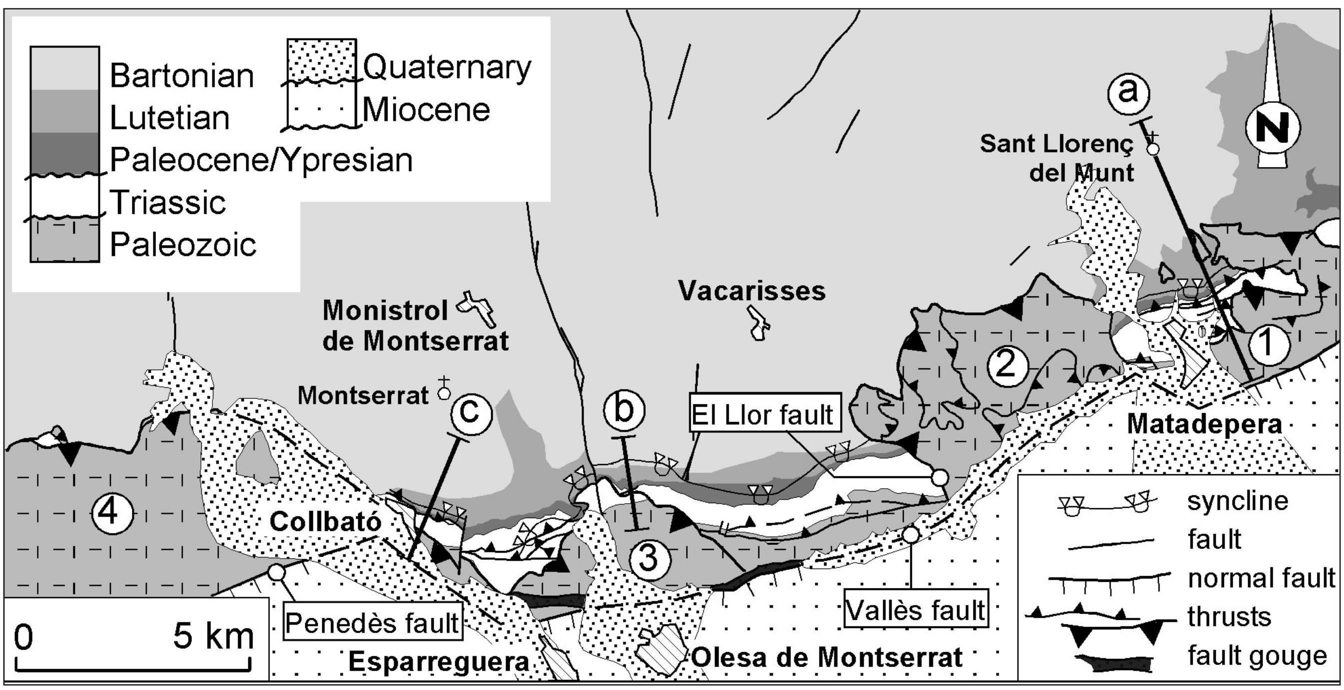

Figure 3. Geologic map of the preserved segment of the compressive, Paleogene Catalan Coastal (Prelitoral) Range and the Ebro foreland margin in the study area. The map is based on our field data and data from [63, 64, 85, 11]. *1* Can Sallent thrust sheet, *2* Les Pedritxes thrust sheet, *3* Agulles thrust sheet, *4* Els Brucs thrust sheet. a–c are cross-sections in Fig. 6 (From [43]).

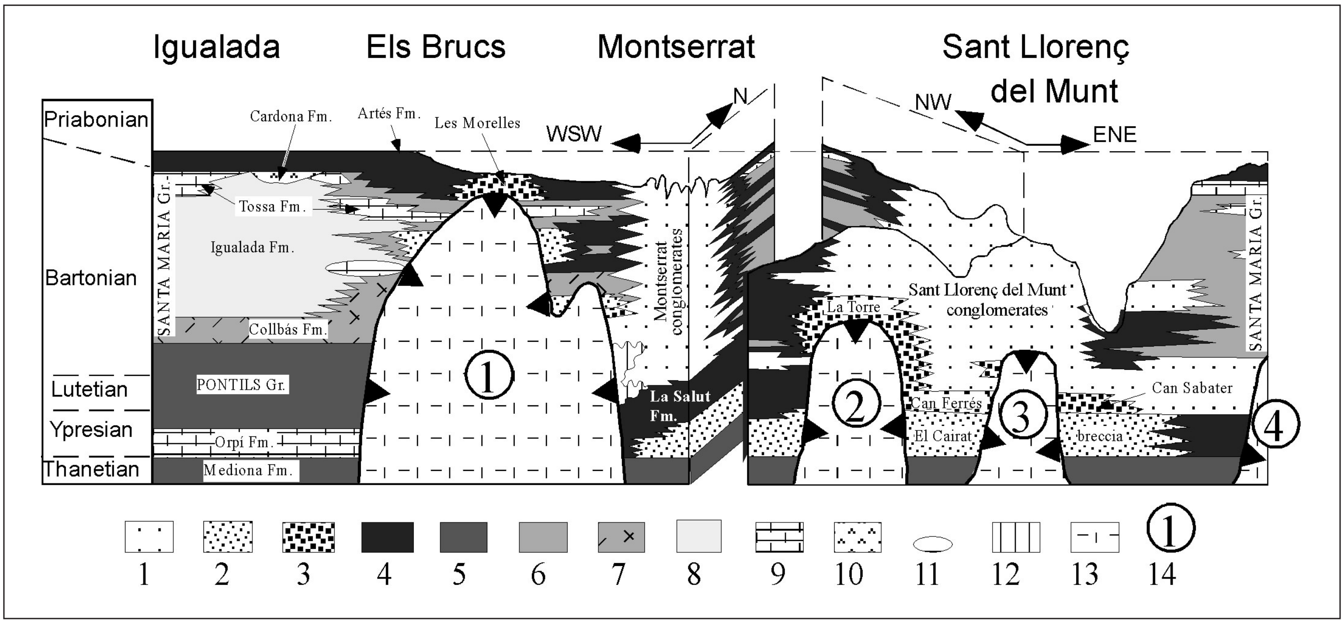

Figure 4. Lithostratigraphy, chronostratigraphy, and depositional environments of the Paleogene of the central part of the eastern margin of the Ebro basin (see inset in Fig. 1b) along a section parallel to the basin margin (no vertical scale). The data are modified from [5]. *1* Polygenic, alluvial 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* near-shore, sandstones, calcarenites, and calcareous mudstones; *8* off-shore 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) (From [45]).

nearly vertical and sometimes bind portions of the range with different deformational styles (e.g., large-scale thrusts vs. intercutaneous thrust wedges).

Although most of the structures described can be observed in the field, some of the intercutaneous thrust wedges were deduced during the construction of detailed, large-scale structural cross-sections (Fig. 6). Intercutaneous thrust wedges have been observed in the field as mid-scale foreland– and hinterland-directed thrusts affecting mainly the Triassic cover. Most of these thrusts and back-thrusts have been associated with the development of intercutaneous thrust wedges (Figs. 5, 6). However, some of these faults can also be interpreted as out-of the syncline thrusts resulting from the formation of a large foreland syncline [43].

Stratigraphy

The stratigraphy of the Paleogene deposits in this area has been well-studied [2, 5, 42]. The different units and formations are summarized in Figs. 4 and 7.

The Mediona formation

This formation is the oldest Paleogene deposit and lies unconformable or paraconformable above Triassic rocks (usually upper Muschelkalk). It is made up of red-orange mudstones and siltstones with frequent paleosoil horizons and rare conglomerates and sandstones. The Mediona formation has been interpreted as fluvial to lacustrine in origin. It is not laterally continuous along the basin margin and it may date from the upper Thanetian and the Ilerdian or part of it [2].

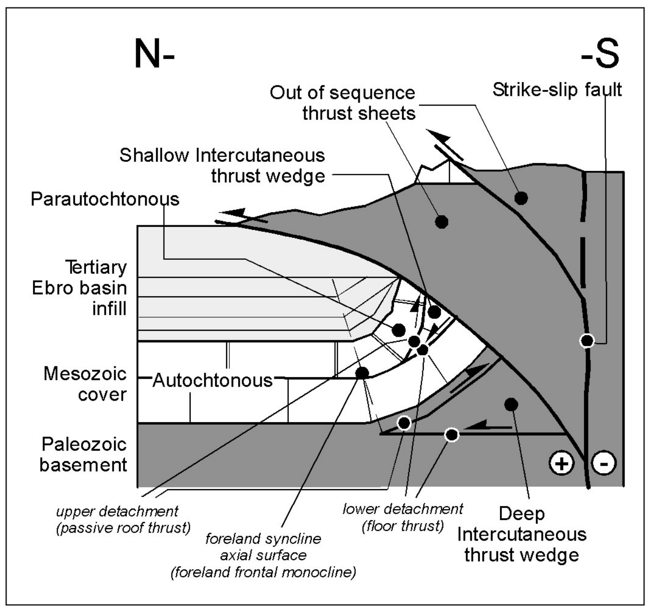

Figure 5. Idealized cross-section summarizing the structure of the portion of the Prelitoral range studied, using nomenclature from [19, 34, 10, 68, 50, 37] (From [43]).

El Cairat breccia formation

This formation mainly consists of cover-derived (Triassic) polymodal breccias with intercalations of red mudstones, siltstones, and minor sandstones, and conglomerates with rounded clasts. The maximum thickness of the El Cairat breccia formation is close to 200 m in the Ripoll river valley (Fig. 7). This unit is present along most of the area studied and has been interpreted as debris-flow deposits at the toe of an

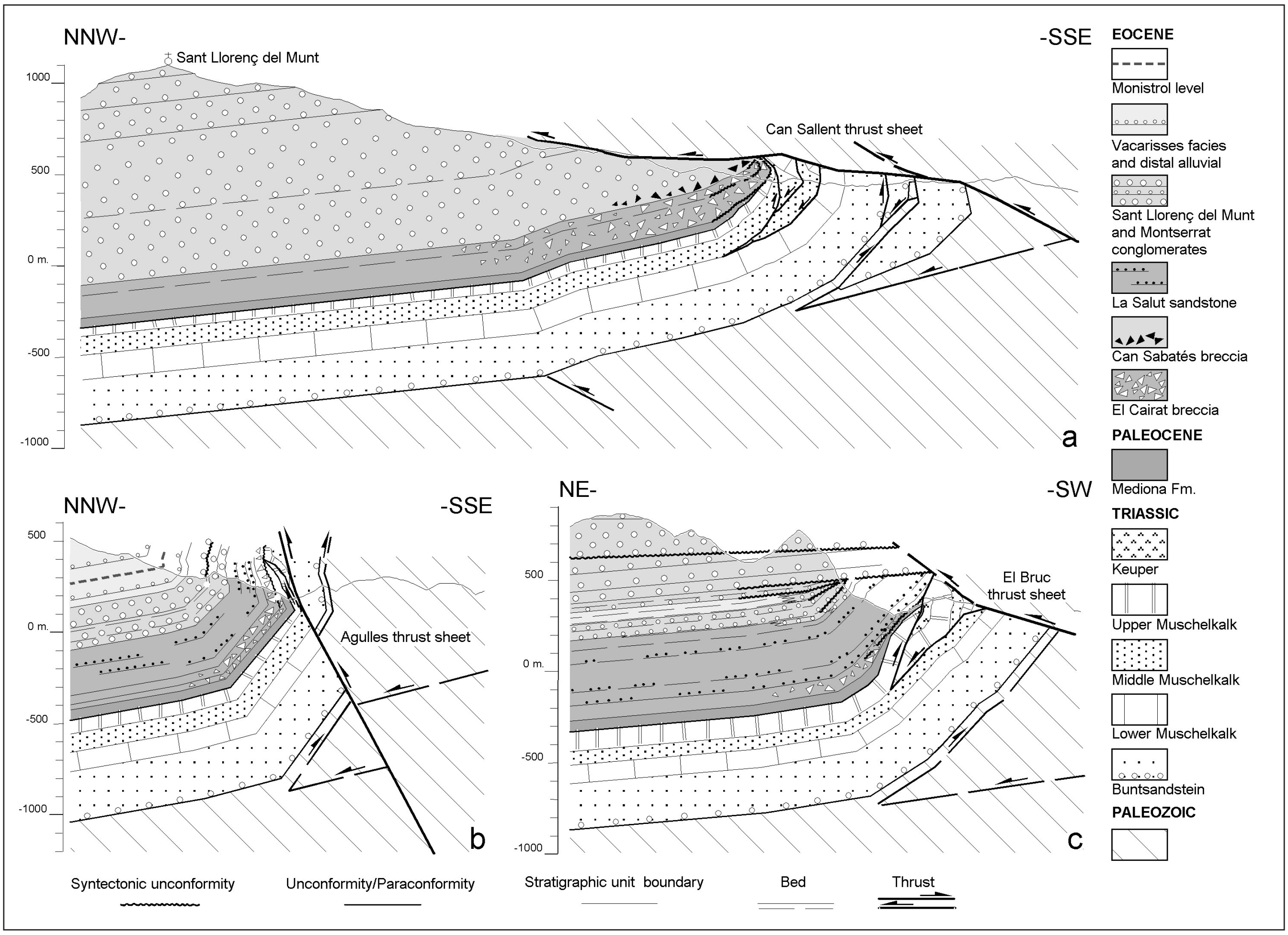

Figure 6. Structural-stratigraphic cross-sections through the Prelitoral range and the Ebro basin margin. (a) Sant Llorenç del Munt area, (b) Sant Salvador de les Espases area, (c) Montserrat area (Modified from [43]).

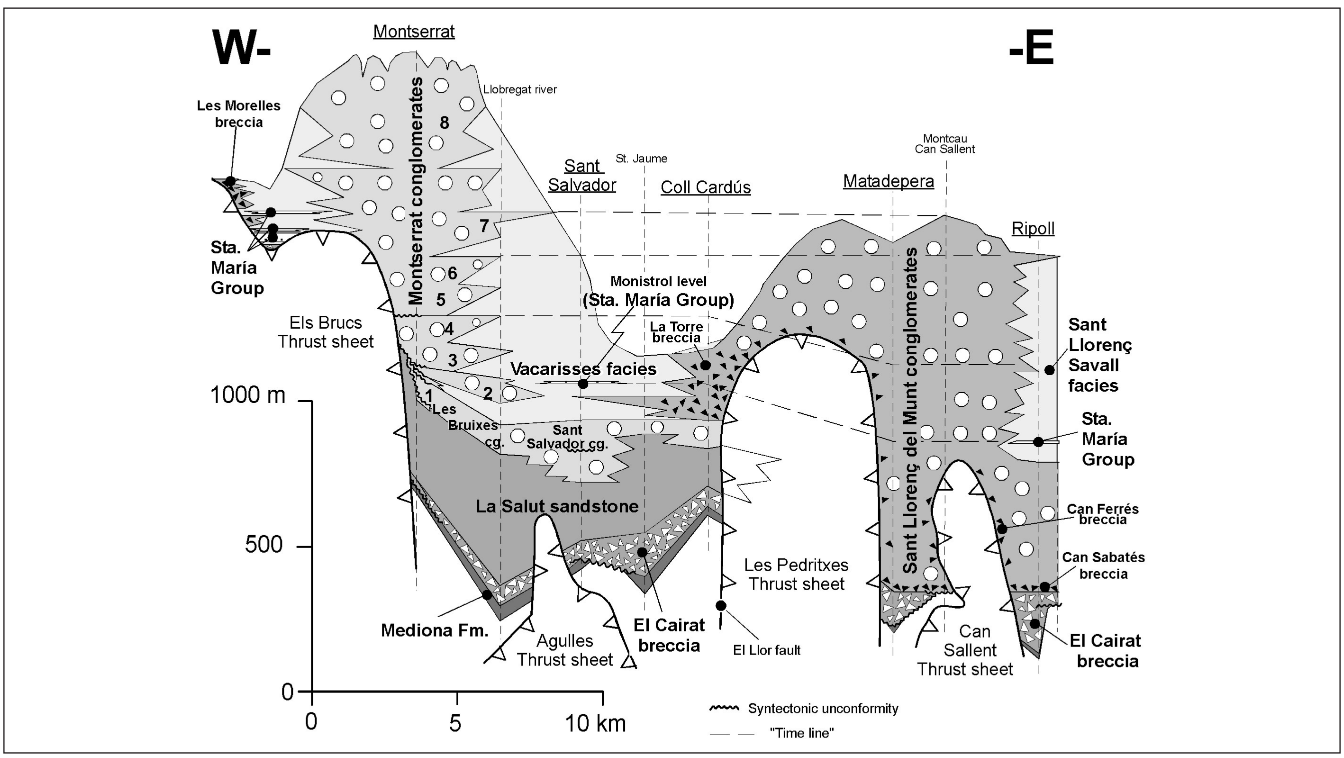

Figure 7. Stratigraphic panel of the Paleogene of the SE margin of the Ebro basin in the Sant Llorenç del Munt-Montserrat area (modified from [5]). Numbers in Montserrat conglomerates correspond to the units defined in [5] (From [43]).

emerging relief of Mesozoic rocks. Olistoliths, mostly made of Triassic blocks, have been previously described [3]. The age of the El Cairat formation is uncertain but may be between early Ilerdian and pre-Lutetian [2].

La Salut sandstone formation

The La Salut sandstone formation crops out in the western part of the study area (Fig. 7). It mainly consists of red sandstones with intercalated mudstones, siltstones, and conglomerates, and its maximum thickness is 349 m [2]. The top of the formation is usually gradual to the conglomeratic formation of Montserrat (Les Bruixes or Sant Salvador de les Espases Conglomerate). The La Salut formation, which dates from the Cuisian-Lutetian [2], has been interpreted as distal alluvial, fluvial deposits with minor palustrine and lacustrine intervals.

Alluvial conglomerates

The two main conglomerates, Montserrat and Sant Llorenç del Munt, were deposited during the Lutetian and Bartonian and differ from each other by geographic location, petrography of the clasts, geometry, and stratigraphic position [2]. These units are non-formal lithostratigraphic units, as defined and used in [72, 2].

The *Montserrat Conglomerate* constitutes the Montserrat massif and passes laterally into finer-grained alluvial deposits (Vacarisses facies) and coastally to marine deposits of the Santa Maria group [62]. Its composition is polymictic but Mesozoic-derived carbonate clasts prevail. This conglomeratic unit has been interpreted as proximal alluvial fan facies that include the syntectonic unconformities reported in [2, 4, 5, 7].

The *Sant Llorenç del Munt Conglomerate* comprises the Sant Llorenç del Munt-Obac massifs and is located in the eastern part of the area studied. It was deposited above the El Cairat formation (Matadepera-Ripoll area), the La Salut formation, and a minor member of the Montserrat Conglomerate (Coll Cardús area). Laterally, the Sant Llorenç del Munt Conglomerate passes into finer-grained alluvial deposits (La Salut, Vacarisses, and Sant Llorenç Savall facies) and coastally to marine deposits of the Santa María group. This conglomerate is polymictic but clasts are mostly derived from the Paleozoic basement. It has been interpreted as proximal alluvial fan facies.

The Minor *Paleozoic-derived breccia units* are laterally equivalent to the Sant Llorenç del Munt and Montserrat Conglomerates. These breccia are made up of the *Can Sabater levels*, *Can Ferrés levels*, *La Torre levels*, and *Les Morelles breccia* (see Figs. 4, 7 for location).

Vacarisses facies

This lithostratigraphic informal unit [2] is made up of red mudstones and siltstones that intercalate conglomerate beds, sandstone layers and sandy to conglomeratic channel fill deposits. The Vacarisses facies are located between the Sant Llorenç del Munt and Montserrat Conglomerates, above the first conglomeratic level of Montserrat (Les Bruixes or Sant Salvador de les Espases Conglomerate). Towards the NW, these facies pass laterally to coastal and marine deposits of the Santa María group [2]. The Vacarisses facies have been interpreted as distal alluvial fan deposits located between the major alluvial fans.

Santa Maria Group

This lithostratigraphic unit [24, 62] consists of the lateral marina equivalents to the Montserrat and Sant Llorenç del Munt Conglomerates. Thus, the Santa Maria group sediments represent the coastal and submarine part of the Sant Llorenç del Munt and Montserrat fan-delta complexes. This group comprises three main formations:

1. *Collbàs formation*: Sandstones with subordinated limestone and marl levels. This unit mainly corresponds to the delta front and near-shore deposits.
2. *Igualada formation*: Blue-gray marls with scarce calcareous and sandy intercalations. This unit corresponds to prodelta and offshore facies.
3. *La Tossa formation*: Coraline limestones comprising subordinate lutitic and sandy levels. This unit corresponds to reef and bioclastic bar environments.

The age of these deposits is considered to be Bartonian [77, 92, 42, 78]. An analysis of the magnetic polarity stratigraphy of the Eocene of the Montserrat area (Fig. 8) was previously reported [45]. Correlation of the magnetic polarity stratigraphy (MPS) obtained with the global magnetic polarity time scale [16] is aided by fauna associated with strata that define the

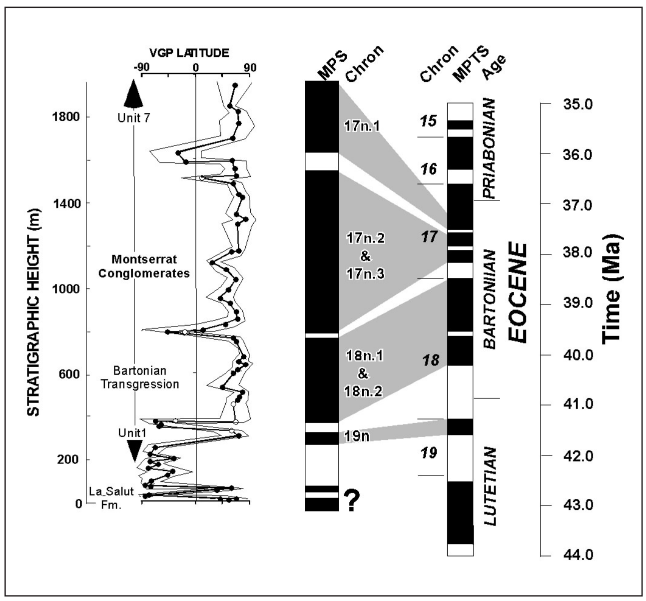

Figure 8. Magnetic polarity stratigraphy for the Montserrat section and correlation with the magnetic polarity time scale [16]. The VGP latitudes of class I and II sites are plotted with their associated 95% confidence intervals. The normal and reversed data define 11 magnetozones, each of which contains two or more sites and includes at least one Class I site. Chronologic tie points, consisting of the Cardona evaporites that overlie the dated succession (see Figs. 2, 3) and of the marine strata of the Bartonian transgression, guide the correlation. This correlation indicates that 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 (From [45]).

«Bartonian transgression» and the age of the Cardona formation [14, 77, 92]. 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. 8). Accordingly, the Montserrat Conglomerate section spans as much as ~4.4 My, from ~37.2 to 41.6 Ma.

In later studies [83], a Priabonian age was assigned to the uppermost levels of the Santa Maria group; alternatively, a Bartonian age for the entire succession has been proposed [79].

Tectosedimentary evolution

Basin margin evolution

A study of the relationships (in maps and cross-sections) among the different tectonic structures and stratigraphic units that crop out from the SE Ebro basin margin led to the proposal of a tectonosedimentary evolution [41, 43, 45], which is summarized in Table 1. The same evolution was observed in all the studied sections along the basin margin:

1. Emplacement of *shallow intercutaneous thrust wedges* (deposition of monomictic, Triassic-derived El Cairat breccia, growth strata, and unconformities).
2. *Folding* related to the emplacement of *deep intercutaneous thrust wedges* (growth strata and unconformities).
3. Major *out-of-sequence thrusting* (development of alluvial fans and lateral fluvial systems).

The *strike-slip fault* is considered to be simultaneous to thrusting (intercutaneous thrust wedges and out-of-sequence foreland directed thrusts) [45, 43].

In the eastern area, these three stages are closer in time (Matadepera and Ripoll sections in Table1), and stages 2 and 3 even seem to be simultaneous or to alternate during a relatively short lapse of time (from the top of the El Cairat breccia to the lower Sant Llorenç del Munt Conglomerates). This is deduced from the folding of the Can Sabater breccia (Palaeozoic-derived breccias that sharply lie over the El Cairat formation), which are presumed to be derived from a major basement-involving thrust sheet. In this case, the evolutionary pattern appears to be 1, 2, 3, 2, and 3. Partial synchronous character of folding (2) and major thrusting (3) have also been observed for the Coll Cardús section.

In the western area, the results are similar, starting with shallow intercutaneous thrust wedge (1), folding due to deep intercutaneous thrust wedge (2), followed by major out-of-sequence thrusting (3). In this area, between the emplacement of shallow and deep intercutaneous thrust wedges, there is a period with no evidence of clear tectonic activity.

Timing of the structures

In spite of the similar evolution of the entire basin margin, the tectonic episodes were not synchronous along the 30-km-long segment of the study region. This small-scale (30 km) migration of the structures towards the SW agrees with the large-scale diachronic character of the SE Ebro basin margin structuration along the 200 km of the Catalan Coastal ranges, as pointed out in other studies [4, 5]. This SW displacement or migration of the deformation may be related to the triggering and onset of stresses transmitted southwards from the northern margin of the Iberian plate underneath the Pyrenees [93].

The emplacement of shallow intercutaneous thrust wedges resulted in the creation and erosion of a juvenile topography made of Triassic rocks. The El Cairat breccia formation was formed by Triassic-cover-derived debris and deposited at the toe of this topography. It passes laterally and vertically to the La Salut beds. As its age is not certain (above lower Ilerdian and pre-Lutetian [2]), it could be relatively heterochronous from section to section. In Table 1, the El Cairat breccia is represented as equivalent to a time-slice, but this may not be the case. Hence, the emplacement of the shallow intercutaneous thrust wedges could have been produced during the Ypresian (from 55.9 to 49.0 Ma, approximately). The shallow intercutaneous thrust wedge affects the lowermost La Salut sandstone deposits in the Collbató (Montserrat) section (Fig. 6c). Thus, if the top of the El Cairat is isochronous, the end of the emplacement of the shallow intercutaneous thrust wedges is younger in the SW area. If the emplacement is coeval, the top of the El Cairat formation is older in this SW section.

The emplacement of deep thrust wedges, as described in Table 1, is diachronous and younger from NE to SW. In the NE sections, the fold related to the emplacement of these intercutaneous thrust wedges affects a region up to the lower Sant Llorenç del Munt Conglomerates, laterally equivalent to the lower part of the La Salut formation (Cuisian-Lutetian, [2]). In the SW sections, the fold-growth associated with the emplacement of the deep intercutaneous thrust wedge took place mostly during formation of the Montserrat Conglomerate units 1 and 2 (uppermost Lutetian and lowermost Bartonian in age [6, 42, 45]). Therefore, in the NE, this deep intercutaneous thrust-wedge-related folding took place between 52.36 and 41.25 Ma (approximately), whereas in the SW, it occurred from 41.6 to 40.4 Ma (approximately) or maybe later. Based on the accurate magnetostratigraphic data [42, 45], it has been possible to estimate the duration of the emplacement of the deep intercutaneous thrust wedge in the Montserrat section as ~1.2 My. Considering an uplift of 558 m for the short limb of the related syncline, an uplift rate of 0.45 mm/year has been calculated for this fold [43].

Analogous to folding, the emplacement of major thrust sheets is also diachronous. In Sant Llorenç del Munt (NE area), major thrust sheets probably started their movement simultaneous with the Can Sabater breccia deposition, equivalent to the La Salut formation, Cuisian-Lutetian in age (52.36–41.25 Ma). In the SW area (Coll Cardús-Sant Salvador-Montserrat), there is also a diachronous character. In the Coll Cardús section, the emplacement of major thrust sheets started simultaneous with the La Torre breccia, lowermost Bartonian in age (~41 Ma). In the Sant Salvador de les Espases section, thrusting is post-folding. Since folding affects the first Bartonian marine wedge (Monistrol Composite sequence [42]), thrusting would have occurred after ~39.7 Ma. In the Montserrat area,

Section / Stratigraphic unit	Montserrat (Collbató-Sant Jeroni)	Sant Salvador de les Espases	Riera de Sant Jaume-Coll Cardús	Sant Llorenç del Munt (Matadepera-Can Sallent)	Sant Llorenç del Munt (Ripoll river)	Section / Stratigraphic unit
Montserrat 5, 6, 7 & 8 conglomeratic units	(3) •Out-of sequence thrusting •Deposition of alluvial conglomerates unconformably above the tilted (rotated?) beds •Erosion of Mesozoic and Paleozoic.	?	?	?	?	
Montserrat 3 & 4 conglomeratic units	(3) •Out-of sequence thrusting •Deposition of alluvial conglomerates unconformably above folded beds •Erosion of Triassic and Paleozoic.	?	(3) •Out of sequence thrust •La Torre Pz-derived breccias. •Erosion of Paleozoic and Triassic.			
Montserrat 1 & 2 conglomeratic units	(2) •Fold growth (Deep thrust wedge) •Deposition of alluvial conglomerates and distal alluvial facies. •Erosion of Triassic and Paleozoic. •Growth strata. •5 Unconformities (fanning) with offlap-onlap wedges.	(2) •Fold growth (deep thrust wedge?) •1 internal unconformity	(3) (2) •Out of sequence thrust and folding (deep thrust wedge) •Deposition of (1) distal alluvial-fluvial La Salut beds, (2) alluvial conglomerates and (3) Pz-derived breccias. •Erosion of Triassic and Paleozoic. •La Torre breccia is deposited above a sharp surface (unconformity?).	(3) •Out of sequence thrust. •Deposition of alluvial conglomerates and Pz-derived breccias. •Erosion of Paleozoic and Triassic. (3) (2) •Out of sequence thrust and/or fold (deep thrust wedges). •Deposition of Sant Llorenç del Munt conglomerates and Pz-derived Can Ferrés breccias. •Erosion of Paleozoic basement and Triassic cover.		Sant Llorenç del Munt conglomerates
La Salut sandstone formation	•No active structure? •Deposition of fluvial-alluvial La Salut Sandstone. •Erosion of Triassic and Paleozoic.	(2) •No active structure? •Fold growth? (1) •Thinning of the series towards south.	•No active structure?	(3) (2) •Out of sequence thrust and or fold (deep thrust wedges). •Exclusive erosion of Paleozoic basement. •Deposition of Can Sabater breccia unconformably onlapping on a sharp erosive surface.	•Deposition of Can Sabater breccia, above a sharp surface.	Can Sabater breccia
El Cairat breccia formation	(1) •Shallow thrust wedge. •Deposition of fluvial-alluvial La Salut Sandstone and Cairat breccia, probably onlapping on an erosive surface. •Erosion of Triassic (mostly Muschelkalk) and Mediona formation towards the top of the structure. •Growth strata. •Probable internal unconformities.	(1) •Shallow thrust wedge •Deposition of El Cairat breccia, onlapping on an erosive surface. •Internal unconformities.	(1) •Shallow thrust wedge? •Internal unconformities?. •Thining of the series towards south.	(1) •Shallow thrust wedges. •Deposition of El Cairat breccia, onlapping on an erosive surface. •Erosion of Triassic (mostly Muschelkalk) and Mediona formation to the top of the structure. •Growth strata. •Internal unconformities?	•Internal unconformities.	El Cairat breccia formation
SW-			El Llor fault		**-NE**	

Table 1. Active structures, sedimentary record, presence of syntectonic unconformities, growth strata, and composition of the source area in five sections across the basin margin, corresponding to different stages during the Paleogene. Black circled numbers indicate the different episodes of tectonosedimentary evolution: *1* shallow intercutaneous thrust wedges, *2* deep intercutaneous thrust wedges and folding, *3* Major out-of-sequence thrusting; gray circled numbers indicate uncertainty. In the Montserrat section, the tectonic activity observed at the base of La Salut sandstone has been assigned to the El Cairat breccia, because in that section the lowermost La Salut formation (affected by shallow thrust wedges) is laterally equivalent to the El Cairat breccia (nearly non-existent in that section) (Modified from [43]).

major thrusting started between the third and fourth conglomeratic wedges (~39.7 to ~39 Ma). During emplacement of those out-of-sequence thrusts, a series of NW-SE transverse faults developed, leading to individualization of the major thrust sheets. Activation of those lateral fault zones favored the creation of paleovalleys, feeding individual and persistent alluvial fans and fan-deltas (Sant Llorenç and Montserrat fans). The fault bounding the Les Pedritxes thrust sheet (leading the individualization of the Sant Llorenç del Munt fan) started its movement much earlier than the one bounding the Els Brucs thrust sheet (resulting in the individualization of the Montserrat fan), again indicating SW displacement of tectonic activity [43].

The age of the last movement of the major thrusts is unclear. The present erosion level does not allow identification of the highest deposits affected by thrusting, and there are no post-thrusting deposits fossilizing the structure (except Quaternary beds). The major thrusts are assumed to have been active at least, until ~41.4 Ma (Can Sallent thrust), ~39.0 Ma (Les Pedritxes thrust), or ~37.5 Ma (Els Brucs thrust).

Basin-margin subsidence and sedimentation rates

The subsidence history of the Ebro basin margin at Montserrat is shown in Fig. 9 (from [45]). Due to the lack of precise dating of the continental deposits lying below the first Bartonian deposits (see section on Montserrat magnetic polarity stratigraphy), the reliability of the subsidence curve for the Ypresian and most of the Lutetian is uncertain. Despite this uncertainty, however, deposition of the Montserrat Conglomerate corresponds to an interval of high rate of tectonic subsidence (Fig. 9) compared to previous stages. The acceleration of subsidence correlates with the latter stages of syncline-anticline pair folding and with emplacement of the Prelitoral thrust (see previous section). In addition, both the compacted sedimentation and the total subsidence rates tend to increase through time (Fig. 9), the latter reflecting progressive sedimentary loading induced by 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. 9).

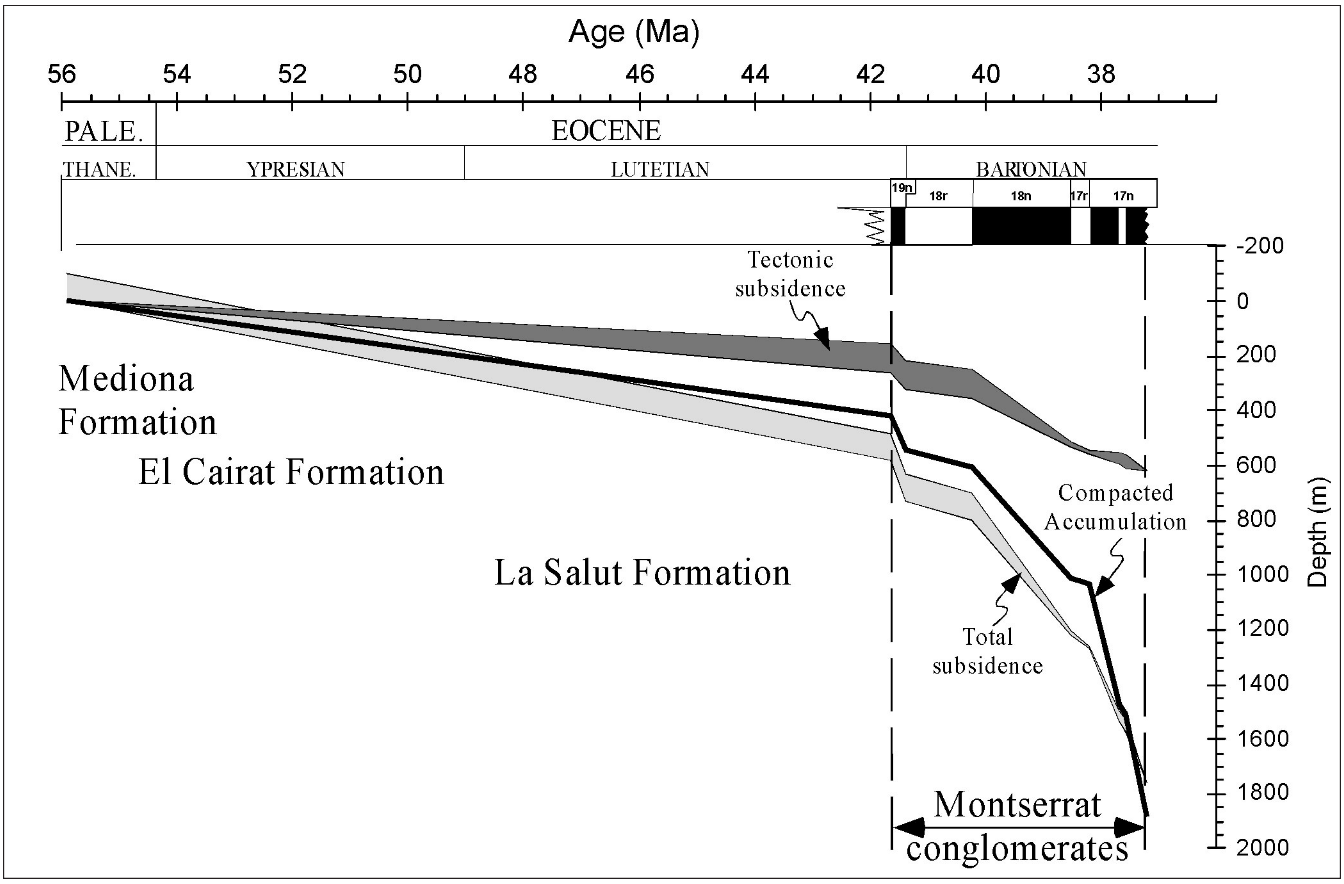

Figure 9. Subsidence history of the Montserrat region. The reliability of the subsidence curve for the Ypresian and most of the Lutetian is uncertain, due to the lack of dating of the continental deposits (Mediona, El Cairat and La Salut formations). The onset of deposition of the Montserrat Conglomerate corresponds to an increase in the rate of tectonic subsidence that correlates with the latter stages of foreland syncline folding and emplacement of the Prelitoral thrust. Compacted sedimentation and total subsidence rates increase 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 (From [45]).

Sedimentology and sequence stratigraphy of the fan-delta complexes

General setting

The Sant Llorenç del Munt and Montserrat fan-delta systems are large fans whose subaerial portions cover a mean minimum area of 350–450 km^2 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 Ma to 37.2 Ma (Bartonian, Middle Eocene) [45].

The key to a Bartonian paleoclimatic reconstruction for the studied area is provided by palynologic data supplemented by sedimentologic, mineralogic, and isotopic observations. On the basis of palynologic data [18], warm and relatively humid conditions were the most likely climatic setting in the studied depositional areas during the Bartonian. These conditions are in accord with other observations reporting the presence of mangrove-swamp paleofloras [1, 12] and with the extensive development of Scleractinian reefs [75, 76, 77], which was synchronous with the development of the Montserrat and Sant Llorenç del Munt fan-deltas [45].

The formation and evolution of the Montserrat and Sant Llorenç del Munt fans are closely related to the tectonic evolution of the adjoining Catalan Coastal Ranges of the Paleogene. Tectonosedimentary relationships along the foreland margin show clearly that the creation and development of both fan-deltas took place during the late stages of anticline-syncline folding and the emplacement of out-of-sequence thrusts. The intersection between frontal thrusts and lateral faults controlled the location of the fan-delta apices of feeding valleys [45, 43] (Fig. 10).

The subsidence history of the basin margin is consistent with a syntectonic development of both fans and indicates that the onset of the Montserrat fan coincided with a clear increase in tectonic subsidence. Subsidence analysis shows that the long-term (4.4 My) sedimentation and total subsidence rates increased through time, the latter recording the progressive loading induced by the accumulated deposits and by the growing thrust load (Figs. 9, 11).

A mean minimum mechanical denudation rate of 100–180 m/My has been calculated for the catchment basins of both fan-deltas and implies a minimum mean elevation for the catchment basins of 700–1250 m (Fig. 11). The development of this high topography close to the shoreline has been 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 [45].

The sudden onset of subsidence at the basin margin reflects rapid growth of the topographic relief, in response to modest shortening that was accompanied by considerable vertical bedrock uplift. Increasing rates of sedimentation and total subsidence recorded in progressively younger fan-delta deposits also point to a rapid uplift, which in combination with the prevailing warm and humid climate resulted in increased denudation rates and an increased sediment supply to the shoreline. The latter, 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, sediment supply was sufficiently rapid that it filled all the available accommodation space and consequently maintained 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 [45].

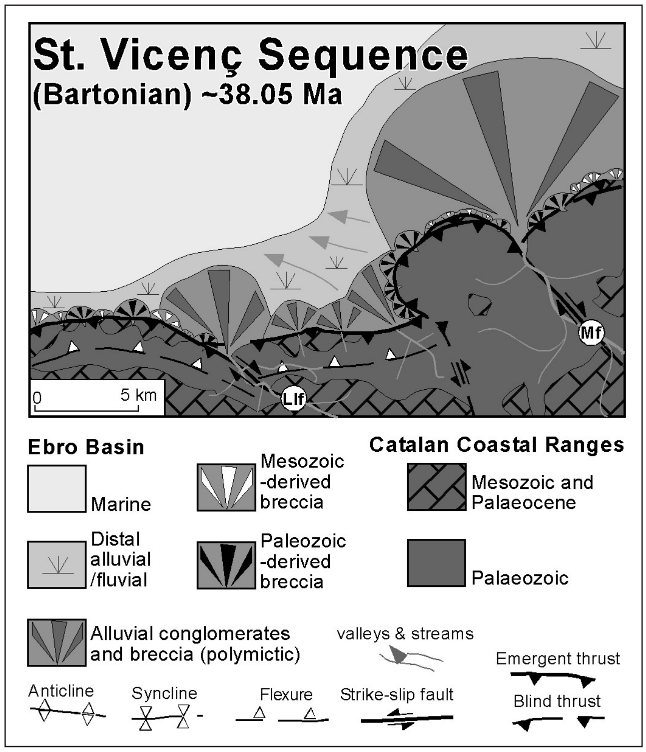

Figure 10. Paleogeographic map of the Montserrat and Sant Llorenç del Munt fan-delta complexes during Sant Vicenç composite sequence. The different sedimentary systems and environments in the basin as well as the active tectonic structures, drainage systems. and distribution of basement and cover outcrops in the adjoining range are shown. Note the location of the Montserrat and Sant Llorenç del Munt fans at the intersection between the frontal and lateral segments of the Prelitoral thrust. The lateral segments correspond to the SE-NW-oriented Llobregat (Llf) and Matadepera (Mf) dextral tear faults (see Fig. 3) (From [43]).

Sedimentology

The Bartonian Sant Llorenç del Munt and Montserrat clastic wedges (Fig. 12) comprise a more than 1000-m-thick succession of alternating terrigenous clastics and carbonates (the latter representing less than 10% of the total thickness). Those sediments accumulated in fan-delta and platform depositional systems, respectively [5, 8, 47, 84, 48, 39, 40, 42, 70, 71].

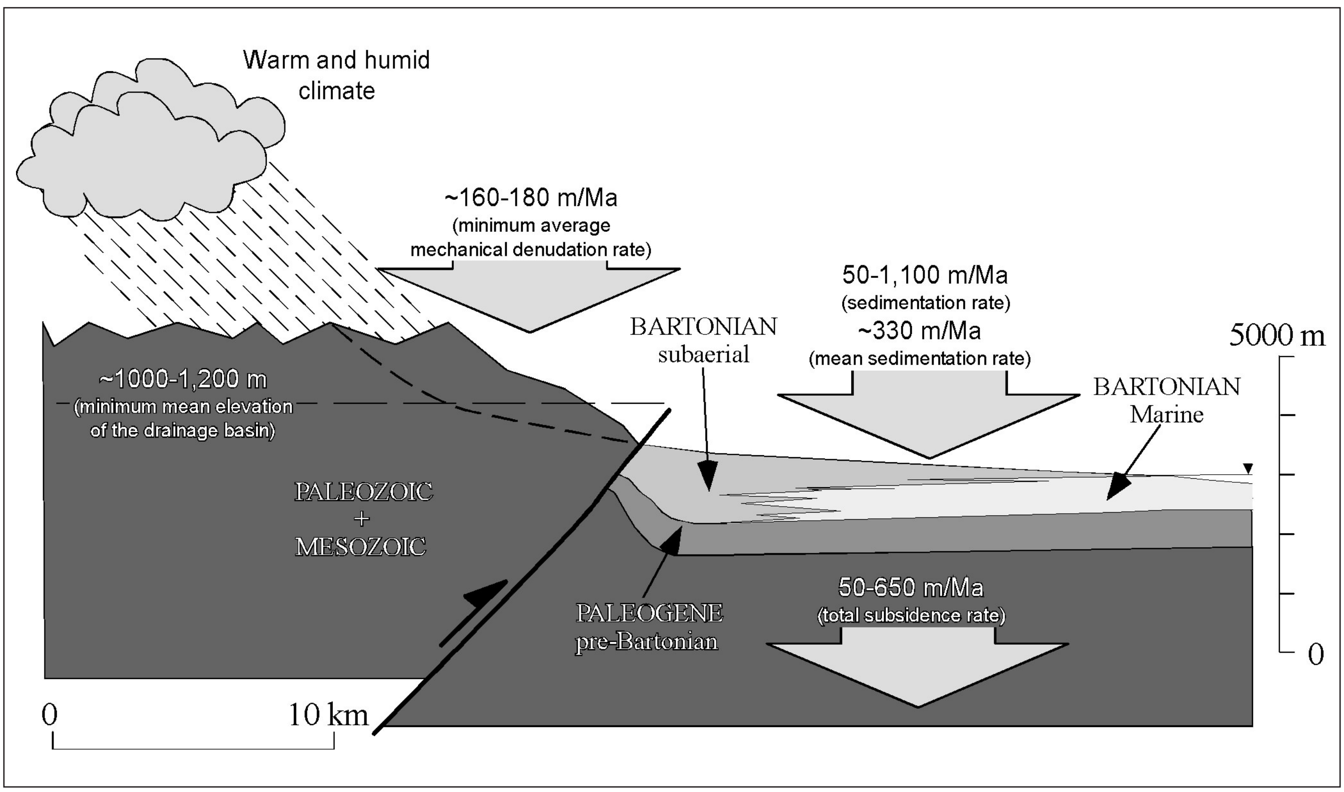

Figure 11. Conceptual model summarizing the tectonosedimentary and tectonogeomorphic setting of the studied fan-deltas, as well as the rates of geologic processes controlling their development during the Bartonian (~4.4 My) (From [45]).

Fan-delta facies model
The fan-delta depositional system can be characterized as an alluvial-fan delta (according to the terminology and classification of [59]). It comprises three main facies associations: alluvial fan, fan-delta front, and fan-delta slope (Figs. 12, 13).

Alluvial fan
The associations of alluvial fan facies on Sant Llorenç del Munt and Montserrat complexes have been described previously [5, 7, 8, 48, 39, 40, 42, 70, 71]. Those facies crop out in the most proximal areas of the basin, near the Prelitoral range, and two main associations of facies (proximal and distal) have been defined. The *proximal alluvial fan* association includes massive conglomerates deposited by sediment gravity flows, sheetflood, and stream flow (braided) deposits, implying the presence of steep gradients. The considerable topographic relief of the catchment areas is inferred to have combined with co-seismic shaking to produce landslides and rockfalls that were reworked as debris– and fluid-gravity deposits on the fan surfaces (i.e., the units of monogenic conglomerates depicted in Figs, 12, 16). These grade distally into an alluvial fan (fan-delta plain/coastal plain) facies association that corresponds to the non-formal stratigraphic units of the Montserrat and Sant Llorenç del Munt Conglomerates, and the Can Sabatés, Can Ferrés, La Torre, and Les Morelles breccias. The *distal alluvial fan* environment is characterized by channel-filled conglomerates and sandstones encased within floodplain, red mudstones, and sandstones. These have been interpreted as deposits from stream and sheet flows. In this environment, the original steep slope of the proximal area is reduced and the deposits are finer-grained due to the less-energic flows. This facies association corresponds to the non-formal stratigraphic unit of the Vacarisses facies and to the Artés formation [44].

Fan-delta front
The fan-delta front (near-shore) is a sandy and conglomeratic facies belt that developed between subaerial and submarine sediments facies associations. It has been widely studied [5, 8, 84, 48, 39, 40, 42, 70, 71] on the Sant Llorenç del Munt and Montserrat complexes.

The deposits of the fan-delta front consist of coalesced, wave-reworked, sandy to conglomeratic mouth-bar facies, mostly deposited from sediment gravity flows, linked to closely spaced or frequently shifting outlets (cf. with the shallow-water, wave-reworked, mouth-bar, fan delta-type of Postma, 1990). Delta-front deposits are usually arranged as coarsening and thickening upwards sequences linked to the progradation of the system in regressive stages. However, the facies also occasionally appear to be associated with transgressive episodes, resulting in fining upwards sequences with important wave-reworking and marine bioturbation. Those facies may partly correspond to the Collbás formation [62].

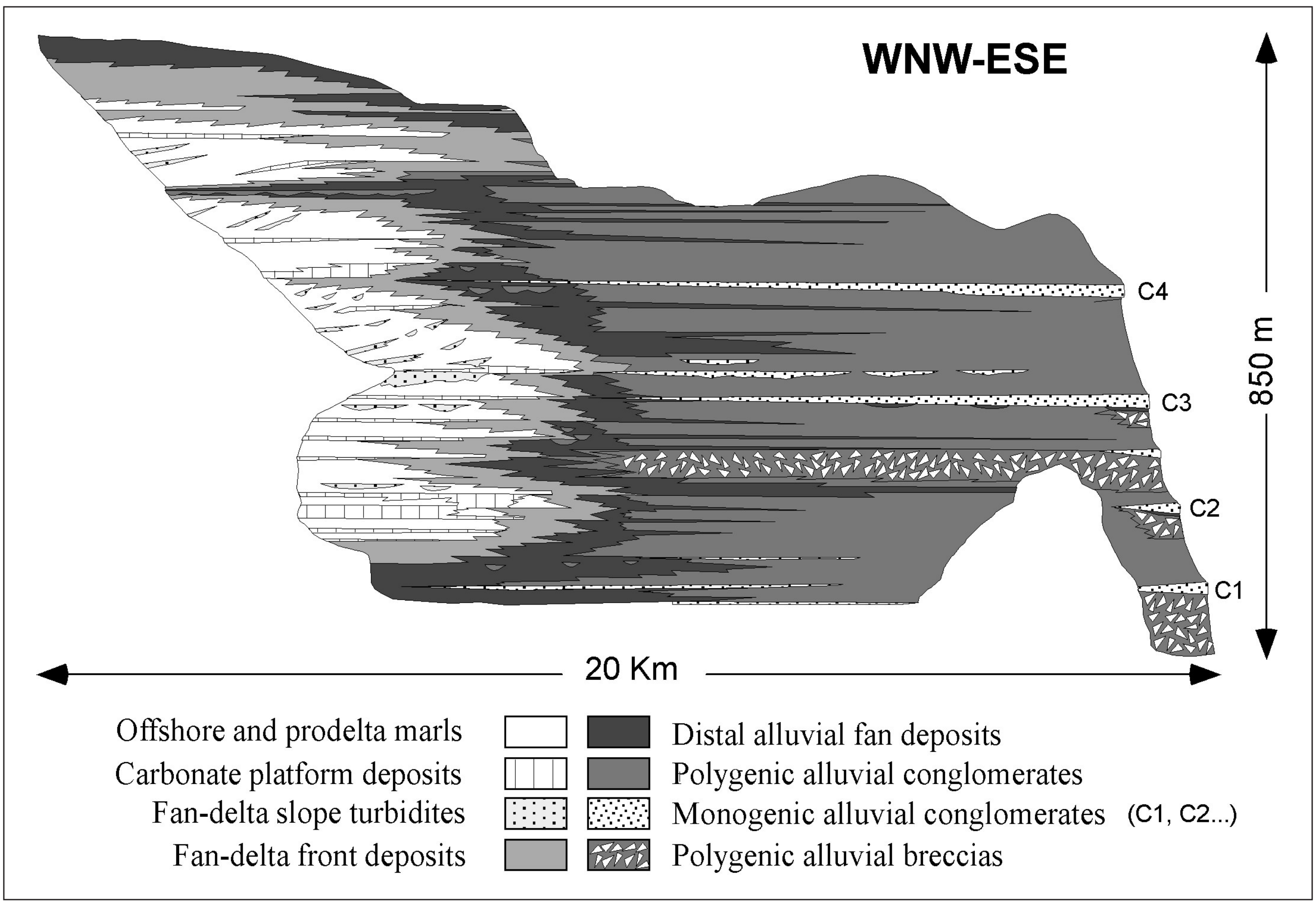

Figure 12. Cross-section along the western part of Sant Llorenç del Munt system. The horizontal and vertical relationships among the different facies belts are shown (From [46])

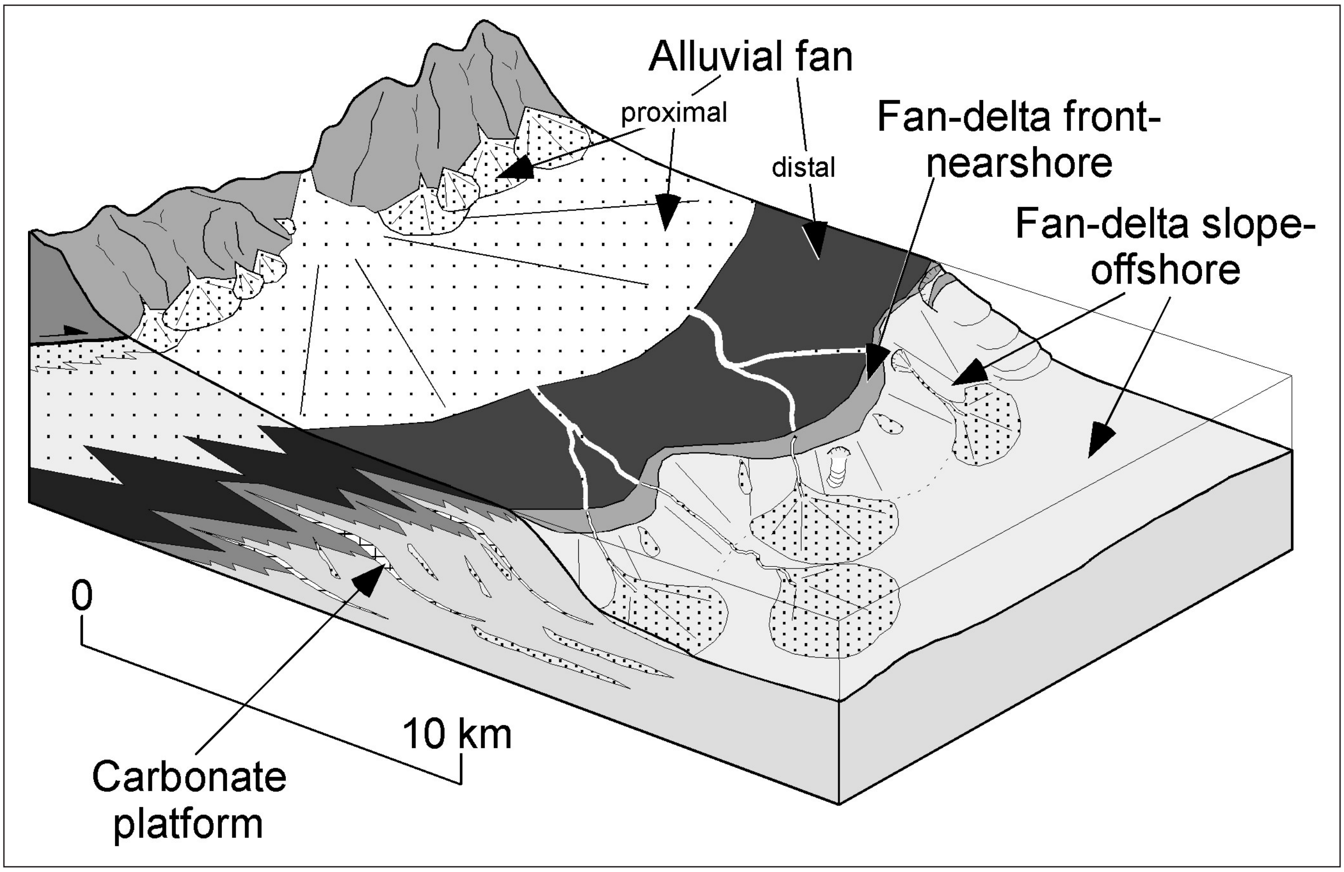

Figure 13. 3-D reconstruction of the relationships among Sant Llorenç del Munt facies belts (From [46]).

Fan-delta slope/offshore

Fan-delta slope and offshore facies associations on the studied fan-delta complexes have been studied previously [5, 48, 39, 40, 42, 49, 53]. The fan-delta slope is mostly formed by blue-gray calcareous mudstones («marls») and represents the most distal facies belt of the system. The deposits are prodelta marls, mainly deposited from suspension and density currents, corresponding to the Igualada formation [62]. They frequently intercalate sandstones and conglomerate beds deposited by turbiditic currents and sediment gravity-flows in gullies and lobes. The ensemble of the slope association is frequently deformed by gravitational phenomena (slumps and slides), resulting in compressional and extensional structures.

Carbonate platform

Associations of carbonate platform facies on the Sant Llorenç del Munt and Montserrat complexes have been widely studied [84, 39, 40, 42, 56, 57]. The carbonate platform depositional system consists of two main facies associations (shallow-water bioclastic bars and reefs) that can be laterally traced into transgressive (wave- and organic-reworked) fan-delta-front sediments. Those sediments are associated with high-frequency transgressive episodes separating general fan-delta progradational stages. The carbonate platform facies can be partly included in the La Tossa formation [62].

Sequence stratigraphy

Some of the most important studies on the Sant Llorenç del Munt, and Montserrat systems were carried out towards the end of the 1980s and first half of the 1990s. At that time, sequence stratigraphy was a relatively new subject and most of the research was focused on its application to field successions. A "new" sequence stratigraphic model was developed following studies of a portion of the Sant Llorenç del Munt fan-delta [39, 40]. That model was later improved [42] and published [46].

On the studied fan-delta successions, shoreline trajectory is the most easily recognizable architectural feature. On the proposed stratigraphic subdivision, sequences and key surfaces have been defined after the study of shoreline trajectories at different scales. The main key surfaces bound sedimentary packages with a common internal shoreline trajectory and indicate a change on this trend (from transgressive to regressive or vice versa) [42 and 46].

Key surfaces

The fan-delta facies display a cyclic arrangement at different temporal and spatial scales (Fig. 12). This cyclicity is linked to the migration of the shoreline through time in response to changes in the ratio between accommodation and sediment supply rates. The shoreline trajectories (see [80, 20, 36, 17, 29, 30]) are dominantly horizontal, landward, or seaward, though some segments are clearly aggradational and rise more steeply. As the shorelines regressed and transgressed, the following laterally extensive surfaces of erosion, slow deposition, or non-deposition were generated and recorded in the sediments (Fig. 14):

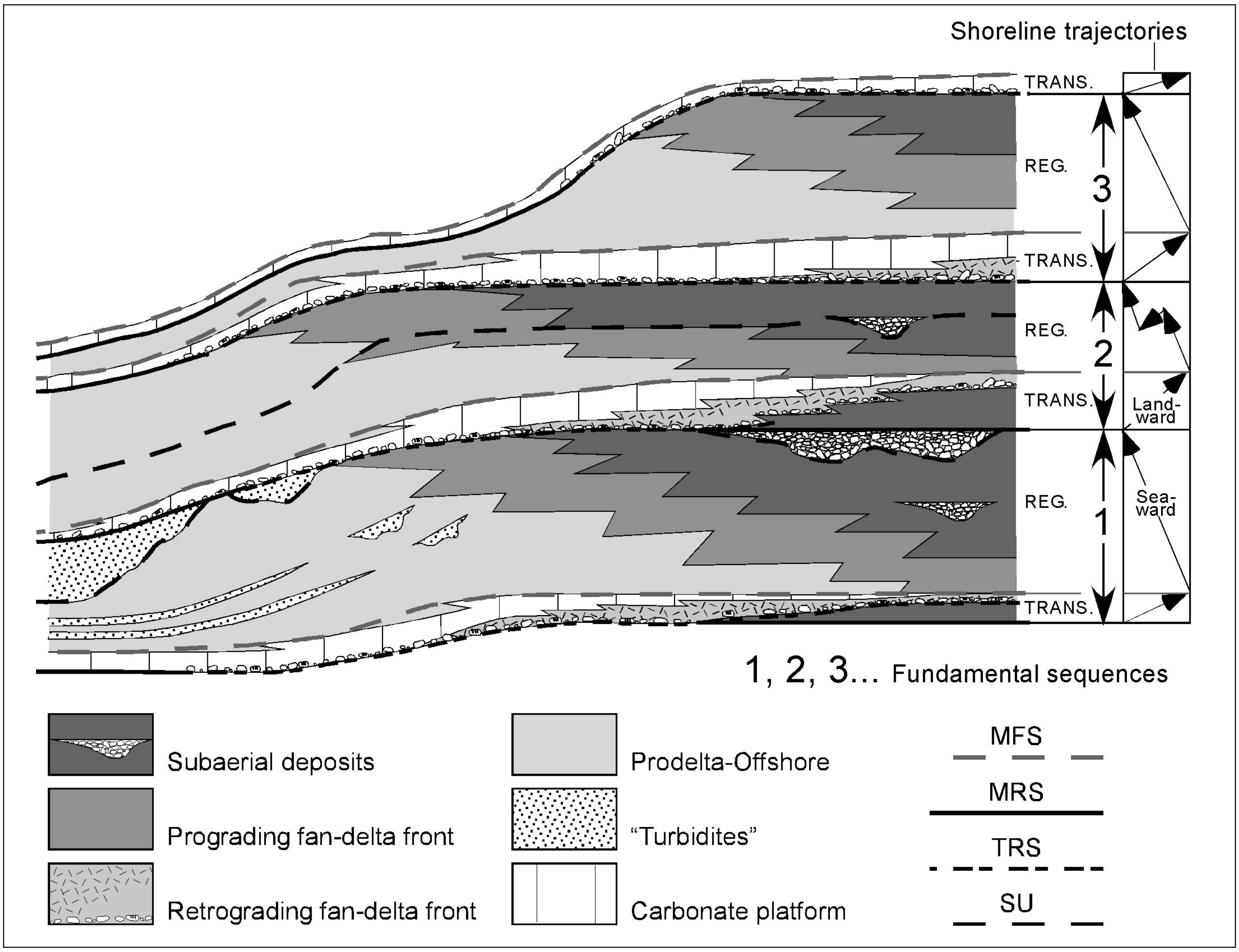

Figure 14. Ideal cross-section showing the expression of T-R fundamental sequences in coastal areas (modified from [46]). MFS, maximum flooding surface; MRS, maximum regression surface (equivalent to transgressive surface); TRS, transgressive ravinement surface; SU, subaerial unconformity (depositional sequence boundary).

- *Maximum regressive surfaces* corresponding to the time of regressive-to-transgressive turnaround of the shoreline. Such surfaces are located at the first evidence of upward deepening following a regression (cf. with the «initial transgressive surface» [61], and the «trangressive surface» [22]).
- *Wave ravinement surfaces* originated during erosional transgression at the time of shoreface retreat, a process involving an intense reworking and winnowing of the preexistent deposits by the actions of wave and storm currents [80, 21, 69]. Commonly, ravinement surfaces are partly superimposed on, and have eroded through previously developed maximum regressive surfaces and/or subaerial unconformities.
- *Maximum flooding surfaces* [67] record the time of change from transgressive to regressive trends and represent the level of deepest water in a vertical section. These surfaces correspond to the maximum landward location of the shoreline and typically develop when terrigenous input rates are at a minimum. They are equivalent to the «final transgressive surface» of [61] and the «maximum transgressive surfaces» of [29].
- *Subaerial unconformities*, which developed in response to relative falls in sea level [86, 88, 89,90], are generally not evident in the studied succession. The existence of this type of surface is only suspected in two cases based on the preservation of deeply incised conglomeratic bodies below ravinement surfaces (Fig. 14). The general lack of evidence for the existence of subaerial unconformities could be related to:

(a) The removal of such surfaces during ensuing transgressions ([94]).
(b) The updip loss of importance of these surfaces, which makes them difficult to distinguish from other autocyclic erosive surfaces;
(c) A general absence of relative falls in sea level during deposition of the investigated succession, as a consequence of the rate of subsidence along the basin margin (Fig. 9) outpacing the rate of falling eustatic sea level (see [81, 25, 65]).

Basic depositional cycles

Since subaerial unconformities are either rare or difficult to distinguish, recognition of the depositional sequences of the Exxon model [87, 66, 67] is not an adequate method to subdivide the studied succession. In contrast, maximum flooding surfaces are frequent, easily identifiable, and well-preserved, and, therefore provide a «genetic stratigraphic» approach [25] suitable for delineating depositional cycles. However, because each genetic stratigraphic sequence includes internally erosive surfaces, such as ravinement and maximum regressive surfaces (if coincident with a subaerial unconformity) (Fig. 14), our approach has been to envelop depositional cycles by combining the ravinement surface with its landward and seaward-related maximum regressive surface. Accordingly, a number of basic, repetitive, transgressive-regressive (T-R) units, called *fundamental sequences* [39, 40, 42, 46] have been defined.

Fundamental sequences are outcrop-scale, 3– to 80-m-thick T-R sequences and comprise two components, almost equivalent to the transgressive systems tract (TST) and regressive systems tract (RST) [23], separated by maximum regressive surfaces (Fig. 14). The lower TST developed in response to periods of decreasing low-terrigenous input to the shoreline or increasing accommodation. An overlying RST provides a record of renewed, increasing high-terrigenous input or decreasing accommodation, resulting in fan-delta progradation. The choice of maximum regressive surfaces as sequence boundaries implies that deposits below the sequence boundary are regressive while those above are transgressive.

The time-span represented by the fundamental sequences ranges from about ~10 000 to ~170 000 years.

Composite T-R patterns

The individual shoreline transits seen in the fundamental sequences combine to yield stacked patterns with longer-term trajectories, analogous to those seen in other fundamental sequences (cf. with the progradational, aggradational, and retrogradational parasequence sets [88, 89 and 90]) (Fig. 15). These changes in the stacking patterns of the fundamental sequences allow recognition of T-R units of regional extent, called *composite sequences* [39, 40, 42, 46] (Figs. 15, 16).

Composite sequences are 100– to 300-m-thick transgressive-regressive sequences, each consisting of a transgressive and regressive couplet. The composite sequences are similar to those described elsewhere [55], in the sense that both have been defined by studying the stacking pattern of higher-frequency sequences. However, they differ in the nature of their basic building blocks. The composite sequence boundaries are low-order maximum regressive surfaces, coincident with the fundamental sequence boundary located at the change from a progradational to a retrogradational stacking pattern (Figs. 15, 16).

A series of sequence sets (transgressive and regressive) have been defined that conform to the complete composite T-R sequences. Transgressive units (transgressive sequence sets, TSS) comprise sets of consecutive fundamental sequences whose stacking pattern shows retrogradational trends, frequently combined with an aggradational component. The overall shoreline-retreat associated with transgressive units (TSS) varies from about 1 km to more than 4.5 km. Regressive units (regressive sequence sets, RSS) are sets of

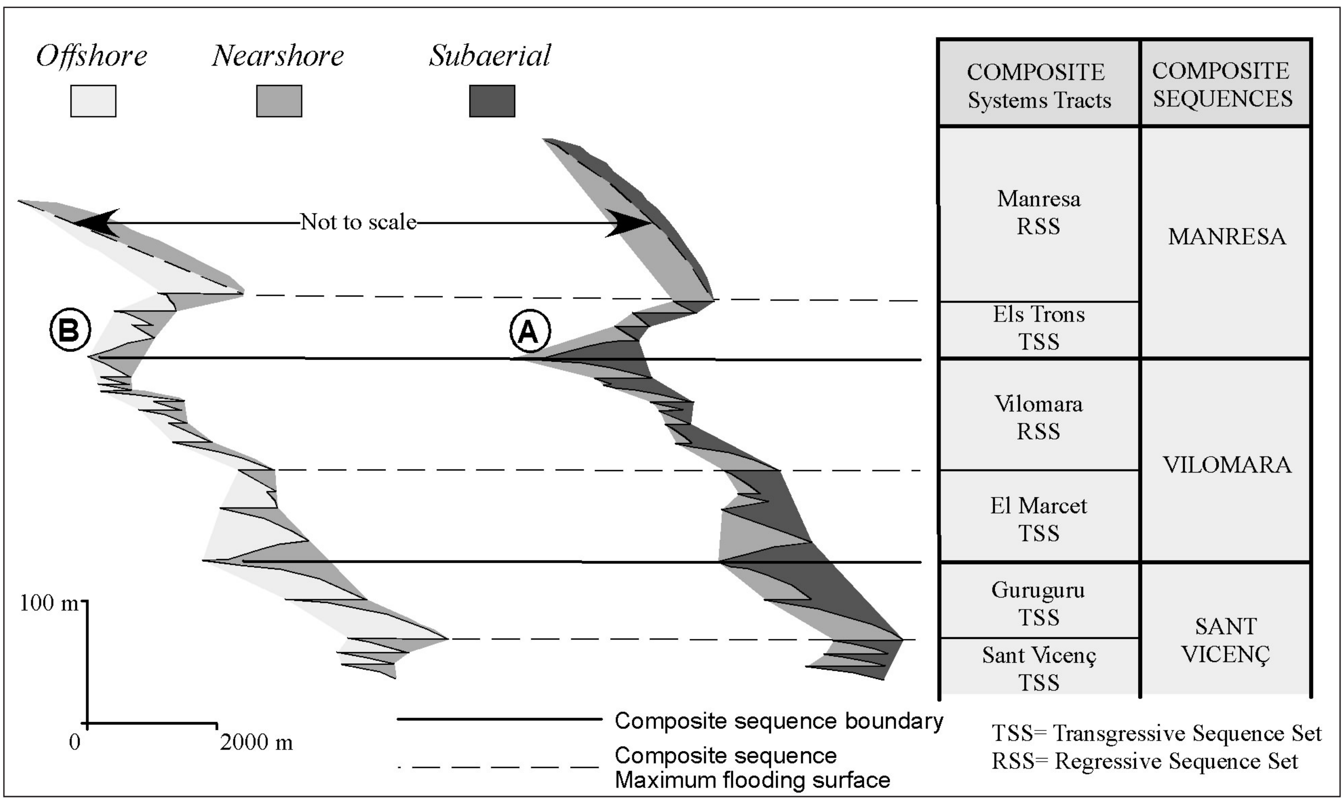

Figure 15. Graphs showing variations in the location of (A) the shoreline and (B) the passage from fan-delta front to offshore environments along the cross-section depicted in Fig. 7. T-R composite sequences and their constituent transgressive and regressive sequence sets are shown. Each of the small wedges represents a T-R fundamental sequence (From [46]).

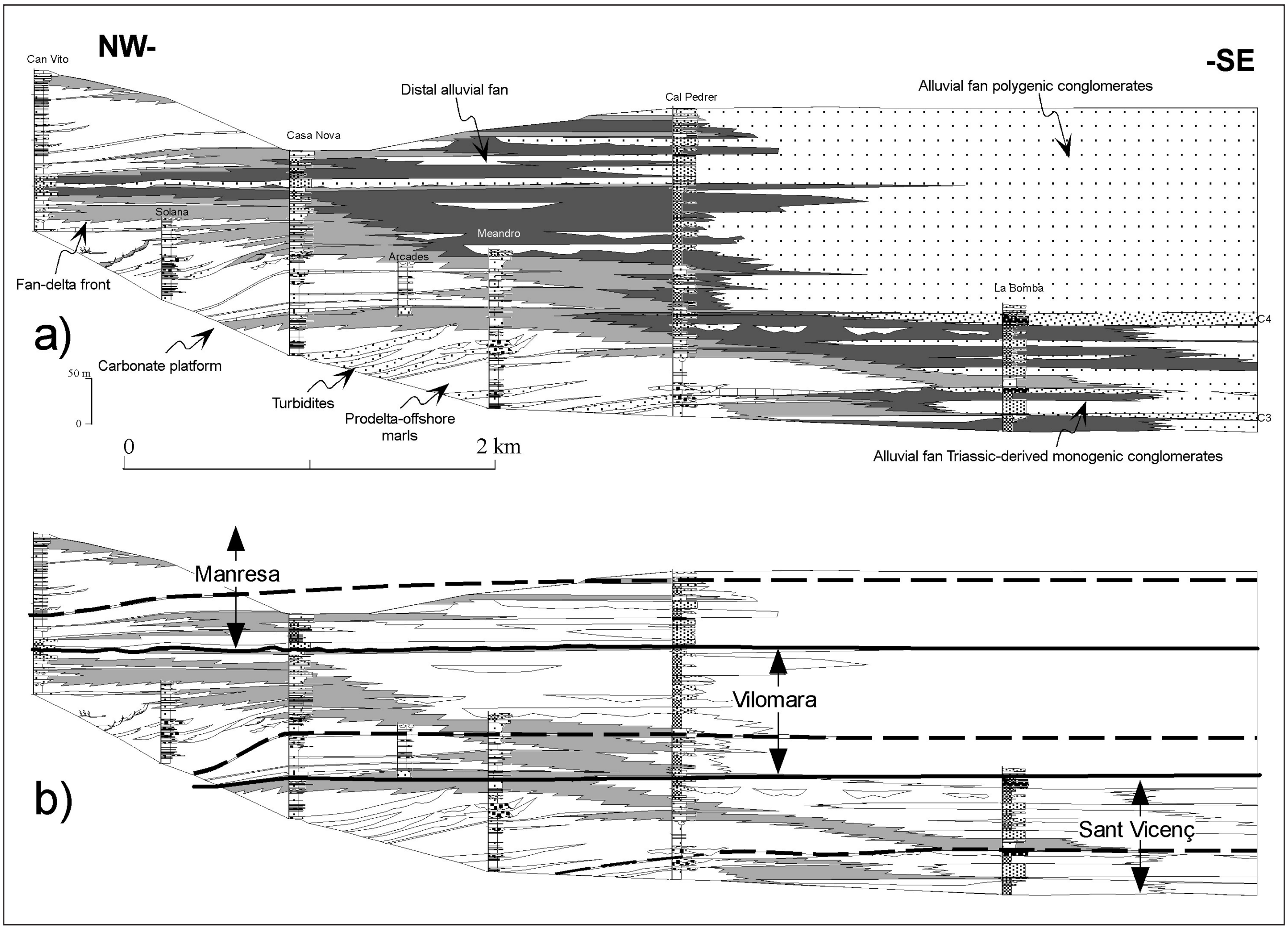

Figure 16. Correlation panel of seven stratigraphic logs in the western part of Sant Llorenç del Munt system. a Facies relationships; b T-R composite sequences and boundaries (continuous lines) and maximum flooding surfaces (dashed lines) (From [46]).

fundamental sequences whose stacking pattern shows an overall progradational trend, always combined with an aggradational component. During the deposition of the regressive part (RSS) of any composite sequence, the overall shoreline-progradational distance varies from about 3.5 to 7.5 km [45].

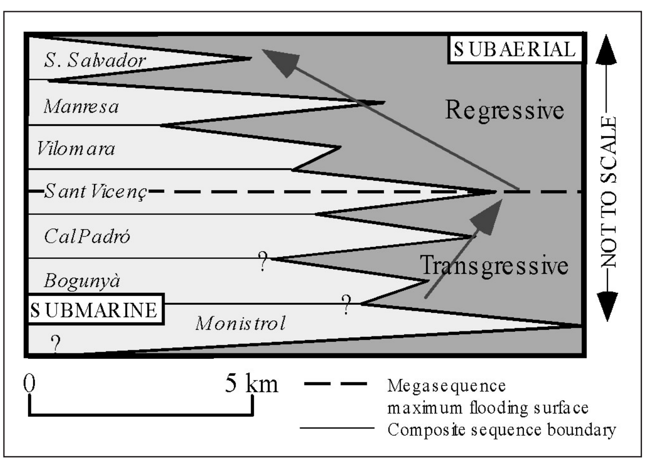

Figure 17. Stacking pattern of the successive T-R composite sequences, exhibiting a transgressive to regressive trend (T-R megasequence) (From [46]).

Composite sequences represent ~90 000– to ~850 000-year episodes [42, 45, 46].

The stacking pattern of the successive composite sequences and the resulting shoreline trajectory (Fig. 17) define a large-scale (more than 1300-m-thick) *composite megasequence*, which represents a discrete stage of the tectonosedimentary evolution in the infill of the eastern part of the south-Pyrenean foreland basin (the Milany depositional sequence [69] and cycle IV [93]). Within this megasequence, the lower part of the succession shows an aggradational to slightly backstepping stacking pattern, recording an overall shoreline retreat of about 0.5 km. The top of this backstepping is the maximum flooding surface of the Sant Vicenç composite sequence, which marks an abrupt vertical change from an aggradational-retrogradational to a progradational stacking pattern. The base of this TSS set (coincident with the base of the megasequence) is unknown due to the outcrop conditions, but it must be somewhere below the lowermost composite sequence (Monistrol; Fig. 17). This boundary records the start of a basin-wide transgressive event (the «Bartonian» transgression). The higher part of the megasequence shows a clear progradational stacking pattern involving an overall shoreline advance of about 10 km. The top of this prograding or RSS coincides with another event of basinal significance, which marks the end of marine conditions in the entire Ebro basin. This event is represented by the deposition of an evaporitic plug (Cardona formation) that overlies the Sant Salvador composite sequence and represents a well-individualized tectonosedimentary evolutionary stage in the infill of the eastern part of the south-Pyrenean foreland basin. It is estimated that sedimentation of the composite megasequence took place during a time span of ~3 My [42, 45, 46].

Controls on T-R cyclicity

The T-R cycles of different scale are superimposed on a hierarchy that records changes in the accommodation and sediment supply of differing magnitudes and durations. Accommodation (the potential space available for sediment accumulation [33]) is governed mainly by eustatic and subsidence-driven sea-level changes. Sediment supply is essentially dependent on climate and the tectonogeomorphic evolution of the catchment basins. The relative importance of these factors in the genesis of the three differentiated hierarchies of T-R sequences is evaluated below.

On the basis of the absolute ages mentioned above (~ 40.2–37.2 Ma). a chronostratigraphic correlation of the *Milany composite megasequence* with the global eustatic chart of [28] has been attempted (Fig. 18). The result shows that the T-R megasequence in our study area has no evident correlation with any of the global curve cycles. Only the top of the megasequence seems to be coincident with a minimum on the sea-level curve from the global chart. This minimum suggests that, at least, the upper boundary of the megasequence could be related to a global eustatic fall in sea level. The observed T-R

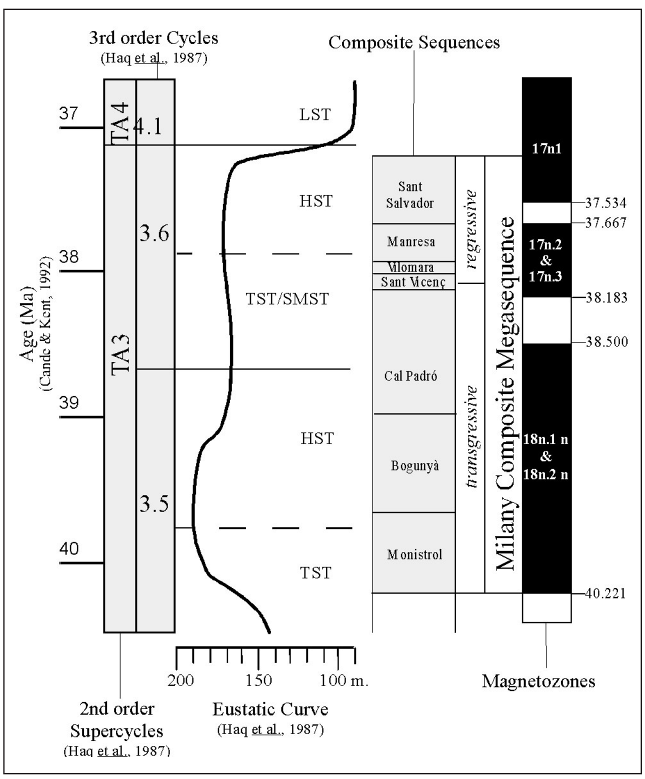

Figure 18. Correlation between magnetozones [16], second– and third-order cycles of the global eustatic curve ([28]), and the defined T-R composite sequences and Milany composite megasequence (From [46]).

trend of the megasequence is hardly explicable in terms of the global eustatic changes recognized in [28], although the uppermost part of the regressive component (between ~37.5 and ~37.2 Ma) could have been partly favored by eustatic, falling sea-level conditions [42, 45, 46].

The subsidence history of the basin margin at the Montserrat region (Fig. 9) shows a general increasing trend of the total subsidence rate coeval with the deposition of the T-R megasequence. This increasing trend clearly accelerated during the sedimentation of the regressive component. Assuming no major eustatic sea-level changes (which seems to be the case, except for the above-mentioned period of sea-level fall; see Fig. 18) and a constant sediment supply, the increasing trend in the total subsidence would cause an overall increase in the accommodation space. This situation should be reflected in the development of a sedimentary succession with a general transgressive or retrograding trend. However, the studied composite megasequence shows an asymmetric trend, with a ~600-m-thick, mostly aggradational, lower TST that is overlain by an ~800-m-thick, essentially progradational, upper RST. This clearly demonstrates that the T-R arrangement of the studied megasequence cannot be tied exclusively to the subsidence history of the basin margin [42, 45, 46].

Thus, it can be concluded that changes in accommodation space linked to the combined action of eustasy and basin-margin subsidence were not the main factors controlling the overall T-R sequential arrangement of the composite megasequence. Instead. increasing sediment supply rates through time in response to the combination of a prevailing warm and humid climate and rapid tectonic bedrock uplift along the basin margin [45] appear to have been the most crucial parameter. The progressive increase in sediment supply initially nearly compensated (i.e., deposition of the TSS) and eventually exceeded (i.e., deposition of the RSS) the increasing accommodation space created by both tectonic and sediment loading (Fig. 9). Throughout the entire interval of fan-delta deposition, the sediment supply was sufficiently rapid that it filled the available accommodation space and consequently maintained the surface of the fan at or above sea level. Thus, the T-R composite megasequence can be characterized as a «supply-dominated» sequence (cf. [25, 82, 52]).

Composite sequences are higher-frequency sequences than the third-order cycles differentiated in the global eustatic chart described in [28]. Consequently, it is practically impossible to tie most of the key stratigraphic surfaces related with the composite sequences to any specific key surface at the global eustatic chart (Fig. 18). From the latter, only the two transgressive maxima located within the 3.5 and 3.6 third-order cycles could be correlated [42] with the regionally widespread [77] maximum flooding surfaces associated with the Monistrol and Manresa composite sequences, respectively. This correlation, along with the continuity of the composite sequences through two different fan-delta systems (Montserrat and Sant Llorenç del Munt), located a few tens of kilometers apart, could be interpreted as evidence of regional, eustatic and/or subsidence-driven, high-frequency accommodation changes. The possible existence, during the late-middle Eocene, of «icehouse» conditions related to the development of the Antarctica ice cap and, therefore, of high-frequency glacioeustatic sea-level changes has been suggested by several authors on the basis of carbon and oxygen isotope data [95, 12]. The influence exerted by high-frequency subsidence variations on the creation of accommodation along the basin margin is ambiguous, because the available time-control of the studied fan-delta successions is not good enough to produce a higher-resolution subsidence-history diagram than that shown in Fig. 9 [42, 45, 46].

A conceptual model involving rapid and episodic variations of subsidence and sediment supply to the shoreline as the two main factors controlling the alluvial architecture of «fourth-order» T-R cycles (equivalent to our composite sequences) in the Montserrat fan-delta was proposed previously [15]. According to this model, tectonic faulting and flexural loading at the basin margin induce episodic subsidence in the adjacent basin. The lower transgressive units of the composite sequences are related to times of rapid tectonic loading in the mountain belt, causing an increase in tectonic subsidence rates relative to the sediment supply in the basin. As erosion rates increased in the mountain belt relative to the rate of tectonic loading, there was an attendant increase in the ratio of sediment supply to subsidence rates in the basin and deposition of the upper regressive unit took place. The observed vertical changes in architecture in the distal alluvial fan facies laterally related to the coastal composite sequences, from isolated ribbons in the transgressive units to more sheet-like bodies in the regressive units, reflect increasing sediment flux towards the shoreline as accommodation space generated by tectonic subsidence decreased and less sediment was trapped upstream.

Both in the Montserrat and Sant Llorenç del Munt fan systems, rapid variations in the rate of gravel supply relative to the rate of subsidence in the basin (cf. [31]) are recorded in the form of succeeding expansions and retractions of proximal alluvial fan conglomerates (Figs. 12, 16). A correlation between these expansions and retractions and the T-R trend of composite sequences can be used to evaluate the relative importance of coarse-grained sediment supply variations in controlling the sequential arrangement in the coastal zone. The results of such correlation show:

1. The maximum flooding surfaces of three composite sequences can be linked to surfaces of maximum alluvial retraction, recorded either in the two fan-delta systems (Cal Padro and Sant Vicenç sequences) or, at least, in the Sant Llorenç del Munt system (Vilomara sequence).
2. The lower boundaries (or maximum regressive surfaces) of two composite sequences (Sant Vicenç and Manresa) fit with surfaces of maximum alluvial expansion in the Sant Llorenç del Munt system.
3. There are some clear misfits, both at small– and large-scale (i.e., the maximum regressive surface of the Sant Vicenç sequence correlates with a surface of maximum retraction in the Montserrat system; Fig. 17).

From the above discussions, it can be concluded that composite sequences developed in response to non-periodic T-R pulses with an episodicity of 10^5–10^6 years and involved coastal displacements on the order of 1–5 km. Most such pulses are believed to reflect the dominance of changes in the rate of sediment supply relative to variations in the rate of accommodation (subsidence plus eustasy), although some major flooding episodes related to increasing accommodation rates could have developed occasionally. Episodic–, tectonic–, (and climatic?)-driven variations in the rate and nature of the sediment supply relative to the rate of subsidence governed the high-frequency sequential arrangement in the subaerial parts of the studied fan-deltas. Since the propagation of the changing sea-level signal decays and finally dies away upstream from coastal areas (cf. [15]), many of the coastal stratigraphic key surfaces cannot be generally tied to any of the key surfaces recognized in the subaerial, alluvial-fan domain and vice versa. This results in a short-distance, coastal-to-alluvial sequence misfit ([42, 45, 46].

The high-frequency (10^4–10^5 years) fundamental sequences record fluctuations in the rate of terrigenous supply. Thus, starvation periods leading to an increase in the rate of intrabasinal carbonate production (i.e., transgressive parts) are succeeded by periods of renewed extrabasinal sediment flux to the shoreline (i.e., regressive parts). The nature and relative importance of the factors controlling these fluctuations remain unknown, but could include a combination of episodic to periodic allocyclic processes (i.e., relative sea-level changes, Milankovitch-related climatic oscillations, and tectonically driven sediment supply pulses) with episodic, autocyclic processes (i.e., lateral shifting of the main feeder distributary channels and their related depositional lobes) [42, 45, 46].

Conclusions

The Sant Llorenç del Munt and Montserrat fan-delta systems are large fans that developed during a 4.4 My time-span, from 41.6 Ma to 37.2 Ma (Bartonian, Middle Eocene) under the prevailing warm and relatively humid climatic conditions. The formation and evolution of those fans, at the SE 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.

Along the ~30-km portion of the Catalan Coastal Ranges studied, most of the Paleogene tectonic structures are contractional (thrusts, backthrusts, and folds) and probably rooted in a major NNE-SSW sinistral strike-slip fault. The tectonic evolution is similar in all the individual sections of the range, starting with shallow intercutaneous thrust wedges, followed by a growing, large foreland syncline (resulting from the emplacement of deep intercutaneous thrust wedges), and a basement involving out-of-sequence thrusting. Paleogene tectonic structures indicate a displacement of the thrust system almost perpendicular to the chain. This displacement was towards the NNW. The intercutaneous thrust wedges can be composite and are usually organized in piggyback sequences. The growth of thrust wedges at depth caused a large, complex, and continuous foreland syncline (frontal monocline). The progressive folding of growth strata is recorded by a series of syntectonic unconformities located at different stratigraphic positions in each section perpendicular to the basin margin. There is a series of faults, transverse to the main structures, that strongly affect the sedimentation because they change the structural style and may also control the localization of paleovalleys, which feed important alluvial systems such as the Montserrat and Sant Llorenç del Munt fans.

The minimum duration of thrusting in the portion of the chain studied is 17 My. Deformation started in the NW sector and propagated towards the SE in a manner similar to the general trend in the entire SE Ebro basin margin.

Tectonosedimentary relationships along the foreland margin show clearly that the creation and development of both fan-deltas took place during the late stages of anticline-syncline folding and emplacement of the out-of sequence Prelitoral thrust. The subsidence history of the basin margin, consistent with a syntectonic development of both fans, indicates that the onset of the Montserrat fan coincides with a clear increase of the tectonic subsidence. Subsidence analysis shows that long-term sedimentation and total subsidence rates increased through time, the latter recording the progressive loading induced by the accumulated deposits and by the growing thrust load. The sudden onset of subsidence at the basin margin reflects rapid growth of the topographic relief, in response to modest shortening accompanied by considerable vertical bedrock uplift. Increasing rates of sedimentation and total subsidence recorded by progressively younger fan-delta deposits also point to rapid uplift, which, 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 initially compensated and eventually exceeded the increasing accommodation space created by both tectonic and sediment loading. Throughout nearly the entire interval of fan deposition, sediment supply was sufficiently rapid that it filled all the available accommodation space and consequently maintained 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.

Two major sedimentary alternating systems (fan-deltas and carbonate platforms) have been defined within the Sant Llorenç del Munt and Montserrat successions. The prograding fan-deltas developed during periods of important alluvial activity and consist of alluvial fan, fan-delta-front, and fan-delta-slope deposits. The proximal alluvial fan is dominated by steep slopes and sediment gravity-flow deposits, while distal parts of the alluvial fan are characterized by channeled streams and floodplain deposits. The fan-delta front was constructed by the building, migration, and later reworking (by coastal currents or organic activity) of mouth bars. The fan-delta slope is composed principally of blue-gray marls, which may be interbedded with sediment gravity-flow deposits, slumps, and slides. The carbonate platforms were formed during periods of low alluvial activity (relative transgressive episodes) and onlap the fan-delta deposits. These platforms are shallow, close to the coast, and sometimes developed coastal and barrier reefs.

There are at least three orders of transgressive-regressive cyclicity, which are linked to the interaction between changes in relative sea level, variations in clastic input, and shifting of the different deltaic lobes.

Subaerial unconformities (and related lowstand systems tracts) developed in response to relative falls in sea level that are generally not recognized along the Montserrat and Sant Llorenç del Munt fan-delta clastic wedges, most likely because the rate of subsidence along the foreland basin margin exceeded that of the falling eustatic sea level. The sequence stratigraphic approach was used to subdivide these clastic wedges into repetitive (3– to 80-m-thick) basic units (T-R fundamental sequences) that are enveloped by a combination of ravinement and maximum regressive surfaces. These sequences are interpreted to record fluctuations in the rate of terrigenous supply to the shoreline in response to an unknown combination of: (1) allocyclic, periodic to episodic, relative changes in sea level, Milankovitch climatic oscillations, and/or tectonic pulses; (2) autocyclic, episodic lateral shifting of distributary channels and mouth-bar lobes.

Repeated changes in the stacking pattern of the fundamental sequences (from retrogradational to progradational) define a number of T-R cycles of regional extent, called composite sequences. These (100– to 300-m-thick) consist of a couplet of two consecutive transgressive and regressive sequence sets. Composite sequences are interpreted as having developed in response to non-periodic pulses with ~90 000–~850 000-year episodicities, reflecting a dominance of changes in the rate of sediment supply relative to variations in the rate of accommodation. Nevertheless, some major flooding episodes related to high rates of subsidence and/or eustatic sea level rise are recorded occasionally. Because the transmission of the changing sea-level signal declines and eventually disappear upstream from the coastal areas, the T-R fundamental and composite sequences cannot be correlated with the trends recognized in the subaerial alluvial-fan domain, which are exclusively controlled by changes in the rate of sediment supply relative to the rate of subsidence change. This results in a clear coastal-to-alluvial sequence misfit.

Analysis of the stacking pattern of the succeeding composite sequences and the resulting shoreline trajectory define a more than 1300-m-thick composite megasequence, which represents a well-individualized tectonosedimentary evolutionary stage in the infill of the eastern part of the south-Pyrenean foreland basin. It is estimated that sedimentation of the composite megasequence took place during a time span of ~3 My. Increasing sediment supply rates through time in response to a combination of the prevailing warm and humid climate and the rapid tectonic bedrock uplift along the basin margin controlled its internal T-R trend. The progressive increase in sediment supply initially compensated and eventually exceeded the increasing accommodation space created by both tectonic and sediment loading. The aggradational (transgressive) and progradational (regressive) trends observed within the megasequence are coeval with a continuous thrusting activity, and not related to succeeding pulses (with million-year episodicities) of thrusting activity and quiescence.

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About the author

Miguel López Blanco is Professor at the Department of Stratigraphy, Palaeontology, and Marine Geosciences at the University of Barcelona. He also belongs to the Excellency Research Group on Geodynamics and Basin Analysis. Since 1987, his research, which has mostly been carried out at the University of Barcelona, in collaboration with other institutions and enterprises (Servei Geològic de la Generalitat de Catalunya, SNEAP, University of Bergen, Norsk Hydro, ARCO, Royal Holloway University of London, YPF, Complutense University of Madrid, IJA, Uppsala University, Pertra and DNO, among others), has been mainly devoted to: (1) field geological mapping, (2) stratigraphic, sedimentologic, and paleoenvironmental analysis of delta and fan-delta complexes, (3) sequential stratigraphic analysis of deltaic successions, (4) geometric, stratigraphic, and sedimentologic characterization and modeling of marine and transitional deposits, (5) characterization, quantification, and dating of tectonic deformation in sedimentary basins and their margins, and (6) regional stratigraphic analysis. Dr. López Blanco started his research on the subject of this paper at the beginning of his scientific career, in collaboration with the Geological Survey of the Generalitat de Catalunya. His Master's thesis (1991) and PhD thesis (1996) focused on the Sant Llorenç del Munt and Montserrat fans. Most of the results of those studies have been published in international scientific magazines. During the last 10 years, detailed research on the tectonosedimentary evolution of the basin margin (published in 2002) and the cementation of sandstones (in prep.) have been carried out in the area by the author.