The deltaic complex of St. Llorenç del Munt (Middle-upper Eocene, SE Catalan basin)

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ABSTRACT

In St. Llorenç del Munt delta complex, four depositional sequences bounded by unconformities have been described, with their main systems tracts. They are named Rellinars sequence, Mura sequence, Manresa sequence and Peramola sequence. The sediments which constitute the depositional sequences are from deltaic origin, and their facies associations have been distinguished from proximally (delta plain) to distally (prodelta) for each sequence. The delta front sediments of each sequence consist of distributary mouth bars cycles or parasequences ranging from fluvial-dominated sediments, near the river mouth, to wave- and storm-dominated ones, basinward. In pelitic environments (usually prodelta and distal delta front) there are instability features resulting from: (1) differential weight between sands and fines of these sedimentary environments, (2) the quantity of fines, and (3) the cyclic bottom weight of the storm waves. Such sedimentary instabilities are gullies, listric sedimentary faults, mudlumps, rotational slides, and balls and pillows. The transgressive systems tracts of each depositional sequence consist of carbonate shelf facies sedimented in areas and periods of low detritical-siliciclastic sediment supply. The lowstand systems tract of the Manresa sequence consists of great scale instabilities associated to a submarine erosion (Maestro, 1989), and in distal areas the sedimentary instabilities form type III turbidites (Mutti, 1985). This sequence has probably got a type I boundary (*sensu* Vail, 1987). The other sequence boundaries are most likely of type II (*sensu* Vail, *op.cit.*).

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Key words: Deltaic complex, Depositional sequences, Systems tracts, Sedimentary instabilities, Sequence boundaries, Middle-Upper Eocene.

RESUMEN

En el complejo deltaico de St. Llorenç del Munt se han descrito cuatro secuencias deposicionales y sus correspondientes cortejos sedimentarios. Las hemos denominado secuencia de Rellinars, secuencia de Mura, secuencia de Manresa y secuencia de Peramola. Los depósitos que las constituyen son de origen deltaico, y cada una de estas está formada desde asociaciones de facies proximales (llanura deltaica) hasta asociaciones de facies distales (prodelta). Las facies más desarrolladas corresponden a depósitos de frente deltaico y están constituídas por barras de desembocadura de canales distributarios, las cuales se distribuyen desde el dominio fluvial, cerca de la desembocacura, hasta el dominio del oleaje y de las tormentas, a medida que nos alejamos de ella. En los ambientes deposicionales de frente deltaico distal y de prodelta, tiene lugar un gran número de inestabilidades sinsedimentarias debido principalmente al peso diferencial de las arenas sobre las pelitas que constituyen estos ambientes deposicionales, al gran predominio de materiales finos y a la carga cíclica que ejercen las olas de tormenta sobre el fondo marino. Estas inestabilidades se presentan en forma de *gullies*, de fallas sedimentarias lístricas, de diapiros fangosos, de deslizamientos rotacionales, y de bolas y *pillows*. Los cortejos transgresivos de cada secuencia están formados por facies de plataforma carbonatada depositadas en áreas y en periodos de escaso aporte de sedimento detrítico-siliciclástico. El cortejo de mar bajo de la secuencia de Manresa está formado por niveles de inestabilidades a gran escala relacionados con una erosión submarina (Maestro, 1989). El límite de esta secuencia probablemente sea de tipo I (según Vail, 1987), ya que en áreas más distales estas inestabilidades dan lugar a turbiditas de tipo III (Mutti, 1985). Los otros límites de secuencia probablemente serían de tipo II (según Vail, *op.cit.*).

Palabras clave: Complejo deltaico, Secuencias deposicionales, Cortejos sedimentarios, Inestabilidades sedimentarias, Límites de secuencia, Eoceno medio-superior.

RESUM

En el complex deltaic de St. Llorenç del Munt s'han distingit quatre seqüències deposicionals delimitades per discordances, i els seus corresponents prismes sedimentaris. Les hem denominat seqüència de Rellinars, seqüència de

Mura, seqüència de Manresa i seqüència de Peramola. Els dipòsits que les constitueixen són d'origen deltaic y cada una d'elles està formada des d'associacions de fàcies proximals (plana deltaica) fins a associacions de fàcies distals (prodelta). Els sediments més desenvolupats corresponen a dipòsits de front deltaic i estan formats per barres de desembocadura dels canals distributaris, els quals es distribueixen de continent cap a mar, des d'un domini fluvial fins a un domini de l'acció de les onades de bon temps y de les tempestes. En els ambients deposicionals de front deltaic distal i de prodelta solen ocòrrer un gran nombre d'inestabilitats sinsedimentaries degut al pes diferencial de les sorres sobre les pelites que constitueixen aquests ambients, a la quantitat de sediments fins y a la càrrega cíclica que sobre el fons exerceixen les onades de tempesta. Aquestes inestabilitats es presenten en forma de *gullies*, de falles sinsedimentàries lístriques, d'illes de fang, de lliscaments rotacionales, y de boles y *pillows*. Els prismes transgressius de cada seqüència estan formats per fàcies de plataforma carbonatadadepositades en àrees y períodes de poc aport de sediments detrítico-siliciclàstics. El prisma de mar baix de la seqüència de Manresa està format per nivells d'inestabilitats sinsedimentàries a gran escala relacionats amb una erosió submarina (Maestro, 1989), ja que en àrees més distals aquestes inestabilitats donen lloc a turbidites de tipus III (Mutti, 1985). El límit d'aquesta seqüència probablement correspongui a una discordancia de tipus I (segons Vail, 1987). La resta de límits descrits probablement van relacionats amb límits de seqüència de tipus II (segons Vail, 1987).

Paraules clau: Complex deltaic, Seqüències deposicionals, Prismes sedimentaris, Inestabilitats sedimentaries, Límits de seqüència, Eocè mitjà-superior.

GENERAL SETTING

The deltaic complex of St. Llorenç del Munt is located in the South-eastern side of the Catalan Central Depression (North-eastern part of the Ebre basin), N of the Catalan Coastal ranges (Fig. 1). During the Cenozoic, the Catalan basin was the foreland basin of the surrounding chains, the Pyrenees in the N and the Catalan Coastal Ranges in the S. During part of the Paleogene the basin was connected to the open sea in the W. It had a large gulf shape which was open to the influence of the Atlantic, and closed by the high reliefs. The basin was filled with terrigenous sediments which formed deltaic complexes

The Catalan Coastal Ranges are an orogenic chain with a Paleozoic basement and a Mesozoic cover. The Triassic sediments represent the cover in the studied area. At first, the range was affected by Hercynian tectonics and afterwards, during the Paleogene, by Alpine tectonic impulses. Vertical basement faults define the dominant features. They are oriented NE to SW and

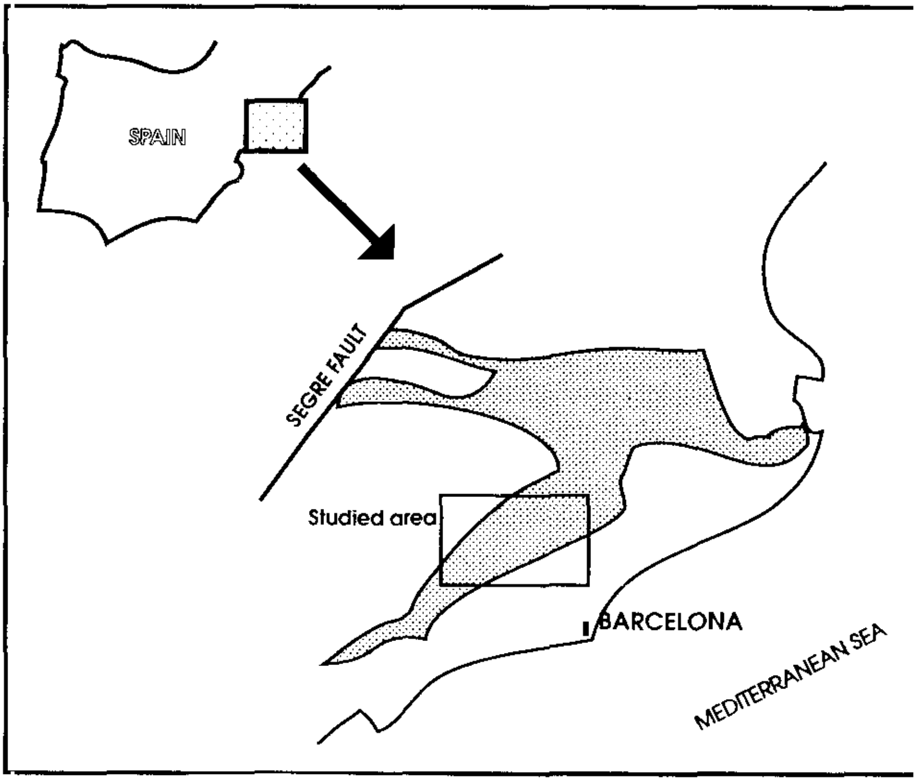


Fig. 1.—General sketch map of the Paleogene deposits in the Catalan region, indicating the area of exposition of St. Llorenç del Munt deltaic complex.

Fig. 1.—Mapa esquemático general de los depósitos paleógenos de la región catalana, indicando el área donde aflora el complejo deltaico de St. Llorenç del Munt.

ENE to WSW. These faults are oblique to the chain and form an *en echelon* system (Guimerà, 1984), with a strike-slip sinister or sinister-revers movement (Anadón *et al.*, 1979).

During the Paleocene and lower Eocene the Ebre basin was a tectonically active margin. Close to it alluvial fans were developed during Alpine tectonics and before marine conditions. During the middle-upper Eocene, the basin was affected by an important marine transgression which caused the development of fan deltas. The source area of the alluvial fans and the fan deltas were sited in the Catalanides. The Triassic (Muschelkalk) and Paleocene covers began to be eroded during the lower Eocene, whereas in the middle-upper Eocene, the erosion affected the Triassic (Buntsandstein) cover and the Paleozoic basement. The sedimentation was conditioned in the studied area by the WNW-ESE (lower Eocene) or the NNW-SSE to N-S (middle-upper Eocene) fault diachronic systems.

STRATIGRAPHY

Two main domains can be distinguished in the margins of the Ebre basin: the alluvial sediments and the deltaic sediments. The alluvial deposits are sedimented during the lower and the uppermost Paleogene. The deltaic deposits are related to the marine domain of the basin (middle-upper Eocene) and they are described in this article. These deltaic sediments constitute the lower part of a Transgressive-Regressive cycle or a second order cycle (TR cycles of Vail *et al*, 1990) The upper part of this cycle consists of the uppermost Eocene-Oligocene alluvial facies exposed in the top of Montserrat mountain and in the Catalan areas of the Ebre basin. The general section of the Paleogene is:

— Paleocene. Formed by red siltstones, with some sandstone and conglomerate layers, and abundant *Microcodium*. These deposits have a high carbonate content, including caliche nodules, calcareous crusts and lacus-trine-palustrine limestones. These sediments lie unconformable over the Meso-zoic substratum. At the top of the alluvial facies there is a condensed paleosol layer showing an important sedimentary break (Anadón & Marzo, 1986).

— Lower Eocene. The base of the lower Eocene sediments in the North-eastern (El Far) and South-western (Igualada) extremes of the studied area is composed of marine Alveolina limestones. Related to these sediments, in the St.Llorenç del Munt-Montserrat area, the deposits consist of continental red sandstones and mudstones. A reddish unit, formed by red marls and sandstones overlies the marine Alveolina limestones, and brechoid alluvial fans overlay the red continental deposits lateral to the limestones. These alluvial fans include subaerial olistostromes of Triassic limestones.

— Middle Eocene. During the middle Eocene the first conglomerate fan deltaic unit is deposited in St.Llorenç del Munt and Montserrat areas. These areas consist of two different depositional systems (Fisher & McGowen, 1967). The petrological content of the distinct fan deltas is different. The Montserrat depositional system contains cobbles of Mesozoic limestones, the St. llorenç del Munt depositional system encloses cobbles of basement and lower Triassic. Reddish alluvial deposits constitute the proximal part of the fan deltas, while in the marine areas a shallow shelf setting is developed frontally.

— Middle-Upper Eocene. The deposition of the middle and upper conglomeratic fan deltaic units occurs in St. Llorenç del Munt, forming a thick prodeltaic platform over the Catalan basin. In the Montserrat area, a mass flow fan delta front developed by coarsening up massive conglomerate assembly and its prodelta is indented with the St. Llorenç one.

ST. LLORENÇ DEL MUNT DELTAIC COMPLEX

As far as St. Llorenç del Munt delta is concerned, four stratigraphic units are defined (Maestro, 1987, 1989) as depositional sequences in the sense of Vail (1987). A succession of proximal deltaic strata and distal shelfal strata form each unit, which is bound by unconformities in the outcrop areas. It is supposed that these boundaries are conformities in the central parts of the Catalan basin. According with Posamentier *et al.* (1988), lowstand systems tracts (LST) consist of delta front and prodelta environments, transgressive systems tracts (TST) consist of calcareous conglomerates and carbonate shelf facies, and highstand systems tracts (HST) consist of proximal alluvial deposits, delta front and prodelta environments. These depositional sequences (Fig. 2) range in age from the upper Lutetian to the middle Priabonian. They can be assigned to 3.5, 3.6, 4.1 and 4.2 third order cycles of the Exxon chart (Haq *et al.*, 1987) in basis on paleontological data (Ferrer, 1971). They are named Rellinars sequence (also defined as lower fan delta in Maestro, 1987), Mura sequence (or middle fan delta), Manresa sequence (or upper fan delta) and Peramola sequence (studied and described in the Oliana area, in Maestro, 1989a, and compared in age with the St. Llorenç del Munt area). In each sequence we can distinguish the different systems tracts related to eustatic changes. In Maestro (1987), before the use of the systems tracts and agreeing to the terminology of the epoch (Mitchum *et al.*, 1977 and Vail *et al.*, 1977), the units of marine carbonates which overlie the deltaic channels and bars, and the white carbonate conglomerates of the proximal areas in St.Llorenç del Munt (Fig. 3), here included in the transgressive systems tract, were comprised into the highstand deposits, and the then-boundaries for each sequence correspond to the maximum flooding surface.

The bounding unconformities of the depositional sequences are mainly of type II (*sensu* Vail, 1987), except the unconformity that separates Mura sequence from Manresa sequence, which is type I limit. The unconformity corresponds to the Bartonian-Priabonian boundary (-39.4 m.y, *sensu* Haq *et al.*, 1987). Great scale instability processes caused the submarine erosion that comes with the relative lowering of the sea level and that induces the destruction of the upper part of the deltaic sediments of Mura sequence (Fig. 2). It is supposed that the eroded deposits generated by these processes are important enough for building a turbiditic system in distal areas of the Catalan basin. Never the less this system is not exposed, although type III turbidites (Mutti, 1985) have been distinguished in the base of the Manresa sequence. The other depositional sequences described show no signs of submarine erosion, and the sedimentary instabilities are chiefly related to the basinward progradation of the deltaic systems during the lowstand and highstand systems tracts. They are exposed from proximal (delta plain) to distal (distal delta front and prodelta) environments. The instabilities are more frequent in distal deltaic settings as a result of having a great proportion of pelitic sediments.

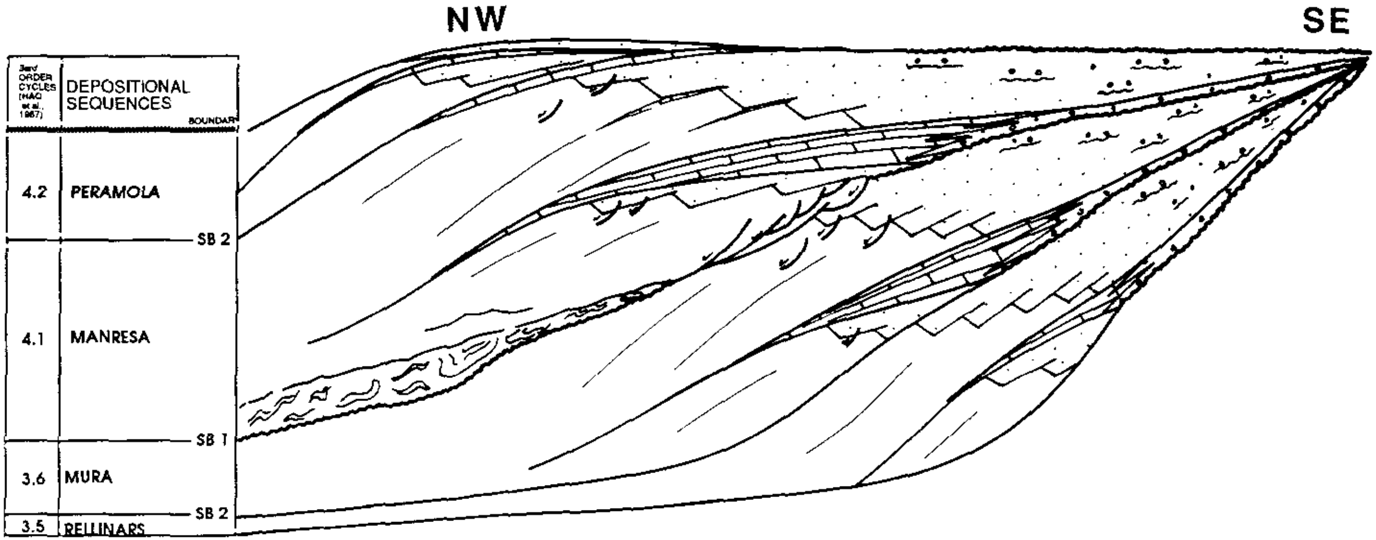


Fig. 2.— Depositional sequences established in the St. Llorenç del Munt deltaic complex (middle-upper Eocene). Correlation with third order cycles of the Exxon chart (Haq *et al.*, 1987). Description of the sequence boundaries (SB 1 indicates a type I unconformity (Vail, 1987), related with submarine and subaerial erosion; SB 2 indicates a type II unconformity, related to subaerial erosion).

Fig. 2.—Secuencias deposicionales descritas en el complejo deltaico de St. Llorenç del Munt (Eoceno medio-superior). Correlación con los ciclos de tercer orden definidos por Haq et al. (1987). Descripción de los límites de secuencia (SB 1 indica una discordancia de tipo I (Vail, 1987), relacionada con erosión submarina y subaérea; SB 2 indica una discordancia de tipo II, relacionada con erosión subaérea).

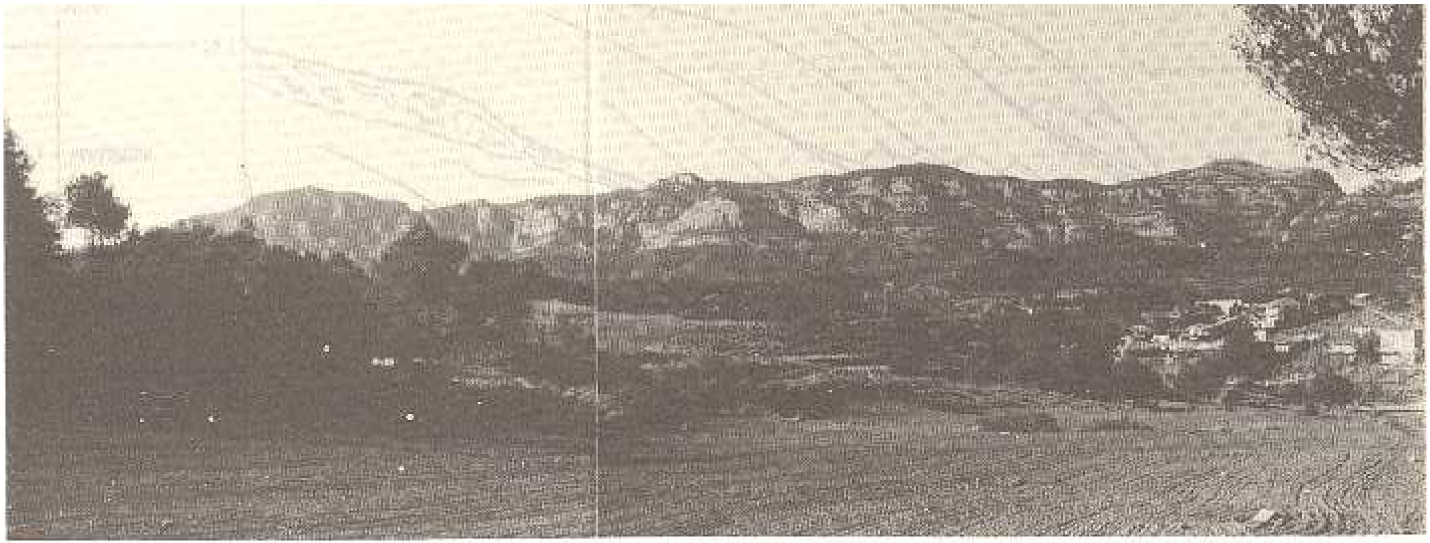


Fig. 3.—Vision S-N of the proximal conglomerates from St. Llorenç del Munt (in the left) to Montcau (in the right). There are some conglomerate units which project into relief because of their carbonate composition and cement. Those bodies represent the transgressive systems tract deposits in the proximal areas.

Fig. 3.—Visión S-N de los conglomerados proximales desde St. Llorenç del Munt (en la izquierda) al Montcau (en la derecha). Algunos niveles de conglomerados resaltan en el relieve, debido a su composición y cemento carbonáticos. Estos cuerpos representan los depósitos del cortejo transgresivo en las áreas proximales.

Rellinars Sequence

The first described sequence consists of proximal deltaic sediments of conglomeratic composition, showing reduced delta front and prodelta, deposited in a lagoonal or shallow shelf environment. Basinward these deposits merge into a shelf facies. Within this sequence we can differentiate lowstand (LST), transgressive (TST) and highstand systems tracts (HST).

LST—A bad exposed prograding deltaic lowermost unit consists of delta plain crevasse couplets, delta front bad developed distributary mouth bars and upper prodelta grey mudstones. This lowstand prograding complex has low thickness and is only represented in the South-western area of St. Llorenç del Munt, near Rellinars village, beneath the marine wedge of the transgressive deposits.

TST—In the proximal areas a transgressive conglomerate unit can be distinguished (Fig. 2), showing a higher percentage of limestone cobbles than the typical conglomerates of St. Llorenç del Munt. The conglomerates are highly consolidated by carbonate cements, which are reflecting in a white colour. These conglomerates ranges basinward to shelfal carbonate deposits, which are only moderately exposed due to be covered by the uppermost deltaic units.

HST—In the proximal areas, the highstand systems tract consists of a progradational conglomerate association, which is well exposed in St. Llorenç del Munt area (Fig. 3). It merges into reddish delta plain deposits (Fig. 5), which are properly developed in the Eastern area. It was deposited in a temporally flooded and plant-rich closed bay environment, with conglomeratic channels and reddish sandstones and siltstones of the interchannel areas. To the N and NW the conglomerate deposits pass into a prograding delta front conglomeratic distributary mouth bars deposits, and to poor exposed prodelta environments. Those deposits are almost covered by the sediments of the Mura sequence.

Mura sequence

This sequence is well exposed in the central and proximal areas of the St. Llorenç del Munt and Montserrat delta depositional systems. The lowstand systems tract (LST) can be recognized mainly in the Montserrat system.

LST—In the frontal areas of the Montserrat fan we recognize a prograding delta composed of coarsening-upward distributary mouth bar cycles which conform the delta front depositional environment. These deposits range basinward to prodeltaic claystones. In St. Llorenç del Munt only the prodeltaic environment with a thick succession of grey mudstones and claystones is exposed. Such deposits represent the lowstand wedge prograding complex (*sensu* Vail, 1987).

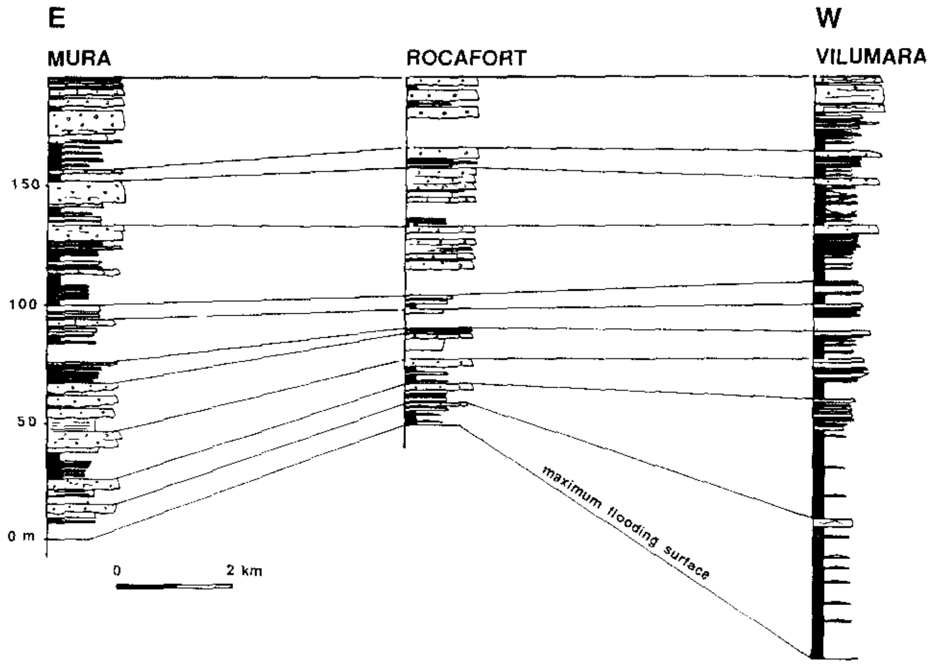


Fig. 4.—E-W evolution of the facies associations for the distinct parasequences distinguished in the H.S.T. of Mura sq. a- Mura cross section consists mainly of delta plain facies associations, as crevasse lobes, overbank deposits and distributary channels. b- Rocafort cross section consists mainly of distributary channel and interchannel facies associations. c- Pont de Vilumara cross section consists mainly of distributary mouth bar cycles (channels, foreshore bars and shoreface deposits) and prodelta facies associations (grey shales, thin bed turbidites and amalgamated layers with hummocky cross stratification). The H.S.T. consists of deltaic coarsening and thickening upward cycle with a progradational trend.

Fig. 4.—Evolución E-W de las asociaciones de facies para las diferentes parasecuencias distinguidas en el H.S.T. de la secuencia de Mura. a- Corte de Mura. Predominan las asociaciones de facies de llanura deltaica (lóbulos de crevasse, facies de overbank y canales distributarios). b- Corte de Rocafort. Predominio de las asociaciones de facies de canal distributario y de intercanal. c- Corte del Pont de Vilumara. Presenta ciclos de barras de desembocadura de canal distributario (canales, barras de foreshore y facies de shoreface) y asociaciones de facies de prodelta (pelitas grises, capas turbidíticas finas y y capas amalgamadas con estratificación cruzada hummocky). El H.S.T. forma un ciclo deltaico progradante, estrato- y grano creciente.

TST—In the proximal conglomeratic areas of St. Llorenç del Munt, a second carbonate conglomeratic unit is identified, similar to the white conglomerate unit described for the TST of the Rellinars sequence. In the intermediate parts of the basin, the TST consists of main minor retrogressive, metric to decametric, carbonate marine cycles which can be identified overlaying the LST. This unit basinward interfingers with coralgal patch reefs growing on the wedge of conglomerates (Fig. 9).

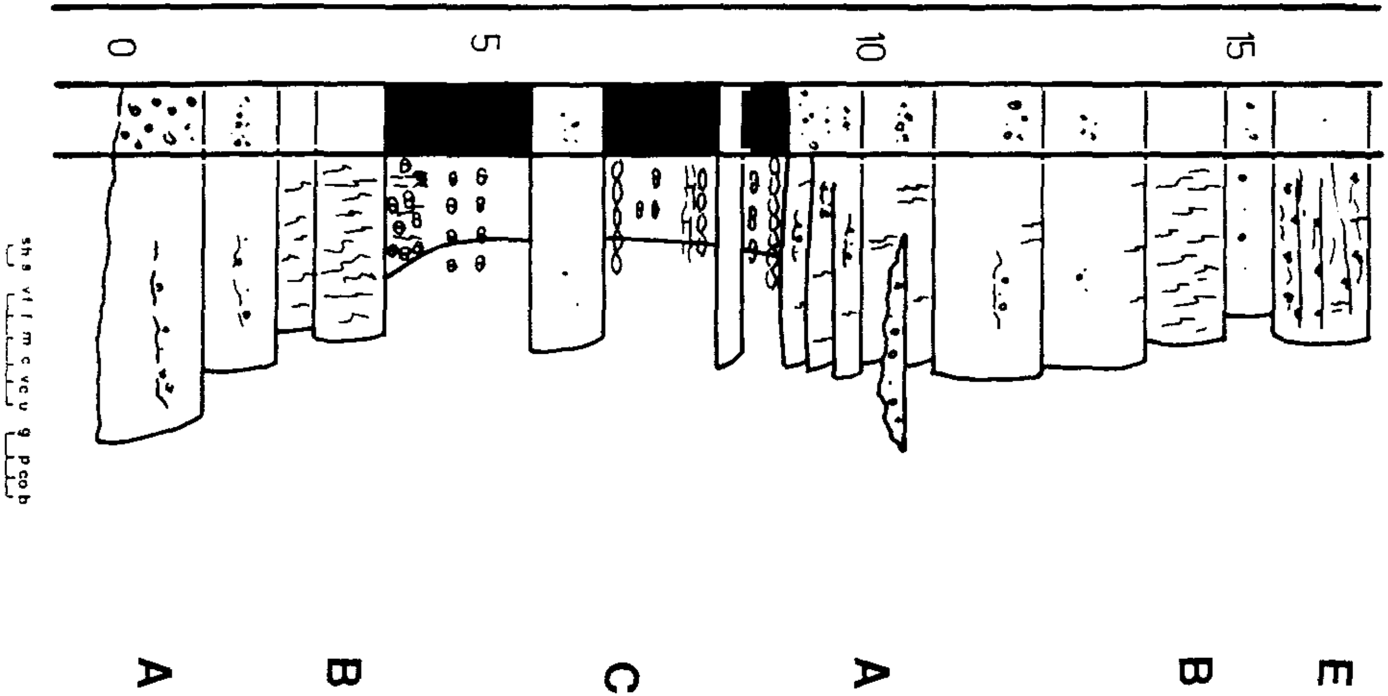
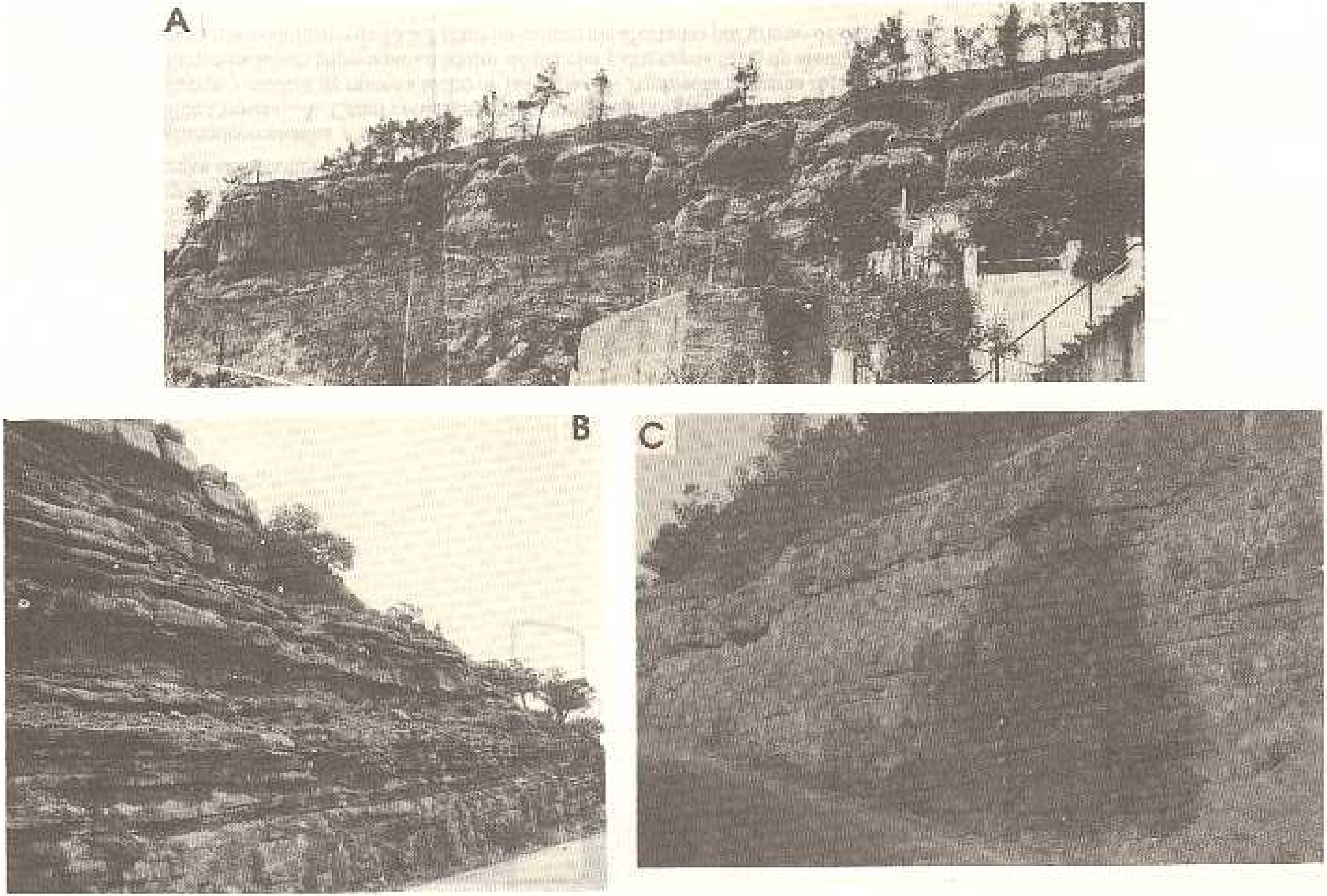


Fig. 5.—Fining and thinning upward cycles of the infilling of a meandering channel in the delta plain environment (Rellinars sequence. Creueta section). A- Conglomerate channel ranging to a very coarse red sandstones without stratification, which includes lags of gravels and rootlets at the top of the beds. B- Coarse red sandstones completely root-bioturbated. C- red overbank shales including abundant caliche nodules and two coarse-to-very coarse massive sandstone beds, which represent crevasse splays. E- Nodular red sandstones (15-30 cm) intensely affected by dessication cracks and rootlets. In the top of the beds milimetrical algae laminites are found.

Fig. 5.—Ciclos granodecrecientes y estratodecrecientes de relleno de canal meandriforme de ambiente de llanura deltaica (secuencia de Rellinars. Serie de la Creueta). A- Canal conglomerático que passa progresivamente a areniscas rojas muy groseras sin estratificación, y que incluyen *lags* de gravas y marcas de raíces a techo de las capas. B- Areniscas groseras rojas totalmente bioturbadas por raíces. C- Pelitas rojas de desbordamiento que incluyen abundantes nódulos de caliche y dos capas rojas de arenisca muy grosera, masivas, que representan crevasse splays. E- Areniscas rojas nodulosas (de 15 a 30 cm) intensamente afectadas por grietas de descación y por raíces. A techo de las capas aparecen laminitas algales.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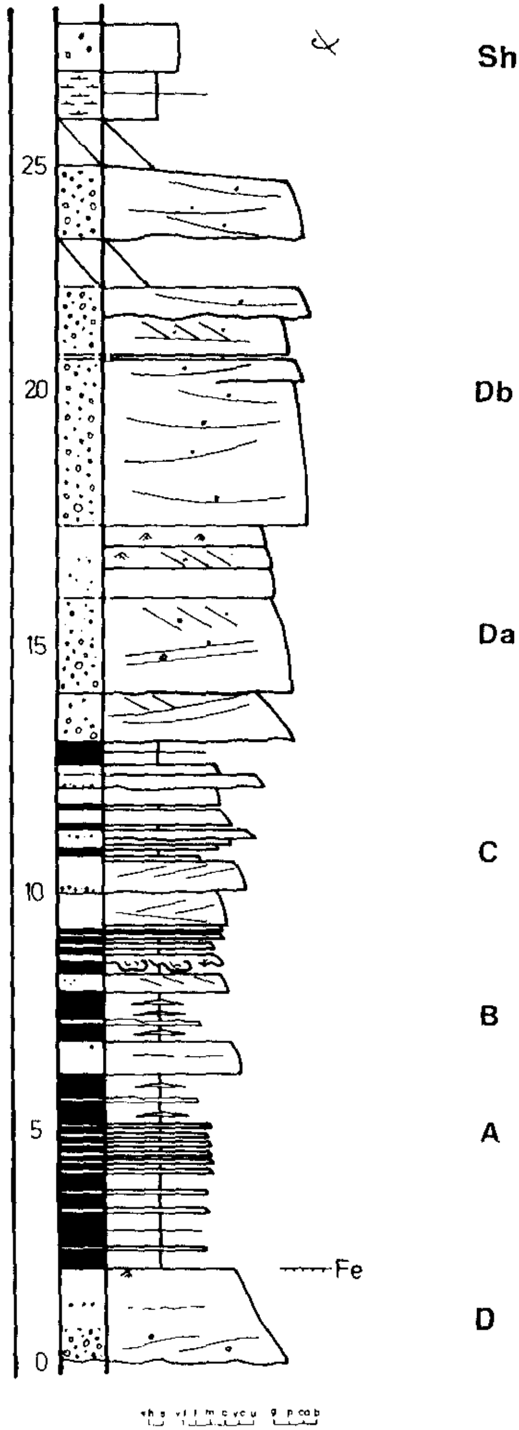
HST—The highstand systems tract in the proximal areas consists of a progradational conglomeratic sequence (Fig. 2). The N and NE reddish delta plain deposits (Figs. 4, 6) develop to the NW shallowing and coarsening up distributary mouth bar sequences (Figs. 4, 7), with a conglomeratic bedset in the uppermost part. These deltaic sequences merge into wave- and storm-reworked distal deltaic facies, with hummocky cross stratification. In the shoreface environments, on-laping reefal limestones develop over the paleotopography of the mouth bar cycles. Fine prodelta deposits built the distal deltaic platform. Near the faulted area of the Llobregat river, affecting the upper part of the prodelta and the lower part of the delta front environments, we find some deformational features such as gullies, rotational slides and mudlumps, induced by differential weight and fault movements. The HST of the Mura sequence has a progradational basinward trend. In its delta front depositional environment we have distinguished, at least, eleven distributary mouth bar cycles or parasequences

Manresa sequence

The erosive unconformity that bounds the Manresa sequence from Mura sequence is clearly marked in the marine areas by kilometric scale sedimentary instabilities that prove the erosion occurred in the uppermost part of the HST deposits of Mura sequence (Fig. 11). In the continental areas we recognize an erosive surface.

Fig. 6.—A- Thick tabular conglomerate body in between delta plain deposits (red sandstones, mudstones and conglomerates), exposed in Rellinars-Castellbell road, and representing a major distributary channel in the delta plain environment. B- Delta plain deposits in Terrassa-Navarcles road (Mura sequence). Red, thin sandstone beds (crevasse splays deposits) alternate with red mudstones of overbank origin, forming subaerial, partially flooded levee deposits, laterally to principal distributary channels. C- Delta plain deposits in the St. Llorenç Savall-Calders road (Mura sequence). Reddish coarse-sandstone beds have erosive bases and are affected by rootlets. They represent crevasse deposits. At top there is a channel of gravels, with high erosive base. Those deposits are related to interdistributary areas and form a minor mouth bar/crevasse couplet.

Fig. 6.—A- Cuerpo tabular potente de conglomerados situado entre depósitos de llanura deltaica (areniscas, pelitas y conglomerados rojos), que afloran en la carretera de Rellinars a Castellbell, y representan un canal distributario mayor en ambiente de llanura deltaica. B- Depósitos de llanura deltaica in la carretera de Terrassa a Navarcles (secuencia de Mura). Las finas capas de arenisca roja (depósitos de crevasse splays) alternan con pelitas rojas, típicas de zonas de overbank, formando parte de depósitos de levee subaérea, parcialmente inundada, y lateral a los canales distributarios principales. C- Depósitos de llanura deltaica en la carretera de St. Llorenç Savall-Calders (secuencia de Mura). Las capas rojas de areniscas groseras presentan bases erosivas y están afectadas por raices. Representan depósitos de crevasse. A techo aflora un canal de gravas con una base fuertemente erosiva. En conjunto representan depósitos de areas interdistributarias y forman una barra de desembocadura menor/asociación de lóbulos de crevasse.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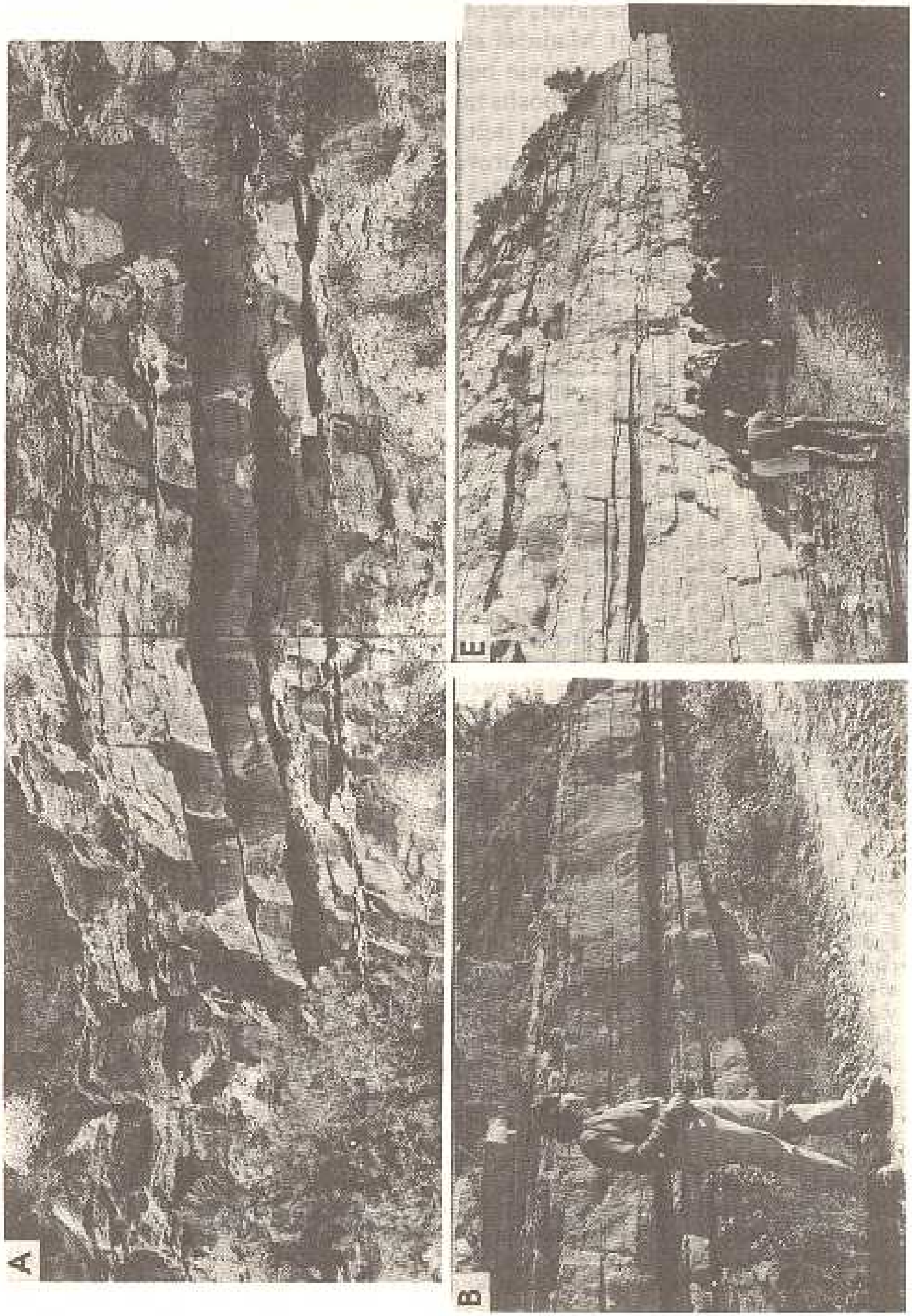
LST—The deepest deposits identified in the deltaic complex, which may be found in the LST of Manresa sequence, are grey shales and silts that contain channel shape sandstone bed sets interpreted as type III turbidites (Mutti, 1985). Those slope deposits range landward to prodelta and delta front prograding facies. These typical deltaic facies have low thickness. The total of these sediments represents the lowstand wedge prograding complex (Vail, 1987). The sedimentary instabilities (Fig. 11) are part of LST and distally they produce the type III turbidites and perhaps a turbiditic system.

TST—In the continental areas the TST consists of a third white conglomeratic unit. In the marine areas two calcareous wedges onlapping the LST deltaic sediments can be identified. In the transition from continental to

Fig. 7.—Complete distributary mouth bar cycle or parasequence (Mura sequence) in El Pont de Vilumara, with the four deltaic facies described in the text. The boundary with the previous parasequence is found in the ferruginized top of a conglomerate-to-very coarse-sand bed (D) which represents the distributary channel facies of the lower deltaic cycle. A- Facies 1: thin bed turbidites, with erosive base, including faunal fragments, alternating with grey mudstones, and related to distal shoreface. B- Facies 2: linsen to wavy stratification level, including grey mudstones, thin beds with ripple trains and thick sandstone beds with hummocky cross stratification, representing shoreface storm deposits. C- Facies 3: medium to coarse sandstone beds alternating with microconglomerate or very coarse sandstones, with moderate to high angle cross planar stratification, typical from foreshore megaripples. The first sandstone bed shows pillow structures. D - Facies 4: represents the distributary channel. Da- lower distributary: conglomerate bed (pebble to microconglomerate) with sand matrix, planar to asymptotical cross stratification, and some wave ripples. Represents the base of the distributary, in storm-reworked foreshore environment, forming megaripples with lateral migration. Db- Upper distributary: thick conglomerate beds (cobble to pebble) with trough cross stratification, typical from fluvial processes and, minority, moderate to high angle planar cross stratification, typical from the upper foreshore megaripples. The marls and the calcarenitic debris (Sh) which overlies the conglomerates form the base of an uppermost parasequence.

Fig. 7.—Ciclo completo de barra de desembocadura de distributario (secuencia de Mura) en el Pont de Vilumara, con las cuatro facies deltaicas descritas en el texto. El límite con la parasequencia precedente se encuentra en el techo ferruginizado de una capa de conglomerados y areniscas groseras (D) que representan las facies de canal distributario del ciclo inferior. A- Facies 1: capas turbidíticas finas, con base erosiva y que incluye fragmentos de fauna, alternando con pelitas grises. Pertenecen al shoreface distal. B- Facies 2: nivel dcon estratificación linsen-to-wavy, donde se incluyen pelitas grises, capas finas de arenisca formando trenes de ripples, y capas de arenisca más potentes con estratificación cruzada hummocky, representando depósitos de tormenta de shoreface. C- Facies 3: capas de areniscas medias a groseras que alternan con areniscas muy groseras y microconglomerados, presentando estratificación cruzada planar de ángulo moderado a alto, típica de los megaripples de foreshore. La primera capa de arenisca presenta estructuras pillow. D- Facies 4: representa el canal distributario. Da- distributario inferior: capa de conglomerados con matriz de arenisca, estratificación cruzada planar a asintótica, y algunos wave ripples. Representa la base del distributario, en un ambiente de foreshore retrabajado por las tormentas, donde se forman megaripples con migración lateral. Db- Distributario superior: capas potentes de conglomerados con estratificación cruzada trough, típica de procesos fluviales y minoritariamente, estratificación cruzada planar de ángulo moderado a alto, típica de los megaripples del foreshore superior. Las margas y el debris calcarenítico (Sh) que aparecen sobre los últimos conglomerados constituyen la base de una nueva parasecuencia.


A
B
E

marine areas some patch reefs facies are deposited overlaying calcareous conglomerate beds.

HST—As in the previous sequence, in the proximal areas, the HST consists of a progradational thick conglomeratic sequence (Fig. 2). The reddish delta plain environments are sited in the NE of the fan. The delta front deposits consist of several shallowing, coarsening up distributary mouth bar sequences (Figs. 8c, d, e) prograding over the Prodelta environments. Reefal

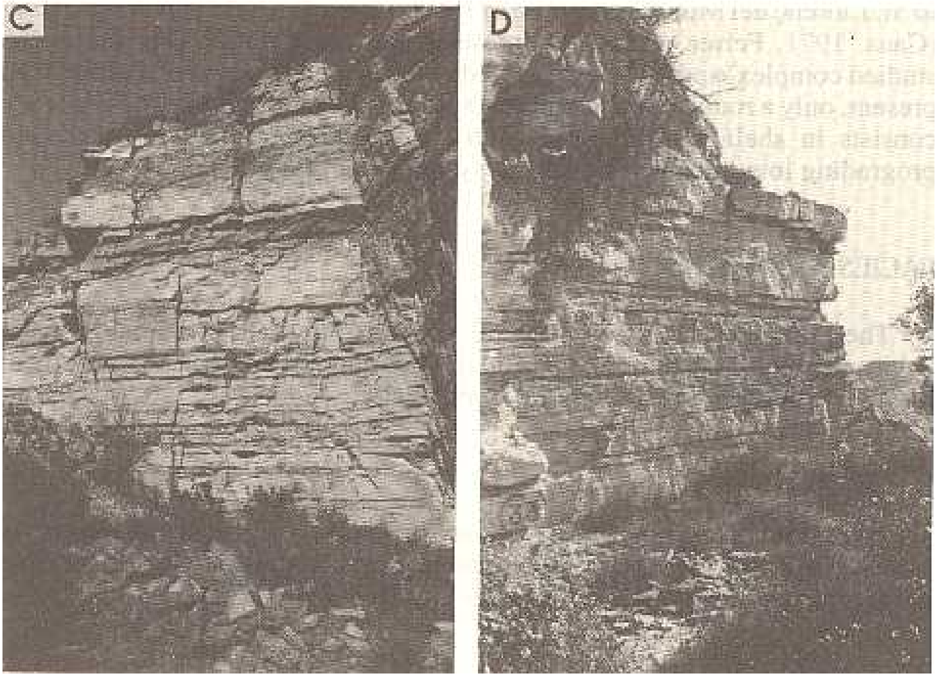


Fig. 8.—A- Facies 2 and 3 of a distributary mouth bar sequence in the Mura-Rocafort road (Mura sequence). The sandstone and gravel beds have tractive plane-parallel laminations, showing lateral migration of the megaripples. Vertical burrows of *Ophiomorpha* are usual. **B**- Facies 3 of a mouth bar cycle (Mura-Rocafort road. Mura sequence) C- Complete sequence of a distributary mouth bar cycle, which represents facies 2, 3 and 4 at top (St. Pau outcrop. Manresa sequence) D- Facies 2 and 3 of a deltaic cycle (St. Pau. Manresa sequence) E- Extensive vision showing the NW accretion of the deltaic bars (St. Pau. Manresa sequence)

Fig. 8.—A- Facies 2 y 3 de una secuencia de barra de desembocadura de distributario en la carretera entre Mura y Rocafort (secuencia de Mura). Las capas de arenisca y de gravas presentan láminas tractivas plano-paralelas, observándose la migración lateral de los megaripples. Son frecuentes los burrows verticales de Ophiomorpha. B- Facies 3 de un ciclo de barras de desembocadura (carretera de Mura a Rocafort. Secuencia de Mura) C- Secuencia casi completa de un ciclo de barras distributarias de desembocadura, presentando las facies 2, 3 y 4 (Afloramiento de St. Pau. Secuencia de Manresa) D- Facies 2 y 3 de un ciclo deltaico (St. Pau. Secuencia de Manresa) **E**- Visión extensa mostrando la acreción hacia el NW de las barras deltaicas (St. Pau. Secuencia de Manresa).

limestones or their storm destroyed calcarenitic equivalent sediments form the topmost deposits of the HST. They deposited when the deltaic sedimentation was lowered due to the commutation of the basin in the studied area. In some cases they represent the late highstand systems tract (Vail, 1987).

Peramola sequence

This sequence, defined in the NW Catalan basin (Oliana area), is correlated to St. Llorenç del Munt area in base of foraminifera and nannoplancton dating (Caus, 1971, Ferrer, 1971). It represents the latest deltaic deposits in the studied complex, and it is well exposed in the N area (Navarcles-Calders). At present, only a rough subdivision into systems tract is possible. The sequence consists in shelf margins systems tract, transgressive systems tract and prograding low thickness highstand systems tract (Fig. 2).

FACIES ASSOCIATIONS

The facies associations will be described from main proximal to distal environments where they are deposited. They support the facies arrangement inside each depositional sequence, indistinctly.

Alluvial cone

The alluvial cone consists of clast- or matrix-supported conglomerate associations, with inclined or subhorizontal disperse stratification and erosive bases. Proximal and distal cone facies can be distinguished.

Proximal Cone

The proximal cone includes massive conglomerates with boulders (up to 1 m thick), disperse stratification and planar internal erosion surfaces. Some massive levels have no stratification, with mass flow or debris flow deposits, and laterally pass to scarce reddish floodplain sandstones. Other conglomeratic facies have horizontal to oblique stratification, with reactivation surfaces and without grading. They represent longitudinal bars which grow according to the polarity of the depositional system. The matrix is coarse sand to microconglomerate. There are quartz, schists, lidites and slates cobbles, supplied by the eroded Hercynian basement of the Catalan Coastal Ranges, and conglomerate, red sandstones and limestones cobbles that have a Triassic and Paleocene cover origin. They represent altogether the proximal facies of an alluvial fan.

Distal cone

Massive conglomerates disposed in sharp base tabular bodies interlayered with reddish mudstones and sandstones of overbank origin. These deposits have abundant rootlets, paleosoils are common. The conglomeratic bodies showing a channel shape have low lateral persistence. The stratification is horizontal, with imbricate cobbles, representing longitudinal bars with the main polarity of the alluvial-deltàic system, high angle planar or oblique, representing transverse bars, and in some cases there are point bar structures. Some low scale sandstone bars or sheets are found between the conglomeratic bodies. The main conglomerate units develop to minor braided to anastomosing channels laterally. As a whole, they represent a braided or an anastomosing fluvio-alluvial system.

Delta plain

Three main types of delta plain deposits can be found. These deposits have a lateral continuity from the distal cone.

Conglomerate channels

The conglomerate channels represent the minor distributaries in the delta plain. They show with great evidence a channel morphology and they are interlayered with reddish mudstones and sandstones. In the channels it is possible to distinguish a fining upward cycle of meandering channel abandonment (Fig. 5) constituted by a lower unit of conglomerates, with sand-matrix and trough cross stratification, associated with longitudinal and transverse bars, and an upper unit of gravelly sandstone bars with trough cross stratification, indicating the gradually flow decrease, when rootlets have no destroy the stratification. Grain-size diminishes from the centre to the margins of the channel. The pebbles are rounded. High angle planar cross stratification and gravelly point bars are developed.

Major distributary channels

The major distributary channels (Fig. 6A) show the same facies arrangement of the massive alluvial cone conglomerates, but with a higher roundness rate. Thus they consist of conglomerates disposed in tabular bodies. The stratification into the distributaries is horizontal, with imbricate cobbles, representing longitudinal bars which reflect the main polarity of the system, but they also show high angle planar or oblique stratification, representing transverse bars.

Overbank deposits

They are formed by interlayering of reddish siltstones and sandstones (Fig. 6B). These massive sand beds (up to 20 cm thick) are sedimented by turbiditic flows and they have erosive bases, disperse grading and rootlets. In some cases we find sandstone beds with climbing ripples.

Crevasse deposits

The crevasse deposits consist of coarse grained sandstone layers (up to 70 cm thick) with erosive bases, grading and disperse gravels. The top of the layers consists of paleosoils with mudcracks and rootlets. During periodical floods cryptalgal laminites formed. Some channels of the braided style, showing a complex internal geometry and a long lateral persistence, are the semiperpetual crevasse channels which form coarsening and thickening up crevasse lobes, with the conglomeratic channel at the top (Fig. 6C). In some cases bioturbation has destroyed all sedimentary structures.

Delta front distributary mouth bars

This environment includes the sediments deposited between the strand line and the shoreface. They are arranged in coarsening and thickening upward cycles of distributary mouth bars. We can distinguish proximal and distal distributary mouth bars. Proximal mouth bar deposits are mainly sedimented in periods of fair weather regime due to fluvial and wave processes. Distal mouth bars are reworked by storm waves. Sands due to the wave induced cyclic weight in the marine bottom are eroded from the delta front (destructive storm facies, Gabaldón, 1989) and resedimented in the prodelta environment as amalgamated layers with hummocky cross stratification (constructive storm facies, Gabaldón, *op.cit.*).

The St. Llorenç delta front contains four main delta front facies arranged in metric to decametric coarsening upward sequences (Figs. 7, 8). From base to top we recognize:

Facies 1

This facies lies at the base of the delta front cycles. It is formed by bioturbated, fine grained thin bed turbidites, with erosive base, horizontal and vertical burrows and including faunal fragments (Fig. 7A). Those sandstone layers alternate with grey mudstones. We find some proximal storm sand layers, alineated pebble layers and faunal debris. The environment of deposition is the shoreface, where the bioturbation is more important than the rising of the sedimentary structures. Those thin beds lay over the prodelta mudstones or the shelf limestones. The boundary between the shoreface beds and the prodelta/shelf mudstones can be in the fair weather waves base (Reineck & Singh, 1972).

Facies 2

This facies is constituted by undulating, medium grained sandstone beds, with parallel tractive laminations forming wave megaripples, linsen to wavy stratified sandstones, thin beds with ripple trains and thick sandstone beds with hummocky cross stratification, which are embedded in grey mudstones (Fig. 7B, 8A, C, D). The environments of deposition are the foreshore and the higher parts of the shoreface bars. The megaripples move to land in the fair weather regime periods. The beds with hummocky stratification represent the shoreface storm deposits. Seaward, these deposits are progressively reworked by the storm waves.

Facies 3

This facies is composed of medium to coarse grained sandstones, with some microconglomerates and very coarse sandstone beds. The thickness of the beds range from 20 cm to 1 m, showing a moderate to high angle cross planar stratification of foreshore megaripples and parallel tractive laminations, which is typical of shore zones (Fig. 7C, 8). These deposits are formed of sediments brought by the river in front of its mouth. As happens with Facies 2, the foreshore bars are reworked by storm waves, seaward.

Facies 4

Facies 4 consists of conglomerate and very coarse sands, typically with trough cross stratification, arranged in channel shape beds. Channels may erode the sandstone bars of Facies 3. In some cases oblique cross stratification, with landward or basinward accretion, is developed at the base of the channel. We can distinguish upper distributary channels and lower distributary ones (Fig. 7D). The latter consist of conglomerate beds (pebble to microconglomerate) with sand matrix, planar to asymptotical cross stratification, and some wave ripples, which represent the base of the distributary channel, in a foreshore environment, forming megaripples with lateral migration. Upper distributary channels consist of thick conglomerate beds (cobble to pebble) with trough cross stratification, typical of fluvial processes and to lesser extend moderate to high angle planar cross stratification,

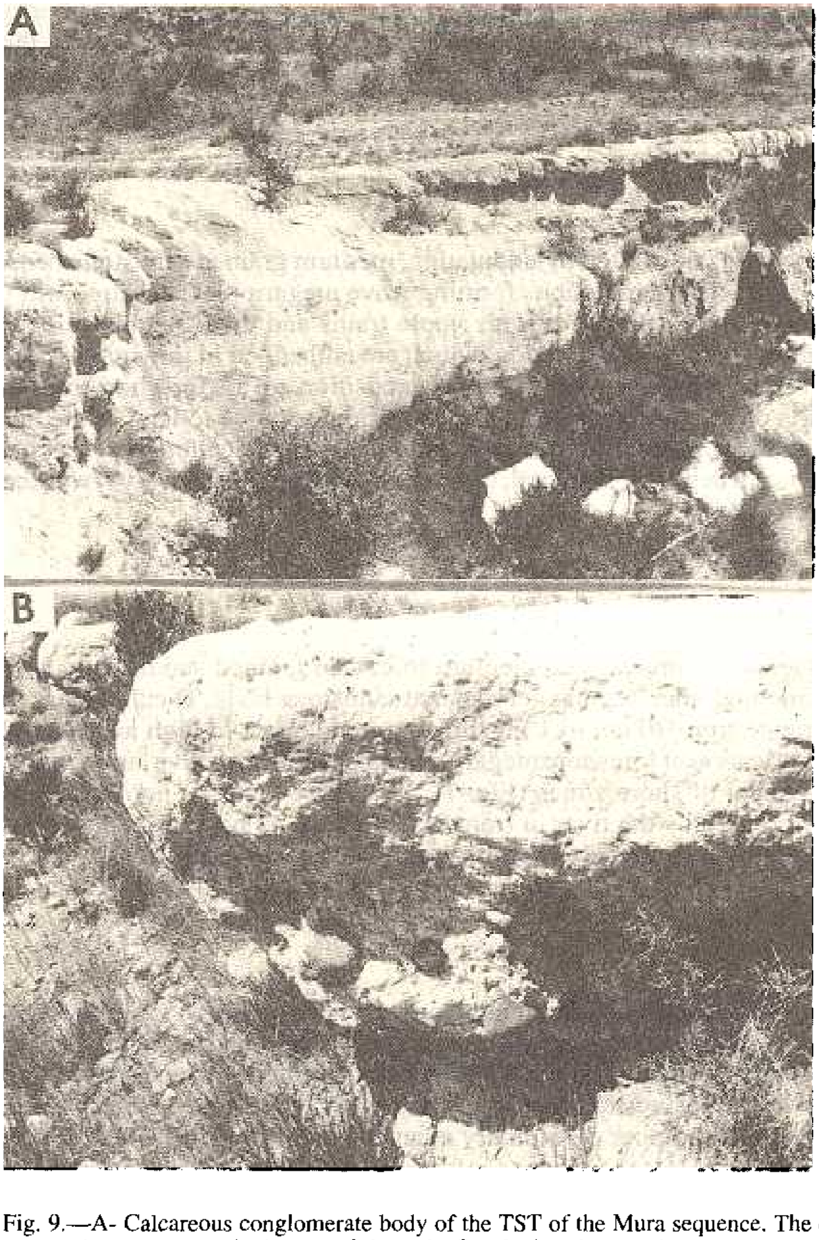


Fig. 9.—A- Calcareous conglomerate body of the TST of the Mura sequence. The calcareous content increase towards the top of the unit. Overlaying the conglomerates a coralline-algal patch reef is exposed. B- Detail of the top of the previous calcareous conglomerate body.

Fig. 9.—**A**- Cuerpo de conglomerados calcáreos del TST de la secuencia de Mura. El contenido en calcárea aumenta hacia el techo de la unidad. Solapando los conglomerados existe un *patch reef* coralino-algal. **B**- Detalle de la parte superior del cuerpo conglomerático anterior.

typical of the upper foreshore megaripples. The thickness of these beds is strongly reduced basinward. They can be interpreted as braided and meandering fluviatile channels which have functioned as delta distributaries, supplying sands and conglomerates from the alluvial cone to the delta front.

SHELF

Two main types of deposits can be found in the shelf environment: marls and limestones. These marls are argillaceous or calcarenitic, and they content rich faunas (Nummulites, molluscs, echinoids, corals, etc), while the limestones consists of grainstones or boundstones (reefs or patch reefs) (Fig. 9). There is also some carbonate debris flow layers that onlap the proximal deltaic sediments. In these proximal areas calcareous debris include some pebbles (Fig. 7Sh), and in prodelta environments, the same layers have a calcarenitic content.

Prodelta

Prodelta deposits are exposed in the Western and North-western areas of the studied zone. We can distinguish two types of deposits (Fig. 10).

— Grey mudstones (silts or shales), which form the main prodelta platform. They are fall-out deposits. Some thin bed turbidites may be interlayered.

— Units of sandstone beds deposited during major storms, which show hummocky cross stratification. The beds have a tractive parallel or low undulating laminations, and their thickness is up to 40 cm. The top of the layers show current ripples. Erosive bases, calcarenitic layers can be interbedded.

Slope

The slope deposits consist of thin bed turbidites showing a channel shape which are interlayered within grey mudstones. They are interpreted as type III turbidites (*sensu* Mutti, 1985).

Destructive deltaic features

The rates of deposition in the continental shelf where St. Llorenç del Munt river delta developed were elevated, with much fine sediment supplied. Incidentally, gravity induced, subaqueous, syndepositional mass movements were generated, and so, important changes took place in the deltaic platform. The river supplied mudstones are rapidly disseminated, building a prodeltaic

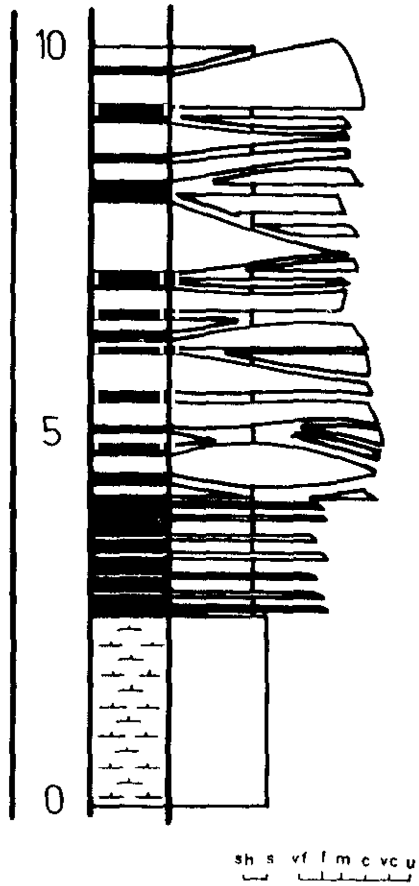


Fig. 10.—Parasequence of Mura sequence showing prodelta facies associations. From base to top, it consists of calcareous marl, thin bed turbidites alternating with grey shale, and a thick body of amalgamated sandstone layers (up to 80 cm) with hummocky cross stratification. (Marganell section).

Fig. 10.—Parasecuencia de la secuencia de Mura mostrando asociaciones de facies de prodelta. De base a techo distinguimos: margas calcáreas, capas turbidíticas finas entre arcillas grises y finalmente un cuerpo potente de capas amalgamadas de arenisca con estratificación cruzada *hummocky*. (Serie de Marganell).

platform. This fast deposition produces a high sedimentary weight of the coarse sediments overlaying subconsolidated, water- and organic matter-rich mudstones of the prodelta slope. A great volume of sedimentary gases are formed from the degraded organic matter, which contribute to increase the water pore pressure. In the offshore areas, multiple winter storms and hurricanes are generated, causing a wave induced cyclic weight in the marine bottom, which also contributes to increase the pore pressure. The sedimentary processes involved in the prodelta platform are produced contemporaneously with the basement fault movement near the Llobregat river faulting area. Many low scale instabilities, usually pillow and ball structures, are found everywhere along the marine areas, from the delta plain to the prodelta.

Two different scale of sedimentary instabilities can be distinguished in the deltaic complex of St. Llorenç del Munt. On the one hand, the great scale instability processes which originated the submarine erosion during the relative lowstand and induced the erosion of the upper part of the preceding sequence. On the other hand, minor scale sedimentary instabilities are specifically related to the progradation of the deltaic systems. They are visible from proximal environments (delta plain, delta front) to distal environments (distal delta front and prodelta), where there is a high proportion of fines (Fig.11).

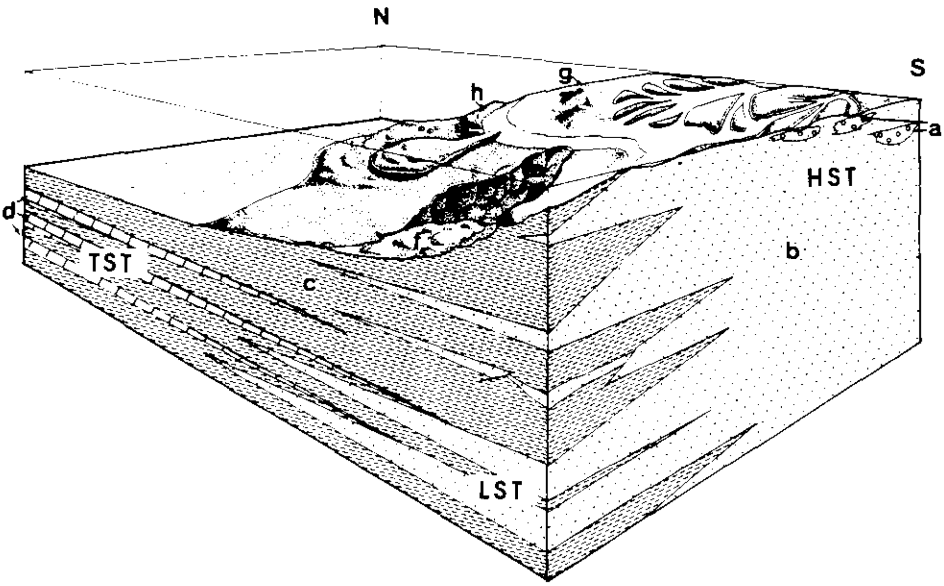


Fig. 11.—Block diagram showing the sedimentary instabilities (Mura sequence) in front of the distributary channel mouth. a-distributary channel, b- delta front deposits, c- prodelta deposits, d- shelf deposits, e- gully of the Cardoner river, f- gully lobes, g- mudlumps of El Pont de Vilumara and, h-patch reef. LST of Mura sequence consists mainly of b and c deposits, TST, in d and c deposits and HST, in a, b, c and h. The base of Manresa sequence is represented by the instability erosional features (e and f).

Fig. 11.—Bloque diagrama mostrando las inestabilidades sedimentarias (secuencia de Mura) frontales a la desembocadura del canal distributario. a- canal distributario, b- depósitos de frente deltaico, c- depósitos de prodelta, d- depósitos de plataforma, e- *gully* del rio Cardoner, f- lóbulos de *gully*, g- *mudlumps* de El Pont de Vilumara y, h- *patch reef.* El LST de la secuencia de Mura está formado por facies b y c, el TST, por facies c y d, y el HST por facies a, b, c y h. La base de la secuencia de Manresa está representada por los fenómenos de inestabilidad erosivos (e y f).

Proximal delta front

The fast deposition of the coarser sediments of the distributary mouth bars over the pelitic sediments, provokes the instability of the mudstones which rise as diapiric intrusions (mudlump) through the deltaic bodies. Those pelitic movements locally produce great subsidence in the sandstone bars. Near El Pont de Vilumara (Mura sequence) there is an up to 8 m pelitic intrusion through a deltaic sandbody, forming a large pillow (Fig. 12A). In the same stratigraphic level unstable mudstones show signs of downward sliding, like slumping and mass flows. The most usual features are small scale balls and pillows. The origin of these structures results from minor mud intrusions in the lowest parts of the deltaic bars combined with the sliding of the sands over the instabilizing mudstones. Distally from the river mouth, the delta front sediments can be affected by small listric faults retrograding up from the upper prodelta. They provoke intraformational unconformities within the deltaic bars.

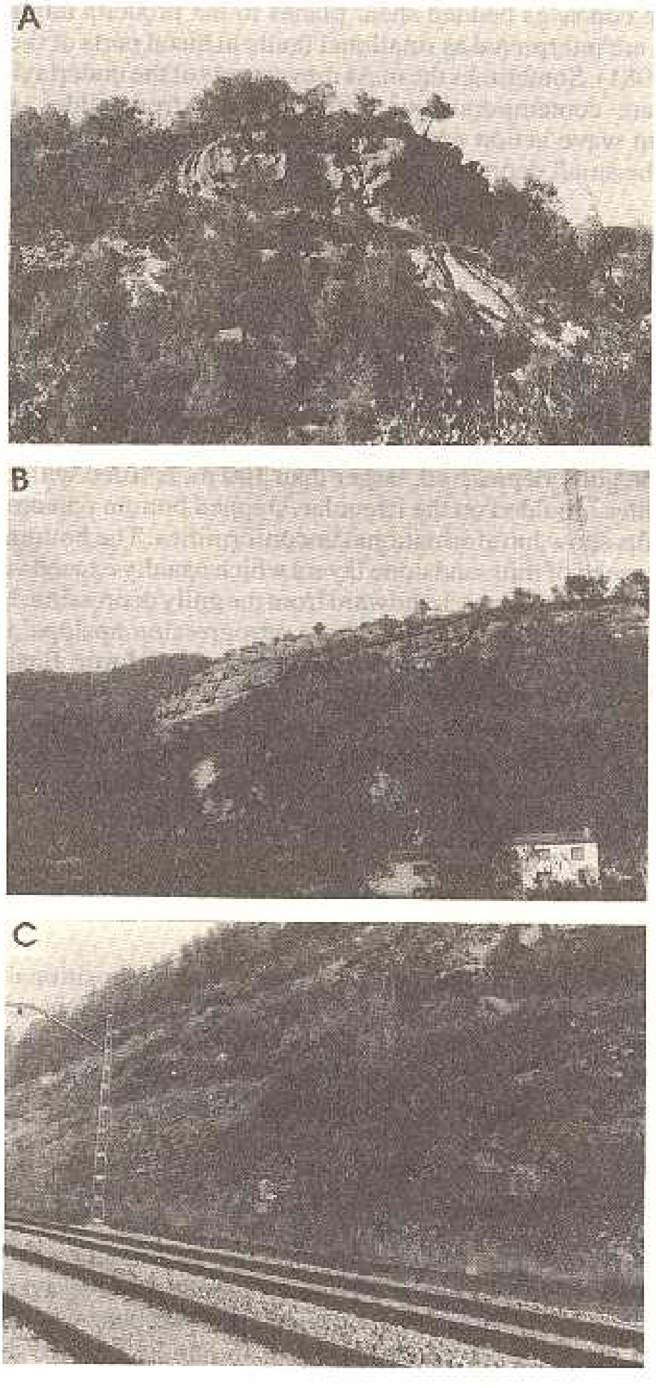
Some instabilities can be found in the shallow delta front, where the distributary mouth bars are shoaled in bay areas. In this environment, mudstones are not as thick as seawards. Those mudstones are autochtonous bay deposits, and some of them are river-supplied. Due to the little thickness of the pelitic sediments, the instabilities formed here are less important. The prevailing structures are pillows and balls, up to 3 m, which affect the whole low thickness distributary bar in the surroundings of Talamanca village. Laterally to the pillows, in the same level, the deltaic sandbody shows signs of shifting over the underlaying mudstones.

Distal delta front

In the Marganell-Castellgalí area, there are blocks of sandstones that have fallen down. They are great distributary mouth bar or distal bar fragments

Fig. 12.—A- Mudlump: diapiric intrusion of prodelta grey mudstones in through a deltaic body, near El Pont de Vilumara, showing a pillow shape. B- Rotational peripheral slide, in Marganell road, formed by a kilometrical delta front block which has slided over a listric bedding fault. C- Gully of the Cardoner river (railway outcrop). Metric sandstone blocks (in the right) on the irregular surface of the bottom of a gully, and posterior infilling of the gully depression by grey mudstones and thin bedded storm sand layers.

Fig. 12.—**A**-*Muldlump*: intrusión diapírica de pelitas de prodelta que atraviesan un cuerpo deltaico, cerca de El Pont de Vilumara, mostrando forma de *pillow* de grandes dimensiones. **B**- Deslizamiento rotacional periférico, en la carretera de Marganell, formado por un bloque kilométrico de materiales de frente deltaico deslizados sobre una falla sedimentaria lístrica. **C**- *Gully* del río Cardoner (afloramiento de la vía del tren). Bloques métricos de arenisca (en la derecha) sobre la superficie irregular del fondo de un *gully*, así como el relleno posterior de la depresión del *gully* por perlitas grises y capas de tempestitas.


A
B
C

slided on the concaves bedded shear planes to the prodelta mudstones (Fig. 12B). These are interpreted as rotational faults in distal parts of the delta front (Coleman, 1981). Sometimes the mass movements of the underlaying prodelta mudstones are contemporaneous with the delta front slides, induced by intense storm wave action and by degasing due to the high organic matter content, in the small depressions of the distal delta front and upper prodelta.

Prodelta

The mudflow gullies and the related depositional lobes are the most usual deformational features of the upper prodelta, in depths from -7 to -100 m, extending radially from each of the distributaries (Coleman, 1981).

There is exposed an irregular blocky bottom hummocky depression, with sandstone blocks up to 7 m (Fig. 12C), locate between Castellgalí and Manresa. The gully depression, larger than 100 m, is filled with thin bedded storm turbidites moulded on the irregular, stepped bottom paleomorphology. These deposits show intraformational unconformities. The bottom blocks (up to 1 m) are formed of thin sandstone layers which usually exceed very few cm, interbedded with mudstones. Landward from the gully depression, a succession of listric, rotational faults resulting from retrogression upslope, inferred the growth of the depression and produced a stepped platform. Basinward, and because of the downslope emptying of the gully depression, chaotic sediments, like mudflows, debris flows including metric sandstone balls, slumps and slurry flows, occur. They are part of the proximal areas of the gully lobe. More distal sediments consist of mudflows and muddy debris flows with a channel shape base between the prodelta and the slope mudstones.

CONCLUSIONS

In St. Llorenç del Munt delta complex, four depositional sequences bounded by unconformities have been described, with their main systems tracts, namely Rellinars sequence, Mura sequence, Manresa sequence and Peramola sequence. The described deposits have mainly a deltaic origin, and their facies associations have been distinguished from proximal to distal in each sequence.

The deltaic environments show three different facies associations: (1) delta plain associations: main and minor distributary channels, crevasses or crevasse lobes, overbank and levee facies; (2) delta front associations: distributary mouth bars, forming thickening, coarsening and shallowing upward cycles. These bars can be fluvial-dominated near the river mouth, and storm and wave dominated offshore; and then the bars with planar cross stratification are transformed to bars with hummocky cross stratification.

Storm reworking is present also, near the shoreline, in the proximal distributary mouth bar. Lastly, (3) prodelta associations, which includes the finest deposits, mainly silts and shales, and storm sand layers.

In pelitic environments sedimentary instabilities usually cause features such as gullies, listric sedimentary faults, mudlumps, rotational slides, balls and pillows. The main factors controlling this instabilities are the differential weight between sands and fines, the quantity of fines, and the cyclic bottom weight of the storm waves. Sedimentary instabilities appear from the delta plain to the prodelta, but the most important features take place in the deepest environments, such as prodelta and upper slope.

A major instability level is found in the boundary of Mura and Manresa sequences, and is related to the submarine erosion in a type I sequence boundary (*sensu* Vail, 1987). The other unconformities are described as type II boundaries.

The shelf facies associations are restricted in space and in time. In space, in areas of low siliciclastic sediment supply, at the base of many deltaic parasequences or distributary mouth bar cycles, and in time, related mainly to transgressive systems tracts.

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