Effects of sea-level changes on a wave-worked Gilbert-type delta (Late Pliocene, Aguilas Basin, SE Spain)

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ABSTRACT

The bay of Cuatro Calas was formed in late Pliocene times by a local downward bending of older Neogene materials, which favoured a relative rise of sea level and invasion by the sea. The studied bay-fill deposits consist of units, with large-scale foresets that filled most of the depression topped by the younger sets of offlapping transition-zone units with an overall tabular shape. As a whole, they generated a Gilbert-type delta morphology that actually is a summatory of smaller-scale delta units deposited during successive highstands of sea level. We can observe only these highstand delta deposits. Lowstand wedges lay under the Present Mediterranean sea.

According to the sedimentological data, we deduce a delta model consisting of a river plain with rapidly shifting channels, a wave-worked delta front with gravelly reflective beaches, a sandy delta platform, and a steep delta slope. The input of sediment was episodic, and the delta remained inactive during long periods, subjected to wave reworking in the shallow areas. The Cuatro Calas Gilbert-type delta fits Postma´s (1990b) prototype 4 («classic Gilbert-

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type»). It is comparable to present-day deltas of ephemeral streams feeding gravelly beaches in SE Spain

Progradation of the delta generated a two-fold large-scale cross-stratification: a lower high-angle related to the advancing delta-foreset and the upper one associated to progradation of beach units.

The development of the complex Gilbert-type delta followed a repetitive pattern in response to fluctuations of sea level: progradation of highstand Gilbert-type delta (stage 1) was followed be entrenchment and coastal wedge in lowstand and early transgression (stage 2). The various parts of the delta reacted differently to these sea-level changes and generated variable facies associations.

The rapid evolution of the bay-fill can be related to high-frequency fluctuations of sea-level already documented in SE Spain during Late Pliocene and Quaternary, superimposed on longer-lasting tectonic uplift.

Key words: fan delta, sea level changes, Neogene, Aguilas Basin, Betic Cordillera

RESUMEN

La Bahía de Cuatro Calas se formó en el Plioceno superior cuando los materiales neógenos más antiguos se flexionaron propiciando una subida relativa del nivel del mar y la inmersión de la nueva cuenca. Los depósitos de relleno de bahía consisten en unidades con grandes foresets, que rellenaron la mayor parte de la depresión, coronados por unidades más jóvenes de la zona de transición deltaica situados en offlap y cuya morfología de conjunto es tabular. Todos ellos, formaron un delta de tipo Gilbert complejo que en realidad es la suma de unidades deltaicas de menor escala depositadas durante periodos de nivel del mar alto (highstands). Sólo se pueden observar los depósitos de highstand. Las cuñas de lowstand se encuentran bajo el Mediterráneo actual.

De acuerdo con los datos sedimentológicos, deducimos un modelo deltaico que consiste en una llanura aluvial con canales de baja estabilidad lateral, un frente deltaico retrabajado por el oleaje con playas reflexivas de gravas, una plataforma deltaica arenosa y un talud abrupto. El aporte de sedimento era episódico y el delta permanecía inactivo durante largos periodos, con las zonas someras sometidas al retrabajado del oleaje. El delta de tipo Gilbert corresponde con el prototipo 4 («delta de tipo Gilbert clásico») de Postma (1990b). Es comparable a los deltas actuales de corrientes efímeras que alimentan playas de grava en el sureste de España.

La progradación del delta generó una estratificación cruzada doble: una de bajo ángulo debida a la progradación de playas de grava y otra de alto ángulo producida por la progradación del talud deltaico (foreset).

Así pues, el desarrollo del delta de tipo Gilbert complejo siguió una secuencia repetitiva en respuesta a las fluctuaciones del nivel relativo del mar: progradación de deltas de tipo Gilbert durante el highstand (estadio 1) seguida de encajamiento y depósito de cuñas costeras durante el lowstand y el comienzo de la transgresión (estadio 2). Las distintas partes del delta reaccionaron de forma diferente a estos cambios del nivel del mar, generando asociaciones de facies variables.

La rápida evolución del relleno de la bahía puede estar relacionada con las fluctuaciones del nivel del mar de alta frecuencia descritas en el sureste español durante el Plioceno superior y el Cuaternario, asociadas con tendencias tectónicas de surrección de mayor alcance.

Palabras clave: fan delta, cambios del nivel del mar, Neógeno, Cuenca de Aguilas, Cordilleras Béticas

INTRODUCTION

The sedimentary facies of fluvially dominated Gilbert-type deltas have been treated in detail by a number of authors in recent years (Postma 1984, Postma & Roep, 1985, Colella *et al.*, 1987; Colella, 1988 a & b; Massari y Colella, 1988; Prior & Bornhold, 1988). Wave reworked Gilbert-type deltas are less well recognized, although some authors pointed to wave-worked «topsets» (Colella, 1988 a & b; Postma & Cruickshank, 1988, Massari & Parea, 1990). The term topset comes from Gilbert (1885), and denotes the subhorizontally deposited alluvial facies which rests on top of the subaquatic, steeply inclined foreset facies. Because the wave-reworking takes place in a zone which is transitional from the alluvial environment into the realm of the delta foreset, the original term topset can not longer be applied s.s. Therefore, Wescott & Ethridge (1980) introduced the term transition zone to denote deposits which are subhorizontally deposited on top of the foreset, and are wholly or partially reworked by waves.

The aim of this paper is to focus on the evolution of the delta systems and the sedimentology of a wave-worked Gilbert type delta on the basis of a case history of late Pliocene age studied in the Aguilas Basin in SE Spain (Fig. 1). The sedimentology of these deposits has been studied in detail for the first time. Emphasis will be placed on the sedimentary facies of the transition zone and the foreset beds.

TECTONIC SETTING OF THE GILBERT-TYPE DELTA

Sedimentation in the late Neogene and Quaternary basins in SE Spain took place in partly-interconnected basins generated by the Iberia-Africa collision.

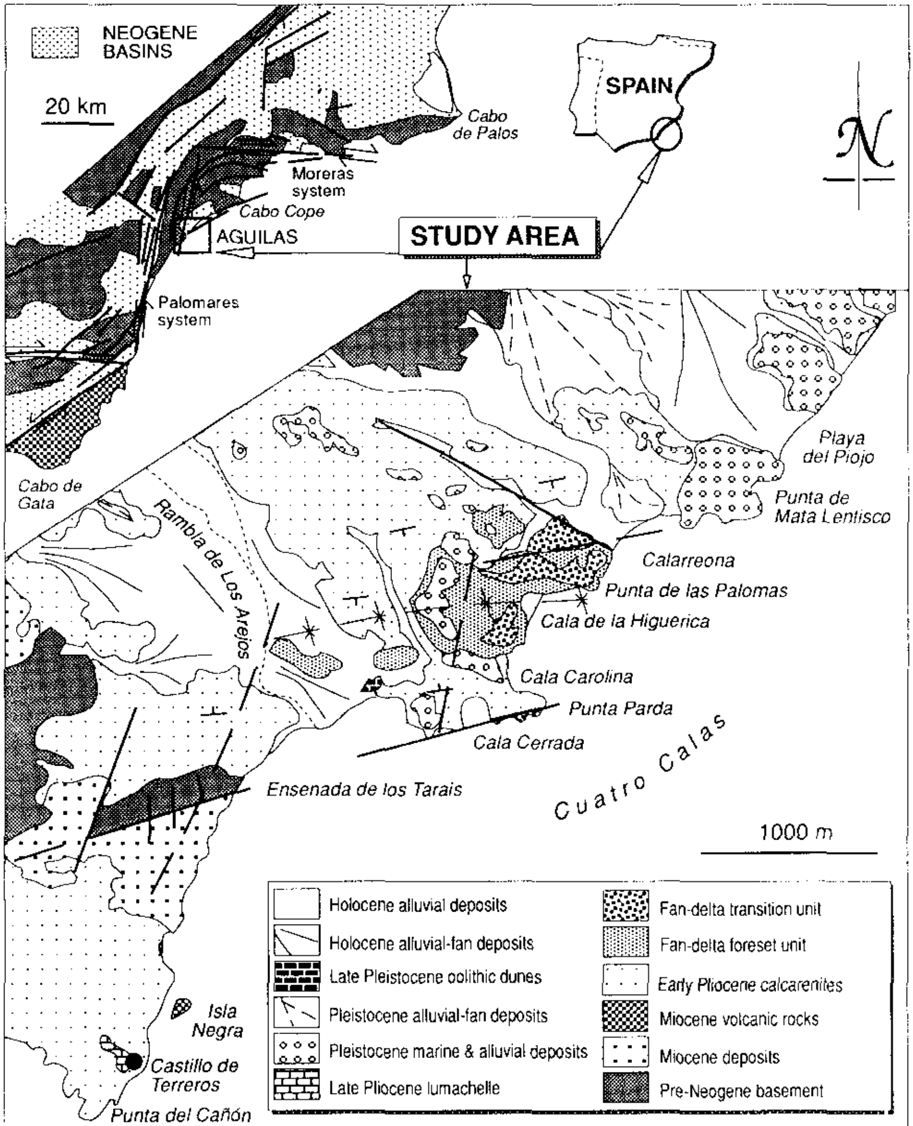

Fig 1.—Location map of the studied area in the structural sketch of the Aguilas Arc (modified after Coppier *et al.*, 1989).

Fig 1.—Localización del área de estudio en el contexto estructural del Arco de Aguilas (modificado de Coppier *et al.*, 1989).

This system, mainly inherited from previous structural stages, was affected by compression oriented roughly N-S, which induced a slight perpendicular extension. During middle Pliocene times, the stress field and the direction of regional shortening shifted from N-S to NW-SE. The tectonic evolution of the late Neogene Basins of the Betics was controlled by an wide NE-SW sinistral lateral shear zone (Fig. 1) (Montenat *et al.*, 1987, Sanz de Galdeano, 1990). The rotation of the stress field had a notable effect upon the cinematics of faulting, and consequently on the geometry and sedimentary filling of the basins. Two types of basins evolved simultaneously: wrench furrows and grabens.

Previously, in the Early and Middle Miocene, the Aguilas Basin was submerged and covered by pelagic sediments. Movement along the fault zones (Moreras and Palomares systems, Fig. 1) resulted in an arc-shaped deformation of the basement (Coppier *et al.*, 1989), and caused regional uplift and continental sedimentation in the Upper Miocene (Montenat *et al.*, 1978).

In the early Pliocene the Aguilas Basin was again submerged, and shallow marine fossiliferous yellow sands and calcarenites were deposited. In late Pliocene, the basin relief changed due to a rotation in the stressfield (Ott d'Estevou & Montenat, 1985; Montenat *et al.*, 1987). Late Pliocene (to Present) NW-SE compression resulted in folding and reactivation of inherited N 70-80°E fault structures, both controlling the formation of troughs (area of Cuatro Calas (Fig. 2). One of these troughs formed a bay marginal to the Mediterranean sea and received sediments from both pre-Tertiary and older Neogene source rocks. The late Pliocene units were deposited in the bay after a relative rise of sea level, partly caused by local downward bending, submerged the basin (Fig. 2).

SEDIMENTOLOGY OF THE LATE PLIOCENE BAY FILL

General

The late Pliocene bay fill is exposed in Cuatro Calas (Fig. 1), between the villages of Terreros (province of Almería) and Aguilas (province of Murcia). Localities cited in the text are numbered from 1 to 8 (Fig. 2), and may be easily found in the field by means of the numbered, white-painted concrete landmarks pin-pointing the coastal zone, which we used as locality references in the text and figures.

The pre-Neogene basement of the basin and the adjacent mountain ranges that acted as source rocks is made up of metamorphic and metasedimentary rocks (quartzites, dolomites, micaschists, phyllites and marbles) of the Internal Zone of the Betic Cordillera (Figs. 1 and 2). Cannibalized Neogene sedimentary and volcanic rocks also contributed to the basin fill.

The bay, marginal to the Mediterranean Sea, extended inland in an western direction and was filled with a complex succession of units separated by erosional surfaces (Fig. 3). These units are informal and have been used in a

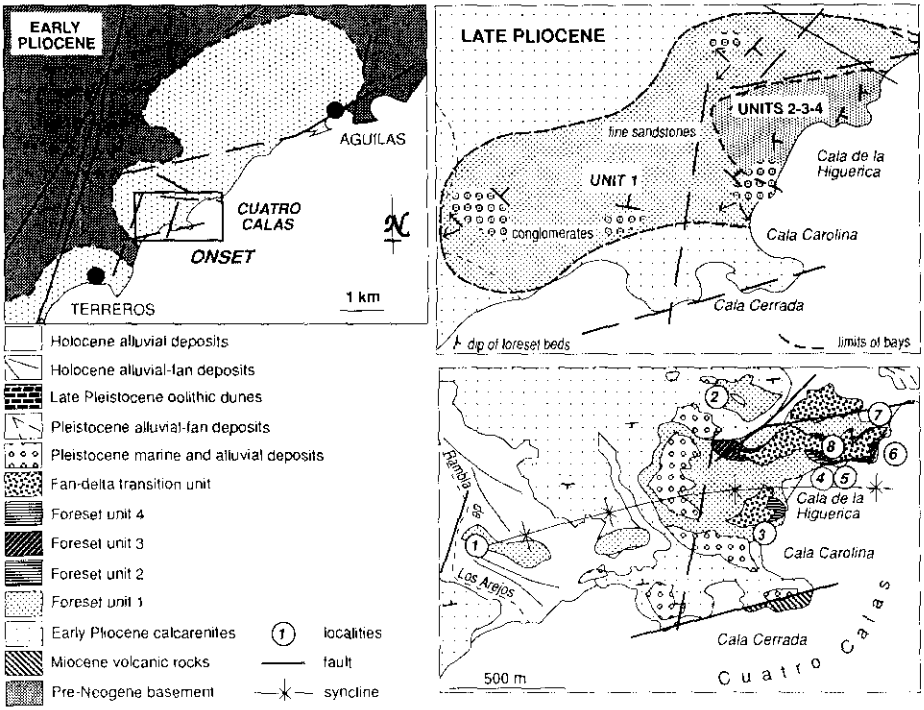

Fig 2.—Above, left: reconstruction of the Aguilas Basin in the early Pliocene. Above, right: some paleogeographical features of the Cuatro Calas area during the late Pliocene. Below: geologic map; note syncline axis.

Fig 2.—Arriba, izquierda, reconstrucción de la Cuenca de Aguilas durante el Plioceno Inferior. Abajo, derecha: algunos rasgos del área de Cuatro Calas durante el Plioceno Superior. Abajo: mapa geológico; obsérvese el eje sinclinal.

descriptive way; no classification is intended. In some cases erosion removed most of the sedimentary record of units. The four older units are large-scale cross-stratified, with well-developed foresets. They were named as Units 1 to 4. The younger units occur under a general tabular geometry made up of a large number of marine and terrestrial deposits arranged in an offlapping pattern in an multistorey transition zone. Marine units were named as M-1 to M-5 whereas terrestrial units were named T-1 to T-3 (Figs. 4 and 5). Units M-0 and T-0, also present in the area mapped in Fig. 2, were not included in the present study. The vertical stacking of all these units generated a Gilbert-type delta morphology (Figs. 3 and 4) which, of course, does not correspond to a single event of delta progradation but, instead, records a complex history of relative sea-level changes, tectonic trends and modifications of sediment supply. However, for any particular time there existed a delta geometry that occupied part of the bay.

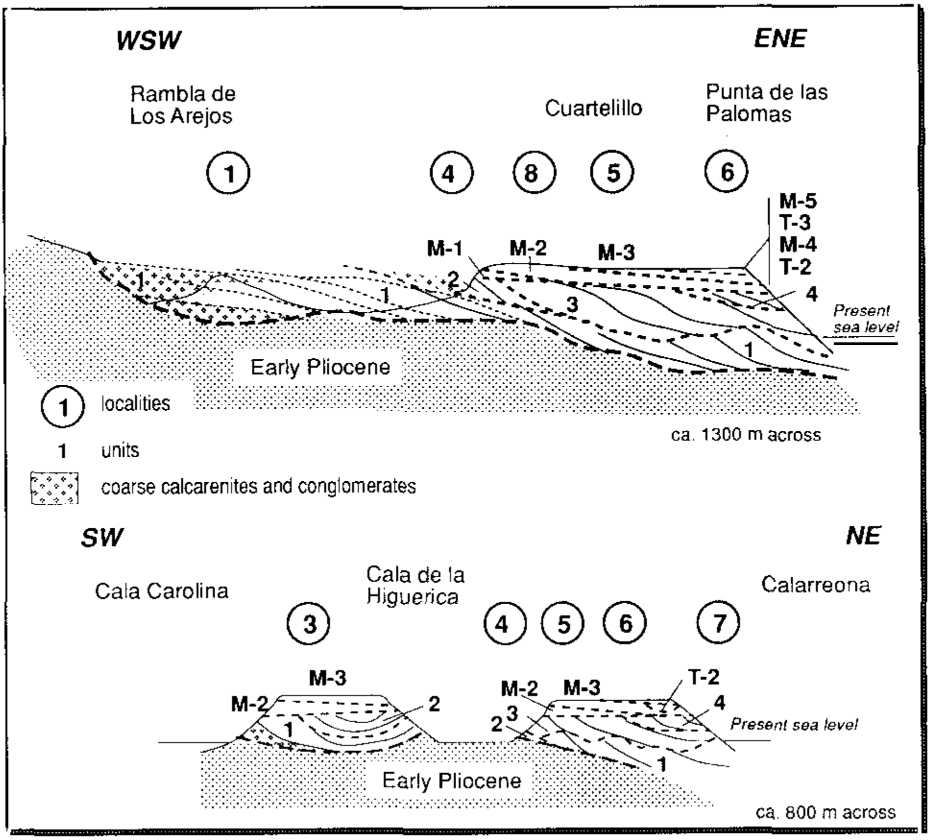

Fig 3.—Schematic cross-sections of the bay-fill in Cuatro Calas.

Fig 3.—Cortes geológicos esquemáticos del relleno de la bahía de Cuatro Calas.

Below we describe briefly the most outstanding features of these units.

Unit 1

Description

Unit 1 is the oldest and the more extensively represented of the basin fill (Fig. 2). It lays unconformably upon fine-grained, fossiliferous lower-middle Pliocene yellow sands and calcarenites. The visible thickness of the unit does not exceed 15-20 m.

The unit consists of pebbly calcarenites, conglomerates, and yellow weakly-cemented micaceous sandstones. The fossil content of coarser-grained layers consists of *Ostrea*, *Pecten*, *Chlamys* and other shallow-marine

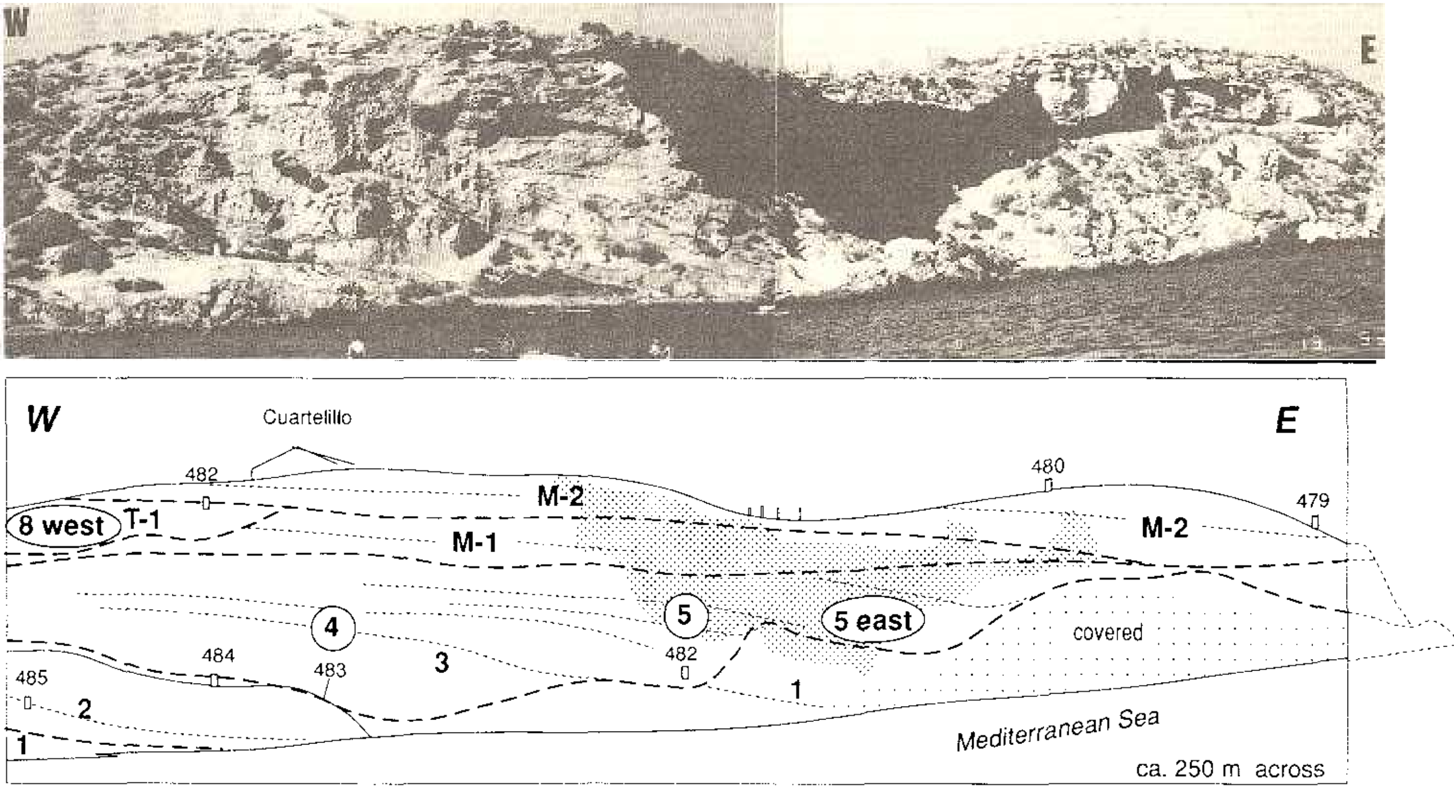

Fig 4.—Panoramic view of the complex Gilbert-type delta, roughly parallel to the progradation, along the northern coast of Cala de la Higuerica. Compare with figure 3. Note that landmark No 482 is repeated and that the one in locality 5 should be actually No 481.

Fig 4.—Panorámica del delta de tipo Gilbert complejo, aproximadamente paralela a la dirección de progradación, en la costa norte de la Cala de la Higuerica. Compárese con la figura 3. Obsérvese que el mojón 482 está repetido y que el mojón del punto 5 debería ser realmente el número 481.

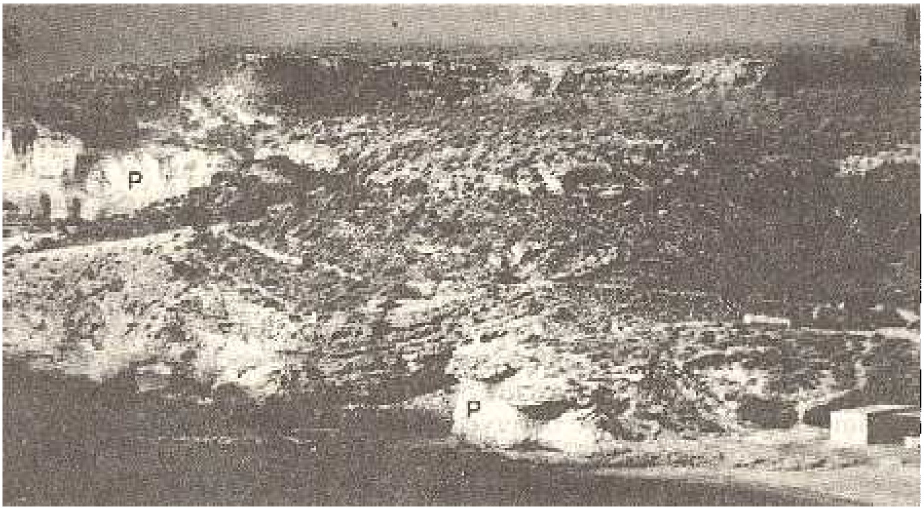
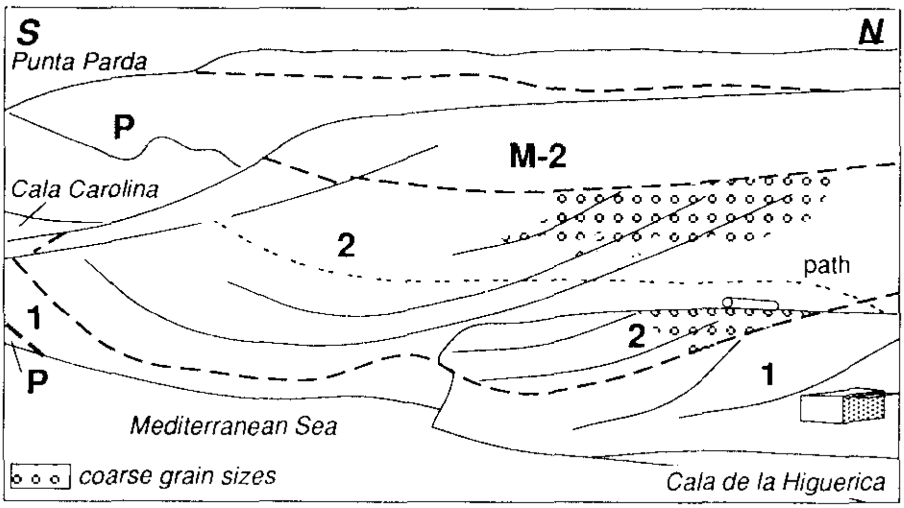

Fig 5.—Panoramic view of the complex Gilbert-type delta, normal to the progradation, between Cala de la Higuerica and Cala Carolina (locality 3). Compare with figure 3.

Fig 5.—Panorámica del delta de tipo Gilbert complejo, perpendicular a la dirección de progradación, entre Cala de la Higuerica y Cala Carolina (punto 3). Compárese con la figura 3.

organisms. Accumulations of bivalves, largely moulds due to leaching and dissolution, are common. The finer-grained layers yield *Chlamys, Ostrea, Pecten, Gryphaea, Balanus*, coralline algae, echinoids and large (up to 60 cm-long) bones of mammals (? whale, Fig.7 A).

Conglomerates occur in the lower part of the unit and also toward the shallow marine areas and margins of the bay, as deduced from detailed mapping and geometry of units. The coarse-grained facies interfinger with finer sandstones and calcarenites which develop large-scale clinoforms toward the basin interior (Figs. 2 and 3).

The interfingering is well observed in Rambla de los Arejos (locality 1, Fig. 6). The conglomerates wedge out to the NW where fine sandstones dominate. Individual sets of cross-bedded conglomerates, up to 50 cm in height, exhibit well preserved megaripple geometry (Fig. 7 B). Successive wedges of trough cross-bedded conglomerates are separated by truncation surfaces. Shells of bivalves and pebbles (0.5 to 2 cm in grain size) of the metamorphic rocks forming the basement of the basin are the coarsest components. Many sets of cross bedding are alternatively dominated by shell and siliciclastic material. It is interesting to note that paleocurrents point to the SW (N 240-270° E), i.e. toward the basin margin.

Similar arrangements are observed in other localities. At locality 2, the erosional base of the unit dips 25-30° to the SE. There, a 40 to 80 cm-thick, set of cross-bedded fossiliferous conglomerate and coarse sandstone rests upon the basal erosional surface and climbs upslope (NW). Foreset laminae, up to 15 cm in thickness, lay almost horizontal or dip very gently to the NW. Truncation surfaces separate successive sets of cross bedding which are 60 to 80 cm long. Shallow-marine fossils are similar to those cited earlier. There are other, coarser-grained layers similar to those described in Rambla de los Arejos, with paleocurrents also pointing to the SW. The overlaying finer-grained facies are poorly represented due to erosion.

Between Cala Carolina and Cala de la Higuerica (locality 3) the erosional surface of the unit dips to the NE (Fig. 3). Here, sets of fossiliferous conglomerates and pebbly coarse-grained calcarenites climb upslope, with paleocurrent measurements ranging from N 150° to 240° E. The interfingering of coarse sediments with more distal, clinostratified, yellow sandstones and calcarenites is well exposed.

The distal facies are large-scale cross-stratified: these are the oldest exposed foreset beds filling the bay. Dips of foreset beds change downslope from 25° to less than 15°. They consist of yellowish cemented sandstones with a white weathered colour. Beds are 25 to 40 cm thick with frequent normal grading ending upward in very fine sand and silt. The internal structure of foreset beds is very faint parallel (and inclined) laminations which may change upslope into cross bedding also directed upslope. Large and abundant shells of *Chlamys* sp are typical for this unit. *Chlamys* is particularly abundant, and well preserved 200 metres west from locality 7. Many shells have attached Balanus up to 15 mm in size. Most layers are intensely burrowed; galleries and tracks occur parallel to the original dip of clinoforms (Fig. 8 A). Burrowing, both vertical and (or) parallel to the original inclined dip, is very intense in many layers, particularly those of the distal zones.

Bottomset beds are not well exposed but they look to be similar to those of the foreset with increasingly finer grain.

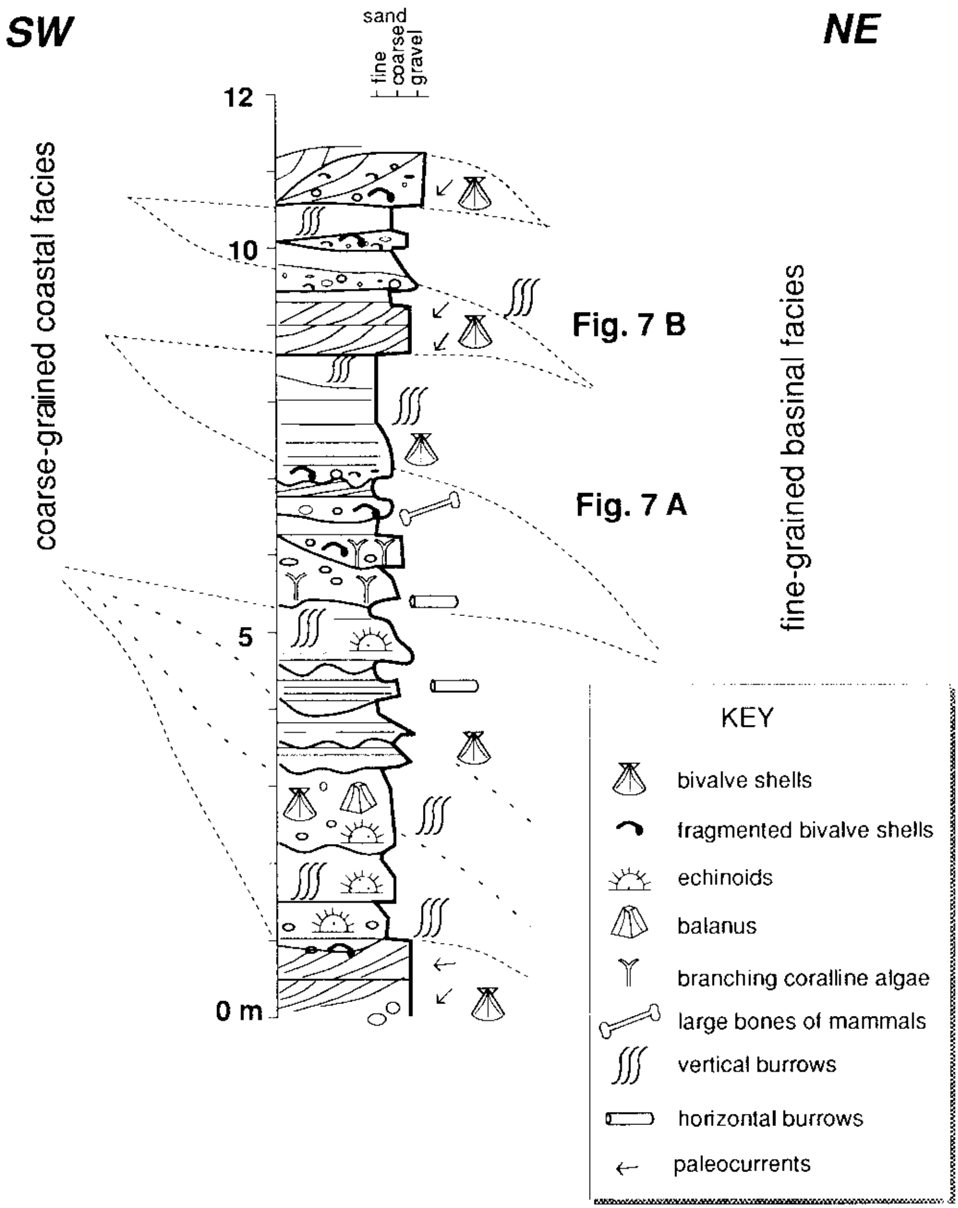

Fig 6.—Section of the coastal deposits of foreset Unit 1 in Rambla de Los Arejos (locality 1).
Fig 6.—Columna de los depósitos costeros de la unidad de foreset 1 en la Rambla de Los Arejos (punto 1).

Interpretation

The coarse sediments of the lower part of the unit (localities 1, 2 and 3) occur on top of erosional surfaces incised during a relative lowstand phase. Sublittoral (nearshore) swash bars migrated toward the shore during the transgression generating cross-sets which climbed up the erosional surface (localities 1, 2 and 3). Continued sea-level rise drowned the bars and left them behind, almost untouched until they were draped by the prograding fine sediments of the clinostratified phase.

Most of the deposits of Unit 1 are coarse sediments in the shallow, proximal areas which changed toward the basin interior into burrowed sandstones and calcarenites with clinostratified foreset structure (Fig. 3). These coarse-grained facies were deposited in the shallow shelf and margins of the bay (Fig. 2) where lunate or sinuous-crested megaripples migrated roughly parallel to the axis of the basin and the inferred elongation of the shelves. Movements of water masses, driven by storm winds blowing from the east, may provide the mechanism driving the megaripples. Coastal and nearshore sediments fed the megaripples. Changes of sediment source controlled by seasonal fluctuations (i.e. river discharge versus beach-derived sediments) may explain the occurrence of dominantly siliciclastic and skeletal/bioclastic intervals in foreset laminae of cross-bedding.

During this stage the sedimentation in the bay was dominated by marine processes and Gilbert-type deltas were not fully developed. Facies architecture of the marine facies does not provide proof of the possible deltaic nature of deposits. The only posseble evidence may be the occurrence of well-rounded coarse conglomerates in proximal zones.

By prograding to the east (N 100-110° E), the conglomerates and fossiliferous sands of Unit 1 draped, and partly filled, the bay (Fig. 3).

Unit 2

Description

Deposits of Unit 2 unconformably overlay the coarse-grained, fossiliferous conglomerates of the Unit 1 in the hill separating Cala de la Higuerica from Cala Carolina (locality 3), resting upon a spoon-shaped surface (Fig. 5). The lithology of foreset beds varies from coarse calcarenites and conglomerates in the proximal shallow areas to burrowed yellow sands and calcarenites in the deeper, somewhat deeper, zone. The change, visible in individual layers, takes place within a few metres. The internal structure of the beds is parallel lamination, particularly visible in the finer facies. Burrowing, both vertical and (or) parallel to the originally-inclined bed surfaces, is very intense particularly in the distal parts of layers.

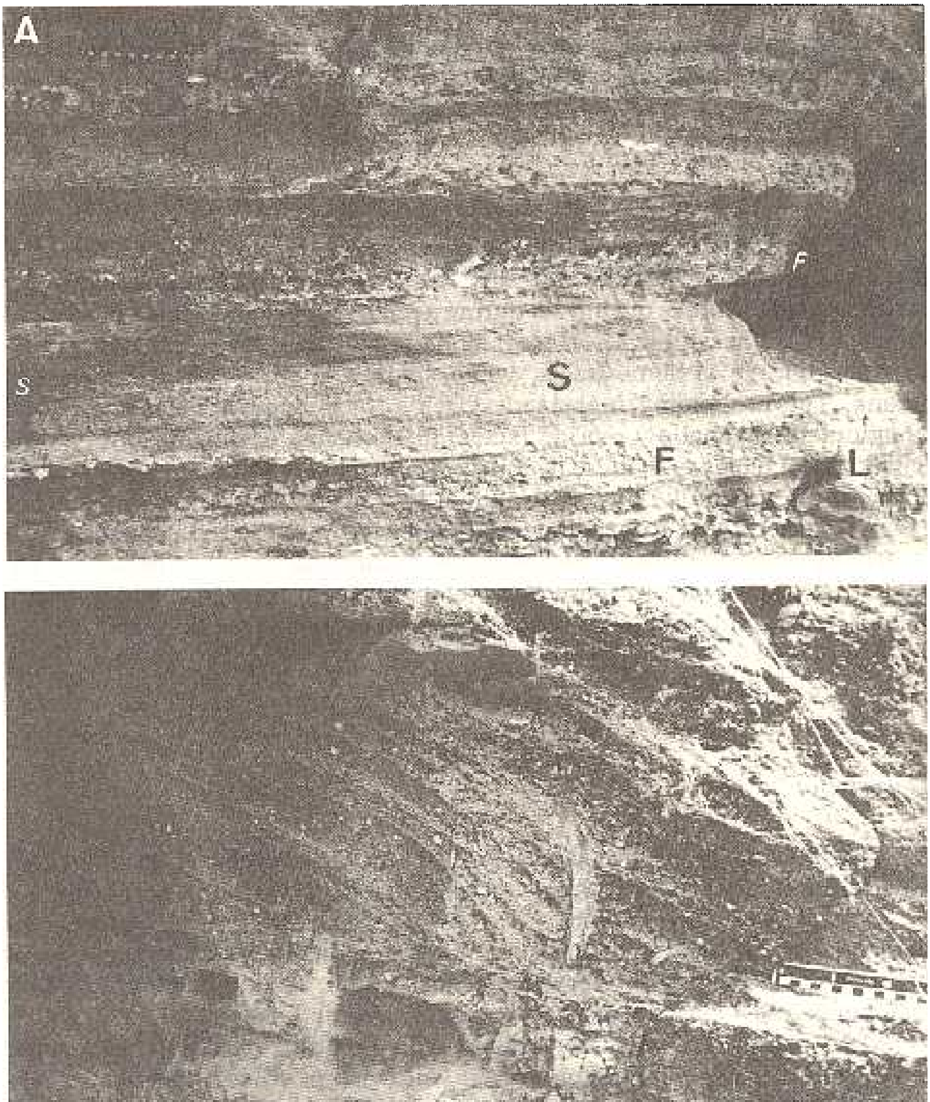

Fig 7.—(A): Interlayered bioclastic calcarenites (F) and parallel-laminated sandstones (S). One of the calcarenite layers contains large bones of mammals (L). (B): set of cross-bedded conglomerate with preserved megaripple morphology, paleoflow to the southwest (right of the observer). Locality 1, see figure 6.

Fig 7.—Calcarenitas bioclásticas (F) y areniscas con laminación paralela (S) interestratificadas. En una de las capas de calcarenitas hay grandes huesos de mamíferos (L). (B): set de conglomerados con estratificación cruzada y morfología de megaripples bien preservada; paleoflujo hacia el suroeste (derecha del observador). Localidad 1 (ver figura 6).

The foreset unit has large scale clinoforms, more than 10 m high. Successive groups of beds record individual phases of progradation. Backsets (sets of upslope-dipping cross-strata, see Postma, 1984; Postma & Roep, 1985; Colella *et al.*, 1987) occur overlying the erosional surface.

Interpretation

Unit 2 filled was deposited in environments similar to those of Unit 1, but the areal extent of the bay was smaller. It filled an irregular topography sculptured in the rocks of Unit 1 1 during a relative lowstand. Calcarenites and coarse sandstones of the lower part, including the basal backsets, correspond to transgressive systems tracts, when shallow marine bars were pushed inland. The prograding highstand systems tract includes calcarenites and conglomerates (shallow-marine facies), that change basinward into yellow sands (distal facies). All these features suggest that the sediment was supplied to the foreset from the higher, proximal part which was closer to the shore (Figs. 2 and 3). As the coarse grained facies is similar to the deposits of the overlying transition-zone unit, there is a more definite evidence of the terrestrial provenance of these materials via fluvial transport, and a deltaic model may be invoked more reasonably. But still, it is not definite.

Unit 3

Description

The large-scale cross-bedded Unit 3 is nicely exposed in the hill of El Cuartelillo (Figs. 3 and 4), resting unconformably upon Units 1 and 2 (Fig. 8).

Foreset beds are typically 25 to 30 cm thick. They are poorly or not cemented at all, coarse to medium sands commonly separated by 5 to 8 centimetre-thick layers of very fine sands to silts. The high content of rock fragments allow classification these sands as lithic arenites.

Many layers are normally graded with thin fine-grained upper parts. Usually, the fine-grained intervals are yellowish in colour whereas coarse-grained intervals are light grey to yellowish. Poorly-defined fining upward sequences, 10-15 m thick are recognized in the direction of progradation.

The internal structure of foreset beds is parallel (and inclined) lamination and undulating lamination, 0.5 to 1 cm thick with low-angle truncation surfaces (locality 5). In some beds, parallel or undulating lamination changes upslope into cross bedding directed upslope. Lamination is sometimes very faint.

Fossil content include: *Modiola* sp (abundant in locality 5-east), *Chlamys* sp, *Pecten* sp, and *Ostrea* sp. Burrows are mostly vertical and they are particularly abundant in the uppermost 2 or 3 m of Units 3 and 3-bis.

Dips of the foreset decreases downslope from 25° to 15° but prominent lateral changes occur due to adaptation to the irregular base. Mean progradation was to the SE (N 130° E).

There are backsets, up to one metre thick, at the base of the unit in locality 4 (Fig. 8 B) and locality 5-east (50 m east of 5, see Fig. 4). They are consist of coarse to very coarse sand (or weakly cemented sandstone). Interset surfaces are erosional. Absolute dip of laminae is ca.15° upslope (NW), but the angle with the interset surface is ca. 25°. In locality 4, scattered boulders 40 cm long (a axis) have attached *Balanus* and *Serpulid* worms indicative of a shallow nearshore origin.

The inclined foreset beds overlay the backsets with a downlap relationship (locality 5-east). An oxidized layer of fine gravel topping the upper backset separates both sub-units. The ferruginous layer is a few centimetres thick.

There is a poorly defined unit, separated from 3 by an erosional surface, which we have named as foreset unit 3-bis because their identical lithologies. It occurs in localities 5 and 6 (Figs. 8 A and 9 A) but the poor quality of the outcrops does not allow a more precise description and reliable differentiation in maps and cross-sections.

Units 3 and 4 will be interpreted together.

Unit 4

Description

Unit 4 crops out in the eastern end of Punta de las Palomas (locality 6, Fig. 9). It rests unconformably upon an erosional surface dissecting materials of Units 3 and 3-bis. Lithology of Unit 4 is normally-graded grey sands. Graded bedding ranges from coarse to fine sands and silts. Some layers contain scattered pebbles with maximum sizes up to 10 cm. The internal structure of foreset beds is parallel lamination. Burrowing is intense, mostly parallel to bedding surfaces. Dips of beds change downslope from 25° to 20°. Progradation was to the east (N 90° E).

The first two beds of unit 4, just above the erosional, irregular surface are backsets (Fig. 9 A). The lower one is an upslope-directed, cross-bedded layer of gravel filling a scoured surface. Foreset laminae of backset are almost horizontal but the angle with the clinoforms is ca 20°. Overlying this bed, there is a second backset layer made up of parallel-laminated sands (lamination parallel to clinoforms) with scattered pebbles that change (upslope) into upslope-directed cross bedding with tangential foreset laminae. The interset surface is rather flat.

As in unit 3, foresets downlap the backset sub-unit. At the top of the backsets, a thin ferruginous layer of fine gravel separates them from the prograding foreset beds.

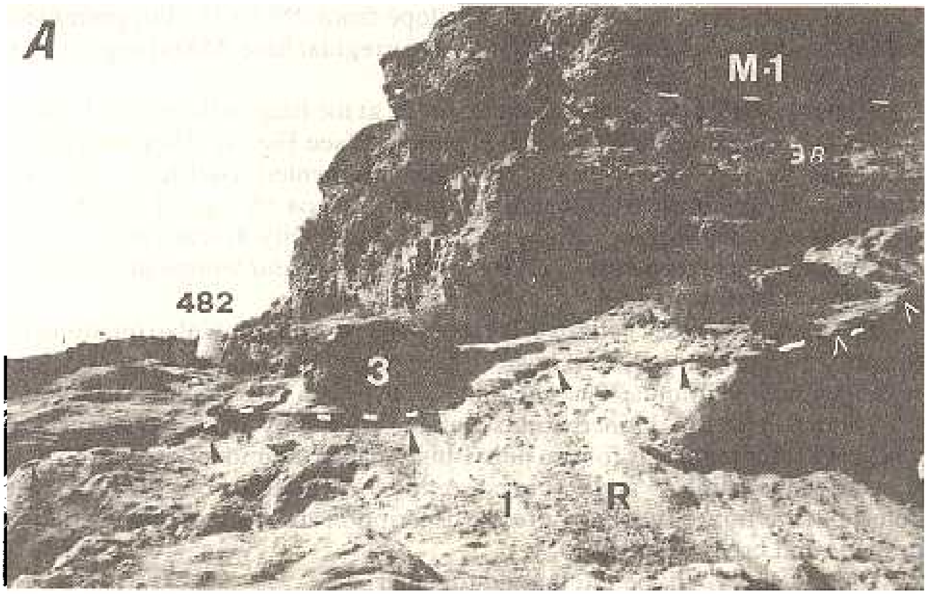

Fig 8.—(A): erosional boundary between foreset Units 1 and 3 (locality 5); 3 B indicates unit 3-bis cited in the text. The top of the section is the marine unit M-1 of the transition zone. Beds of Unit 1 are intensely burrowed (R). (B): erosional limit between Units 2 and 3 (locality 4). Backsets (*B*) and isolate boulders (G) with attached *Balanus* and serpulid worms at the lower part

Interpretation of Units 3 and 4

Clinoforms evidence the progradation of units under the action of sediment laden currents which supplied sand to the basin margin and slope. Most probably the internal structure of the foreset resulted from an alternation of short periods with hyperpicnical flows down the delta slope (dominance of sedimentation) and longer periods of quietness (dominance of burrowing). Short lived, spasmodic flows moving down the slope of the fan delta generated faint parallel lamination and normal graded bedding. We assume that supercritical (high) flow regime conditions might account for the generation of undulating lamination and upslope cross-bedded sandstones as indicated by Nemec (1990). On the other hand, densely burrowed layers indicate repeated pauses in sedimentation during which the foreset surface, at the water/sediment interface, was colonized by animals that excavated complex galleries.

The large-scale erosional surfaces in the foreset facies are steep-sided and progress deep into the previous foreset deposits (Fig. 5). They exhibit variable orientations. We interpret these surfaces as the result of incision and partial destruction of delta-front and foreset deposits during relative falls of sea level. Rebuilding of delta foreset during later relative highstands generated the erosional unconformities. The foreset deposits of Units 1 to 4 prograded to E, ESE, SE, and E respectively (Fig. 2).

It is known that wave reworking causes continuous destruction of the delta in a wave-dominated environment, but is less during high-discharges (Postma pers. com. 1991). Probably waves played a role as erosional agents but they were active only when oscillations of sea level approximated the relatively-deep zones of the delta to the wave base level and allowed erosion of the bottom. We do know that waves alone can produce these surfaces. Currents, probably seaward-directed underwater (? subaerial) flows, may play a major role as well.

Geometry and vertical relationships of deposits, indicate that backsets were generated before the progradation of foreset beds, because of the downlap arrangement. The backsets overlying the erosional surfaces were deposited during relative lowstand or early transgressive episodes. An additional proof of the discontinuity between these two facies is the ferruginous

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of unit 3. There are backsets in Unit 2 as well (below the large boulder, G). Landmarks are 70 cm high. Compare with figure 4 for location.

Fig 8.—Contacto erosivo entre las unidades 1 y 3 (punto 5); 3 B indica la unidad 3-bis citada en el texto. El techo de la sección es la unidad marina M-1 de la zona de transición. Las capas de 1 están intensamente bioturbadas (R). (B): límite erosivo entre las unidades 2 y 3 (punto 4). En la parte baja de la unidad 3 hay backsets (*B*) y bloques aislados (G) con *Balanus* y gusanos serpúlidos fijos a ellos. También se ven backsets de la unidad 2 (bajo el bloque G). Los mojones miden 70 cm de altura. Compárese con la figura 4 para la situación.

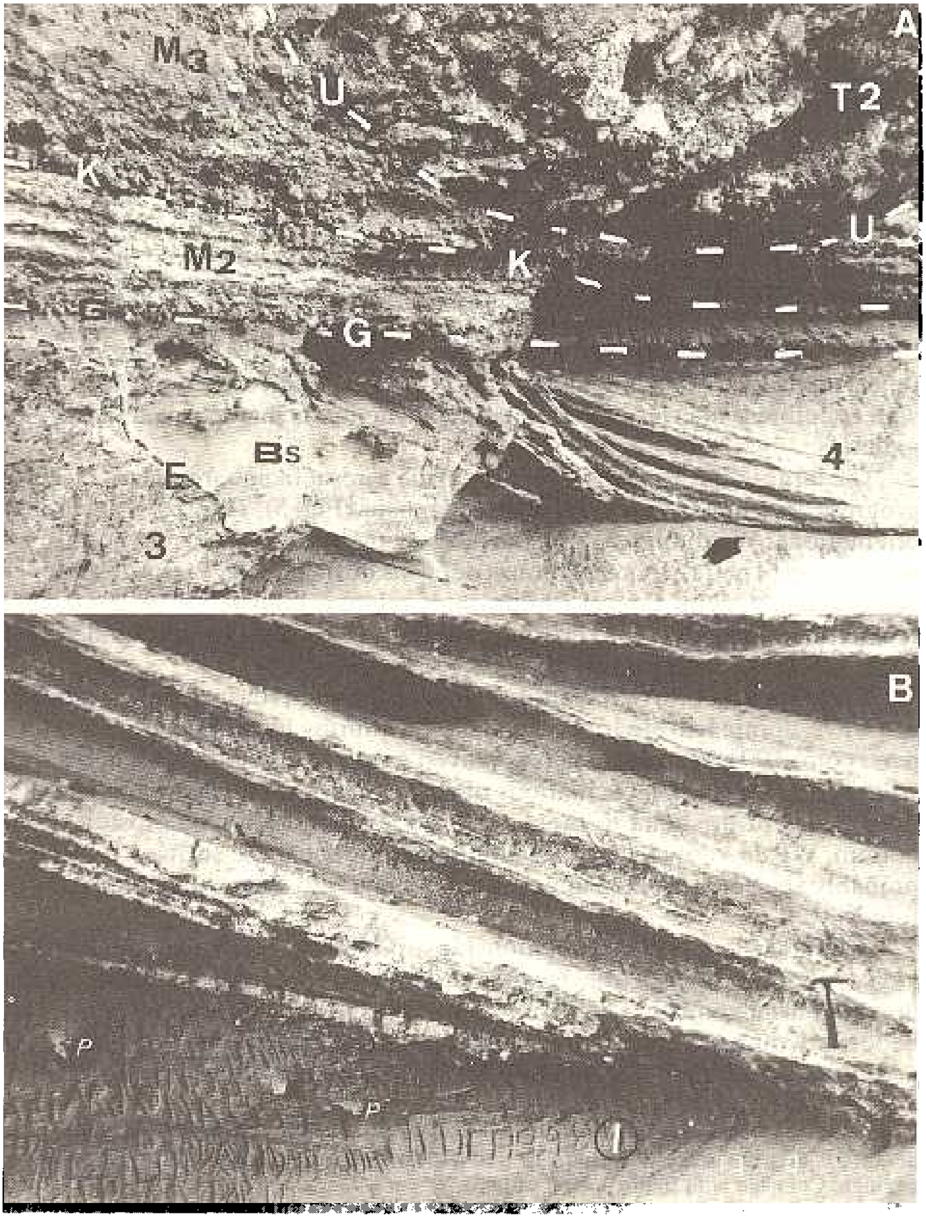

Fig 9.—(A): irregular, erosional boundary (E) between the densely-burrowed foreset Unit 3 (actually 3-bis) and the foreset unit 4. The surface is overlain by backsets (BS) which in turn are downlapped (arrow) by the prograding foresets of unit 4. Above the erosional surface (K) there are marine and terrestrial Units (M-2, M-3 and T-2) of the transition zone, bounded by erosional surfaces (G, U). Note the steep channel margin (U) and channel-fill cross-bedding inclined to the observer in terrestrial unit T-2. The area exposed in the centre of the photograph is 7 m high.

(oxidized) layer of fine gravels separating them (localities 5 east and 6), which we interpret as a condensation layer due to the relative starving of deposits after the transgression and before the full progradation of the overlying delta-foreset during the highstand.

Massari & Parea (1990) observed that backsets in fan deltas are related to erosional surfaces connected to relative sea-level changes of eustatic origin. Backsets seem to be preferentially associated with segments of the delta built on during phases of relative highstand of base level, probably characterized by more intense reworking by storm-driven flows. They stated that backsets may be related to storm- or flood-induced, offshore directed highly concentrated flows that may undergo acceleration down the steep gradient of the foreset slope and transformation into supercritical density underflows subject to hydraulic jumps.

Transition-zone Units

Description

Coarse-grained deposits overlay the foreset unit. They are separated by a flat, erosional surface (Figs. 4, 5, 9 A and 11 A) slightly inclined in the same direction as the average delta progradation (ESE).

The transition zone is composed of an offlapping sequence of marine (shallow to coastal) and terrestrial (fluvial) deposits (Fig. 10). Distinction between deposits of the two environments was based on petrographic composition, textures (mostly clast shapes, roundness and packing), fossil content, boring of clasts, colour, etc. These are essentially the criteria listed by Ethridge & Wescott (1984) with specific modifications useful for Mediterranean late Neogene and Quaternary deposits (Bardají *et al.*, 1990; Dabrio, 1990).

Shallow marine to coastal deposits (Units M-1 to M-5) consist of well sorted, rounded and notably spherical clasts (Fig. 11 B). Quartzite is the dominant component with other metamorphic rocks (dolomite, micaschists)

(B): close up (arrow in the previous picture) of the parallel-laminated, inclined beds of unit 4. Note scattered pebbles (P) an burrowing. The encircled ruler is 15 cm long.

Fig 9.—(A): contacto erosivo e irregular (E) entre las unidades de foreset 3 (realmente la 3-bis), que está muy bioturbada, y 4. La superficie está cubierta por varios backsets (BS) los cuales, a su vez, están coronados por las capas inclinadas del foreset de 4 formando un downlap (flecha). Sobre la superficie erosiva (K) hay unidades marinas y continentales (M-2, M-3 y T-2) de la zona de transición, limitadas por superficies erosivas (G, U). Nótese el margen abrupto del canal (U) y la estratificación cruzada de relleno de canal, inclinada hacia el observador, de la unidad T-2. La altura del área expuesta en el centro de la fotografía es de unos 7 m. (B): detalle (ver la flecha en la fotografía anterior) de las capas inclinadas y con laminación paralela de la unidad 4. Hay clastos dispersos (P) y bioturbación. La regla incluida en el círculo mide 15 cm.

contributing in minor proportion. Lateral associations and vertical facies succession consist of a fining-upward sequence, one to three metres thick. The lithology is well-sorted coarse sandstones and fine conglomerates. The coarsest grain sizes accumulate in the lower part, upon an erosional surface. Bedding forms inclined large-scale, low-angle (5° to 8°) cross-stratification. Local upslope imbrication of flat clasts and sets of cross bedding, usually pointing upslope occur associated to the fining up sequence. Marine fossils include skeletal fragments of bivalve shells and coralline algae. Many dolomite clasts are bored by lithophaga. Dominant colours are light-yellow to grey.

Terrestrial (fluvial) deposits (T-1 to T-3) include more irregular, angular clasts with major component of metamorphic rocks: micaschists, phyllites, dolomite and other rock fragments in a coarse sand matrix (Fig. 11 C and 11 D). They are derived from the pre-Neogene basement, almost untouched during transport. In contrast to the marine (beach) units, clasts of quartzite are subordinate or almost absent.

We distinguished coarse-grained and fine-grained facies that can be described as channel fill conglomerates and tabular or irregular sandy clay facies respectively. Typical channel-fill deposits consist of conglomerates with angular and flat-shaped clasts; these features enhance the tendency to imbrication. Channel-fill deposits exhibit scoured bases (Fig. 11 C) and local trough cross bedding with both open and filled framework (Fig. 11 D). Paleoflow directions deduced from channel scouring, imbrication and local cross bedding, point to E and SE, i.e. to the paleo sea (Fig. 10). The tabular fine grained facies are orange and reddish sandy clays with burrowed, root horizons and reddened layers (Fig. 11 C).

Interpretation

Marine layers are interpreted as deposited in coarse-grained beaches of the reflective type because of their lateral associations and vertical facies succession are comparable to those described for this type of coastal deposits (Dabrio, Zazo & Goy, 1984; Dabrio, Goy & Zazo, 1985; Bardají *et al.* 1990).

Foreshore deposits display a large-scale (up to three metres thick) cross stratification inclined about 8° to the sea (Figs. 9 and 10). The coarsest fractions available in the beach accumulate at the lower part indicating the plunge step. The flat, gently inclined erosional surfaces cutting through foreshore deposits record changes of beach profile, which usually are related to storm erosion. Shoreface deposits, when preserved, consist of trough cross-bedded and wave-ripple cross-laminated sands with scattered nearshore fossils.

Reflective beaches occur in the fronts of present-day deltas of the SE coast of Spain. In Present examples, coastal dynamics and grain sizes couple to

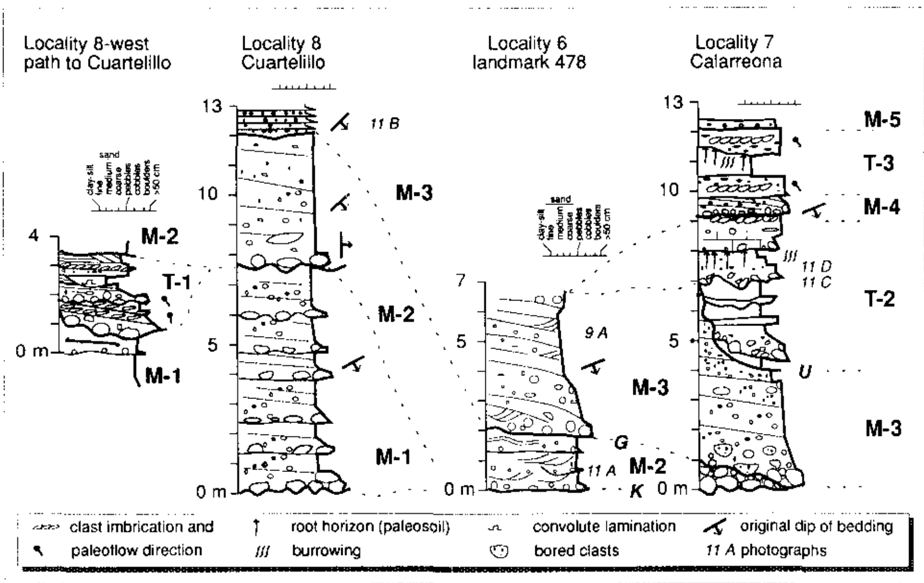

Fig 10.—Representative sections measured in the transition-zone units, and correlation traced by lateral continuity of layers in the outcrop, to evidence the geometry of units. G, K, and U are the erosional surfaces pictured in figures 9 A and 11 A.

Fig 10.—Series representativas levantadas en las unidades de las zona de transición y correlación efectuada por continuidad lateral de capas, que revela la morfología de las unidades. G, K y U son las superficies erosivas ilustradas en las figuras 9 A y 11 A.

produce beaches where most of the energy of waves is reflected (Sonu, 1973; Guza & Inman, 1975; Short, 1979; Wright *et al.*, 1979); flow directions are opposite, essentially both to the land and seaward. Most of the sediment accumulates in the upper foreshore, generating high berms. Accumulation of these beaches require waves less than 1 m high and coarse sediment (Md > 0.6 mm), although they can stand moderate to high energy when grain sizes are larger (Short & Wright, 1983). Thus, they are sheltered and accretional beaches (Bryant, 1983) dominated by accumulation, lateral uniformity and temporal stability. Sediment input by rivers is transported alongshore by wind-driven littoral drift feeding the beach. The small volume of sediment available to these beaches allows rapid changes of the beach profile (Short & Wright, 1983), often triggered by variations in grain size (Short, 1984). The shoreface is gently inclined, but relatively deep, with scarce, sandy deposits and no bar development. This is a major difference with the dissipative high-energy conglomeratic coasts described by Bourgeois & Leithold (1984).

Terrestrial deposits are interpreted as fluvial deposits of braided, probably ephemeral, rivers with rapidly shifting channels and a finer grained flood plain where pedogenic processes favoured by plant growth took place. These

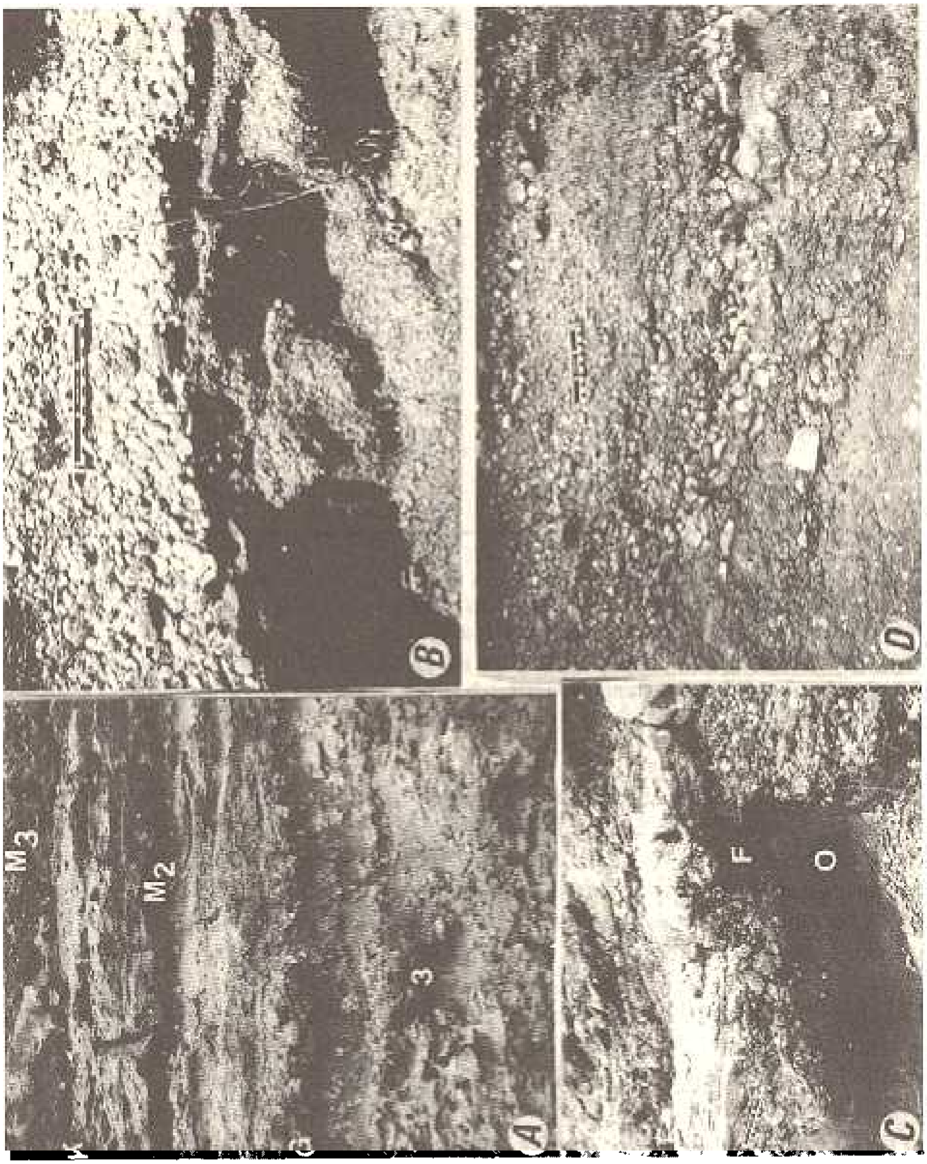

Fig 11.—Photographs of the transition zone units with locations shown in figure 10. (A): densely burrowed upper part of foreset Unit 3 (3-bis); section oblique to strike (note crude almost horizontal bedding) and erosional boundary (G) with transition zone units M-2 and M-3. Wave cross-bedded fine gravels of M-2 correspond to upper shoreface deposits. The large-scale cross-bedded M-3 (see figure 9 A) is a reflective beach deposit (only the coarse-grained plunge step deposits visible) prograding to ENE. (B): well-sorted, rounded fine and coarse conglomerates in the upper foreshore of M-3 (locality 8). (C): channel-fill conglomerates (R) with erosional,

fluvial systems are apparently similar to those existing nowadays in the area but with less tendency to incision.

In the environments described, sediment fluxes derived from land may enter the basin and be deposited within the transition zone or the delta foreset, and be rapidly covered by wave-worked sands. In this case, distinction between such marine deposits with a «terrestrial» texture and real terrestrial deposits may be very difficult. The occurrence of root layers (soil profiles) in all the terrestrial layers (Fig. 6) are interpreted as indicative of true subaerial conditions. However we can not exclude the possibility that some units with terrestrial appearance may in fact have a marine origin. In any case this will not significantly modify the implications for the interpretation of sea-level changes.

There are prominent compositional and textural differences between the coarse-grained marine and alluvial deposits. Conglomerates deposited in the nearshore are better rounded and sorted; in addition, they are mostly composed of quartz. As the described marine units correspond to highstand phases and fluvial units to lowstands, these differences can be related to variable input due to sea-level changes. During lowstands, rivers transport to the former shelf large amounts of siliciclastic sediments in response to the lower base level. These trasnported deposits had accumulated in river valleys during preceding higher stages of sea level. On the contrary, highstands imply a relative shortage of alluvial input (particularly the coarsest grain sizes) to the shore because much of it had been left behind, trapped as fluvial valley-fills in proximal river courses. So, there was a decrease in the input of coarse sediment to the highstand delta, and the associated beaches became somewhat starved. Thorough movement of clasts by littoral drift along the coast improved sorting, roundness and almost completely abraded the less resistant rock fragments. As the observed Gilbert-type delta was deposited during highstands (lowstand deposits lay below Present sea level), there was a relative shortage of gravel and relative increase of abrasion-resisting rocks

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scoured lower boundary and (O) flood-plain mudstones. (D): Channel fill with trough cross bedded conglomerates (Gt facies) with open and closed framework. Compare textures with photograph B. Photographs C and D are from unit T-2 in locality 7.

Fig 11.—Fotografías de las unidades de la zona de transición con la situación indicada en la figura 10. (A) parte superior de la unidad de foreset 3 (3-bis) muy bioturbada. La sección es oblicua a la dirección (nótese la estratificación casi horizontal). Contacto erosivo (G) con lasunidades de la zona de transición M-2 y M-3. Los conglomerados con estratificación cruzada de oleaje de M-2 corresponden a depósitos de la parte superior del shoreface. La Unidad M-3 con estratificación cruzada de gran escala (ver figura 9 A) es un depósito de playa reflexiva (sólo se ven los materiales gruesos del plunge step) que progradaba hacia el ENE. (B) Conglomerados bien redondeados finos y gruesos en el foreshore superior de M-3 (punto 8). (C) Conglomerados de relleno de canal (R) con base erosiva sobre lutitas (O) de la llanura de inundación. (D): Conglomerados de relleno de canal con estratificación cruzada en surco (facies Gt) y trama abierta y cerrada. Compárense las texturas con la fotografía B. C y D corresponden a la unidad T-3 en el punto 7.

(quartz and quartzite). Gravels did not significantly move to the shoreface because of the development of reflective beaches.

Marine and terrestrial units occur interbedded and detailed tracing of layers connecting the measured sections was needed to recognize them. Successive incision and deposition of units induce complex lateral relationships, as exposed around «El Cuartelillo» (localities 6 to 8, Fig. 10). Marine Units M-1 and M-2 are separated by terrestrial T-1, with M-3 capping the section. These units are partly eroded; the terrestrial unit T-2 fills a deep incision and is followed upwards by a coastal marine unit with foreshore facies exposed (M-4), a new terrestrial unit (T-3) and the uppermost preserved marine unit, M-5 (Fig. 10).

The convergence of facies, and the laterally-discontinuous nature of alluvial deposition makes it very difficult to trace the precise vertical upper limit of the transition-zone units, and to distinguish them from the younger alluvial-fan de-posits related to ephemeral rivers (*ramblas*). However, we suggest that the transition zone includes up to M-5; the terrestrial deposits of T-5 are a younger part of the alluvial units mapped in the area around Cuatro Calas (Figs. 1 and 2).

DISCUSSION

Wave-worked Gilbert-type delta model

According to the sedimentological data presented we can interprete a delta connected to a river plain with rapidly shifting channels. Rivers flowed mostly from the north, bringing coarse sediment to the shore and shallow sea (Fig. 12). The coarser grain sizes were captured by littoral drift and transported alongshore until they were accumulated into the gravelly reflective beaches of the wave-worked delta front, where the plunge-step deposits indicate very precisely the position of the water line as documented by Dabrio *et al.*, (1985) and Bardají *et al.* (1990). We propose that a delta platform extended seaward of the wave-worked delta front, as documented by the plane morphology of the upper part of the sigmoidal foreset beds and their vertical stacking (Fig. 4). The platform was mostly covered with sand and scattered pebbles which were transported to deeper waters during rough weather episodes (storm) and major floods (Fig. 12), and incorporated into the foreset beds. Direct transport of coarse fluvial sediments to the distal delta front and slope across the platform may take place during these high energy events. The sandy platform acted somewhat as a by-pass zone. The sigmoidal geometry of beds (Fig. 4) suggests that erosion during storms and major floods allowed sedimentation and vertical stacking of foreset beds. Benthic communities actively burrowed the bottom of the platform and obliterated the original physical sedimentary

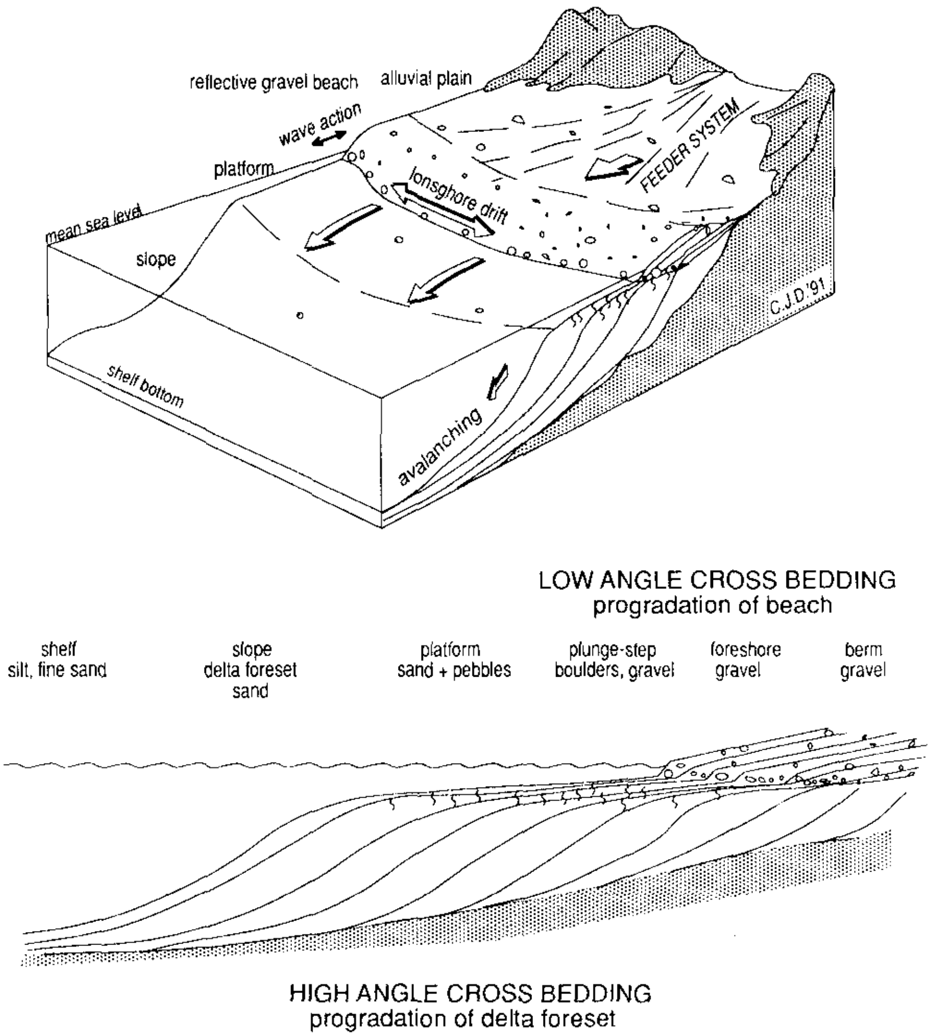

Fig 12.—Schematic conceptual model of wave-dominated Gilbert delta in Cuatro Calas bay (Aguilas Basin) and development of a two fold cross bedding during delta progradation.

Fig 12.—Modelo conceptual esquemático del delta de tipo Gilbert retrabajado por el oleaje en Cuatro Calas (cuenca de Aguilas) y desarrollo de dos sets de estratificación cruzada durante la progradación deltaica.

structures, as seen in the uppermost 1 to 3 metres of Unit 3 and 3-bis (Figs. 9 A and 11 A). A steep slope with dips ranging from 25° to 12° connected the delta platform with the shelf. Graded bedding and intense burrowing of delta-foreset (slope) beds indicate an episodic input of sediment: downslope avalanching was followed by long inactive periods.

The important wave reworking in the delta front (transition-zone Units M-1 to M-5) also indicates that the alluvial input was episodic. The coastal processes had time to sort out and distribute alongshore (mostly as littoral drift) the available sediments between successive river floods. In our experience, based upon direct observations of deltas along the mediterranean coast of southeastern Spain, the model is comparable to present-day deltas of ephemeral streams (*ramblas*) which feed coarse-grained beaches (Dabrio & Polo, 1981; Bardají *et al.*, 1990).

The absence of gravelly, mouth-bar deposits which are typical when the fluvial input is concentrated in point sources (Postma, 1990 a, b) strongly supports the idea that rivers delivered sediment to large segments of coast (line source).

Progradation of the delta generated a two-fold large-scale cross-stratification: a lower high-angle related to the advancing delta-foreset, and the upper one associated to progradation of beach units (Fig. 12).

As suggested by one of the referees, the foresets may correspond to large-scale trough cross bedding with giant sets separated by sharp erosional surfaces. In our opinion, the paleogeographic reconstructions of the basin margins that is closed at the back and of reduced size, the rather homogeneous direction of progradation, the similar lithologies in foreset and transition-zone units (particularly in Units 3, 3-bis and 4) and the difficulty of invoking a mechanism able to move the large-scale megaforms (megaripples) in such a restricted space suggest a bay-fill connected to fluvial systems that generated a delta geometry.

Delta classification

Deltas may be fed by single rivers which may develop a braided distributary plain or by alluvial-fan systems. The increased knowledge of delta processes and deposits and the growing interest in fan-delta systems have resulted in several important questions which must consider the precise meaning of the term fan delta or delta, and how to recognize them in the fossil record. Ethridge & Wescott (1984), Mc Pherson *et al.* (1987, 1988), Nemec & Steel (1988) and Nemec (1990) discussed various types of classifications and criteria of recognition.

Ethridge & Wescott (1984) distinguished three types of fan deltas: slope, shelf and Gilbert-type deltas. Massari & Colella (1988) further developed the models of fan deltas presenting a review of their distinguishing features. According to these authors, Gilbert-type deltas are associated to small and tectonically unstable basins, having irregular, indented shorelines, restricted gulfs and locally steep slopes. Input of coarse sediment was into protected embayments, marginal to a laterally-confined, low energy basins (Colella *et al.*, 1987) and steep nearshore slopes (controlled by active faults and folds).

This environment favours the deposition of large-scale foresets (Dune & Hempton, 1984). Differential tilting and subsidence of adjacent blocks may lead to an erratic pattern of sediment dispersal.

Postma (1990b) stressed the depositional architecture and facies of river and fan deltas instead of the alluvial feeder system and the actual modifying basinal processes for delta classification. The basis for a universal delta classification should consider: feeder system, depth ratio, river-mouth processes and diffusion processes due to waves, tides and gravity. In this way Postma (1990b, p. 17) described 12 major prototype deltas.

The Cuatro Calas Gilbert delta fits prototype 4 («classic Gilbert-type») which develops in shallow waters fed by steep-gradient (ca. 0.4°), often gravelly, alluvial systems comprising closely spaced, highly mobile (unstable) bedload channels. Sediment input to the delta front is essentially a line source, a multitude of distributary channels whose effluents merge to provide a more-or-less uniform supply of sediment along the delta front (Type B feeder systems). The palaeogeography at Cuatro Calas shows a location near mountain ranges. We did not recognize definite alluvial-fan facies in the topset (transition zone) deposits of Cuatro Calas, but only deposits of alluvial channels (some of them very prominent, locality 8-east, 6) and flood plain. However, the proximity to a tectonically-active basin margin and the abundance of younger alluvial-fan deposits recognized by mapping (Fig. 1) may point to a fan-delta setting.

Sequence stratigraphical framework and complex

Gilbert-type delta

The bay of Cuatro Calas was generated during late Pliocene times by a local downward bending of older Neogene materials which favoured a relative rise of sea level and invasion by the sea. The studied bay-fill deposits consist of units with large-scale foresets that filled most of the depression and were covered by younger sets of offlapping units (the transition-zone units) with an overall tabular geometry (Fig. 3). As a whole, they generated a Gilbert-type delta morphology that is actually a summatory of smaller-scale delta units deposited during successive highstands of sea level. At present we can observe only the highstand delta deposits, lowstand wedges laying under the present Mediterranean sea.

Evidence for sea-level changes comes from the erosional surfaces found in the foreset and the transition zone deposits. The largest surfaces involved major incisions excavated into previous foreset units during lowstand phases. The gentle changes of strike and dip of delta-foreset beds from Unit 1 to Unit 4 (N 90° E, N 100° E, N 130° E, N 90° E respectively, Fig. 2) reflect small lateral shifts of the active lobe in successive highstand deltas. These modifications may be related to synsedimentary uplift of the northern margin of the bay more or less coeval with the sea-level fluctuation. We ruled out a slump origin for these surfaces in the foreset, for as far as we could observe there was no evidences of slump processes or collapsed materials.

More data can be obtained about the depositional history from the study of the transition zone, because it records the offlap of marine and terrestrial units (Fig. 10). The offlapping pattern must imply repeated oscillations of relative sea level (Fig. 13). A common feature of these deposits is their scour-and-fill trend: they fill spaces eroded into previous coastal units and adapt to each other´s morphology using the compensation space available. The study of the vertical displacements of the plunge-step facies indicates that, apparently, there is almost no difference in absolute water-depth involved in these changes. We take this as evidence of the scarcity of vertical accommodation space left for deposition, because the top of the fan-delta prism and the sea level or the base level of rivers were too close to each other. This may also explain the erosion along the topmost part of the foreset sandstone units. These features are our main argument for eustatic instead of tectonic causes. In any case there was a tectonic trend to uplifting areas to the west and north of the bay during the late Neogene and Pleistocene, as documented in areas nearby (Bardají *et al.*, 1990).

There are examples in the geological literature of erosional surfaces in foreset deposits that have been interpreted as having either eustatic or tectonic origin. Massari & Parea (1990) observed erosional surfaces in the upper foreset and topset units and there interpretation was that they were caused by relative sea-level changes of eustatic origin. These authors could not recognize a strong tectonic control but, instead, concluded that there was a continued trend to uplifting of the area during the time of deposition. On the contrary, Colella (1988 a & b) and Gawthorpe & Colella (1990) interpreted the erosional surfaces in the foresets of Gilbert deltas as related to recurrent large-scale slip events of synsedimentary faults marking the back edge of the foreset unit. Such movements caused rejuvenation of the fault scarp, failure (slump) of the delta front, and stacking of several groups of foreset beds separated by slide surfaces. Such changes did not imply a major change in the direction of foreset progradation.

Sequence stratigraphy of the delta-foreset units is explained by fluctuations of sea level. Erosional incisions were excavated during lowstands. The lower coarse-grained sub-units overlying the erosional surfaces, with cross-bedding directed up the paleoslope (unit 1), those called backsets in the lower Units 2, 3 and 4 are the transgressive systems tracts followed by a condensation layer (the ferruginous gravels of Units 3 and 4) when transgression progressed. The foreset units *s. str.* are the highstand systems tracts of the successive units which downlap the transgressive systems tract. New falls of sea level produced erosional surfaces. In this way, the four recognized units are related to a pattern of sea level changes.

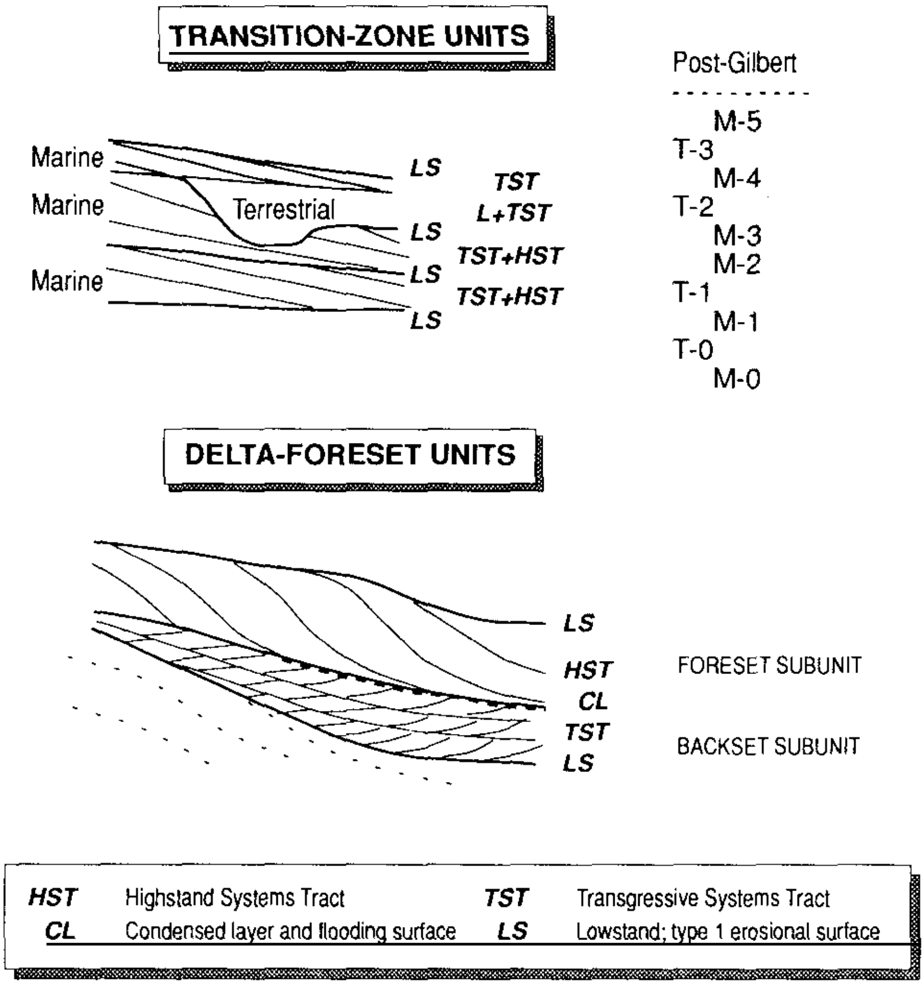

Fig 13.—Response of delta front and slope of a Gilbert-type delta to sea level changes and sequence stratigraphy of the bay-fill of Cuatro Calas.

Fig 13.—Respuesta del frente deltaico y el talud de un delta de tipo Gilbert a los cambios de nivel del mar y estratigrafía secuencial del relleno de bahía de Cuatro Calas.

At least five main depositional events are distinguished in the transition zone (Fig. 13). In general, highstand to early lowstand prograding beach units were partly eroded during a relative fall of sea level (lowstand), and lowstand-to-early-transgressive deposits covered the resulting valleys. Marine transgressive-to-highstand deposits covered the encased terrestrial deposits. Relative changes of sea level are necessary to explain the vertical stacking of units and the repeated incision without further evidence of neat increase of sea level. Alluvial deposits filled scoured topographies eroded in older coastal ridges well below the sea level that existed during the sedimentation of the ridges.

The marine unit M-5 represents the last transgression recorded in the area, most probably related to tectonic movements that uplifted the margin of the basin to horizons no longer under the reach of the sea. Younger terrestrial episodes (Figs. 1 and 2) integrate a post-Gilbert alluvial event.

Thus, the development of the complex Gilbert-type delta followed a repetitive pattern in response to relative changes of sea level (Fig. 14): progradation occurred in highstands and entrenchment and coastal wedge in lowstand and early transgression. A highstand Gilbert-type delta (Stage 1) prograded when the sea level rose above the delta prism. Falls of sea level induced erosion of part of the delta prism (Stage 2), both by wave action and by entrenchment of fluvial channels. The cannibalized detritus and the fluvial input were carried down to the shelf and accumulated into lowstand (? deltas) wedges. Later rises of sea level allowed progradation of the partly-destroyed highstand delta (Stage 3). Progradation of delta lobes may have occurred in a direction similar or oblique to that of the former highstand delta, probably due to the need to adapt to the previously eroded, irregular relief and progradation within fan-dissecting valleys (Muto & Okada, 1991). Beaches in the delta front prograded seaward with variable angles because of changes in the shore orientations induced by littoral drift and local constraints. Consequently they may diverge somewhat from the average delta-lobe progradation.

The various parts of the delta reacted differently to these sea-level changes and generated variable facies associations.

Progradation of complex delta prisms does not imply a continuous stillstand as previously assumed for simple Gilbert-type deltas (Ethridge & Wescott, 1984, Postma y Roep, 1985). Progradation may occur over a very short time interval, possibly during a period of slow sea-level changes or during a long-time interval during sea-level stand-still. Most probably sea-level changes contributed to the destruction of the convex-upward upper part of the sigmoidal foresets of some units (2, 3-bis, 4), the development of erosional surfaces separating foreset and transition-zone deposits.

Sea-level curves for late Pliocene and Pleistocene are characterized by successive low-frequency cycles of rise and fall; four of these cycles happened in late Pliocene with sequence-boundary ages: 3.8, 3.0, 2.4 and 1.6 million years and another in early Pleistocene with upper boundary age: 0.8 million years (Haq *et al.*, 1988). This rapid evolution may account for subaerial exposure and drowning of large parts of the basin margin, but they are not fast enough to justify the stacking of units and the repeated scour-and-fill pattern observed in Cuatro Calas. Therefo-re our observations connect these small-scale changes to the high-frequency fluctuations of sea level already documented in SE Spain during the Late Pliocene and Quaternary (Bardají *et al.*, 1990) superimposed on longer-lasting tectonic uplift.

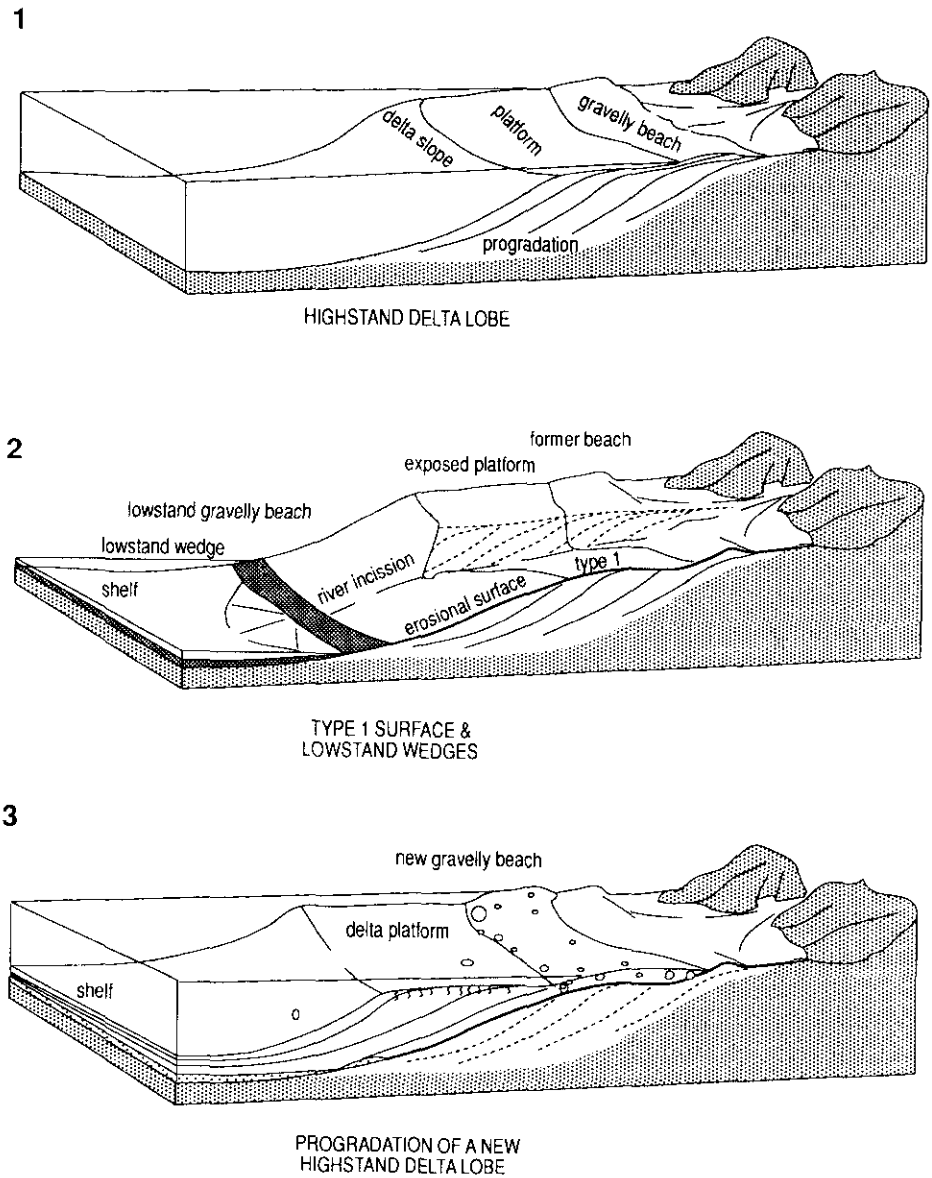

Fig 14.—Repetitive pattern of relative sea-level fluctuations and development of complex compound Gilbert-type deltas in Cuatro Calas.

Fig 14.—Esquema repetitivo de fluctuaciones del nivel relativo del mar y desarrollo de un delta complejo de tipo Gilbert en Cuatro Calas.

CONCLUSIONS

The bay of Cuatro Calas was generated during late Pliocene times by a local downward bending of older Neogene materials which favoured a relative rise of sea level and invasion by the sea. The studied bay-fill deposits consist of units with large-scale foresets that filled most of the depression topped by younger sets of offlapping transition-zone units with an overall tabular shape. As a whole, they generated a Gilbert-type delta morphology that is a summatory of smaller-scale delta units deposited during successive highstands of sea level. We can observe only the highstand delta deposits. Lowstand wedges lay under the Present Mediterranean sea.

According to the sedimentological data presented, before we propose a delta connected to a river plain with rapidly shifting channels. Rivers flowing mostly from the north delivered sediment to large segments of coast (line source). The coarser grain sizes were captured in the gravelly reflective beaches of the wave-worked delta front. A delta platform, covered with burrowed sand and scattered clasts extended seaward of the wave-worked delta front. A steep slope with dips ranging from 25° to 12° connected the delta platform with the shelf. Graded bedding and intense burrowing of delta-foreset (slope) beds indicate an episodic input of sediment: downslope avalanching was followed by long inactive periods. Wave reworking of the delta front also indicates episodic alluvial input. The Cuatro Calas Gilbert delta fits Postma´s (1990b) prototype 4 («classic Gilbert-type»). It is comparable to present-day deltas of ephemeral streams feeding gravelly beaches in SE Spain.

Progradation of the delta generated a two-fold large-scale cross-stratification: a lower high-angle related to the advancing delta-foreset and the upper one associated to progradation of beach units.

Evidence of sea-level changes comes from the erosional surfaces found in the foreset and the transition zone deposits. Sequence stratigraphy of the foreset units is explained by fluctuations of sea level. Erosional incisions were excavated during lowstands. The lower coarse-grained sub-units overlying the erosional surfaces, with cross-bedding directed up the paleoslope (Unit 1) and backsets in Units 2, 3 and 4, which are transgressive systems tracts followed by a condensation layer (the ferruginous gravels of Units 3 and 4) when transgression progressed. The foreset units *s. str.* are highstand systems tracts downlapping the transgressive systems tract. At least five main depositional events are distinguished in the transition zone. Highstand to early lowstand prograding beach units were partly eroded during a relative fall of sea level (lowstand) and lowstand to early transgressive deposits filled the resulting valleys. Marine transgressive-to-highstand deposits covered the encased terrestrial deposits. The marine unit M-5 represents the last transgression recorded in the area. Most probably delta sedimentation come to an end because of tectonic uplift of the basin margin. Younger terrestrial episodes integrate a post-Gilbert alluvial event.

Thus, the development of the complex Gilbert-type delta followed a repetitive pattern in response to fluctuations of sea level: progradation of highstand Gilbert-type delta (Stage 1) was followed by entrenchment and coastal wedge in lowstand and early transgression (Stage 2). The various parts of the delta reacted differently to these sea-level changes and generated variable facies associations.

Progradation of complex delta prisms does not imply a continuous stillstand as previously assumed for simple Gilbert-type deltas.

The rapid evolution of the bay-fill can be related to high-frequency fluctuations of sea level already documented in SE Spain during Late Pliocene and Quaternary, superimposed on longer-lasting tectonic uplift.

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REFERENCES

BARDAJI, T.; DABRIO, C. J.; GOY, J. L.; SOMOZA, L., & ZAZO, C. (1990). Pleistocene fan deltas in southeastern Iberian Peninsula: sedimentary controls and sea-level changes. *Spec. Publs. int. Ass. Sediment.* **10**: 129-151.

BOURGEOISS, J., & LEITHOLD, E. L. (1984). Wave-worked conglomerates-Depositional processes and criteria for recognition. *Can. Soc. Petr. Geologists, Memoir,* **10**: 217-235.

BRYANT, E., (1983). Sediment characteristics of some Nova Scotian beaches. *Maritime Sediments and Atlantic Geology.* **19**: 127-142.

COLELLA, A. (1988 a). Gilbert-Type fan deltas in the Crati Basin (Pliocene-Holocene, Southern Italy). *Excursion Guidebook, Int. Workshop on Fan deltas, Calabria.* 19-81.

COLELLA, A. (1988 b). Pliocene-Holocene fan deltas and braid deltas in the Crati Basin, southern Italy: a consequence of varying tectonic conditions. In: W. Nemec y R. J. Steel (eds.) *Fan Deltas: Sedimentology and Tectonic Settings.* Blackie and Son Ltd, Glasgow. 50-74.

COLELLA, A.; DE BOER, P. L., & NIO, S. D. (1987). Sedimentology of a marine intramontane Pleistocene Gilbert-type fan-delta complex in the Crati Basin, Calabria, Southern Italy. *Sedimentology.* **34**: 721-736.

COPPIER, G.; GRIVEAUD, P.; LAROUZIERE, F. D.; MONTENAT, C., & OTT D'ESTEVOU, P. (1989). Example of Neogene tectonic indentation in the Eastern Betic Cordilleras: the Arc of Aguilas (Southeastern Spain). *Geodinamica Acta,* **3**: 37-51.

DABRIO, C. J. (1990). Fan-delta facies associations in Late Neogene and Quaternary basins of southeastern Spain. *Spec. Publs. int. Ass. Sediment.* **10**: 91-111.

DABRIO, C. J.; GOY, J. L., & ZAZO, C. (1984). Dinámica litoral y evolución costera en el Golfo de Almería desde el «Tirreniense» a la actualidad. *I Cong. Español de Geología, Segovia*, I: 507-522.

DABRIO, C. J.; GOY, J. L., & ZAZO, C. (1985). A model of conglomeratic beaches in tectonically-active areas (Late Pleistocene-actual, Almería, Spain). *Abstr. Int. Ass. Sediment. 6th. Europ. Reg. Mtg., Lleida.* Univ. de Barcelona, 104-105.

DABRIO, C. J., & POLO, M. D. (1981). Dinámica litoral y evolución costera de El Puerto de Mazarrón (Murcia). *Bull. R. Soc. Hist. Nat. (Geol.)*, **79**: 225-234.

DUNNE, L. A., & HEMPTON, M. R. (1984). Deltaic sedimentation in the Lake Hazar pull-apart basin, southeastern Turkey. *Sedimentology*, **31**:401-412.

ETHRIDGE, F. G., & WESCOTT, W. A. (1984) Tectonic setting: recognition and hydrocarbon reservoir potential of fan-delta deposits. *Can. Soc. Petr. Geologists, Memoir*, **10**: 217-235.

GAWTHORPE, R. L., & COLELLA, A. (1990). Tectonic controls on coarse-grained delta depositional systems in rift basins. *Spec. Publs. int. Ass. Sediment.* **10**: 113-127.

GILBERT, G.K. (1885). The topographic features of lake shores. *Ann. Rep. U. S. geol. Surv.* **5**: 69-123.

GUZA, R. T., & INMAN, D. L. (1975). Edge waves and beach cusps. *J. Geophys. Res.* **80**: 2997-3012.

HAQ, B. V.; HARDENBOL, J., & VAIL, P. R. (1988). Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. *S.E.P.M. Spec. Publ.* **42**: 72-108.

MASSARI, F, y PAREA, G. C. (1990). Wave-dominated Gilbert-type gravel deltas in the hinterland of the Gulf of Taranto (Pleistocene, southern Italy). *Spec. Publs. int. Ass. Sediment.* **10**: 311-311.

MASSARI, F., & COLELLA, A. (1988). Evolution and types of fan-delta systems in some major tectonic settings. *Can. Soc. Petr. Geologists, Memoir*, **10**: 103-122.

MCPHERSON, J. G.; SHANMUGAM, G., & MOIOLA, R. (1987). Fan deltas and braid deltas: varieties of coarse-grained deltas. *Bull A.A.P.G.* **99**: 331-340.

MCPHERSON, J. G.; SHANMUGAM, G., & MOIOLA, R. (1988). Fan deltas and braid deltas: conceptual problems. *In*: W. NEMEC & R. J. STEEL (eds.) *Fan Deltas: Sedimentology and Tectonic Settings.* Blackie and Son Ltd, Glasgow. 15-22.

MONTENAT, C.; OTT D'ESTEVOU, P., & MASSE, P. (1987). Tectonic-sedimentary characters of the Betic Neogene Basins evolving in a crustal transcurrent shear zone (SE Spain). *Bull. Centre Rech. Explor. Prod. Elf Aquitaine*, **11**: 1-22.

MONTENAT, C.; RENEVILLE, P. DE, & BIZON, G. (1978). Le Néogène des environs d'Aguilas (provinces de Murcia et d'Almería) Cordillères Bétiques, Espagne. *Bull. Mus. natn. Hist. nat., Paris, Sciences de la Terre*, **68**: 37-54.

MUTO, T., & OKADA, H. (1991). A comment on modelling the paleogeography of confined and unconfined marine Gilbert-type deltas. *Cuad. Geol. Iberica*, 15 (this volume)

NEMEC, W, & STEEL, R. J. (1988). What is a fan delta and how do we recognize it? *In*: W. NEMEC & R. J. STEEL (eds.) *Fan Deltas: Sedimentology and Tectonic Settings.* Blackie and Son Ltd, Glasgow. 3-13.

NEMEC, W. (1990). Deltas-remarks on terminology and classification. *Spec. Publs. int. Ass. Sediment.* **10**: 3-12.

POSTMA, G., & ROEP, TH. B. (1985). Resedimented conglomerates in the bottomsets of Gilbert-type gravel deltas. *J. sediment. Petrol.* **55**: 874-885.

POSTMA, G. (1984). Slumps and their deposits in fan delta front and slope. *Geology.* **12**: 27-30.

POSTMA, G. (1990 a). An analysis of the variation in delta architecture. *Terra Nova*, **2**: 124-130.

POSTMA, G. (1990 b). Depositional architecture and facies of rivers and fan deltas: a synthesis. *Spec. Publs. int. Ass. Sediment.* **10**: 13-27.

POSTMA, G., & CRUICKSHANK, C. (1988). Sedimentololgy of a late Weichselian to Holocene terraced fan delta, Varangerfjord, northern Norway. *In*: W. NEMEC & R. J. STEEL (eds.) *Fan Deltas: Sedimentology and Tectonic Settings*. Blackie and Son Ltd, Glasgow. 144-157.

PRIOR, D. B., & BORNHOLD, B. D. (1988). Submarine morphology and processes of fjord fan deltas and related high-gradient systems: modern examples from British Columbia. *In*: W. NEMEC & R. J. STEEL (eds.) *Fan Deltas: Sedimentology and Tectonic Settings*. Blackie and Son Ltd, Glasgow. 125-143.

SANZ DE GALDEANO, C. M. (1990). Geologic evolution of the Betic Cordilleras in the Western Mediterranean, Miocene to the present. *Tectonophysics*, **172**: 107-119.

SHORT, A. D., & WRIGHT, L. D. (1983). Physical variability of sandy beaches. *In*: *Sandy beaches as ecosystems*. Dr W. Junk Publishers, The Hague. 133-144.

SHORT, A. D. (1979). Wave power and beach-stages: a global model. *Proc. 16th Int. Conf. Coastal Eng. Hambourg*, 1145-1162

SHORT, A. D. (1984). Temporal change in beach type resulting from a change in grain size. *Search*, **15**: 228-230

SONU, C. J. (1973). Three dimensional beach changes. *Jour. Geol.* **81**: 42-64.

WESCOTT, W. A., & ETHRIDGE, F. G. (1980). Fan-delta sedimentology and tectonic setting-Yallahs fan delta, southeast Jamaica. *Am. Ass. Petrol. Geol. Bull.* **64**: 374-399.

WRIGHT, L. D.; CHAPPELL, J.; THOM, B. C.; BRADSHAW, M. P., & COWELL, P. (1979). Morphodynamics of reflective and dissipative beach and inshore systems: Southeastern Australia. *Mar. Geol.* **32**: 105-140.

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