Fan-delta slope deposits and sequences in the Murcia-Carrascoy Basin (Late Neogene, S.E. Spain)

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ABSTRACT

Tortonian sedimentation in the Betics records a major tectonic event, the largest orogenic deformation of the cordillera, superimposed on the larger-scale, third-order TB 3.2 cycle of eustatic sea-level change. A first interpretation of the Sequence Stratigraphy of the Murcia-Carrascoy basin is presented. Uplift of positive reliefs around the basin favoured the deposition of thick successions of conglomerates evidencing cannibalism. Facies associations witness deposition on the steep slope of a basin, fed by mountain rivers that supplied coarse sediments to the basin. The resulting fan delta is comparable in many respects to those described in fjords, and a depositional model is presented.

Key words: fan delta, slope, Sequence Stratigraphy, Late Neogene, Murcia, S. E. Spain

RESUMEN

La sedimentación tortoniense en las Béticas registra la superposición de un gran evento tectónico, correspondiente a la deformación más importante de la cordillera, y del ciclo global TB 3.2 de cambios del nivel de mar. Se

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ofrece la primera propuesta de interpretación de la cuenca de Murcia-Carrascoy en términos de Estratigrafía Secuencial. La surrección de relieves positivos alrededor de la cuenca favoreció el depósito de potentes acumulaciones de conglomerados que manifiestan la autofagia de la cuenca. Las asociaciones de facies indican que el depósito se produjo en un talud de cuenca abrupto alimentado por ríos de montaña que aportaba materiales de grano grueso. El fan delta resultante es comparable en muchos aspectos a los descritos en fiordos y se presenta un modelo sedimentario.

Palabras clave: fan delta, talud, Estratigrafía Secuencial, Neógeno Superior, Murcia, Sureste de España.

INTRODUCTION

Late Neogene sedimentation in the Eastern Betic Cordillera (southeastern Spain) occurred in a complex tectonic and paleogeographic framework of large islands, surrounded by partly-interconnected basins.

The Murcia-Carrascoy basin (Fig. 1) is a part of the larger Mar Menor basin which received large volumes of sediments. The area lays in the left-lateral shear zone of the eastern Betics. The basin is situated upon two fault systems (N40°-50° E and N80° E) which, at least during a part of their history, acted with sinistral strike-slip movement. Several unconformities interrupt the sedimentary infilling of the basin owing to active synsedimentary tectonics, the sediments displaying prominent wedging out (Montenat, 1973). Transverse faults (N130° E) cross the former systems. Active neotectonic and high seismicity are common in the area nowadays.

The basement of the basin and the adjacent mountain ranges that acted as source rocks for sediments, are made up of metasedimentary and metamorphic rocks belonging to the Internal Zones of the Betics.

The aim of this paper is to propose a sequence stratigraphy model for the basin, and to interpret the coarse-grained sediments that were deposited during a transgressive event, giving a sedimentary model able to explain the associations of facies. This paper adds information and fresh interpretations to the Field-trip Guidebook used during the Workshop (Dabrio *et al.*, 1990).

LATE NEOGENE HISTORY OF THE BETICS

During the Late Neogene major orogenic deformation of the Betics occurred. So, deposition was conditioned by tectonic activity although there is record of eustatic sea-level changes as well. A better understanding of the Late Neogene history of the basins may help to explain the conspicuous occurrence of fan-delta facies in many places in the cordillera.

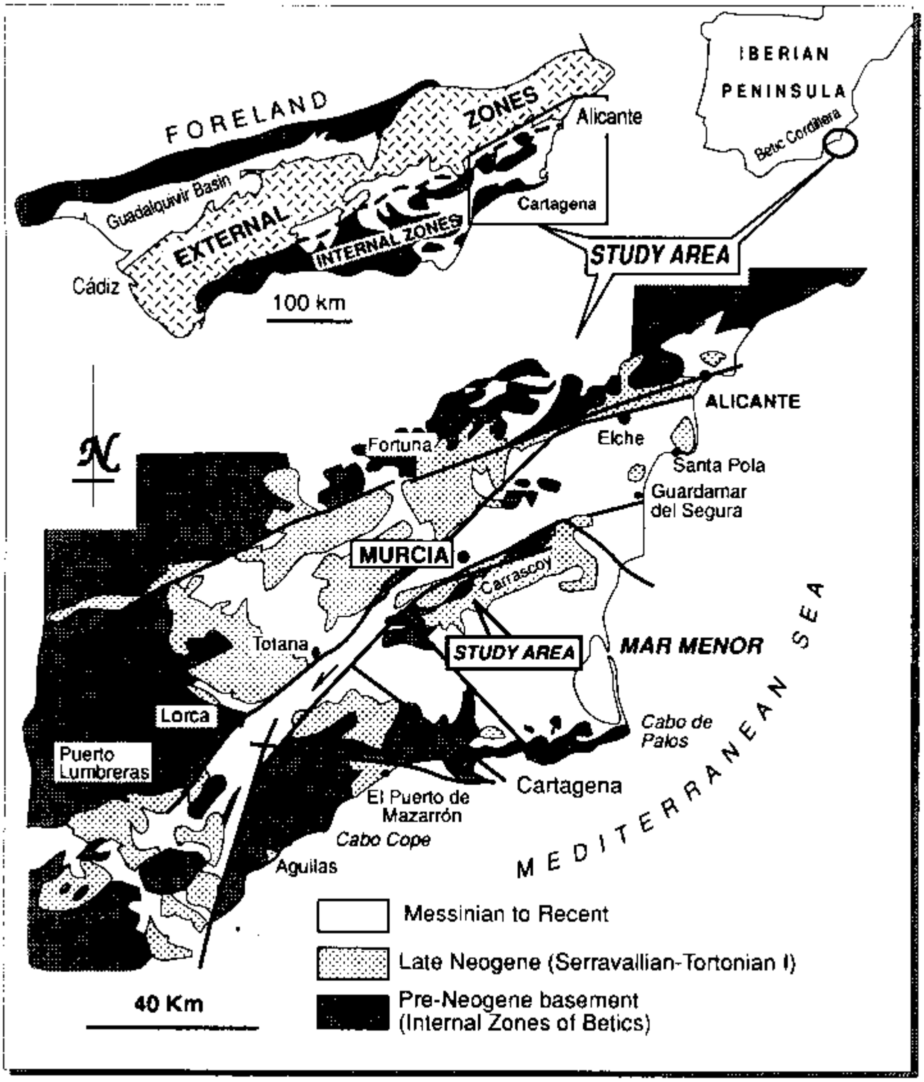


Fig 1.—Geological sketch of the SE Spain and location map of the study area (simplified from Olaverry & Rey, 1980). In the map of the Betic Cordillera, white areas indicate Neogene basins.

Fig 1.—Mapa geológico esquemático del sureste de España y situación del área estudiada (simplificado de Olaverry y Rey, 1980). Las zonas en blanco del mapa de las Cordilleras Béticas indican las cuencas neógenas.

During the Langhian and Serravallian, most basins developed along two large fault zones directed ENE-WSW all along the Betics. NW-SE to WNW-ESE compression induced dextral strike-slip displacements along these faults (Sanz de Galdeano, 1990).

A dramatic change of dynamics and paleogeography happened during the Tortonian, when the direction of compression began to rotate to the NNW-SSE (Montenat *et al.*, 1987, Larouzière *et al.*, 1987) inducing large displacements of the NE-SW sinistral faults of the Betics and Rift (Larouzière *et al.*, 1988). Strong control by faults directed NW-SE and NE-SW conditioned the generation of new polygonal-shaped basins. Most of the basins are intramontane, dominated by vertical movements, but lateral (strike-slip) displacements strongly affected deposition in some basins. Left-lateral movements took place in Carrascoy as well (Dabrio, 1990; Sanz de Galdeano, 1990).

A well documented unconformity is usually recorded at the base of the Late Tortonian successions. Generalized uplift of the areas around the basins resulted in the deposition of thick successions of conglomerates (in fan delta settings) and deposition of breccias filling submarine troughs. By the end of the Tortonian large positive relief existed.

New changes in the direction of compression occurred during the Messinian, Pliocene and Quaternary times, producing renewed movements along faults (Montenat *et al.*, 1987, Goy *et al.*, 1990).

The evidence above shows that Tortonian sedimentation in the Betics records mostly a major tectonic event superimposed on a larger-scale cycle of eustatic sea-level change.

Dabrio (1990) proposed a basin margin model with a narrow sloping shelf that was connected distally to an abrupt slope. Tectonically-induced subsidence favoured the accumulation of thick prisms of sediment which prograded to the basin (i. e. to the southeast). Martínez del Olmo & Jurado (1991) reached a similar conclusion and pointed out that the scarcity of turbidite deposits, the high argillaceous content and the sharp facies changes from the basin margin to the basin interior observed near Carrascoy confirms that there existed only a narrow siliciclastic shelf, in contrast to the wide Late Neogene shelf found in the Valencia margin.

Well-rounded clasts in conglomerates eroded, from both extra-basinal and older Neogene deposits indicate the cannibalistic nature of the basin, doubtless related to syntectonic movements. Coarse grain-sizes and reworked shallow-marine fossils indicate deposition near the basin margin, but not necessarily in shallow waters.

LATE-NEOGENE SEQUENCE STRATIGRAPHY

The Late Tortonian and Early Messinian deposits (also called Tortonian II-Messinian I, Dabrio, 1990) studied reflect the TB 3.2 third-order cycle of the global relative sea-level changes (Haq *et al.*, 1988) which is also registered in many other basins of the Betics (Sierro *et al.*, 1990; Pomar, 1991; Esteban, *in prep*).

Montenat (1973) described microfossils found in these rocks that can be used to date the depositional sequences. Samples collected near the base of the La Atalaya Marlstones indicate ages close to the limit Serravallian-Tortonian and Lower Tortonian with *G. menardii* (Zone N-15), but more upwards *G. acostaensis* indicates a Tortonian age (Zone N-16)

Below, we propose a first interpretation of the Sequence Stratigraphy (Fig. 2).

We think that the marlstones with turbidites and megabreccia layers called the La Naveta marlstones (Dabrio, 1990), the Guardia Civil marlstones (Núñez *et al*., 1974), and the coarse-grained sediments of the Puerto de la Cadena conglomerates (approximately equivalent to the Columbares sandstones and conglomerates, Núñez *et al*., 1974) correspond to the lowstand systems tract (LSST) which we infer were largely magnified by tectonic events. Coarsening-up megasequences, tens of metres thick, recognized in the Puerto de la Cadena Conglomerates (Dabrio 1990) record progradation of fan delta lobes. The initial transgressive (marls) and regressive (conglomerates) cycles correspond to a whole local, third or fourth order, tectonic cycle. This tectonic cycle is included in an eustatic cycle or depositional sequence. Planktonic foraminifers found in the La Naveta marlstones are the same as in the underlying units (*G. acostaensis*) with the addition of *G. pseudomiocenica*, *G. scitula ventriosa*, etc. They indicate a Late Tortonian age (Montenat, 1973).

Rapid transgression and subsidence of the fan-delta clastic wedges created steep slopes in the final stages of development and deposition of the transgressive systems tract (TRST), studied in this paper. These materials lay unconformably upon the Puerto de la Cadena conglomerates (Fig. 3); less than 1 km to the WSW, the erosion has almost completely eliminated the upper sequence of the underlying conglomerates.

The 1000 m-thick Torremendo marlstones record progradation of basin and slope deposits with local shallow turbidite channels during the highstand (HSST). Planktonic foraminifers include *G. dutertrei*, *G. humerosa*, *G.* aff *plesiotumida*, and *T. multiloba*, soon joined upwards by *G. mediterranea*, *G. conomiozea*, and *G. scitula ventriosa*, indicative of Late Tortonian and Messinian ages (Zone N-17) (Montenat, 1973).

During the late highstand and the early stages of sea-level fall, progradation of carbonate shelf and deposition of shallow-marine calcarenites occurred (La Virgen calcarenites, Montenat, 1973 also called El Rebate sandstones, Núñez *et al*., 1974).

Martínez del Olmo & Jurado (1991) consider a single Serravallian-Tortonian episode, which they call an *eustatic sedimentary cycle*, comparable to those distinguished in the Neogene of the Valencia continental margin. The cycle includes a transgressive sequence with one to three fining and thinning up sequences. The top of the transgressive deposits coincides with maximum clay content. These deposits correspond in part to La Naveta (= Guardia Civil) marlstones. The regressive part of the eustatic sedimentary cycle has

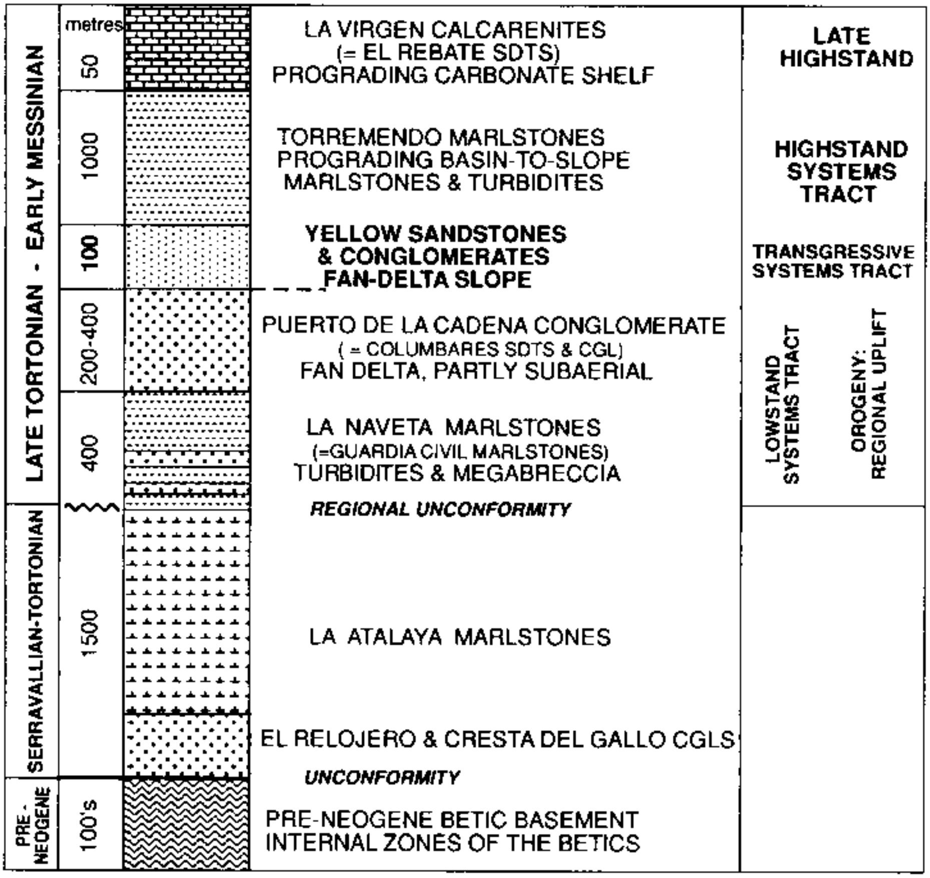


Fig 2.—Stratigraphic framework of Serravallian-Tortonian deposits in Murcia-Carrascoy basin. CGL: conglomerates; SDTS: sandstones.

Fig 2.—Encuadre estratigráfico de los materiales del Serravalliense-Tortoniense en la cuenca de Murcia-Carrascoy. CGL: conglomerados; SDTS: areniscas.

conglomerates with coarsening-up megasequences interpreted as high-energy deltaic (fan delta) deposits (Puerto de la Cadena conglomerates = Columbares sandstones and conglomerates) and a thick succession of basin, slope and shelf deposits (Torremendo marlstones and La Virgen calcarenites).

Deposition of fan-delta conglomerates indicates the intramontane location of the Murcia-Carrascoy basin with active synorogenic margins. However, the basin was marginal to the continental margin of Valencia. The regressive episode generated in a basin with steep margins related to synsedimentary tectonic subsidence had a rate that clearly surpassed the input of sediment (Martínez del Olmo & Jurado, 1991).

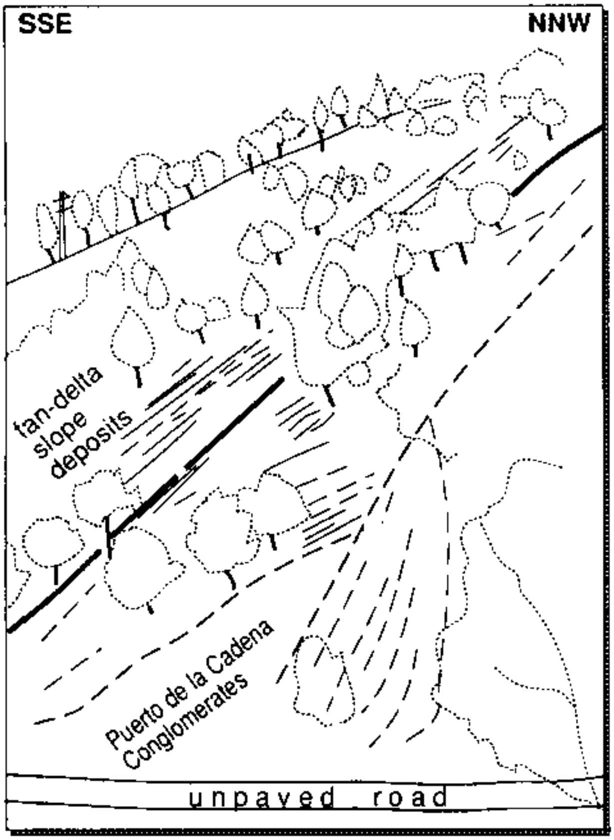


Fig 3.—Sketch drawn from a photograph of the unconformable limit (thick line) between the studied deposits and the Puerto de la Cadena conglomerates near the Casa Motor and La Naveta farm, ca. 250 m WSW from km 403.3 (national road 301). Modified and re-interpreted from Dabrio *et al.*'s (1991) figure 20.

Fig 3.—Esquema del límite discordante (línea gruesa) entre los materiales estudiados y los conglomerados del Puerto de la Cadena, cerca de la Casa Motor y la finca La Naveta, unos 250 m al WSW del km 403,3 de la carretera nacional 30. Dibujado a partir de una fotografía. Modificación y reinterpretación de la Fig. 20 de Dabrio *et al.* (1991).

DESCRIPTION AND INTERPRETATION OF DEPOSITS

The sediments studied have several lithologic types ranging from conglomerates to yellow sandstones and siltstones with calcarenite layers which are several centimetres to tens of centimetres thick (Fig. 4). Clast composition shows their provenance from metamorphic and metasedimentary rocks of the Internal Zones of the Betics: phyllades, quartzites, dolostones and volcanic rocks are most abundant.

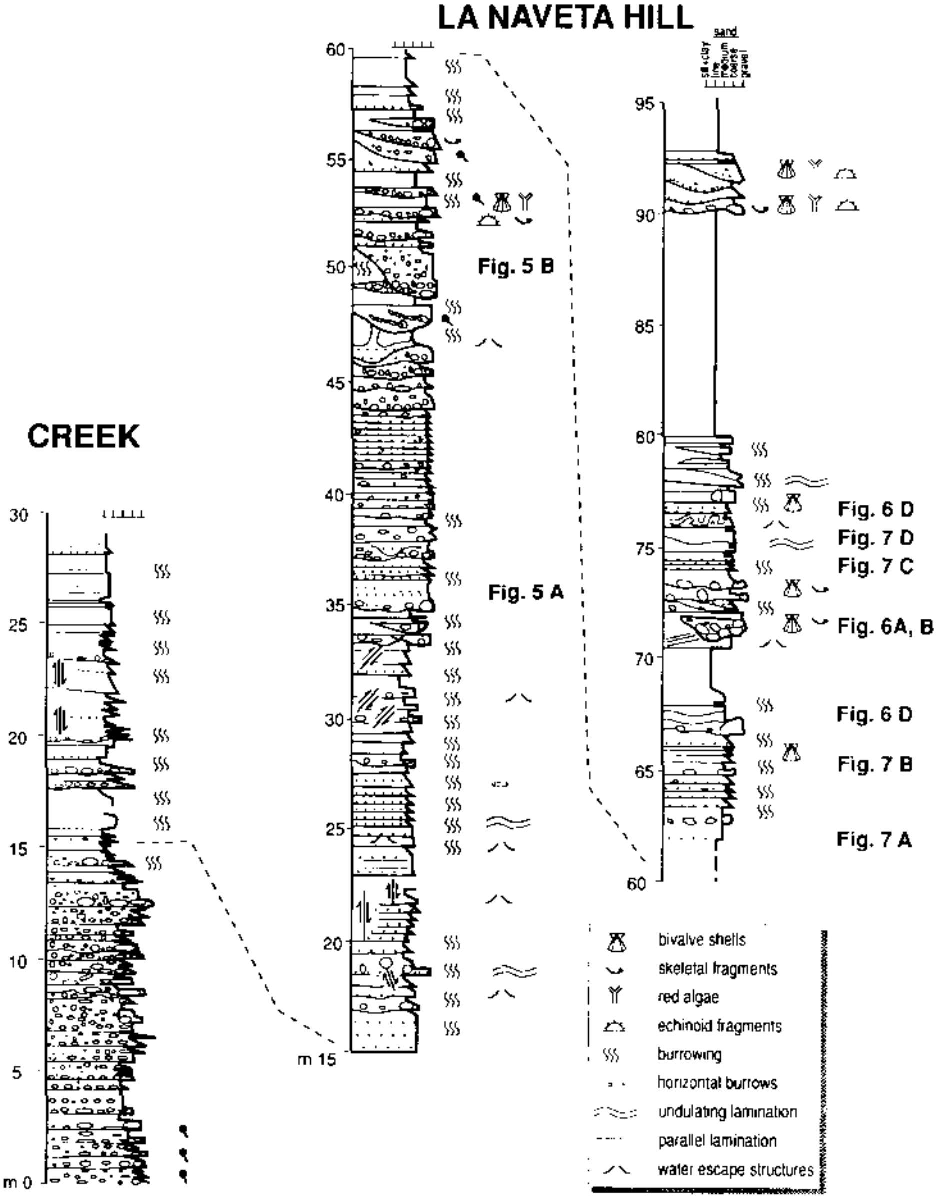


Fig 4.—Stratigraphic section with indication of photographs in figures 5, 6 and 7. The basal part of the section (left) was measured along the creek visible in Fig. 3 (to the reader's left); the rest (centre and right) in the hill of La Naveta farm.

Fig 4.—Sucesión estratigráfica con indicación de las figuras. La parte basal de la sección (columna de la izquierda) se levantó en el arroyo visible en la Fig. 3 (a la izquierda del lector) y el resto (columnas del centro y de la derecha) en la colina de la finca La Naveta.

Conglomerates

The conglomerate facies is best-represented in the basal and middle parts of the succession with several types recognized.

Conglomeratic layers

The conglomerate layers are 10 to 20 cm thick with plane or gently scoured bases with clasts that are rounded pebbles and cobbles that pass upward into coarse to medium sandstone (Fig. 5 A); this change is sharp. Other sequences comprise only fine gravel to medium-fine sandstone which can be burrowed (Fig. 5 A, lower sequence).

Sometimes these sediments can be interpreted as suspension, with limited traction (Fig. 5 A), deposits (Postma, Nemec & Kleinspehn, 1988) or normally graded (?) gravel layers (Lowe, 1982). Other beds (metre 40 of the section in Fig. 4) are very coarse sand to fine gravel with outsized, imbricated pebbles floating in the middle-upper part of the bed. These probably represent deposition in the interface separating a lower zone of laminar inertia flow and an upper zone of high-density turbulent suspension (Postma *et al.*, 1988).

Conglomeratic channel fills

Lenticular shaped masses of conglomerate are interpreted as filling channels (Fig. 5 B). These deposits contain some clasts which are imbricated have grain size distribution with (coarse-tail) inverse and normal graded bedding. Mean grain size is pebble to cobble with some small boulders. Channels are tens of metres wide and up to 3 m deep. Clast imbrication indicates sediment transport to the southeast.

The proposed method of transportation was by cohesionless, high-concentration flows resulting in debris flows (see discussion about these processes in Lowe, 1982, Nemec, 1990 and Postma *et al.*, 1988). Large, imbricated boulders with a(p) a(i) fabric placed some distance above the lower limit (bottom of the channel) may represent processes similar to those cited in the previous case.

Gully fills

Disorganized, heterometric masses of sediment containing large cobbles and boulders are found filling channels (gullies) less than 20 m wide and 1 to

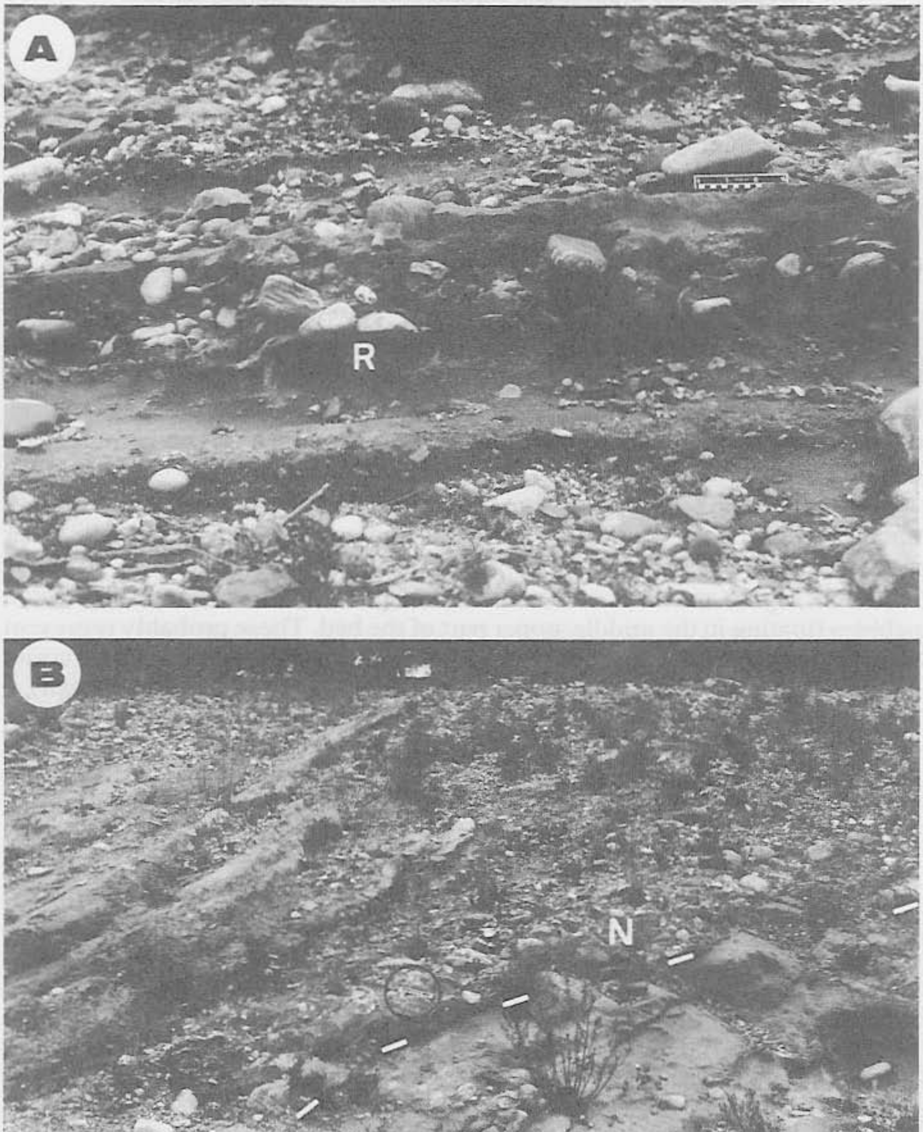


Fig 5.—(A) Clast supported conglomerate with fine-gravel matrix, rounded pebbles overlaid by burrowed (R) sandstones; sharp separation between these two lithologies. (B) Conglomerate channel fill. Note imbrication (N) and coarser grain near the channel-bottom (white lines). Bedding dips to the left (SE). Scale is 15 cm long.

Fig 5.—(A) Conglomerado clasto-soportado de cantos redondeados y matriz de grava fina, seguidos de areniscas bioturbadas (R); ambas litologías están separadas por una superficie neta. (B) Relleno de canal de conglomerados. Obsérvese la imbricación (N) y el tamaño de grano más grueso cerca del fondo del canal (líneas blancas). La estratificación se inclina hacia la izquierda (sureste). La escala en ambas fotografías mide 15 cm.

1.5 m deep (Fig. 6 A and B). There are both angular and rounded clasts. A crude normal graded bedding is observed. Gullies have steeply-incised sidewalls cutting through older, almost horizontal deposits; sometimes incision cut down into previous sandy channel-fill deposits (Fig. 6 B).

These are interpreted as gullies eroded by turbidity currents, later filled by sediment-gravity flows moved by basal inertia flows and high-density turbidity currents (Prior & Bornhold, 1989).

Sandstones

Sandstone beds (Fig. 6 C and 7) consists of coarse to fine sand a few to tens of centimetres thick. Normal grading is common. There are several types.

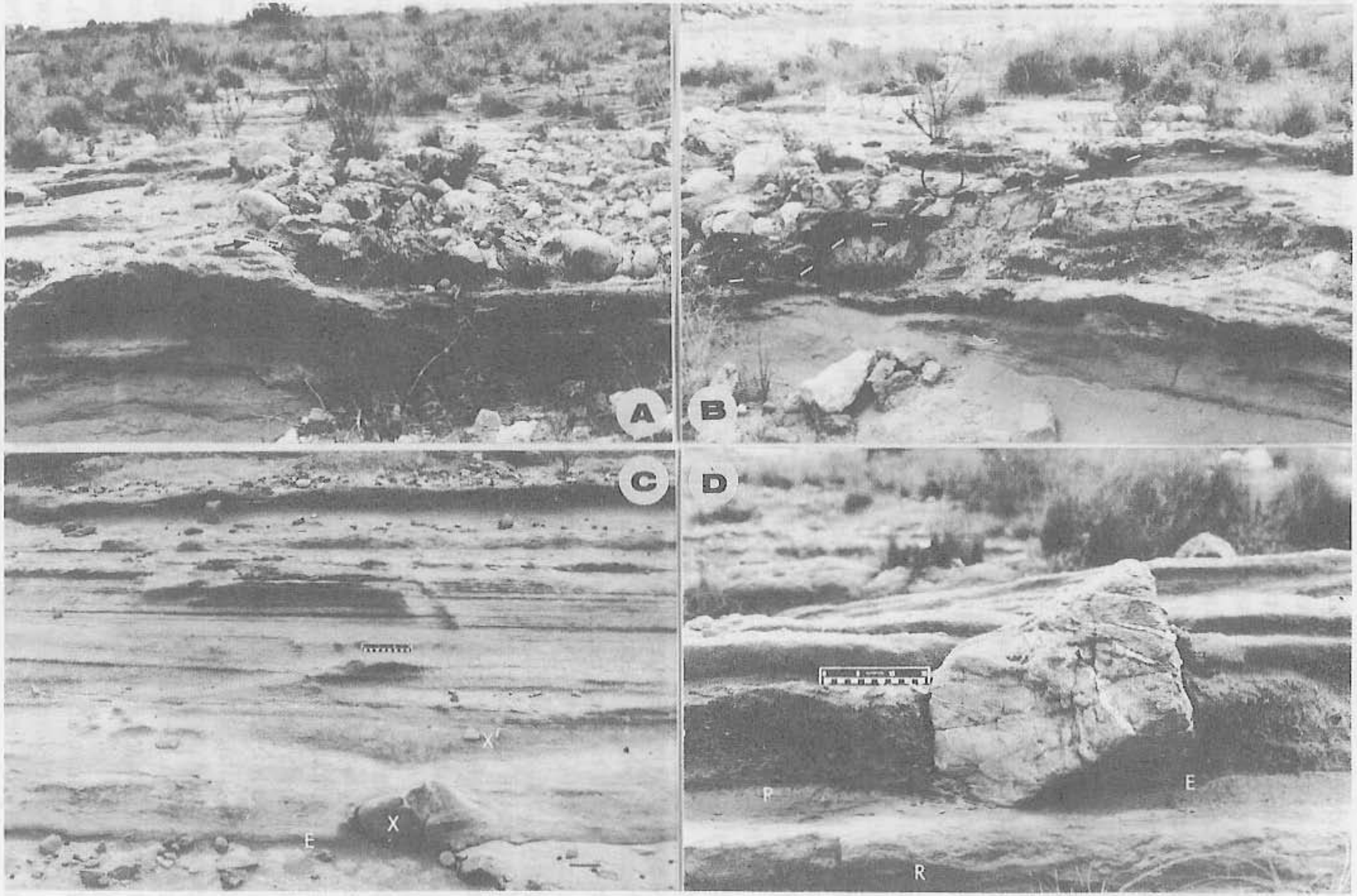
Layers of *normally-graded, structureless or faintly laminated sandstone*, with sharp flat or gently erosional bases (Fig. 6 C, 7 A). Scattered, outsized pebbles occur grouped in either clusters or isolated. Sometimes these pebbles form an irregular, discontinuous layer at the base of the normally-graded coarse to very coarse sandstone (Fig. 6 A, 7 A, C). In many other beds clasts float roughly in the middle section of the bed (Fig. 7 A) or at its top (Fig. 6 C)

These deposits can be interpreted as the result of high-density turbidity currents with large clasts dragged at their bases and left behind as lags. Postma *et al.* (1988) proved that large clasts floating within the bed were first suspended by strong turbulent lift, and then glided along the boundary between a highly-concentrated, non-turbulent base called the inertia-flow layer and the overlying, faster-moving turbulent-flow layer. Clasts commonly display an a(p) a(i) fabric which, according to these authors results from the highly concentrated grain dispersions of the underlying inertia-flow regime. Clusters of floating clasts may be due to the tendency of a large clast to form an obstruction and trap for other clasts gliding along the same surface.

Isolated poorly rounded or angular, scattered boulders up to 40 cm in diameter (Fig. 6 C, D) occur in the sandstone layers. Sometimes these show an arcuate, semicircular accumulation of pebbles on the assumed up-current side. Apparently the larger clast acted as an obstacle and trap for the smaller-sized boulders. Other pebbles occurring are included into very fine gravel-sized conglomeratic layers (Fig. 6 D).

There are several possible origins for these clasts. Many of them may be boulders dragged by turbidity currents and left behind as lags. Another explanation may be that they are «outrunners», i.e. clasts originally transported at the top of debris-flow bodies moved by the traction phase of the passing turbidity current, and deposited distally downslope within sandy turbidites (Postma *et al.*, 1988). Such an origin is considered likely as most of these boulders in sandstones were associated with boulder-filled gullies (Fig. 4).

Parallel-laminated yellowish sandstone (Fig. 6 C, 7 C, D) with lamination that may be deformed by water-escape structures (Fig. 7 C, D) or may be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obscure or very faint (Fig. 6 C lower part, 7 C lower part) probably resulting from dewatering.

These are interpreted as deposits of high-density turbidity currents having traction and suspension divisions described in Lowe's (1982) terms.

Undulating laminated sandstones with metric wave-length may be associated with parallel lamination (Fig. 7 A, C), probably resulting from adaptation to previous bottom reliefs.

Gentle, smooth erosional surfaces truncate bedding, separating sets of beds (Fig. 7 B). This is interpreted as resulting from erosion of the bottom and draping by younger deposits.

Fossils

Macro fossil content occurs largely as transported skeletal remains, which integrate a large part of the coarser-grained intervals within sandstone layers.

Many layers contain an abundant shallow-marine benthic fauna: frequently oysters and pectinids, cirripeds, abundant needles and fragments of sea-urchins, fragments of several types of bryozoans. Flora includes red algae and rhodoliths.

Fossil content increases from metre 50 upwards (Fig. 4) with the abundance of marlstone.

Biogenic structures

Biogenic structures include vertical a horizontal bioturbation. Burrowing is a common feature of some sandstone layers, particularly in the finer-

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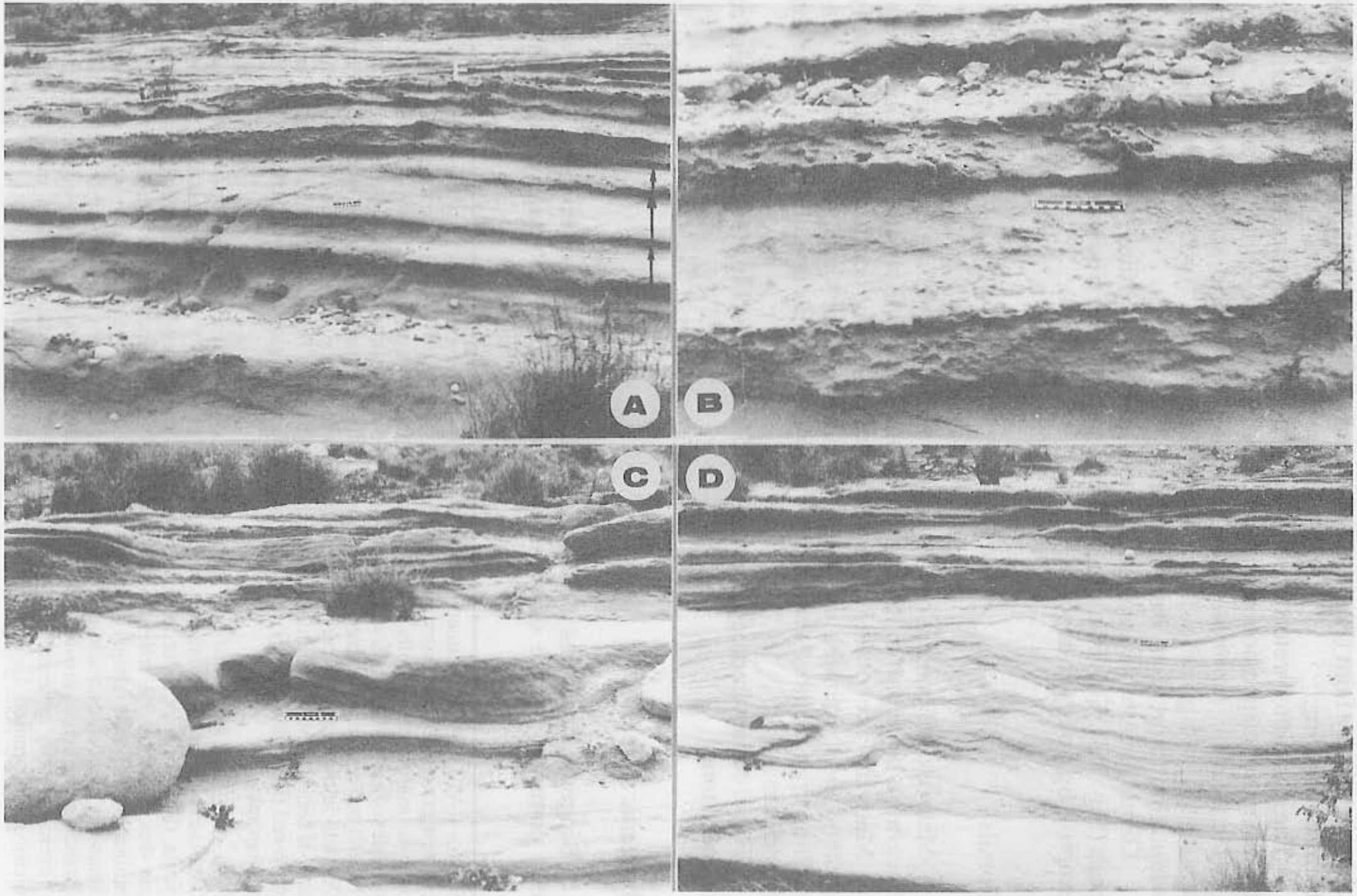
Fig 6.—(A) Gully with steep walls filled with heterometric coarse-grained sediment. The coarsest grain sizes concentrate near the base and wall. Arrow pointing to the scale bar. (B) The opposite margin of the gully (photographs 6 A and B cover almost the whole gully) with two episodes of gully fill (note discontinuous lines marking the limits): inclined-laminated sandstones (below) and coarse grain sizes. Ruler encircled. (C) Laminated sandstones with isolated cobbles (X) both in the erosional surface and floating in sandstone some distance above the erosional base of bed. (D) Isolated boulder in a 15 cm-thick layer of fine gravel and coarse sandstone; (R) burrowed fine sandstone; (E) erosional base of microconglomerate bed. Scale is 15 cm long in photographs.

Fig 6.—(A) Canal estrecho (gully) de paredes abruptas relleno de conglomerados heterométricos. Los clastos de mayor tamaño se acumulan cerca del fondo y de las paredes. La flecha indica la escala. (B) Margen opuesta del mismo canal (las fotografías A y B lo cubren casi por completo) con dos episodios de relleno (las líneas discontínuas indican los límites): areniscas con laminación inclinada (abajo) y conglomerados. El círculo marca la regla de escala. (C) Areniscas laminadas con cantos aislados (X) en la superficie erosiva y flotando en la arenisca a alguna distancia sobre la base erosiva. (D) Bloque aislado en una capa de 15 cm de espesor de grava fina y arenisca muy gruesa; (R) arenisca fina bioturbada; (E) base erosiva del nivel microconglomerático. La escala mide 15 cm en todas las fotografías.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grained silty tops (T_d) of the normal graded beds (Fig. 5 A, 6 C, 7 A, B). Intense burrowing eventually obliterates primary sedimentary structures of layers (Fig. 7 B) but differences in grain size and cementation are still observable. Burrowed layers occur grouped (Fig. 7 A, B); this is believed to be related to periods of slowed deposition with reduced sedimentation rates.

FACIES ASSOCIATIONS

The described lithologies tend to occur in some intervals of the stratigraphic section (Fig. 4). We assume that these deposits are integrated into associations with a genetic meaning (Fig. 8).

These associations reflect particular conditions of sedimentation resulting from coincidence of sedimentary processes; ultimately this will offer a key to interpreting the sedimentary environment and to the proposal of a feasible model. We have informally termed these facies association with capitals from A to E in descending order of dominant grain sizes. Naturally no terminological implications should be taken from this description.

Association A

Conglomerates filling channels or in thick, irregular-based layers (Fig. 5 B). We believe this represents the more «proximal» facies association, deposited by high-density flows and debris flows. It is comparable to the zone of channels feeding deeper-water realms.

Association B

Gravels to coarse sandstones with planar lower boundaries; imbricated, outsized clasts floating in many layers. This represents a zone of coarse-

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Fig 7.—(A) Vertical accumulation of normal-graded sandstone layers (arrows show a few of such layers) with isolated, rounded floating pebbles floating in structureless or faintly laminated sandstones. (B) Close-up of 7 A to show intensely burrowed sandstones. Vertical arrow illustrates a normally-graded bed. (C) Water-escape structure in parallel-laminated sandstone. Undulating lamination is visible in the upper in the far end. (D) Parallel-laminated layers of sandstone deformed by water-escape structures. Scale is 15 cm long in photographs.

Fig 7.—(A) Apilamiento vertical de areniscas con granoclasificación positiva (las flechas indican algunos de esos niveles) con cantos aislados, redondeados flotando en areniscas sin estructura interna visible o débilmente laminadas. (B) detalle de la anterior para mostrar areniscas intensamente bioturbadas. La flecha vertical indica un nivel con granoclasificación positiva. (C) Estructura de escape de agua en areniscas con laminación paralela. Al fondo se observa laminación ondulada. (D) Areniscas con laminación paralela deformados por escape de agua. La escala mide 15 cm en todas las fotografías.

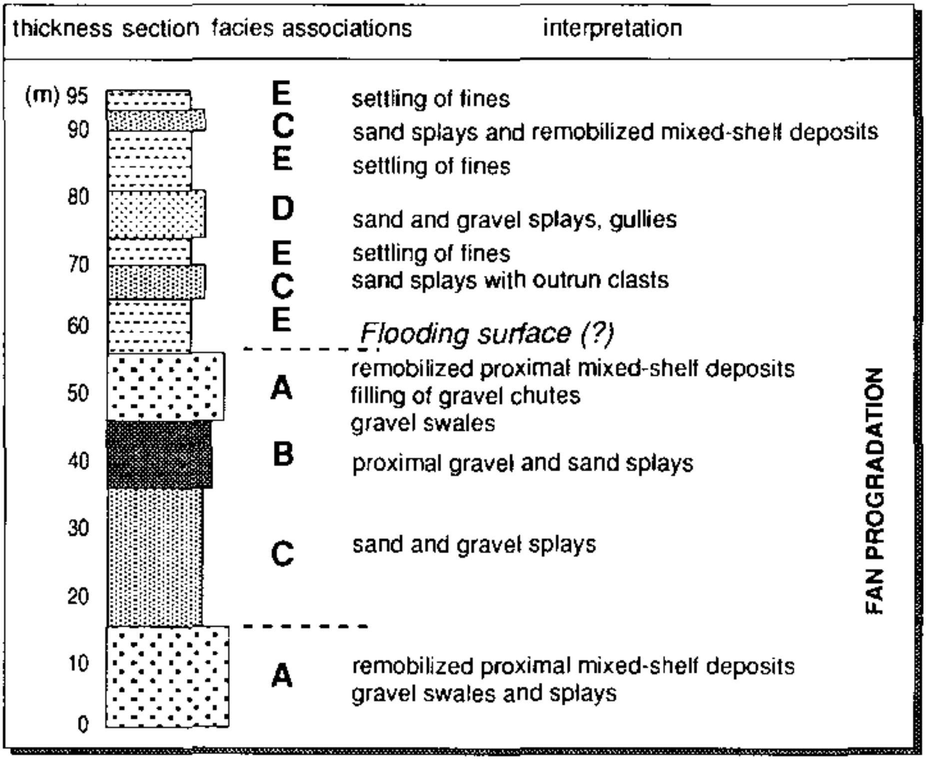

Fig 8.—Facies associations described in the text and interpretation.

Fig 8.—Asociaciones de facies descritas en el texto e interpretación.

grained and sandy splays at the downslope end of gravel-filled channels and gullies.

Association C

Medium-coarse sands to gravel with intense burrowing and outsized clasts, water-escape structures and synsedimentary faulting. This is interpreted as a zone of dominantly sandy splays found downslope from the channels and gullies marked by rapid deposition and instability. Large clasts outrun coarser-grained debris flows.

Association D

Dominated by parallel-laminated, normally-graded sandstones with outsized boulders, water-escape and undulating lamination together with layers of calcarenites with complete oysters and pectinids. Some of these layers are lumachelles. Incised coarse conglomerate layers (gully fills).

Association E

Yellowish mudstones and marlstones represent basinal facies.

SEDIMENTARY MODEL AND DISCUSSION

We propose the described facies associations as being genetically related, i. e., they represent deposition on the steep slope of a basin distally connected to a mountain valley or river that supplied the coarse sediments to the basin. Sporadic, but vigorous, discharges provide the material of coarse grain size and account for the episodic character of the deposits. This types of underwater accumulation of coarse clastics is a type of fan delta which may, or may not, have a subaerial expression (Prior y Bornhold, 1990; Nemec, 1990, Postma, 1990 a & b). As stated by Postma (1990 a & b) delta characteristics, particularly architecture and sedimentary facies, are essential to recognize deltas.

The proposed model incorporates the facies associations listed earlier; facies association A is the most proximal and facies association D the most distal (Fig. 9). Association E represents fine-grained basin deposition.

Sedimentation on the steep slopes of coarse-grained deltas has received much attention in the last years both in fossil (Postma, 1984; Massari, 1984; Postma & Roep, 1985; Postma *et al.*, 1988; among many others) and Recent (Prior & Bornhold, 1988, 1989, 1990) deposits.

Nemec (1990) carried out a careful analysis of sediment movement on steep delta slopes. According to him, on steep delta slopes, the potential for downslope transport of sediment intermittently exceeds the rate of sediment supply. The slopes are conductive to small and large-scale instability, which makes them subject to intermittent local retreat by mass failure, and to more continuous processes of mass-movement. Settling from suspension and dumping from bedload traction are the principal modes of sediment supply by stream effluents, whereas mass movement is the main conveyor of the sediment on the subaqueous slope itself. Debris flows and turbidity currents are among the important mechanisms of sediment transport and deposition on steep slopes of coarse-grained deltas (Massari, 1984, Prior & Bornhold 1988, 1990, Bornhold & Prior, 1990).

Turbidity currents on delta slopes tend to deposit their coarsest load near the source and carry finer material downslope (Massari, 1984). However, they may also trap large clasts in traction in the frontal part, then drop them

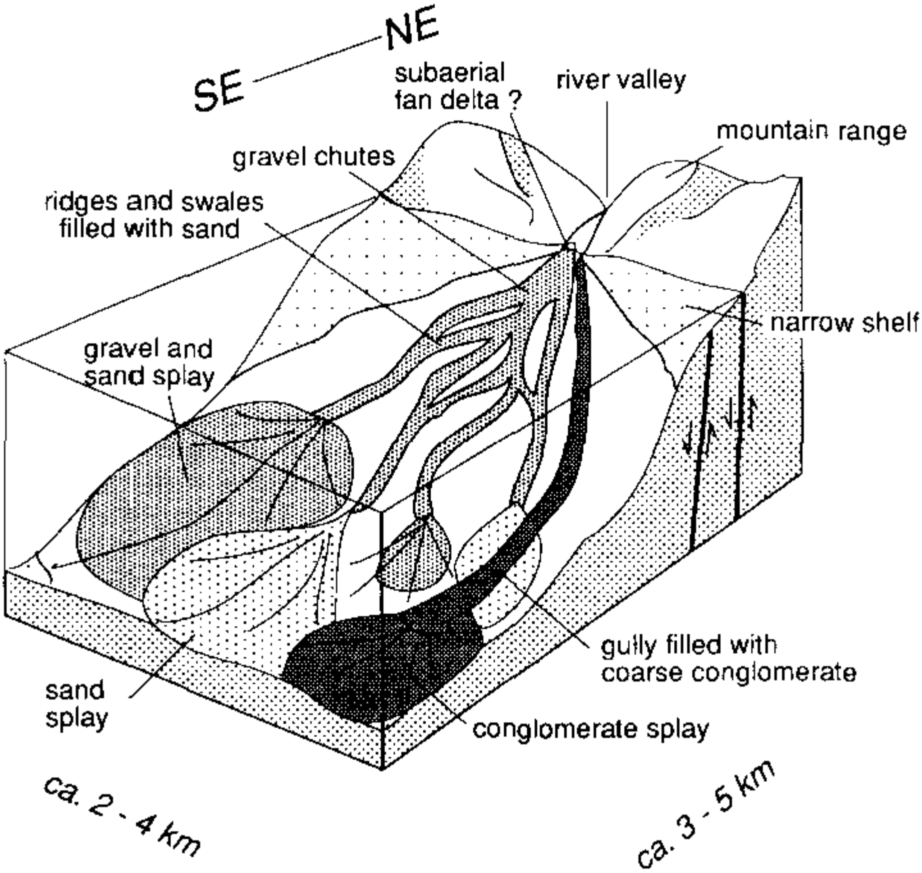

Fig 9.—Sedimentary model of steep-slope fan delta in Murcia-Carrascoy, inspired in fjord fan deltas (Prior & Bornhold, 1990). See text for explanation.

Fig 9.—Modelo sedimentario de fan delta con talud abrupto en la cuenca de Murcia-Carrascoy, inspirado en los fan deltas de fiordos (Prior y Bornhold, 1990). Explicación en el texto.

preferentially in the hydraulic jump conditions of a slope break or delta-toe zone (Postma *et al.*, 1988, Nemec, 1990). Coarse sediment may be transferred to the lower slope by sliding, slumping and as debris flows in chute-and-lobe systems (Prior & Bornhold 1988, 1989, 1990, Nemec, 1990). After being filled with sandy or coarser-grained sediments, chute and gully deposits form finger-like bodies extending from the upper slope downwards surrounded in a mass of finer-grained deposits (Surlyk, 1987; Shanmugan & Moiola, 1991).

At least three different mechanisms can generate density currents in delta settings. They may (i) derive from dispersed head-parts of subaqueous debris flows, (ii) be generated directly by sediment-laden stream effluents as «hyperpycnical» density underflows or (iii) derive from flood-stage stream effluent less directly, by intense sediment fall out from the suspension plume that may evolve into a sheet-like underflow. Turbidity currents will tend to be short-lived in the first case but they may range from brief surges to more continuous (hours to days) density «streams» (Nemec, 1990).

Present analogues for our model may be the fjord fan deltas of British Columbia described by Prior & Bornhold (1988, 1989, 1990) and Bornhold & Prior (1990). A brief account follows. Fjord fan deltas have steep longitudinal profiles (average slopes 13°) fed with coarse-grained sediments from fjord-side rivers. Most of these fan deltas lack the subaerial expression of a fan but they do exhibit well-developed submarine cone shapes.

Building of fjord fan deltas needs a combination of processes taking place with various frequencies and magnitudes including subaqueous debris avalanching, inertia flows, turbidity flows, slope failure and settling of suspensions from buoyant plumes. Long-term fan development responds to changes in sediment supply from the coastline and reduction in underwater relief and slope gradients.

Prior & Bornhold (1990) proposed a four-stage synthetic evolutionary sequence that reflects differences in process combinations as the fan delta develops. A crucial point is that underwater fan progradation, aggradation and basin filling reduce offshore relief, bottom slopes and gravitational stresses. There is a progressive reduction in sediment supply to the underwater slopes, as the subaerial fan component grows, and offshore relief declines. In practical terms this means a noticeable change in the dominant transport processes and deposits, from debris avalanching to inertia flows to turbidity flows and to slope instability.

We suggest that facies associations in the Murcia-Carrascoy compare well with stages 2 and 3 of the evolutionary model described by Prior & Bornhold (1990). These fan deltas are dominated by inertia flows, that disperse coarse gravel and sand from the fan apex across the underwater cone over steep slopes. High-density turbidity currents accompany inertia flows (see Postma *et al.*, 1988) eroding chutes which transport sand downslope (Prior & Bornhold, 1989).

The coarse basal part and the coarsening-up middle part of the succession include three facies associations which may be interpreted as deposits of gravel chutes plus ridges and swales filled with gravel (association A), gravel and sandy splays at the downslope end of gravel-filled channels (swales) and gullies (association B) and thin, indistinct splays of sand and fine gravels in the downslope end of the ridge and swale zone (associations C and D) with isolated gullies filled with deposits of confined inertia flows (Fig. 9). Fine carbonate-rich mudstones and marlstones accumulated during quieter periods. Vertical buildup results from progradation of these subenvironments.

We did not find proof of generalized *in situ* slope failure such as slump scars and slides. However much of the sediment gravity-flows may be laterally (upslope) related to these phenomena.

The proposed model explains the coarsening up trend of the middle part of the section, but needs more explanation to match comparison with fjord models.

As noted before, evolutionary models of fjord fan deltas exhibit a fining up general trend and a progressive shallowing up character (Prior & Bornhold, 1990) because of the progressive filling of the basin and the absence of tectonically-induced subsidence. This is not the case in the Murcia-Carrascoy area where a prograding, coarsening-up trend is well documented (Fig. 4 and 8) in the lower part of the section. We think that this reflects progradation of a fan delta during a stage of sea level stability following tectonic uplift. Combination of uplift and the lowstand of global cycle TB3.2 produced an oversized relative sea-level fall.

We assume that several positive oscillations of relative sea-level are recorded in the section as changes of grain size and sedimentary facies. Unfortunately, we could not trace the flooding surfaces even after careful search; thus, we can not offer a detailed description. We propose that the changes from conglomerates to sandstone (ca. metres 15 and 57, Fig. 4) indicate the probable location of these surfaces. The coarse grained, lower deposits upon the basal unconformity may represent a tectonic event that probably produced a relative lower-order fall of sea level and erosion. These lowstand conglomerates (metres 0 to 15, Fig. 4) are followed upwards by the major prograding episode recorded as the coarsening up sequence (metres 15 to 57). The smaller-scale coarsening-up megasequences evidence progradation of gullies and gravelly ridges and swales in proximal steep-slopes. Later progradations of the fan delta were recorded in the section as well (metres 57 to 95) but only the more distal deposits have been reflected in this particular area (Fig. 8). Most probably, the changes of facies associations result from small-scale fluctuations of sea level or some tectonic activity, but we lack a definite conclusion. Renewed transgression forced the shallower environments further landward and the Torremendo marlstones were deposited on the new shelf-to-slope environment that prograded upon the former basin and slope settings.

As a whole, theses deposits represent a thick fining up succession which include the lowstand coarse-grained fan delta deposits of the Puerto de la Cadena, the transgressive fan-delta slope studied in this paper, and the finer grained basin-to-slope Torremendo marlstones deposited during the highstand. The depositional sequence (Fig. 2) also includes the storm-worked shallow-water carbonates (La Virgen calcarenites) that prograded during the late highstand.

CONCLUSIONS

We propose as a first interpretation of the Sequence Stratigraphy in the Murcia-Casrrascoy the following depositional sequence. Marlstones with turbidites and megabreccia layers (La Naveta marlstones) and fan-delta conglomerates (Puerto de la Cadena) correspond to the lowstand systems tract largely magnified by tectonic effects.

Rapid transgression and subsidence upon the fan-delta clastic wedges created steep slopes and deposition of the transgressive systems tract studied in this paper.

The overlying Torremendo marlstones record progradation of basin and slope marine deposits. During the late highstand and the early stages of sea-level fall, the shallow-marine La Virgen calcarenites were deposited.

High-density flows, debris flows, high-density turbidity currents and the settling of fines are the most prominent sedimentary processes. We have distinguished five facies associations in the yellowish sandstones which we interpret to correspond to deposition in various settings along a steep basin slope. Coarsening-up megasequences record progradation of gravelly ridge and swale and gullies in proximal steep-slope fan deltas. This happened after tectonic uplift and a major sea-level fall during the lowstand of global cycle TB3.2. We suspect that flooding surfaces related to transgression exists in the basal and central part of the section. After that, progradation involved more distal deposits that probably record small-scale fluctuations of sea level.

Present analogues for this model may be the fjord fan deltas of British Columbia. The described facies associations compare to stages 2 and 3 of the evolutionary model described by Prior & Bornhold (1990). These fan deltas are dominated by inertia flows that disperse coarse gravel and sand from the fan apex across the underwater cone over steep slopes. High-density turbidity currents accompany inertia flows eroding chutes which transport sand downslope.

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