DELTA-FRONT FACIES ASSOCIATIONS OF ANCIENT FLOOD-DOMINATED FLUVIO-DELTAIC SYSTEMS

E. Mutti, R. Tinterri, D. di Biase, L. Fava, N. Mavilla, S. Angella and L. Calabrese

Dipartimento di Scienze della Terra, University of Parma, Parco Area delle Scienze, 157/A, 43100 Parma, Italy
e-mail: mutti@unipr.it

Abstract: Ancient flood-dominated fan-delta and river-delta systems of tectonically-active basins can be viewed as essentially small and immature fluvial systems (in the sense of Schumm, 1977) with relatively high-elevation catchment basins, short and high-gradient transfer zones, and marine depositional zones where transport and deposition are dominated by hyperpycnal flows. The delta-front deposits of these ancient systems are represented by facies and facies associations whose stratigraphic and sedimentological importance has been largely overlooked in previous literature. Both fan-delta and river-delta systems contain a common and very distinctive terminal depositional element consisting of sharp-based and parallel-sided, graded sandstone beds commonly containing HCS. These sediments, herein termed "flood-generated delta-front sandstone lobes", form impressive sedimentary accumulations in many basins worldwide. Commonly mistaken for storm-dominated nearshore and shelfal deposits, these sandstone lobes probably represent the most genuine expression of fluvial-dominated delta-front sedimentation. In ancient river-delta systems, river-mouth deposits show a great variability in terms of geometry and facies types, essentially recording the locally prevailing conditions ranging from extensive erosion and sediment bypass to deposition of the entire sediment load carried by sediment-laden stream flows entering seawaters. Flood-related processes are intrinsically catastrophic and, as such, under-represented in modern settings. It thus appears that ancient flood-dominated fluvio-deltaic systems cannot be described and interpreted following current sedimentological models for fluvial and deltaic sedimentation. Actually, these models are largely derived from modern depositional environments dominated by "normal" fluvial and marine processes. There are, on the other hand, impressive similarities between ancient flood-dominated fluvio-deltaic systems and turbidites - another category of catastrophic deposits which is under-represented in modern basins. Comparing facies and processes of these two groups of sediments deposited by density currents can provide significant insight into both types of sedimentation.

Key words: flood-related sedimentation, ancient flood-dominated fan-delta and river-delta systems, hyperpycnal flows, mouth bars, delta-front sandstone lobes, tectonism, climate, sea-level variations.

Resumen: Los sistemas deltaicos de abanicos aluviales y de deltas fluviales dominados por avenidas en cuencas tectónicamente activas pueden ser vistos esencialmente como sistemas fluviales inmaduros (en el sentido de Schumm, 1977) con cuencas de recepción relativamente elevadas, zonas de transferencia cortas y de alto gradiente y zonas deposicionales marinas donde el transporte y la sedimentación están dominados por flujos hiperpícnicos. Los depósitos de frente deltaico de estos sistemas antiguos están representados por facies y asociaciones de facies cuya importancia estratigráfica y sedimentológica ha sido generalmente pasada por alto en la literatura anterior. Tanto los sistemas de deltaicos de abanicos aluviales como los de deltas fluviales contienen un elemento deposicional terminal muy característico que consiste en capas gradadas de areniscas tabulares con base neta que generalmente contienen HCS. Estos sedimentos, aquí llamados 'lóbulos areniscosos de frente deltaico asociados a avenidas', forman acumulaciones impresionantes en muchas cuencas sedimentarias de todo el mundo. Generalmente confundidos con depósitos costeros de plataforma dominados por tormentas, estos lóbulos areniscosos probablemente representan la expresión más genuina de la sedimentación de frente deltaico dominada por procesos fluviales. En deltas fluviales antiguos, los depósitos de desembocadura fluvial muestran una gran variabilidad en términos de geometría y tipos de facies, generalmente registrando las condiciones localmente predominantes que van desde erosión extensiva y *bypass* de sedimento hasta deposición de toda la carga sedimentaria, transportada por flujos de corrientes cargadas de sedimento (sediment-laden stream flows) que entran en aguas marinas. Los procesos relacionados con avenidas son intrinsecamente catastróficos y, como tales, estan infra-representados en ambientes actuales. Por consiguiente, los sistemas fluvio-deltaicos dominados por avenidas no pueden ser descritos ni interpretados siguiendo los modelos habituales de sedimentación fluvial y deltaica. En realidad, estos modelos derivan en gran parte de ambientes deposicionales actuales dominados por procesos fluviales y marinos "normales". Por otro lado, hay similitudes importantes entre sistemas antiguos de deltas fluviales dominados por avenidas y turbiditas, que son otra categoría de depósitos catastróficos que están infra-representados en cuencas modernas. Comparar las facies y procesos de estos dos grupos de sedimentos depositados por corrientes de densidad puede aportar nuevos y relevantes puntos de vista para ambos tipos de sedimentación.

Palabras clave: ambientes deltaicos, fan-deltas, modelos de facies, tectónica, clima, variaciones eustáticas.

Mutti, E., Tinterri, R., di Biase, D., Fava, L., Mavilla, N., Angella S. and Calabrese L. (2000): Delta-front facies associations of ancient flood-dominated fluvio-deltaic systems. *Rev. Soc. Geol. España,* 13 (2): 165-190

The origin and characteristics of hyperpycnal flows at modern river mouths have received increasing attention from sedimentologists in recent years (*e.g.*, Sparks *et al.*, 1993; Mulder and Syvitski, 1995; Skene *et al.*, 1997; Mulder *et al.*, 1998; McLeod *et al.*, 1999). The results of this research, stemming from the theory on delta formation by Bates (1953) and subsequent papers by Wright *et al.* (1986) and Prior *et al.* (1986) on the modern Yellow River, seem to leave little doubt that hyperpycnal flows (inversely buoyant plumes) originating during floods represent a fundamental process in delta construction. Surprisingly, no real attempts have been made to assess to what extent this kind of sedimentation is recorded in ancient strata.

Although partly perceived in earlier work (*e.g.*, Martinsen, 1990), the importance of floods and related hyperpycnal flows in controlling the growth of ancient deltaic systems has been documented only recently by Mutti *et al.* (1996, with references therein). On the basis of extensive research carried out on a significant number of ancient basin fills from different geologic settings and ranging in age from Mesozoic to Pleistocene, these authors have shown that ancient flood-dominated fluvio-deltaic systems are the fundamental stratigraphic component of most alluvial and shallow-marine successions of tectonically active basin fills - a conclusion in some way predicted by Milliman and Syvitski (1992, p. 541) for ancient active margin sedimentation on the basis of the characteristics of modern, small- and medium-sized mountainous rivers and the potential of these rivers to contribute sediment to the sea.

In this paper, we further expand on flood-dominated fluvio-deltaic sedimentation of tectonically active basins focusing in particular on delta-front facies associations and inferred depositional processes of marine fan-delta and river-delta systems dominated by hyperpycnal flows. To this purpose, we will avail ourselves of examples from the Eocene strata of the south-central Pyrenean foreland basin - a basin where flood-dominated sedimentation appears to be crucial to a better understanding of the complex interaction between tectonism and climatic and relative sea-level variations, as expressed by dramatic cyclic changes in sediment flux to the sea through time (Mutti *et al.*, 1996, 1999).

Although overlooked in previous literature, flood-dominated fluvio-deltaic sedimentation probably offers a very significant clue to the interpretation of most of the spectacularly exposed fluvial, lacustrine and shallow-marine terrigenous strata that were deposited in the south-central Pyrenean domain between late Cretaceous and Oligocene concurrently with the progressive uplift of the chain. For the reader's convenience, figure 1 shows the main stratigraphic units which are referred to in the following sections.

We are fully aware of the fact that many of the interpretations offered in this paper are preliminary and, as such, potentially controversial; on the other hand, this is one of the very first attempts to consider ancient flood-dominated fluvio-deltaic systems and their still basically undescribed facies in terms of processes whose knowledge is also in its infancy, being mostly inferred from sparse observations on some modern deltas, limited experiments, and numerical modeling. Therefore, the main purpose of this paper is to show how much work is still needed to fill this gap in the study of fluvio-deltaic sedimentation.

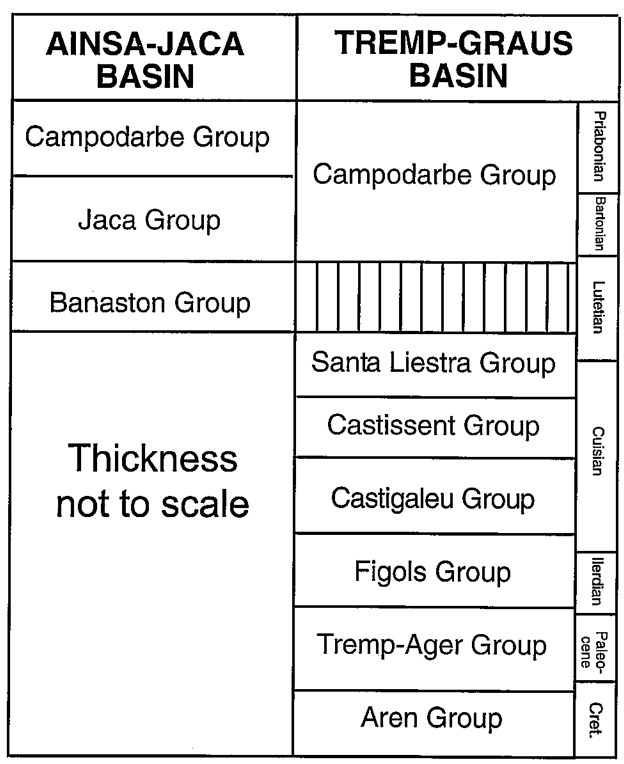


Figure 1.- General stratigraphic subdivisions of the upper Cretaceous to upper Eocene strata of the Tremp-Graus and Ainsa-Jaca basins in the south-central Pyrenees (based on Mutti *et al.*, 1994 and Remacha *et al.*, 1998).

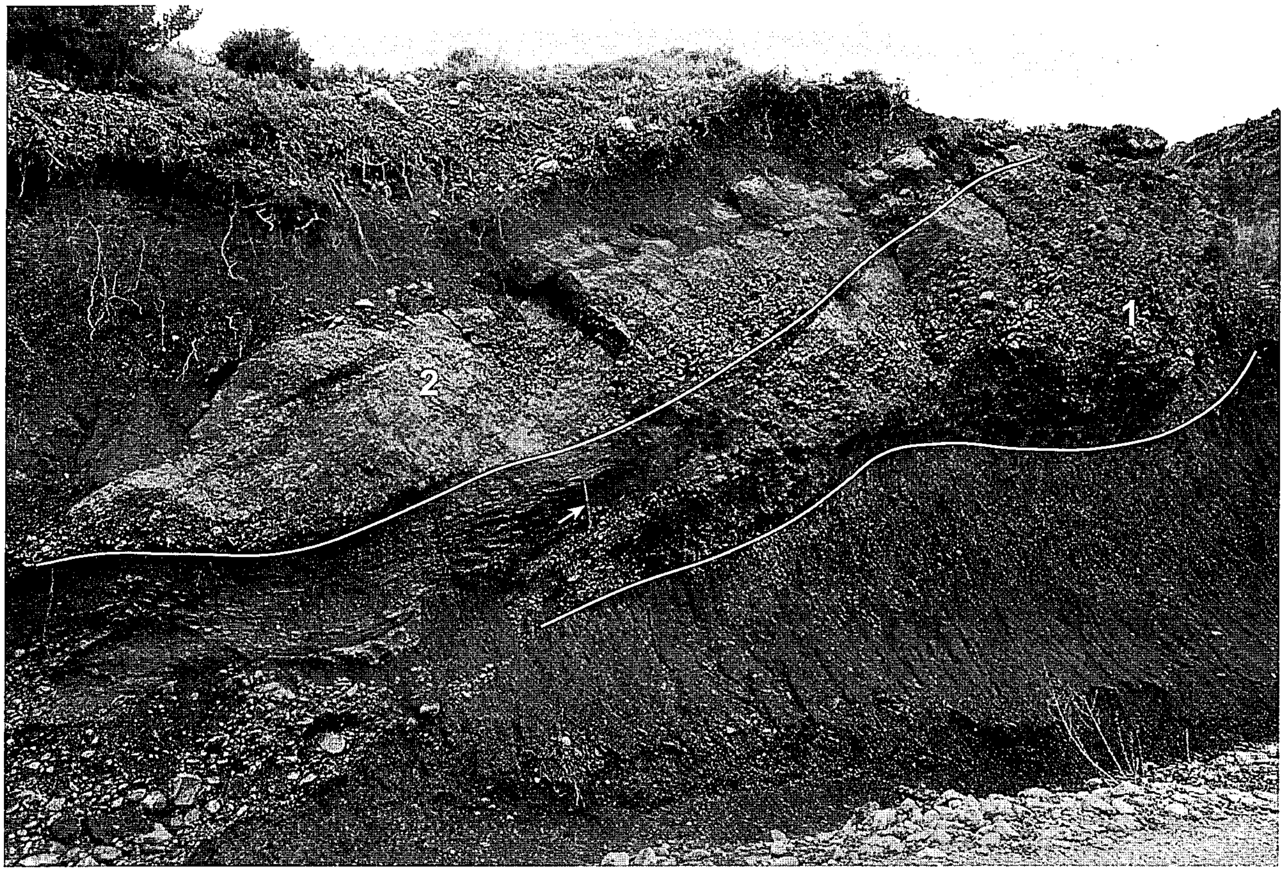


Figure 2.- Flood-generated coarse-grained bars. Individual flood-units show a well-defined vertical and downstream normal grading (from right to left). Bars of this type are very common in terminal flood basins and ephemeral lakes. First recognized and described by Mutti *et al.* (1996), and termed by these authors "flood-generated sigmoidal bars", these flood-units are herein interpreted as the deposit of a composite sediment flow (see later) characterized by a markedly inverse grain-size segregation during transport and early phases of sedimentation. Within each unit, the basal and upstream, clast-supported and crudely-stratified conglomerate resting on a pronounced erosive surface is thought to be the deposit of the head of a hyperconcentrated flow which was forced to deposit its load because of frictional freezing. The crude stratification of the conglomerate division is produced by a trailing, progressively more dilute turbulent flow which bypassed the frozen, coarse-grained deposit of the hyperconcentrated flow (see text for more extensive discussion). Upper part of the Tremp-Ager Group along the road Aren-Berganuy.

General characteristics of ancient flood-dominated fluvio-deltaic systems

Ancient flood-dominated fluvio-deltaic systems can be viewed as essentially small and immature fluvial systems (in the sense of Schumm, 1977) with relatively high-elevation catchment areas, short and high-gradient transfer zones, and marine depositional zones where transport and sedimentation were dominated by hyperpycnal flows. Although quite different in terms of sandbody geometry, facies and processes (see later), systems of this kind share many features with the broad category of the "coarse-grained deltas", including both river and fan-deltas, as amply discussed by many authors (for a synopsis see Colella and Prior, 1990) and considered as highly sensitive recorders of tectonic activity and climatic and sea-level variations. More significantly, ancient flood-dominated fluvio-deltaic systems can be regarded as the ancient analogs of the modern "small- and medium-sized mountainous rivers" of Milliman and Syvitski (1992) and the "dirty rivers" of Mulder and Syvitski (1995). In modern settings, these rivers are characterized by a high sediment flux to the sea due to the elevation of their drainage basins and their proximity to the shoreline. These factors strengthen the role of flooding in that sediment concentration of flood-related flows is not reduced by energy dissipation and sedimentation in alluvial flood basins and coastal plains. Consequently, many of these rivers can generate frequent hyperpycnal flows over the year.

The depositional setting, facies distribution patterns and sandbody geometry of these modern deltas remain largely undescribed and therefore little understood. In addition, it appears quite obvious that the subaqueous segments of these depositional systems are difficult to study in modern settings; therefore, it can be argued that, once correctly recognized, ancient flood-dominated delta-front strata can provide some useful information to partly fill this gap.

As outlined by Mutti *et al.* (1996), ancient flood-dominated fluvio-deltaic systems consist of a great variety of facies and facies associations deposited in both alluvial and shallow-marine environments. All these sediments are characterized by the pervasive occurrence of sedimentation units each displaying a distinct vertical and longitudinal grading produced during a discrete flood event. These elementary flood-units differ considerably from each

Figure 3.- Graded and parallel-sided sandstone beds deposited by hyperpycnal flows in a shelfal environment. Bardas Blancas Formation, Neuquén Basin, Argentina.

other in virtue of the many local controlling factors such as, in particular, the volume, sediment concentration and duration of individual flood events, the type of process and sediment involved, and the local environment of deposition. As a result, individual flood-units may vary from crudely graded, small and lenticular coarse-grained bars produced by the sudden deceleration of small-volume and short-duration flash floods (Fig. 2) to graded and relatively well-sorted sandstone beds with impressive lateral extent deposited by long-lived hyperpycnal flows in marine delta-front environments (Fig. 3).

In this paper, we focus primarily on facies and facies associations that characterize marine delta-front strata, *i.e.* a relatively limited number of facies types and facies associations which form in response to the deceleration and transformations experienced by flood-generated flows when entering seawaters in fan-delta and river-delta systems. Although treated in a number of papers from a conceptual standpoint (*e.g.*, Wright, 1977; Prior *et al.*, 1986; Wright *et al.*, 1986; Sparks *et al.*, 1993; Mulder and Syvitski, 1995; Skene *et al.*, 1997; Mulder *et al.*, 1998; McLeod *et al.*, 1999), these processes are still difficult to link to specific facies and facies associations of both modern and ancient deposits. Although intergradational in terms of physiography and depositional processes, fan-delta and river-delta systems can be considered as the end members of flood-dominated fluvio-deltaic sedimentation dominated by relatively unconfined hyperconcentrated flows and channelized sediment-laden stream flows, respectively (see later).

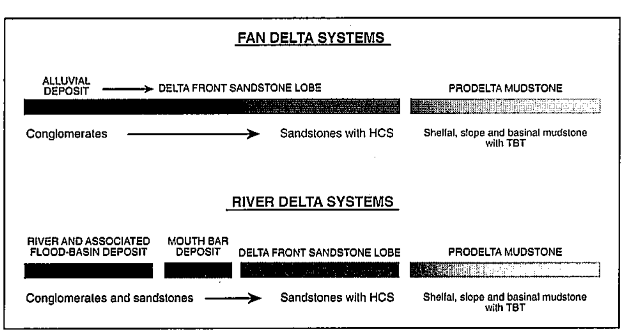


Figure 4.- Basic component elements of fan-delta and river-delta systems (from Mutti *et al.*, 1996).

The basic depositional elements of fan-delta and river-delta systems are shown in figure 4. For the reader's convenience and to avoid terminology problems as best as possible, Table I summarizes the main types of flow as intended in this paper.

Delta-front sandstone lobes deposited by hyperpycnal flows

Both flood-dominated ancient fan-delta and river-delta systems contain a common and very distinctive

Flow types as intended in this paper			*Flow rheology*	*Sediment support mechanisms*	*Depositional mechanism*	*Flow characteristics*	*References*
Cohesive debris flow		Non-Newtonian	Bingham plastic	Matrix strenght	Cohesive freezing	Very high-density, mud-rich flows with negligible grain-to-grain friction	Lowe (1982)
Hyperconcentrated flow (cohesionless debris flow or granular flow)		Non-Newtonian	Poorly understood	Excess pore pressure, dispersive pressure and matrix strenght	Frictional freezing along flow boundaries	Very high-density flows with inverse longitudinal grain-size segregation	Mutti et al. (1996) Mutti et al. (1999) Major and Iverson (1999)
Composite sediment-laden stream flow		Non-Newtonian	Poorly understood	Excess pore pressure, dispersive pressure, matrix strenght and turbulence	Frictional freezing, traction, and traction plus fall-out	High-density flows, with inverse longitudinal grain-size segregation, consisting of a preceding dense frontal granular flow followed by an intermediate flow (turbulent SLSF) and a more dilute stream flow	Composite sediment flows of Sohn et al. (1999)
Sediment-laden stream flow (SLSF)	High-density turbulent flow	Non-Newtonian	Fluid	Turbulence	Traction plus fall-out	High-density flows with normal vertical grain-size segregation	Pierson and Costa (1987 Costa (1988) Todd (1989) Smith and Lowe (1991) Mutti et al. (1996)
	Traction carpet	Non-Newtonian	Dilatant plastic	Dispersive pressure	Frictional freezing and traction		
Stream flow		Newtonian	Fluid	Turbulence	Traction	Very low-density turbulent flow	Costa (1988) Pierson and Costa (1987) "Clear water stage" of Mutti et al. (1996)

Table I.- Main types of flood-generated flows as intended in this paper.

terminal depositional element consisting of sharp-based and parallel-sided graded sandstone beds commonly containing hummocky cross-stratification (HCS). These sandstone beds typically form packets, 3-15 m thick, alternating with muddier deposits which may be locally highly fossiliferous and bioturbated. These sediments, which are remarkable for their lateral continuity and their internal cyclic stacking pattern (Figs. 5 and 6), form the typical delta-front facies association of flood-dominated fluvio-deltaic system recording the final sandy depositional zone of hyperpycnal flows. In a previous paper (Mutti *et al.*, 1996) we termed these sediments "shelfal sandstone lobes"; herein, we prefer to redefine them as "flood-generated delta-front sandstone lobes", a term implying a more explicit fluvio-deltaic origin. Vertical and lateral stratigraphic relationships indicate that these lobes pass basinward into mudstone-dominated prodelta facies; and that their landward equivalents are represented by alluvial and shallow-marine conglomerates and pebbly-sandstones in fan-delta systems

Figure 5 - Example of tabular delta-front sandstone lobes deposited in a river-delta system dominated by highly-efficient sediment-laden stream flows (see text). Sandstone packets, between 3-15 m thick and separated by muddier facies, can be traced for several km. Basal part of the Figols Group, Tremp area.

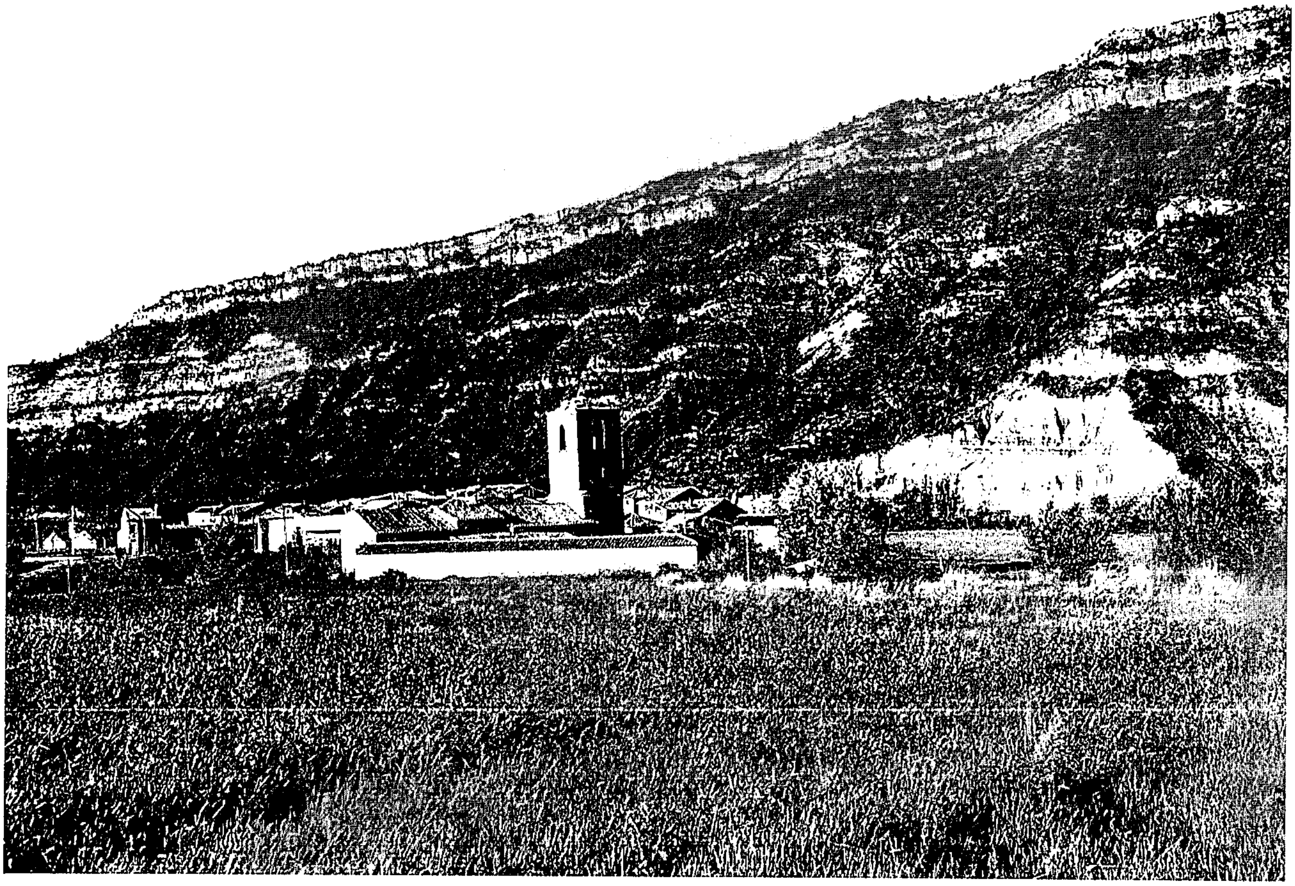


Figure 6.- Spectacularly exposed delta-front sandstone lobes of the Santa Liestra fan-delta system in the Esera valley at Santa Liestra. These sandstone facies grade northward into a similarly thick section of conglomerates in less than three kilometers (compare with Fig. 8).

and very distinctive mouth-bar deposits in river-delta systems. Farther landward, the mouth-bar deposits grade into fluvial and associated flood-plain facies.

Flood-generated delta-front sandstone lobes probably represent the most genuine expression of fluvial dominated delta-front sedimentation, since, in the absence of hyperpycnal flows, river-borne sands can only be redistributed in the marine environment by waves and tides, most commonly in the proximity of river mouths. These flood-generated sandstone lobes form huge sedimentary volumes in the fill of ancient tectonically-active basins, suggesting that their stratigraphic importance has been largely overlooked in previous literature. A notable exception is that of Goldring and Bridges (1973) who first perceived the stratigraphic importance of these nearshore and shelfal deposits in the ancient record, termed them "sublittoral sheet sandstones", and proposed various origins including storms, tsunamis, floods, tides, rips and turbidity currents.

Flood-generated delta-front sandstone lobes have been most commonly mistaken for storm-dominated nearshore and shelfal deposits because of the common occurrence of HCS, a structure generally considered to be diagnostic of combined-flow conditions associated with storm activity along high-energy coasts (*e.g.*, Duke *et al.*, 1991, with references therein). In reality, combined-flow conditions are inherent to the dynamics of flood-generated flows and particularly to those flows which enter seawater as hyperpycnal flows (*e.g.*, Mutti *et al.*, 1996). This, combined with local and regional stratigraphic relationships between alluvial and nearshore facies established for a great number of ancient fluvio-deltaic systems (for a more detailed discussion see Mutti *et al.*, 1996; see also Mutti *et al.*, 1998), rules out the possible interpretation of delta-front sandstone lobes in terms of storm-dominated deposits. Some typical features of these deposits are illustrated in figure 7.

In both fan-delta and river-delta systems, delta-front sandstone lobes are interbedded with and grade into finer-grained facies deposited by dilute hyperpycnal flows and, most commonly, buoyant plumes emanating from river mouths. Data currently available from outcrop studies are insufficient to provide significant information on the deposits of such processes, essentially represented by apparently monotonous successions of mudstone-dominated facies. Hypopycnal flows can form either under conditions of normal flood stages of a river, as commonly observed in modern settings, or through the separation and lift-off of more dilute flows from an underlying hyperpycnal flow. The importance of hypopycnal plumes as "mud-suppliers" in tectonica-

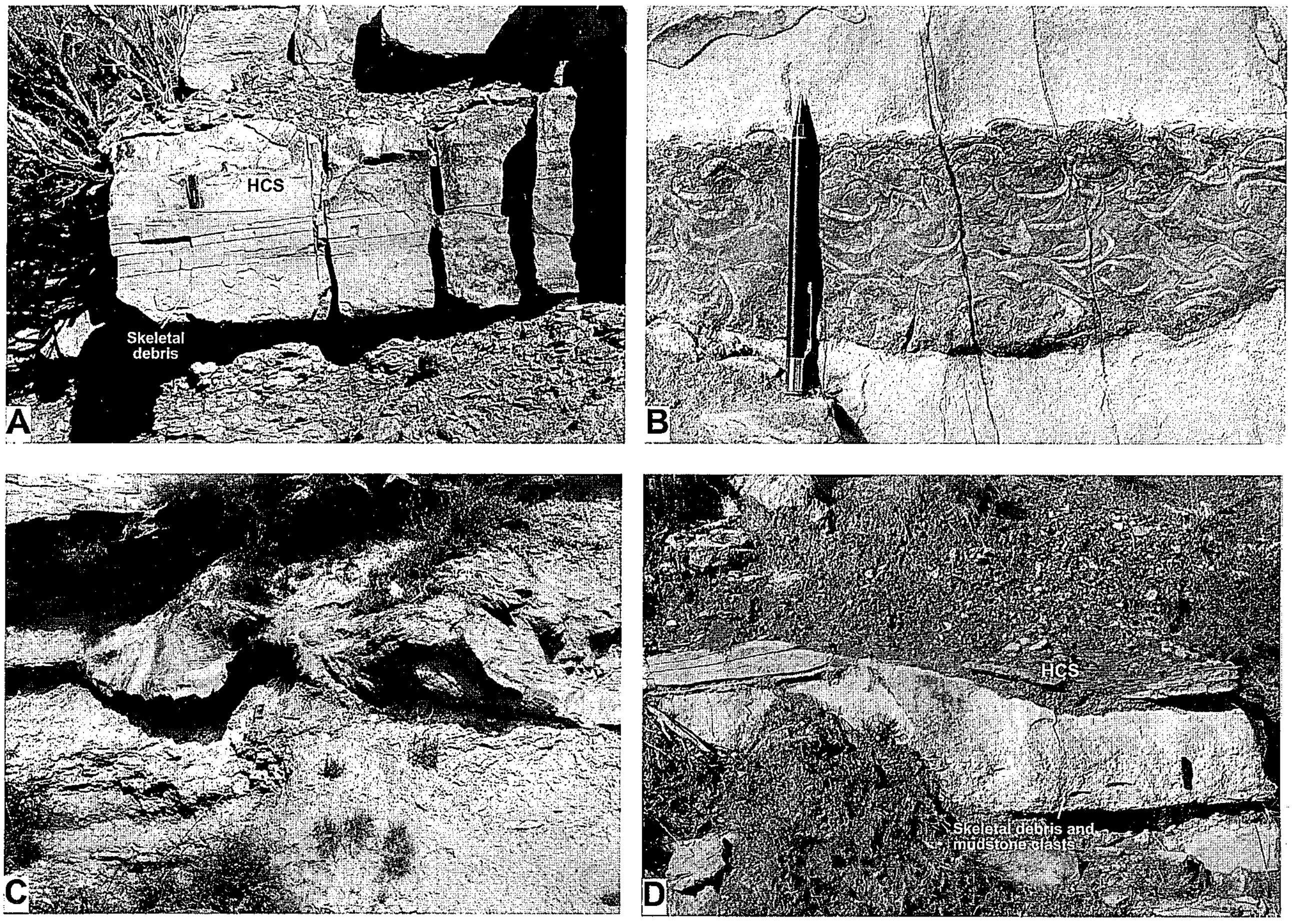


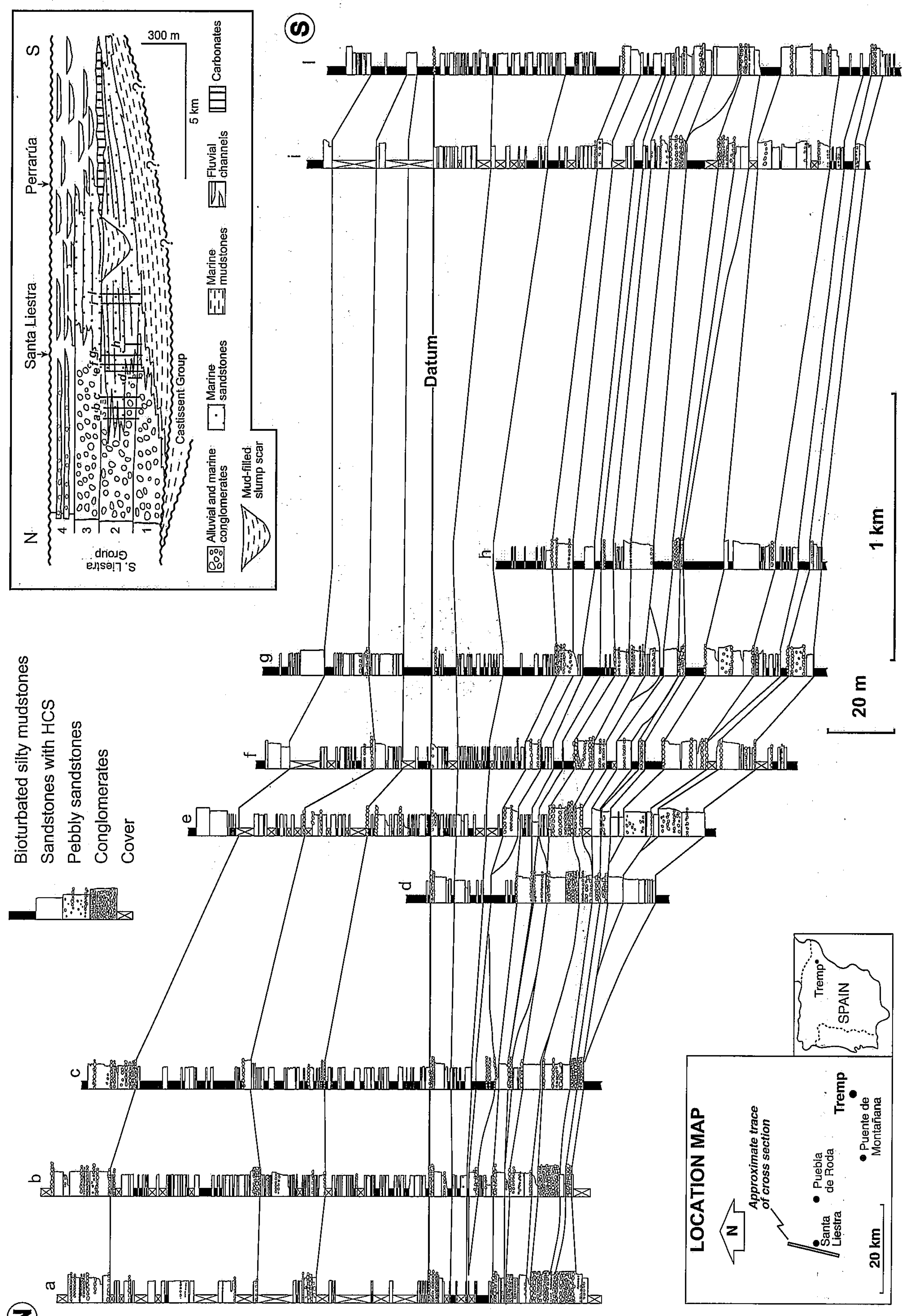
Figure 7.- A) Example a of sharp-based and graded sandstone bed deposited in a shelfal environment by a hyperpycnal flow. Note the occurrence of HCS in the middle part of the bed. Note also the abundant skeletal debris in the basal part of the bed (*cf.* Fig. 7B). Bardas Blancas Formation, Nequén Basin, Argentina. B) Close-up of Fig. 7A showing the basal division of the sandstone bed containing abundant skeletal debris (mostly valves of the pelecypod Trigonia). These intrabasinal skeletal debris indicates that hyperpycnal flows were able to produce substantial bed erosion and therefore increase their density to become self-sustained flows (see text for more details). C) Ball-and-pillow structure in a graded sandstone bed deposited by a hyperpycnal flow in a delta-front environment. This type of immediately post-depositional structure, produced by loading and favoured by the broadly lenticular, convex-up geometry of sandstone beds containing large-scale HCS, is common in delta-front sandstone lobe successions due to high-rates of sedimentation (*e.g.*, Sabiñanigo Sandstone of the Jaca Group). The example shown in the photograph is from the Santa Liestra Group, near Fantova. D) Example of a graded sandstone bed deposited by a hyperpycnal flow in a distal delta-front environment. Note the relatively coarse-grained, basal sandstone division with abundant mudstone clasts and skeletal debris (larger foraminifera). The top of this division is a convex-upward surface moulded by a turbulent flow with a strong oscillatory component; this flow is responsible for the deposition of the overlying and finer-grained sandstone division with HCS.

lly active basins has been amply discussed by Nemec (1995); the various processes leading to the separation of hypopycnal plumes from associated hyperpycnal flows have been discussed at length by (Wright *et al.*, 1986; Sparks *et al.*, 1993; McLeod *et al.*, 1999) on the basis of experimental work and numerical modeling.

Facies, facies associations and inferred depositional processes of fan-delta and river-delta systems are briefly discussed in the following sections.

Fan-delta systems

The type of ancient fan-delta system considered in this paper is very common in the fill of many structurally-confined basins and consists of individual flood-units expressed by essentially tabular bodies that can be traced directly from alluvial into shallow-marine environments without intervening beaches or tidal flats. Where preserved, the shorezones are mainly recorded by lenses of sandstone, rich in skeletal debris, deposited by weak wave and storm activity. These sediments separate alluvial and coastal plain fines from marine mudflats, thus suggesting an overall low-energy marine basin between periods of time during which flood-dominated sedimentation prevailed. Typical examples of this kind of fan-deltas are found in the Cretaceous of the Neuquen basin, Argentina, and particularly in wedge-top basins like the Pleistocene of the southern Apennines, and the Eocene of the south-central Pyrenees, Spain (Mutti *et al.*, 1996). The stratigraphic cross-section of figure 8 depicts part of the spectacularly exposed Cuisian-Lutetian Santa Liestra Group, in the Esera valley, south-central Pyrenees, where some 500 m of conglomerates fed from the north by the growing Pyre-


Bioturbated silty mudstones
Sandstones with HCS
Pebbly sandstones
Conglomerates
Cover
N
S
a
b
c
d
e
f
g
h
i
l
Datum
20 m
1 km
Santa Liestra
Perrarúa
300 m
5 km
S. Liestra Group
Castissent Group
Alluvial and marine conglomerates
Marine sandstones
Marine mudstones
Fluvial channels
Carbonates
Mud-filled slump scar
LOCATION MAP
Approximate trace of cross section
Santa Liestra
Puebla de Roda
Tremp
Puente de Montañana
20 km
SPAIN

nean chain pass into a similarly thick succession of delta-front sandstone lobes in a basinward direction.

Because of their internal geometry, facies and facies associations, these systems are difficult to frame within current sedimentological models of fan-deltas. The latter essentially include slope-type and shelf-type fan-deltas as discussed by many authors (Ethridge and Wescott, 1984; Postma, 1990). The flood-dominated fan-delta systems described in this paper share the geometry of shelf-type fan-deltas, but differ from the latter in that they are almost entirely composed of facies types generated by flood-generated flows in their both alluvial and marine components. Apparently, systems of this type are unreported from modern settings either because they are extremely rare or have not yet been recognized.

Facies tracts and inferred processes

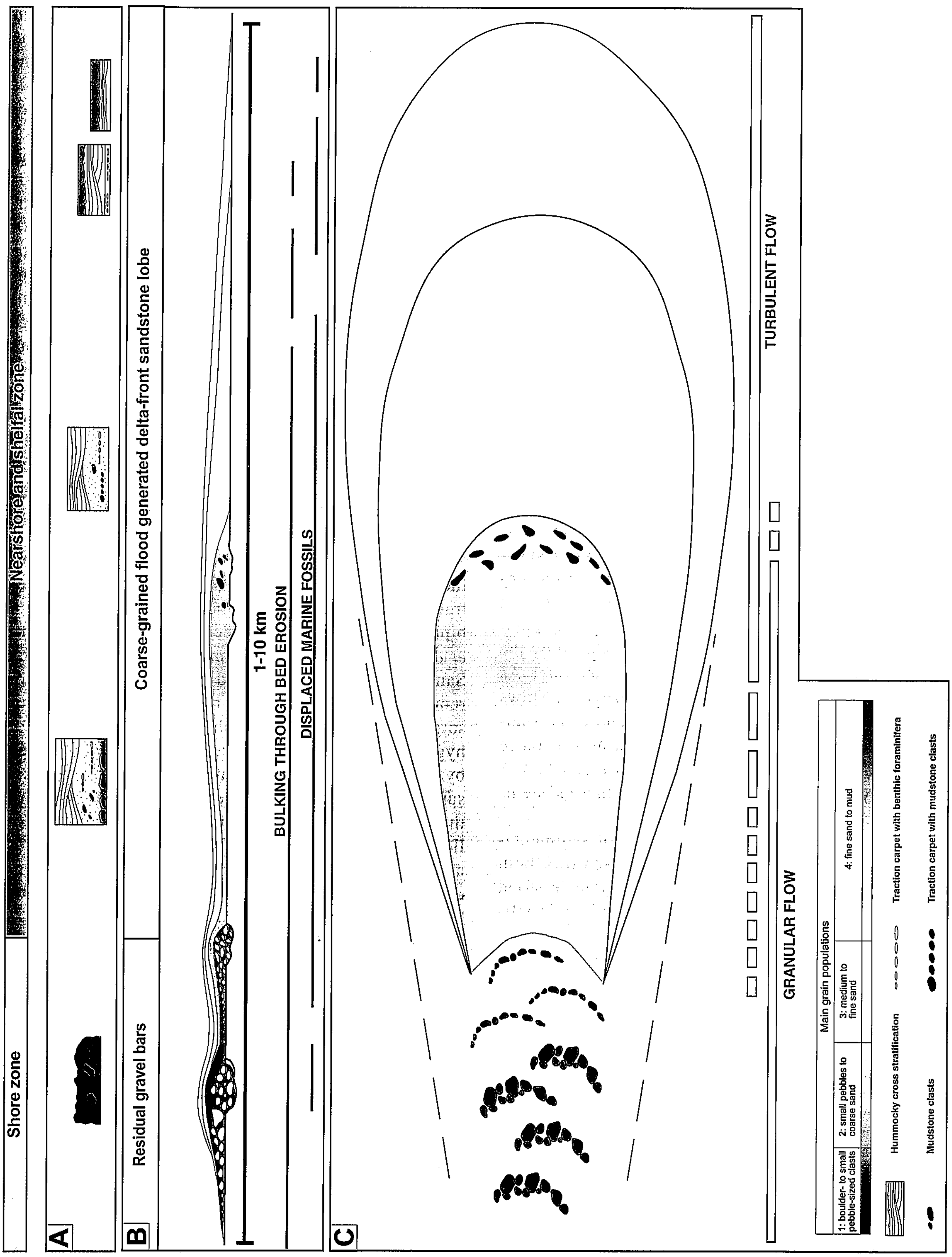
Facies tracts and stratigraphic relationships observed in flood-dominated fan-delta systems suggest an origin from subaerially-derived, catastrophic hyperconcentrated flows. Although subaerial, these flows are probably similar to the submarine "flowslides" of Norem *et al.* (1990), and thus initially triggered by sediment liquefaction on relatively steep slopes. Once substantially accelerated along high-gradient and entrenched fluvial valleys, these flows enter seawaters at short distance from fan apexes, thus maintaing sufficient momentum to reduce the deceleration produced by the change in slope, friction and mixing with seawater. As a result, the flows can move as hyperpycnal flows across gently sloping and even flat nearshore and shelfal regions carrying their sediment load at a distance controlled by the efficiency of each flow (see later). A common type of facies tract observed in these systems is shown in figure 9.

The processes involved in this kind of sedimentation are quite complex mainly because these flows, both subaerial and subaqueous, remain poorly understood despite the many papers that have dealt with their definition and characteristics over the past thirty years (*e.g.*, Middleton and Hampton, 1973; Nemec and Steel, 1984; Pierson and Costa, 1987; Costa, 1988; Coussot and Meunier, 1992; Kim *et al.,* 1995; Shanmugam, 1996, 2000; Major and Iverson, 1999). As used in this paper, a hyperconcentrated flow is intended as a high-density, inertia-driven mixture of sediment and water that moves downslope under conditions of high pore-fluid pressure (see Table I). Based on field observations, experimental debris flows, and numerical modeling, pore-fluid pressure appears to play a key role in effectively reducing friction within both subaerial and submarine hyperconcentrated flows (*e.g.*, Norem *et al.,* 1990; Mohrig *et al.,* 1998; Major and Iverson, 1999; and Mutti *et al.,* 1999), thus substantially increasing their run-out. We are aware of the fact that the term "hyperconcentrated flow", as used in this paper, may be a source of confusion. The term is actually used by most authors to describe flows which are transitional between debris flows and streamflows. However, the prefix "hyper" (from the Greek "huper") actually implies the sense of "over", "above", "exceeding" or "excessive" (from the Concise Oxford Dictionary of Current English). Therefore, within a spectrum of density flows, the term "hyperconcentrated flow" should be used to define that cohesionless debris flow which is the most dense.

The ideal scheme of figures 9B and 9C illustrates the processes which can be inferred from the facies tract of figure 9A. The scheme is derived from that of bipartite turbidity currents recently proposed by Mutti *et al.* (1999) and partly stemming from the work by Sanders (1965), Ravenne and Beghin (1983) and Norem *et al.* (1990). In bipartite turbidity currents, a coarse-grained granular flow (cohesionless debris flow or hyperconcentrated flow of Table I), essentially driven by inertial forces under conditions of excess pore pressure, initially forms the faster-moving frontal part of the current in which the coarsest particles tend to collect along the flow edges. The granular flow moves ahead of a more dilute turbulent flow carrying suspended finer-grained sediment until it is decelerated by decreased shearing and internal friction due to the loss of pore-fluid prêssure through water escaping; the granular flow is thus bypassed by the more dilute turbulent flow which has a much longer run-out. The whole process implies an inverse (fining upcurrent) longitudinal grain-size gradient during the early phases of transport and deposition followed by a normal (fining downcurrent) gradient during the subsequent depositional stages (see Mutti *et al.,* 1999 for a more extensive discussion).

Based on field observations on ancient alluvial strata, Sohn *et al.* (1999) have recently suggested a similar model introducing the concept of composite sediment flow. A flow of this kind includes a preceding debris flow (cohesive or cohesionless), a trailing watery flow (streamflow), and an intermediate flow (hyperconcentrated flow). The model, however, does not take into account the importance of pore-fluid pressure nor the

Figure 8.- Stratigraphic cross section of part of the Santa Liestra Group in the Esera valley, representing a spectacular example of a flood-dominated fan-delta system. From north to south, the lower part of the cross section depicts the facies change from conglomerates deposited through the frictional freezing of hyperconcentrated flows to graded sandstone beds with HCS deposited by trailing turbulent flows (see text for a more extensive discussion). As indicated by interval geometry, this first phase of deposition takes place concurrently with uplift in the north and subsidence in the south. Above the datum, the trend is inverted and the section expands northward as a result of a later thrust propagating farther southward. The uplift related to this thrust is clearly indicated by large-scale slump scars and the onset of carbonate deposition in the south (see insert). Original field data from Ph. Crummeyrolle (1987); new interpretation added.


Shore zone
Nearshore and shelfal zone
A
B
Residual gravel bars
Coarse-grained flood generated delta-front sandstone lobe
1-10 km
BULKING THROUGH BED EROSION
DISPLACED MARINE FOSSILS
C
GRANULAR FLOW
TURBULENT FLOW
Main grain populations
1: boulder- to small pebble-sized clasts
2: small pebbles to coarse sand
3: medium to fine sand
4: fine sand to mud
Hummocky cross stratification
Traction carpet with benthic foraminifera
Mudstone clasts
Traction carpet with mudstone clasts

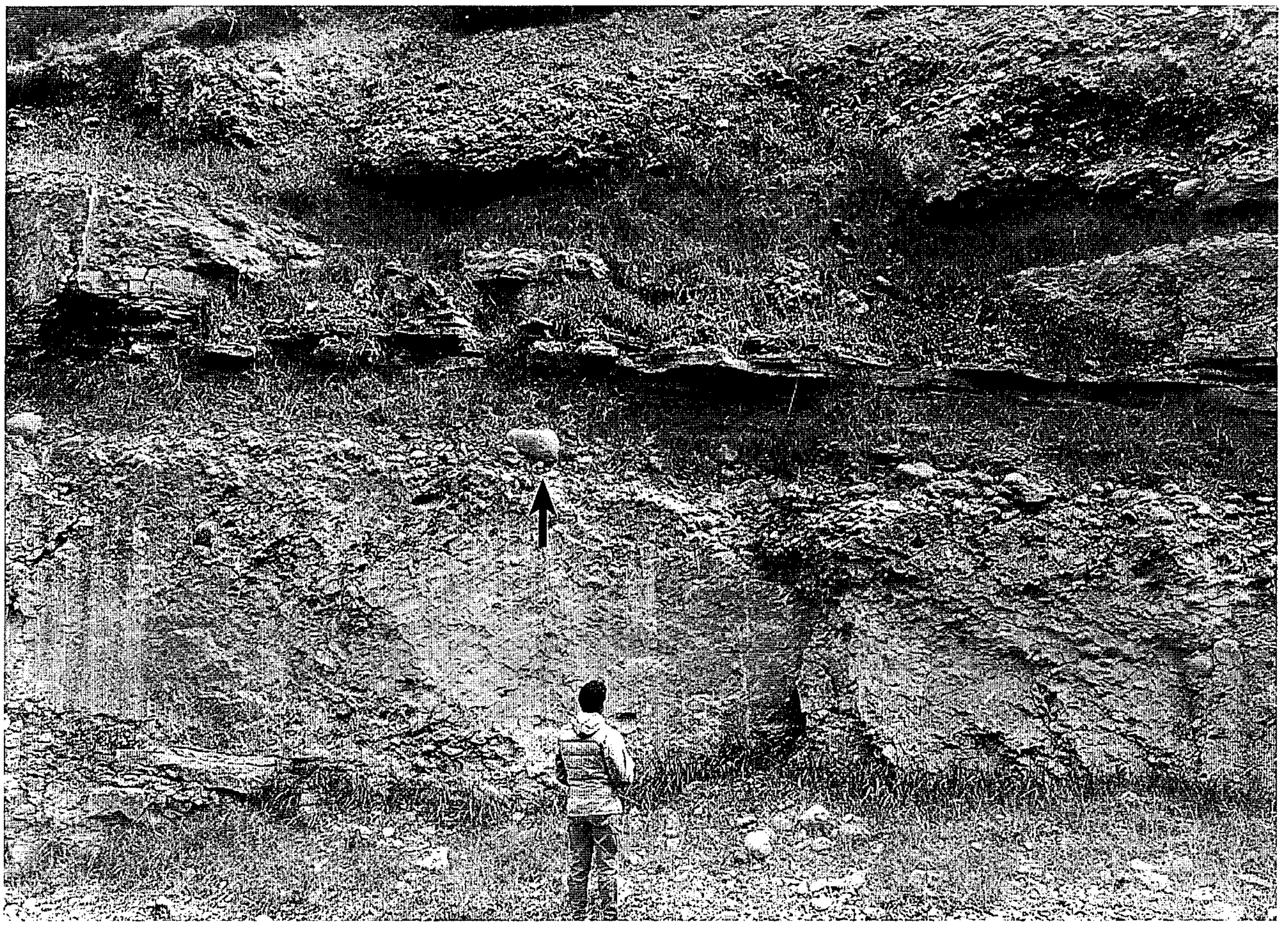


Figure 10.- Conglomerates deposited by hyperconcentrated flows in a fan-delta system. Note the irregular bedding geometry mainly produced by the frictional freezing of the heads of successive sedimentation waves. Individual conglomerate units commonly show pebble and cobble alignments at their top (indicated by arrow) resulting from extensive reworking produced by bypassing turbulent flows (see text for details). Santa Liestra Group, roadcut north of Santa Liestra.

mixing with ambient fluid, two important factors in controlling transport and sedimentation in the marine environment. This kind of flow (see Table I) is briefly discussed in the following sections dealing with river-delta systems.

In its proximal sector, the facies tract of figure 9A can be interpreted as the product of a sustained flood-generated bipartite current in which an initially faster-moving, hyperconcentrated flow (granular flow) probably moves, as suggested by Major and Iverson (1999) and Sohn *et al.* (1999), through a series of surges. Successive surges, or sedimentation waves, are composed of progressively finer-grained sediment and each of them bypasses the deposit left behind by the former ones (Mutti *et al.*, 1999). Deposition can occur through the frictional freezing of the coarsest clasts collected at the leading edges of each surge or through the *en-masse* freezing of the entire surge. Surging will continue until water and sediment escaping and grain-to-grain and bed friction force the granular flow to stop.

Figure 9.- The commonly observed facies tract of flood - dominated fan-delta systems (A). This facies tract is particularly well exposed in the fan-delta systems of the Santa Liestra Group, between the Isabena and Esera valleys (see Fig. 8). The interpretation of the facies tract is shown in cross-sectional and plan-view diagrams (B and C). See text for a detailed discussion. Note the importance of successive sedimentation waves.

More basinward, the facies tract of figure 9A implies a quite different sedimentation associated with the more dilute turbulent flow. This flow, which is continuously fed from behind as long as the flood continues, thickens in the shorezone due to mixing with seawater (Wright, 1977; McLeod *et al.*, 1999), and additional thickening must occur seaward through turbulence generated at the boundaries of the preceding granular flow. During the process, however, we argue that the lower part of the turbulent flow must increase its sediment concentration through (1) fall-out from the overlying suspension (cloud collapse in the sense of McLeod *et al.*, 1999), (2) sediment escaping from the underlying granular flow due to the loss of pore-fluid pressure (see extensive discussion in Mutti *et al.*, 1999), and (3) substantial bed erosion (Mutti *et al.*, 1996). In other words, the deceleration of the flow due to mixing with seawater is exceeded by the acceleration

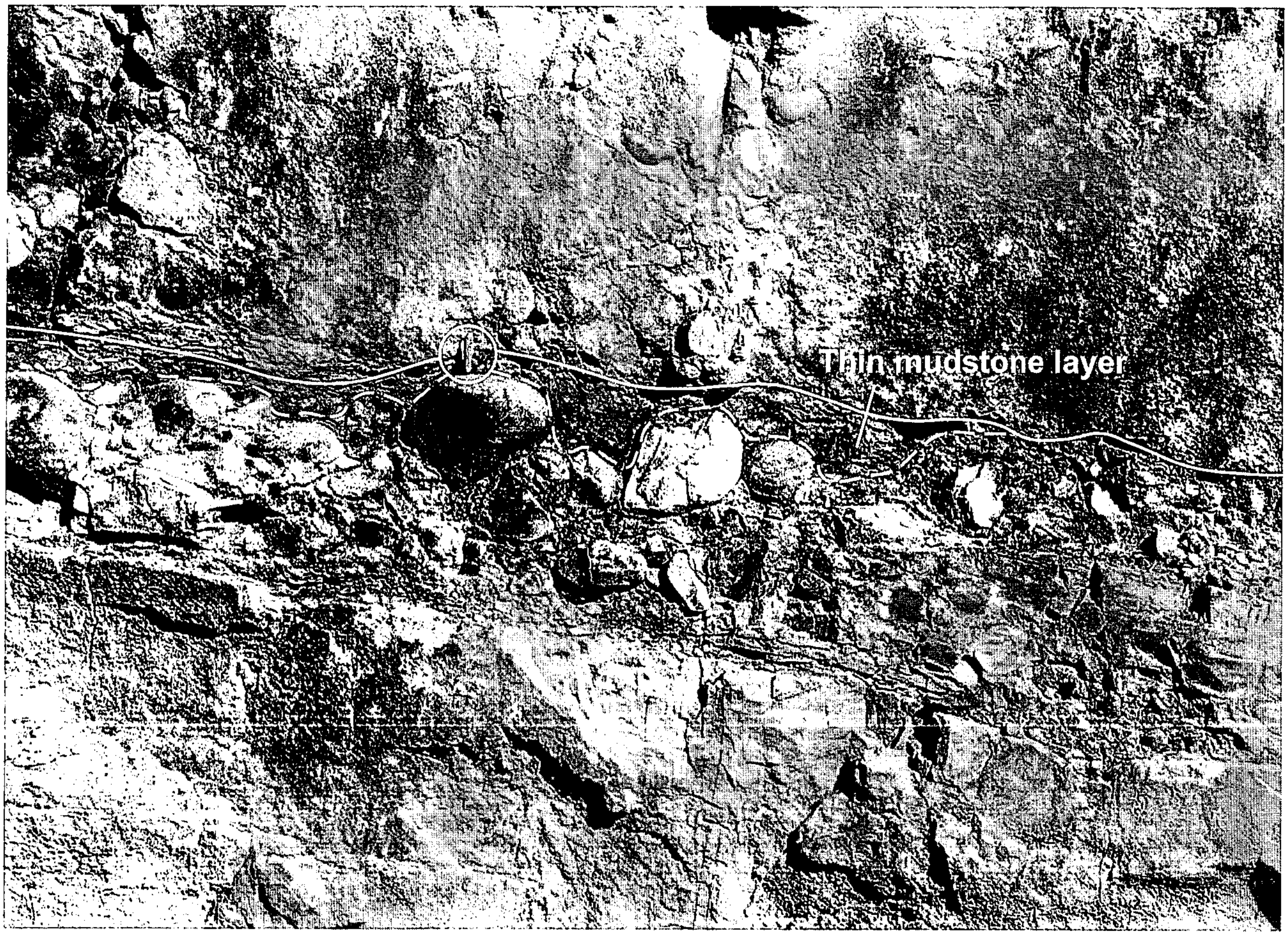


Figure 11.- Cobble and pebble alignment resting on top of a sandstone unit and sharply overlain by a thin mudstone layer. The alignment was produced by prolonged traction exerted by an overlying bypassing turbulent flow. The finely-laminated mudstone layer probably represents the latest and dilute stage of the same flood. Santa Liestra Group, roadcut north of Santa Liestra.

imparted by the increased sediment concentration resulting from the incorporation of fine-grained sediment. As a result, the lower part of the flow becomes a relatively high-density turbulent flow that will eventually bypass the frozen, coarser-grained deposits of the basal decelerating granular flow and move farther basinward carrying its sediment load to more distal delta-front regions.

Bed erosion is clearly indicated by the commonly very abundant rip-up mudstone clasts and shell debris eroded by the turbulent head of the preceding granular flow, incorporated within subsequent surges and typically observed in the lower part of the sandstone divisions deposited by the trailing turbulent flow (Fig. 7D).

Individual beds, or flood-units, forming in these depositional settings can greatly vary from each other also within the same depositional system mainly as a function of the efficiency of each flow. The concept of flow efficiency as related to turbidite sedimentation has been discussed in many papers (*e.g.*, Mutti, 1979, 1992b; Pickering *et al.,* 1989; Allen and Allen, 1990; Richards *et al.,* 1998) with reference to the ability of the flow to carry its sediment load in a basinward direction. The concept has been recently expanded to incorporate also the ability of the flow to segregate its grain-size populations into distinct facies types with distance (Mutti *et al.,* 1999). Very highly efficient flows can fully segregate the grain-size populations contained within the flow with distance, thus producing relatively well-sorted facies types, each characterized by distinctive internal structures. Conversely, very poorly efficient flows can only partly segregate their different grain-size populations, thus producing a more limited number of facies types generally characterized by poor textural sorting and less distinctive internal structures. In bipartite turbidity currents, flow efficiency has to be considered separately for the two component flows (basal granular flow and overlying turbulent flow).

The same basic concepts can be used for the bipartite currents that are thought to be responsible for transport and deposition in flood-dominated fan-delta systems. The facies tract shown in figure 9A refers to very highly efficient bipartite currents that can produce an effective vertical and longitudinal segregation of the grain-size populations contained in both the basal granular flow and overlying turbulent flow. All other things being equal, the efficiency of the basal granular flow - *i.e.* its ability to transport coarse-grained clasts over considerable distances - essentially resides in its ability to maintain substantial excess pore pressure to prevent grain-to-grain and bed friction. The efficiency

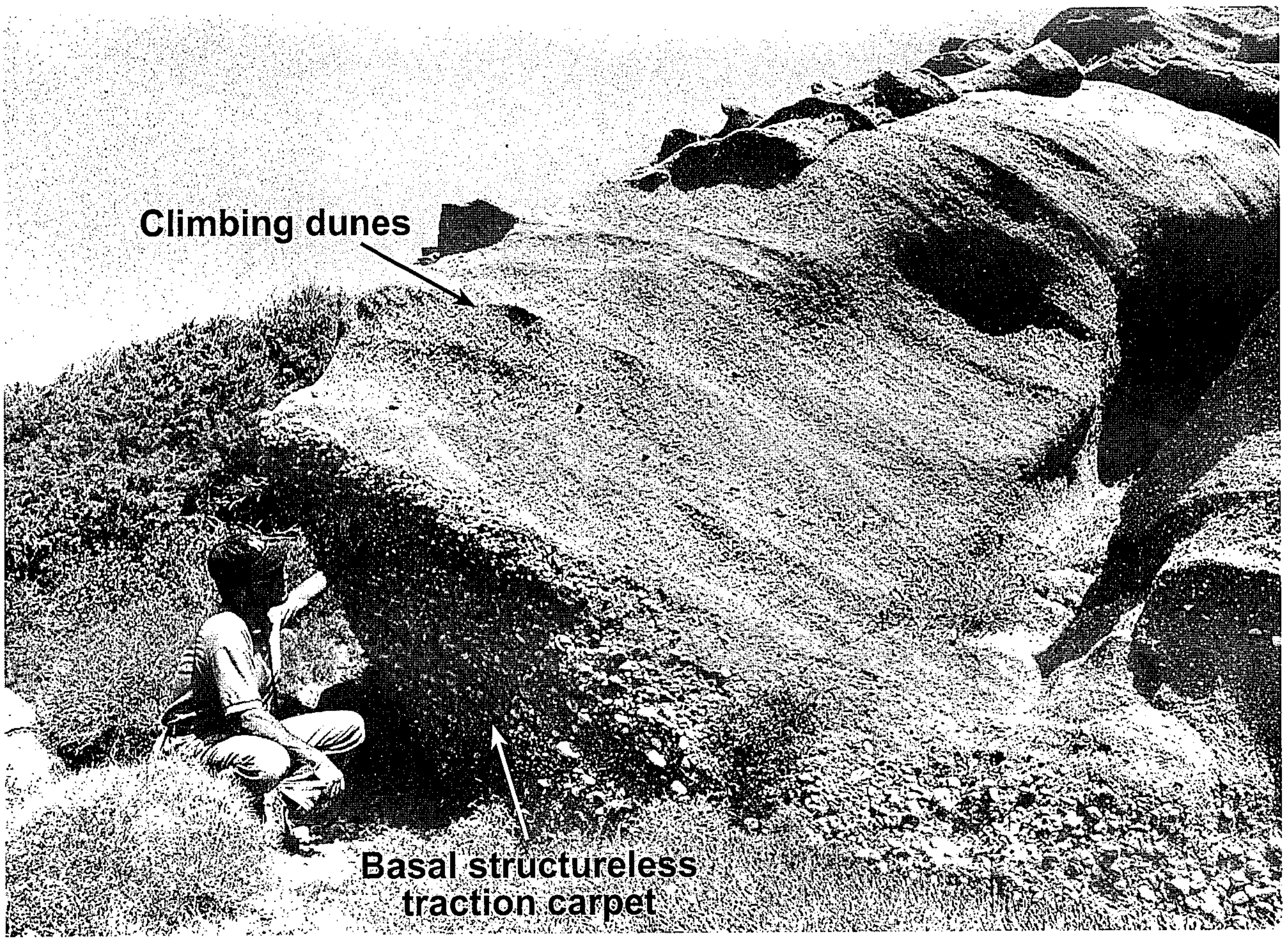


Figure 12.- Typical example of flood unit deposited by a waning sediment-laden stream flow. The basal structureless division, consisting of pebble-sized conglomerate with sandy matrix, is thought to represent a traction carpet frozen due to friction. This division is overlain by an overall graded sandstone division, with small pebbles in its lower part, showing climbing dunes with preservation of sandstone laminae on stoss sides. Note the progressive thinning upward of individual sets of cross laminae. Lacustrine Pliocene strata,Island of Rhodes, Greece.

of the turbulent flow depends primarily on the amount of turbulent energy generated at flow boundaries and, therefore, on the amount of relatively fine-grained sediment the flow can incorporate from the basal granular flow and bed erosion taking place at the head of the latter.

Highly-efficient flows produce sediment bypass and therefore very distinctive grain-size breaks in the deposit. Spectacular examples of bypass can be observed in the Santa Liestra Group, where conglomerate divisions representing the frozen coarse-grained heads of hyperconcentrated flows are abruptly covered by thin mudstone layers deposited by the very dilute tail of the flows. Mudstone drapes are deposited following a phase of strong traction and reworking by a bypassing turbulent flow leading to the formation of very distinctive pebble and cobble alignments. Some of these features are illustrated in figures 10 and 11.

River-delta systems

River-delta systems dominated by flood-related processes show a great variety of intergradational depositional styles ranging from very small and coarse-grained systems built by ephemeral and very high-gradient streams to relatively large and longer-lived systems in which thick and laterally extensive sandstone bodies were deposited in delta-front regions through time. The Eocene strata of the southern Pyrenees contain nearly all the possible varieties of this kind of sedimentation in a large number of deltaic systems that can be recognized from the uppermost Cretaceous Aren Sandstone to the final infill of the marine basin during Bartonian and Priabonian (Fig. 1). More specifically, spectacular examples of these delta systems can be observed in the Aren Sandstone, the Figols, Castigaleu and Castissent groups, and the Bartonian and Priabonian Sabiñanigo and Atarès formations of the Jaca Group.

Flood-dominated river-delta systems differ from fan-delta systems in that they contain mouth-bar deposits recording the complex interaction of processes which characterize river mouths when flood-generated sediment-laden stream flows enter seawaters. Wright (1977, with references therein) has extensively reviewed river-mouth processes for a significant number of modern rivers, and defined the basic mouth-bar types for inertia-, friction-, and buoyancy-dominated effluents (see also Nemec, 1995). Because of their den-

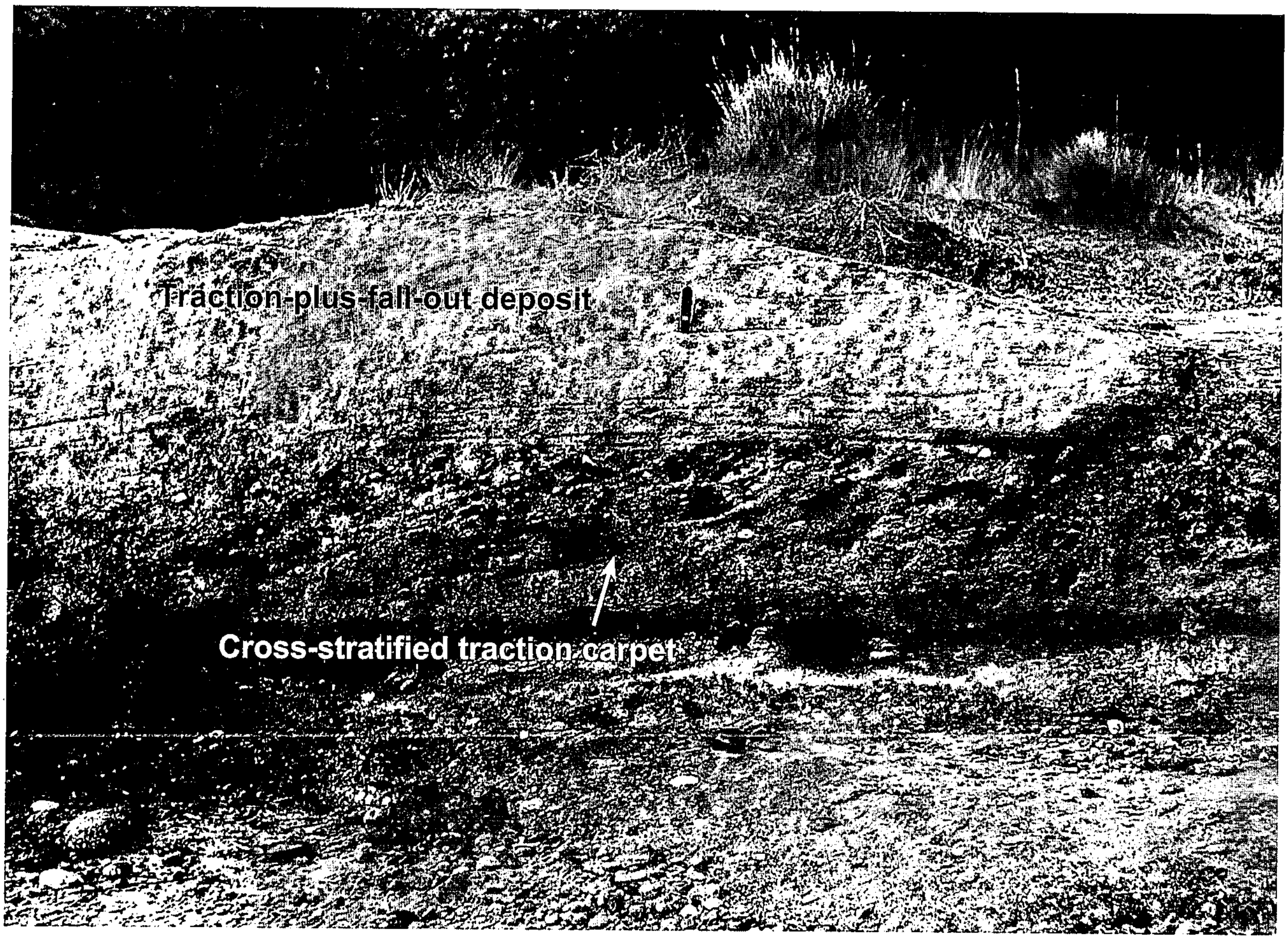


Figure 13.- Cross-stratified pebbly-sandstone forming the basal division of a flood unit deposited by a sediment-laden stream flow. The pebbly-sandstone is interpreted as a traction carpet. Note the abrupt grain-size break at the boundary between the traction carpet and the overlying laminated sandstone deposited by a turbulent flow. Internally-stratified and structureless traction carpets are commonly intergradational. Castissent Group.

sity and momentum, sediment-laden streamflows must enter seawater as inertia-dominated outflows, thus forming either axial or plane turbulent jets, depending on the depth of seawater at and seaward of the river mouths. Wright *et al.* (1986) and Prior *et al.* (1986) have emphasized the importance of these sediment-laden turbulent flows exiting the mouth of the modern Yellow River delta. These authors could observe relatively low-density plumes forming wide-spread underflows over the delta-front region, and infer the occurrence of higher-density plumes with a strong erosive character based on the presence of subaqueous valleys partly filled with mud. Field observations from ancient flood-dominated river-delta systems, although much smaller than the modern Yellow River, provide further and significant insight into this kind of sedimentation in terms of geometry, facies types and facies associations. In particular, these observations add useful information about the depositional relationships between mouth-bar and lobe deposits, the latter being unreported from modern settings.

In ancient river-delta systems, river-mouth deposits show a great variability in terms of geometry and facies types essentially recording locally prevailing conditions that may range from erosion and sediment bypass to deposition of the entire sediment load. Facies distribution patterns are thus mainly controlled by how much sand is trapped at river mouths and how much can escape this region through hyperpycnal flows which can move farther basinward and deposit their sand load as delta-front lobes. For convenience, this ratio can be considered in terms of flow efficiency (see later).

Facies and inferred processes

As inferred from facies and facies associations and sandbody geometry, sedimentation in river-delta systems is dominated by flow types which are different from but partly intergradational with the hyperconcentrated flows of fan-delta systems. The facies types of the flood-units observed in the alluvial segments of these delta systems suggest that transport and sedimentation is essentially controlled by two types of intergradational flows: (1) sediment-laden streamflows, and (2) composite sediment-laden stream flows (Table I).

Sediment-laden stream flows, commonly containing a relatively thin and coarse-grained traction carpet at their base, are apparently more common in relatively

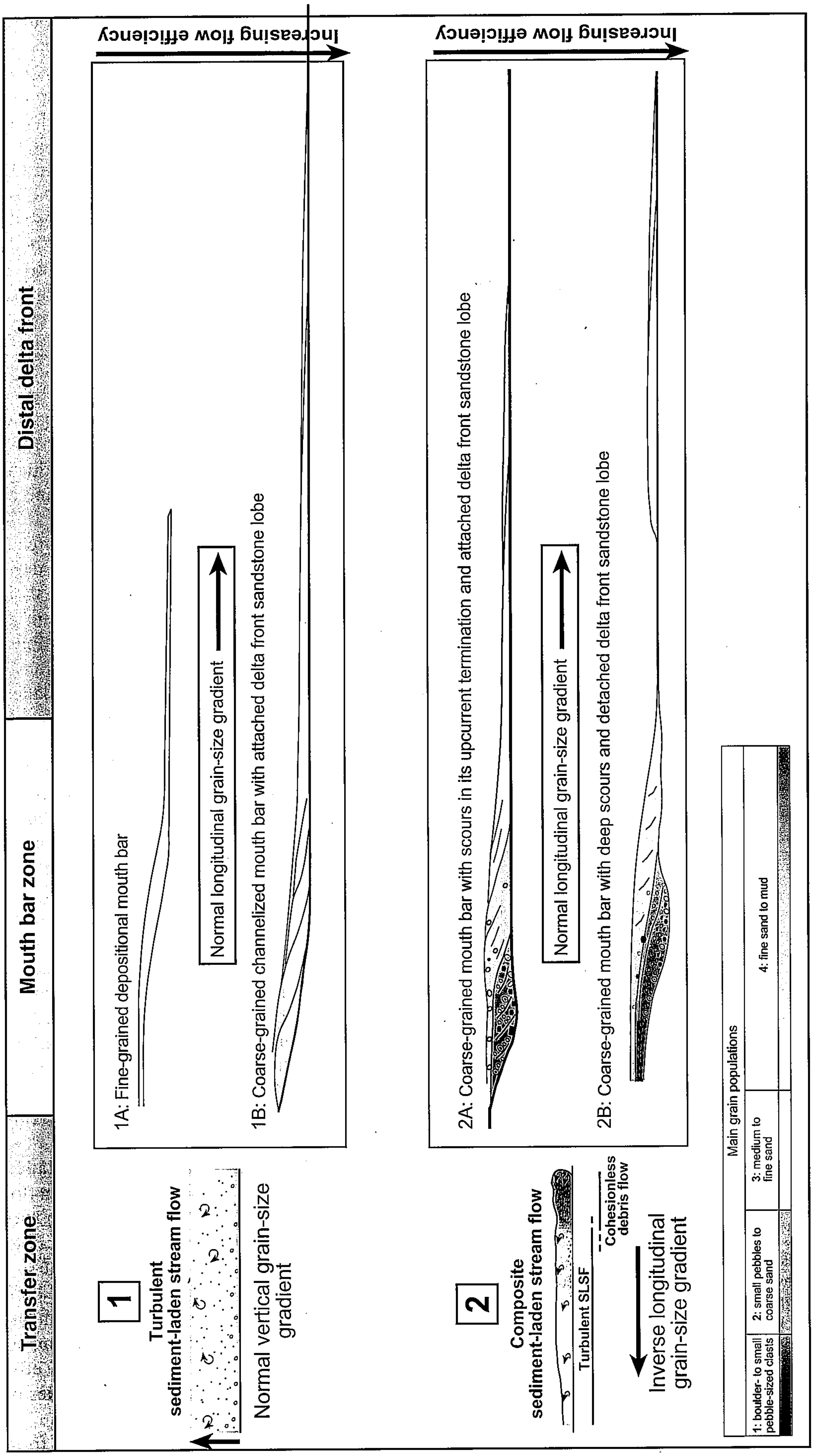


Figure 14.- Diagrams showing the main facies tracts as observed in flood-dominated river-delta systems (see text for explanation).

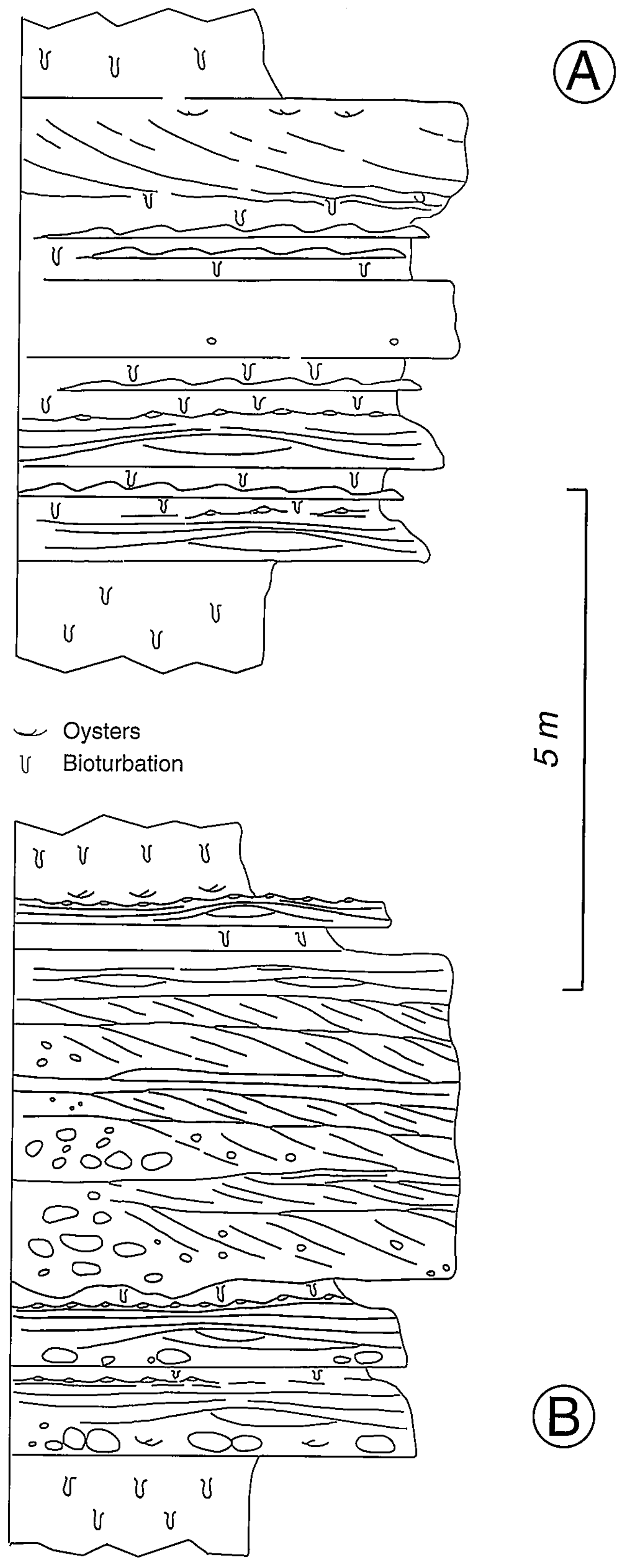


Figure 15.- Examples of facies sequences observed in delta-front strata. A) fine-grained mouth-bar deposits on more distal delta-front sandstone lobes (compare with photograph of Fig. 16B). B) Coarse-grained mouth-bar deposits showing the downcurrent transition from structureless pebbly sandstones (hyperconcentrated flow deposit) to sigmoidally-shaped sets of cross laminae progressively thinning in a downcurrent direction (compare with photograph of Fig. 18). These mouth-bar deposits overlie sandstone lobe sediments with HCS and basal pebble alignments. Both examples are from the stratigraphically upper part of the Figols Group in the Tremp area (from Mutti *et al.*, 1996).

mature and low-gradient systems lacking substantial amounts of gravel. In these fully turbulent and density-stratified flows, sand and mud are essentially transported as suspended load and their deposition takes place through traction-plus-fall-out processes in overall vertically graded flood-units (Figs. 12 and 13). Excellent examples of these flood-units can be observed in the sandstone sheets occurring in the lower part of the Castissent Group. During their declining stage, when sediment concentration has become negligible, some floods move as streamflows ("clear-water" stage of Mutti *et al.*, 1996), thus reworking the sandy deposits of former flood stages into purely tractive bedforms.

In relatively smaller, higher-gradient and gravel-rich systems, facies characteristics of flood-units suggest transport and deposition from more complex types of flow characterized by a marked inverse longitudinal grain-size segregation. These flows are similar to the composite sediment flows of Sohn *et al.* (1999) which, as noted earlier, include a preceding, dense granular flow ("debris flow") followed by an intermediate flow ("hyperconcentrated flow") and a more dilute stream flow. The model proposed by Sohn *et al.* (1999) is derived from ancient alluvial fan strata and, therefore, their "debris flows" can be seen in terms of hyperconcentrated, cohesionless flows as discussed in earlier sections. Essentially, these composite sediment flows are transitional between hyperconcentrated and sediment-laden streamflows and are referred to in this paper as "composite sediment-laden streamflows".

Characteristically, the deposit of these flows in the fluvial environment is recorded by bipartite beds each consisting of a basal conglomeratic division, commonly clast-supported, overlying by a coarse-grained sandstone or pebbly-sandstone division which can be either crudely or internally stratified. These deposits, which essentially coincide with those described by Todd (1989), form highly lenticular units because of extensive scouring, and only rarely contain finer-grained and thoroughly laminated divisions at their top, mainly because fine-grained sediment was kept in suspension by the flow and carried farther downcurrent. In the Eocene of the south-central Pyrenees, excellent examples of these fluvial deposits can be observed in particular in the alluvial component of the Castigaleu Group outcropping in the general area between Tremp and Puente de Montanyana.

As observed in ancient strata, sediment-laden stream flows and composite sediment-laden stream flows produce substantially different types of mouth bars and delta-front lobes when entering seawater at river mouths. The basic facies tracts of these different settings are diagramatically shown in figure 14. For both sediment-laden streamflows and composite sediment-laden streamflows, figure 14 indicates the end-members of the observed facies tracts as related to flow efficiency. Figures 15 and 16, illustrate some examples of these different delta-front settings.

Poorly-efficient sediment-laden streamflows form very simple facies tracts, basically showing the abrupt

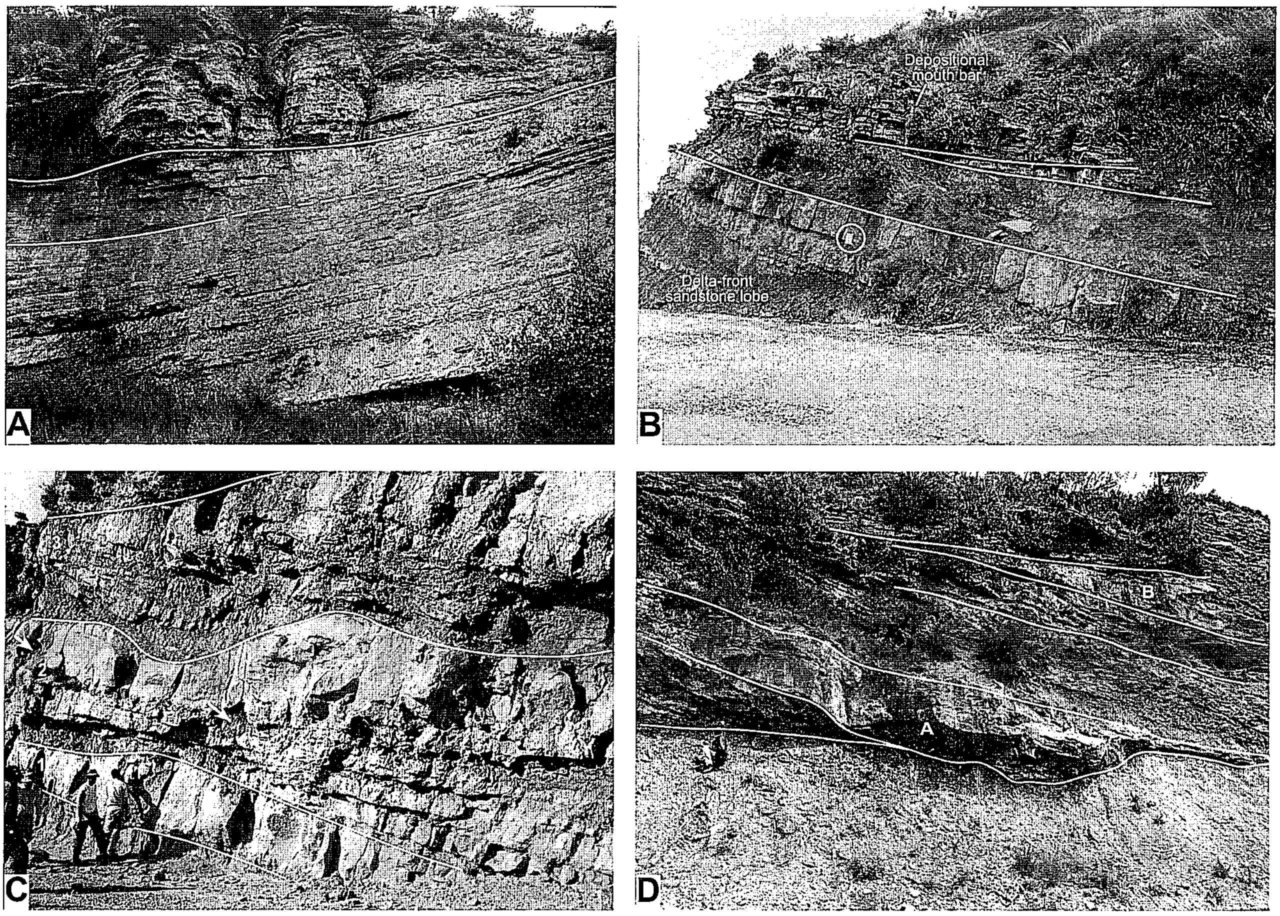


Figure 16.- A) Example of a mouth-bar facies association deposited by small-volume and relatively low-density underflows (poorly-efficient flows of Fig. 14 - 1A) that were forced to deposit their fine-grained sand load on the bar slope due to sudden flow deceleration. Note the three basic elements of the bar: crest, slope, and toe. Individual flood-units thin and fine out over short distance. Atarés Formation (Jaca Group), west of Jaca. B) Examples of a depositional mouth-bar unit prograding through low-angle clinoforms on top of more distal and vertically-accreted delta-front sandstone lobes (Figols Group in Tremp area). C) Complex geometry and stacking pattern of mouth-bars sediments deposited by composite sediment-laden stream flows entering a brackish basin. Note deep scouring, large mudstone clasts (arrows), and poorly-defined frontal accretion in the unit 3 (Castigaleu Group, Val Isabena area). D) Mouth-bar complex showing a coarse-grained, channelized body terminating abruptly in a downcurrent direction (A). This unit is thought to represent the deposit of a highly-erosive and bypassing flow (see highly-efficient flows of Fig. 14 - 2B). Higher in the section, mouth-bar deposition continues through predominant, frontally-accreting strata associated with less erosive flows (B). General paleocurrent direction from left to right. Castigaleu Group, Isabena valley.

deceleration of relatively dilute, flood-generated suspensions when entering seawater (Fig. 14-1A). Characteristically, the deposit of these currents are sharp-based and graded beds, commonly less than 20 cm thick, consisting of fine sand and silt with locally abundant plant fragments. Internal depositional divisions are generally poorly developed and restricted to parallel and small-scale cross laminae; small wave-ripple laminae may be common at the top of individual beds.

Beds of this type are almost invariably arranged into clinoforms connecting the crest of the mouth bar with its toe. Along these sloping surfaces, individual sandstone beds thin and fine out over short distances in a seaward direction, passing into prodelta mudstone-dominated facies. The best interpretation that can be offered for these deposits is that of McLeod *et al.* (1999) involving a sudden gravitational collapse of suspension clouds due to mixing with seawater, the formation of density currents, and their rapid deceleration followed by deposition along the bar slope. The common lack of mudstone divisions at the top of these beds suggests that most of the mud was kept in suspension by buoyant plumes and thus carried farther seaward.

Mouth-bar deposits of this type form very distinctive progradational units, with individual thicknesses commonly between 1-5 m and slope varying as a function of the water depth at and seaward of the river mouth. The internal geometry of these units, the lack of prominent scours, and the overall fine-grained texture suggest they originate from very poorly efficient flows. These deposits may thus be regarded as the ancient analog of modern fluvial-dominated mouth bars forming during "normal" flood stages characterized by dilute sediment-laden stream flows approaching homopycnal conditions. Reworking by marine processes (see later) may occur at the top of some bars. No sandstone lobes are observed interbedded with or seaward of these bars, indicating that these floods were not able to generate hyperpycnal flows.

Good examples of this type of bar can be observed in several stratigraphic units of the south-central Pyre-

Figure 17.- Downstream accreted, sigmoidal units, consisting of coarse-grained sandstone, formed at the river mouth of a small delta system. Uppermost part of the Figols Group, Tremp area. For more details see text and caption to Fig. 18.

nees, particularly in the Figols Group and in the Atarés Formation (Jaca Group).

Figure 14-1B shows the facies tract of highly-efficient sediment-laden streamflows characterized by relatively long duration and high sediment concentration. The facies tract shows that the coarser-grained sediment (mostly coarse and medium sand) is deposited at river mouths whereas fine sand and mud are carried seaward into distal delta-front regions to form sheet-like, graded sandstone beds (delta-front sandstone lobe). Based on the observed impressive lateral extent of most sandstone lobes, these facies tracts must have been generated by prolonged flows whose sediment load was primarily represented by fine sand and mud.

Apparently, settings of this type develop when the deceleration of sediment-laden streamflows, due to friction and mixing, forces individual flows to deposit their coarser-grained sediment load at river mouths. However, the flow can maintain sufficient velocity and sediment concentration to enter seawater and move as a highly efficient hyperpycnal flow continuously fed from upcurrent.

The facies formed at river mouths can greatly vary as a function of many factors and particularly the shear stress exerted by the part of the turbulent flow which can exit these mouths. Although displaying various types of bedding geometry and internal depositional structures - including plane-bed laminae, climbing dunes and very complex styles of cross stratification herein omitted (see Mutti and Tinterri, in preparation), river-mouth deposits most commonly show a typical sigmoidal cross stratification developed at different physical scales as a function of the magnitude and duration of individual flows. Examples of this kind of bedding are shown in figures 17 and 18.

First described by Mutti *et al.* (1996) in a preliminary way, sigmoidal cross stratification produced by flood-generated flows is characteristically expressed by sigmoidally-shaped sets of cross laminae which markedly thin and fine out downcurrent and are truncated upcurrent by a flat or slightly convex-upward erosional surface. Individual sigmoidal units, separated by slightly finer-grained partings, accrete frontally to form composite stratal units in which individual lamina-sets progressively thin and flatten in a downcurrent direction, thus indicating overall waning-flow conditions. This sigmoidal bedding should not be mistaken for the tidal sigmoidal bedding (Mutti *et al.*, 1984, 1985) associated with lunar and lower-frequency astronomic cycles. Mud drapes and current reversal, as well as many other distinctive features of tide-dominated facies, are lacking in flood-dominated sediments. The origin of flood-generated sigmoidal bedding is beyond the purpose of this paper, though it is clearly produced by traction exerted by bypassing and turbulent flows, pulsating and overall waning with time.

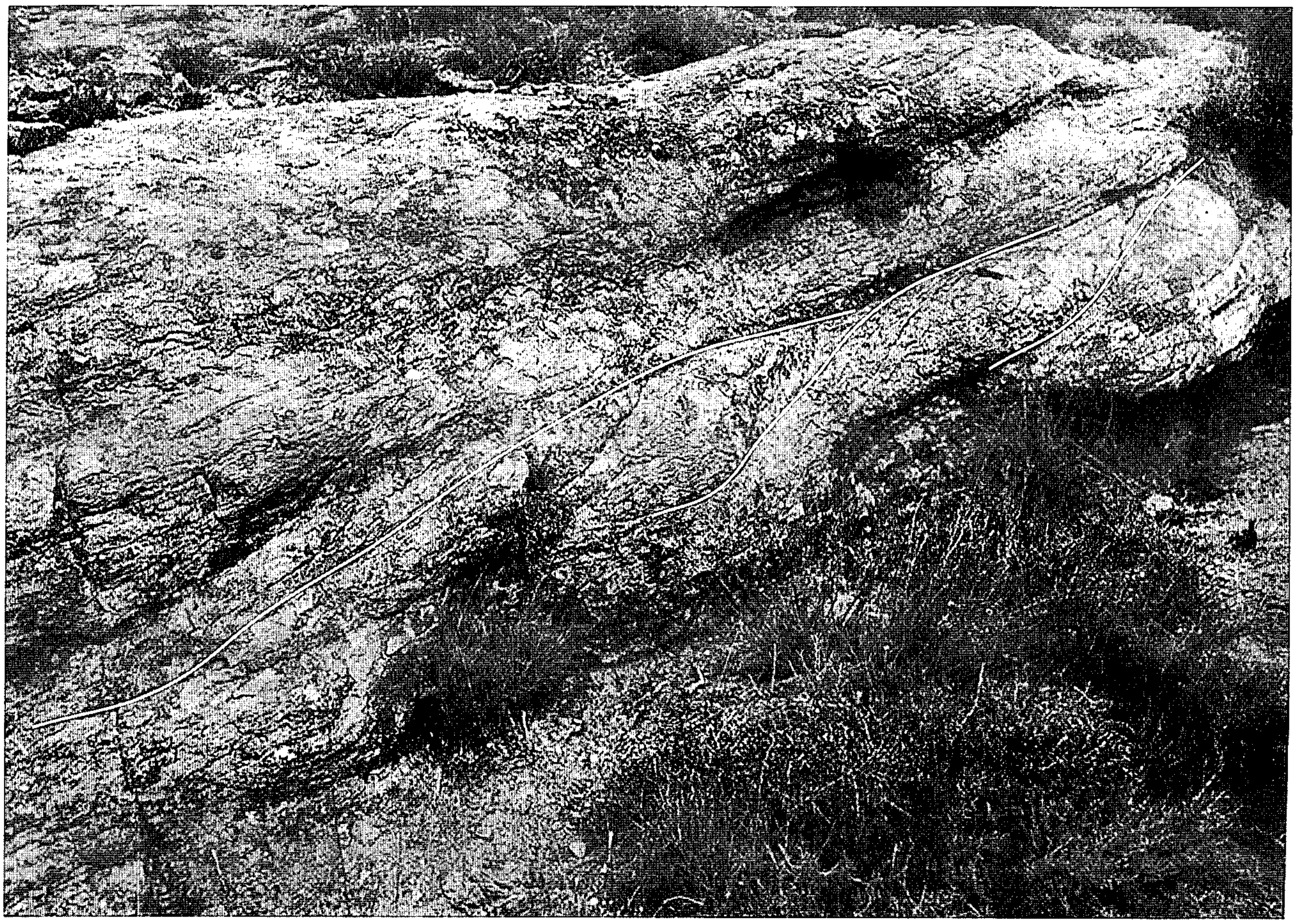


Figure 18.- Internally cross-stratified sigmoidal sandstone units comprising a frontally-accreted composite unit in which individual sigmoids thin and flatten in a downcurrent direction (from right to left). Note the well-defined sigmoidal geometry of individual units, as well as the sligthly convex-upward erosive surface representing the top of the composite sigmoidal unit. See text for more details. Same stratigraphic unit and location as figure 17.

The mouth-bar deposits associated with highly-efficient sediment-laden streamflows may be locally affected by marine reworking, especially tidal currents, suggesting that the rivers responsible for these flows were relatively permanent features, thus permitting the onset of tidal current circulation at their mouths. The extent to which this reworking occurs is probably largely controlled by the local configuration of the receiving basin and the river regime. The Figols strata spectacularly exposed in the Ager syncline show all the transitions between tide- and flood-dominated delta-front settings (Mutti *et al.,* 1985, 1994). Most commonly, however, tidal reworking appears to be limited to the uppermost part of individual mouth-bar deposits, concurrently with declining flood-dominated sedimentation.

Mouth-bar deposits produced by highly-efficient sediment-laden streamflows characteristically fill broad erosional depressions, or channels, cutting into marine strata, thus indicating the highly erosive character of these flows when entering seawater. Bed erosion is also indicated by abundant shell debris, particularly oysters, and rip-up mudstone clasts. Flows of this type can be significantly compared with the "strongly hyperpycnal channelized underflows" inferred by Wright *et al.* (1986) from the delta-front channels of the modern Yellow River.

Sandstone lobes associated with these settings can partly interfinger with mouth-bar deposits but characteristically form more seaward, probably as completely detached features, extending up to several kilometers away from river mouths. An example of this kind of setting from the middle part of the Figols Group near Tremp is illustrated by the map and cross section of figure 19.

Although the hyperpycnal flows generating sandstone lobes are essentially sustained from upcurrent as long as individual floods continue, bed erosion, as indicated by small mudstone clasts and abundant skeletal debris, must increase the density of these flows, though to a lesser extent than in fan-delta systems (see above).

Figure 14-2A shows the facies tract related to relatively poorly-efficient, composite sediment-laden streamflows. In its proximal sector, the facies tract is characterized by a very distinct vertical and longitudinal normal grain-size segregation, from cobble- and pebble-sized clasts to coarse and medium sand. These deposits form bars which can result from an individual flood event or from the stacking of several flood-units. The internal geometry of these bars shows all the variations from high- to very low-angle frontal accretion as a function of the water depth seaward of river mouths. Clast- or sand-supported conglomerates, commonly

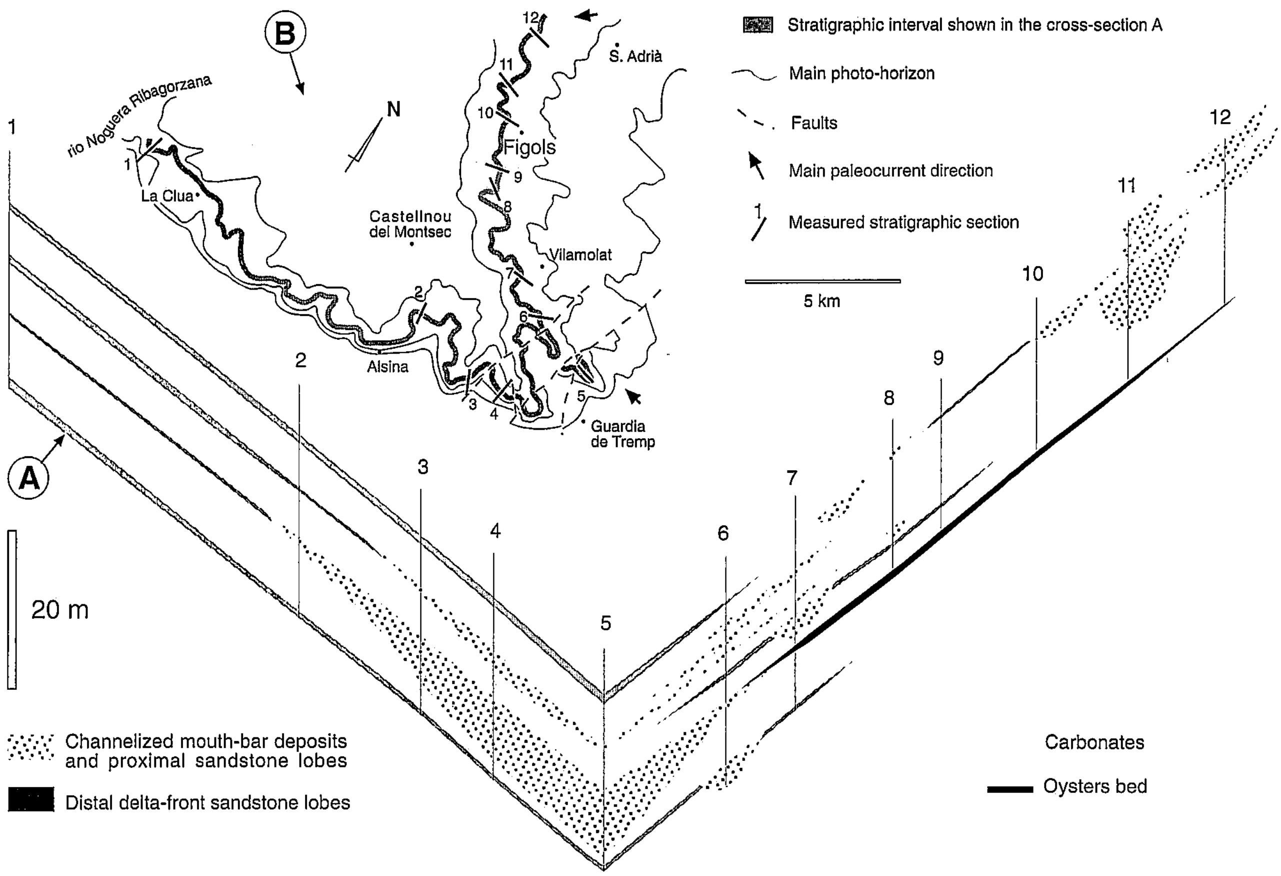


Figure 19.- Stratigraphic cross-section and sketch map showing facies relationships within a river-delta system originated from highly-efficient sediment-laden stream flows (*cf.* Fig. 14 - 1B). Mouth-bar and proximal lobe deposits are confined within channels; more distally, delta-front sandstone lobes form tabular units that can be traced for several kilometers. The fluvio-deltaic strata are overlain by a transgressive carbonate unit. Middle part of the Figols Group, Tremp region.

resting on erosional surfaces, form the upcurrent termination of each flood-unit passing into downstream accreting pebbly-sandstone units which can be either structureless or internally crudely stratified; farther downstream, these pebbly-sandstone units pass into coarse- to medium-grained sandstones which are commonly characterized by internally cross-stratified sigmoidal units thinning and fining seaward. Medium- to fine-grained sandstone lobes occur interbedded with and immediately seaward of these facies.

The facies distribution patterns observed in this type of delta-front setting suggest deposition from composite sediment-laden streamflows with a marked inverse grain-size segregation during transport. When entering seawaters, the head of these flows is frozen by friction and successive sedimentation waves carry progressively finer-grained sediment in a seaward direction, forming a downstream accreting bar. The trailing fully turbulent flow bypasses these sediments and deposits its load farther seaward as a tabular unit (lobe).

Delta-front depositional settings of this type, bearing obvious similarities with those of flood-dominated fan-delta systems (see above), are quite common in the south-central Pyrenees. Excellent examples can be observed in the upper part of the Figols Group in its type-section, in the Castissent Group in the Isabena valley, and particularly in the lower part of the Santa Liestra Group in the Esera valley, near Fantova.

Figure 14–2B shows the facies tract of highly efficient composite sediment-laden streamflows. Essentially, the tract is similar to that of figure 14–2A, with which is commonly associated and intergradational. However, a much higher efficiency of individual flows is indicated by the better grain-size segregation in a downcurrent direction, accompanied by extensive bypass, and spectacular scours produced by the head of these flows (Fig. 16D).

Sequence-stratigraphic aspects

Many of the problems related to the sequence-stratigraphic interpretation of flood-dominated fluvio-deltaic systems have been amply discussed in a previous paper (Mutti *et al.*, 1996). Herein, we emphasize some of the problems related to the nature of small- and large-scale sedimentary cyclicity.

Figure 20 shows the basic sequential arrangement of flood-dominated delta-front facies and its interpretation with specific reference to river-delta deposits. These sequences, which have individual thicknesses com-

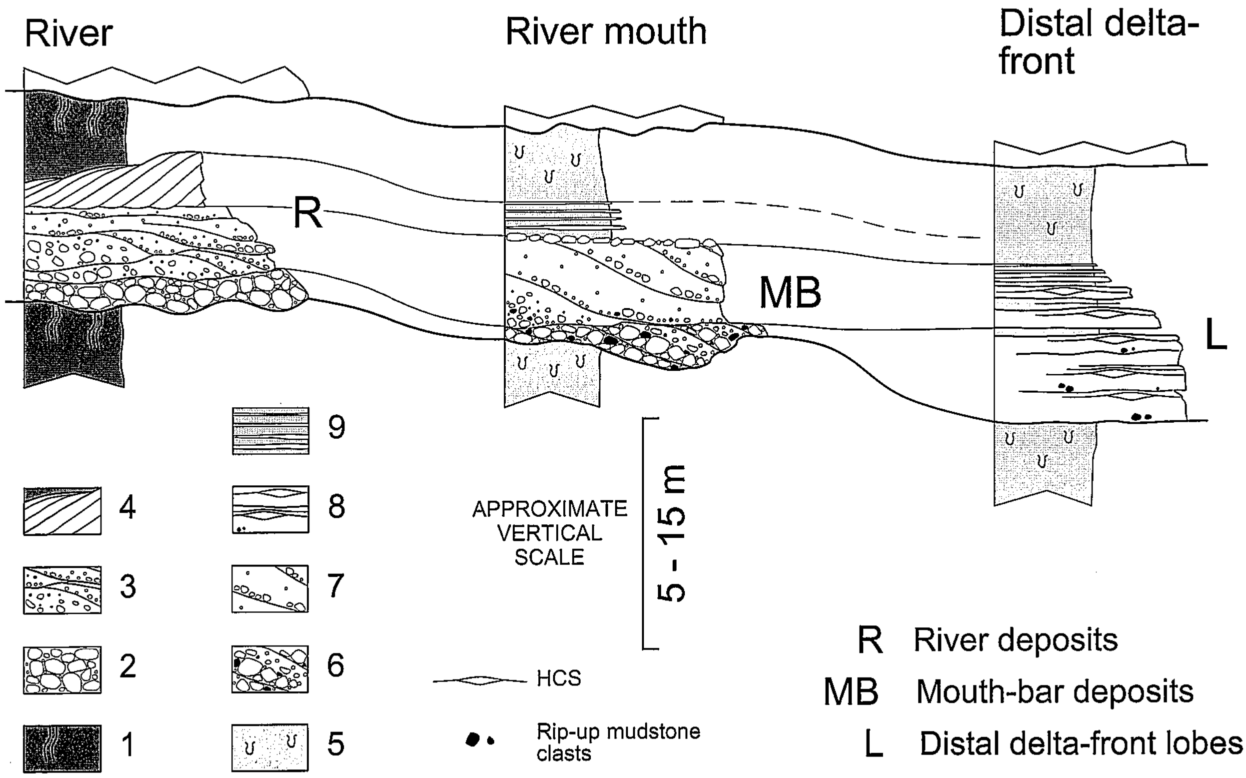


Figure 20.- Idealized example of the different expressions of an elementary depositional sequence formed in a flood-dominated fluvio-deltaic system (see text for explanation). 1) flood-plain fines and paleosols; 2) conglomerate lag; 3) extensively scoured, downstream accreting sandstone and conglomerate flood-units; 4) laterally- accreted sandstone bars; 5) brackish and marine mudstones; 6) coarse-grained and channelized mouth-bar deposit; 7) bar-slope deposit; 8) delta-front sandstone lobe; 9) fine-grained and thin-bedded sandstone lobes. Slightly modified after Mutti *et al.* (1996).

monly between 5-15 m, have been termed "elementary depositional sequences" (EDS) and form the background depositional motif of most fluvio-deltaic successions, particularly in the Eocene strata of the south-central Pyrenees (Mutti, 1989; Mutti *et al.*, 1994, 1996; Davoli, 1996). Waehry (1999) has shown for the Ilerdian Figols Group that this kind of cyclicity is developed on a temporal scale roughly fitting the Milankovitch periodicity of 20-40 ky.

As indicated in figure 20, an elementary depositional sequence is essentially a forestepping-backstepping wedge of flood-generated sandstone facies punctuating an otherwise mud-dominated succession in both marine and alluvial strata. In the marine environment, particularly in some stratigraphic units of the Eocene of the south-central Pyrenees (*e.g.*, Figols and Castigaleu groups), foramol-type carbonates may be associated with this kind of cyclic stacking patterns forming units that migrate landward following the retreat of the deltaic sandstone facies.

The internal geometry and facies types of the ideal elementary depositional sequence of figure 20 indicate an initial phase of prevailing erosion and bypass in lower river reaches and their mouths with deposition of aggrading sandstone lobes seaward. This stage of growth is dominated by highly efficient hyperpycnal flows. When the volume, sediment concentration and momentum of floods decrease, *i.e.* flow efficiency is lowered, the main deposition of sand occurs at river mouths giving way to prograding sand bars with or without attached sandstone lobes. Typical shoaling-upward successions form during this stage which are expressed by facies sequences where sandstone lobes are directly overlain by offlapping mouth-bar sandstone facies or their distal, finer-grained toes (Fig. 20). Following this, sand deposition shifts landward either abruptly or gradually and fluvial channels fill in through aggradation and laterally-accreting bars until sand deposition comes to an end and also fluvial channels are blanketed with fine-grained alluvial facies and soils.

It seems difficult to explain sequences of this kind without recognizing cyclic climate changes as a first-order factor in controlling sedimentation. Catastrophic floods can originate only if large amounts of water are made available in drainage basins over short periods of time through heavy rainfalls, snow and ice melting, or breeching of naturally-dammed lakes (Costa and Schuster, 1988), mainly depending on the latitude and physiography of the setting considered. Gradual decrease in water and sediment availability results in the end of flood-dominated sedimentation and eventually in its replacement by finer-grained sedimentation developed during a substantial deactivation of fluvial activity and in most cases an actual cessation of it.

A basic issue of the above is how sequences of this type relate to high-frequency sequence stratigraphy, *i.e.*

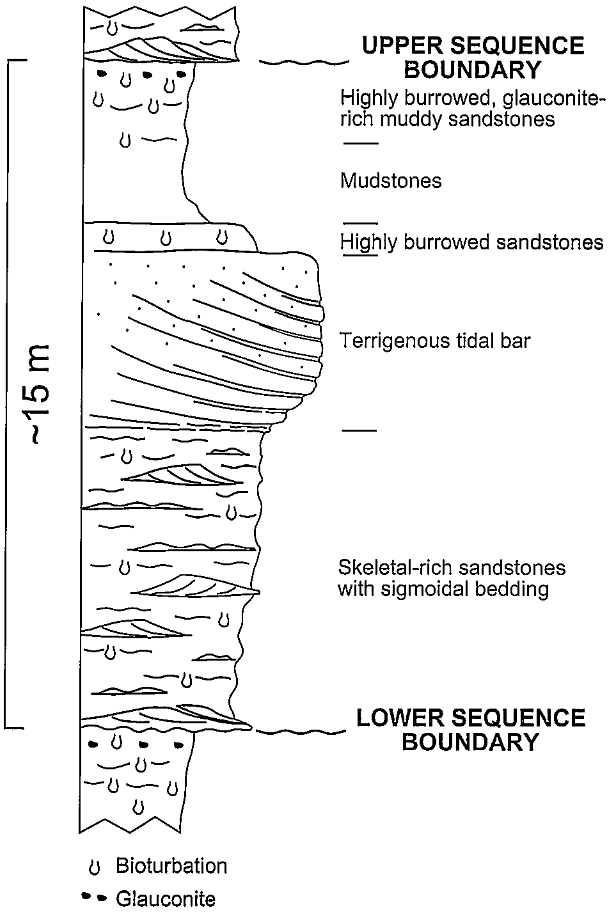


Figure 21.- Elementary depositional sequence from delta-front strata of a tide-dominated delta system (based on measured sections from the lower part of the Figols Group, southern limb of the Ager syncline). The sequence is bounded below and above by two surfaces indicating an abrupt shallowing of the depositional profile (see text for explanation).

the 4th- and 5th-order cycles of eustasy-driven sea-level changes (see Van Wagoner *et al.*, 1990; Mitchum and Van Wagoner, 1991). Floods are generated in the drainage basins and upper reaches of rivers, that is at elevations where baselevel variations produced by relative sea-level changes have negligible effects on stream profile and regime (Ethridge *et al.*, 1998). On the contrary, coastal plains and adjacent delta-front regions may be substantially affected by changes in accommodation associated with relative sea-level variations and their sediments are among those which best record these variations both conceptually (*e.g.*, Posamentier *et al.*, 1988) and in the actual stratigraphic record, particularly in Pleistocene strata where glacio-eustatic cycles are well documented (*e.g.*, Abbott and Carter, 1994, 1997).

It is, therefore, possible that high-frequency flood-dominated sedimentation is controlled by two main extrinsic factors: climate in the drainage basins and sea-level in the marine depositional zones. The scheme of figure 20 can actually be interpreted in terms of both climate changes that control the forestepping-backstepping of flood-dominated sandstone facies, and relative sea-level variations that, at the same time, would determine water depth changes and accommodation through time. In such sequence-stratigraphic scheme, the association of distal sandstone lobes and the overlying prograding mouth-bar deposits would represent a small-scale prograding lowstand delta reaching stillstand conditions at the time of the mouth-bar progradation. This would be followed by a more or less abrupt transgression and related maximum flooding surface associated with increased water depth due to sea-level rise and eventually by the deposition of highstand mudstones.

The validity of a model also implying the importance of high-frequency sea-level variations is strongly supported by data from the rare examples of tide-dominated deltaic systems occurring in the Eocene of the south-central Pyrenees. Among these examples, the tide-dominated delta systems of the Ilerdian Figols Group outcropping in the Ager syncline are probably the best studied and understood.

In the delta-front strata of such systems, dominated by tidal bar deposition (Mutti *et al.*, 1985), elementary depositional sequences are very common, particularly in the lower part of the Figols strata where they are developed at the same physical and temporal scale as those discussed above for flood-dominated sedimentation. These sequences can be physically traced for several kilometers (Mutti *et al.*, 1994). The example of figure 21 clearly indicates that the vertical facies succession can only be explained through high-frequency small-scale sea-level variations resulting in changes of water depth through time, thus ruling out a possible autocyclic origin. An initial sudden shallowing of the depositional profile is marked by the sharp contact between skeletal-rich sandy facies, with tidal sigmoidal bedding, and underlying highly burrowed and glauconite-rich muddy sandstones that formed in deeper waters only slightly affected by weak and short-lived tidal currents. Above the basal skeletal-rich tidal sandstone facies are river-born terrigenous tidal bars prograding under apparent conditions of stillstand (Fig. 21). These bars are in turn overlain by highly burrowed sandstones and eventually capped by a highstand mudstone-dominated facies.

The schemes of figures 20 and 21 emphasize the remarkable overall similarities between tide- and flood-dominated delta-front strata in terms of physical scale and vertical facies organization. The comparison suggests that there may be a relation between high-frequency cycles of sea-level variation and climate changes on the Milankovitch scale of cyclicity. Sea-level changes would control accommodation near baselevel in coastal plains and shallow-marine regions through the migration of the equilibrium point, whereas climate would primarily control the sediment flux to the sea through floods and related hyperpycnal flows entering seawaters - *i.e.* as an extrinsic factor controlling primarily the regime of fluvial systems above their baselevel. The problem remains whether the boundaries of the elementary sequences showing either a shallowing of the depositional profile (Fig. 21) or the sudden appearance of sandstone facies generated by hyperpycnal flows (Fig. 20) are synchronous or not. The data presently available do not offer any solutions to this problem. Although from a stratigraphic standpoint the two surfaces can probably be considered as time-equivalent, we argue that climate and sea-level changes may be slightly diachronous.

As observed particularly in the Eocene strata of the south-central Pyrenees, elementary depositional sequences stack to form larger-scale depositional sequences which record regional forestepping-backstepping cycles of fluvio-deltaic systems tracts developed during periods of time matching those of the 3rd-order cycles of sequence stratigraphy. In the Eocene of the south-central Pyrenean foreland basin, these larger-scale and longer-lived sequences are invariably bounded by tectonically-induced angular unconformities related to thrust propagation and are associated with thick accumulations of turbidite sandstones in the western and deeper part of the basin (Hecho Group of Mutti *et al.*, 1972). These units, termed "allogroups" by Mutti *et al.*, (1988, 1994), have been interpreted mainly as the product of Davisian-like cycles involving phases of tectonic uplift followed by subsidence and denudation (Mutti *et al.*, 1996). These cycles, mainly controlled by tectonism, would determine basinwide cyclic variations in the sediment flux to the sea - the highest flux being recorded by turbidite deposition.

Tectonism would control the large-scale basin-fill architecture whereas cyclicity developed over shorter periods would control small-scale forestepping-backstepping cycles of fluvio-deltaic sediments as primarily related to climate changes. These problems are well beyond the purposes of this paper, but are briefly mentioned because of their inherent importance in the study of fluvio-deltaic systems of tectonically active basins.

Conclusions

We have attempted in this paper to show some of the features that characterize ancient flood-dominated fluvio-deltaic systems of tectonically-active basins, and, particularly, their delta-front regions dominated by hyperpycnal flows in both fan-delta and river-delta systems. This kind of sedimentation entails a series of sedimentological problems that have been largely overlooked in previous literature, thus opening new and highly significant fields for future research.

In ancient flood-dominated fluvio-deltaic systems, both transport and sedimentation are related to gravity-driven sediment/water mixtures that originate in drainage basins and have their depositional zones in marine deltas and fan-deltas. As inferred from their deposits, these density currents vary from hyperconcentrated flows (cohesionless debris flows) to dilute and fully turbulent flows through a series of intergradational flow types which become particularly complex when these flood-generated flows enter seawaters. Most of the facies observed are essentially unreported, or uncorrectly interpreted, in previous literature and the processes inferred are largely conceptual, mostly derived from turbidite sedimentation. Despite these limitations, the preliminary attempt made in this paper to discuss the complexity of flood-dominated fluvio-deltaic sedimentation appears necessary to stimulate extensive research in this field.

Flood-related processes are intrinsically catastrophic and, as such, under-represented in modern settings. It thus appears that ancient flood-dominated fluvio-deltaic systems cannot be described and interpreted following current sedimentological models for fluvial and deltaic sedimentation (*e.g.*, Miall, 1992; Walker and James, 1992; Reading, 1996). Actually, these models are largely derived from modern depositional environments dominated by "normal" fluvial and marine processes (for an extensive discussion see Mutti *et al.*, 1996). There are, instead, impressive similarities between ancient flood-dominated fluvio-deltaic systems and turbidites - another category of catastrophic deposits under-represented in modern basins. Comparing facies and processes of these two groups of sediments deposited by density currents can provide significant insight into both types of sedimentation (*e.g.*, Mutti *et al.*, 1999).

Ancient flood-dominated fluvio-deltaic systems appear mainly to be developed in structurally-confined, wedge-top basins of thrust-and-fold belts, like for instance in the Tremp Unit of the south-central Pyrenees (see above), the Tertiary Piedmont Basin in north-western Italy (Artoni *et al.*, 1999), and the Pliocene and Pleistocene piggy-back basins of the northern (Roveri *et al.*, 1998) and southern (Mutti *et al.*, 1996) Apennines. Apparently, there is a clear relationship between the onset of this type of sedimentation and the uplift of orogenic wedges. This uplift generates relief along the inner margin of wedge-top basins and favours the development of small- and high-gradient fluvial systems with catchment areas at a short distance from the shoreline. These fluvial systems, pertaining to the "small- and medium-sized mountainous rivers" of Milliman and Syvitski (1992), can periodically shed impressive amounts of gravel, sand and mud into adjacent marine basins through flooding, *i.e.* through cyclic climate changes (Mutti *et al.*, 1996).

For the reasons mentioned above, ancient flood-dominated fluvio-deltaic systems are certainly among the most sensitive recorders of tectonism, climate changes and relative sea-level variations, the basic factors which control the rate of sediment flux to the sea. Cyclic stacking patterns of forestepping-backstepping flood-dominated fluvio-deltaic wedges essentially contain the record of the interaction of the above factors through time. If we consider that tectonic uplift can take place at rates of 2.7-4.3 m/ k.y. (*e.g.*, Keller *et al.*, 2000; see also Mutti, 1992a), reading this interaction at the scale of climate Milankovitch rhythms and even that of the millennial cycles of Dansgaard (Dansgaard *et al.* 1993; Bond *et al.*, 1997), does represent a challenge for future sedimentological, structural, paleoclimatological and sequence-stratigraphic research.

This paper is dedicated by Emiliano Mutti to his brotherly friend Joan Rosell who taught him much of what he knows about the Pyrenees during unforgettable days of joint field work and inspiring discussions. Many thanks are also due to the senior author's one-time students (especially F. Fonnesu, E. Remacha, Ph. Crummeyrolle, P. Dattilo, S. Mora, E. Tebaldi, G. Davoli and A. Waehry), M. Sgavetti for photostratigraphic interpretations and interest in this research, and C. Zavala for his enthusiasm and help in the field. Much of this research was generously funded by the Consiglio Nazionale delle Ricerche, Rome, and by MURST.

References

Abbott, S.T. and Carter, R.M. (1994): The sequence architecture of mid-Pleistocene (*c.* 1.1 - 0.4 Ma) cyclothems from New Zealand: facies development during a period of orbital control on sea-level cyclicity. In: *Orbital Forcing and Cyclic Sequences* (P.L. de Boer and D.G. Smith, Eds), *Spec. Publs Int. Assoc. Sediment.*, 19: 367-394.

Abbott, S.T. and Carter, R.M. (1997): Macrofossil associations from mid-Pleistocene cyclothems, Castlecliff section, New Zealand: implications for Sequence Stratigraphy. *Palaios*, 12: 188-210.

Allen, P.A. and Allen, J.R. (1990): *Basin analysis, principles and applications*. Blackwell Scientific Publication, Oxford, 451 p.

Artoni, A., di Biase, D., Fava, L., Iaccarino, S., Mavilla, N., Mutti, E., Papani, L., Sgavetti, M. and Turco, E. (1999): Nuovi dati per l'interpetazione stratigrafico-deposizionale dell'Oligocene superiore e Miocene inferiore nel Bacino Terziario Piemontese. *Atti Riun. Autunn. Conv. Ann. G.I.S. del C.N.R., Rimini, Giorn. Geol.*, 61: 199-202.

Bates, C.C. (1953): Rational theory of delta formation. *Amer. Assoc. Petrol. Geol. Bull.*, 37: 2119-2162.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I. and Bonani, G. (1997): A pervasive millennial-scale cycle in north Atlantic Holocene and glacial climates. *Science*, 278: 1257-1266.

Colella, A. and Prior, D.B. (Eds) (1990): *Coarse-Grained Deltas. Spec. Publs Int. Assoc. Sediment.*, 10, 375 p.

Costa, J.E. (1988): Rheologic, geomorphic and sedimentologic differentiation of water floods, hyperconcentrated flows and debris flows. In: *Flood Geomorphology* (V.R. Baker, R.C. Kochel and P.C. Paiton, Eds), Wiley-Interscience Publ., New York, 113-122.

Costa, J.E. and Schuster, R.L. (1988): The formation and failure of natural dams. *Geol. Soc. Amer. Bull.*, 100: 1054-1068.

Coussot, P. and Meunier, M. (1992): Recognition, classification and mechanical description of debris flow. *Earth-Sci. Rev.*, 40: 209-227.

Crumeyrolle, Ph. (1987): *Stratigraphie physique et sédimentologie des systémes de dépôt de la séquence de Santa Liestra (Eocéne sud-pyrénéen).* Ph.D. thesis, University of Bordeaux III, 216 p.

Davoli, G. (1996): *Facies e stratigrafia fisica ad alta risoluzione dell'Allogruppo di Castigaleu, nell'area compresa tra il passo di Montllobat e il Rio Noguera Ribagorzana (Eocene inferiore, Pirenei centro-meridionali).* Ph.D. thesis, University of Parma, 112 p.

Duke, W.L., Arnott, R.W.C. and Cheel, R.J. (1991): Shelf sandstones and hummocky cross-stratification: new insights on stormy debate. *Geology*, 19: 625-628.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjornsdottir, A.E., Jouzel, J. and Bond, G. (1993): Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature*, 364: 218-220.

Ethridge, F.G. and Wescott, W.A. (1984): Tectonic setting, recognition and hydrocarbon reservoir potential of fan delta deposits. In: *Sedimentology of Gravels and Conglomerates* (E.H. Koster and R.J. Steel, Eds), *Can. Soc. Petrol. Geol. Mem.*, 10: 217-235.

Ethridge, F.G., Wood, L.J. and Schumm, S.A., (1998): Cyclic variables controlling fluvial sequence development: problems and perspectives. In: *Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks* (K.W. Shanley and P.J. McCabe, Eds), *S.E.P.M. Spec. Publ.*, 59: 17-29.

Goldring, R. and Bridges, P. (1973): Sublittoral sheet sandstones. *Jour. Sed. Petrol.*, 43: 736-747.

Keller, E.A., Seaver, D.B., Laduzinsky, D.L., Johnson, D.L. and Ku, T.L. (2000): Tectonic geomorphology of active folding over buried reverse fauls: San Emigdio Mountain front, southern San Joaquin Valley, California. *Geol. Soc. Amer. Bull.*, 112: 86-97.

Kim, S.B., Chough, S.K. and Chun, S.S. (1995): Bouldery deposits in the lowermost part of the Cretaceous Kyokpori Formation, SW Korea: cohesionless debris flows and debris falls on a steep-gradient delta slope. *Sedim. Geol.*, 98: 97-119.

Lowe, D.R. (1982): Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents. *Jour. Sed. Petrol.*, 52: 279-297.

Major, J.J. and Iverson, M.R. (1999): Debris-flow deposition: effects of pore-fluid pressure and friction concentrated at flow margins. *Geol. Soc. Amer. Bull.*, 111: 1424-1434.

Martinsen, O. J. (1990): Fluvial, inertia-dominated deltaic deposition in the Namurian (Carboniferous) of northern England. *Sedimentology*, 37: 1099-1114.

McLeod, P., Carey, S. and Sparks, S.J. (1999): Behaviour of particle-laden flows into the ocean: experimental simulation and geological implications. *Sedimentology*, 46: 523-536.

Miall, A.D. (1992): Alluvial Deposits. In: *Facies Models - Response to Sea Level Change* (R.G. Walker and N.P. James, Eds), *Geol. Assoc. Canada*: 119-142.

Middleton, G.V. and Hampton, M.A. (1973): Sediment gravity flow: mechanics of flow and deposition. In: *Turbidites and deep-water sedimentation* (G.V. Middleton and A.H. Bouma, Eds), *Pacific Section S.E.P.M. Short Course Notes*, 1: 1-38.

Milliman, J.D. and Syvitski, J.P.M. (1992): Geomorphic and tectonic control of sediment discharges to the ocean: the importance of small mountainous rivers. *Jour. Geol.*, 100: 525-544.

Mitchum, R.M. and Van Wagoner, J.C. (1991): High-frequency sequences and their stacking patterns: sequence-stratigraphic evidence of high-frequency eustatic cycles. *Sedim. Geol.*, 70: 131-160.

Mohrig, D., Whipple, K.X., Hondzo, M., Ellis, C. and Parker, G. (1998): Hydroplaning of subaqueous debris flows. *Geol. Soc. Amer. Bull.*, 110: 387-394.

Mulder, T. and Syvitski, J.P.M. (1995): Turbidity currents generated at river mouths during exceptional discharges to the world oceans. *Jour. Geol.*, 103: 285-299.

Mulder, T., Syvitski, J.P.M. and Skene, K.I. (1998): Modeling of erosion and deposition of turbidity currents generated at river mouths. *Jour. Sed. Research*, 68: 124-137.

Mutti, E. (1979): Turbidites et cones sous-marins profonds. In: *Sedimentation Detritique (Fluviatile, Littorale et Marine)* (P. Homewood, Ed.), *Institut de Geologie, Université de Fribourg*: 353-419.

Mutti, E. (1989): Alcuni problemi relativi all'applicazione dei concetti della stratigrafia sequenziale all'Eocene e al Cretacico superiore sud-pirenaici. *Numero Spec. Notiziario G.I.S.*, 4: 37-53.

Mutti, E. (1992a): Relazioni tra Stratigrafia Sequenziale e Tettonica. *Mem. Soc. Geol. Italiana (1990)*, 45: 627-655.

Mutti, E. (1992b): *Turbidite sandstones*. AGIP - Istituto di Geologia Università di Parma, 275 p.

Mutti, E., Allen, G.P. and Rosell, J. (1984): Sigmoidal cross-stratification and sigmoidal bars: depositional features diagnostic of tidal sandstones. *Int. Assoc. Sedimentol., 5th European Meeting on Sedimentology, Marseille, Abstracts Book*: 312-313.

Mutti, E., Davoli, G., Mora, S. and Sgavetti, M. (Eds) (1994): The Eastern Sector of the South-Central Folded Pyrenean Foreland: Criteria for Stratigraphic Analysis and Excursion Notes. *Second High-resolution Sequence Stratigraphy Conference, Tremp*, 83 p.

Mutti, E., Davoli, G., Tinterri, R. and Zavala, C. (1996): The importance of fluvio-deltaic systems dominated by catastrophic flooding in tectonically active basins. *Mem. Sci. Geol.*, 48: 233-291.

Mutti, E., Luterbacher, H.P., Ferrer, J. and Rosell, J. (1972): Schema stratigrafico e lineamenti di facies del Paleogene marino della Zona Centrale Sud-Pirenaica tra Tremp (Catalogna) e Pamplona (Navarra). *Mem. Soc. Geol. Italiana*, 11: 391-416.

Mutti, E.,Rosell, J., Allen, G.P., Fonnesu, F., and Sgavetti, M., (1985): The Eocene Baronia tidedominated delta-shelf system in the Ager basin. In: *Excursion 13 (M. D. Mila and J. Rosell, Eds), Int. Assoc. Sedimentol., 6th European Meeting on Sedimentology, Lerida, Excursions Guidebook*: 579-600

Mutti, E., Seguret, M. and Sgavetti, M. (1988): Sedimentation and Deformation in the Tertiary Sequences of the Southern Pyrenees. *Amer. Assoc. Petrol. Geol. Mediterranean Basin Conference, Spec. Publ., Field Trip*, 7, 157 p.

Mutti, E., Tinterri, R. and Remacha, E. (1998): On the importance of flood-generated delta-front sandstone lobes with HCS in tectonically active basins. *15th Int. Assoc. Sedimentol. Congress, Alicante, Abstracts Book*: 571-572.

Mutti, E., Tinterri, R., Remacha, E., Mavilla, N., Angella, S. and Fava, L. (1999): An introduction to the analysis of ancient turbidite basins from an outcrop perspective. *Amer. Assoc. Petrol. Geol., Continuing Education Course Note Series*, 39, 61 p.

Nemec, W. (1995): The dynamics of deltaic suspension plumes. In: *Geology of Deltas* (M.N. Oti and G. Postma, Eds), A.A. Balkema, Rotterdam: 31-93.

Nemec, W. and Steel, R.J. (1984): Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass-flow deposits. In: *Sedimentology of Gravels and Conglomerates* (E.H. Koster and R.J. Steel, Eds), *Can. Soc. Petrol. Geol. Mem.*, 10: 1-31.

Norem, H., Locat, J. and Schieldrop, B. (1990): An approach to the physics and the modelling of submarine flowslides. *Mar. Geotechnology*, 9: 93-111.

Pickering, K.T., Hiscott, R.N. and Hein, F. J. (Eds) (1989): *Deep marine environments: clastic sedimentation and tectonics*. Unwin Hyman Ltd, London, 416 p.

Pierson, T.C. and Costa, J.E. (1987): A rheologic classification of subaerial sediment-water flows. In: *Debris flows/avalanches: process, recognition, and mitigation* (J.E. Costa and G.F. Wieczorek, Eds), *Geol. Soc. Amer., Reviews in Engineering Geology*, 7: 1-12.

Posamentier, H.W., Jervey, M.T. and Vail, P.R. (1988): Eustatic controls of clastic deposition I - Conceptual framework. In: *Sea level changes: an integrated approach* (C.K. Wilgus, B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross and J.C. Van Wagoner, Eds), *S.E.P.M. Spec. Publ.*, 42: 109-124.

Postma, G. (1990): Depositional architecture and facies of river and fan deltas: a synthesis. In: *Coarse-Grained Deltas* (A. Colella and D.B. Prior, Eds), *Spec. Publs Int. Assoc. Sediment.*, 10: 13-27.

Prior, D.B., Yang, Z.S., Bornhold, B.D., Keller, G.H., Lin, G.H., Wiseman, Jr W.J., Wright, L.D. and Lin T.C. (1986): The subaqueous delta of the modern Huanghe (Yellow River). *Geo-Mar. Lett.*, 6: 67-75.

Ravenne, C. and Beghin, P. (1983): Apport des expériences en canal à l'interprétation sédimentologique des dépôts de cônes détritiques sous-marins. *Rev. Inst. Franc. Pétrol.*, 38: 279-297.

Reading, H.G. (Ed.) (1996): *Sedimentary Environments: Processes, Facies and Stratigraphy* – third edition. Blackwell Science, Oxford, 688 p.

Remacha, E., Fernández, L.P., Maestro, E., Oms, O. and Estrada, R. (1998): The upper Hecho Group turbidites and their vertical evolution to deltas (Eocene South-central Pyrenees). *15th Int. Assoc. Sedimentol. Congress, Alicante, Field Trip Guidebook*: 1-25.

Richards, M., Bowman, M. and Reading, H. (1998): Submarine-fan systems I: characterization and stratigraphic prediction. *Mar. Petr. Geol.*, 15: 689-717.

Roveri, M., Manzi, V., Bassetti, M., Merini, M. and Ricci Lucchi, F. (1998): Stratigraphy of the Messinian post-evaporitic stage in eastern-Romagna (northern Apennines, Italy). *Giorn. Geol.*, 60: 119-142.

Sanders, J.E. (1965): Primary sedimentary structures formed by turbidity currents and related resedimentation mechanisms. In: *Primary sedimentary structures and their hydrodynamic interpretation* (G.V. Middleton, Ed.), *S.E.P.M. Spec. Publ.*, 12: 192-219.

Schumm, S.A. (1977): *The Fluvial System*. John Wiley and Sons., New York, 338 p.

Shanmugam, G. (1996): High density turbidity currents: are they sandy debris flow? *Jour. Sed. Research*, 66: 2-10.

Shanmugam, G. (2000): 50 years of the turbidite paradigm (1950s-1990s): deep-water processes and facies models – a critical perspective. *Mar. Petr. Geol*, 17: 285-342.

Skene, K.I., Mulder, T. and Syvitski, J.P.M. (1997): INFLO1: a model predicting the behaviour of turbidity currents generated at river mouths. *Computer Geosci.*, 23: 975-991.

Smith, G.A. and Lowe, D.R. (1991): Lahars: volcano-hydrologic events and deposition in the debris flow-hyperconcentrated continuum. In: *Sedimentation in volcanic settings* (R.V. Fisher and G.A. Smith, Eds), *S.E.P.M. Spec. Publ.*, 45: 59-70.

Sohn, Y.K., Rhee, C.W. and Kim, B.C. (1999): Debris flow and hyperconcentrated flood-flow deposits in an alluvial fan, northwestern part of the Cretaceous Yongdong Basin, central Korea. *Jour. Geol.*, 107: 111-132.

Sparks, S.J., Bonnecaze, R.T., Huppert, H.E., Lister, J.R., Hallworth, M.A., Mader, H. and Phillips, J. (1993): Sediment-laden gravity currents with reversing buoyancy. *Earth Planet. Sci. Letters*, 114: 243-257.

Todd, S.P. (1989): Stream-driven, high-density gravelly traction carpets: possible deposits in the Trabeg Conglomerate Formation, SW Ireland and some theoretical considerations of their origin. *Sedimentology*, 36: 513-530.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M. and Rahmanian, V.D. (1990): Siliciclastic sequences stratigraphy in well logs, cores and outcrops: concepts for high-resolution correlation of time and facies. *Amer. Assoc. Petrol. Geol., Methods in Exploration Series*, 7, 55 p.

Waehry, A. (1999): Facies analysis and physical stratigraphy of the Ilerdian in the eastern Tremp-Graus Basin (south-central Pyrenees, Spain). *Terre et Environment, Inst. Forel, Dép. De Min. Dép. de Géologie et Paléontologie, Section des Sciences de la Terre*, Université de Genève, 15, 191 p.

Walker, R.G. and James, N.P. (Eds) (1992): Facies Models - Response to Sea Level Change. *Geol. Assoc. Canada*: 119-142.

Wright, L.D. (1977): Sediment transport and deposition at river mouths: a synthesis. *Geol. Soc. Amer. Bull.*, 88: 857-868.

Wright, L.D., Yang, Z.S., Bornhold, B.D., Keller, G.H., Prior, D.B. and Wiseman, Jr W.J. (1986): Hyperpycnal plumes and plume fronts over the Huanghe (Yellow River) delta front. *Geo-Mar. Lett.*, 6: 97-105.

Manuscript received 30 March 2000
Accepted 1 June 2000