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The Importance of Ancient Fluvio-Deltaic Systems Dominated by Catastrophic Flooding in Tectonically Active Basins

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ABSTRACT - Ancient fluvio-deltaic systems deposited in tectonically active basins are essentially built up by inter-gradational fan-delta and river-delta systems dominated by catastrophic flooding. These systems and their component depositional elements cannot therefore be described and interpreted in terms of current sedimentological models based on "normal" fluvial and deltaic processes, facies and geomorphic settings derived from the study of modern environments. Direct and indirect sedimentological and stratigraphic evidence indicates that "normal" sedimentation occurred also in these systems, but its preservation potential appears to be very small with the exception of tidal diffusion in estuarine settings. Facies and facies associations of ancient flood-dominated depositional systems include a very broad spectrum of essentially poorly described and understood sediments that vary from thick-bedded and disorganized conglomerates to thin-bedded graded mudstones via a great variety of pebbly-sandstone and sandstone facies. Despite this variability, all these sediments are characteristically composed of graded flood units in both alluvial and marine environments. The greatest preservation potential of individual flood units is found in the final marine depositional zones of each system considered. Ancient flood-dominated fluvio-marine systems comprise huge accumulations of conglomerates, sandstone and mudstone facies whose origin and stratigraphic importance have been essentially overlooked in previous literature. These depositional systems can be understood only in terms of tectonically-controlled physiographic settings characterized by small and medium-sized fluvial systems with high-elevation drainage basins and high-gradient transfer zones located close to marine basins. In settings of this type, sediment flux to the sea can dramatically increase when climatic conditions provide sufficient amounts of water to produce catastrophic floods. These floods generate mixtures of water and sediment that can enter sea waters with sufficient velocity and sediment concentration to produce hyperpycnal flows and related, self-sustained turbidity currents. The resulting depositional settings are thus dominated by flood-related facies that can develop in shelfal or deeper marine regions. Thick and laterally extensive successions of shelfal sandstone lobes with flood-generated HCS are the fundamental depositional element of both fan-delta and river-delta systems considered in this study. These lobes are essentially similar to deeper-water turbidite sandstone lobes in terms of geometry, facies tracts, and high-frequency cyclic stacking patterns. Shelfal sandstone lobes probably represent the only possible expression of fluvial-dominated delta-front sandstone facies, since, in the absence of flood-generated hyperpycnal flows, river-borne sands can only be redistributed in marine environments by waves and tides. As indicated by their overall stacking patterns, the evolution of ancient flood-dominated fluvio-deltaic systems with time is apparently controlled by the initial uplift of the drainage basin, the rate of denudation, the gradient of each system, and the volume and sediment concentration of individual floods, the latter being a function of the amount of water and sediment made available to the system considered. A flood-dominated system of this type comes to an end when the sediment flux to the sea is progressively reduced to "normal" conditions. This occurs when relief and elevation of drainage basins and related sediment availability, as well as the gradient of transfer zones, have been substantially reduced through progressive denudation and sediment exportation to marine depositional zones. The occurrence of cyclic stacking patterns developed at different hierarchical orders is one of the most striking aspects of flood-dominated fluvio-deltaic systems. The most complete record of this cyclicity is preserved in the final depositional zone of each system. These stacking patterns are apparently very similar to those which are thought to be characteristic of sequence-stratigraphic models. Despite this apparent similarity, we suggest that the overall vertical evolution of flood-dominated systems is primarily controlled by Davisian-type cycles produced by alternating periods of orogenic uplift and denudation. In their most complete development, these cycles are ideally recorded by an overall forestepping-backstepping succession recorded by a basal turbidite system (basin floor fan of sequence stratigraphy) overlain by a flood-dominated fluvio-deltaic system which passes upward and landward into a "normal" fluvial or fluvio-deltaic system with time. Higher-frequency stacking patterns developed within each of the above stages are essentially produced by forestepping-backstepping episodes of sand deposition which are essentially controlled by cyclic climatic variations. The relationships between Davisian-type and higher-frequency climatic cycles and eustasy-driven cycles of relative sealevel variations remain to be explored through careful stratigraphic, sedimentological and structural studies carried out without preconceived ideas. It is likely, however, that the eustatic control on flood-dominated sedimentation patterns of high-gradient, tectonically active settings cannot generally compare with the importance of tectonism and related cycles of uplift and denudation.

Key words: catastrophic floods, flood-dominated fluvio-deltaic systems, tectonic active basins, Davisian cycles, climate, high-frequency cyclicity, flood-generated shelfal sandstone lobes, fluvio-turbidite systems.

RIASSUNTO - Sulla base di studi condotti per oltre un quinquennio su successioni sedimentarie di età variabili dal Trias fino al Pleistocene ed ubicate in aree geografiche ed in contesti geodinamici diversi, sembra evidente che i sistemi deposizionali fluvio-deltizii fossili formatisi in bacini tettonicamente attivi siano principalmente costituiti da depositi di piene fluviali catastrofiche e dall'estensione delle stesse in adiacenti bacini marini o lacustri sotto forma di flussi iperpicnali e correnti di torbida. Relativamente a questo specifico tipo di sistemi ubicati in bacini tettonicamente attivi, i modelli sedimentologici sulla sedimentazione fluvio-deltizia noti in letteratura non forniscono criteri di riconoscimento ed interpretazione adeguati. In realtà, tali modelli sono in grande misura basati su contesti fisiografici, processi e facies osservabili in ambienti attuali, ossia in condizioni "normali". Queste ultime possono riassumersi nel predominio di processi trattivi e facies corrispondenti nei sedimenti fluviali e di processi marini, come onde e maree, nelle aree di fronte deltizio ove le sabbie portate dai fiumi vengono ridistribuite. E' del tutto verosimile che processi "normali" di questo tipo abbiano avuto una notevole importanza anche durante lo sviluppo dei sistemi fluvio-deltizii dominati da piene catastrofiche. Il potenziale di preservazione dei loro sedimenti è tuttavia trascurabile rispetto a quello dei depositi prodotti da piene catastrofiche. Facies e associazioni di facies dei sistemi fluvio-deltizii dominati da piene catastrofiche costituiscono un ampio spettro di sedimenti in gran parte poco conosciuti sia per quanto riguarda le loro caratteristiche, sia per quanto riguarda l'origine ed i processi idrodinamici relativi. Nonostante la loro grande variabilità in termini di tessiture e strutture sedimentarie, questi depositi sono tuttavia invariabilmente costituiti, sia in ambiente continentale, sia marino, da strati gradati, ciascuno originatosi attraverso un originario flusso di piena e dalle sue trasformazioni sottocorrente. Il maggior potenziale di preservazione di questi depositi è osservabile nelle successioni che registrano le originarie zone di deposizione finale di ciascun sistema. Nel riempimento di bacini tettonicamente attivi, i sistemi fluvio-deltizii dominati da piene catastrofiche (essenzialmente sistemi di *fan-delta* e *river-delta*) costituiscono enormi volumi sedimentari la cui importanza stratigrafica è stata certamente sottovalutata nel passato. Questi sistemi possono essere compresi nel loro significato geologico soltanto se visti entro contesti fisiografici controllati tettonicamente e caratterizzati da sistemi fluviali di piccole o medie dimensioni. In tali contesti, questi sistemi hanno di regola bacini di drenaggio a quote relativamente elevate, zone di trasferimento ad alto gradiente e distanze relativamente modeste tra bacini di drenaggio e zone di sedimentazione finale. Il flusso di sedimento che ogni sistema fluviale di questo tipo può fornire ad adiacenti bacini marini può enormemente aumentare quando condizioni climatiche appropriate forniscano in tempi brevi grandi quantità di acqua ai bacini di drenaggio e alle zone di trasferimento. In tali condizioni si sviluppano piene catastrofiche di grande volume e con alta concentrazione di sedimento che possono entrare in adiacenti bacini marini come flussi iperpicnali. In ambiente marino, tali flussi, specialmente in sistemi di delta-conoide, spesso innescano vere e proprie correnti di torbida che si possono propagare in aree di piattaforma ed in molti casi di scarpata-bacino. L'elemento deposizionale fondamentale dei sistemi fluvio-deltizii dominati da piene catastrofiche è rappresentato da spesse ed estese successioni di lobi arenacei di piattaforma. Questi lobi, sotto molto aspetti simili a quelli dei sistemi torbiditici profondi, sono costituiti da strati tabulari e gradati con sviluppo quasi costante di HCS. Per questo tipo di struttura, e relativamente al tipo di sistemi considerati, viene qui fornita una nuova interpretazione rispetto a quella comunemente accettata ed implicante l'effetto di tempeste da moto ondoso. I lobi arenacei di piattaforma probabilmente rappresentano la sola e più genuina espressione sedimentaria di fronti deltizii dominati da processi fluviali (piene catastrofiche) anche in ambiente marino. Come risulta dai loro schemi di impilamento (*stacking pattern*), l'evoluzione dei sistemi fluvio-deltizii fossili dominati da piene catastrofiche è apparentemente controllato da un'iniziale fase di sollevamento tettonico dei bacini di drenaggio, dal loro tasso di denudamento, dal gradiente di ciascun sistema ed infine dal volume e concentrazione dei flussi di piena. Sistemi di questo tipo vengono disattivati quando il flusso di sedimento diminuisce e ciascun sistema ritorna ad una sua condizione "normale". Ciò avviene attraverso la riduzione della quota dei bacini di drenaggio, del gradiente del sistema e della disponibilità di sedimento a seguito del progressivo denudamento e conseguente trasferimento di sedimento alle zone deposizionali. La presenza di impilamenti ciclici sviluppati a differenti ordini gerarchici è uno degli aspetti più vistosi dei sistemi fluvio-deltizii dominati da piene catastrofiche. In ragione del potenziale di preservazione, la registrazione migliore di questa ciclicità è osservabile nei sedimenti che rappresentano la zona finale di deposizione di ogni sistema. Gli impilamenti ciclici osservabili a periodo relativamente lungo sono molto simili a quelli descritti negli schemi stratigrafico-sequenziali (cicli e sequenze di terzo ordine). Nonostante questa apparente similitudine, si ritiene che l'evoluzione verticale della sedimentazione in bacini tettonicamente attivi, dove le piene catastrofiche controllano gran parte dei processi e delle facies che ne derivano, sia principalmente governata da cicli di tipo Davisiano prodotti dall'alternanza di periodi di sollevamento tettonico e di denudamento. Quando questi cicli sono pienamente sviluppati, la loro espressione è data da una successione sedimentaria di avanzamento/recessione (*forestepping/backstepping*) delle facies arenacee, qui ritenuta interamente controllata da piene fluviali catastrofiche e da una subsidenza tettonica che si può assumere come relativamente costante. La successione inizia con un sistema basale torbiditico seguito verso l'alto da un sistema di piattaforma-scarpata terminantesi verso l'alto, e verso il margine del bacino, con un sistema fluviale o fluvio-deltizio "normale". Questa successione verticale è in realtà il risultato di un unico sistema deposizionale operante nel tempo, qui definito come "fluvio-torbiditico", e delle sue differenti espressioni a seconda dell'evoluzione del ciclo sollevamento tettonico/denudamento che lo controlla. La ciclicità sviluppata su periodi più brevi, o ad alta frequenza, che è caratteristica di tutti i sistemi esaminati, è qui semplicemente interpretata come il prodotto di cicliche variazioni climatiche che, fornendo o non fornendo acqua ai bacini di drenaggio in tempi brevi ed in maniera atta a favorire piene catastrofiche (precipitazioni intense, scioglimento di nevi e ghiaccio, rilascio di grandi volumi d'acqua a seguito di cedimenti di dighe naturali formate da ghiaccio o da frane, *etc.*), determinano la formazione di cicli di avanzamento/recessione di facies arenacee nelle zone deposizionali di ciascun sistema. In quale modo la ciclicità sedimentaria di cui sopra si possa collegare agli schemi della stratigrafia sequenziale ed al concetto di *accommodation*, legato alle relazioni tra eustatismo e subsidenza, rimane da stabilire sulla base di studi sedimentologici, stratigrafici e strutturali strettamente integrati. E' soprattutto evidente che parte della sedimentologia attuale dei depositi terrigeni vive su idee in buona misura preconcette e sulla convinzione che i modelli di cui si dispone rap-

presentino un punto di arrivo. Buona parte di questi modelli, sui quali sono sfortunatamente basati molti schemi stratigrafico-sequenziali, necessita una profonda e critica revisione.

P a r o l e   c h i a v e : *piene fluviali catastrofiche, sistemi fluvio-deltizii dominati da piene catastrofiche, bacini tettonicamente attivi, cicli davisiani, clima, ciclicità ad alta frequenza, lobi arenacei di piattaforma generati da piene fluviali, sistemi deposizionali fluvio-torbiditici.*

RESUMEN - Los estudios estratigráficos y sedimentológicos realizados durante más de cinco años en numerosas cuencas sedimentarias tectónicamente activas (tabla 1) indican que los sistemas fluvio-deltaicos fósiles están dominados por avenidas fluviales catastróficas. Las evidencias sedimentológicas y estratigráficas muestran que si bien la sedimentación "normal" ocurre en estos sistemas, el potencial de preservación de los depósitos es muy limitado excepto la difusión mareal en el ambiente estuarino. Los sistemas fluvio-deltaicos han acumulado enormes volúmenes de facies conglomerádicas, arenosas y pelíticas cuyo origen e importancia estratigráfica no han sido adecuadamente valorados en la literatura precedente. Por consiguiente, estos sistemas deposicionales no pueden ser analizados utilizando los modelos sedimentológicos convencionales, basados en el estudio de procesos, facies y contextos geomorfológicos derivados del estudio de ambientes actuales. Las facies y asociaciones de facies de los sistemas fluvio-deltaicos fósiles comprenden un amplio espectro de sedimentos poco conocidos y pobremente descriptos, los que varían desde espesos cuerpos conglomerádicos mal organizados a pelitas finamente laminadas, pasando por una vasta gama intermedia de areniscas y areniscas conglomerádicas. A pesar de esta variabilidad, estas facies integran capas gradadas reconocibles tanto en ambientes aluviales como marinos. Numerosos ejemplos bien documentados permiten interpretar que dichas capas gradadas fueron generadas por la irrupción de flujos hiperconcentrados de origen subaéreo en la cuenca marina, los que en razón de su elevada densidad se desplazaron hacia el interior de la misma como flujos hiperpícnicos. Durante el tránsito de estos flujos sobre zonas marino marginales, la erosión submarina puede incorporar y transportar hacia las zonas más profundas un volúmen importante de sedimentos de grano fino y fragmentos de fósiles acumulados durante condiciones "normales" de sedimentación. Dependiendo del contexto fisiográfico, los flujos hiperconcentrados sufren durante su evolución corriente abajo numerosas transformaciones, dando como resultado final corrientes de turbidez de baja densidad. El fenómeno de transformación puede observarse en los depósitos originados por la dilución de flujos de menor volúmen y duración, donde las facies sucesivas de dicha transformación se encuentran en contacto físico, definiendo una barra sigmoidal fluvial. Se reconocen dos tipos de sistemas fluvio-deltaicos: abanicos deltaicos *(fan-deltas)* y deltas fluviales *(river-deltas)*. La diferencia fundamental entre ambos está en que los sistemas de abanicos deltaicos no son confinados, mientras que los sistemas de delta fluvial muestran zonas de transferencia canalizadas. El cortejo de facies idealizado de sistemas de abanicos deltaicos se compone por depósitos de flujos hiperconcentrados que pasan corriente abajo a facies producidas por corrientes de turbidez de alta y de baja densidad. Los sistemas de deltas fluviales muestran en cambio un cortejo de facies integrado por depósitos de flujos hiperconcentrados que evolucionan a facies de corrientes saturadas de sedimento (*sediment-laden stream flow deposits*) en zonas canalizadas, las cuales son a su vez seguidas por depósitos de corrientes de turbidez de alta y de baja densidad. El elemento deposicional más importante en los sistemas fluvio-deltaicos se integra por espesas sucesiones de lóbulos arenosos de plataforma de gran continuidad lateral con *hummocky cross-stratification*. En este trabajo las estructuras sedimentarias de tipo *hummocky* no son consideradas como diagnósticas de ningún tipo de ambiente sedimentario en particular, aunque su presencia se encuentra frecuentemente asociada a depósitos de corrientes diluidas relacionadas con avenidas. Los lóbulos arenosos de plataforma constituyen el frente deltaico de estos sistemas, los que muestran geometrías, cortejos de facies, y patrones cíclicos de apilamiento de alta frecuencia (*high-frequency cyclic stacking patterns)* similares a los lóbulos turbidíticos. Los sistemas fluvio-deltaicos dominados por avenidas pueden desarrollarse solamente en marcos fisiográficos controlados tectónicamente, caracterizados por sistemas fluviales de pequeña y mediana escala con redes de drenaje localizadas en zonas elevadas, y áreas de transferencia de alto gradiente adjacentes a cuencas marinas. En este tipo de contexto, el aporte sedimentario hacia la cuenca se incrementa drásticamente cuando las condiciones climáticas proveen volúmenes de agua suficientes como para producir avenidas catastróficas. El patrón de apilamiento general indica que la evolución temporal de los sistemas fluvio-deltaicos se encuentra controlado por el levantamiento inicial de la red de drenaje, la tasa de denudación, el gradiente de cada sistema, y el volúmen y concentración de los flujos individuales. Este último a su vez es función del volúmen de agua y sedimento disponible. Los sistemas se desactivan cuando el aporte sedimentario a la cuenca marina se reduce progresivamente hasta alcanzar condiciones "normales" de sedimentación. Esto ocurre cuando los factores anteriormente mencionados pierden importancia a causa de la denudación progresiva y el transporte del sedimento hacia las zonas deposicionales marinas. La presencia de patrones de apilamiento cíclicos de diferentes órdenes jerárquicos es uno de los aspectos más característicos de los sistemas fluvio-deltaicos dominados por avenidas. El registro más completo de esta ciclicidad se encuentra en la zona deposicional de cada sistema, donde el ordenamiento cíclico resulta notablemente similar a los modelos de la estratigrafía secuencial. No obstante esta aparente similitud, en este trabajo se sugiere que la evolución temporal de los sistemas dominados por avenidas catastróficas se encuentra principalmente controlada por ciclos de tipo davisiano, producidos por períodos alternantes de levantamiento tectónico y denudación. En su mayor desarrollo, estos ciclos muestran una sucesión general de avance-retroceso (*forestepping-backstepping*) del sistema deposicional. Esta se integra por un sistema turbidítico basal (abanico de fondo de cuenca en la estratigrafía secuencial) sucedido por un sistema fluvio-deltaico dominado por avenidas, el cual evoluciona temporalmente en sistemas fluviales o fluvio-deltaicos "normales". Los patrones de apilamiento de más alta frecuencia dentro de cada uno de los estadios están vinculados a episodios de avance-retroceso de acumulaciones arenosas controlados por variaciones climáticas cíclicas. Las relaciones entre los ciclos de tipo davisiano, los ciclos climáticos de alta frecuencia, y los ciclos de variaciones eustáticas constituyen un campo de investigación futuro a afrontar mediante estudios estratigráficos, sedimentológicos y estructurales de detalle llevados a cabo sin modelos preconcebidos. No obstante, parece claro que en cuencas tectónicamente activas la incidencia de las variaciones eustáticas no puede compararse con la importancia de los ciclos de levantamiento y denudación.

Palabras clave: avenidas catastróficas, sistemas fluvio-deltaicos dominados por avenidas, cuencas tectónicamente activas, ciclos davisianos, clima, ciclicidad de alta frecuencia, lóbulos arenosos de plataforma, sistemas fluvio-turbidíticos.

INTRODUCTION

The results of extensive field studies carried out on a number of ancient fluvial and deltaic systems located in different types of tectonically active basins (Table 1) show that the volumetrically predominant proportion of these systems records original depositional zones characterized by flood-dominated sedimentation in both alluvial and marine strata. In our opinion, current sedimentological models of alluvial and deltaic sedimentation, mainly based on geomorphic characteristics, processes and facies of modern rivers, deltas and fan-deltas (see summaries in Collinson, 1986; Elliott, 1986; McPherson *et al.,* 1987, 1988; Nemec and Steel, 1988; Nemec, 1990; Postma, 1990a, 1990b; Miall, 1992; Orton and Reading, 1993; Blair and McPherson, 1994) are thus apparently of relatively little value for the interpretation of fluvial and deltaic systems in active settings where large sediment availability, steep gradients and proximity to source areas strengthen the role of catastrophic flooding.

Our data reinforce growing geomorphological and sedimentological evidence derived from the study of modern active margin settings indicating that the importance of small and medium-sized mountainous rivers in contributing sediment to ocean basins has been largely underestimated in previous work, and that flood-related hyperpycnal flows and turbidity currents may play a major role in carrying fluvial sediment directly to deep marine basins (Milliman and Syvitski, 1992; Mulder and Syvitski, 1995). In tectonically-controlled physiographic settings characterized by narrow shelves and large sediment availability, terminal depositional zones of ancient flood-dominated fluvial systems can be represented by thick accumulations of shelfal graded beds with HCS (Mutti, 1992b) and may extend as far as deep marine regions, thus directly combining fluvial and turbidite sedimentation in fluvio-turbidite depositional systems (Mutti *et al.*, 1994c).

The conclusions drawn from both modern and ancient fluvio-deltaic systems dominated by flood-related processes may have important and still largely unexplored implications on sequence-stratigraphic models (*e.g.*, Posamentier and Vail, 1988; Posamentier and James, 1993) which are still mainly based on passive-margin settings fed by large river systems with relatively constant discharge and low sediment concentration. In similar fluvial systems flood-related sedimentation is essentially restricted to alluvial regions and plays therefore a minor role at river mouths.

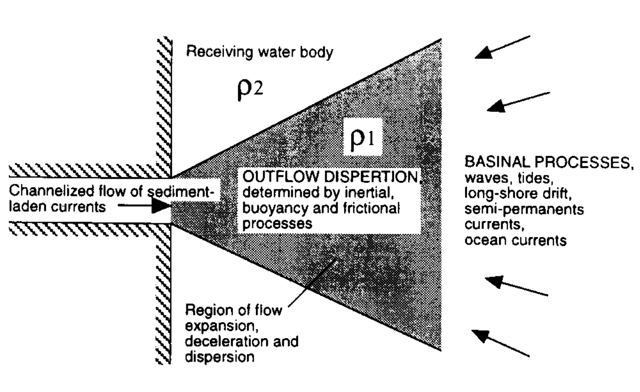
Basin fills dominated by catastrophic flooding show considerable departures from depositional patterns predicted by sequence-stratigraphic models. In tectonically active basins, sediment flux to the sea dramatically increases when tectonic uplift generates high-elevation drainage basins and steep-gradient fluvial systems from which sediment is periodically flushed to adjacent marine basins by catastrophic floods.

On the basis of selected examples from various basin fills (Tab. 1), the purposes of this paper are (1) to illustrate the main depositional settings and facies tracts of flood-dominated fluvio-deltaic systems, and (2) to briefly discuss some of the problems raised by the sedimentary cyclicity that can be observed at different physical and temporal scales in these systems in terms of forestepping-backstepping sandstone bodies.

Current models of modern fluvio-deltaic sedimentation

Modern deltaic sedimentation has been dealt with in a number of papers, special publications and text books with emphasis on modern physiographic settings and processes and facies types that are observed in or inferred from a number of modern deltas. Current models have been mainly derived from fundamental work by Harold Fisk (see summary in Gould, 1970), Coleman and Wright (1975) and Wright (1977), and heavily rely on the ternary classification of Galloway (1975). An extensive review of these models has been provided by Elliott (1986) in a highly perceptive comparison of modern and ancient delta systems (see also Postma, 1990a).

The diagram of figure 1 shows the main factors controlling fluvio-deltaic sedimentation in modern and relatively large fluvio-deltaic systems. The scheme emphasizes the basic relationships existing at river mouths between effluent river water and the characteristics of and the processes acting in the receiving basin. In case of purely fluvial-dominated systems, buoyancy, inertia and friction



$\rho 1 < \rho 2$ hypopycnal flow
$\rho 1 = \rho 2$ homopycnal flow
$\rho 1 > \rho 2$ hyperpycnal flow

Fig. 1 - Diagram showing the main controlling factors of modern fluvio-deltaic sedimentation (slightly modified after Elliott, 1986).

control these relations and determine the local characteristics of deltas particularly in terms of sand and mud distribution and mouth-bar geometry. The different mouth-bar types that can develop mainly as a function of the density difference between river outflow and sea water can be conveniently considered in terms of homopycnal, hypopycnal and hyperpycnal river outflows (Bates, 1953; Elliott, 1986).

In describing delta systems of passive continental margins fed by large rivers entering ocean basins and characterized by predominant fine-grained sediment load "classical" models of deltaic sedimentation (see Coleman and Wright, 1975; Galloway, 1975; Wright, 1977; Orton, 1988; Orton and Reading, 1993) can probably apply. Most of these deltas are dominated by hypopycnal flows (see review in Nemec, 1995, with references therein), and are thus better characterized by rapid deposition of sand at river mouths and by large buoyant plumes that carry mud farther basinward. Hyperpycnal flows are rare in these systems since most of the sediment carried by rivers in flood is sequestered in alluvial flood basins and coastal flood plains thus reducing sediment concentration of final river outflows (Mulder and Syvitski, 1995; see also Milliman and Syvitski, 1992).

More comprehensive models for fluvio-deltaic sedimentation have been recently provided by McPherson *et al.* (1987, 1988), Nemec and Steel (1988), Nemec (1990), Postma (1990a, 1990b, with references therein) and Orton and Reading (1993). These attempts consider deltaic sedimentation in a broader sense than in previous literature and include in this type of sedimentation both fan-deltas and river-deltas. In his delta classification, Postma (1990a, 1990b) considers the different styles of "steady-state" growth of deltas taking into account several controlling factors including (1) feeder systems (fluvial regime and sediment load), (2) water depth and depth ratio of receiving basins, (3) river-mouth processes, and (4) diffusion processes due to waves, tides and gravity (*i.e.* creep, slide and sediment flow due to sediment instability on steep delta slopes). At least twelve basic delta prototypes are defined on the basis of this approach (see Postma, 1990a, his fig. 2). Despite its general importance, the Postma classification unfortunately does not include and discuss specific facies types and facies sequences that could be used to discriminate among the different types of delta in outcrop or core studies.

The general applicability of the classifications discussed above to ancient deltaic sedimentation remains largely untested particularly in terms of the relative importance of hyperpycnal flows in delta-front regions and of how "steady states" of modern river-deltas and fan-deltas change with time as a result of both intrinsic and extrinsic factors controlling fluvio-deltaic sedimentation during its development. Attempts to provide conceptual models of "evolutionary states", with particular reference to fan-delta systems, have been discussed in a very general way only in a limited number of papers (*e.g.*, Ethridge and Wescott, 1984; Massari and Colella, 1988; Prior and Bornhold, 1990).

"Normal" versus "catastrophic" flood-related processes

What the term "catastrophy" really means in the evolution of geological systems is well beyond the scope of this paper. The interested reader is referred to fundamental and fascinating papers and books which have attempted to highlight the importance of natural catastrophes, the way in which they have altered temporary steady states of geological systems, and how we can recognize them in the stratigraphic and paleontological record (*e.g.* Gretener, 1967; Dott, 1983, 1988; Clifton, 1988; Huggett, 1989, 1990; Lecce, 1990; Ager, 1993 *cum bibl.*). Basically, catastrophic events do exist, are hierarchically ordered, and affect the equilibrium state of geological systems in many different ways, most of which are not catastrophic in nature in the common usage of the term (Schumm, 1977, 1981).

The assumption made in this paper is that most of the catastrophic processes observed in modern environments are still part of the "normal" spectrum of fluvial and marine processes. For example, catastrophic floods (debris flows and sheet flows) through which most alluvial fans are growing at present or have grown during Holocene are catastrophic events which are, in fact, very poorly efficient mechanisms of sediment transport since they simply transfer sediment from its source area to the closest mountain front, *i. e.* to the point where flows confined in entrenched and high-gradient streams become unconfined and are forced to deposit most of their sediment load in cone-shaped features. Excellent papers describe processes and facies related to these poorly efficient depositional systems, characteristically made up of texturally immature clasts and whose size and volume are necessarily modest (*e.g.*, Blair and McPherson, 1994). In reality, present catastrophic floods are at least one order of magnitude smaller than those of late Pleistocene (Evans and Clague, 1994), and probably even smaller than catastrophic floods which occurred in earlier periods of the Earth's history and which still remain essentially unrecognized in their stratigraphic record.

For the purposes of this paper, we refer to "normal" floods those flood-generated water-sediment mixtures that are responsible for the accumulation of graded flood-units in a variety of high-gradient alluvial environments such as alluvial fans and rivers with highly fluctuating discharge, and in more mature river systems through "normal" overbank processes. These sediments have been described in an abundant literature concerning both modern and ancient depositional systems (see summaries in Walker and Cant, 1984; Collinson, 1986; Miall, 1992). Such flows apparently never reach sufficient volume and sediment concentration to carry substantial amounts of sand into adjacent marine basins. The definition of "normal" process is consequently extended also to most hyperpycnal flows and low-density turbidity currents developed at the mouths of modern rivers (*e.g.*, Mulder and Syvitski, 1995), since these flows apparently never reached sufficient sediment concentration and velocity to carry substantial amounts of sand in adjacent marine basins (see later).

The term *catastrophic floods* is restricted hereafter to flood-generated flows of sufficient volume, velocity and sediment concentration to deposit graded flood units far away from their original drainage basins. These catastrophic floods enter marine basins as highly hyperpycnal flows generating self-sustained turbidity currents which are able to carry large volumes of sand over considerable distances.

The approach of this study

As outlined by Schumm (1977, 1981), a fluvial system can be seen as a whole, consisting of three genetically inter-related zones: (1) a drainage basin (Zone 1) which supplies sediment and water, (2) a sediment transfer zone (Zone 2), *i.e.* a river which removes the waste of the drainage basin, and (3) a terminal depositional zone (Zone 3) where sediment accumulates in alluvial fans, fan-deltas, alluvial plains, or deltas. The evolution of fluvial systems through time results from the interaction of extrinsic and intrinsic factors controlling erosional and depositional processes in the three zones above which, together, form a strictly inter-related process-response system.

Stratigraphers and sedimentologists have rarely attempted to consider the fluvial system in such a broad sense. Current sedimentogical models have rather the tendency to describe the different zones of the fluvial system as genetically independent systems. Therefore, these models emphasize separately processes and facies of river deposits (*e.g.*, Miall, 1978, 1992; Allen, 1983a, 1983b; Friend, 1983; Rust, 1984; Rust and Koster, 1984; Walker and Cant, 1984; Collinson, 1986), alluvial-fan and fan-delta systems (*e.g.*, Rust and Koster, 1984; Collinson, 1986; McPherson *et al.,* 1987, 1988; Nemec and Steel, 1988; Nemec, 1990; Blair and McPherson, 1994), as well as the different types of river-delta systems (*e.g.*, Coleman and Wright, 1975; Elliott, 1986; Postma, 1990a). All these schemes, which are strongly based on processes, sediments and geomorphic characteristics observed in modern and specific environments, have led to a very fragmentary view of the entire fluvial system, and therefore to a complex and static taxonomy of fluvial and deltaic facies and styles for purposes of stratigraphic analysis.

To a stratigrapher, the main implication of Schumm's concepts is perhaps that the most complete record of the evolution of ancient fluvial systems is likely to be preserved in their depositional zones because of their higher preservation potential (Schumm, 1981, pp. 27-28). Therefore the basic problem is to understand to what extent processes and facies of modern fluvial zones can be linked together from transfer to depositional zones. There is little doubt that such a link is difficult to establish on the basis of "normal" processes operating in modern fluvial and deltaic environments mainly because of their present highly diversified depositional patterns. "Normal" processes are essentially independent of each other from a genetic standpoint. Tractive fluvial currents are thought to predominate in river systems characterized by a variety of channel styles, bars, and bedforms (see summaries in Miall, 1985, 1992); debris flows and sheet floods predominate in alluvial fans and in the alluvial component of fan-deltas (*e.g.* Miall, 1978, 1992; Blair and McPherson, 1992, 1994); wave, tides and storms account for much of the final phases of sediment transport and deposition in the marine components of both fan-deltas (*e.g.*, Orton, 1988; Orton and Reading, 1993) and river-deltas (*e.g.* Coleman and Wright, 1975; Galloway, 1975; Wright, 1977; Orton, 1988)

Flooding - a catastrophic process strongly emphasized by geomorphologists as the most effective in shaping the fluvial landscape in the long term - has long been underestimated by sedimentologists and essentially restricted to debris flows and sheet flows of alluvial fans (*e.g.*, Miall, 1978, 1992). However, there is ample geomorphological and sedimentological evidence for the importance of catastrophic flooding in late Pleistocene alluvial basins (*e.g.*, Bretz, 1925; Baker and Nummedal, 1978; Baker and Bunker, 1985; Atwater, 1987; Rudoy and Baker, 1993; Smith, 1993) and, although with a much lower degree of catastrophism, in many modern alluvial fans, fan deltas and rivers (McKee *et al.,* 1967; Williams, 1971; Beaty, 1974, 1990; Blair, 1987; Wells and Harvey, 1987; Prior and Bornhold, 1989, 1990; Bornhold and Prior, 1990; Kochel, 1990; Wescott, 1990; Pickup, 1991; Blair and McPherson, 1992, 1994; Evans and Clague, 1994). In addition, a number of papers have dealt with sedimentary structures associated with floods in modern and ancient fan deltas (Ballance, 1984, 1988; Nemec and Steel, 1984; Marzo and Anadón, 1988; Flint and Turner, 1988; Prior and Bornhold, 1989, 1990; Buatois and Mángano, 1995) and river systems (*e.g.* Tunbridge, 1981; Smith, 1986, 1987; Røe, 1987; Smith and Lowe, 1991; Fraser and Bleuer, 1988; Dawson, 1989; Todd, 1989; Bristow, 1993; Massari *et al.,* 1994). Flood-generated hyperpycnal flows have been documented in modern deltas (*e.g.*, Lambert *et al.*, 1976; Sturm and Matter, 1978; Lambert and Hsü, 1979; Weirich, 1986; Wright *et al.,* 1986; 1988; Bornhold and Prior, 1990; Zeng *et al.*, 1991; Mulder and Syvitski, 1995) and in both modern and ancient fan-deltas (*e.g.*, Ballance, 1988; Dabrio and Polo, 1988; Prior and Bornhold, 1989, 1990). Despite this abundant information, no real attempts have been made to assess the stratigraphic importance of flood-related sedimentation in ancient strata.

The approach in the present study has been, therefore, to assess the importance of this type of sedimentation through the analysis of a significant number of ancient fluvial systems with particular emphasis on the strata of their original depositional zones, *i.e.* the strata that should best record the development of individual fluvial systems in terms of genetically linked erosional and depositional processes with time. The purpose of this approach is to explore how flood-related sedimentation may represent the only potentially unifying process permitting the establishment of relatively simple depositional models for the description and a better understanding of fluvio-deltaic systems formed in tectonically active, high-gradient settings and fed by relatively small and high gradient rivers.

Source of data

Over the past seven years we have carried out extensive field studies on many ancient fluvial and fluvio-deltaic systems, both marine and lacustrine, located in tectonically active basins, *i.e.* basins where relatively high-gradient rivers discharged their water and sediment load in depositional zones relatively close to their source zones. The main systems considered and their general characteristics are shown in table 1.

Detailed sedimentological and stratigraphic studies were carried out particularly in upper Cretaceous and Paleogene strata of the south-central Pyrenean foreland Basin, Spain, in Oligocene strata of the collisional Tertiary Piedmont Basin (TPB) in north-western Italy, and in the late Pliocene-Pleistocene collisional Sant'Arcangelo Basin, in the southern Apennines, Italy. The results of these studies, supplemented by detailed observations made by the senior author in spectacularly exposed Mesozoic fluvial and fluvio-deltaic systems in the back-arc Neuquén, San Jorge and Cuyo basins, Argentina, indicate that catastrophic floods dominated transport and sedimentation in the depositional zones of the systems considered.

Depending upon the local tectonic and physiographic setting and on the volume, sediment concentration and

Tab. 1 - List, location and main characteristics of the stratigraphic units considered in this work

Country	Basin	Stratigraphic unit	Age	Type of flood-dominated depositional systems recognized in this work	Diffusion processes	General references
ARGENTINA	Neuquen Basin	Cuyo Group	Early to Middle Jurassic	Marine fan-deltas and marine river-deltas	Tides (waves)	5; 6; 9
ARGENTINA	Neuquen Basin	Tordillo Fm.	Kimmeridgian	Lacustrine fan-deltas and lacustrine river-deltas	———	5; 6; 9
ARGENTINA	Neuquen Basin	Mulichinco Fm.	L. Valanginian	Marine river-deltas and marine fan-deltas	Tides and waves	4; 9
ARGENTINA	Neuquen Basin	Agrio Fm. Avilé Mb.	L. Hauterivian	Lacustrine fan-deltas and marine river-deltas	Tides	9
ARGENTINA	Neuquen Basin	Agrio Fm. Upper Mb.	L. Hauterivian to Barremian	Marine river-deltas	———	9
ARGENTINA	Neuquen Basin	Huitrín Fm. Troncoso Mb.	Aptian	Lacustrine fan-deltas	———	9
ARGENTINA	Neuquen Basin	Rayoso Fm.	Albian to Cenomanian	Lacustrine fan-deltas	———	9
ARGENTINA	Neuquen Basin	Neuquén Group	Cenomanian to Campanian	Lacustrine fan-deltas and lacustrine river-deltas	———	9
ARGENTINA	Cuyo Basin	Río Mendoza Fm.	Triassic	Lacustrine fan-deltas	———	7; 8; 10
ARGENTINA	Cuyo Basin	Potrerillos Fm.	Triassic	Lacustrine fan-deltas	———	7; 8; 10
ARGENTINA	Cuyo Basin	Río Blanco Fm.	Triassic	Lacustrine fan-deltas	———	7; 8; 10
ARGENTINA	S.Jorge Basin	Las Heras Group Mata Siete Fm.	Aptian Barremian	Lacustrine fan-deltas	———	1; 3
ITALY	Tertiary Piedmont Basin	Molare Fm.	Rupelian	Marine fan-deltas and lacustrine fan-deltas	———	13
ITALY	Sant'Arcangelo Basin	Catarozzo Gp.	L. Pliocene	Marine fan-deltas	———	16
ITALY	Sant'Arcangelo Basin	Aliano Gp.	E. Pleistocene	Marine fan-deltas and lacustrine fan-deltas	———	16
ITALY	Sant'Arcangelo Basin	Tursi Gp.	E. Pleistocene	Marine fan-deltas	———	16
SPAIN	South - central Pyrenean Basin	Aren Gp.	Maastrichtian Campanian	Marine river-deltas, marine fan-deltas and lacustrine fan-deltas	Tides (Waves)	11; 14
SPAIN	South - central Pyrenean Basin	Tremp Gp.	Paleocene L. Cretaceous	Lacustrine fan-deltas and river-deltas	———	14; 15
SPAIN	South - central Pyrenean Basin	Figols Gp.	Ypresian	Marine river-deltas	Tides (Waves)	12; 15
SPAIN	South - central Pyrenean Basin	Castigaleu Gp.	Ypresian	Marine river-deltas and lacustrine fan-deltas	Tides	12; 15
SPAIN	South - central Pyrenean Basin	Castisent Gp.	Ypresian	Marine river-deltas, marine fan-deltas and lacustrine fan-deltas	Tides	12; 15
SPAIN	South - central Pyrenean Basin	Santa Liestra Gp.	Lutezian Ypresian	Marine fan-deltas	———	2; 12

General references: 1 - Barcat *et al.*, 1989; 2 - Crumeyrolle and Mutti, 1986; 3 - Fitzgerald *et al.*, 1990; 4 - Gulisano *et al.*, 1984; 5 - Gulisano and Gutierrez Pleimling, 1994a; 6 - Gulisano and Gutierrez Pleimling, 1994b; 7 - Kokogian *et al.*, 1993; 8 - Kokogian and Mancilla, 1989; 9 - Legarreta and Gulisano, 1989; 10 - Moratello, 1993; 11 - Mutti and Sgavetti, 1987; 12 - Mutti *et al.*, 1988; 13 - Mutti *et al.*, 1995; 14 - Nagtegaal, 1972; 15 - Puigdefábregas *et al.*, 1989; 16 - Zavala and Mutti, in press.

momentum of flood-generated flows, the depositional zones of flood-dominated systems may develop in alluvial flood basins and lakes or extend seaward in nearshore, shelfal and slope-basinal environments, thus forming a continuum from alluvial to deep-marine turbidite sedimentation. We will concentrate hereafter particularly on those systems whose sandy terminal depositional zones are located in nearshore and shelfal marine settings and can be essentially described as flood-dominated fan-delta and river-delta systems (see later).

The great number of systems examined and the general scope of this paper do not permit a detailed description and discussion of all the systems considered. Some of the general characteristics of these systems, as well as pertinent bibliographic references, are listed in table 1. Figures 22 to 27 illustrate the depositional setting of some of these systems through detailed stratigraphic cross sections. In the captions to these figures, and where necessary, additional stratigraphic and sedimentological information is provided for each system considered.

ANCIENT FLOOD-DOMINATED FLUVIO-DELTAIC SYSTEMS

General characteristics

We use the term "flood-dominated fluvio-deltaic system" to denote depositional systems predominantly made up of flood units in both their alluvial and marine strata. These units, each of which is deposited by an individual flood event and can thus be regarded as a bed in the sense of Campbell (1967), are composed of a variety of facies types ranging from unstratified conglomerates to graded mudstones through a variety of internally stratified and unstratified pebbly sandstone and sandstone facies. Although several authors (see Collinson, 1986, *cum bibl.* and Miall, 1992, *cum bibl.*) have attempted to describe and interpret some of these deposits, the great majority of flood-generated facies and facies associations remain largely undescribed in the existing literature. Because of their inherent complexity (Fig. 2), most of these facies are difficult to interpret in terms of specific processes. Only a limited number of facies types and facies associations will be thus considered in this paper.

Within each system and in a general downcurrent direction, individual flood units vary from highly lenticular and coarse-grained units bounded by erosional surfaces to laterally extensive beds of graded sandstones and mudstones separated by even and parallel bedding surfaces. As a result, overall proximal-distal trends of facies distribution can easily be established within each system on the basis of textural characteristics and bedding style. The proximal strata of flood-dominated fluvio-deltaic systems are typically made up of coarse-grained and amalgamated flood units. In a downcurrent direction, textural segregation produced by transport gives way to progressively better graded and finer-grained flood units characterized by an increasing tabular geometry. The final marine depositional zones of flood-dominated fluvio-deltaic

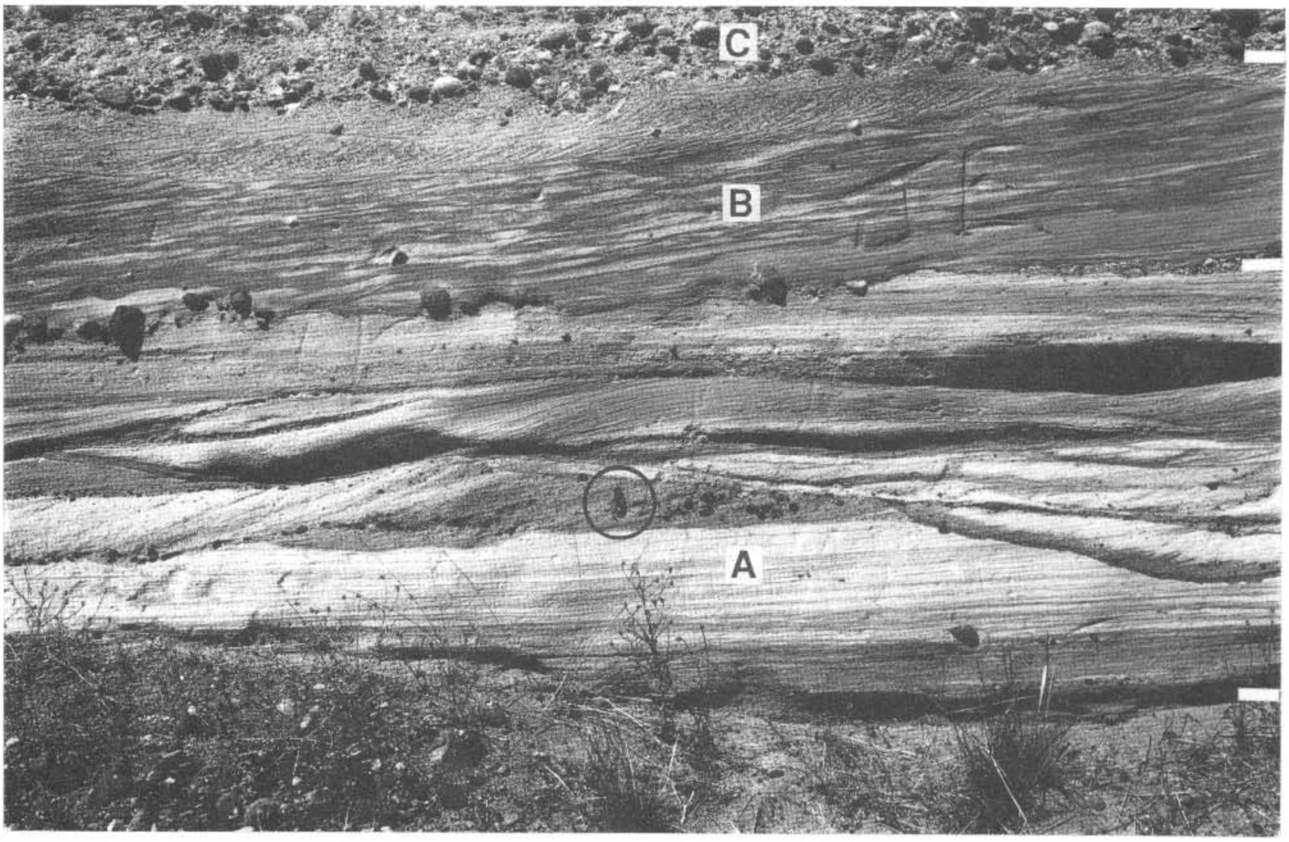


Fig. 2 - Example of flood-generated facies showing the great variety of internal structures, texture, and bedding geometry of these sediments. Unit A is essentially made up of traction and traction-plus-fallout deposits characterized by slightly inclined stratification, coarse-grained megaripples, and hummocky-like structures, recording an increase in the rate of sedimentation toward the top. Unit B is interpreted as an aeolian deposit which reworks and truncates the underlying flood-generated strata. The pebble alignment at the base of the unit is thought to represent a deflation surface. Unit C is interpreted as the deposit of a flood-generated hyperconcentrated flow. The main paleocurrent direction is from right to left. Late Neogene continental strata, near Las Lajas, Neuquén Basin, Argentina.

systems are therefore invariably recorded by thick accumulations of sharp-based graded sandstone beds that grade seaward into shelfal, slope and basinal successions of graded mudstones and fine-grained and thin-bedded sandstones.

BASIC COMPONENT ELEMENTS OF FLOOD-DOMINATED FAN-DELTA AND RIVER-DELTA SYSTEMS

Although highly variable in terms of size, facies characteristics and specific depositional patterns, flood-dominated fluvio-deltaic systems can be framed within a broad spectrum of inter-gradational types whose end members are represented by fan-delta and river-delta systems. These two types of systems and their basic component elements are shown in figures 3 and 4 respectively. These elements are easily recognizable in most ancient fluvio-marine successions and can be used as operational units for purposes of stratigraphic analysis. Within each system considered, the lateral and vertical stratigraphic relationships of the component elements delineate the basic depositional model of the system and its evolution with time, *i.e.* the "steady state" of the system at each considered time and the "evolutionary state" (in the sense of Postma, 1990a) of the system with time, respectively.

Flood-dominated fan-delta systems are illustrated by detailed stratigraphic cross sections describing the Eocene Santa Liestra Group in the south central Pyrenees (Fig. 22), the Oligocene Molare Formation, Tertiary Piedmont Basin, Italy (Fig. 23), and the Pleistocene of the Sant'Arcangelo basin, southern Apennines, Italy (Fig. 24); flood-dominated river-delta systems are illustrated by detailed cross sections of the Eocene Figols (Fig. 25), Castigaleu (Fig. 26) and Castisent (Fig. 27) groups from the south-central Pyrenees.

Prodelta mudstones with thin-bedded and fine-grained sandstones and shelfal sandstone lobes with HCS (see later) form the volumetrically most important components of both types of systems. In basins characterized by pronounced shelf-slope breaks, prodelta mudstones commonly extend basinward as thick slope wedges which may interfinger with basinal, sand-rich turbidite systems (see later). In shelfal environments, these sediments are commonly bioturbated and may be locally highly fossiliferous.

In a landward direction, prodelta deposits grade into shelfal, tabular bodies composed of graded sandstone beds with HCS which record the final depositional zones of the sand load carried by most flood-generated turbidity currents (see later). These tabular bodies, usually developed as m-thick features separated by muddier facies, are referred to hereafter as "shelfal sandstone lobes with HCS" because of their striking similarities with deeper-water turbidite sandstone lobes as defined by Mutti and Ghibaudo (1972) and Mutti and Ricci Lucchi (1972). Flood-generated shelfal sandstone lobes can be regarded as the genuine delta-front deposits of fluvial-dominated deltaic systems, *i.e.* systems in which strictly fluvial processes can actually carry their sand to nearshore and shelfal regions without intervening substantial diffusion operated by waves and tides. Plates XII and XIII illustrate some typical examples of flood-generated shelfal sandstone lobes.

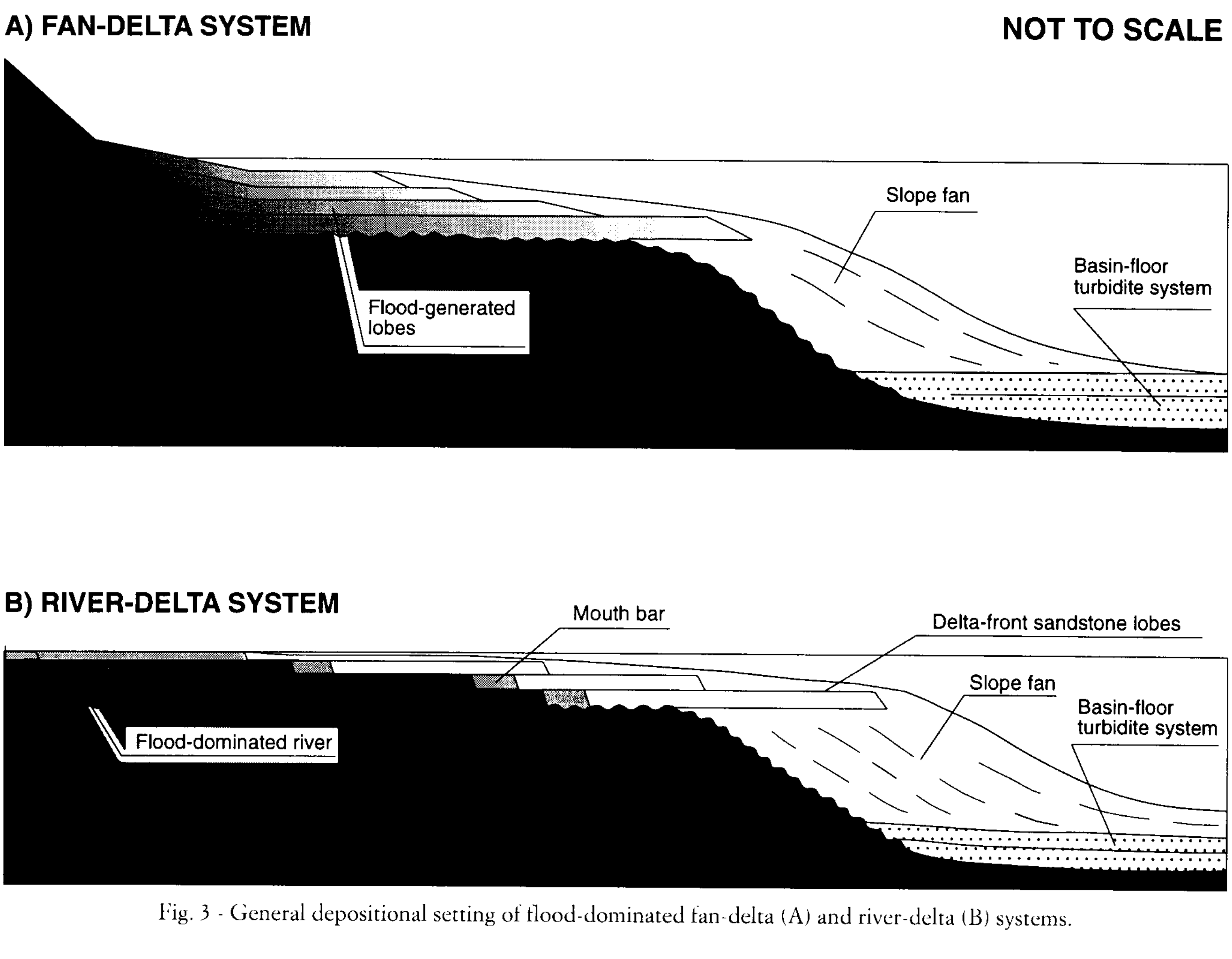


Fig. 3 - General depositional setting of flood-dominated fan-delta (A) and river-delta (B) systems.

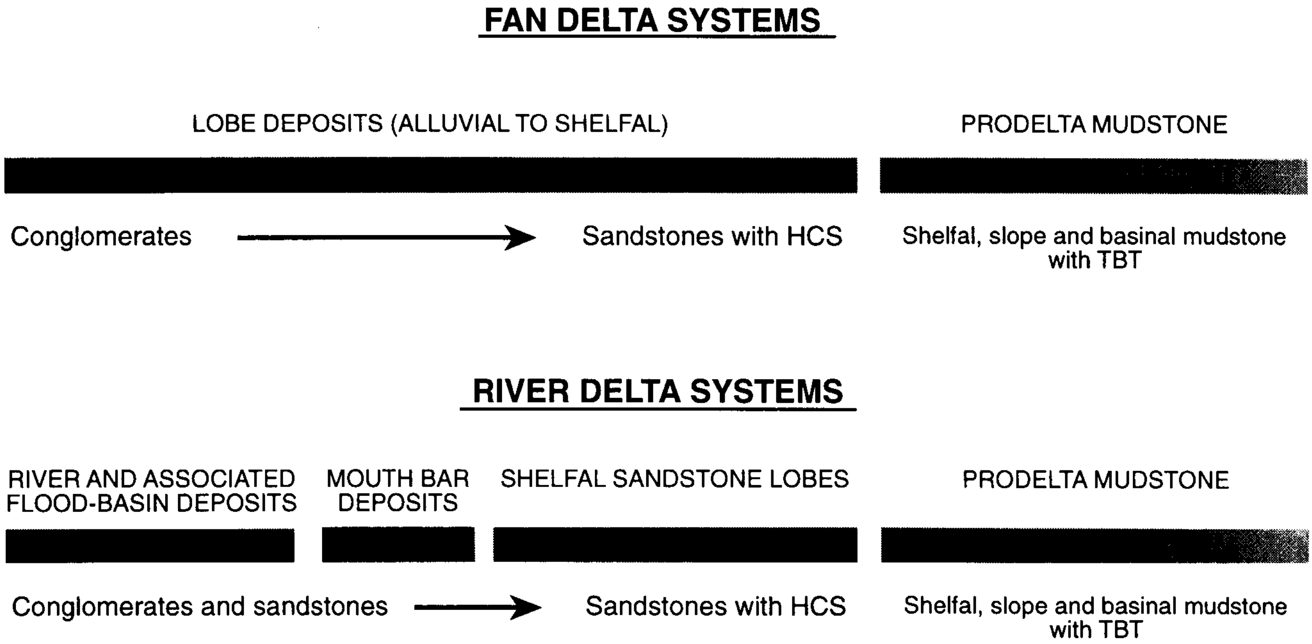


Fig. 4 - Basic component elements of flood-dominated fan-delta and river-delta systems.

In flood-dominated fan-delta systems, shelfal sandstone lobes with HCS build up thick and laterally extensive successions of graded sandstone beds which grade landward into amalgamated pebbly-sandstone and conglomeratic facies. These settings are clearly the result of deposition dominated by unconfined, catastrophic flows.

In flood-dominated river-delta systems, shelfal sandstone lobes with HCS deposited by unconfined flows form the bulk of these systems in shelfal regions. In such systems, shelfal sandstone lobes with HCS, which are commonly finer-grained and thinner-bedded than in flood-dominated fan-delta systems, are replaced in a landward direction by seaward offlapping mouth-bar sandstone facies which grade farther landward into extensively scoured and lenticular coarse-grained river deposits associated with flood-basin mudstones and fine-grained sandstones. In systems of this type, river-mouth bar processes (mainly related to the volume and sediment concentration of river outflow) become crucial in determining the textural characteristics and the volume of sediment that may be carried farther seaward.

The main difference between the two types of depositional settings resides in the fact that in fan-deltas flood-generated flows enter adjacent marine basins directly as unconfined, highly concentrated sheet-like flows, whereas, in river-deltas, flood-generated flows move as essentially confined flows along river reaches and alluvial basins and spread out only at river mouths. Depositional processes and resulting facies types are considerably different in the two types of settings.

Marine diffusion processes affect primarily river-delta systems through tidal action. Both fan-delta and river-delta systems develop substantial accumulations of shallow-marine turbidite sandstone facies with HCS in their shelfal regions - a type of stratification generally thought to be indicative of storm-dominated nearshore and shelfal environments. These two points are briefly discussed below.

Marine diffusion processes and related facies associations

Marine diffusion processes produced by wave and tidal action or sediment failure (see summary in Postma, 1990b, with references therein) are virtually unrecorded in flood-dominated fan-delta systems. The lack of wave- or tide-dominated facies in the shallow-marine strata of these systems is probably related to the low preservation potential of these facies which, if formed, were completely eroded by subsequent flood-related processes and therefore resedimented seaward of their original position.

In river-delta systems, diffusion processes are essentially recorded by tide-dominated or tide-influenced facies in mouth-bar deposits or in strata formed in the lower reaches of otherwise flood-dominated rivers. Broadly speaking, these tide-dominated or tide-influenced deposits define estuarine settings herein simply defined as depositional zones where fluvial and tidal processes interact (for a more extensive and exhaustive discussion of estuarine settings the reader is referred to Allen, 1991; Darlymple *et al.*, 1992).

The importance of tidal action in flood-dominated river-delta systems varies greatly from one system to another. In large systems, tidal diffusion commonly gives way to volumetrically important sedimentary bodies that are either entirely tide-dominated or preserve more or less developed intercalations of flood-generated facies. In some systems, flood-generated facies show distal fringes reworked by virtually contemporaneous tidal action; in other systems, tidal action becomes effective only upon cessation of flood-related sedimentation, *i.e.* after phases of active forestepping of flood-generated sandstone facies. Both types of setting can be observed in the river-delta system represented by the lower Eocene Roda Sandstone in the Figols Group of the south-central Pyrenees (Fig. 25).

All the systems considered are conspicuous for the lack of facies produced by substantial and prolonged wave action in beach and barrier island environments. The only notable exceptions are represented by small-scale barrier-island complexes associated with regional transgressive events in the Eocene Figols Group of the Ager syncline and by low-energy beach deposits in the Cretaceous Aren Sandstone, south-central Pyrenees, and in the Pleistocene strata of the Sant'Arcangelo basin, southern Apennines (Tab. 1).

THE ORIGIN OF SHALLOW-MARINE TURBIDITY CURRENTS AND RELATED HCS

The way in which catastrophic flood-generated sediment-water mixtures may transform into turbidity currents and therefore into essentially self-sustained currents that can travel in sea water over considerable distances is discussed in several papers (*e.g.* Pantin, 1979; Parker, 1982) and particularly in the excellent review by Normark and Piper (1991) dealing with the ignition of turbidity currents in marine basins. Ignition is basically a process through which a suspension current undergoes sudden acceleration and increase in volume above a critical sediment concentration. Continued flow dilution because of mixing with ambient fluid is thus compensated by bulking, *i.e.* the entrainment of new sediment by the flow through erosion which results in increased sediment concentration.

As pointed out by Mulder and Syvitski (1995), a minimum sediment concentration of about 35-45 kg/m^3 is required for the development of a hyperpycnal flow in sea water. As a result most of the turbidity currents associated with floods in modern settings are low-density currents which are able to transport seaward only fine-grained sediment

Normark and Piper (1991) and Zeng *et al.* (1991) have suggested that the ignition of sand-rich turbidity currents in modern delta settings must be essentially related to sediment-instability along delta edges, probably triggered by flood events.

The characteristics of flood-generated shelfal sandstone lobes as described in this study strongly suggest that many hyperconcentrated flows and, to a lesser extent, sediment-laden stream flows were apparently able to ignite both high- and low-density turbidity currents in marine environments simply because of their momentum. Within individual beds, ignition is recorded by the abundance of mudstone clasts and fossil debris ripped up from the marine substratum (Pl. I, Fig. d; Pl. III, Figs a, b, d; Pl. IV, Fig. c), indicating that hyperconcentrated flows became self-sustained turbidity currents through a phase of important submarine erosion. Impressive amounts of fossil debris were thus displaced by these currents toward progressively deeper-water and distal shelfal environments (Mutti, 1992b). The loss of momentum of hyperconcentrated flows must therefore have been partly compensated by continuous sediment supply from the subaerially derived flow and by the transformation of the frontal part of the flow into a self-sustained turbidity current.

As discussed above, the typical sedimentary expression of flood-dominated fluvio-deltaic systems is the development of laterally extensive shelfal sandstone lobes with HCS.

HCS and similar styles of bedding can result from different types of processes associated with (1) purely oscillatory flows (Southard *et al.,* 1990), (2) purely unidirectional flows with high rates of sedimentation (Allen and Underhill, 1989), and (3) combined flows characterized by both unidirectional and oscillatory components (Nøttvedt and Kreisa, 1987; Arnott and Southard, 1990). Essentially, combined-flow conditions may lead to the formation of both isotropic and anisotropic HCS (in the sense of Arnott and Southard, 1990), the latter including a variety of stratification types. Therefore, it appears that HCS and similar styles of bedding are not univocally diagnostic of a specific type of process or environment. Pl. I, Figs a, b, c, d, Pl. IV, Fig. c, Pl. V, Figs a and b illustrate some examples of this type of stratification from a variety of depositional settings in the systems considered in this study.

Table 2 lists some of the most important papers that have dealt with HCS over the last two decades. Inspection of the general depositional settings from which sandstone facies with HCS are reported in these papers shows that, with the exception of the examples in column 4, where HCS is associated with beach deposits, this type of stratification is found in association with both river-delta and fan-delta systems (columns 2 and 4 respectively). HCS is also reported from fluvial facies, *i.e.* from strata formed in depositional environments clearly unaffected by wave action (column 1).

The origin of HCS in shelfal sandstone facies has long been debated in previous literature (*e.g.*, Campbell, 1966; Harms *et al.*, 1975, 1982; Duke, 1985; Greenwood and Sherman, 1986; Nøttvedt and Kreisa, 1987; Arnott and Southard, 1990; Southard *et al.*, 1990; Duke *et al.*, 1991), although generally associated with storm activity either in terms of storm surges (*e.g.*, Morton, 1981; Swift *et al.*, 1983) or of density currents triggered by wave loading and ensuing liquefaction and resuspension of nearshore sands (*e.g.*, Hamblin and Walker, 1979; Wright and Walker, 1981; Leckie and Walker, 1982; Nelson, 1982; Myrow and Hiscott, 1991).

Tab. 2 - Occurrence of HCS in fluvial, river-delta, fan-delta, and beach deposits as reported in pertinent literature

Fluvial deposits	River-delta deposits	Fan-delta deposits	Beach deposits
Williams, 1971	Dott and Bird, 1979	De Celles, 1987	Campbell, 1966, 1971
Rust and Gibling, 1990	Hamblin and Walker, 1979	Colmenero *et al.*, 1988	Harms *et al.*, 1975, 1982
Dam and Andreasen, 1990	Wright and Walker, 1981	Flint and Turner, 1988	Kumar and Sanders, 1976
Cotter and Graham, 1991	Dott and Bourgeois, 1982	Maejima, 1988	De Raaf *et al.*, 1977
Browne and Plint, 1994	Leckie and Walker, 1982	Marzo and Anadón, 1988	Bourgeois, 1980
	Nelson, 1982	Massari and Parea, 1988	Kreisa, 1981
	Walker *et al.*, 1983	Massari and Parea, 1990	Hunter and Clifton, 1982
	Leithold and Bourgeois, 1984	DeCelles and Cavazza, 1992	Dott and Bourgeois, 1982
	Chan and Dott, 1986		Swift *et al.*, 1983
	Surlyk and Noe-Nygaard, 1986		Walker *et al.*, 1983
	Eyles and Clark, 1988		Bourgeois and Leithold, 1984
	Winn, 1991		Aigner, 1985
	Higgs, 1991		Greenwood and Sherman, 1986
	Myrow, 1992		Handford, 1986
	Myrow and Hiscott, 1991		
	Buatois and Mángano, 1995		

Both interpretations assume that the oscillatory component of storm-generated flows is produced by waves.

On the basis of stratigraphic and depositional relationships reconstructed for many flood-dominated fluvio-deltaic systems considered in this study and, particularly, on the detailed reconstruction of local facies tracts (Pl. III, Fig. d; Pl. IV, Fig. a; Pl. V, Fig. b), we conclude that most of the shelfal sandstone facies with HCS associated with these systems are inherent with flood-related processes. Because of their sediment concentration and momentum, large-volume catastrophic hyperpycnal flows must be locally able to set in motion shallow sea waters (Mutti, 1992b), thus strongly enhancing the oscillatory component that would be locally added to the flow by "normal" wave action. The problem, which is beyond the purposes of this paper, probably involves more complex hydrodynamic processes. More specifically, internal waves generated along density interfaces within each flow (see Wright *et al.,* 1988) are likely to play an important role in the formation of HCS in shelfal sandstone lobes.

Whatever its origin, the oscillatory component does not generally affect the lower and denser part of the flow but becomes important when the upper and less dense part of the flow deposits its sediment load (see also De Celles and Cavazza, 1992). As a result, distal shelfal lobes deposited by low-density turbidity currents are characterized by relatively fine-grained sandstone beds where HCS is the dominant depositional structure.

The above conclusion is strongly supported by the lack of high-energy, wave-dominated shoreline deposits in all systems considered in this study (see previous section on marine diffusion processes). Most probably, basins located in active tectonic settings and particularly in thrust-fold belts, are generally relatively small, narrow and elongate features where substantial and prolonged wave action is probably prevented by basin configuration and limited connection with oceans.

Basic facies tracts of flood-dominated fan-delta and river-delta systems and their interpretation

Flood-dominated fan-delta and river-delta systems are characterized by distinctive facies tracts, *i.e.* facies types that originate from the transformations of flood-generated flows during their basinward motion along the erosional and depositional profile of each system considered. Flow transformations and their bearing on resulting facies tracts of both subaerial and submarine sediment gravity flows have been discussed in several papers (*e.g.*, Bouma, 1962; Lowe, 1982; Fisher, 1983; Weirich, 1989; Normark and Piper, 1991; Mutti, 1992a).

Elements and inferred flood-related processes of flood-dominated fan-delta and river-delta systems are shown in the general diagrams of figures 5 and 6 respectively. The different processes thought to be responsible for the deposition of flood-generated facies are summarized and defined in table 3 (see also Pierson and Costa, 1987).

Whatever their origin (see extensive reviews in Blair and McPherson, 1994), cohesive debris flows and hyperconcentrated flows are considered to represent the initial phases of flooding in both alluvial fans and rivers. We emphasize herein the importance of hyperconcentrated gravity flows in the sense of Mutti (1992a), *i.e.* flows which are transitional between cohesive debris flows and high-density turbidity currents. These flows, which retain some strength but have already developed large-scale internal turbulence, produce sheet-like and internally unstratified beds of overall crudely graded conglomerate and pebbly-

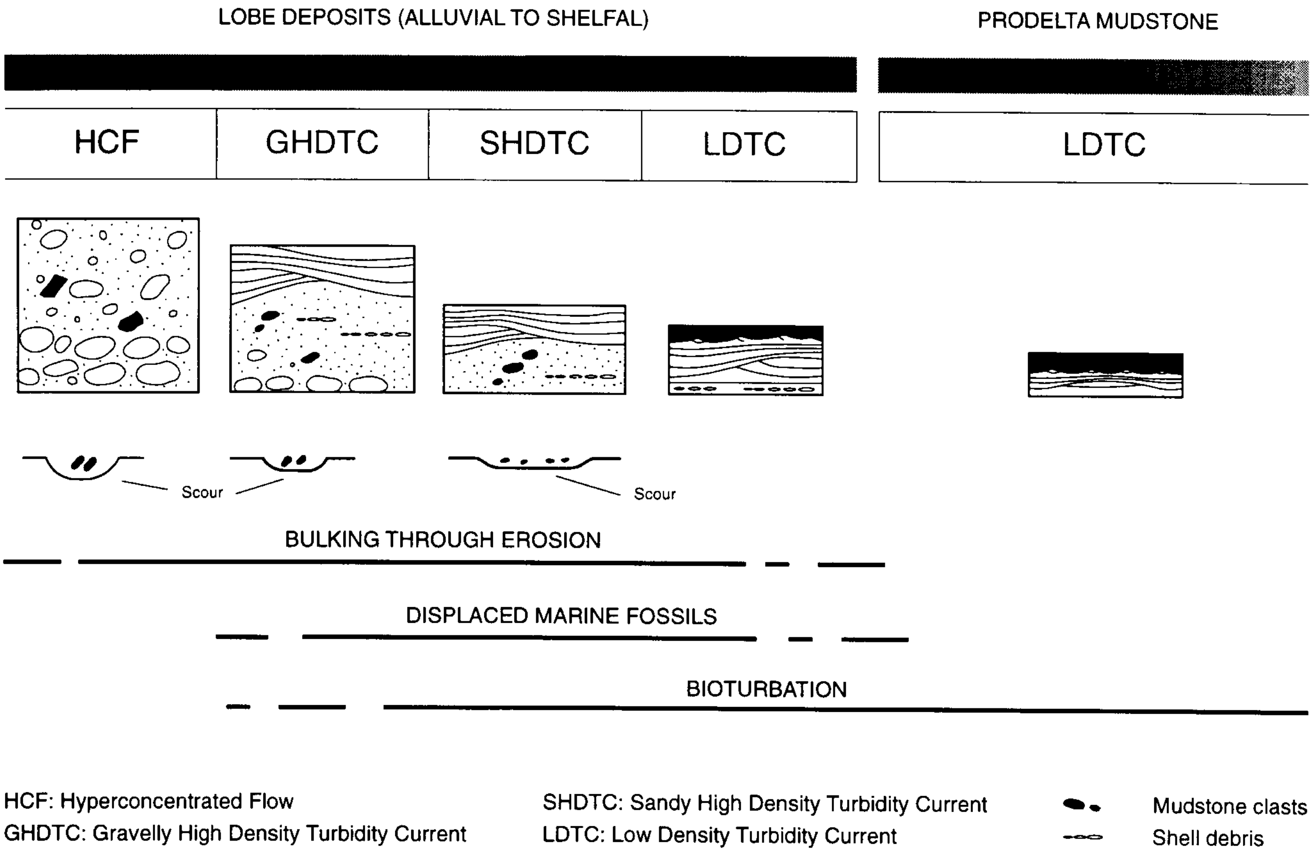


Fig. 5 - Elements, basic facies tract and inferred depositional processes of flood-dominated fan-delta systems. See text for explanation.

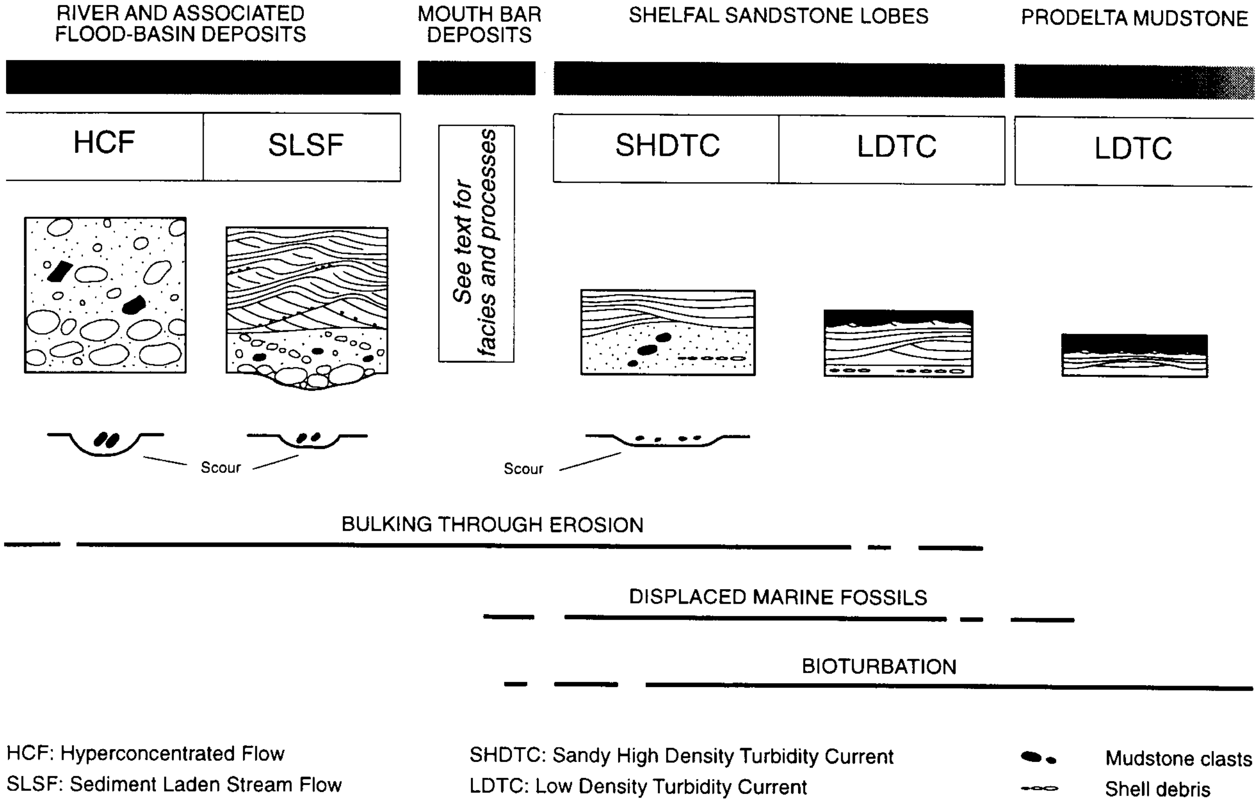


Fig. 6 - Elements, basic facies tract and inferred depositional processes of flood-dominated river-delta systems. See text for explanation.

sandstone facies (Fig. 7) probably representing a considerable proportion of ancient debris-flow deposits described in the literature. As indicated by deep basal erosional surfaces and the occurrence of out-size rip-up clasts (Fig. 8), these beds record deposition from highly mobile and catastrophic flows with intense turbulence.

In flood-dominated fan-delta systems, hyperconcentrated flows enter adjacent marine basins as hyperpycnal flows that entirely or partly transform into high-density turbidity currents. The latter progressively transform into low-density turbidity currents.

In river-delta systems, hyperconcentrated flows transform into sediment-laden stream flows, *i.e.* highly turbulent flows that carry most of their load in suspension. Sediment-laden stream flows produce complex facies types essentially resulting from traction-plus-fallout processes associated with confined flows that are able to carry as suspended load grain-size populations ranging from small pebbles to mud (see later).

Sediment-laden stream flows may reach river mouths or progressively mix with clear water, thus depositing most of their sediment load in upper river reaches. In the first case, the entire sediment load is deposited at the river mouth if the river outflow has insufficient sediment concentration and momentum to overcome frictional forces and density contrast with sea water. For increasing river-outflow density and momentum, progressively larger proportions of the sediment load are carried farther seaward by hyperpycnal flows, thus escaping reworking by tides and waves.

Tab. 3 - Main types of flood-generated flows and related characteristics as intended in the present paper

Flow types (present paper)	Flow rheology *	Sediment support mechanisms *	Depositional mechanisms *
Cohesive debris flow	Plastic	Matrix strenght	Cohesive freezing
Hyperconcentrated flow	Plastic (transitional to fluid)	Matrix strenght Large-scale turbulence Buoyancy Dispersive pressure	Cohesive freezing Frictional freezing
Sediment-laden stream flow	Fluid	Turbulence Hindered settling	Traction Traction + fall-out
High-density turbidity current	Fluid	Large-scale turbulence Hindered settling Dispersive pressure	Traction Traction carpert "En-masse" deposition
Low-density turbidity current	Fluid	Turbulence	Traction + fall-out

* From Lowe, 1979; 1982; Nardin *et al.*, 1979; Mutti, 1992a.

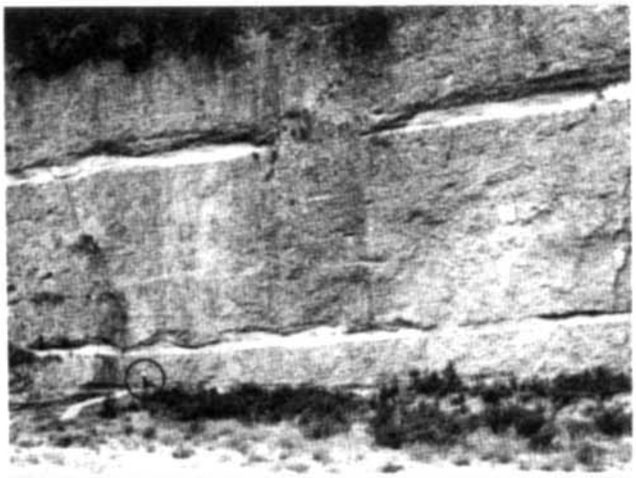


Fig. 7 - Meter-thick packages of conglomerates and pebbly sandstones deposited by hyperconcentrated flows and separated by thinner and laterally persistent mudstone units. Within each coarse-grained package, individual beds are either amalgamated due to local and shallow scouring or separated by thin and laterally discontinuous mudstone partings. Shallow scours are visible at the base of the middle coarse-grained unit. Note the overall tabular geometry of the coarse-grained deposits. Encircled person for scale. Tursi Group, Sant'Arcangelo basin, southern Apennines.

Before describing the basic facies tracts of both fan-delta and river-delta systems dominated by catastrophic flooding, we briefly discuss in the following section the importance of "flood-generated sigmoidal bars" (Mutti *et al.*, 1994e). These bars record a relatively simple type of flow transformation through which hyperconcentrated flows change into more dilute and turbulent types of flow.

Both flood-generated sigmoidal bars and river-mouth bars are omitted in the description of the basic facies tracts of both fan-delta and river-delta systems that will be discussed in later sections. Sigmoidal bars, if fully developed through the deposition of the bulk of the sediment load after flow transformation, are actually attached facies tracts (in the sense of Mutti, 1992a), produced by relatively small-momentum flows, that extend over relatively short distances. These bars are thus useful for an understanding of process-related facies associations but do not represent an important depositional element on a broader scale. River-mouth bars are sandstone bodies made up of frontally accreting individual flood-units recording deposition from a series of relatively small-momentum river-outflows which cannot be fully transformed into turbidity currents. As discussed in more detail in later sections, the characteristics of mouth-bar deposits vary greatly from one system to another and also within the different stages of growth of the same system. Basically, the complete development of a sigmoidal bar and the thick and extensive development of individual mouth-bars are both indicative of relatively poorly-efficient flows which are not able to carry farther downcurrent most of their sediment load. The general facies tracts discussed in later sections are instead characteristic of relatively high-momentum flows whose final depositional zones are primarily recorded by shelfal sandstone lobes.

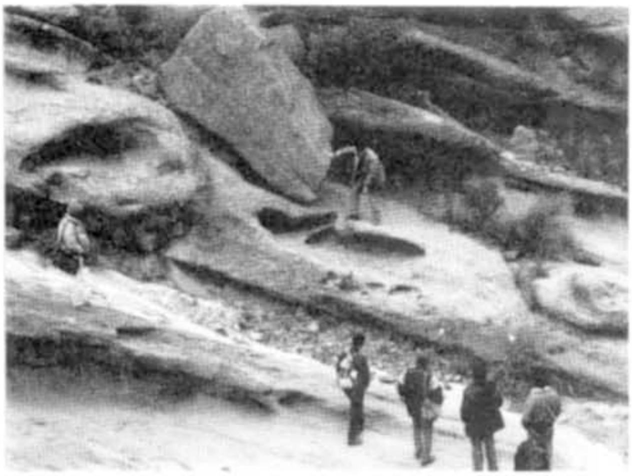


Fig. 8 - Out-size mudstone clasts within a crudely graded pebbly-sandstone unit deposited by a hyperconcentrated flow. Potrerillos Formation, Cuyo Basin, Argentina.

The importance of flood-generated sigmoidal bars

Although the downcurrent transformations of flood-generated flows can be inferred from facies changes in the same direction, the way in which these transformations occur remains difficult to understand in detail because, particularly in large systems, the resulting facies changes take place over relatively great distances and are therefore difficult to observe at outcrop scale.

The problem can be partly overcome through the study of the facies changes produced by relatively small-volume and short-duration flows in alluvial flood basins. The sudden transformation of these flows into highly turbulent and progressively more dilute types of flow is recorded by very distinctive sedimentary units, termed herein "flood-generated sigmoidal bars". Flood-generated sigmoidal bars are m-thick, lenticular features extending over distances of some meters or few tens of meters and represent a very common type of one-event deposit in many systems. The typical development of these bars is associated with the transformation of hyperconcentrated flows where entering shallow ephemeral lakes or where these flows underwent transformation at breaks in slope or at the exit of confined conduits. Excellent examples of this type of deposit are particularly well exposed in the alluvial Cretaceous and Triassic strata of the San Jorge and Cuyo basins, Argentina (Tab. 1).

Each bar has a marked sigmoidal shape in cross sections parallel to paleoflow direction; in cross-current cuts, individual bars are highly lenticular and bounded by concave-upward erosional surfaces in their upcurrent portions. Lensing becomes progressively broader and smoothly convex-upward in a downcurrent direction where the bounding surfaces of each bar have the tendency to become depositional.

Individual sigmoidal bars have geometry, textural characteristics and internal structures that may vary from one system to another. Despite local differences, flood-generated sigmoidal bars have, however, three common and diagnostic characteristics including (see Pl. II, Figs a to d):

(1) A distinctive vertical and lateral succession of depositional divisions associated with an overall vertical and longitudinal grading;

(2) Within each bar, high-angle cross strata predominate in the upcurrent portion of the bar; these are replaced in a downcurrent direction by progressively lower-angle cross strata eventually becoming horizontal in the distal portion of the bar;

(3) Deep scouring and amalgamation features characterize the upcurrent portion of individual sigmoidal bars. Scouring decreases progressively in a downcurrent direction where finer-

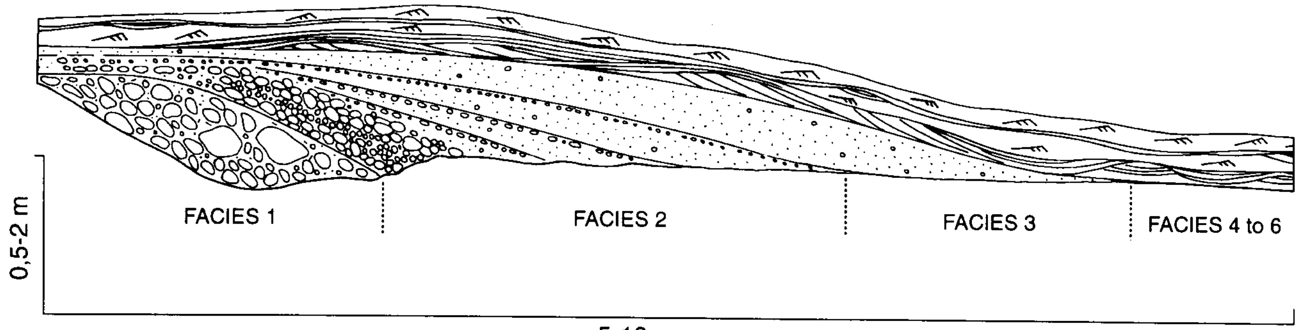


Fig. 9 - Geometry and component facies of a flood-generated sigmoidal bar showing its complete development. Paleocurrent direction is from left to right. See text for explanation concerning facies and processes. Slightly modified after Mutti *et al.*, 1994e.

grained divisions tend to flatten-out and conformably rest on the underlying deposits.

As shown in figure 9, the complete sequence of depositional divisions, or facies, which can be observed within individual bars include:

Facies 1 - A basal division represented by unstratified clast- or sand-supported pebbly conglomerate which abruptly wedges out in a downcurrent direction;

Facies 2 - Downcurrent accreting, high- to low-angle cross strata most commonly made up of pebbly sandstones and coarse-grained sandstones. Scattered out-size particles (pebble- and granule-size) are commonly present along stratification surfaces. Low-angle cross strata become progressively convex upward downcurrent. Each stratum can thus be traced upcurrent from a relatively thick and low-angle dipping cross unit into a progressively thin and horizontal unit that accretes vertically above the underlying divisions.

Both facies 1 and 2 typically rest on a basal scour surface which bounds each sigmoidal bar in its upcurrent portion (Fig. 9). Following upward, are progressively finer-grained facies that accrete both vertically and downstream. From base to top, these divisions include:

Facies 3 - A crudely graded, internally unstratified division of coarse to medium sandstone;

Facies 4 - A broadly wavy- to horizontally-stratified division of medium-grained sandstone;

Facies 5 - A division of current laminated fine- to very fine-grained sandstone and siltstone showing horizontal, broadly wavy and small-scale cross stratification, and

Facies 6 - A mudstone division.

Both facies 4 and 5 commonly show combined-flow stratification expressed by various types of HCS. Large-scale anisotropic HCS is gradually replaced upward by smaller-scale and predominantly isotropic HCS.

The process recorded by the vertical and lateral succession of depositional divisions within individual sigmoidal bars is essentially a hydraulic jump similar to that described by Weirich (1989) for the transformation of a debris flow into a highly turbulent density current in an artificial lake, accompanied by flow expansion and deceleration with ensuing rapid deposition of the sediment load. Energy dissipation through intense turbulence is here thought to be the main cause of extensive and deep scouring observed in the upstream terminations of sigmoidal bars (see above). Facies 3 through 6 probably record the rapid reduction in sediment concentration that is typical of most floods after attainment of peak flow conditions (*e.g.*, Mulder and Syvitski, 1995).

The facies tract observed within sigmoidal bars indicates deposition from frictional freezing of a hyperconcentrated flow or from its basal gravelly portion (Facies 1), followed upward by sediment deposited by tractional processes associated with increasing fallout (Facies 2); these basal divisions are overlain by a division resulting from "en-masse" deposition (Facies 3) followed upward by internally stratified and progressively finer-grained sandstone deposited by traction-plus-fallout processes associated with combined-flow conditions (Facies 4 and 5). The occurrence of various types of HCS resulting from combined-flow conditions is very common, suggesting that also in this case (see above) shallow and standing bodies of water were set in motion by hyperconcentrated flows or this motion was acquired by the more dilute portion of the flow itself during its sudden deceleration in a subaerial terminal flood basin. The latter interpretation is strongly supported by the fact that, in most cases, flood units with HCS directly rest on paleosols, thus indicating that the oscillating water was actually part of the flood itself. Facies 6 records the final settling of mud from a quasi-static flow. *Mutatis mutandis*, the facies tract is strikingly similar to that described by Lowe (1982, his fig. 12) for submarine gravity flows and particularly to the facies tract described by Mutti (1992a, his fig. 31) for poorly efficient, small-volume gravity flows generating sigmoidal units with an attached facies tract.

As in the classic Bouma sequence of turbidite strata (Bouma, 1962), the complete succession of depositional divisions within a flood-generated sigmoidal bed is rarely developed. More commonly, these internal successions are incomplete for either non deposition, erosion or both.

Sigmoidal bars showing a relatively full development of their internal depositional divisions (Fig. 10A) imply that the bulk of the sediment load is deposited in physical continuity immediately upon flow transformation. The resulting sigmoidal bar represents in this case an essentially attached facies tract (see above), although part of the finer-grained population (very fine sand and mud) may be detached to form tabular beds in a slightly more distal position.

Other bars commonly consist of top-missing, highly lenticular and coarse-grained units; in these cases, the finer-grained population is entirely kept in suspension by the turbulent density current produced during flow transformation. This finer-grained sediment is thus carried to more distal depositional zones. The resulting deposits are tabular graded beds of thoroughly current-laminated fine-grained sandstone beds capped by mudstone divisions. This depositional setting, implying sediment bypass and the formation of a detached facies tract, is shown in figure 10C. Sigmoidal bars with transitional characteristics between the two end members above are very common in many systems (Fig. 10B).

Successive sigmoidal bars may commonly stack downstream and vertically to build up composite sandstone bodies which are

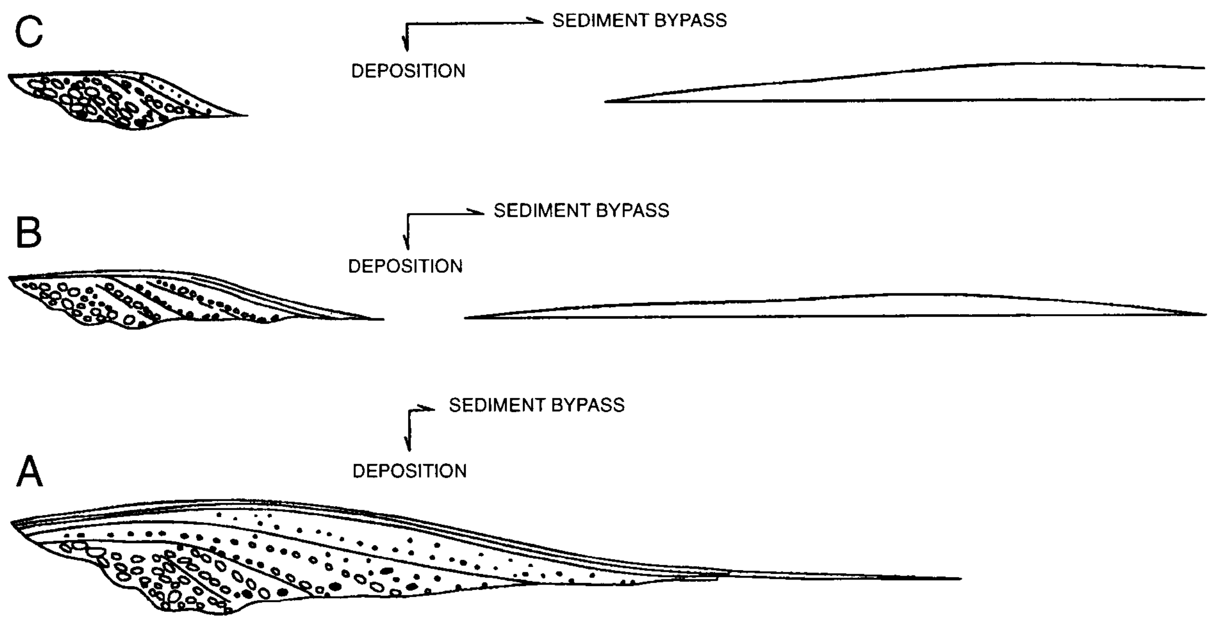


Fig. 10 - Main types of flood-generated sigmoidal bars as related to flow momentum. Diagrams from A to C indicate progressively higher momentum of the flow and therefore an increasing sediment bypass. See text for explanation.

essentially a specific case of prograding mouth bar (see later).

Sedimentary units with characteristics very similar to those of the sigmoidal bars described above have been described by Allen (1983a, 1983b) from the Old Red Sandstone. In particular, Allen (1983b, p. 286, see also his figs 1 and 3) defines sedimentation units which " are bounded above and below by erosion surfaces and, in streamwise vertical section, appear nearly parallel-sided, except at the upstream end where the basal scour commonly is scoop-shaped. The maximum thickness is seldom more than 1-2 m or less of 0.4 m, the streamwise length ranging between 5 and 30 times the thickness. Each unit comprises a lower cross-bedded portion (foreset) from which the stratification surfaces can be traced upward and over *without a break* into parallel-laminated part (topset) similar to the foreset below in bedding dip-azimuth but lower in bedding inclination". Allen (1983b, p. 289) does not relate such sedimentation units to a flow transformation process and, despite the considerable differences in scale and grain-size, interprets such units as humpback bars on the basis of their similarities with the humpback dunes produced in flume experiments by Saunderson and Lockett (1983). Because of their depostional setting and scale, we tentatively reinterpret herein the humpback bars of Allen as flood-generated sigmoidal bars.

Basic facies tract of flood-dominated fan-delta systems

The depositional setting derived from the study of ancient flood-dominated fan-deltas is apparently more simple that the ones discussed in the literature. Stratigraphic relationships and facies associations established from a number of marine fan-delta systems developed in relatively shallow water ("shelf-type" deltas of Ethridge and Wescott, 1984; shallow-water deltas with shoal-water profile of Postma, 1990a, his fig. 2) show that such systems have marine depositional zones entirely recorded by shelfal, flood-dominated coarse-grained lobes and by finer-grained prodelta deposits developed in either distal shelfal or slope regions. The only "normal" marine sediments that alternate with flood-generated facies in shallow-water and shelfal regions are represented by thin to very thin units of highly bioturbated and locally fossiliferous mudstones and sandy mudstones and occasional intercalation of highly fossiliferous carbonates. All the systems considered lack evidence of marine reworking produced by wave or tidal action.

The basic facies tracts observed in these systems (Fig. 5) are relatively simple, and are essentially represented by a lateral association of facies types that, in a downcurrent direction, record the progressive transformation of subaerially derived hyperconcentrated flows into high- and low-density turbidity currents. The main facies types are briefly described below. The deposits of cohesive debris flows are omitted from the description because of their exceedingly rare occurrence.

1 - Hyperconcentrated flow deposits (Pl. III, Figs c and d). These sediments represent the most proximal and immature deposits that are found in flood-dominated fan-delta systems. These consist of laterally extensive, thick to very thick and commonly amalgamated beds of very poorly sorted, ungraded or crudely graded conglomerates which are characterized by a more or less abundant matrix made up of coarse- to medium-grained sandstone and granule conglomerate. These beds, which are commonly bounded by markedly scoured basal surfaces, may locally display some crude, low-angle stratification dipping in a downcurrent direction and contain abundant rip-up clasts derived from the erosion of both alluvial and marine fine-grained deposits.

2 - Gravelly high-density turbidity current deposits (Pl. IV, Figs a and b). This facies consists of thick to very thick, graded and locally amalgamated pebbly-sandstone beds where the basal conglomeratic division progressively thins in a downcurrent direction and is eventually represented by alignments of isolated pebbles at the very base of individual beds. The sandy portions of these beds are characterized by progressively better developed inter-

nal depositional divisions ranging from a basal structureless and crudely graded division to upper and finer-grained divisions with HCS. The basal sandstone division is commonly characterized by abundant shale clasts and shell debris. The transition between hyperconcentrated flows and gravelly high density turbidity currents (not shown in the diagram of Fig. 5) may be locally represented by convex-upward lenses of clast-supported conglomerates left behind and partly tracted bypassing flows.

3 - Sandy high-density turbidity current deposits (Pl. IV, Figs c and d). These sediments are represented by generally medium to thick, graded sandstone beds separated by thin mudstone partings. In these beds a basal coarse-grained division with very abundant shell debris and shale clasts is overlain by finer-grained divisions with HCS and fine-grained shell debris aligned along traction carpets and lamination surfaces.

4 - Proximal low-density turbidity current deposits (Pl. V, Figs a and b). This facies is made up of fine-grained and graded sandstone beds with HCS and abundant shell debris that can be either concentrated in the basal part of individual beds or aligned along lamination surfaces.

5 - Distal low-density turbidity current deposits (Pl. V, Fig. a). These sediments consist of thin to very thin, fine grained graded beds characterized by small-scale HCS and oscillatory ripples that grade seaward into graded mudstone beds.

Both high- and low-density turbidity current deposits are generally interbedded with highly bioturbated and fossiliferous sandy and silty mudstones.

Conglomerates are interpreted as alluvial and shallow-marine deposits formed through frictional freezing of hyperconcentrated flows or left behind by hyperconcentrated flows that transformed into self-sustained high-density turbidity currents which were unable to carry seaward pebble- and cobble-sized particles. Facies produced by gravelly and sandy high-density turbidity currents are the volumetrically most important components of shelfal sandstone lobes of these systems, thus indicating that the great majority of hyperpycnal flows could transform into high-density turbidity currents. The lateral extent (up to some tens of kilometers) of the resulting deposits (Pl. X, Figs a, c, d; Pl. XI, Fig. a; Pls XII and XIII) and the abundance of depositional divisions produced by traction-plus-fallout processes indicate that the original flows were of relatively very large volume and long duration, *i.e.* flows continuously fed by sub-aerially derived hyperconcentrated flows entering seawaters.

From the above data, it can be concluded that the stratigraphic record of these flood-dominated fan-delta systems in their terminal depositional zones indicate that flooding and related hyperpycnal flows and turbidity currents were the only important processes in exporting sediment from drainage basins to the sea. It may be added that the "steady state" of modern fan-deltas can be highly misleading in the interpretation of their ancient analogs. Clearly, "steady states" observed in modern settings have little preservation potential and their deposits must be cyclically swept out by catastrophic floods. On a smaller physical scale and over very short periods of time, a similar process has been envisaged by Bornhold *et al.* (1994) from modern fjords of British Colombia.

The volume of sediment involved in individual flood events as well as the total volume of sediment involved in individual depositional systems suggest that flood-dominated fan-delta systems must originate from extremely catastrophic processes whose magnitude is difficult to perceive on the basis of our knowledge of modern fluvial sedimentation. In this respect, ancient flood-dominated fan-delta systems can only be compared with deep-water sand-rich turbidite systems of tectonically active basins where similarly huge volumes of sediment are deposited by catastrophic processes over relatively short periods of time. The facies tract of Fig. 5 shows that flood-generated deposits of fan-delta systems are very similar to those observed in many deep-water turbidite systems (compare with facies schemes and inferred depositional processes of Mutti, 1992a). The stratigraphic importance of shelf-type, flood-dominated fan-delta systems has been certainly underestimated in previous literature.

Basic facies tract of flood-dominated river-delta systems

General

Ancient river-delta systems dominated by catastrophic flooding are very difficult to frame within classification schemes derived from modern deltas (*e.g.*, Elliott, 1986; Postma, 1990a, 1990b) in that facies types, facies associations and depositional settings reconstructed from ancient flood-dominated systems do not fit any "steady state" observed in modern deltas. The only possible modern analogs are those fluvio-deltaic systems fed by mountainous "dirty" rivers (Mulder and Syvitski, 1995) that experience frequent floods to generate hyperpycnal flows in sea waters, and some fjord river-deltas with similar characteristics (*e.g.*, Bornhold and Prior, 1990; Prior and Bornhold, 1990). In both cases, however, the bulk of the sediment carried to the sea is essentially represented by mud.

These systems are difficult to describe and interpret because of the great variability and complexity of their component facies types and facies associations in river and river-mouth deposits (Fig. 2). The facies tract of figure 6 is of general validity in relation to distal depositional zones mainly dominated by low-density turbidity currents; these zones are most commonly recorded by shelfal sandstone lobes with HCS alternating with finer grained facies. In more proximal sectors, each system actually develops facies tracts that can be described and understood only on the basis of a case-by-case analysis.

River and mouth-bar deposits of ancient flood-dominated river-delta systems are briefly described and discussed below.

River deposits

The complexity of flood-dominated river deposits is largely a function of local controlling factors (*e.g.*, river size and gradient, type of sediment available, magnitude and duration of flood-generated flows, extent of alluvial flood basins and coastal plains, etc.); however, the main problem resides in the fact that these river deposits, recording periods of time during which rivers behave mainly as transfer zones, are inherently characterized by an extremely low preservation potential.

In rivers, erosion and lack of accommodation generate vertical and lateral successions of flood-units that are highly lenticular and typically top missing either because of non deposition or subsequent erosion. Increased preservation potential develops in the latest phases of sedi-

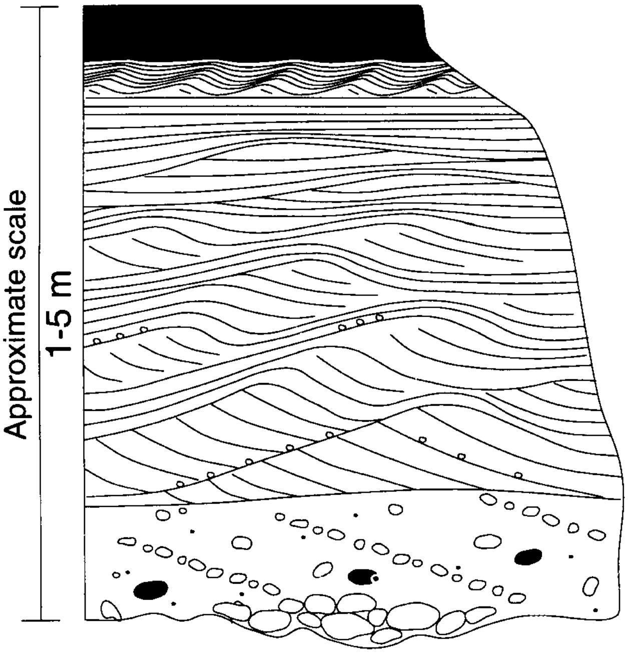


Fig. 11 - Idealized vertical facies sequence of a flood unit deposited by a waning, sediment-laden stream flow. Note the overall vertical grading and the occurrence of climbing dunes in the middle portion of the unit (see text for more details).

mentation, when the magnitude of individual flows decreases and rivers change in character, passing from predominantly sediment transfer zones into predominantly depositional zones. The facies tract of flood-dominated river deposits indicated in figure 6 shows this phase of sedimentation for large-volume and long-duration flows and thus omits the residual deposits that are laid down in river channels during phases of sediment bypass. These residual sediments are represented by amalgamated coarse-grained facies showing all the transitional types between unstratified to crudely stratified conglomerates and pebbly sandstones. Strictly speaking, only these sediments, if present, are probably correlative with the development of substantial accumulations of shelfal sandstone lobes.

The sequence indicated in figure 11 describes flood units with an ideally complete development of internal depositional divisions laid down by waning sediment-laden stream flows of relatively long duration generated by floods with a sufficiently high discharge. In ascending stratigraphic order, these facies types include:

1 - Unstratified to crudely stratified matrix- to clast-supported conglomerates commonly resting on deeply erosional surfaces and containing abundant out-size clasts of fresh-water mudstones, soils and plant debris (Pl. V, Fig. c; see also Pl. VIII, Figs a and c).

2 - Crudely cross-stratified and very poorly sorted pebbly sandstones commonly characterized by abundant mudstone clasts of fresh-water mudstones, soils and plant debris (Pl. V, Fig. d; see also Pl. VIII, Fig. a).

3. - Coarse- to very coarse-grained and poorly sorted sandstones characterized by sets of high-angle cross strata bounded by erosive surfaces. Both laterally and vertically, these cross strata commonly grade into structureless divisions (Pl. VI, Fig. a).

4 - Coarse- to medium-grained and poorly sorted sandstones forming frontally and vertically accreting sets of climbing dunes which may be locally separated by low-angle and wavy erosional surfaces (Pl. VI, Fig. b to Pl. VII, Fig. b).

5 - Medium- to fine-grained sandstones characterized by sets of relatively thick and high-amplitude sinusoidal strata commonly separated by erosional surfaces of similar geometry (Pl. VI, Fig. c and Pl. VII, Fig. c).

6 - Fine- to very fine-grained sandstones and coarse-grained siltstone characterized by thin, horizontal laminae grading upward into climbing ripples and associated sinusoidal laminae (Pl. VIII, Fig. b).

7 - Massive mudstones.

The sequence of figure 11 (see also Fig. 12) is interpreted herein as the deposit of a long-duration, large-volume and highly turbulent sediment-laden stream flow whose velocity and sediment concentration progressively decreased with time. During the first stages of deposition (facies 1) most of the flow bypasses, leaving behind gravel bars. When deposition starts, tractional processes predominate (facies 2 and lowest part of facies 3) because of high flow velocity and low rate of sediment fallout. Owing to increasing rates of sediment fallout and decrease in flow velocity, traction-plus-fallout divisions of progressively finer-grained material are deposited until mud can settle through a quasi-static suspension. Except for its coarser grain size, this vertical succession is remarkably similar to that produced by traction-plus-fallout processes in very fine sand and mud (see the classical paper by Jopling and Walker, 1968).

Fluctuating flow conditions, which are common to most floods in modern river systems (*e.g.*, Strahler, 1969; Costa and Jarret, 1981; Baker and Bunker, 1985; Smith, 1993) are generally recorded by repeated grading within overall graded flood units as well as, at times, by stratified climbing dunes passing laterally into structureless sandstones (sudden increase in the rate of deposition). More generally, combined-flow conditions are recorded by various types of HCS.

The full development of vertical facies sequences as shown in figure 11 commonly occurs in lateral flood basins where the final deposits of individual floods can be entirely preserved. Along axial river zones, these sequences are typically incomplete because of either non deposition or subsequent erosion. Axial river channel facies are thus generally recorded by highly lenticular flood units mainly made up of residual coarse-grained facies or by the basal divisions indicated in the sequence of figure 11.

A significant example of river deposits of this type, produced by large-volume and long-duration flows, is that of the lower Eocene Castisent Group in the easternmost sector of the south-central Pyrenees (Tab. 1). The fluvial portion of this group (cf. Castisent Formation of Nijman and Nio, 1975), described and interpreted as a bed-load dominated fluvial sheet sandstone with local development of coarse-grained point-bar facies in classic papers by Nijman and Puigdefábregas (1978) and Marzo *et al.* (1988), can be better interpreted as a spectacular flood-dominated river system flowing along an elongate structural depression and consisting of amalgamated graded flood units in its axial zone and associated tabular units, or lobes, separated by mudstones and paleosols in lateral flood basins.

Plate VIII, Figs a, b, c show some significant features of these sediments, including spectacular examples of current reversal.

Fig. 12 - Example of flood unit deposited by a waning, sediment-laden stream flow. Note the overall grading and the development of climbing dunes, with preservation of sandstone laminae on stoss sides, lying above a basal, structureless pebbly sandstone deposited by the basal, hyperconcentrated part of the flow (lacustrine Pliocene strata, Island of Rhodes, Greece).

In the case of sediment-laden stream flow of progressively smaller volume and shorter duration, the facies types observed in river deposits indicate a substantial reduction of both tractional and traction-plus-fallout sedimentary structures in coarse-grained deposits, as a result of sedimentation from flows which were unable to produce in-equilibrium bed forms. As shown by plate IX, Fig. c, individual flood units tend to become progressively smaller and approach the geometry and internal organization of sigmoidal bars (see above). These units typically contain a basal coarse-grained division consisting of unstratified and poorly sorted pebble and cobble conglomerate and pebbly sandstone which grade upward and downstream into crudely, high- to low-angle cross-stratified and poorly sorted pebbly sandstones and coarse-grained sandstones. For sufficient flow-duration and strength, some of these cross bedded facies may be arranged in sets of cross strata with a typical sigmoidal geometry, that become progressively smaller in a downcurrent direction (Pl. IX, Figs a and b). The uppermost and finer-grained divisions of these units, if deposited and preserved, consist of wavy to horizontal strata associated with combined-flow features (mostly anisotropic HCS).

Examples of these flood-units, which can be easily mistaken for downstream accreting bars as illustrated by Miall (1985, 1992) from both modern and ancient fluvial deposits dominated by "normal" streamflow processes, are illustrated in plate IX, Figs c and d.

A detailed stratigraphic and sedimentological reconstruction of river deposits dominated by relatively small-volume and short-duration floods has been recently provided by Davoli (1996) for the lower Eocene Castigaleu Group,

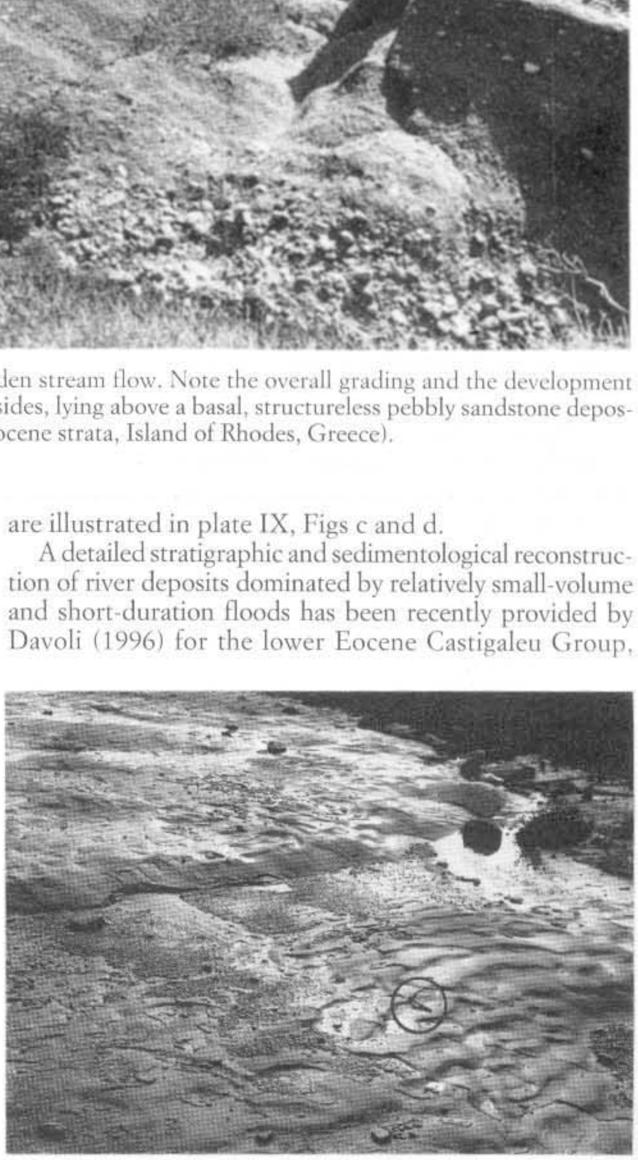


Fig. 13 - Preserved bed forms (megaripples and ripples) produced by "normal" stream flow processes at the top of a flood unit in the lower Eocene Castisent Group, south-central Pyrenees, Spain. The bed forms are capped by mudstones deposited during the latest stage of the flood (see text for more details). Encircled pen for scale.

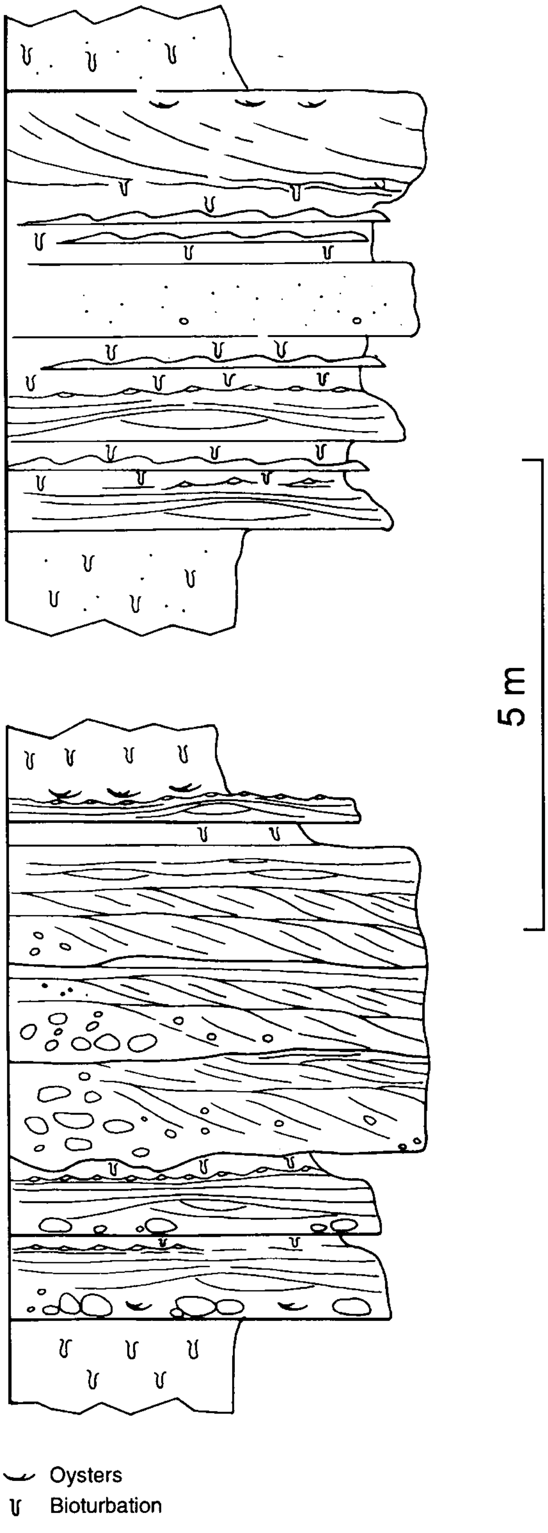


Fig. 14 - Examples of facies sequence showing shelfal sandstone lobes overlain by gently, seaward dipping mouth-bar strata. Both examples are derived from the lower Eocene Figols strata, south-central Pyrenees, near Tremp (compare with photograph of Plate X, Fig. a).

south-central Pyrenees (Tab. 1). Part of the results of this work are incorporated in the cross section of figure 26.

Tractional processes related to "normal" streamflow conditions are rare in most of the river deposits considered in this study. Exceptions are found where late-stage flood-generated flows, with substantially reduced sediment concentration, tend to rework the deposits of earlier flood stages. These reworking features mainly consist of sets of trough-cross stratification and, more rarely, of large- and small-scale bed forms draped by latest stage mudstones (Fig. 13).

Mouth-bar deposits

Flood-dominated river-delta systems are characterized by the development of a mouth-bar depositional element that essentially acts as a filter separating the sand that will be trapped at river mouths from the sand and mud that will be transferred to shelfal regions by turbidity currents.

Mouth-bar deposits form where confined hyperconcentrated flows or sediment-laden stream flows enter marine basins. Here, because of friction, buoyancy and density contrast with sea water, the flows are forced to either entirely deposit their sediment load, or deposit the coarser part of it and keep moving into sea water as hyperpycnal flows with reduced sediment concentration. As a result, mouth-bar geometry and facies characteristics of flood-dominated river-delta systems can only be described and interpreted on a case-by-case basis. For these reasons, we give below a brief and cursory description of these sediments and on purpose omit many facies types whose characteristics and origin remain highly problematic.

The general geometry of mouth-bar deposits is expressed by bodies of sandstones and pebbly-sandstones with occasional conglomerates whose component beds stack into frontal accretion patterns, *i.e.* into seaward offlapping and thinning out successions. The offlap angle may vary from 30° to a few degrees; the basal contact of these bodies may be sharp and erosive in their landward portions but becomes typically transitional seaward. The thickness of individual mouth-bar bodies usually ranges between 1-5 m. Figure 14 shows the general vertical facies sequence that characterizes mouth-bar bodies. These units commonly rest on delta-front sandstone lobes and are progressively overlain by muddier, bioturbated and locally fossiliferous facies (Pl. X, Fig. a).

Marine mouth-bar deposits can be entirely flood-dominated, thus consisting of sharp-based graded flood units, or beds, with virtually no reworking by wave or tidal action. The internal structures of these beds depend mainly on the textural composition and concentration of the sediment load carried by individual sediment-laden stream flows.

In small and high-gradient fluvial systems, floods can carry directly to adjacent marine basins highly-concentrated suspensions of coarse-grained sediment that produce frontally accreting graded units. Each of these units shows rapid downcurrent facies changes from structureless pebbly sandstone into sandstone divisions with predominant tractional features which, in turn, pass into finer-grained traction-plus-fallout structures. These frontally accreting deposits are essentially similar to sigmoidal flood units observed in river deposits (see above). The distal portions of these units consist of thin beds of fine-grained sandstone with internal small-scale cross-stratification separated by mudstone partings. These distal facies are commonly highly bioturbated. A setting of this type is shown in the example of figure 25 from the lower Eocene Figols Group in the south-central Pyrenees.

In lower-gradient rivers, where sediment-laden stream flows were originally more dilute or underwent a decrease in sediment concentration through deposition in alluvial flood basins, mouth-bar deposits are considerably finer-grained (Pl. X, Fig. b).

Where mouth bars develop in marine settings characterized by substantial tidal activity, the toes of flood-generated mouth bars are reworked by tides immediately after deposition of individual flood units. In this type of settings, decreased flood frequency and magnitude is typically accompanied by strong and extensive tidal reworking of flood-generated facies and, therefore, by the formation of transgressive, tide-dominated sandstone wedges that extend landward within lower fluvial reaches. A typical example of tidal reworking of flood-generated mouth-bar sandstone facies is shown in figure 25 from the lower Eocene Roda Sandstone (Figols Group, south-central Pyrenees). Tidal sandstone wedges extending into lower river reaches of the lower Eocene Castigaleu Group have been described in considerable detail by Davoli (1996).

CYCLIC STACKING PATTERNS OF ANCIENT FLOOD-DOMINATED FLUVIO-MARINE SYSTEMS AND SOME IMPLICATIONS

Fluvial strata are characterized by cyclic stacking patterns developed at different physical and temporal scales. The many possible causes of this cyclicity have been discussed in many papers by geomorphologists (*e.g.* Schumm, 1977, 1981; Hilton Johnson, 1982), sedimentologists (*e.g.* Allen, 1983a; Miall, 1992; De Boer *et al.* 1991), and stratigraphers (*e.g.* Posamentier and James, 1993) in terms of both autocyclic and allocyclic controlling factors.

As originally suggested by Schumm (1977, 1981), this cyclicity should be particularly well developed and preserved in the sediments of the original depositional zones of each system where the evolution of the system with time is best recorded. The results of our study strongly support this assumption, indicating that both flood-dominated fan-delta and river-delta systems of tectonically active settings extend into marine regions through thick accumulations of sandstone facies recording forestepping-backstepping episodes of sand deposition developed at different, hierarchically-ordered physical scales. These episodes must have been controlled by a similarly ordered temporal cyclicity of causative processes.

Whatever the origin of these processes and of their cyclic recurrence, facies and facies associations indicate that flooding is the main factor controlling deposition in the systems considered. The sudden onset of catastrophic floods cause dramatic forestepping of sandy depositional zones; ensuing backstepping is produced by the decrease of the catastrophic character of individual floods until "normal" conditions are re-established. These "normal" conditions apparently coincide with periods of time during which fluvial systems become virtually inactive and, therefore, cannot flush significant amounts of water and sediment to adjacent marine basins. Extensive units of mudstones and associated carbonates in marine regions and flood-basin fines in alluvial settings record these periods of time during which the activity of fluvial systems is probably restricted to the very proximity of their source zones. The process controls both high- and low-frequency cyclicity.

High-frequency cyclicity is recorded by m-thick facies sequences which are probably deposited in periods of time of 10^3 and 10^4 years (see Mutti *et al.*, 1994b) and may therefore compare with 5th and 4th order cycles of sequence stratigraphy, respectively (see Posamentier and Vail, 1988; Van Wagoner *et al.*, 1990; Mitchum and Van Wagoner, 1991; Vail *et al.*, 1991).

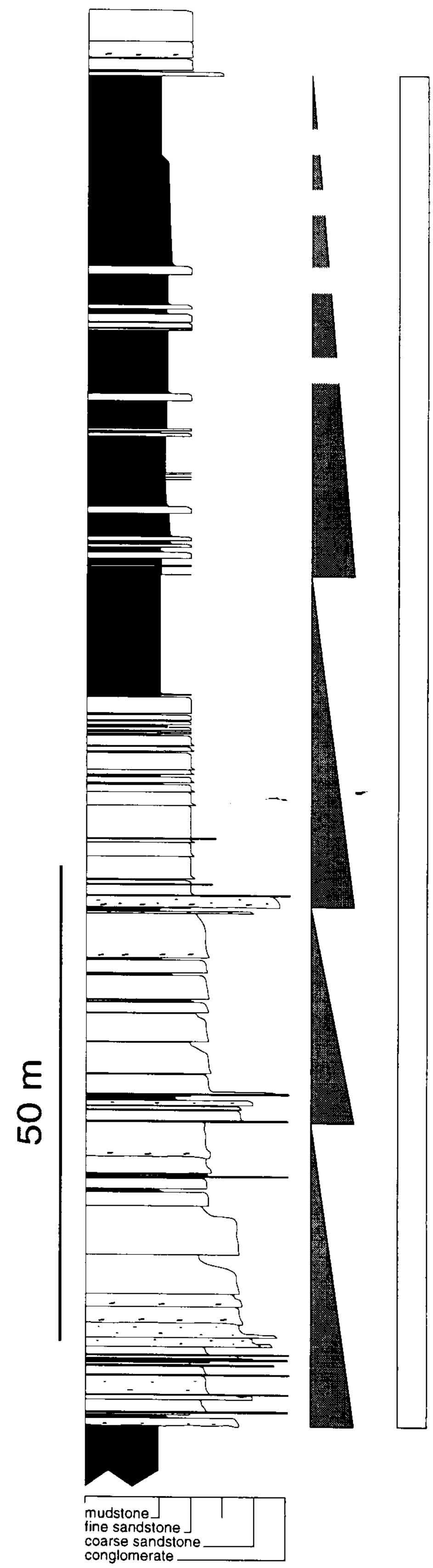


Fig. 15 - Cyclically stacked shelfal sandstone lobes from the lower Pleistocene Aliano Group, southern Apennines. Two hierarchical orders of cyclicity are indicated, each of which shows an overall fining-upward trend. This section is a detail of section 3 of the cross section of Fig. 24.

This type of cyclicity is very well recorded in both shelfal and alluvial sandstone lobes, *i.e.* in strata representing flood-related terminal depositional zones. Examples of this cyclicity are shown in figures 22 to 27 illustrating both fan-delta and river-delta systems.

These high-frequency cyclic stacking patterns are commonly represented by facies sequences in which relatively thick and coarse-grained sandstone beds grade upward into progressively thinner and finer-grained sandstone beds eventually capped by mudstone facies. These sequences are typically m-thick features which may stack into higher-order sequences with aggregate thickness up to some tens of meters characterized by a similar overall vertical facies trend (Fig. 15).

The cyclic patterns of these shelfal sandstone lobes are remarkably similar, in both physical scale and internal organization, to those observed in deep-marine turbidite sandstone lobes and interpreted as the result of forestepping-backstepping episodes of sand deposition related to a high-frequency, cyclic variation in the volume of gravity flows (Mutti *et al.*, 1994b). A similar interpretation is given herein for flood-generated shelfal sandstone lobes. Therefore, the thinning- and fining-upward facies sequences developed within shelfal sandstone lobe successions imply that the volume of flood-generated sediment-water mixtures decreased with time after an initial phase during which very large-volume flows produced an abrupt basinward forestepping of sandstone facies. Plates XI, Fig. d and XI, Fig. c (see also Pl. XI, Fig. b) compare elementary facies sequences generated by turbidity currents in a deep-water depositional system and by flood-related turbidity currents in an ephemeral lake.

In the proximal sectors of flood-dominated fan-delta systems high-frequency cyclicity is largely obscured by amalgamation and non deposition. In river-delta systems, this type of cyclicity is recorded in mouth-bar deposits and also, although to a lesser extent, in some river deposits. In both cases, cyclicity is expressed by the repetition of facies sequences indicating phases of basinward progradation of flood-generated sandstone facies followed by more or less abrupt backstepping.

In mouth-bar sediments, this type of depositional motif is shown in figure 14, and by the example of figure 25 depicting the depositional setting of the lower Eocene Roda Sandstone in the Figols Group of the south-central Pyrenees (Tab. 1).

In river deposits, high-frequency cyclicity is of fundamental importance for an understanding of the fluvial regime in transfer zones. A very common type of facies sequence observed in these sediments, particularly in systems characterized by relatively small-volume floods (*e.g.*, Davoli, 1996), includes a basal coarse-grained facies recording periods of sediment by-pass overlain by finer-grained deposits that are characteristically arranged in progressively smaller and narrower flood-generated point-bar systems until sandy fluvial sedimentation comes to an end. As a result, these sandstone bodies are abruptly capped by flood-plain mudstones with paleosols (Fig. 16).

The same forestepping-backstepping motif is present, although with different local expressions produced by the progressive backstepping of sandy depositional zones, in three fundamental elements of flood-dominated fluvio-deltaic systems. The cyclicity observed in shelfal sandstone lobe successions records phases of maximum forestepping of sandstone facies that occur when the volume and sediment concentration of flood-generated flows are sufficient to produce self-sustained shelfal turbidity currents. These currents can carry most of their sand load to distal shelfal regions. The cyclicity of mouth-bar deposits records phases of decreased flood efficiency, *i.e.* phases during which hyperpycnal flood-generated flows deposit most of their sand load as offlapping successions at river mouths. Finally, facies sequences of river deposits

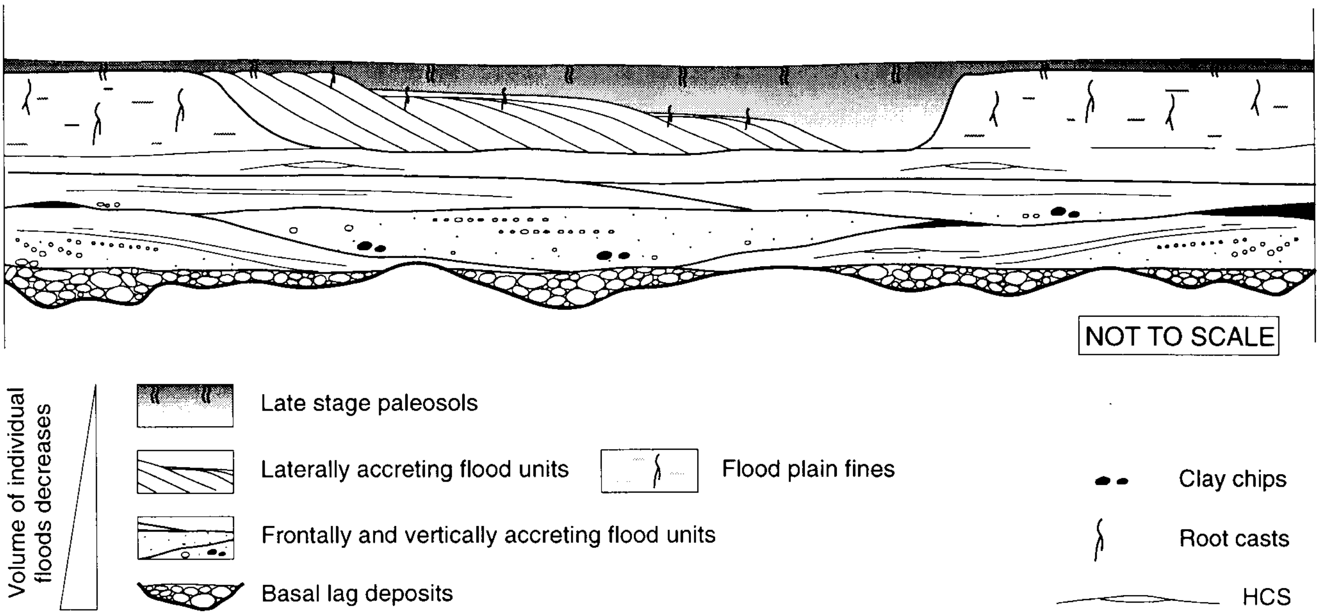


Fig. 16 - Facies sequence from flood-dominated river and associated flood-plain deposits laid down by relatively small volume flows. From base to top, the sequence shows a gradual decrease in the volume of individual floods. The basal part of the sequence consists of amalgamated lenses of coarse-grained, mainly residual facies. Higher in the sequence, progressively smaller-volume flows form point bars of similarly decreasing size. Based on data from the Lower Eocene Castigaleu Group, south central Pyrenees (after Davoli, 1996).

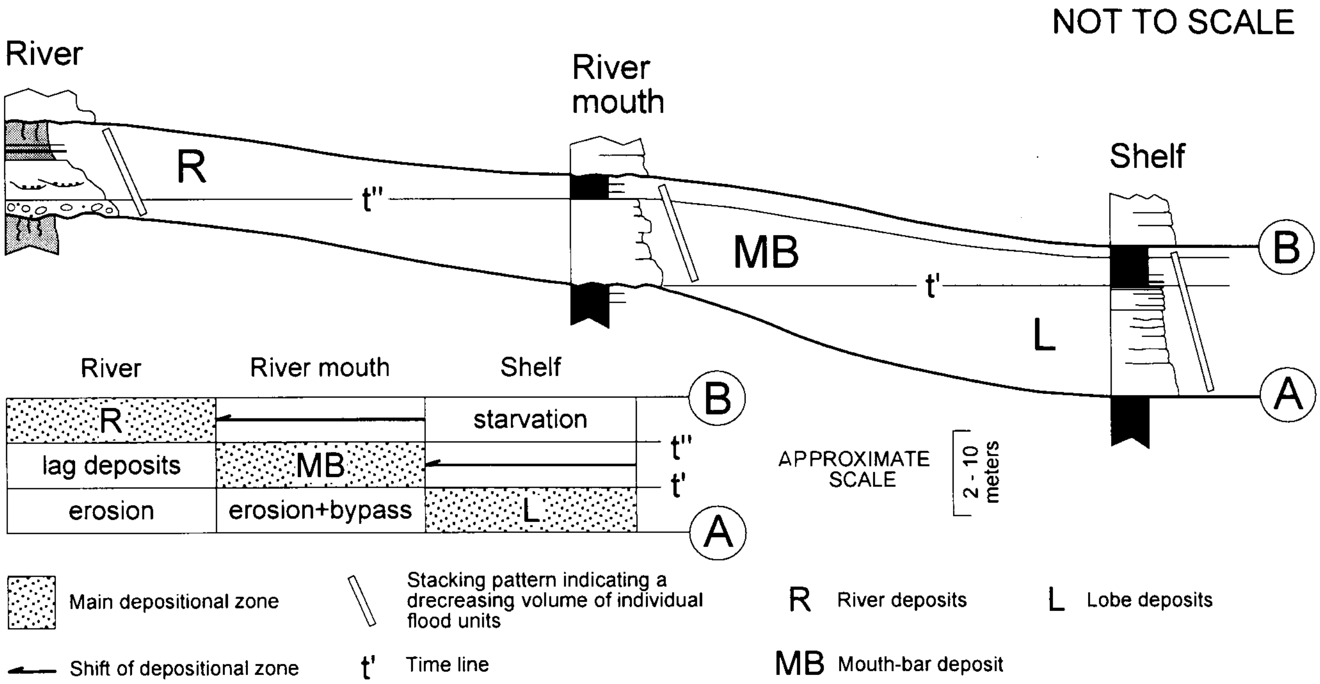


Fig. 17 - Diagram showing the landward shift of depositional zones with time within a flood-dominated river-delta system formed during a high frequency forestepping backstepping cycle (see text for detailed explanation).

record the latest and very poorly efficient flood-generated flows that can only fill upper river reaches through progressively thinner and finer-grained deposits.

The above relationships are summarized in the diagram of figure 17, which shows a fluvio-deltaic sandstone wedge formed during a high-frequency forestepping-

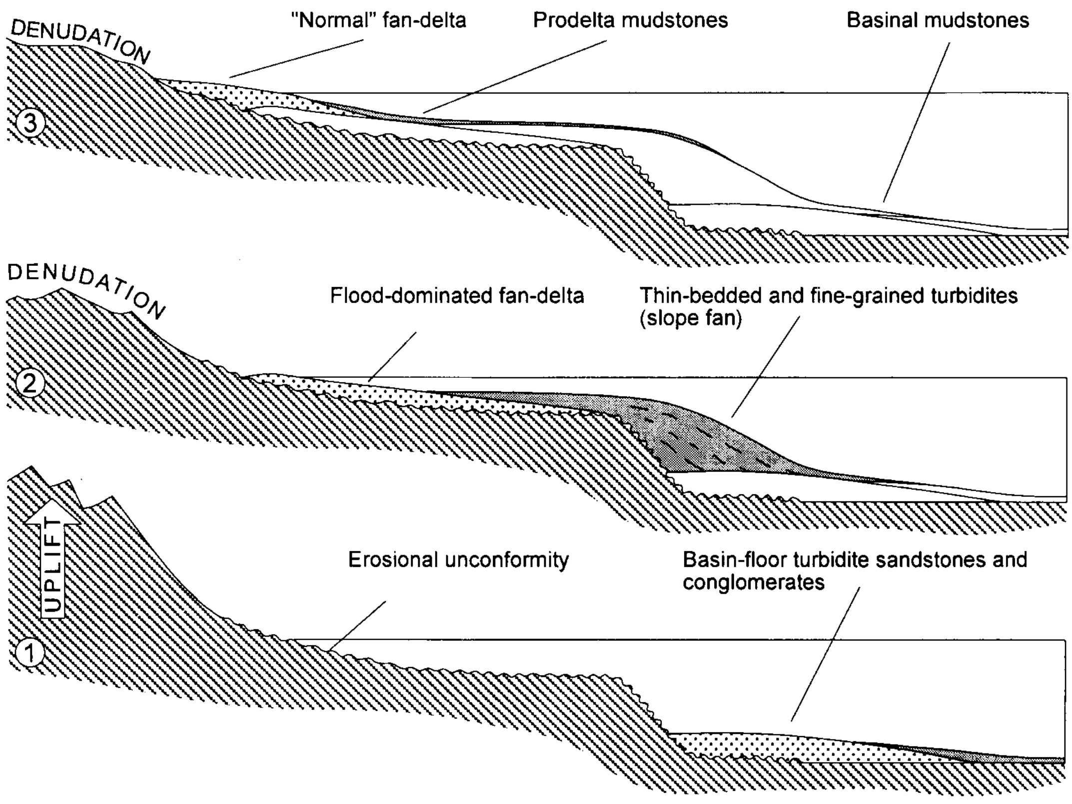


Fig. 18 - Diagram showing the complete evolution of a "Davisian-type" cycle (see text for explanation).

backstepping cycle. It will be noted that, although representing the result of the same overall evolution, facies sequences of shelfal lobe, mouth-bar, and river deposits do not record strictly time-equivalent events. Reading the complete evolution of a forestepping-backstepping, high-frequency cycle of a fluvio-deltaic system is actually very difficult. The cycles displayed by shelfal lobes record periods of time which are largely unrecorded in mouth bar deposits and difficult to read in the residual, coarse-grained facies of river deposits. Mouth-bar deposits are replaced by bioturbated mudstones in the lobe region and must be correlative with residual river deposits. The final fluvial infill of river systems through very small-volume floods records a period of time during which the fluvial system is already disconnected from the sea and mudstone facies drape underlying sandstone units from land to sea.

The setting delineated above strongly suggests that climate is the main factor controlling sedimentation patterns and facies distribution in the systems considered. Problems of climate, with its local, regional and global variations, and their causative factors, are clearly well beyond the limited objectives of this paper. Therefore, we limit ourselves to basing our considerations on the premiss that within each system, whatever the local climatic conditions, catastrophic flooding occurs when large amounts of water are made available to fluvial source and transfer zones through heavy rain falls, ice and snow melting, or the failure of naturally dammed lakes (see Baker and Bunker, 1985; Costa, 1988; Costa and Schuster, 1988). This sudden release of large amounts of water causes flood-generated mixtures of sediment-water to move periodically basinward, removing the waste of drainage basins and incorporating previous alluvium and marine sediments through large-scale erosion. Decrease in the amount of water available in the source zone produces a gradual backstepping of flood-generated facies with time until floods become so small that they deposit most of their sediment load within upper river reaches in progressively smaller channels. In the absence of sufficient amounts of water, fluvial systems probably fill with newly produced alluvium in their proximal alluvial components, such as "normal" alluvial fans and uppermost river reaches. Under such circumstances, only mud can be carried farther downslope to terminal flood basins.

Low-frequency cyclicity characterizes the way in which depositional systems stack within basin fills and thus entails periods of time and sediment thicknesses that best fit 3rd order cycles of sequence stratigraphy, *i.e.* the depositional sequences in the sense of Vail (1987). Figure 3 shows ideal settings of this type for flood-dominated fan-delta and river-delta systems respectively. In both cases, these systems are underlain by turbidite systems, thus forming, altogether, more general types of depositional systems termed herein "fluvio-turbidite systems".

This order of cyclicity implies the vertical transition from a basal, forestepping turbidite system to progressively backstepping shelfal sandstone lobes followed upward

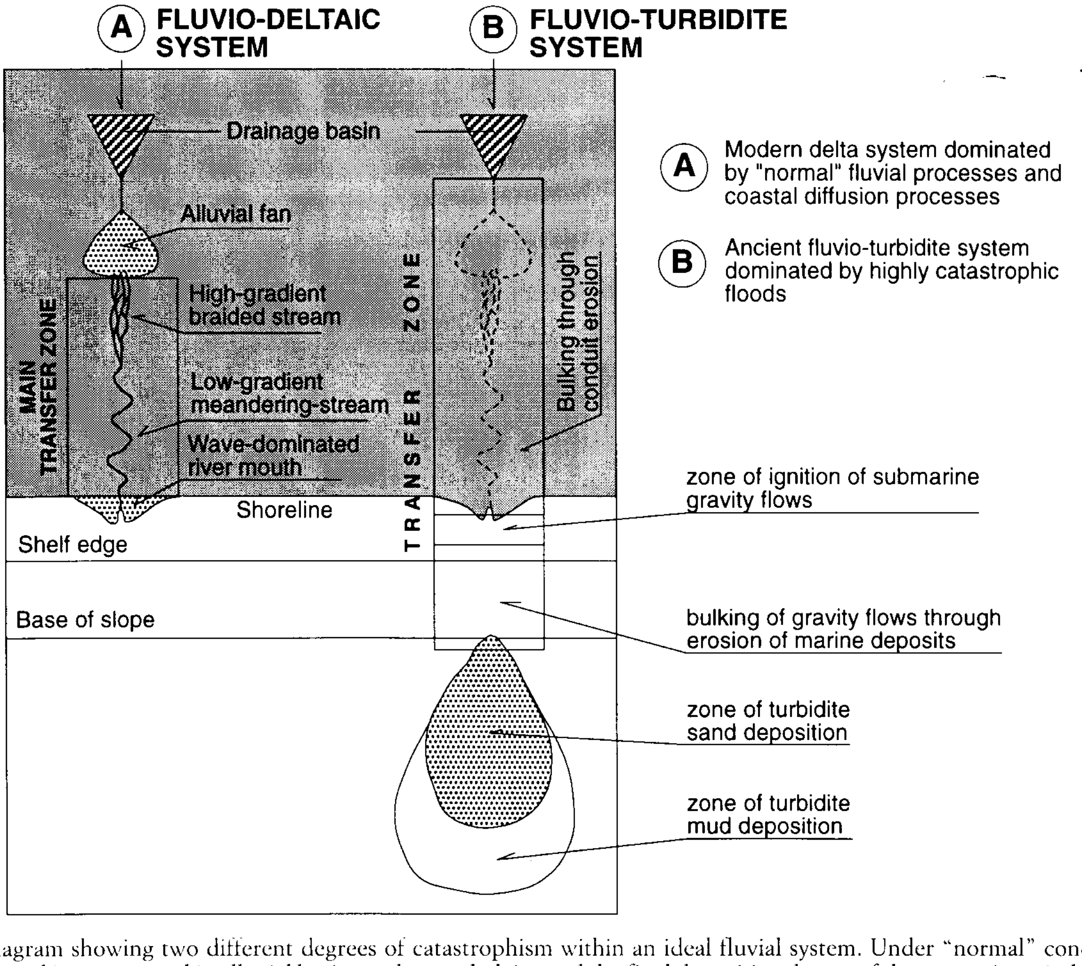


Fig. 19 - Diagram showing two different degrees of catastrophism within an ideal fluvial system. Under "normal" conditions (A), most of the sand is sequestered in alluvial basins and coastal plains and the final depositional zone of the system is entirely controlled by wave action; the depositional setting is that of a "normal" fluvio-deltaic system. Under "highly catastrophic" conditions (B), the final depositional zone is represented by deep-marine, turbidite sandstone lobes and most of the former setting has become a transfer zone. See text for a more extensive discussion.

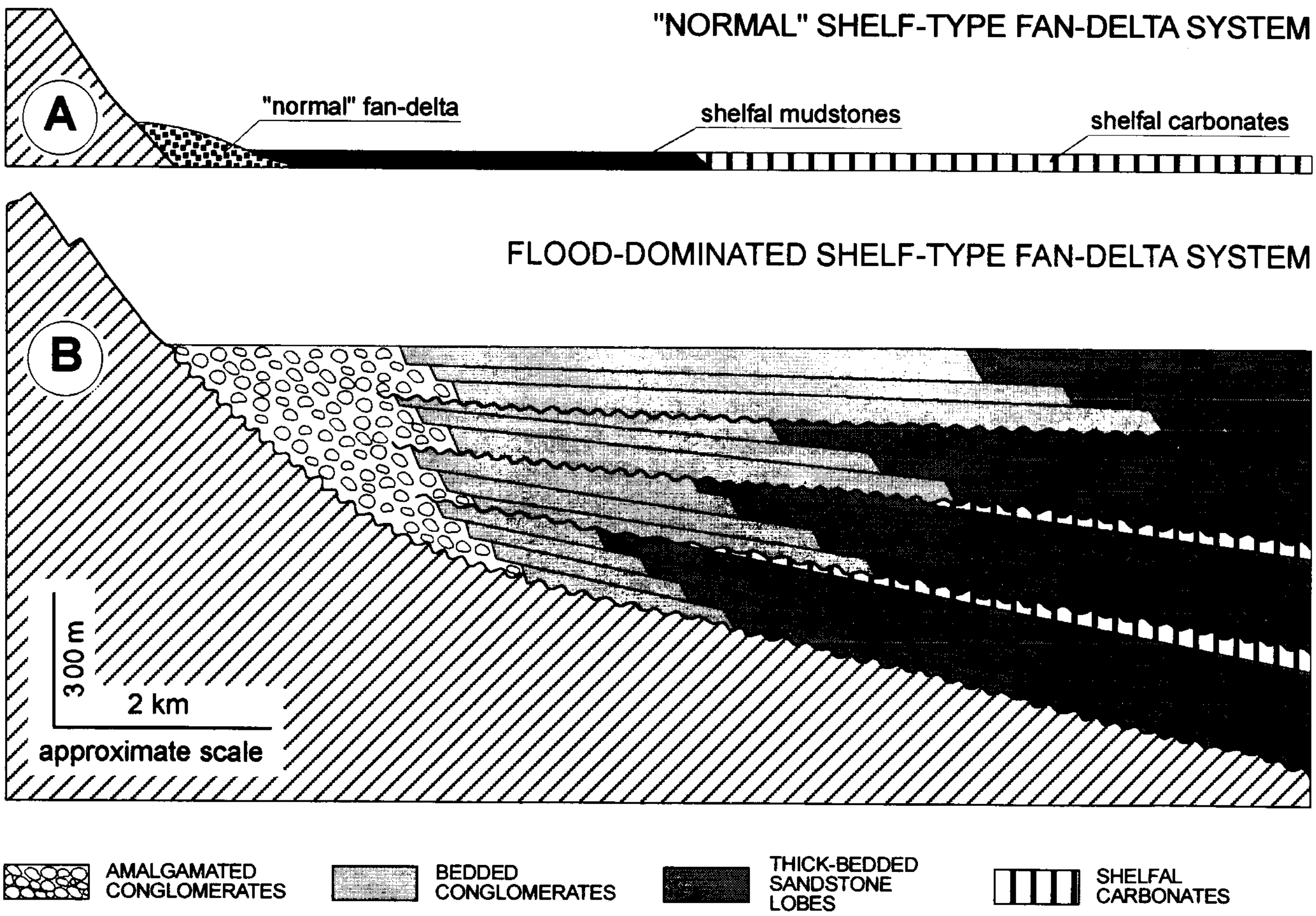


Fig. 20 - Diagram showing how the sediment flux to the sea varies with time and how the preservation potential of flood-generated deposits (B) is by far higher than the one of "normal" sediments deposited in the absence of catastrophic floods (A). See text for a more extensive discussion.

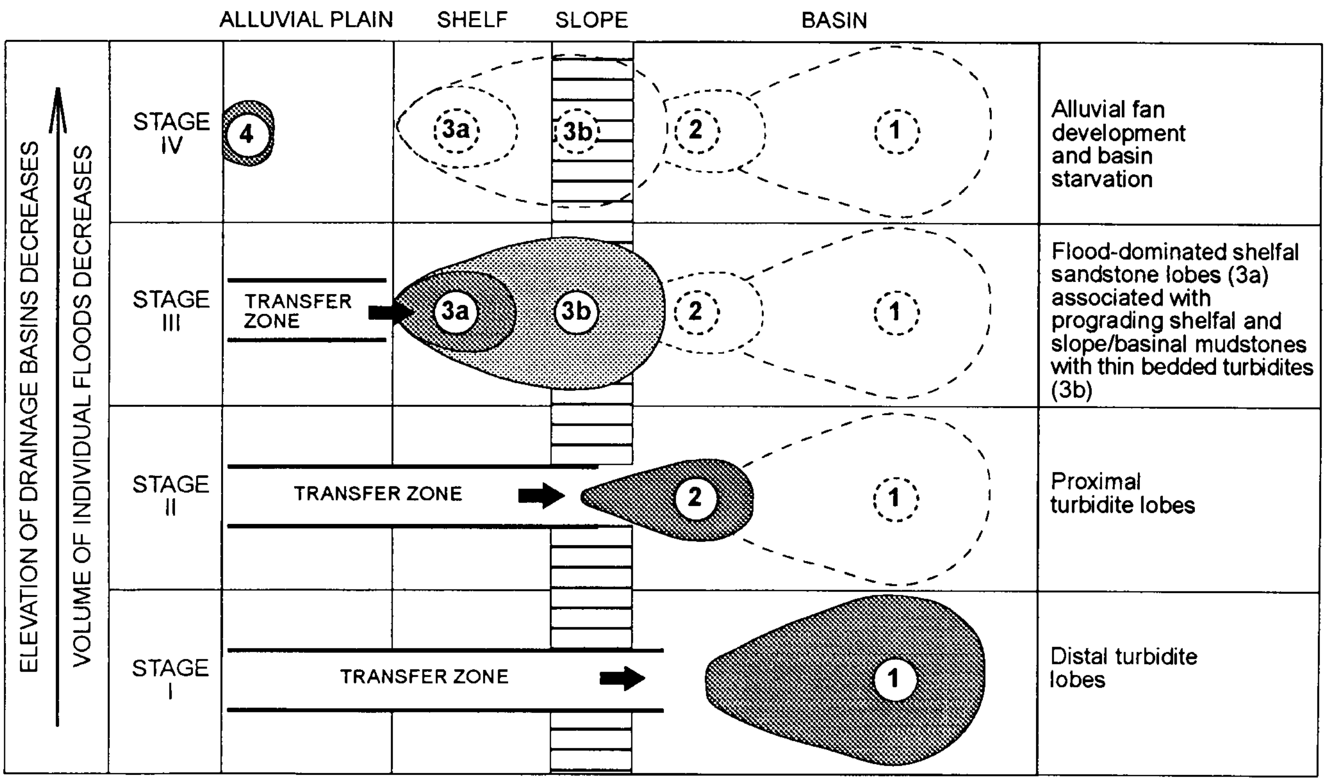


Fig. 21 - The different stages of growth of an ideal fluvio-turbidite system formed during an uplift/denudation cycle. Due to the progressive decrease of the elevation of the drainage basin and ensuing decrease of sediment availability, the depositional zones of the system progressively backstep in a landward direction. See text for discussion.

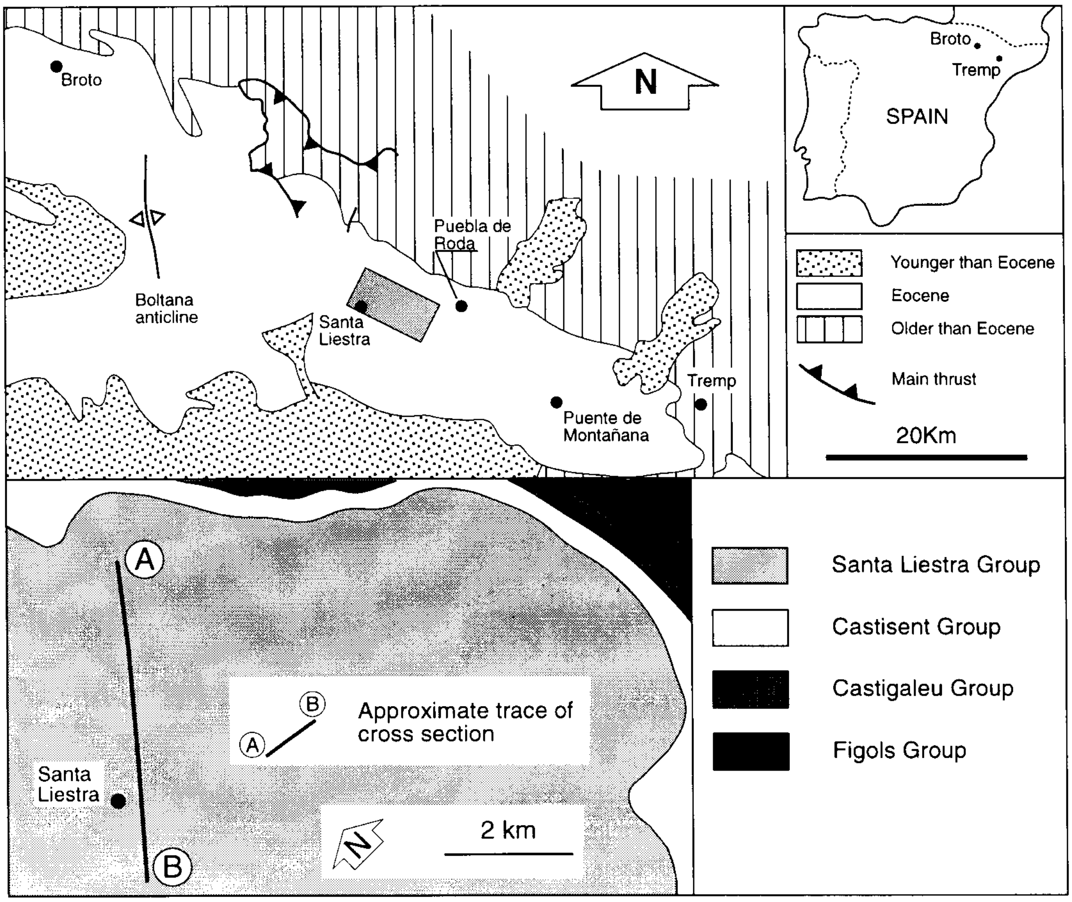


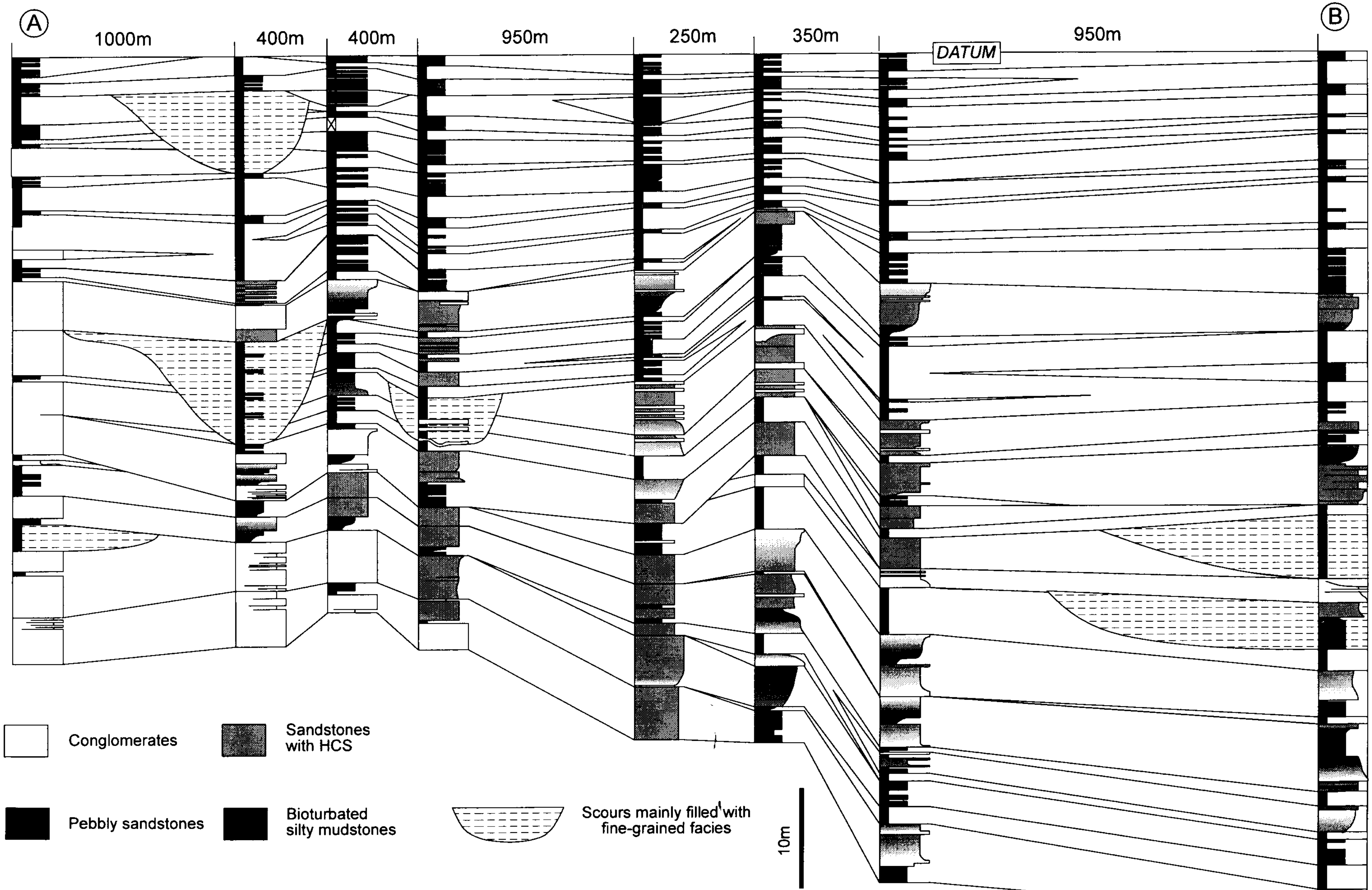
Fig. 22 - Location map (above) and detailed stratigraphic cross section (on the opposite page) of a portion of the lower to early Middle Eocene Santa Liestra Group (south-central Pyrenees, Spain) along the Esera valley. The cross section shows the downcurrent transition from conglomerate and pebbly-sandstone facies to progressively finer-grained and bioturbated facies of a flood-dominated fan-delta system. The diagram depicts the marked tabular geometry of flood-generated lobes, as well as the many distortions of such geometry as a result of ongoing tectonic deformation. The stacking pattern shows a well developed cyclicity at different hierarchical scales. The cross section is slightly modified after Crumeyrolle (1987).

by a general disappearance of flood-dominated sandstone facies. Figure 18 attempts to provide a model for these vertical successions simply in terms of geomorphic cycles where a phase of tectonic uplift is followed by denudation.

For small and medium sized mountainous river systems, Milliman and Syvitski (1992) have pointed out how the sediment flux to the sea is essentially related to the elevation of drainage basins and to their proximity to the shoreline. These factors strengthen the role of flooding in that sediment yield is directly proportional to the elevation of drainage basins and sediment concentration of flood-generated flows is not reduced by energy dissipation and sedimentation in alluvial flood basins and coastal plains. In modern settings, many of these rivers are "dirty rivers" in that they can enter sea water with sufficient sediment concentration to generate frequent hyperpycnal flows over the year. Milliman and Syvitski (1992) have also emphasized the relationships between sediment yield, drainage basin elevation and tectonism (see also Schumm and Rea, 1995).

Our data substantiate the above conclusions from modern settings. Huge volume of ancient flood-dominated sediments actually form the fill of basins associated with active tectonic settings where uplift and subsidence create sediment and space respectively. On the basis of our data, and particularly on the geological setting of the south-central Pyrenees where the relationships between episodic thrust propagation and sedimentation are relatively well understood (*e.g.*, Mutti and Sgavetti, 1987; Mutti *et al.*, 1988, 1994d; Puigdefábregas *et al.*, 1989), we suggest that a simple way to interpret many terrigenous basin fills associated with tectonically active settings can be represented by relatively low-frequency cycles of uplift/denudation punctuated by higher-frequency climatic cycles. The first cyclicity accounts for sediment availability through time. The second provides the water through which sediment can be periodically flushed to the sea by flood-related processes. The model of figure 19 thus emphasizes fluvio-turbidite systems as the most natural response to the first-order controlling factors discussed above. The model implies that at least part of the turbidite systems associated with these settings are directly or indirectly generated by catastrophic floods of very large volume during periods of time when the elevation of drainage basins is highest, *i.e.* immediately after phases of substantial tectonic uplift (see also Klein, 1985; Mutti *et al.*, 1994c).

Specific examples of cyclic stacking patterns of ancient flood-dominated fluvio-deltaic systems from different tectonic settings are shown in figures 22 to 27. These examples emphasize the importance of uplift/denudation cycles punctuated by higher-frequency climatic cyclicity also on a shorter temporal scale, that of high-frequency cyclicity of sequence stratigraphy.



Main paleocurrent directions are from the north

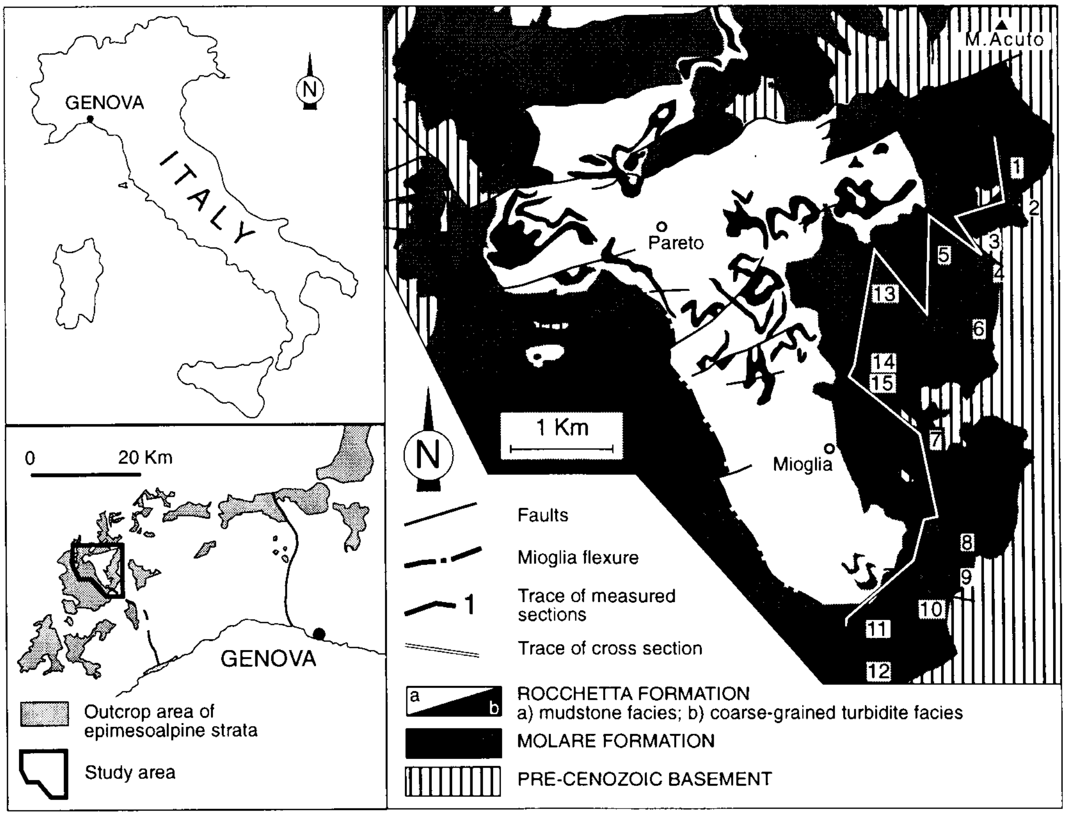


Fig. 23 - Location map (above) and stratigraphic cross section (on the opposite page) of the lower Oligocene Molare Formation (Tertiary Piedmont Basin, Italy). The local succession was deposited in a highly mobile tectonic setting. The first diagram of the cross section (A) illustrates the early phase of basin infilling, which took place in an extensional tectonic regime. These sediments consist of lacustrine and marine, flood-dominated fan-delta deposits derived from the northern margin of the basin. Following a phase of tectonic inversion, the upper part of the basin fill (diagram B of the cross section) records an abrupt deepening of the basin accompanied by sedimentation from southerly derived gravity flows which partly cannibalized the underlying Molare strata in tectonically uplifted areas (from Mutti *et al.*, 1995).

In particular, figure 24 shows an example of marine and lacustrine flood-dominated fan-delta deposits from the lower Pleistocene Sant'Arcangelo basin, in the southern Apennines, where thrust propagation interferes with climatic cyclicity. The lower and marine portion of the section is spectacularly subdivided into a series of unconformity-bounded stratigraphic units each of which is the product of a cycle of uplift/denudation. Based on the biostratigraphic data provided by Pieri *et al.* (1994), the temporal scale of these cycles is well within the 4th order of sequence-stratigraphic schemes. Each unconformity-bounded unit contains climatically-induced facies cycles expressed by cyclically stacked shelfal sandstone lobes (see also Fig. 15). The same stacking pattern characterizes the upper and lacustrine portion of the basin fill.

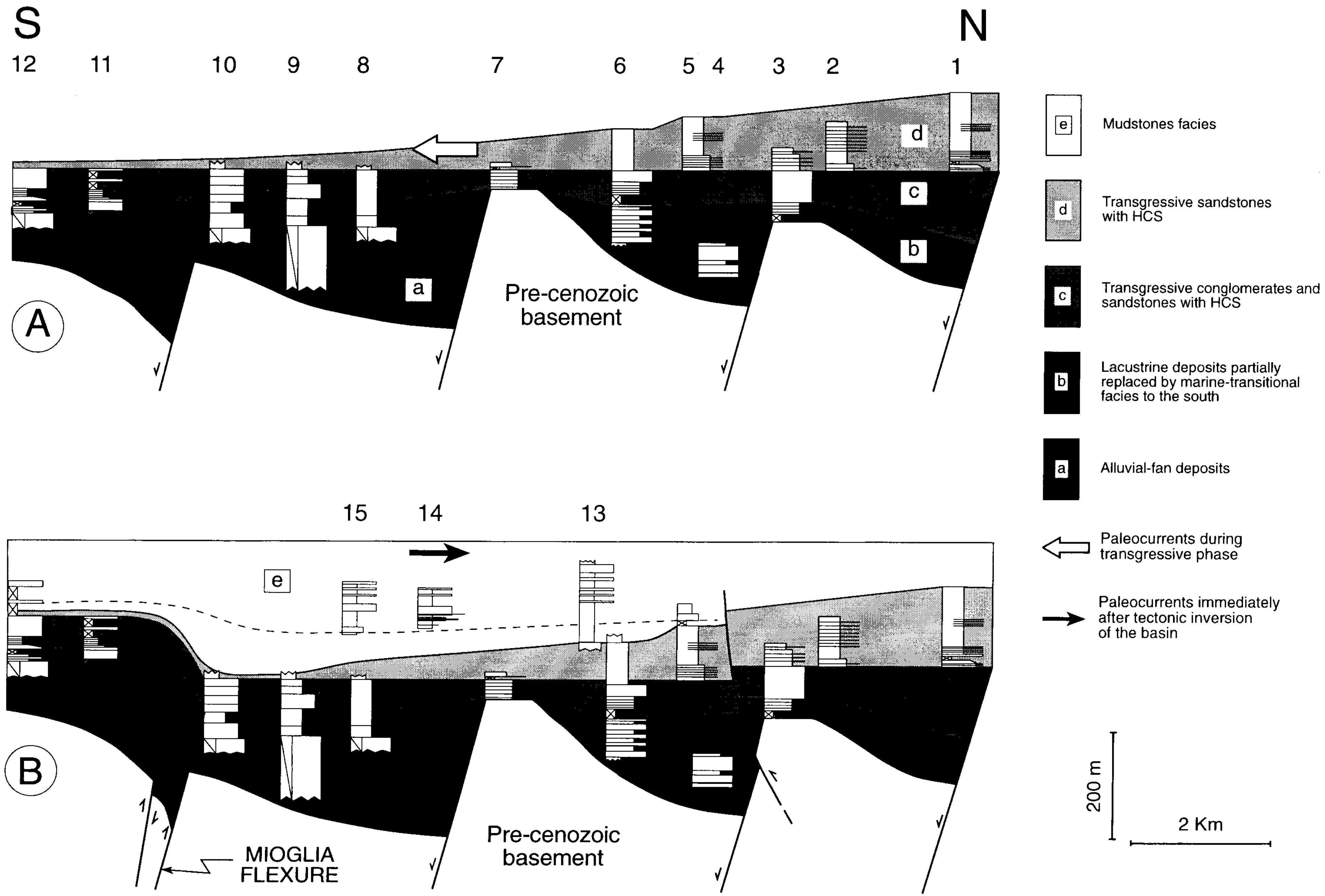
Similar relationships can be inferred from the stratigraphic cross sections of figures 22 and 25, respectively describing the Eocene Santa Liestra Group and lower Eocene Roda Sandstone (Figols Group) in the south-central Pyrenees. Short-lived, episodic uplift associated with high-frequency cyclicity has been amply documented and discussed by Mutti and Sgavetti (1987), Mutti (1990), and Mutti *et al.* (1994a) from the upper Cretaceous Aren Sandstone, a unit which was deposited during the earliest phases of thrust propagation in the eastern part of the south-central Pyrenees.

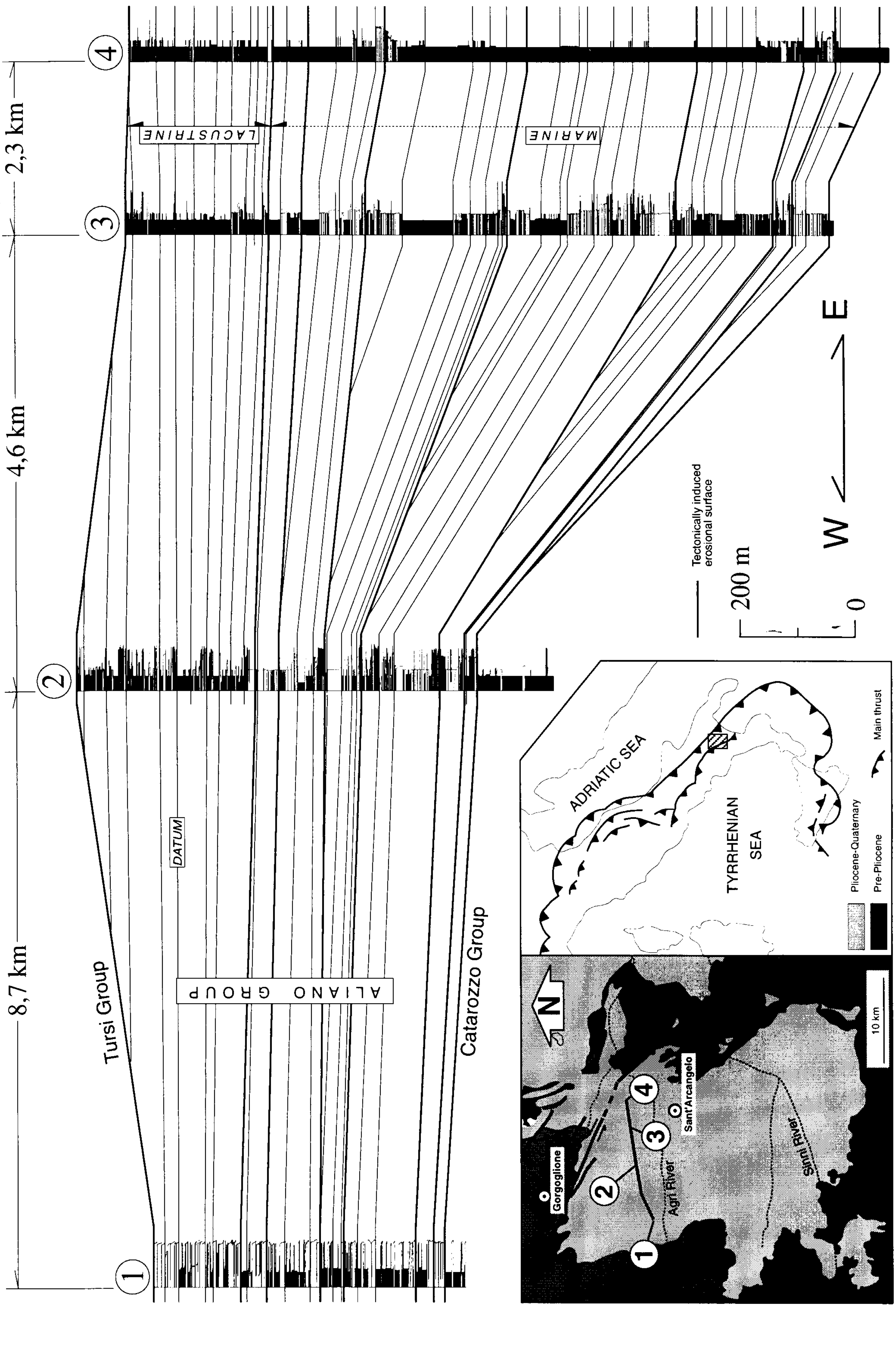
Figure 26 illustrates the depositional setting and stacking pattern of the Eocene Castigaleu Group, south-central Pyrenees, through a cross section showing the transition between fluvial and deltaic facies over a distance of about 30 km. The unit, which is bounded below and above by major and regional tectonically-induced unconformity surfaces, was deposited in a period of about 1 Ma: its internal stacking pattern is thus recording high-frequency cyclicity (Davoli, 1996). Also in this case, the basal and the uppermost parts of the unit show interference between short-lived, episodic uplift and high-frequency cyclic stacking patterns. A period of relative tectonic quiescence occurred during the deposition of the medial part of the unit which is characterized by a remarkably isopachous correlation pattern.

The basic issue with the cyclicity of ancient flood-dominated fluvio-marine systems is in which way climatic changes unambiguously documented by facies characteristics can be linked with cyclic patterns of relative sealevel variations and accommodation of sequence stratigraphy, thus entailing a series of problems which are largely beyond the purposes of this paper and will be only partly and briefly discussed in the following section.

DISCUSSION AND CONCLUSIONS

The data presented and discussed in this paper show that the depositional zones of ancient fan-delta and riv-


S
N
12
11
10
9
8
7
6
5
4
3
2
1
d
c
b
a
Pre-cenozoic basement
A
15
14
13
e
B
MIOGLIA FLEXURE
Pre-cenozoic basement
e
Mudstones facies
d
Transgressive sandstones with HCS
c
Transgressive conglomerates and sandstones with HCS
b
Lacustrine deposits partially replaced by marine-transitional facies to the south
a
Alluvial-fan deposits
Paleocurrents during transgressive phase
Paleocurrents immediately after tectonic inversion of the basin
200 m
2 Km



1
2
3
4
8,7 km
4,6 km
2,3 km
Tursi Group
ALIANO GROUP
DATUM
Catarozzo Group
LACUSTRINE
MARINE
Tectonically induced erosional surface
200 m
0
W
E
Gorgoglione
Agri River
Sant'Arcangelo
Sinni River
10 km
N
ADRIATIC SEA
TYRRHENIAN SEA
Pliocene-Quaternary
Pre-Pliocene
Main thrust

Fig. 24

er-delta systems associated with tectonically active basins are almost entirely recorded by flood-generated facies and facies associations.

No modern alluvial fans, fan-deltas or river-deltas have geologically persistent "steady states" which can be significantly compared with those of the ancient systems discussed in this paper. The only notable exception is that of fjord-related depositional systems (*e.g.*, Bornhold and Prior, 1990; Normark and Piper, 1991; Zeng *et al.*, 1991), although the data available on these systems are still limited to relatively thin veneers of modern sediments. In their modern expression, the small and medium-sized mountainous "dirty" rivers of Milliman and Syvitski (1992) probably represent a stage of relatively low discharge and predominance of "normal" stream-flow processes of river systems that, in different climatic conditions, would be the best candidates for producing depositional systems similar to those described in this paper.

Ancient flood-dominated fluvio-deltaic systems vary greatly in terms of depositional patterns mainly as a function of their tectonic and physiographic setting and the degree of catastrophism involved in sedimentation. In each basin, these factors control how much of the sediment carried by catastrophic floods will be deposited in alluvial, nearshore, shelfal and slope-basinal environments. All other things being equal, the amount of sediment that can be carried by flood-generated flows to the sea is mainly a function of the distance between the drainage basins and the shoreline and of the topographic gradient along this distance.

As shown by Milliman and Syvitski (1992; see also Schumm and Rea, 1995), sediment yield is essentially related to the elevation of drainage basins and ultimately to the tectonic setting. Floods generated in such settings by heavy rainfall, snow and ice melting, and breaching of naturally dammed lakes may thus carry downstream huge amounts of sediment that can be partly or entirely sequestered in alluvial flood basins. However, where mountain fronts are close to the shoreline, floods will be able to carry the vast majority of their sediment load directly to the sea. The data discussed in the preceding sections indicate that the latter conditions account for the depositional settings and facies distribution patterns of most ancient fluvio-deltaic systems associated with tectonically active basins and thus normally fed by small and medium-sized mountainous rivers.

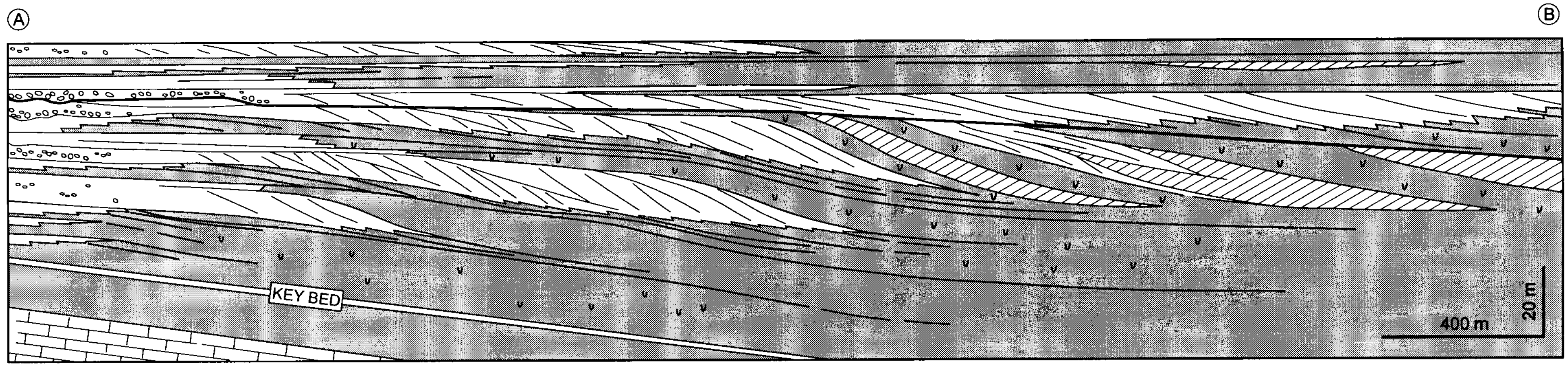
The most typical expression of ancient, flood-dominated fluvio-deltaic systems is represented by shelfal sandstone lobes with HCS which, particularly in the case of flood-dominated fan-delta systems, may comprise huge sedimentary accumulations whose origin and stratigraphic importance have been largely overlooked in previous literature. Shelfal sandstone lobes with HCS are essentially shallow-marine turbidites originated by the transformation of flood-generated hyperpycnal flows into self-sustained turbidity currents carrying along a flood-related oscillatory-flow component.

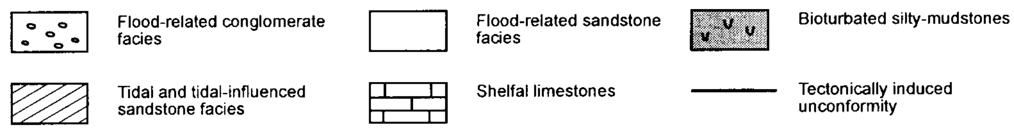
If not carefully framed within detailed correlation patterns of vertical and lateral stratigraphic relationships, shelfal sandstone lobes with HCS can easily be mistaken for either shelfal, storm-dominated deposits or sharp-based shoreface sandstone facies. This misinterpretation has hampered, in most cases, the correct recognition of the fluvio-deltaic nature of these sediments and, therefore, led to misleading paleogeographic reconstructions. In reality, shelfal sandstone lobes with HCS represent the most genuine expression of fluvial-dominated fan-delta and river-delta systems; only flood-generated hyperpycnal flows and related turbidity currents can actually transport sand far away from the shorezone, thus escaping marine diffusion processes.

In flood-dominated fan-delta systems, facies tracts are relatively simple, being essentially produced by unconfined flows undergoing progressive downslope transformations. In flood-dominated river-delta systems, facies tracts are more difficult to establish and interpret because of the greater variability of facies and inferred processes in both mouth-bar and river deposits. River mouths act as a filter for flood-generated sediment-laden stream flows, determining how much of the sediment load of these flows will be dropped at river mouths, and how much of this load will instead be carried farther seaward by flood-generated turbidity currents to form shelfal sandstone lobes with HCS. The momentum of individual sediment-laden stream flows, as well as buoyancy, frictional forces and marine diffusion at river mouths, are the main controlling factors in determining the local characteristics of mouth-bar deposition. As a result, the problem can be solved only on a case-by-case basis.

In river deposits, flood-generated processes are recorded by distinctive flood units characterized by both vertical and longitudinal grading and by residual, amalgamated conglomerates laid down by bypassing flows during periods of intense flooding. The component facies of individual flood units vary from unstratified or crudely graded conglomerates and pebbly sandstones to thin, graded mudstone units through a variety of internally stratified pebbly sandstone and sandstone facies. Deposition of these facies, within each flood unit, is controlled by traction and traction-plus-fallout processes associated with waning flow conditions and progressive decrease in sediment concentration. Climbing dunes and large-scale sinusoidal laminae characterize the early stages of traction-plus-fallout sedimentation. If not carefully examined, most of these internally stratified facies can easily be mistaken for those produced by "normal" streamflow pro-

Fig. 24 - Location map and stratigraphic cross-section of the lower Pleistocene Aliano Group in the Sant'Arcangelo basin, southern Apennines. The cross-section shows a marine flood-dominated fan-delta system overlain by a similar type of system deposited in a lacustrine environment. In both systems, which display spectacular internal cyclic stacking patterns, there is a clear transition from alluvial conglomerates in the west to sandstone lobes and mudstone facies in the east. Facies and facies associations indicate deposition by flood-generated flows. Individual sandstone lobes have a tabular geometry and can be physically traced across most of the study area. Each lobe is composed of graded beds which, in a downcurrent direction, record the transformation from hyperconcentrated flows into low-density turbidite currents. Both marine and lacustrine strata lack evidence of "normal" diffusion processes. Tectonically-induced angular unconformities occur in the lower, marine part of the section recording uplift/denudation cycles. Note that the sandstone lobes contained between these angular unconformities have an essentially tabular geometry and display internal cyclic stacking patterns thought to be climatic in origin. Paleontological data (Pieri *et al.*, 1994; Hippolyte *et al.*, 1994) indicates an early Pleistocene age for the Aliano Group. This leads to the conclusion that the recurrence period of episodic tectonic uplift is at least within a 4th-order cyclicity. See text for a more detailed discussion.





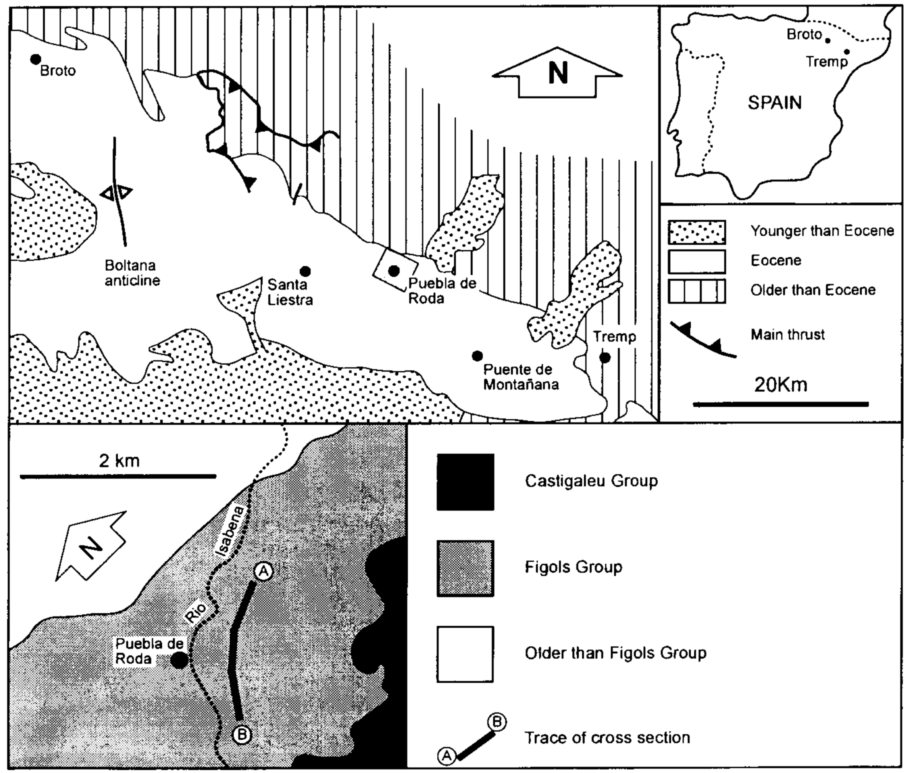


Fig. 25 - Location map and stratigraphic cross section of the lower Eocene Roda Sandstone (Figols Group, south-central Pyrenees) in the Isabena valley. From north to south, the cross section shows the transition from channelized pebbly-sandstone facies into bioturbated silty-mudstones within the mouth bar complex of a flood-dominated river-delta system. Tidal sandstone facies and tidal-influenced flood-dominated sandstone facies can be recognized in the right portion of the diagram. The former accumulated through the reworking of river-borne sand during periods of weak fluvial progradation; the latter occur at the toes of flood-generated units, thus indicating reworking immediately after deposition of individual flood units. A tectonically-induced unconformity, recording a major phase of tectonic uplift, separates the Roda succession (see text for a more detailed explanation). The cross section is slightly modified after Crumeyrolle *et al.*, 1992.

cesses. The latter are very rarely recorded, being represented by large- to medium-scale trough-cross stratification and locally preserved bed forms at the top of individual flood units during the latest stages of each flood when, because of reduced sediment concentration, the flow is gradually approaching waterflood and "normal" streamflow conditions.

Most of the facies observed in both flood-dominated river-mouth and river deposits have been largely overlooked in previous literature and, therefore, require further and extensive sedimentological studies both in terms of description and interpretation. Only part of these structures have been briefly described in earlier sections of this paper.

As anticipated by Schumm (1977, 1981), the final depositional zones of fluvio-deltaic systems are characterized by an extremely well-developed sedimentary cyclicity recording the evolution of each fluvial system with time. This cyclicity, which is particularly well preserved in flood-dominated shelfal sandstone lobe successions, indicates high-frequency forestepping-backstepping episodes of sand deposition developed at different, hierarchically-ordered scales. We have interpreted these cyclic stacking patterns as primarily produced by climatic cycles, *i.e.* cycles that controlled, for each fluvial system considered, the onset and disappearance of local conditions favoring the development of catastrophic flooding through time. We emphasize again here that an understanding of this cyclicity in terms of climatic factors is extremely difficult on the basis of available data and thus beyond the scope of this paper. We simply note that the facies and facies cycles observed in the many depositional systems considered necessarily indicate the presence of a high-frequency climate-related cyclicity in fluvio-deltaic systems dominated by catastrophic flooding of tectonically active basins. Sediment availability through time is also important and relates to the new alluvium produced in drainage basins which, in the absence of floods, can be temporarily stored either in upper fluvial reaches, alluvial fans and terminal flood basins or in "normal" fan-delta and river-delta systems.

This raises the problem of the preservation potential of "normal" sediments within flood-dominated fluvio-deltaic systems. As noted in earlier sections, and particularly in the case of fan-delta systems, "normal" sediments appear to be virtually unrecorded in the alluvial and marginal marine portions of the systems considered.

The diagram of figure 20 , which is largely based on the depositional setting of flood-dominated fan-delta strata in the Santa Liestra Group (Tab. 1), compares "normal" and "catastrophic" sedimentation and shows how "normal", alluvial and marginal marine sediments are periodically cannibalized by catastrophic floods. The diagram also partly answers the basic question of Milliman and Syvitski (1992, p. 540) concerning what is the sediment flux to the sea. These authors subdivide the question into two parts: (1) how much sediment is carried by rivers, and (2) how much sediment escapes the present-day land/estuarine environment. The same authors admit that, on the basis of the data available from modern river systems, the answer to the two parts of the question is more or less the same - we don't know. The question can be partly answered through the diagram of figure 20 that depicts the stratigraphic record of the growth of a fan-delta system. The diagram shows that the sediment flux to the sea varies with time. Under conditions of "normal" sedimentation, most of the available sediment is trapped in the land/marginal marine environment; "catastrophic" conditions, periodically alternating with "normal" conditions through climatic cycles, introduce newly produced alluvium and remove, through erosion, the alluvial and nearshore sediments deposited during "normal" conditions. As a result, although in reality the growth of the fan-delta system of figure 20 took place through alternating periods of "normal" and "catastrophic" sedimentation, only the latter is entirely preserved in the stratigraphic record. On a much shorter temporal scale, a similar scenario can be inferred from the depositional setting of modern fjord-related depositional systems (*e.g.*, Normark and Piper, 1991; Zeng *et al.*, 1991).

Most of the flood-dominated fluvio-deltaic systems described in this paper are associated with deeper-water turbidite systems within depositional settings similar to those shown in the diagrams of figure 3. For convenience, we have used the sequence-stratigraphic terms of "basin-floor fan" and "slope fan" to denote these deep-water, turbidite deposits (for their definition and discussion, see Vail, 1987; Posamentier and Vail, 1988; Mutti and Normark, 1991; Normark *et al.*, 1993). In these systems, flood-generated processes form the natural link between fluvial, deltaic and turbidite sedimentation through a continuum of facies types indicating deposition from waning flows. An ideal flood-dominated system of this type, herein termed "fluvio-turbidite system" (see above), develops through four main stages of growth each of which relates to a different degree of catastrophism (Fig. 21). The degree of catastrophism can be simply expressed, within each system considered, by the distance of the sandy depositional zones from the original drainage basin. All other things being equal, this distance is controlled by the volume and momentum of flood-generated flows and, therefore, also by sediment availability in the drainage basins and transfer zones that controls the final sediment concentration of each flood.

Fluvio-turbidite systems are apparently the result of cycles of uplift/denudation which are similar to Davisian cycles (the erosion cycle of Davis, 1899), although characterized by considerably shorter duration. These shorter-lived cycles, herein referred to as Davisian-type cycles, can never reach the planation stage during the development of a thrust-fold belt because of the high-frequency repetition of phases of orogenic uplift (see above). Also these Davisian-type cycles imply that the sediment yield of related fluvial systems decreases with time after an initial phase of uplift. This decrease in sediment availability is herein thought to be the main controlling factor of the overall stacking pattern of the ideal system of figure 21, which shows a progressive backstepping of its sandy depositional zones from basinal, turbidite sandstone lobes (basin floor fan) into shelfal sandstone lobes and eventually into "normal" fluvio-deltaic or alluvial strata. With reference to an alluvial-shelfal depositional setting, Davisian-type cyclicity associated to tectonic uplift with a superimposed higher-frequency climatic cyclicity is shown by the spectacular example of the Pleistocene Sant'Arcangelo basin, in the southern Apennines (Fig. 24).

Although largely overlooked by stratigraphers, the importance of Davisian cyclicity, with its self-maintaining character associated to episodic orogenic uplift and en-

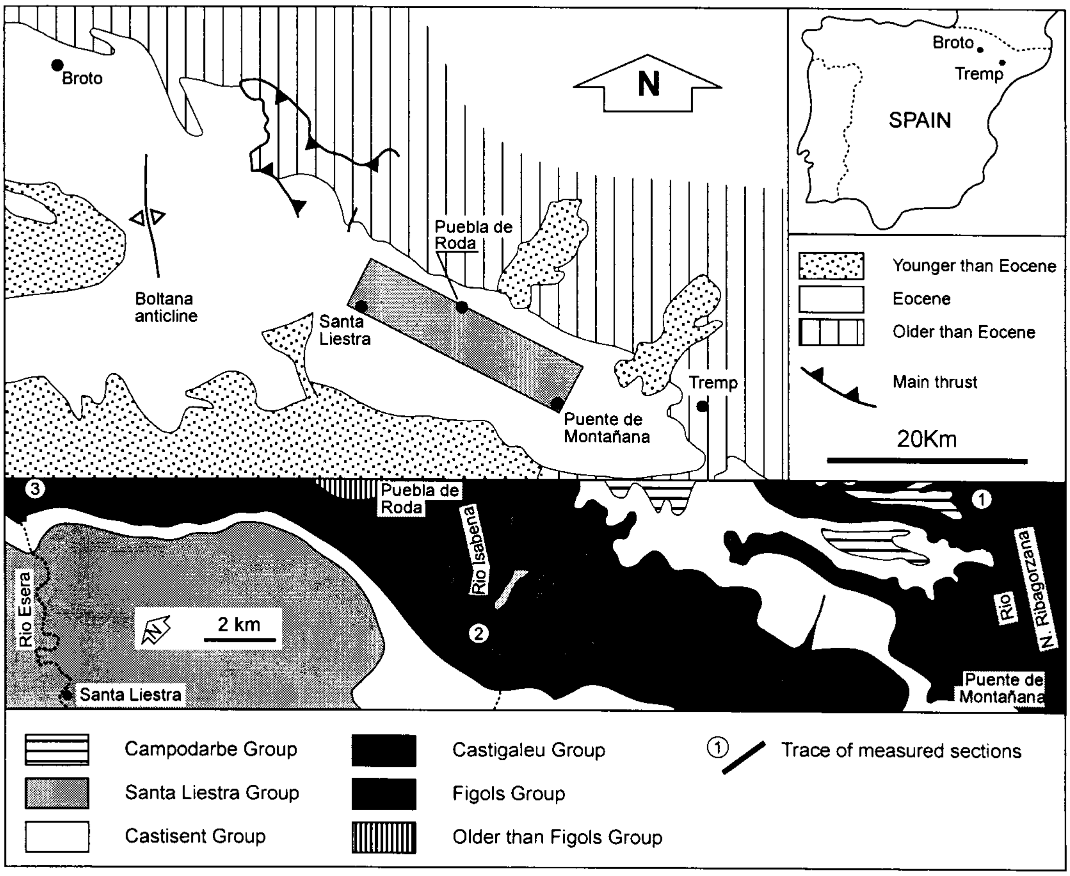


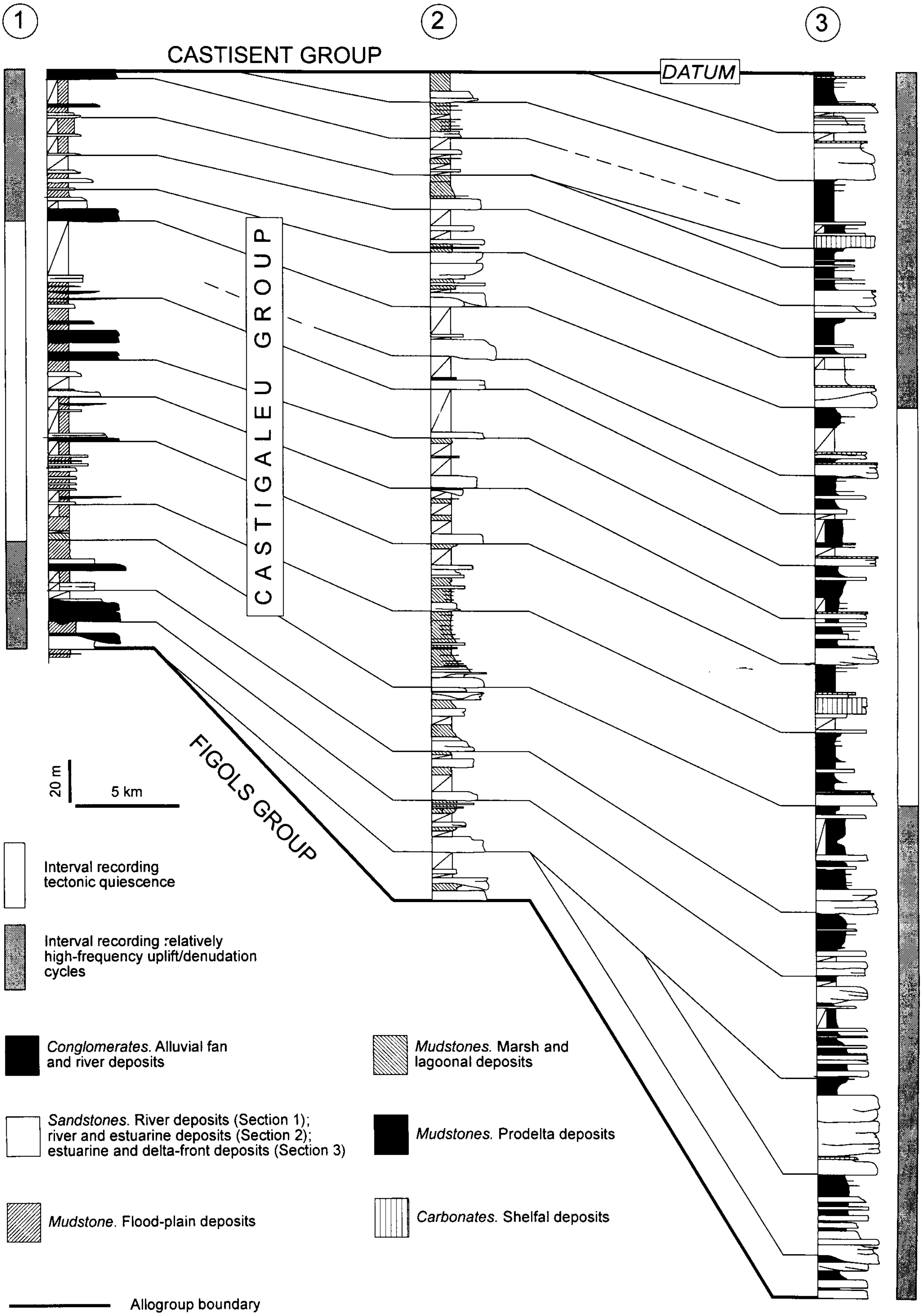
Fig. 26 - Location map (above) and tentative stratigraphic cross section (on the opposite page) of the lower Eocene Castigaleu Group (south-central Pyrenees, Spain), between the Noguera Ribagorzana and the Esera valleys. The detailed correlation pattern shows the relationships between alluvial fan and fluvial deposits (section 1) and delta front and shelfal sediments (section 3), via marginal-marine deposits mostly represented by estuarine sandstones and mudstones (section 2). The Castigaleu Group was probably deposited during a 3rd-order cycle of relative sealevel variation (Mutti *et al.*, 1988; Davoli, 1996) characterized by an overall relative tectonic quiescence. The central portion of the succession is actually characterized by isopachous correlation patterns recording high-frequency forestepping/backstepping cycles most probably resulting from a combination of climatic and eustatic controlling factors. The lowermost and uppermost portions of the succession are however characterized by the occurrence of relatively high-frequency uplift/denudation cycles which are expressed by angular unconformities and truncation surfaces. See text for discussion. Slightly modified after Davoli (1996).

suing denudation, and of the higher-frequency cyclicity related to intrinsic controlling factors of fluvial systems, as well as the implications of these types of cyclicity on the stratigraphic record, have been long emphasized in previous geomorphological literature (Schumm, 1963, 1977, 1981). Wescott (1993) and Wright and Marriott (1993) have recently pointed some of the problems of fluvial sedimentation related to this kind of cyclicity and sequence-stratigraphic models.

The problem of relating the overall stacking patterns of flood-dominated fluvio-turbidite systems with those predicted by sequence-stratigraphic models within 3rd-order cycles of relative sealevel variations is well beyond the scope of this paper. However, we will briefly and tentatively discuss some of the aspects of the problem because of its fundamental importance for a better understanding of the clastic fill of many basins associated with tectonically active settings.

In foreland basins of thrust-fold belts, the flexural subsidence of the external zones and the tectonic uplift of the inner ones can satisfactorily explain accommodation and sediment availability for the development of the thick accumulations of flood-dominated depositional systems that occur in such basins, particularly in their "molasse" stage (*sensu* Ricci Lucchi, 1986), *i.e.* when the internal zones underwent sufficient uplift to become a substantial component of the source area of the system. Within settings of this type, relatively low-frequency tectonic and geomorphic cycles of uplift and denudation, produced by major phases of episodic uplift, may explain the overall stages of growth and related stacking patterns of flood-dominated depositional systems as shown in figures 24 and 26. Very similar stacking patterns have been amply documented also for endorheic lacustrine fluvio-deltaic successions (*e.g.* Legarreta *et al.*, 1993) and are typically developed in the Cretaceous San Jorge Basin (Tab. 1), thus suggesting that these stacking patterns may also develop in the absence of eustasy-driven sealevel variations. The first-order controlling factor of such depositional setting may thus be represented by tectonism.

As noted in earlier sections, high-frequency forestepping-backstepping episodes of sand deposition within flood-dominated fluvio-deltaic systems appear to be primarily controlled by climatic changes and sediment availability through time. How and to what extent these low- and high-frequency stacking patterns fit sequence-strati-



1
2
3
CASTISENT GROUP
DATUM
CASTIGALEU GROUP
FIGOLS GROUP
20 m
5 km
Interval recording tectonic quiescence
Interval recording :relatively high-frequency uplift/denudation cycles
Conglomerates. Alluvial fan and river deposits
Sandstones. River deposits (Section 1); river and estuarine deposits (Section 2); estuarine and delta-front deposits (Section 3)
Mudstone. Flood-plain deposits
Mudstones. Marsh and lagoonal deposits
Mudstones. Prodelta deposits
Carbonates. Shelfal deposits
Allogroup boundary

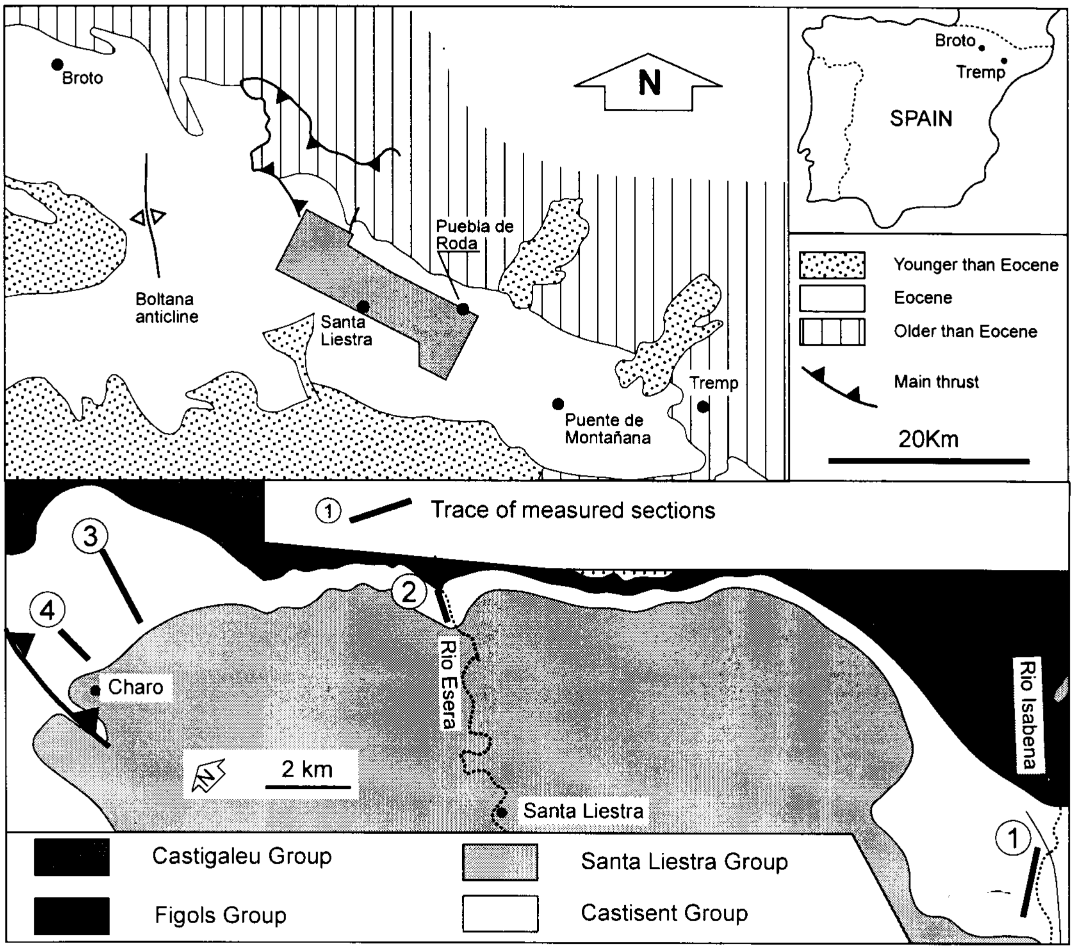


Fig. 27 - Location map (above) and stratigraphic cross section (on the opposite page) of the lower Eocene Castisent Group (south-central Pyrenees) between the Isabena Valley and the Charo region. The cross section shows the relationships between the different elements of a flood-dominated river-delta system. The correlation pattern depicts the basinward transition from river and flood plain deposits, in the east (section 1), to marginal-marine sediments mainly characterized by mouth-bar deposits (section 2), and eventually to shelf and slope sediments in the west (sections 3 and 4). Data from unpublished work by the authors and L. Baruffini, P. Dattilo, L. Marianini, S. Stocchi and E. Tebaldi.

graphic models based on eustasy-driven cyclic variations in accommodation are open to discussion and wait for careful and detailed studies of flood-dominated basin fills through highly integrated sedimentological and structural analyses.

A further step toward the same direction is probably a very careful and critical revision of the facies types that form the basis of sequence-stratigraphic models and of their subsequent application to many basin-fills worldwide. There is little doubt about the fact that eustasy-driven sealevel variations do exist and will primarily control the position of the shoreline in relatively low-gradient depositional settings, thus decreasing or increasing the width of coastal and low-gradient alluvial plains. As a consequence, this will control the amount of flood-generated water and sediment that will be sequestered in these regions, and will thus affect the sediment concentration of river outflows when entering sea waters. However, the problem remains of how these variations interact with Davisian-type and climatic cycles in tectonically active basins. If the conclusions drawn in this section are at least partly correct, a better understanding of the relationships between tectonism, climate and eustasy may lead to establish future sequence-stratigraphic patterns that should be considerably more complex but of greater general validity than the ones currently in use.

One of the most important problems to be solved for a better understanding of the evolution of tectonically active basins certainly resides in the episodic character of the orogenic uplift and in our ability to recognize its incremental development through the stratigraphic record.

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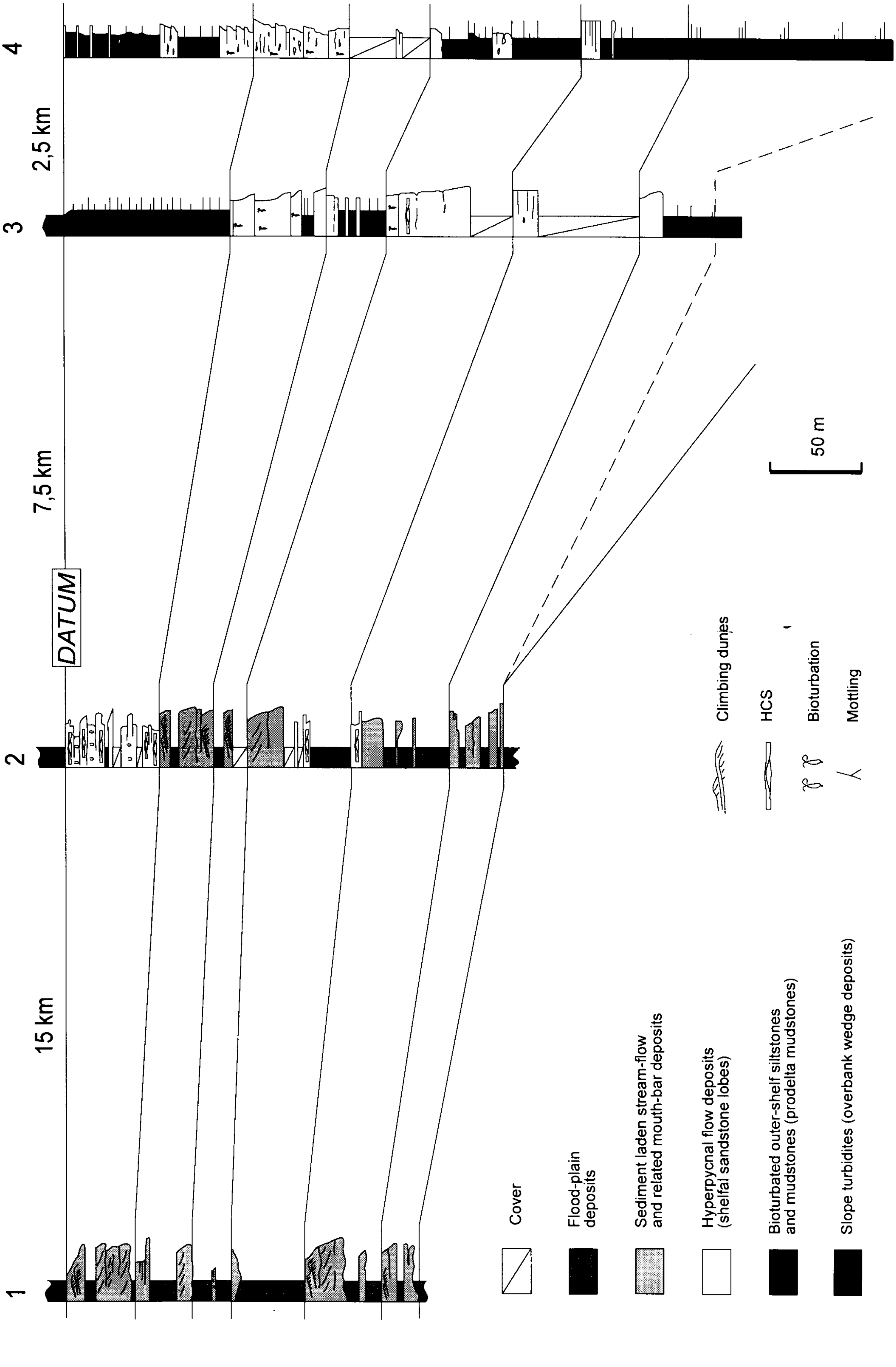

1
2
3
4
15 km
7,5 km
2,5 km
DATUM
50 m
Climbing dunes
HCS
Bioturbation
Mottling
Cover
Flood-plain deposits
Sediment laden stream-flow and related mouth-bar deposits
Hyperpycnal flow deposits (shelfal sandstone lobes)
Bioturbated outer-shelf siltstones and mudstones (prodelta mudstones)
Slope turbidites (overbank wedge deposits)

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EXPLANATION OF PLATES I - XIII

Plate I

Fig. a - Low-angle cross strata (hummocky-type cross stratification) in medium- to coarse-grained sandstone interpreted as the deposit of a hyperpycnal flow in a flood-dominated, marine fan-delta system. Upper part of the Molare Formation, Tertiary Piedmont Basin, northern Italy.

Fig. b - HCS formed by a relatively low-density turbidity current in sandstone lobe strata of a flood-dominated lacustrine fan delta system. Encircled knife for scale. Huitrín Formation, Troncoso Member, Neuquén Basin, Argentina.

Fig. c - Example of large-scale HCS in a very thick, graded sandstone bed deposited by a flood-generated turbidity current. Sandstone lobes of a flood-dominated marine or lacustrine fan-delta system. The wave length of the HCS is probably in excess of 100 m. Encircled person for scale. Agrio Formation, Avilé Member, Neuquén Basin, Argentina.

Fig. d - A typical graded bed of a shelfal sandstone lobe in a flood-dominated marine fan-delta system. In its basal division, the bed contains abundant fossil debris (mostly valves of the pelecypod Trigonia; see detail in plate III, Fig. a) ripped up from the marine substratum; the upper part of the bed is characterized by HCS indicating traction plus fallout processes associated with combined-flow conditions. Bardas Blancas Formation, Neuquén Basin, Argentina.

PLATE II

Fig. a - Stacking of amalgamated, graded flood units characterized by erosive basal contacts indicated by arrows. The lower units represent sigmoidal bars each of which includes a basal division of sand-supported conglomerate with scattered cobbles and boulders that passes upward into high- to low-angle cross strata made up of pebbly sandstone. Each of these bars records the transformation of a hyperconcentrated flow into a more dilute and turbulent density current. Current is from right to left. Encircled field book for scale. Molare Formation, Tertiary Piedmont Basin, northern Italy.

Fig. b - Same outcrop as in plate II, Fig. a. Graded flood unit deposited through the freezing of a hyperconcentrated flow. The unit contains floating out-size clasts (cobbles and boulders) that were supported within the flow by the residual flow strength. These out-size clasts are typical of many hyperconcentrated-flow deposits (compare with turbidite F2 deposits of Mutti, 1992a). Molare Formation, Tertiary Piedmont Basin, northern Italy.

Fig. c - Frontal accretion of two top-missing, coarse-grained sigmoidal bars separated by a finer-grained facies (indicated by arrow). These bars were deposited in an ephemeral lacustrine environment and each of them records the transformation of a hyperconcentrated flow into a turbulent and progressively more dilute density current . Each bar is characterized by facies 1 and 2 (see text). The absence of Facies 3, 4 and 5 indicates that finer grained sediment was entirely kept in suspension by the turbulent, density current produced after flow transformation. Current direction from right to left. Hammer for scale. Compare with figure 10c. Tremp-Ager Group, south-central Pyrenees.

Fig. d - The photograph shows a sigmoidal bar in a cut perpendicular to current direction. Note the sharp and erosive basal contact and the apparent lack of internal stratification within the unit. Same outcrop as in c.

PLATE III

Fig. a - Detail of the basal division of a graded bed from a shelfal sandstone lobe in a marine, flood-dominated fan-delta system. Note the abundance of fossil debris (mostly valves of the pelecypod Trigonia) indicating erosion of the marine substratum by a turbidity current during its bulking phase. See text for explanation. Bardas Blancas Formation, Neuquén Basin, Argentina.

Fig. b - Detail of the basal division of graded bed from a shelfal sandstone lobe deposited in a marine, flood-dominated fan-delta system. Note the abundance of fossil debris (mostly larger foraminifera) at the base of the division and in overlying traction carpets, and the local occurrence of rip-up mudstone clasts (arrow). Santa Liestra Group, south-central Pyrenees.

Fig. c - Hyperconcentrated-flow deposit showing large-scale rip-up mudstone clasts indicated by the dashed white line. Deep scours and mudstone clasts are typical of the deposits of these highly erosive flows. Encircled field book for scale. Tremp-Ager Group, south-central Pyrenees.

Fig. d - Sand-supported, crudely graded conglomerate deposited by a hyperconcentrated flow. Note large mudstone clasts (indicated by arrow) at the base of the unit and a thin and laterally discontinuous sandstone division at the top. Santa Liestra Group, south-central Pyrenees.

PLATE IV

Fig. a - Pebble alignments at the base of crudely graded sandstone beds which are either internally unstratified or current laminated. These flood units are thought to represent the deposit of hyperpycnal flows or gravelly, high-density turbidity currents that formed through the transformation of a hyperconcentrated flow. See text for explanation. These sediments are interpreted as shelfal sandstone lobes of a flood-dominated marine fan-delta system (see cross section of Fig. 23). Molare Formation,Tertiary Piedmont Basin, northern Italy.

Fig. b - Examples of dune-shaped, convex-upward lenses of clast-supported conglomerates at the base of two beds deposited by long-lived and high-discharge hyperpycnal flows in a shelfal lobe succession. Current from right to left. Encircled pen for scale. Tursi Group, Sant'Arcangelo basin, southern Apennines.

Fig. c - Graded sandstone bed with abundant fossil debris and mudstone clasts in its basal division. This division is erosively overlain by HCS. The basal part of the bed is interpreted as the deposit of a sandy, high-density turbidity current. The overlying division containing HCS was deposited by a more dilute portion of the flow characterized by the presence of a strong oscillatory component (see text for explanation). Shelfal sandstone lobes of the Santa Liestra Group, south-central Pyrenees.

Fig. d - Graded sandstone bed with a basal, laterally discontinuous pebbly sandstone division overlain by finer-grained divisions containing HCS. The bed is interpreted as the deposit of a gravelly, high-density turbidity current, and is part of a succession of sandstone lobes in a flood-dominated lacustrine fan-delta system. Ebro basin, south-central Pyrenees.

PLATE V

Fig. a - Graded and sharp-based sandstone beds with HCS deposited by proximal and distal low-density turbidity currents in a sandstone lobe succession of a flood-dominated fan-delta system. Agrio Formation, Neuquén Basin, Argentina.

Fig. b - Graded and sharp-based sandstone bed with HCS deposited by a low-density turbidity current in shelfal sandstone lobes of a flood-dominated fan-delta system. Encircled knife for scale. Santa Liestra Group, south-central Pyrenees.

Fig. c - Unstratified to crudely cross-stratified, poorly sorted and amalgamated units made up of pebbly sandstones and conglomerates with scattered mudstone clasts (indicated by arrows). These deposits, which occur at the base of a flood-dominated fluvial succession, are thought to represent the residual deposit of bypassing sediment-laden stream flows. Castisent Group, south-central Pyrenees.

Fig. d - Poorly sorted and crudely cross-stratified pebbly sandstones at the base of a flood unit deposited by a waning sediment-laden stream flow. Current is from right to left. Encircled knife for scale. Castisent Group, south-central Pyrenees.

PLATE VI

Fig. a - Large-scale cross-stratified sandstones at the base of a flood-unit within a succession of flood-dominated river deposits. This type of stratification forms in the early phases of deposition of sediment-laden stream flows when rates of sediment fallout are still relatively low and tractional processes predominate (see text for explanation). Current is from right to left. Castisent Group, south-central Pyrenees.

Fig. b - Typical bedding pattern associated with deposition of climbing dunes in a river deposit. These features form due to high rates of sediment fallout from a waning sediment-laden stream flow. Note how the stoss sides of individual bed forms are draped with sediment (see text for explanation). Current is from right to left. Encircled pencil for scale. Tordillo Formation, Neuquén Basin, Argentina.

Fig. c - Medium-scale cross-stratified sandstones associated with the migration of climbing dunes within the upper part of a flood unit deposited by a sediment-laden stream flow in a river system. Note alternating sets of cross laminae with thinner and more laterally continuous sinusoidal laminae. Current is from left to right. Encircled field book for scale. Castisent Group, south-central Pyrenees.

Fig. d - Large-scale climbing dunes deposited by sediment-laden stream flows. Sets of large-scale cross strata are separated by either erosional surfaces or thinner sets of draping, sinusoidal laminae. These sediments are interpreted as river deposits within a large estuarine complex. Current is from right to left. Aren Sandstone, south-central Pyrenees.

PLATE VII

Fig. a - Bedding pattern associated with climbing dunes of progressively smaller size due to decreasing flow velocity within a flood unit deposited by a sediment-laden stream flow. Note also the increasing proportion of sets of sinusoidal laminae toward the top of the unit. These sediments occur in an estuarine setting characterized by moderate tidal diffusion. Current is from right to left. Encircled knife for scale. Figols Group, south-central Pyrenees.

Fig. b - Graded flood unit deposited by a sediment-laden stream flow. The unit is characterized by a basal unstratified pebbly-sandstone facies overlain by progressively thinner sets of cross strata deposited as climbing dunes during waning flow condition. Current is from left to right. Encircled knife for scale. Lacustrine Pliocene sediments, Island of Rhodes, Greece.

Fig. c - Flood units deposited by sediment-laden stream flows in a succession of river strata. White bold lines indicate different flood units; dotted lines indicate internal sinusoidal lamination. Castisent Group, south-central Pyrenees.

PLATE VIII

Fig. a - Example of flood units deposited by sediment-laden stream flows in a lateral flood basin. Numbers indicate successive flood events. Note the deeply erosive character of individual flood units. Each of these units consists of a basal, coarse-grained division made up of crudely stratified pebbly sandstones whose general transport direction is from right to left (downflood direction), and of upper and finer-grained divisions showing transport direction in the opposite direction (upflood direction). These relationships indicate that during its first phase of deposition sediment-laden stream flows were moving upslope across an inclined lateral flood basin or within a backflooded valley. Only during late-stage conditions, the upper and more dilute part of each flood was able to move back toward the main flood basin. Castisent Group, south-central Pyrenees.

Fig. b - Detail of climbing ripples and sinusoidal laminae moving upflood. Upper division of flood unit 3.

Fig. c - Detail of the basal division of flood unit 2 showing abundant mudstone clasts ripped-up from an underlying slack-water mudstone unit (indicated by arrow).

PLATE IX

Fig. a - Sigmoidal sets of large- to medium-scale cross strata produced by the sudden deceleration of a sediment-laden stream flow entering shallow marine waters at river mouth. Current is from right to left. Note that individual sigmoidal units become smaller and tend to flatten in a downcurrent direction. Encircled knife for scale. Figols Group, south-central Pyrenees.

Fig. b - Detail of exposure shown in Fig. a depicting the typical geometry of sigmoidal sets of cross strata produced by decelerating sediment-laden stream flows at river mouths. Encircled knife for scale. Figols Group, south-central Pyrenees.

Fig. c - Downflow accreting sigmoidal sets of cross strata formed by a decelerating and probably pulsating sediment-laden stream flow in a succession of river deposits. Current from left to right. Castisent Group, south-central Pyrenees.

Fig. d - Downflow accreting sets of cross laminae observed within a parallel-sided and sharp-based sandstone bed. These sigmoidal sets, which are laterally separated by and partly grade downcurrent into finer-grained and thinly laminated deposits, are thought to be the deposit of a hyperpycnal flow and to have formed under fluctuating-flow conditions. Encircled knife for scale. Huitrín Formation, Troncoso Member, Neuquén Basin, Argentina.

Plate X

Fig. a - Example of mouth-bar deposits characterized by low-angle, seaward dipping cross strata. These mouth-bar sediments (indicated by arrow) are underlain by shallow-marine sandstone lobe deposits consisting of tabular, graded sandstone beds with HCS. Encircled field book for scale. Figols Group, south-central Pyrenees.

Fig. b - Close-up of a mouth-bar deposit showing broadly sigmoidally-shaped, low-angle cross strata dipping in a seaward direction (right). Each of these strata is internally current laminated (mostly small-scale cross stratification) and grade seaward into thin and laterally more continuous beds of current-rippled sandstone with occasional small-scale wave-ripples at their tops. These sediments are interpreted as the deposit of sediment-laden stream flows that are forced to decelerate in shallow sea waters. Castigaleu Group, south-central Pyrenees.

Fig. c - Typical geometry and vertical cyclic stacking pattern of flood-generated sandstone lobes formed in ephemeral lakes (see also plate XIb). Aren Sandstone, south-central Pyrenees.

Fig. d - Geometry and internal bedding pattern of a flood-generated shelfal sandstone lobe made up of parallel-sided and graded sandstone beds with HCS (see plate I, Fig. d). Bardas Blancas Formation, Neuquén Basin, Argentina.

Plate XI

Fig. a - Cyclic stacking pattern of flood-generated shelfal sandstone lobes in a marine fan-delta depositional system. Arrows indicate the main boundary surfaces of superposed, fining- and thinning-upward facies sequences. Santa Liestra Group, south-central Pyrenees.

Fig. b - Cyclic stacking pattern of flood-generated sandstone lobes in an ephemeral lake environment. Arrows indicate the boundary surfaces of some thinning- and fining-upward facies sequences. Aren Sandstone, south-central Pyrenees.

Fig. c - Typical facies sequence observed in flood-generated sandstone lobes. In this specific example, the lobe (whose boundaries are indicated by arrows) formed in an ephemeral lake environment and consists of an overall fining- and thinning-upward succession of graded sandstone beds which is capped by reddish mudstones with local evidence of subaerial exposure. The next sequence shows a similar vertical development. These facies sequences record high-frequency, forestepping-backstepping episodes of flood-dominated sand deposition (see text for more details).
Ebro Basin, eastern Pyrenees.

Fig. d - Facies sequences developed in deep-marine turbidite sandstone lobes. Note the remarkable similarity between the stacking pattern of these deep-marine deposits and that shown in Fig. c (see text for discussion). Arrows indicate the major facies sequences. Castisent Group, south-central Pyrenees.

Plate XII

Examples of flood-generated shelfal sandstone lobes showing their tabular geometry and their characteristic cyclic stacking pattern discussed in the text.

Fig. a - Succession of shelfal sandstone lobes from flood-dominated fan-delta system (Sant'Arcangelo basin, southern Apennines).

Fig. b - Succession of shelfal sandstone lobes from flood-dominated fan-delta system (Santa Liestra Group, south-central Pyrenees).

Fig.c - Succession of shelfal sandstone lobes from flood-dominated river-delta system (Figols Group, south-central Pyrenees). Arrows indicate the base of individual lobes.

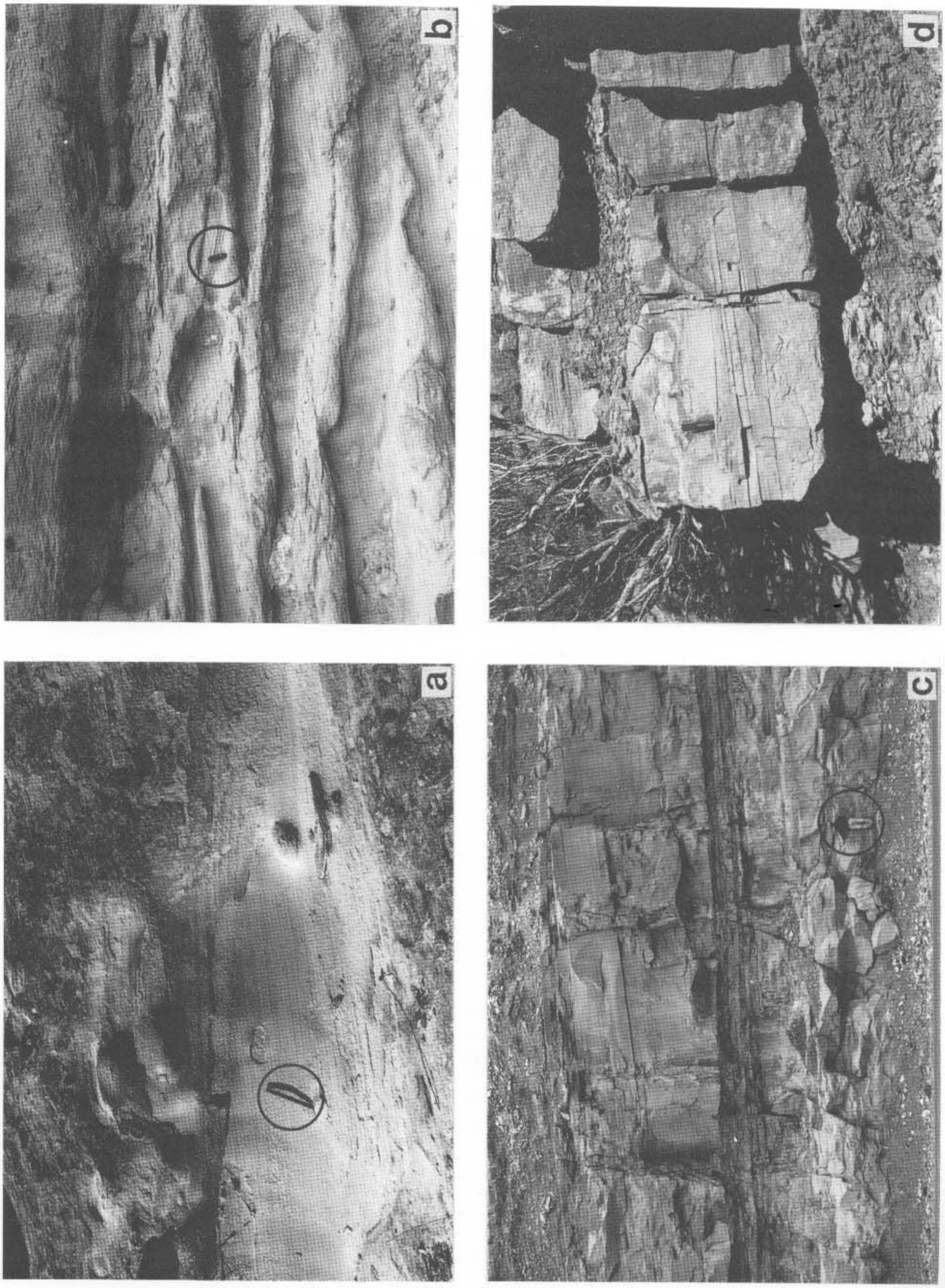
Fig. d - Succession of shelfal sandstone lobes from flood-dominated river-delta system (Figols Group, south-central Pyrenees).

Plate XIII

Fig. a - Succession of shelfal sandstone lobes associated with flood-dominated fan-delta system (Mulichinco Formation). Note the lateral continuity of individual sandstone beds and the well-developed cyclic stacking pattern.

Fig. b - Succession of flood-generated sandstone lobes in a very complex setting. These lobes, which consist of thick and amalgamated sandstone beds, probably formed in a flood-dominated river-delta system whose terminal depositional zone developed in a desiccated marine basin. These sandstone lobes overly and are overlain by offshore or basinal fossiliferous marine mudstones through very sharp contacts (see arrow). A tentative explanation of settings of this type has been offered by Mutti *et al.* (1994f), (unnamed member of the Agrio Formation, Neuquén Basin, Argentina).

Fig. c - Succession of shelfal sandstone lobes associated with flood-dominated fan-delta system showing the spectacular lateral continuity of individual sandstone beds as well as the well-developed cyclic staciking pattern (Bardas Blancas Formation, Neuquén Basin, Argentina).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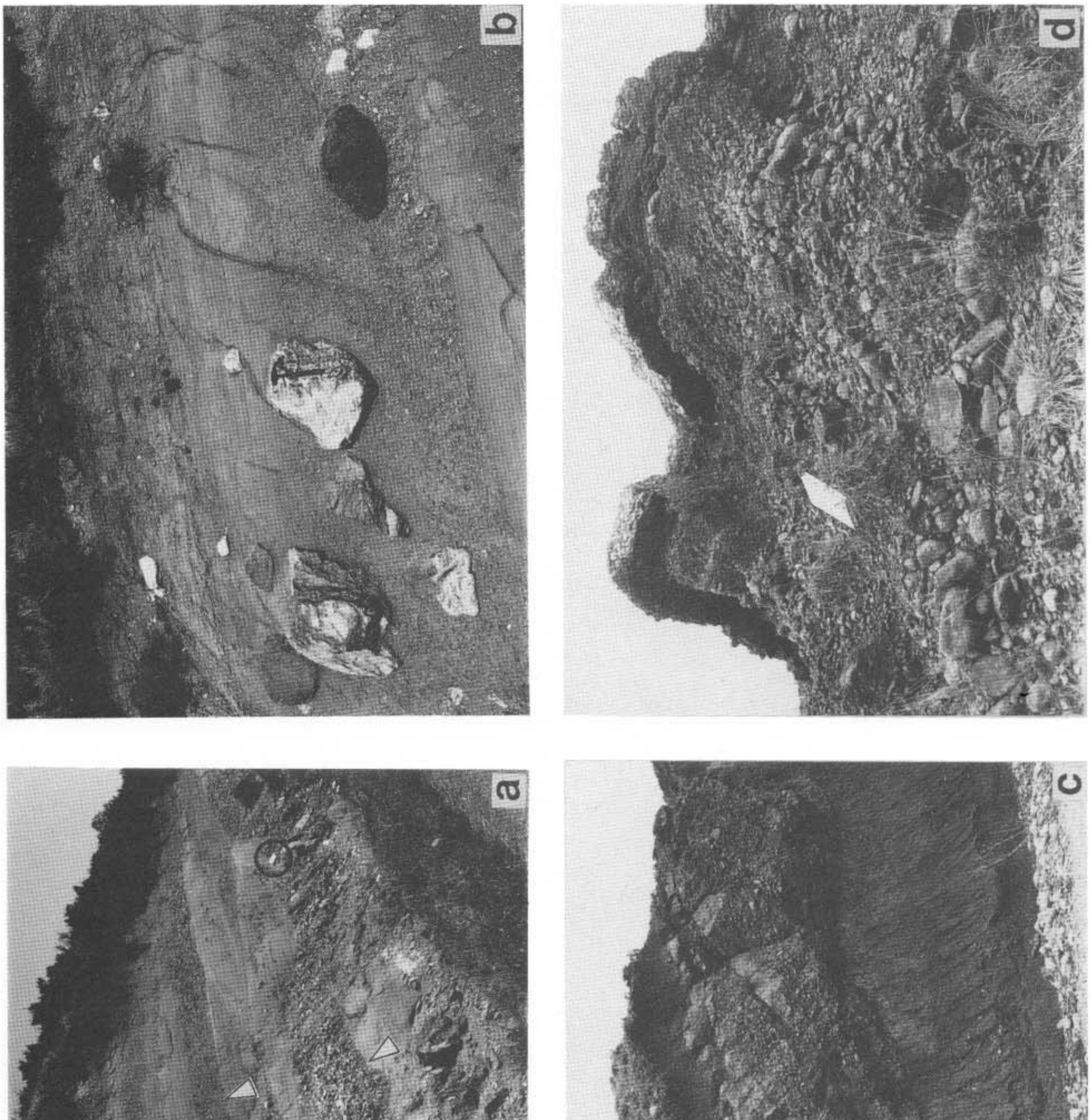
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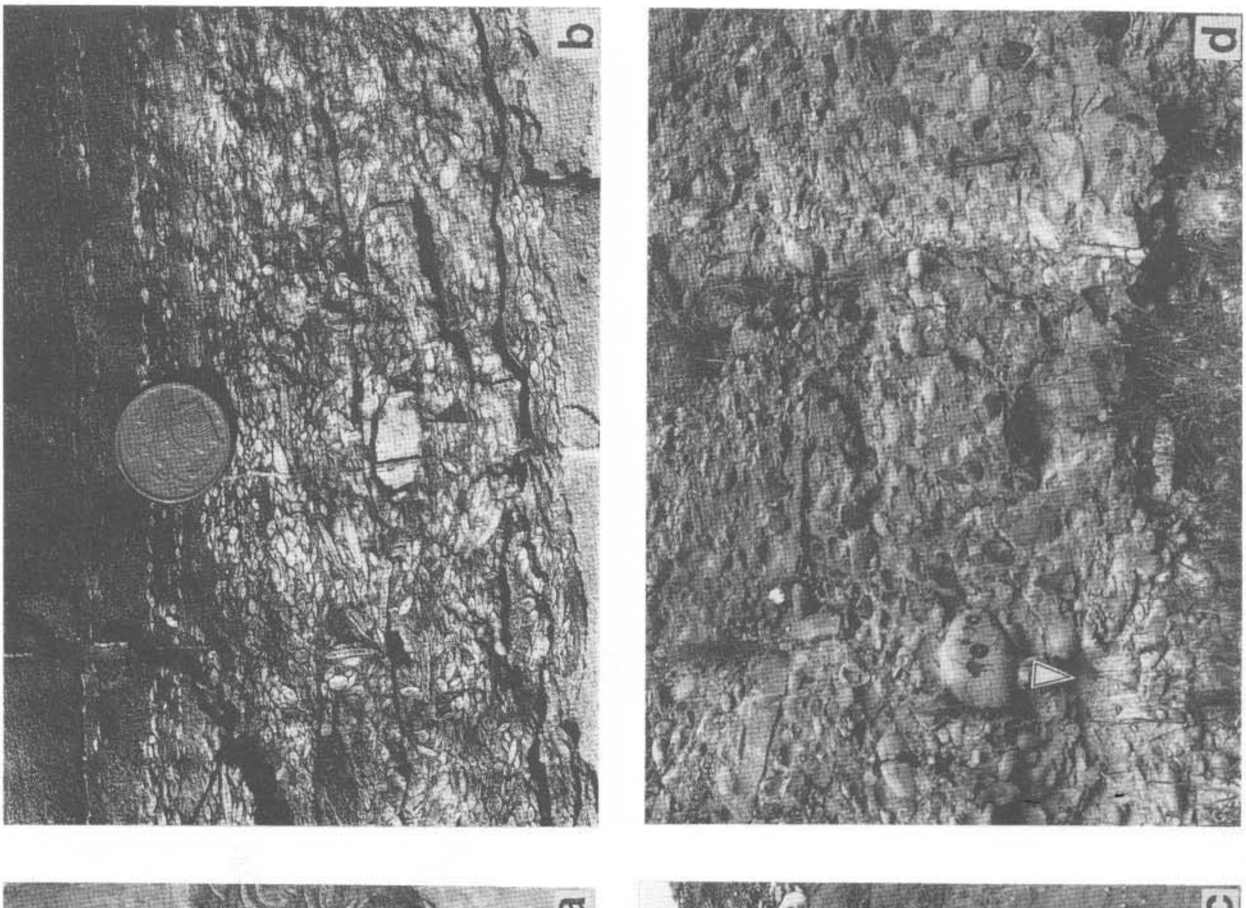
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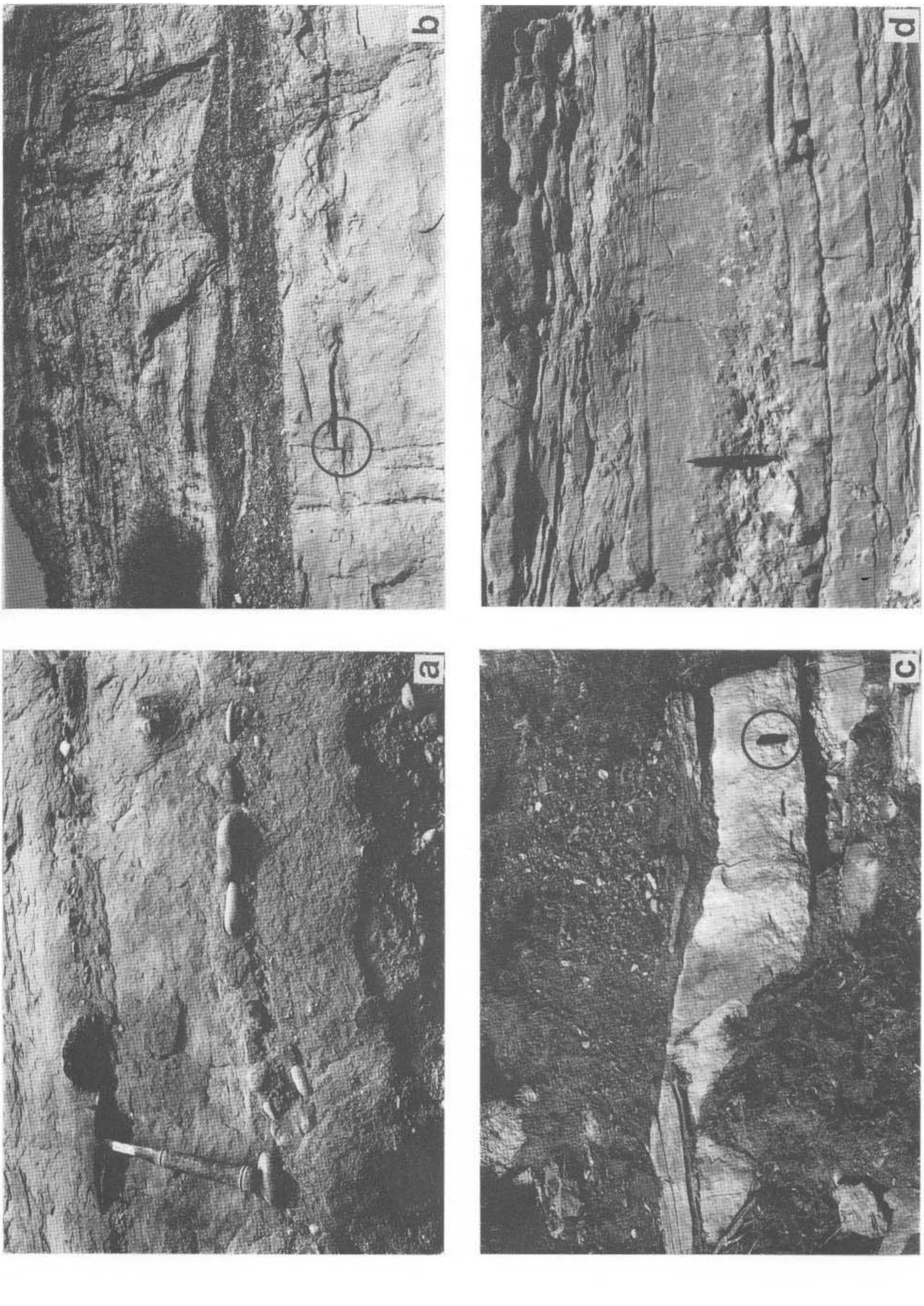
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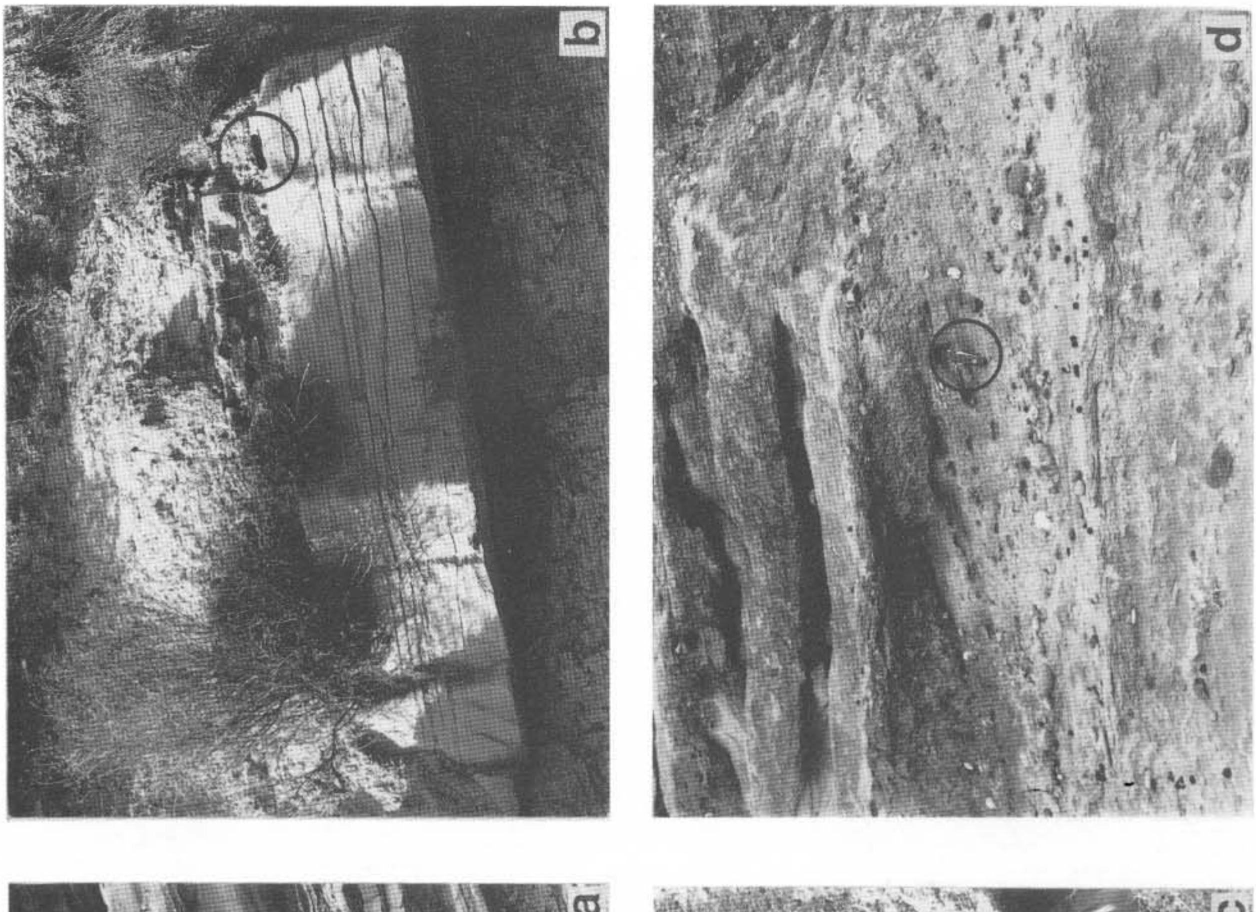

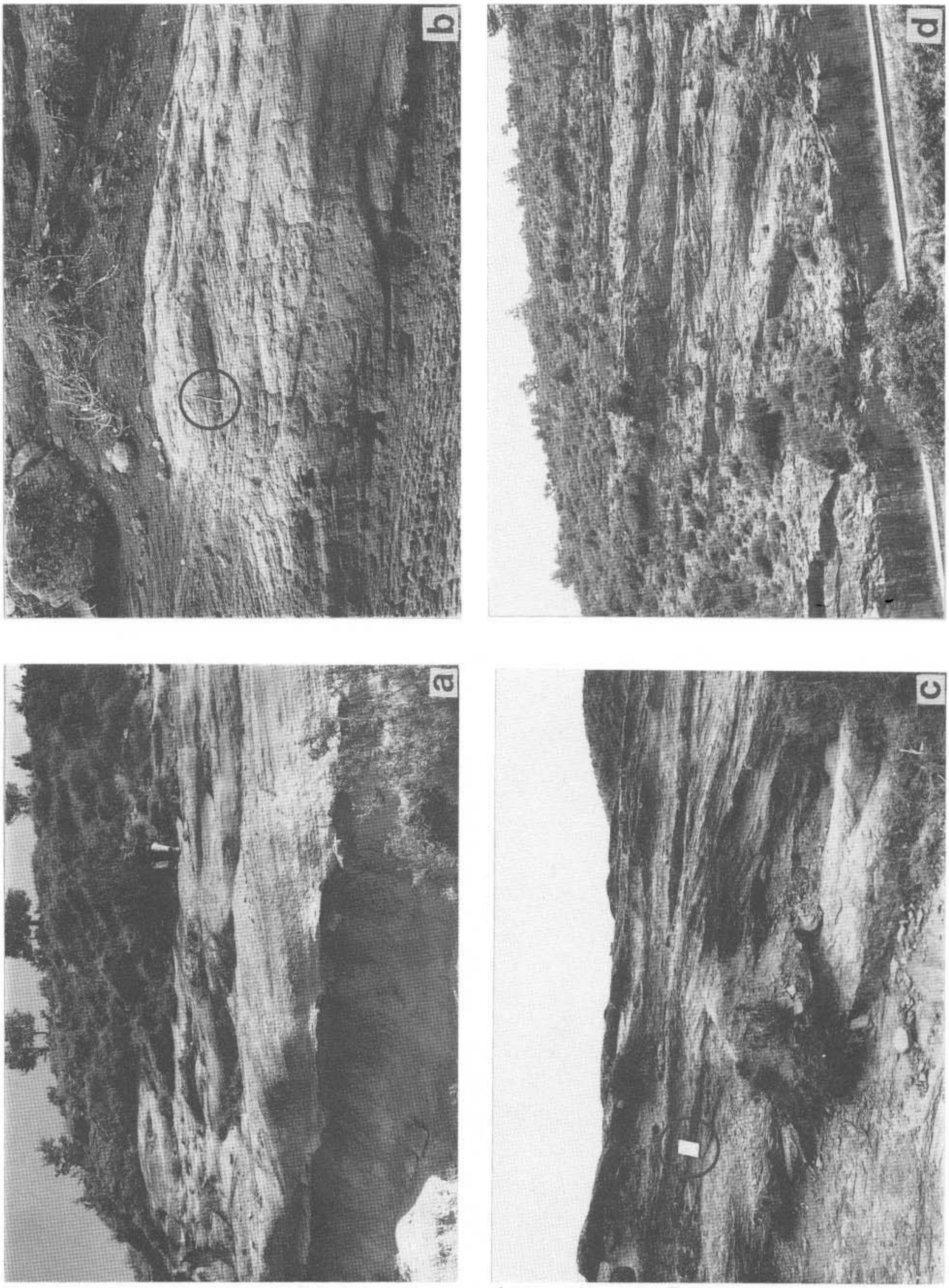
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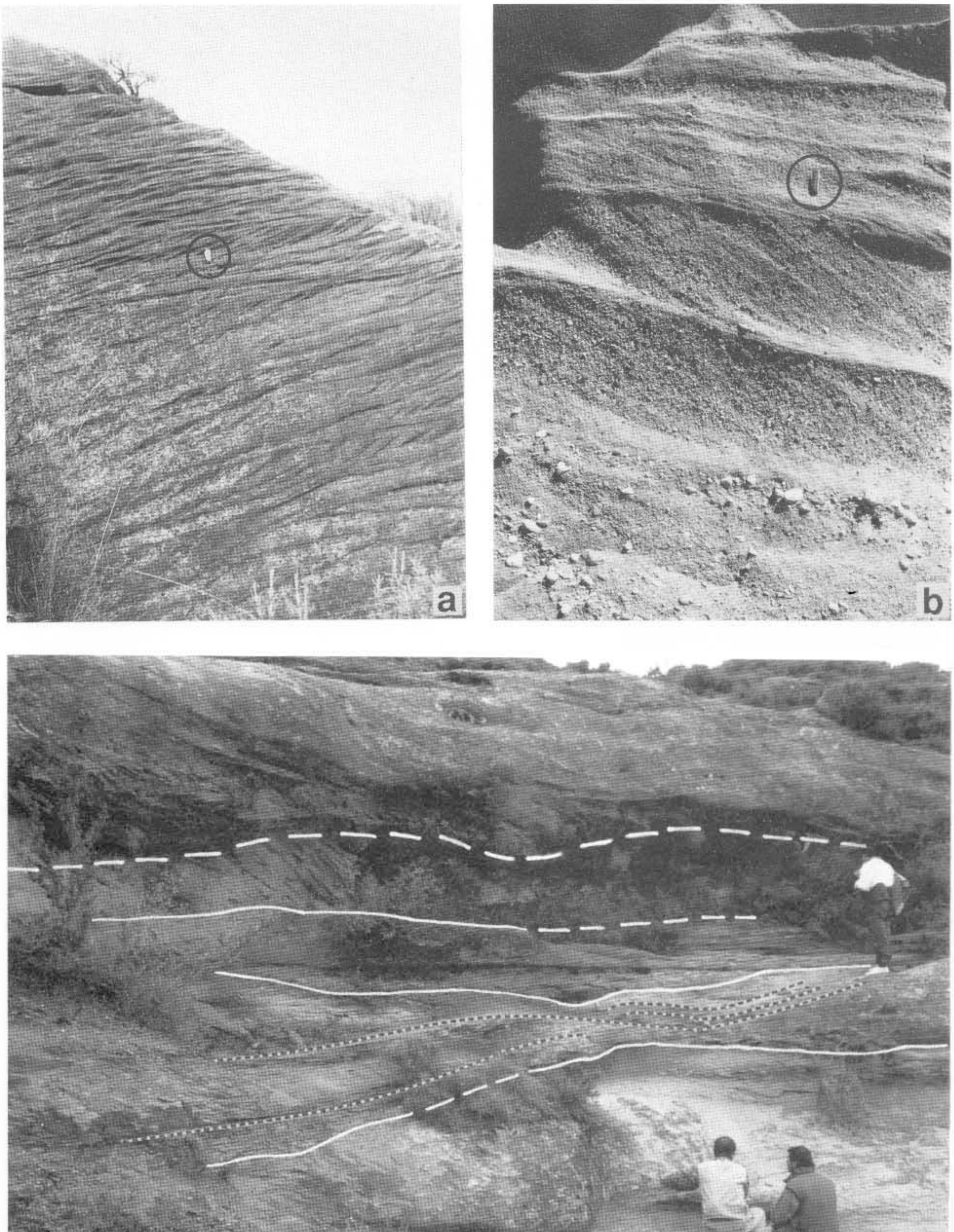
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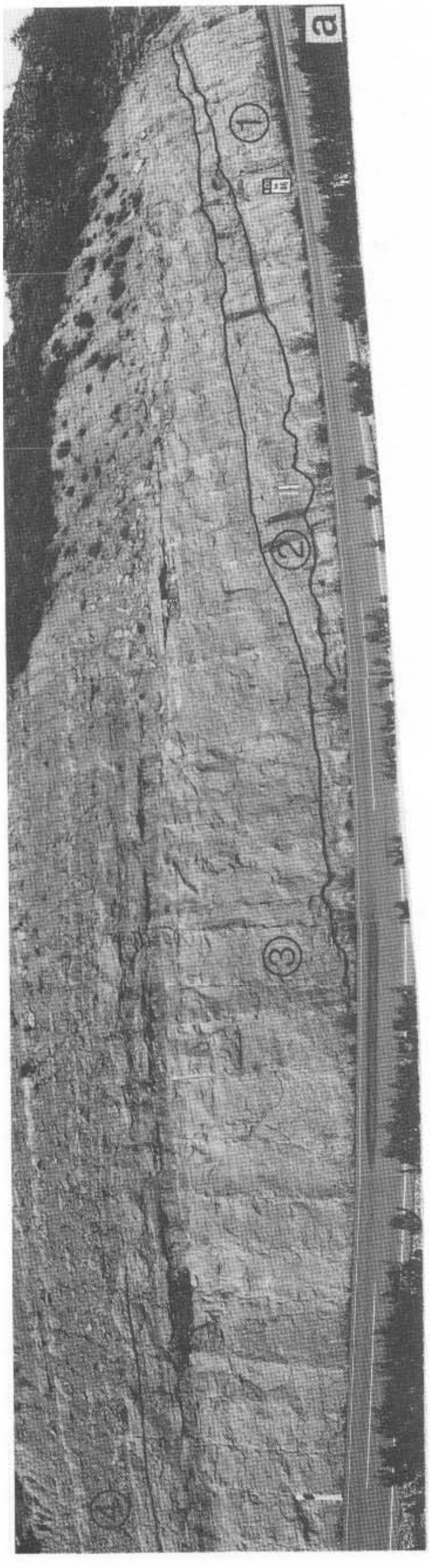
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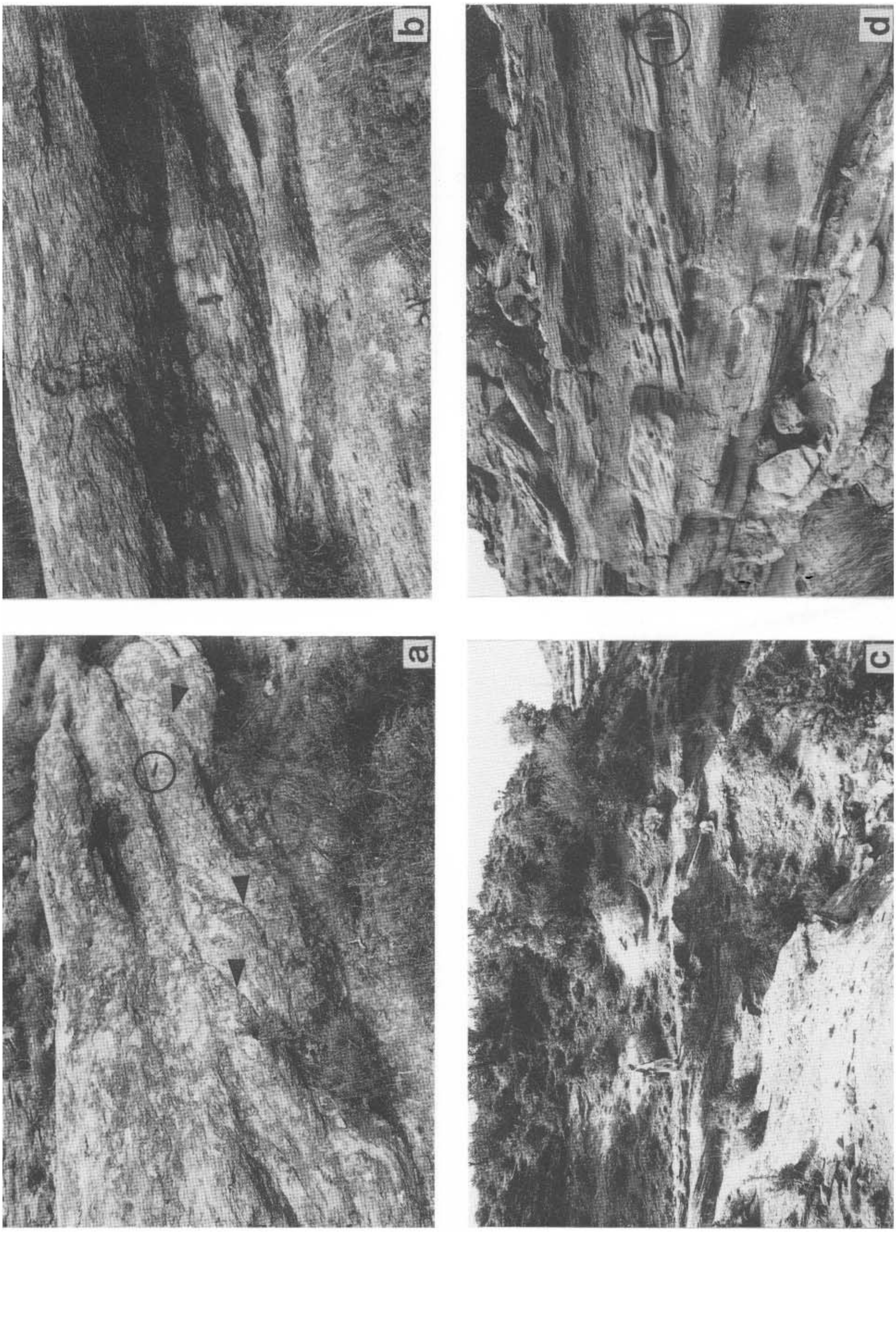
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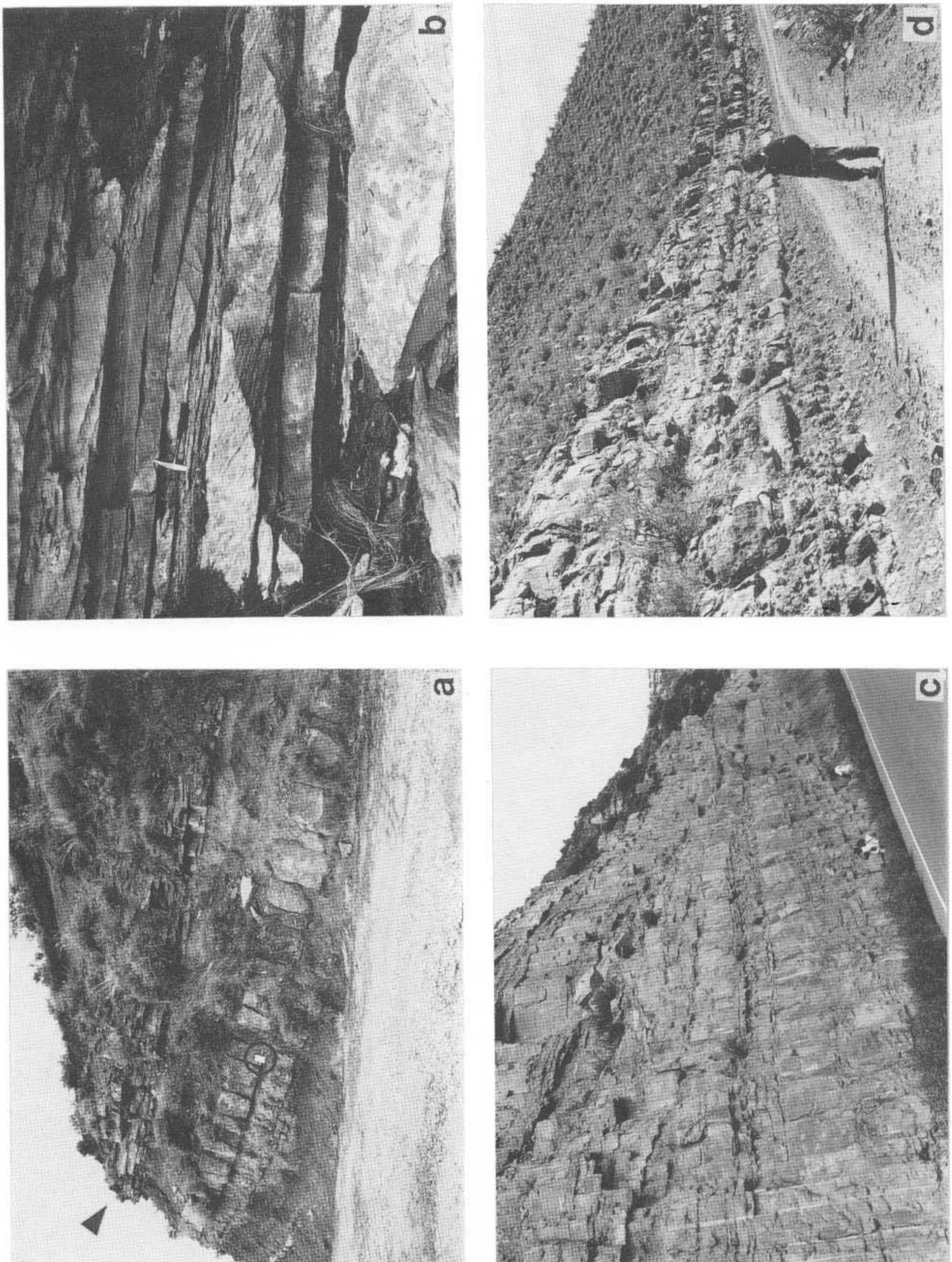
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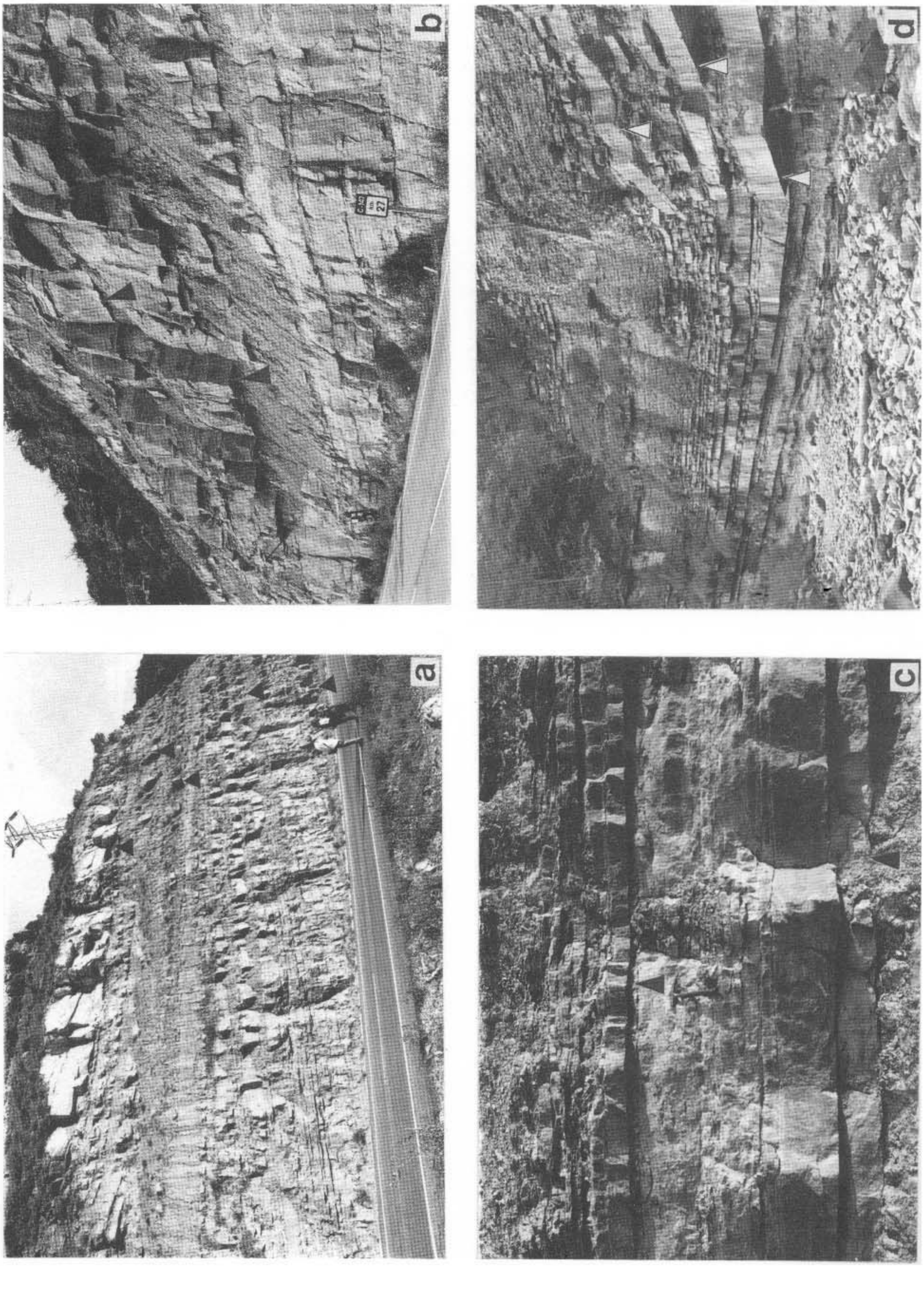
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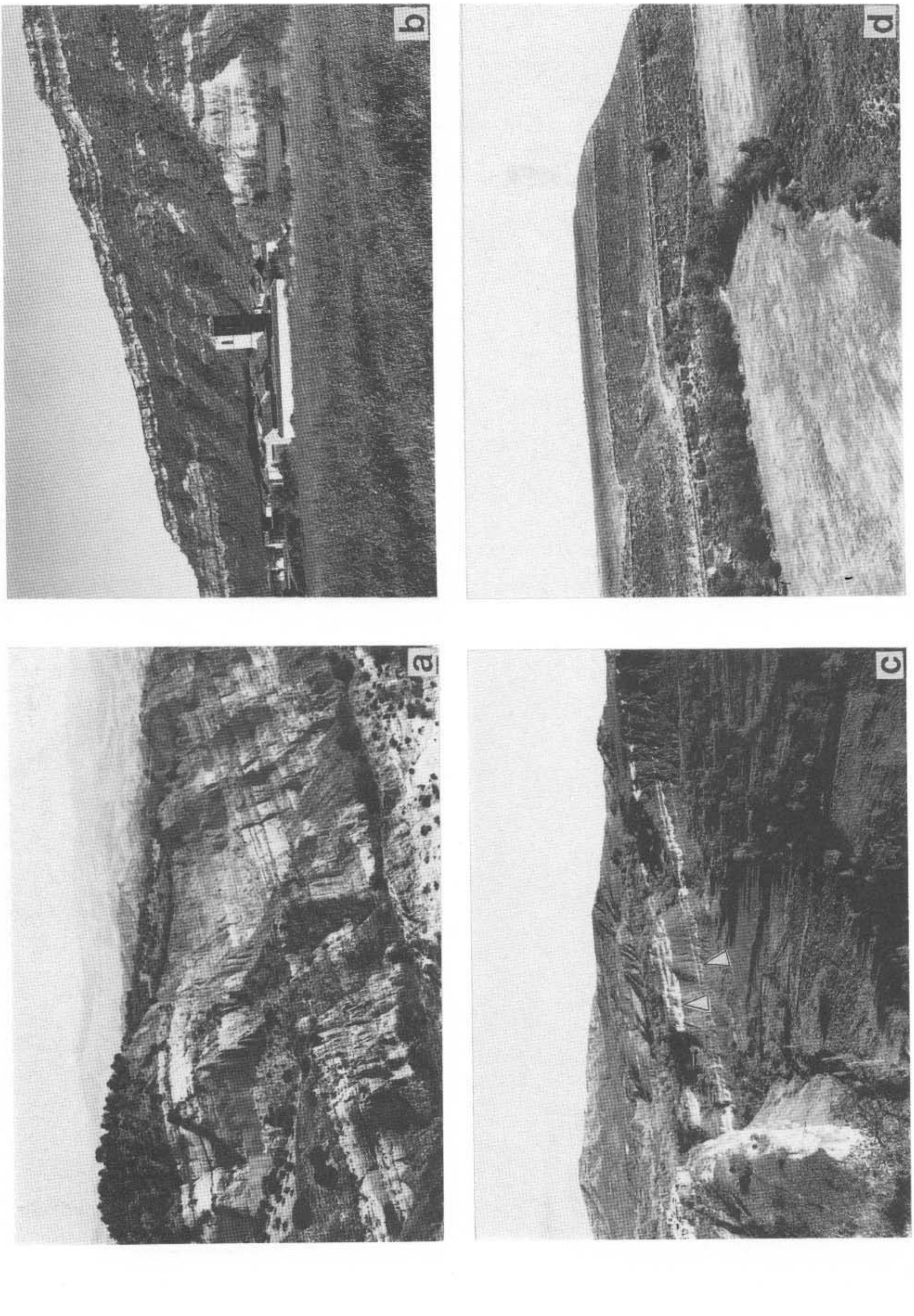
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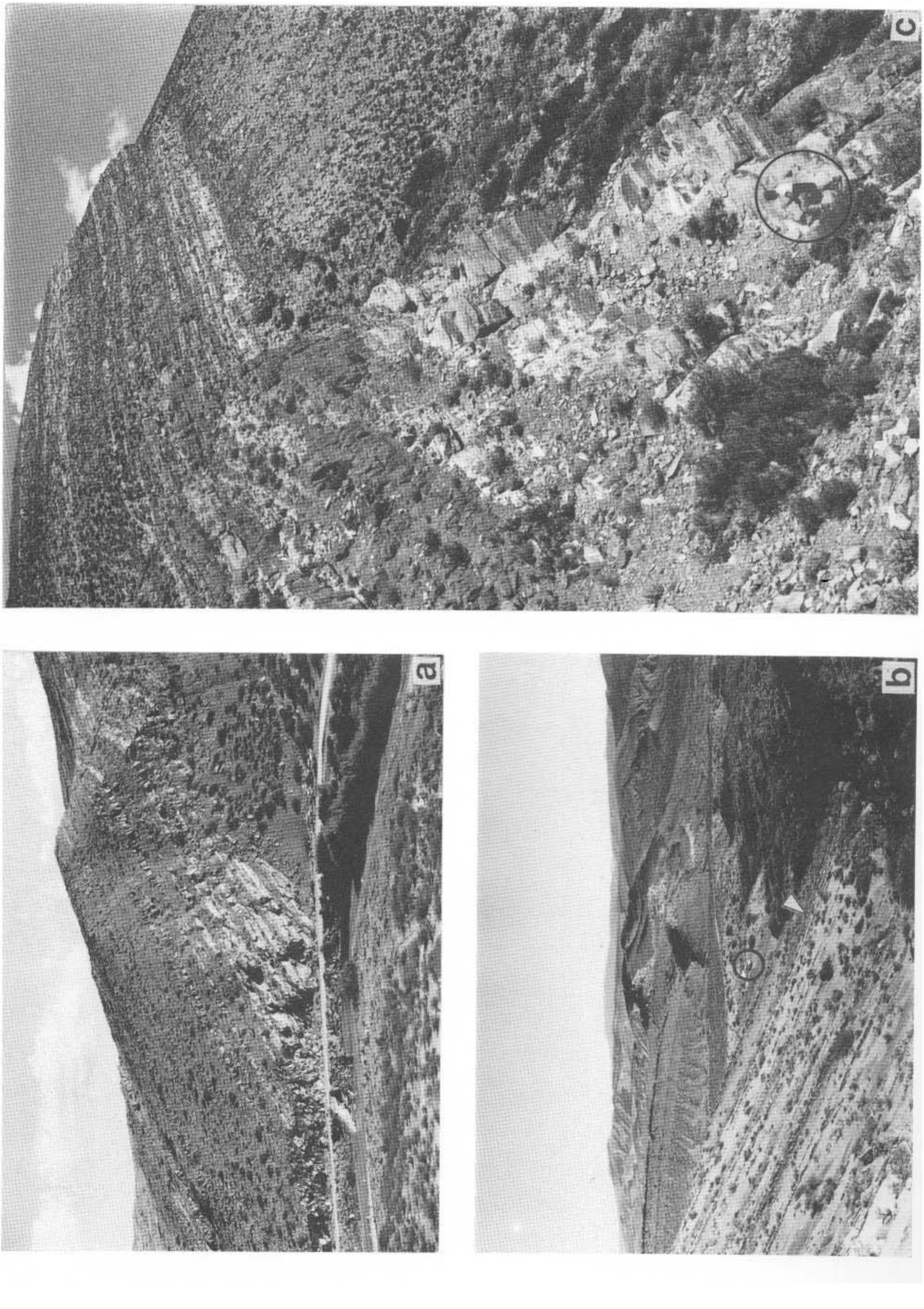
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