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Sedimentary lobes in a tidally influenced alluvial area, Capella Formation, Tremp-Graus Basin, Southern Pyrenees, Spain

Margarita Cuevas Gozalo
Comparative Sedimentology Division, Publ. 54. Comparative Sedimentology Division, Institute of Earth Sciences, Budapestlaan 4, P.O. Box 80.021, 3508 TA Utrecht, The Netherlands

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Abstract

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Among the coarse clastic deposits of the mainly alluvial Capella Formation several sediment bodies with characteristics of depositional lobes are recognized. These lobes are characterized and distinguished from other macroforms by their geometry, basal contact and lithofacies.

A classification of the lobes is proposed on the basis of the geometry and the lithofacies. The most common *geometrical type* is tabular to wedge-shaped; a second geometrical type is sigmoidal. Two main *lithofacies types* are distinguished on the basis of the bedding pattern: a horizontally and an inclined bedded type.

The lobes were deposited in the lower part of an alluvial fan system. The sedimentation of some of the lobes was influenced by tidal currents. Several models of sedimentary lobes are recognized: overbank splay lobes, terminal lobes, debris flow lobes and spillover lobes.

Introduction

The Tremp-Graus Basin is located in the Southern Pyrenees, in the provinces of Lérida and Huesca, Spain (fig. 1). During the Palaeocene this basin constituted a marginal trough, to the south of the tectonically active Pyrenean axial zone.

Recent studies of the basin (Nio et al. 1984) have shown the sedimentation pattern to be complex, probably tectonically controlled, with an alternation of transgressive and regressive sequences.

The Capella Formation was defined by Garrido Megías (1968) as a continental formation of Late Lutetian age. During the Lutetian the central part of the Tremp-Graus Basin was a large embayment (Nijman & Nio 1975), protected from the open marine part of the basin in the west by a barrier island system (Donselaar & Nio 1982). Locally the Capella Formation grades upwards into a lagoonal facies (Garrido Megías & Ríos Aragües 1972). Nijman & Nio (1975) interpreted the Capella Formation as the fluviatile upper part of a general regressive megasequence. Generally, the Capella Formation consists of alluvial sediments deposited under the influence of tidal action (Cuevas Gozalo 1984).

The Formation consists mainly of fine-grained deposits, i.e. ochre, brown or red terrigenous mudstones. Most of the interbedded sandstone bodies are laterally discontinuous. Towards the top of the Formation, however, more continuous, sheet-like sandstone bodies appear. Conglomer-

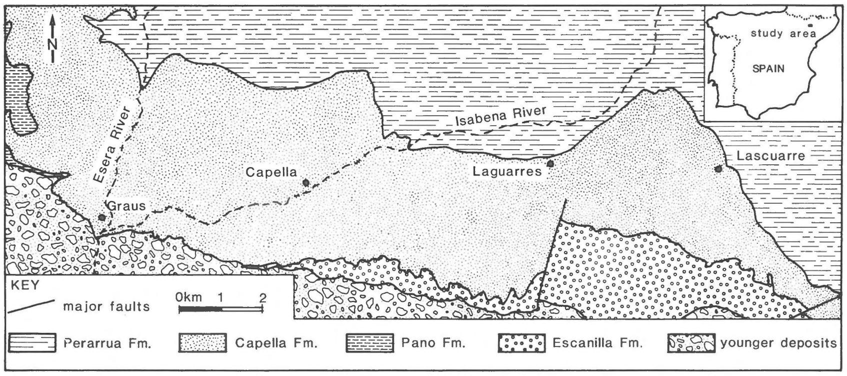

Fig. 1. Geographical and geological setting of the Capella Formation in the study area. The sedimentary formations shown in the legend form a sequence and young from left to right.

ates also occur, but they are mainly restricted to the eastern part of the basin.

The studied area, around the Isábena and the Esera rivers, province of Huesca (fig. 1), contains many good exposures which allow a three-dimensional study of the sediment bodies.

The study of the sandstone and conglomerate bodies in both transverse and longitudinal sections allows the recognition of *two main morphological types*:

- Sediment bodies with a *distinct channel geometry* (infilling forms), which result from deposition over a continuous erosive concave surface. These channels are formed and infilled by alluvial and tidal systems. Besides the simple type which has a concave-planar geometry in transverse cross section (ribbon type of Friend et al. 1979) other infilling forms are also present as vertical aggradation bodies of large lateral extent and as lateral accretion bodies.
- Sediment bodies with a *lobate geometry*, i.e. lobes (upbuilding forms).

This paper will discuss the geometry, lithofacies and genesis of the latter.

General geometry and lithofacies of the lobes

Several types of lobes can be distinguished on the basis of their geometry in longitudinal (axial) section as well as on their lithofacies.

The geometry of the lobes is characterized by a wedging out in downcurrent direction (longitudinal section). *Two types* can be distinguished: *tabular to wedge-shaped* and *sigmoidal* (fig. 2).

Lobes with a *tabular to wedge-shaped* geometry are characterized by a continuous decrease in thickness from the proximal to the distal part (fig. 2,A and 3).

Lobes with a *sigmoidal* geometry are characterized by a thickening in their proximal part and a progressive thinning towards the distal part (fig. 2,B).

In transverse section the geometry of both types of lobes is more complex. The proximal parts show a tabular to slightly plano-convex geometry; the distal part on the other hand is plano convex (figs. 4 and 5).

Besides the two lobe geometries, *two major lithofacies types* can be differentiated on the basis

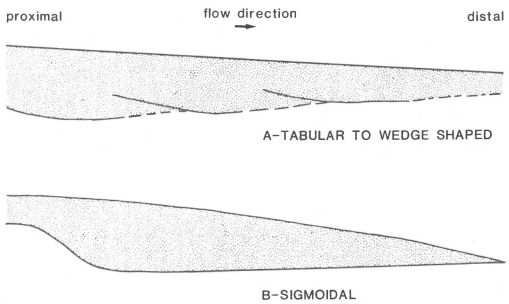

Fig. 2. External geometries of the lobes in axial section. Two main types are differentiated: (A) tabular to wedge-shaped and (B) sigmoidal.

Fig. 3. Wedge-shaped lobe in axial section; scale length is 5 m.

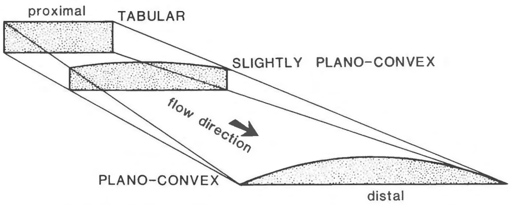

Fig. 4. External geometries of the lobes in transverse section. A gradual change can be observed from a tabular geometry in the proximal part of the lobe to a plano-convex geometry in the distal part.

Fig. 5. Plano-convex geometry of a lobe in transverse section of the distal part. Scale length is 1 m.

of the internal bedding (figs. 6 and 7 and table 1):

Lithofacies type A is characterized by horizontal bedding, formed by vertical stacking of subhorizontal, tabular to wedge-shaped beds, whereas lithofacies type B shows inclined bedding, formed by lateral superposition of beds. The beds are inclined with respect to the upper and lower surfaces of the lobe. The lower boundaries of the beds occasionally have an erosive character: the erosive surfaces are generally well developed in the lower part of the lobe. Generally, this erosive lower boundary passes distally into a gradational boundary with a mudstone substratum (figs. 8 and 9).

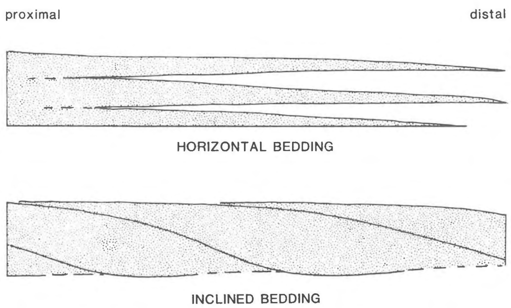

Fig. 6. The two main lithofacies types of the lobes, based on the bedding pattern: Lithofacies A or horizontal bedding, Lithofacies B or inclined bedding.

Lithofacies type B is the most common and shows a very variable bedding pattern in transverse section, depending on the type of lobe and on the position within the lobe. The proximal parts are characterized by a 'trough' bedding pattern, while a 'concentric' bedding pattern occurs in distal parts (figs. 10 and 11).

The tabular to wedge-shaped lobes are associated with either lithofacies type A or lithofacies type B. The sigmoidal lobes display only lithofacies type B.

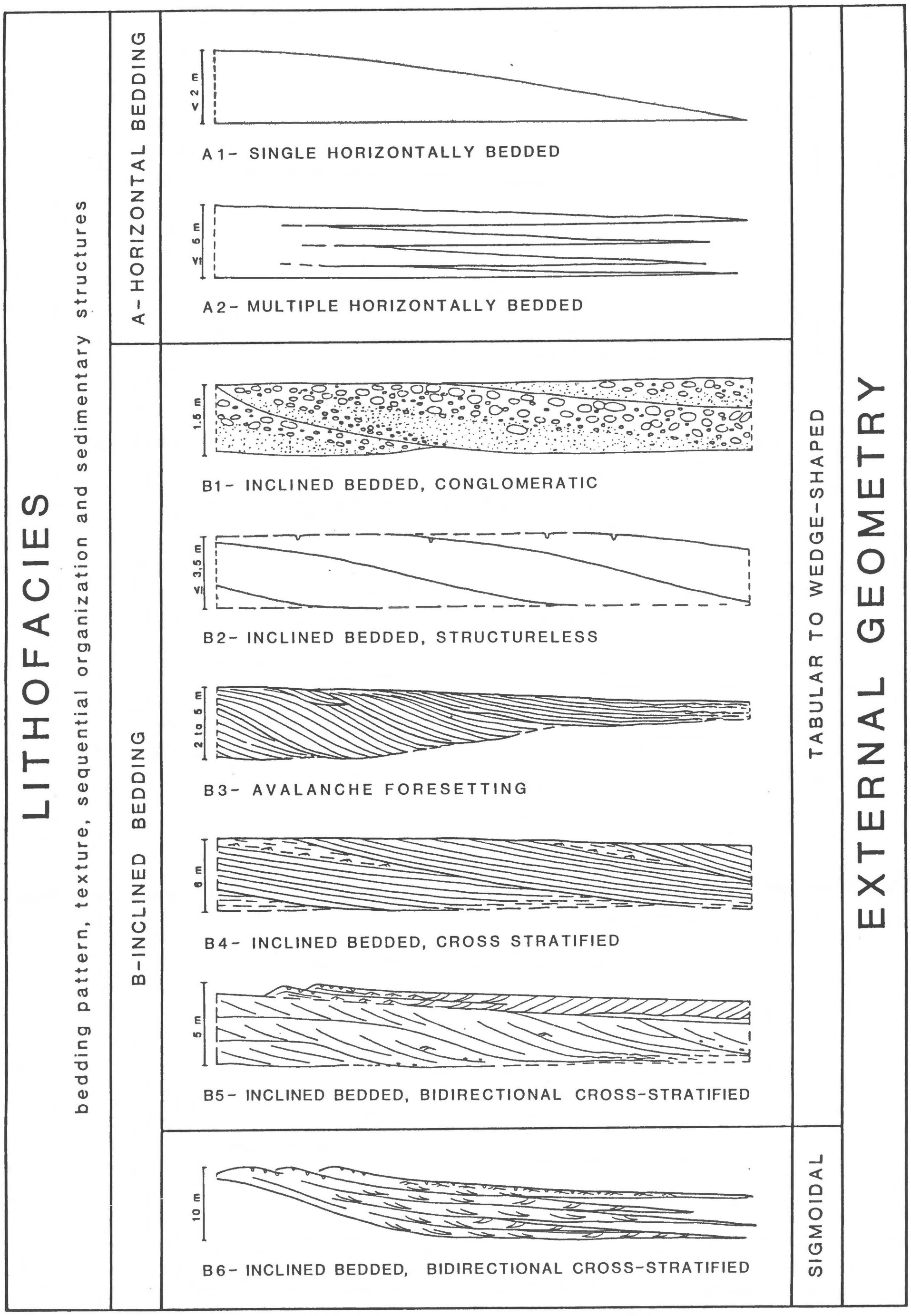

Fig. 7. Classification of the Capella Formation lobes. The characteristics used for the classification are the external geometry in axial section and the lithofacies. The horizontal scale is slightly reduced relative to the vertical scale.

Lithofacies of the tabular to wedge-shaped lobes

The tabular to wedge-shaped lobes display either the lithofacies type A (horizontal bedding) or the lithofacies type B (inclined bedding) described above. A subdivision of these lithofacies types is made on the basis of texture and sedimentary structures (fig. 7 and table 1). Unless an other

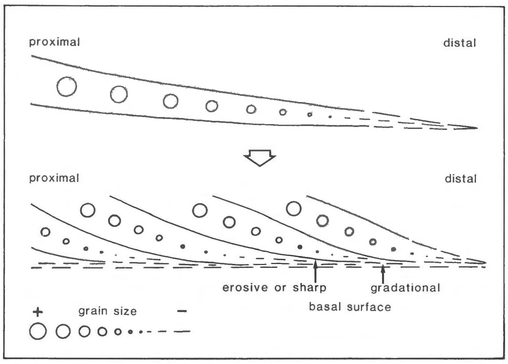

Fig. 8. Erosive to gradational lower contact formed by the superposition of beds with fining texture in downcurrent direction.

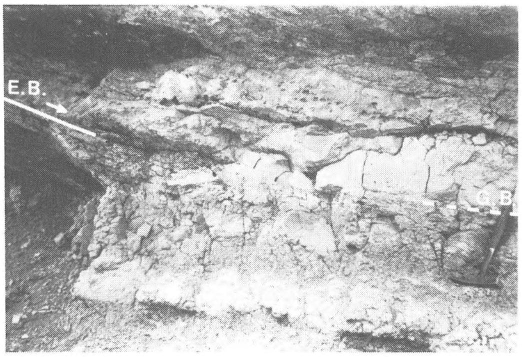

Fig. 9. Change in the nature of the lower contact of a lobe in the downcurrent direction, from erosive (E.B) to gradational (G.B). Hammer length is 28 cm.

composition is indicated, the lobes consist of sand.

Lithofacies A1. Single, horizontally bedded lobes

Lithofacies A1 consists of a single horizontal bed up to 2 m thick, and is characterized by a plano-convex or multiple plano-convex geometry in transverse section; the bed wedges out towards the distal part.

Lithofacies A2. Multiple, horizontally bedded lobes

Lithofacies A2 consists of several vertically stacked horizontal wedge-shaped beds. The proximal part of the lobes generally shows an amalgamation of beds. The distal pinching out of a bed is accompanied by a fining of the grain size. The lobes

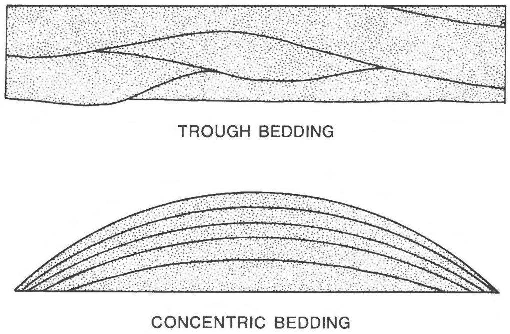

Fig. 10. Two characteristic bedding patterns of lithofacies type B in transverse section, the trough bedding pattern and the concentric bedding pattern.

Fig. 11. Transverse section of the distal part of a lobe of lithofacies B6. Note the plano-convex geometry and the concentric bedding pattern. Scale length is 7 m.

have an average thickness of 1-2 m with a maximum of 5 m.

Lithofacies B1. Inclined bedded, conglomeratic lobes (fig. 12)

These lobes are about 1.5 m thick and a few tens of meters in longitudinal extent. They are built up of a series of inclined, partly overlapping conglomeratic beds, each up to 1 m in thickness (fig. 12 a). The conglomeratic beds show reversed grading: the lower part is sandy, the upper part consists of a poorly sorted matrix-supported conglomerate (fig. 12 b).

Table 1. Geometry and lithofacies of the sedimentary lobes in the Capella Formation. The different lobe types represented in figure 7 are indicated here in the left column. (1) L: longitudinal section; T: transverse section, Tp: of the proximal part, Td: of the distal part. (2) Lo: lower boundary: U: upper boundary.

Lobe type	Geometry (1)	Lower & upper Boundaries (2)	Lithofacies: Bedding pattern (1)	Texture	Grain size sequence	Primary sedimentary structures	Countercurrent sedim. struct.	Bioturbation & Mottling
A1- Single horizontally bedded	L: wedge-shaped T: plano-convex or multiple plano-convex	Lo: slightly erosive to gradational	single horizontal bed	fine sand to silt or very coarse sand	fining upwards	?		very intense
A2- Multiple horizontally bedded	L: wedge-shaped T: tabular to plano convex	U: gradational to finer deposits	vertical stacking of single horizontal beds	fine sand to silt	Repeated fining upwards			
B1- Inclined bedded, conglomeratic	tabular	Lo: erosive U: sharp	inclined bedding	sand and a poorly sorted mixture of sand, pebbles & cobbles	coarsening-upwards	matrix supported conglomerate		
B2- Inclined bedded, structureless	L: tabular T: tabular to slightly plano-convex	Lo & U: gradational	inclined beds, tangential to lower & upper lobe boundaries	fine to very fine sand	coarsening fining upwards	?		very intense
B3- Inclined bedded; avalanche foresetting	L: wedge-shaped T_p: tabular T_d: plano-convex	Lo: erosive to gradational U: sharp or gradational	L: inclined bedding defined by sets of avalanche laminae T_p: trough bed. T_d: concentric		coarsening-fining upwards	avalanche foreset lamination	occasionally tangential cross stratification and ripple cross-lamination	occasionally on the upper surface
B4- Inclined bedded, cross-stratified	L: wedge-shaped T_p: tabular T_d: slightly plano-convex	Lo: erosive to gradational U: gradational	L: inclined bedding T: trough bedding	medium sand to silt	coarsening-repeated fining-upwards	low-angle cross-stratification; subordinate cross-stratif. & ripple cross-lamination	very rarely cross-stratif. & ripple cross-lamination	intense on the upper surface
B5- Inclined bedded, bidirectional cross-stratified		Lo: erosive to gradational U: sharp	Ridges in the upper part (B5)			lag deposits; cross-stratification	cross-stratif. & ripple cross-lamination in the upper part	very intense on the ridges
B6- Inclined bedded, bidirectional cross-stratified, sigmoidal	L: sigmoidal T_d: plano-convex	Lo: erosive U: gradational	L: inclined bedding; ridges in the uper part T_d: concentric bedding		alternating sand and silt deposits; upper part is fining upwards.	cross-stratification	very common: cross-stratif.; ripple cross-lamination on the upper surface	very intense on the upper surface and ridges

Lithofacies B2. Inclined bedded, structureless lobes

The lobes of lithofacies type B2 are typically about 2 m thick with a maximum of 3.5 m; the longitudinal extent is several tens of metres. The sandy lobes grade down- and upwards into silty deposits. Primary sedimentary structures are absent, probably because of intense bioturbation.

Lithofacies B3. Avalanche-foresetting lobes

The dominant sedimentary structure is avalanche foresetting. The dip angles of the avalanche foreset laminae are 8° to 11° in the upper part of the lobe increasing to 33° in the middle part. The bottomsets are angular to tangential (fig. 7, B3).

Together with a thinning of the lobe towards the distal part, there is a change from high to low inclination in the foreset laminae. The structures finally grade into ripple cross-lamination.

Counter-current structures were also observed. They appear as sets of tangential cross-stratification, less than 20 cm thick, and ripple cross-lamination. Evidence of counter-current cross-stratification is restricted to the middle and lower part of the avalanche foresetting, whereas ripple cross-lamination is more widely distributed.

One of the studied avalanche foresetting lobes exhibits, in transverse section, a shallow concave erosive form in the upper part (fig. 5). This erosive form represents the feeder channel that prograded over the lobe. The erosive surface is overlain by low-angle cross-stratification. The erosive surface passes laterally into avalanche foreset laminae.

Lithofacies B4. Inclined bedded, cross-stratified lobes

Lobes of lithofacies B4 are typically up to 6 m thick with a longitudinal extent from several tens of metres up to a few hundred metres.

In transverse section the proximal part of the lobe displays a trough bedding pattern. The troughs are several metres wide and up to 2 m thick; in longitudinal section they can be seen to be built up of low-angle cross-stratification (dip angles

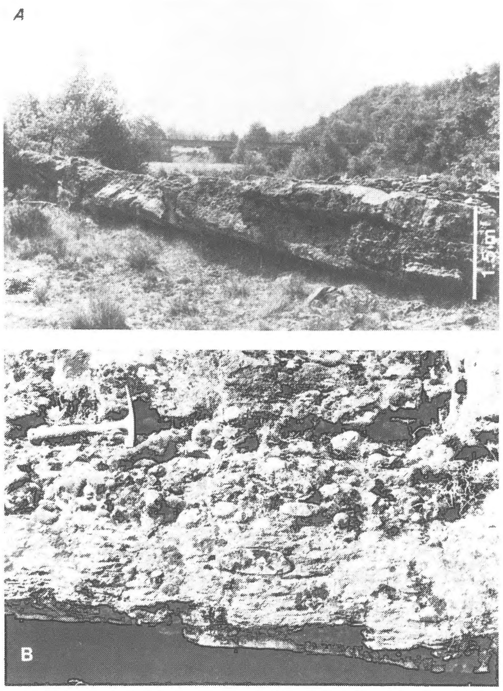

Fig. 12. Conglomeratic lobe of lithofacies type B1. A: Note the tabular geometry and the inclined bedding (left). B: coarsening upward sequence from sand to poorly sorted, matrix-supported conglomerate. Hammer length is 28 cm.

2° - 12°) (fig. 13). Subordinate structures are trough cross-stratification and ripple cross-lamination. The sedimentary structures indicate transport parallel to the wedging direction of the lobe. The grain size and the thickness of the sedimentary structures decrease upwards within each bed.

Lithofacies B5. Inclined bedded, bidirectional cross-stratified lobes

In longitudinal section the bedding surfaces of this lobe type show a slight inclination at the upper part of the lobe. They tend to steepen towards the lower part of the lobe and are occasionally erosive at its base. The erosive character of the bedding surfaces passes into a gradational contact with the muddy substratum in the downcurrent direction; this change is associated with a textural fining of the deposit (fig. 9).

A transverse section of the proximal part of the lobe, however, exhibits a trough bedding pattern in the lower part. The troughs are relatively small, have an erosive base and fine upwards from medium sand to silt. Lag deposits of small pebbles and oncolites are common. Oncolites occur both as imbricated fragments, i.e. clearly transported, or as more extensive planar fossil bodies, horizontally interstratified in the lag, suggestive of an in-situ formation. Oxidized plant fragments are present in the silt deposit.

The dominant sedimentary structure is angular cross-stratification; it is generally oriented in the direction of the bed inclination. Cross-stratification and ripple cross-lamination with opposite orientations are also present. They occur mainly at the top of the lobe, overlying sets of downdip oriented cross-stratification.

The sets of these counter-current structures pinch out in the migration direction. The thinning of the sets is associated with a transition from angular cross-stratification in the thicker part of the set into tangential cross-stratification, ripple cross-lamination and poorly developed parallel lamination in the thinner part (fig. 14). Mud laminae and

Fig. 13. Low-angle cross-stratification in a lobe of lithofacies type B4. Hammer length is 30 cm.

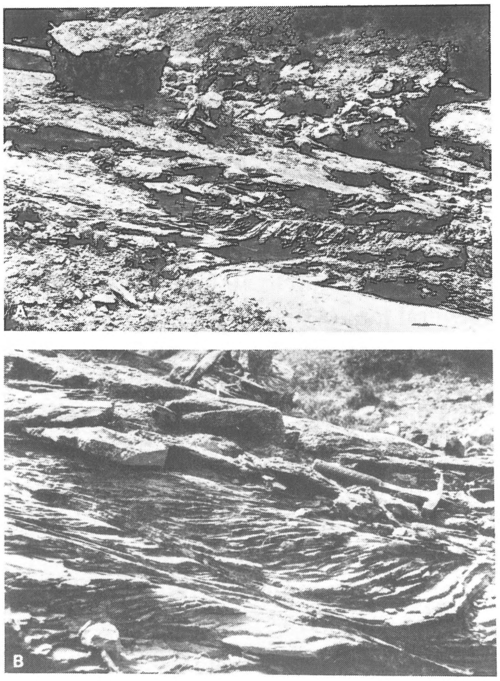

Fig. 14. Counter-current cross-stratification in the upper part of a lobe of lithofacies type B5. The sets of counter-current structures pinch out in the migration direction. A: the thinning of the sets is associated with a transition from tangential cross-stratification to ripple cross-lamination and poorly developed parallel lamination towards the higher part of the inclined depositional surface. B: detail of the tangential cross-stratification and the discontinuity surfaces (mud drapes) within the foreset laminae. Hammer length is 28 cm.

repeated discontinuity surfaces are commonly intercalated within the foresets of these structures. The amalgamation of several thin, poorly laminated sets creates a form with a convex-up morphology. These convex forms have an elongation parallel to the strike of the lobe surface and a slip face facing in the downdip direction. Parallel lamination is poorly preserved in these forms because of the intense bioturbation. In the field these convex-up forms are arranged parallel to each other revealing a ridge and swale topography. These features show similarities to the scroll bar topography described at the top of point bar deposits (Sundborg 1956, Puigdefabregas 1973, Nami 1976, Nanson 1980, Van der Meulen 1982).

Lithofacies of the sigmoidal lobes

The sigmoidal lobes have been found to be always associated with lithofacies type B (inclined bedding) (fig. 7 and table 1). A characteristic sigmoidal lobe is described here:

Lithofacies B6. Inclined bedded, bidirectional cross-stratified lobes.

This type of lobe has a sigmoidal geometry in longitudinal section. The contact with the substratum is erosive. The beds are inclined and, characteristically, some of them do not grade into the finer deposits of the distal part but pinch out with sharp contacts.

The lobe shows a plano-convex geometry with a locally deeply scoured lower surface in transverse section. The bedding pattern is concentric and convex-upwards.

The primary sedimentary structures are cross-stratification of both the angular and the tangential type and ripple cross-lamination. The cross-stratification is indicative of migration directions both down and up the inclined bedding planes; reactivation surfaces are common. The inclined upper surface of the lobe is covered with small scale ripples. Convex-up ridges as described for lithofacies B5 occur in the upper part of the lobe.

Discussion and interpretation

Sedimentary lobes with lithofacies A have been found associated with channelized bodies, either as overbank deposits of the channel (overbank splay lobes) or as channel terminal lobes. The overbank splay lobes, with a thickness of up to 1.20 m, occur at the sides of the main channel deposit. Topographically they are elevated several metres in relation to the channel floor. In the case of channel terminal lobes (fig. 15) the lobe occurs as the distal continuation of the channel deposit; the depth of the channel decreases towards the lobe. The lobe is approximately at the same topographic height as the channel deposit; the erosive lower surface of

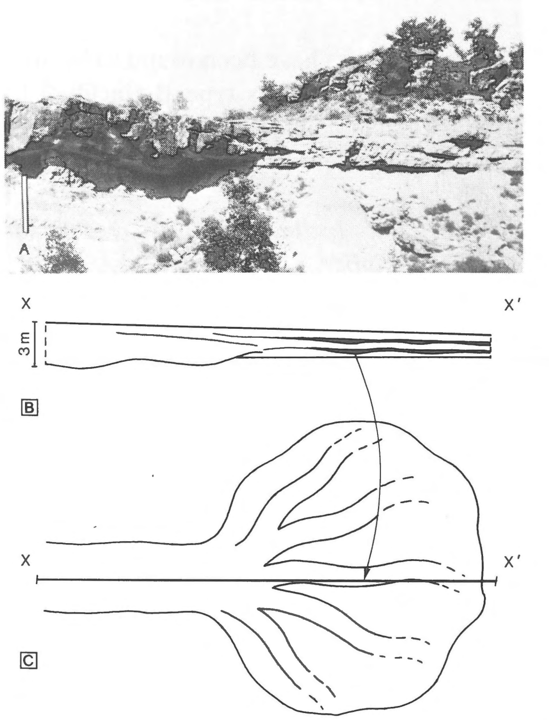

Fig. 15. Terminal lobe with lithofacies type A2 (right) at the mouth of a channel (left). A and B: axial section; the depth of the channel decreases towards the lobe; the erosive lower surface of the channel passes into the terminal lobe. C: Inferred plan view of the channel - terminal lobe complex.

the channel passes into the terminal lobe. The channel terminal lobes are comparable to the terminal fans of Friend (1978) which are suggested to be the result of a decrease in transport capacity. This results in a channel pattern of distributive type, and the ultimate disappearance of all channels.

The conglomeratic lobes with lithofacies B1 are interpreted as debris-flow lobes on the basis of the matrix-supported character, the poor sorting of the conglomerate and the reverse grading. This lithofacies is very restricted within the studied deposits.

For the lobes with lithofacies B2, an origin similar to that of lithofacies A (overbank splay lobes and terminal lobes) is inferred.

The lobes with lithofacies B3, which consist of avalanche foresetting, are interpreted as small deltas deposited in a standing water body such as a lagoon. They are formed as a result of radial overbank flooding of a feeder channel, i.e. the lobe consists of both a terminal fan and lateral levees, both made up of avalanche foresetting laminae. The feeder channel is not always present over the delta lobe, probably because of channel shifting over the deltaic complex.

The more complex lobes are those with lithofacies B4, B5 and B6. They are relatively large, with thicknesses from 5 up to 10 m, and an axial extent from several tens of metres up to 400 m. No feeder channels have been observed overlying these lobes and they are therefore interpreted as *spillover lobes*. Spillover lobes are formed at the mouth of a channel; the lobe is higher than or at the same level as the base of the feeder channel. Consequently, progradation of the channel results in the destruction of the proximal part of the lobe. Spillover lobes were described first by Ball (1967) from the marine sand belts of the Bahamas; these are lobate accumulations of sediment with plano-convex geometry in transverse section. Sediment bodies comparable to the 'spillover lobes' have been observed in the Parker River estuary (Atlantic coast of the U.S.A.) by DaBoll (1969 a, fig. 8b-1) and Hayes (1969, fig. 25-1). These are intertidal, lobate, small sand bodies, with either ebb or flood orientation. The lobes are covered by sandwaves oriented in the direction of the locally dominant current. The lobes are fringed by shields; the sedimentary structures in the shields are oriented in the direction of the subordinate current. The flood tidal deltas described in the same area by Boothroyd (1969). DaBoll (1969 b), Greer (1969), Hartwell (1969) and Boothroyd & Hubbard (1975) are comparable to the spillover-lobe sand deposits described above in that both sedimentary forms consist of a sandwave flat fringed by shields, spits and channels. The feeder channel, a tidal inlet in the case of the flood tidal deltas, shallows towards the lobe flat in both cases. Shields and marginal channels of tidal deltas are dominated by the tidal counter-current (Hayes 1975, 1980). The basic difference between spillover lobes and tidal deltas is the scale; a flood tidal delta usually consists of several spillover lobes (Ball 1967, fig. 3; Hine 1975), while a spillover lobe is a single sedimentary macroform.

A model of fluvial-ebb tidal spillover lobe is proposed for the lobes of the Capella Formation with lithofacies B4, B5 and B6 (fig. 16). They show a SW direction of progradation and are therefore ebb-oriented (the hinterland lay to the NE; Nijman & Nio 1975). The fluvial-ebb spillover lobes were formed at the mouth of a tidally influenced alluvial channel. Horizontal segregation of ebb and flood currents occurred in the intertidal area over and around the lobe. The spillover lobe bedforms are mainly ebb-oriented since the ebb current was strengthened by the river discharge. Flood-dominated structures, which are found in minor amount, probably form the lobe shields. During low river water stages, the river discharge diminishes and the supplied sediment becomes finer. At the same time, a greater symmetry of ebb and flood current intensities occurs, which allows a better development of the flood-oriented bedforms on the shields. The definitive abandonment of the lobe in consequence of the shifting of the feeder channel may lead to the reworking of the lobe by tidal currents and to the final dominance of flood bedforms on the upper surface of the lobe.

The lobes with lithofacies B4 consist of several fining upward beds. The sedimentary structures in these lobes are mainly ebb-oriented. Each fining upward bed represents a period of river discharge reactivation and subsequent waning. The scarcity of flood-oriented structures indicates a dominance of river/ebb currents, even during stages of low river discharge. This fact may be explained either by a special protected location of the lobe in the tidal flat or by weak tides during its formation.

The lobes with lithofacies B5, although ebb-dominated, show clear evidence of flood currents, which are even dominant on the upper part of the lobe. The sets of flood oriented cross-stratification and ripple cross-laminaton on the upper part of the lobe represent the flood shield deposits. In the lobes with lithofacies B6, the influence of flood currents is manifested throughout the whole lobe. The upper surface of the lobe is covered by flood-oriented small scale ripples, associated with finer grained deposits and with an intense burrowing. These small scale structures represent the reworking of the lobe by flood currents after abandonment of the lobe.

The comparison of lithofacies B4, B5 and B6 suggests that deposition occurred under different tidal conditions. Lithofacies B4 appears to have been deposited in a system with, locally, a considerable asymmetry between flood and ebb, while particularly lithofacies B6 suggests a more symmetrical system of tidal currents.

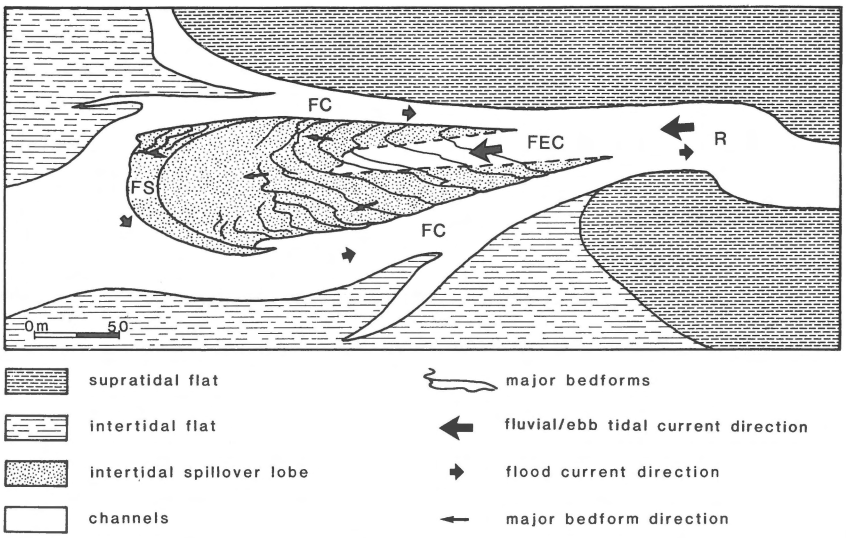

Fig. 16. Sedimentary model for spillover lobes in an intertidal flat. R: tidally influenced river; FEC: fluvial-ebb tidal channel; FS: flood shield; FC: marginal flood channel. The spillover lobe geometry is adapted from Hayes' (1969) photography of an intertidal sand body in the Parker River Estuary.

Conclusions

The coarse deposits of the Capella Formation have been considered to consist mainly of fluvial channel deposits, among which point bar sequences prevail (Nijman & Nio 1975, Atkinson 1983). However, many of these 'point bar' lithosomes, when carefully examined, suggest a different interpretation. The inclined bedding pattern (epsilon stratification of Allen 1963), associated with a fining upward sequence of the deposit, is not characteristic only of point bar deposits. Sediment bodies with the same characteristics and down-dip oriented sedimentary structures can be recognized in the Capella Formation, and are interpreted as depositional lobes. In some cases the lobes show bar ridges similar to those described for the upper part of point bars (Sundborg 1956), with abundant burrowing and mottling. In the case of the lobes, the ridges are generally oriented perpendicular to the main paleocurrent direction. The lobe ridges are generated by reworking of the lobe by water currents opposite to the direction of lobe progradation.

From the plano-convex geometry of some of the sandstone bodies in terminal transverse section it can be inferred that these bodies are depositional lobes. They can be clearly distinguished from the channel features.

The grain size variations in each bed of some sandy lobes (typically a fining in the younging direction) attest to a periodicity in the water and/or sediment discharge. This periodicity may be related to climatic factors such as seasonal periods. It is inferred that rapid deposition and a high preservation potential characterize these lobes.

The sedimentary lobes of the Capella Formation are related to an alluvial system characterized by relatively fine grained deposits, mainly mudstones and sandstones. An alluvial fan environment is suggested by the presence of debris-flow lobes. Beside these, other types of lobes were deposited in the alluvial fan, i.e. terminal lobes at the distal part of streams, or small deltas when the feeder channels reached a standing water body. Where the alluvial fan was affected by tidal currents a more complex system of lobes developed: the spillover lobes.

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