Cuadernos Geología Ibérica	Vol. 10	Págs. 9-30	Madrid 1986

SANDSTONE-BODY STRUCTURE AND RIVER PROCESS IN THE EBRO BASIN OF ARAGON, SPAIN

PAR

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SUMMARY

The Miocene fluvial sediments of the Aragon part of the Ebro basin, northern Spain, provide remarkable exposures of sandstone bodies. Three different types of sandstone bodies can be distinguished in terms of the form of their external morphology: ribbons, sheets and amalgamated complexes. The internal structures of the ribbon sandstone bodies show that they resulted from at least one channel incision event, followed by the plugging of the channel, sometimes achieved only after a whole series of incision and plugging cycles. In contrast, the sheet sandstone bodies may have resulted from either channelised or unchannelised flow. Where channels were involved, they show evidence of migration by lateral bank erosion, either involving a single phase of progressive migration, or involving complex reworking of the earlier phases of channel deposits. Amalgamation occurred when the erosion that preceded ribbon or sheet sandstone deposition cut into an earlier sandstone body. When this created a complex geometry, we distinguish a separate type.

Ribbon bodies will tend to result from ephemeral river flow or periodic uplift of the alluvial surface. Amalgamation will tend to result from changes of hydrology, local alluvial uplift or tectonic tilting.

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RESUMEN

Los sedimentos fluviales del Mioceno de la zona aragonesa de la cuenca del Ebro (Fig. 1), presentan afloramientos excepcionales para el estudio de los cuerpos arenosos. Según la *morfología externa* (Figuras 2-4), se pueden distinguir tres tipos diferentes: «ribbons» (cuerpos alargados), mantos («sheets») (Figs. 2-3), y complejos amalgamados (Fig. 4).

La *estructura interna* de los cuerpos arenosos de tipo *«ribbon»* (Figs. 5-6) indica que son el resultado de, al menos, un episodio de encajamiento del canal, al que sigue un episodio de taponamiento del mismo, a lo cual se llega a veces tras una serie de ciclos y encajonamiento y taponamiento. Por el contrario, los *mantos* arenosos (sheet sandstone bodies) (Fig. 7) son el resultado tanto de corrientes canalizadas como no canalizadas. Cuando existen canales, éstos presentan signos evidentes de una migración por erosión lateral de las orillas. Este proceso se puede producir tanto en una fase única de migración progresiva, como tras un complejo retrabajamiento de los depósitos de canales de las fases anteriores. Se producen *complejos amalgamados* (Fig. 8) cuando la erosión que precede a la sedimentación del «ribbon» o del manto (sheet), profundiza hasta un cuerpo arenoso anterior. Cuando este proceso crea una geometría compleja, distinguimos entonces un tipo de cuerpo diferenciado de los otros dos.

Los cuerpos tipo «ribbon» son normalmente el resultado de corrientes fluviales efímeras o de elevaciones periódicas de la superficie aluvial. Los complejos amalgamados son normalmente el resultado de cambios de hidrología, elevaciones aluviales locales o bien basculamientos tectónicos.

1. INTRODUCTION

The Cenozoic Ebro and south Pyrenean basins, of northern Spain, have become classic areas of the world for investigating alluvial sedimentation.

Many alluvial formations are differentiated into discrete bodies of coarse-grained sediments, decimetres to several metres in thickness and tens or hundreds of metres-wide, that are surrounded by a matrix of alluvial mudrock (siltstone and claystone). In the semi-arid climate of the Ebro basin, because of the lack of thick vegetation and soil cover, these bodies weather out and erode preferentially from the mudrock, so that unusually complete geometrical information is available at outcrop. There is, however, a parallel disadvantage, for reasons that are not yet clear; the fine detail of stratification generally tends to have been poorly picked out by diagenesis and weathering.

In this paper, we review the range of geometry and internal structure that we have studied in the central, largely Miocene, outcrops of the Ebro basin (Fig. 1). These lie in the old kingdom of Aragon, the present provinces of Huesca, Zaragoza and Teruel.

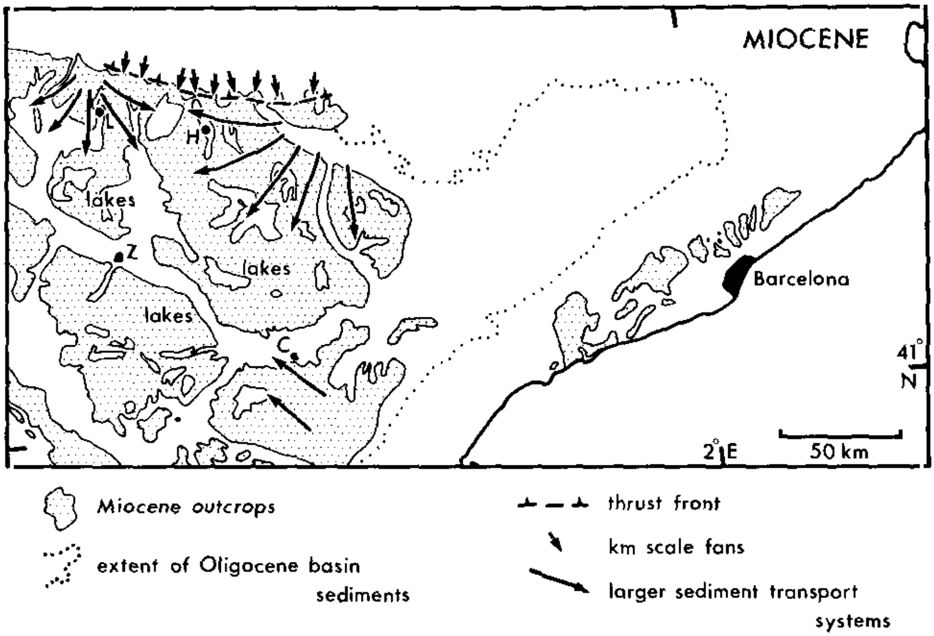


FIG. 1.—*Location and geological map of north-eastern Spain, based on the 1/1 million geological map by the Instituto Geologica y Minero de España, 1980. Miocene outcrops are shown, generalized. The limit of Oligocene outcrops provides an approximate margin for the Ebro basin. Three main Miocene alluvial systems are shown. Z, Zaragoza; L, Luna; H, Huesca; C, Caspe.*

FIG. 1.—*Localización y mapa geológico del nordeste de España, basado en el mapa geológico 1:1.000.000 del I.G.M.E. (1980). Afloramientos miocenos simplificados. El límite de afloramientos oligocenos, delimita aproximadamente el borde de la cuenca del Ebro. Se indican los tres principales sistemas aluviales del Mioceno. Z, Zaragoza; L, Luna; H, Huesca; C, Caspe.*

The sediments that we shall be discussing accumulated in three distinct alluvial systems (Fig. 1), two are characterised by radial palaeocurrent patterns, and provenance from the Pyrenees (Fig. 1). These were the Luna and the Huesca systems, that entered the Ebro basin, to west and east, respectively, of one of the southernmost Pyrenees thrust ramps active at the time. Meanwhile in the southernmost corner of the Ebro basin, the Caspe-Alcañiz system (named Guadalope-Matarranya by CABRERA, COLOMBO and ROBLES, 1985) accumulated in the angle between the coastal Catalan range to the south-east, and the Iberian range to the south-west.

RIBA, VILLENA and QUIRANTES (1967) recognised the extraordinary interest of the area of exhumed palaeochannels (ribbons in our terminology) in the southern area, near Caspe (Fig. 1). But it was PUIGDEFABREGAS (1973) (PUIGDEFABREGAS and VAN VLIET, 1978) who first drew international attention to the fluvial sedimentology of the Ebro basin, when he described the exhumed point-bar deposits of the Murillo el Fruto area (west of the area of Fig. 1). FRIEND, SLATER and WILLIAMS (1979) briefly outlined a general classification into ribbon and sheet sandstone bodies, using examples from both north and south Aragon. FRIEND (1978) also described the way that some Ebro basin alluvial systems passed downstream from coarse proximal sequences into distal, fine-grained, and the even more distal, carbonate and gypsum lake and playa-lake sequences.

In this paper we shall not attempt to review the work recently completed and continuing in the eastern (Catalan), largely Eocene and Oligocene, lower part of the Ebro basin fill. A broader range of environments controlled these older and more easterly episodes of sedimentation. Eocene shallow, carbonate and mud accumulating seas, and fan deltas, existed before the alluvial and lacustrine environments, became established in the Oligocene. Some recent eastern Ebro papers include: MALMSHEIMER and MENSINK (1979); ALLEN and MATTER (1982); ALLEN and MANGE-RAJETSKY (1982); ALLEN, CABRERA, COLOMBO and MATTER (1983); ANADON, MARZO and PUIGDEFABREGAS (1985); CABRERA, COLOMBO and ROBLES (1985).

2. EXTERNAL GEOMETRY OF THE SANDSTONE BODIES

Since the paper by FRIEND, SLATER and WILLIAMS (1979), we have continued to find a first-stage, field classification of sandstone bodies into ribbons and sheets, very useful. However we find a new class of 'amalgamated complexes' to be necessary, to cover bodies where neither sheet nor ribbon form is dominant, because of the complex amalgamations present.

Figs. 2 to 4 illustrate the major variants in our external form classification, and stress the critical role of *external form* by representing the sandstone bodies with solid black shading. There is a distinctive lithofacies of closely interbedded sandstone and mudstone sheets, with sheet thicknesses varying from a few to a few tens of centimetres. This lithology, intermediate between the sandstone of the bodies and the general alluvial mudrock surround, is shown as a distinct lithology in Figs. 2 and 4.

We shall discuss and illustrate the definition of the three sandstone body classes first, and then consider the river processes involved in later sections.

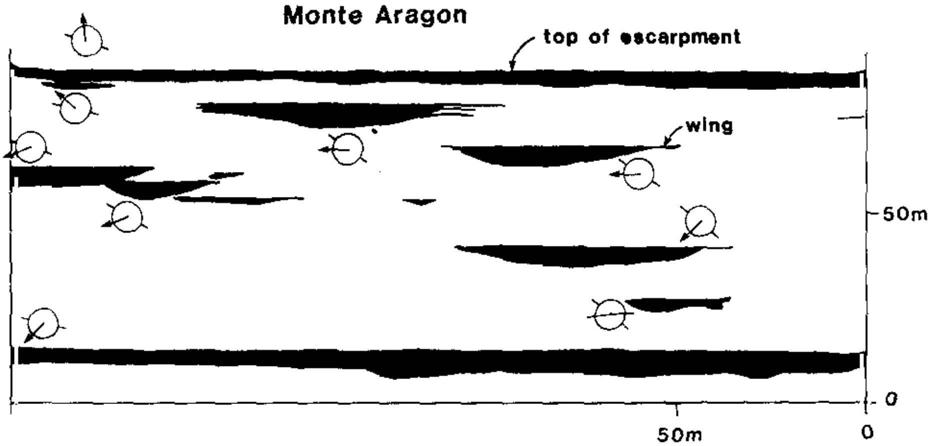


FIG. 2.—*Aproximately vertical plane profile showing sandstone bodies in the escarpment near Monte Aragón, about 5 km ENE of central Huesca city (Map Reference 184707). Sandstone bodies are in black, unshaded material being alluvial mudrock. Circles are used to indicate palaeoflow (arrows) or ribbon orientation (diameters). Ticks outside circles indicate orientation of profile. All orientations are relative to north at top of circle.*

FIG. 2.—*Perfil en una sección vertical en la que se observan los cuerpos arenosos en la ladera cerca de Monte Aragón, a unos 5 km en dirección ENE de la ciudad de Huesca (referencia del mapa 184707). (En negro los cuerpos arenosos, en blanco los sedimentos aluviales lit́iticos. Se utilizan los círculos para indicar las paleocorrientes —flechas— o la orientación de los «ribbons» —diámetros—. La orientación del perfil está marcada por trazos en el exterior de cada círculo. Todas las orientaciones están referidas al norte, situado en la parte superior del círculo.)*

a) *Ribbon sandstone bodies*

These bodies are elongate in plan form (Fig. 3), and defined by their relatively small width/thickness ratio of less than 15. This apparently arbitrary figure still seems to correspond well to a natural division between sandstone body types that is present in many field areas. The width measured must

1) not include the thin wings, well seen in many of the sandstone bodies in Fig. 2.

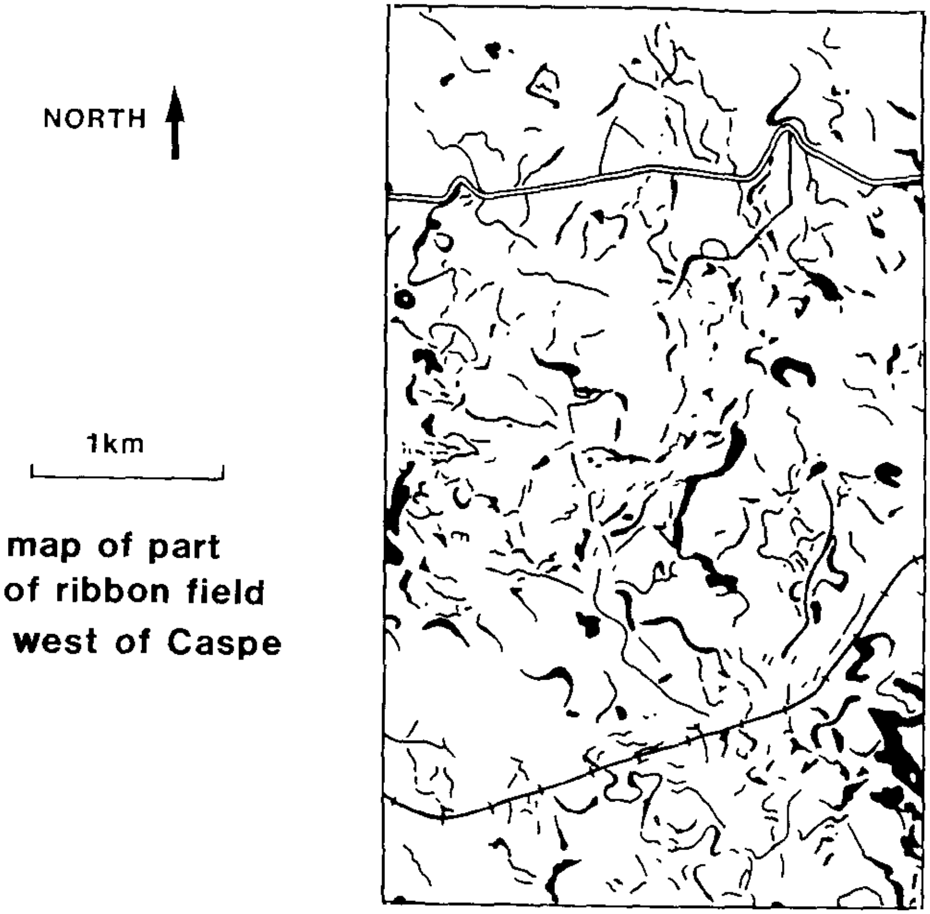


FIG. 3.—*Map of part of area west of Caspe (fig. 1), showing remarkable outcrop pattern of sandstone bodies (black). Surrounding fields, unshaded, are underlain by alluvial mudrock. The upper part of the map is traversed by the Caspe to Escatron road (C 221) and the apex of the larger sharp deflection in the road is 13.6 km in direct line west of Caspe. The Caspe to Zaragoza railway traverses the lower part of the map. The map is based on a map prepared by R. C. Williams (unpublished Cambridge Ph. D. thesis), in turn based on the analysis of RIBA, VILLENA and QUIRANTES (1967).*

FIG. 3.—*Mapa de parte de la zona oeste de Caspe (Fig. 1), en la que se muestra el esquema de afloramientos de los cuerpos arenosos (en negro). Las áreas circundantes (en blanco) están constituidas por sedimentos aluviales lutíticos. La carretera de Caspe a Escatrón (C 221) corta la parte superior del mapa, estando localizada la curva cerrada que se observa en ella, a 13,6 km en línea directa al oeste de Caspe. El ferrocarril de Caspe a Zaragoza corta la parte inferior del mapa. Este mapa está basado en el realizado por R. C. Williams (Tesis Doctoral ,Univ. Cambridge, inédita) a su vez basado en los análisis de RIBA, VILLENA y QUIRANTES (1967).*

2) be adjusted to estimate the width measured perpendicular to the long axis of the ribbon, often measured by palaeoflow indicators in the sandstone body.

Fig. 2 provides an excellent illustration of the appearance in vertical profile, of two sandstone sheets and nine sandstone ribbons of varying sizes. Most of the ribbons appear to be fairly simple in form, although three of them show amalgamation, or interconnection.

Fig. 3 illustrates part of the largest area of plan exposure of sandstone bodies known to us in the Ebro basin. Very large numbers of sandstone bodies stand out as ridges and local plateaux, anything from 2 to 10 m. above fields that are generally underlain by the alluvial mudrock surrounding the sandstone (or locally here, conglomerate) bodies. Some of the ribbons are highly sinuous, others gently sinuous or almost straight. Some of the straight ribbons have distinct, angular, bends in them.

b) *Sheet sandstone bodies*

These bodies are defined as having a greater width/thickness ratio than 15, where width is measured perpendicular to palaeoflow direction.
Fig. 2 illustrates two examples of sheet sandstone bodies, and some of the less linear bodies on the plan view map (Fig. 3) are probably also parts of sheets.

c) *Amalgamated sandstone body complexes*

This new class of sandstone body is necessary to describe the complex amalgamations of ribbons and sheets that are associated with rather high sandstone to mudrock ratios. Both the cases illustrated by us (Fig. 4, a & b), also contain rather high proportions of finely interbedded sandstone and mudrock. They show evidence of relief of metres in the scoured surfaces that form the bases of some of the component sandstone bodies.

3. RIVER PROCESSES OF RIBBONS

The recognition of the size and shape of river channels and the discovery of in-channel sediment bars are major steps in interpreting ancient alluvial sediments (FRIEND, 1983). Both can be relatively easily achieved in ribbon sandstone bodies.

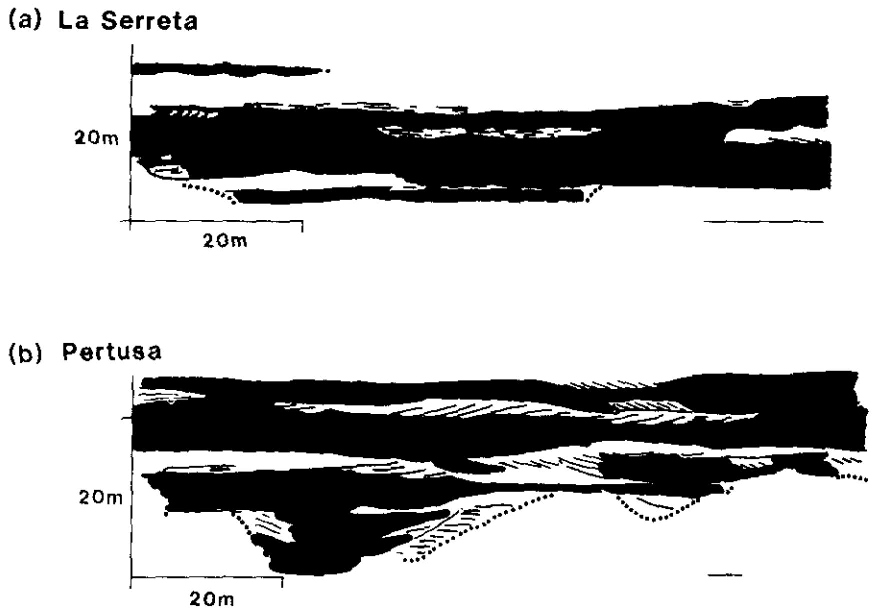


FIG. 4.—*Two approximately vertical-plane profiles showing sandstone bodies (black), sandstone-mudrock interbedded sequences (lines), and alluvial mudrock (unshaded). a) La Serreta, 15.2 km SSE of central Huesca city, near road to Piraces (Map Reference, 220553). b) Pertusa, 22.4 km SE of central Huesca city, west side of Rio Alcanadre gorge, map reference 378540.*

FIG. 4.—*Secciones verticales en las que se observan los cuerpos arenosos (en negro), las secuencias de alternancias areniscas-lutitas (líneas de trazos) y los materiales lutíticos aluviales (en blanco). Las líneas de puntos indican los límites del afloramiento. a) La Serreta, 15,2 km al SSE de la ciudad de Huesca cerca de la carretera a Piraces (referencia del mapa 220553). b) Pertusa, 22,4 km al SE de la ciudad de Huesca, en la margen oeste de la garganta del río Alcanadre (referencia del mapa 378540).*

Some ribbons have a *simple sandstone-fill* (Fig. 5f, g) apparently representing single episodes of channel cutting, followed by rapid plugging by sand. Most cases of this are relatively small, with ribbon widths of a few metres. Clearly exposed ribbons larger than this invariably show evidence of a complex channel-fill history.

A ribbon partly exposed by a new irrigation canal cut at Pertusa (Fig. 5a-c) provides an excellent example of a *multistorey channel fill.* To the south-west of this artifical cross-section, the ribbon is exposed as an exhumed ridge until cut by the road. At this point, trough cross-stratification shows that the palaeoflow was to the southwest. In the cross-section (Fig. 5a) major scour-surfaces that generally cross-cut the underlying stratification, divide the fill into a number of storeys.

The position, and angle of these scour surfaces suggest that the ribbon may have an internal geometry (Fig. 5b) divided by a series of scour surfaces produced by the erosion of a sequence of progressively narrower channels. In Fig. 5b, the position of the talwegs or deepest point's of each channel erosion episode are suggested, and it is clear that they moved successively upwards and eastwards within the original major channel form.

The sediment making up the storeys provides evidence, particularly in storey 2, that the deeper axial parts of the channel were transporting and depositing medium sand, while the channel banks were accumulating muds with thinner sand intervals.

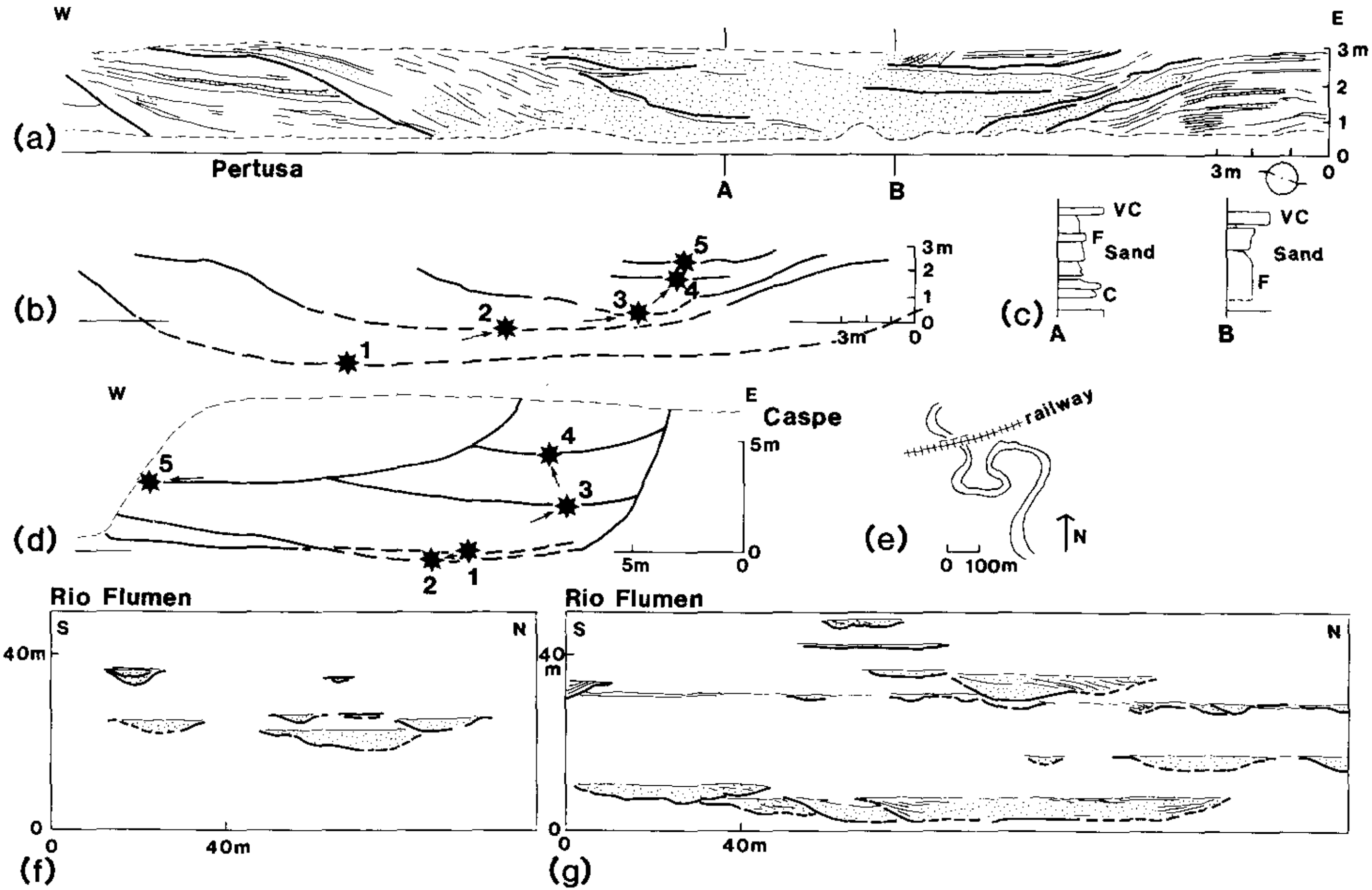
The storey structure just described provides evidence for an initial erosional episode that produced a channel about 50m wide and 6m deep, which was then partially or completely plugged by a succession of episodes of deposition alternating with channel erosion. The special feature, in this case, is that each erosional episode scoured a smaller channel than the previous one, and was contained within the deposits of the previous plugging episode. The final channel was under 10m wide and 1m deep.

Fig. 5, d & e show a similar storey analysis, and map, from one ribbon chosen from the Caspe ribbon field (Fig. 3). The exhumed ribbon has a relief of about 7m above the neighbouring field, and at least its upper storeys were formed by a highly sinuous, north-west flowing channel.

The storey analysis here shows a more erratic pattern of cut and fill. The talweg of the channel appears to have cut deeper during episodes 2 and 5 than during the immediately preceding episodes, and it has also moved erratically sideways. The general map of the area (Fig. 3) shows the way that ribbons of highly varying plan form cut each other, and this effect could clearly produce erratic multi-storeying in some localities. However there is no outcrop evidence that ribbon crossing is responsible for the multistoreying in the particular cross-section just described, and we conclude therefore, that multiple episodes of cutting and filling along the same feature took place.

Figs. 5f and g show two vertical plane profiles of valley walls of the Rio Flumen. In these alluvial sections, ribbons of a great variety of sizes are present. They rarely show any degree of multi-storey fill, but do show some examples of amalgamation of ribbons - both vertically and laterally.

Many ribbons show distinct *bar forms* in cross-section. Our first example (Fig. 6a) comes from the excavations of the Canal de les Bardenas in the Luna system (Fig. 1). This very large sandstone body is only just a ribbon, being about 135m wide and 9m thick. It has a simple fill, undivided by major scour surfaces. The main feature of



W
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(d)
5m
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railway
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(f)
Rio Flumen
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m
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40m
(g)

the fill is stratification produced by the growth of a 'plane-bedded' simple bar (ALLEN, 1983), in the centre of the channel. Decimetre-scale cross-stratification shows that megaripples migrated along the flanks of the central bar as it grew. The higher parts of the bar grew by vertical accretion of the slightly undulating crestal surface. During the last stages of channel-fill, the bar separated two channels, one of which filled simply by vertical and lateral accretion, and the other of which filled more irregularly with episodes of lateral bar growth. Major periodic decrease of discharge in this channel is demonstrated by this example.

Our second example of bar forms in ribbons comes from the two opposite sides of the cut excavated for the Cinca Canal (Figs. 6, b & c). The major sandstone body here is 1.5m thick. Reconstruction of the plan-view trend of this ribbon, assuming some degree of curvature (Fig. 6c), results in an estimate of the width of the ribbon, perpendicular to its trend, of 21m. The northern-side section through this ribbon shows that the channel-fill includes a distinct lateral bar that grew, with an early stage bench morphology (TAYLOR and WOODYER, 1978) attached to the western bank of the channel, before symmetrically plugging the rest of the channel with strata of fine sand and mud. In contrast, the southern-side section shows an early stage

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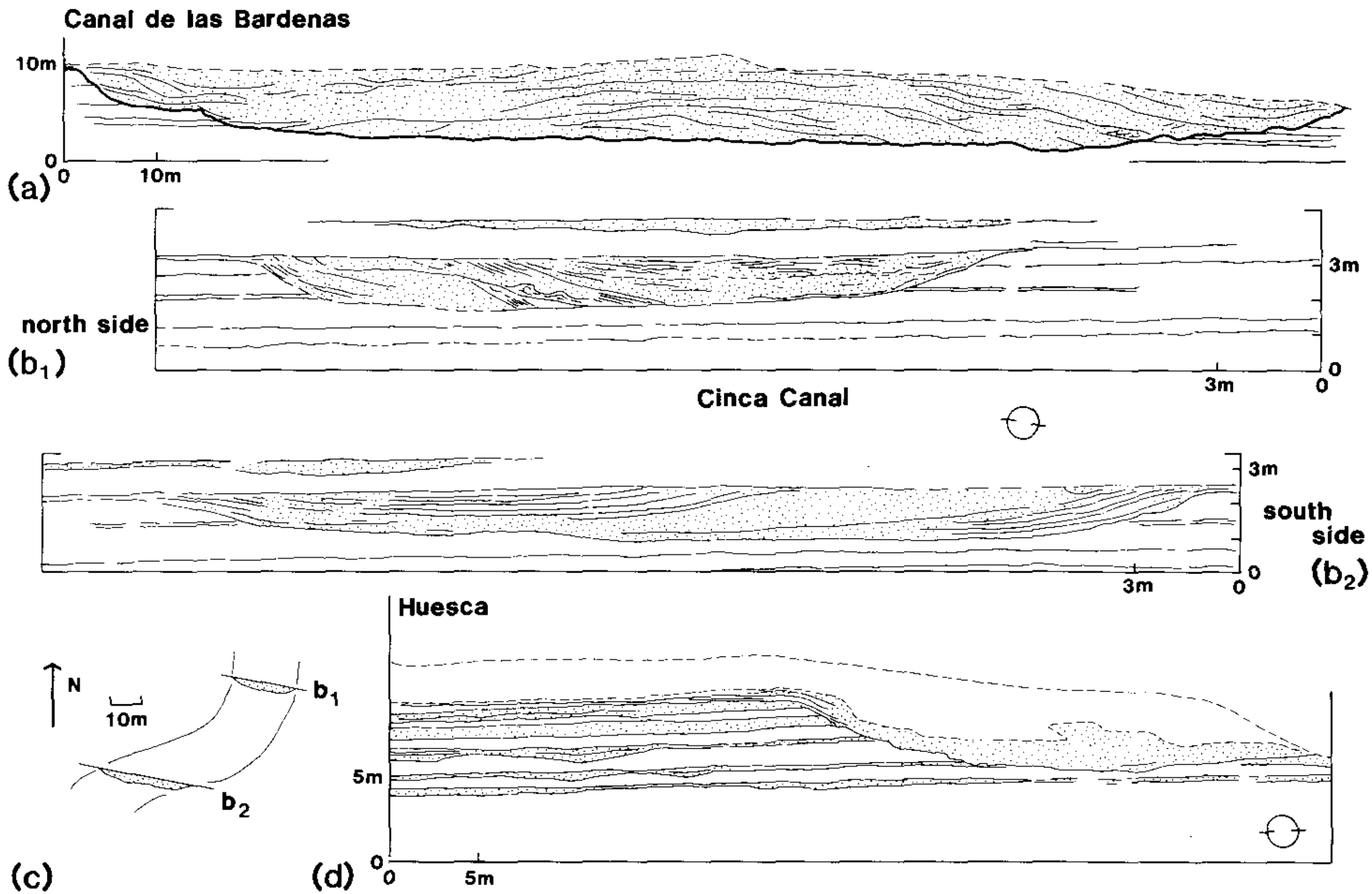
FIG. 5.—*a) Approximately vertical plane, profile in cut for irrigation canal, north of Pertusa, 22 km SE of central Huesca city, map reference 376551, near Pertusa to Antillon road. Sandstones are stippled, mudrocks are unshaded. b) same profile as a) with hypothetical major scour surfaces plotted, and talwegs of channel forms marked and numbered in time sequence. c) sedimentary logs at positions 'A' and 'B' on a). d) hypothetical analytical sketch, similar to b), through a sandstone ribbon in the area west of Caspe (locality see Fig. 3). The exposure is formed by the railway cut, and can be located on Fig. 3 by the high sinuosity of the ribbon - see e). e) sketch map of sinuous ribbon cut by railway - see d). f) approximately vertical plane profile of valley wall of Rio Flumen, showing sandstone bodies (stippled) in alluvial mudrock (unshaded). Locality is 11 km NNE of central Huesca city, map reference 167780. g) same as f) but map reference 165787.*

FIG. 5.—*a) Perfil en una sección casi vertical localizada en un canal de riego, al norte de Pertusa, 22 km al SE de la ciudad de Huesca (referencia del mapa 376551) cerca de la carretera de Pertusa a Antillón. Las areniscas están representadas con puntos y las lutitas en blanco. b) El mismo perfil que en a) marcando las supuestas superficies erosivas mayores, y los talwegs de los canales, numerados según su formación sucesiva. c) Columnas correspondientes a los puntos «A» y «B» en el perfil a). d) Esquema analítico hipotético, similar a b), de un «ribbon» arenoso en el área de Caspe (ver la Fig. 3 para localización). El afloramiento se localiza en el corte del ferrocarril, y puede ser identificado en la Fig. 3 por la alta sinuosidad del «ribbon» (ver e). e) Esquema del «ribbon» sinuoso cortado por el ferrocarril (ver d). f) Sección vertical de la ladera del valle del río Flumen, con los cuerpos arenosos marcados con puntos y los materiales lutíticos aluviales en blanco. La localidad se sitúa a 11 km al NNE de la ciudad de Huesca (referencia del mapa 167780). g) Como f) pero con referencia del mapa 165787.*


Canal de las Bardenas
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Cinca Canal
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growth of a lateral bar attached to the eastern bank of the channel. This situation implies that the channel was filled by growth of a system of alternating lateral bars (COLLINSON, 1970), probably on the insides of curves in the channel. The curvature of the channel is independently suggested by the difference in its apparent maximum width between the two parallel sections (Fig. 6c). As bar growth continued, and channel size decreased, so channel sinuosity must have increased.

The last feature of the ribbons that we shall discuss is the presence of *wings*, sheets that extend laterally from the top of some ribbons. These vary in the degree to which they are present (Figs. 2, 5 & 6), sometimes being absent altogether. We show one example (Figs. 6d), exposed by excavation for the main road (N240) just east of Huesca. The ribbon illustrated can be followed for more than 1 km to the NNW with plentiful trough cross-stratification proving palaeoflow in that direction. In the road-cut (Fig. 6d) stratification involving thin (cm) mudrock strata, alternating with fine sandstone, climbs up within the ribbon, over the lip of the bank and extends flatly into the wing. The wing can be folloved for 50 m to the west approximately perpendicular to flow with thinning of its component strata. The lower component unit of the wing appears to have been deposited before any of the sand forming the present channel-fill. It was then followed by a series of vertical accretion events, each of which can be correlated with some of the present sand-fill of the channel.

Wings were formed during episodes of overbank flooding when sand accumulated on the alluvial plain. They provide the possibility of relating the sedimentation in the channel with the more widespread

FIG. 6.—*Except for c), these are approximately vertical-plane profiles through sandstone bodies. Sandstone is stippled. Circles with ticks on their circumferences indicate orientation of profiles relative to north at top of circle. a) cut for irrigation canal, Canal de las Bardenas, approximately 45 km west of Huesca city, map reference 622731 at km mark 87.9 km along the canal. b_1 and b_2) north and south sides of Cinca irrigation canal, as shown in c). Location 18.5 km SSW of central Huesca city, map reference 060520 c) sketch map showing interpretation of channel form intersected by b_1 and b_2. d) cut on north side of main road, N240, 2.4 km east of Huesca city.*

FIG. 6.—*Perfiles obtenidos en secciones verticales de los cuerpos arenosos, (excepto c). Las areniscas están marcadas en puntos. Las marcas en el exterior de los círculos indican la orientación de los perfiles según el norte, que está situado en la parte superior del círculo. a) Corte del canal de riego (Canal de las Bárdenas), situado a unos 45 km al oeste de la ciudad de Huesca (referencia del mapa 622731) en el punto kilométrico 87,9 a lo largo del canal. b_1 b_2) Márgenes norte y sur del canal de riego del Cinca, tal y como se observa en c). Se sitúa 18,5 km al SSW de la ciudad de Huesca (referencia del mapa 060520). c) Esquema en el que se representa la interpretación de la forma del canal cortado por b_1 y b_2. d) Corte de la margen septentrional de la carretera principal, N 240, 2,4 km al este de la ciudad de Huesca.*

accretion of the alluvial surface. In the majority of cases wings indicate that the channel filling, or ribbon-constructing, episodes correspond to the accretion of, at most, a few cm of the alluvial surface, and probably therefore took place over time periods of the order of hundreds or a few thousands of years, at most, and perhaps much less.

4. RIVER PROCESSES OF SHEETS

The classic, simplest mechanism for forming a sheet sandstone body by *steady lateral channel migration* is illustrated by a body, largely of fine sand, exposed in the northwestern cut face made for part of the Cinca canal (Fig. 7a). The thickness of this sheet is 1.85 m and it is exposed over 130 m by the northeast - southwest local trend of the canal, which is nearly perpendicular to the northwesterly flow direction indicated by cross-lamination. Large cross-stratification dipping southwest extends from top to bottom of the sheet and is of epsilon type (ALLEN, 1963), apparently marking point or side-bar accretion from a laterally migrating channel. Particularly clear examples of this large cross-stratification often marked by a thickening upwards mud layer, occur at rather regular intervals of 2 to 6 m along the sheet. In between these cross-strata small-scale cross-stratification is locally visible, and this was the structure that provided the northwesterly palaeoflow measurements. The dip of the large cross-strata varies from 5 to 9° towards the northeast end of the sheet, to 17° at the more southwest end of the sheet. The final position of the channel is marked, at the southeast end of the sheet, by its form, plugged partly by sand and partly by mud, lighter in colour than the alluvial mud outside the cut-bank.

One remarkable feature of this sheet is its sharp and planar upper surface. Most of the large-scale cross-stratification terminates sharply at this upper surface although some locally becomes asymptotic to the upper surface. No overlying layers of sand appear that could represent alluvial ridges.

We now illustrate a sandstone body at Pertusa (Fig. 7b), that was also produced by *lateral channel migration.* The sandstone is very coarse in some parts of the lower part of the sheet. Lateral migration by the channel has built epsilon cross-stratification extending through from 1.5 m to 2.5 m of the sheet. However the cross-strata are not planar, and their form fully defines a lateral sequence of benches at levels intermediate between the lowest toe of the lateral bars and their uppermost levels. A similar morphology to this was described by HARMS, MACKENZIE & McCUBBIN (1963), from the Red River, U.S.A., and was explained in terms of the time duration for which particular river levels were held. Rather similar benches built of mud and sand laminae have also been described from Australian suspended-load rivers by TAYLOR and WOODYER (1978). After deposition of the part of the sheet cut by this outcrop at Pertusa, a small channel incised into its upper levels, and was then plugged by sediment.

Another sandstone sheet body at Pertusa (Fig. 7c) is typical of the large number of *complex sheets*. The sheet has an irregular upper and lower surface, irregularities often corresponding in form and size to the channel forms and sediment bars that can be identified in parts of the sandstone sheet today. The internal structure of the sheet is *multistorey*, and *multilateral* in terms of the sequences of cutting and filling of individual component bodies some of which are component ribbons formed by plugging of incised channels (eg 4). The sheet as a whole, then, provides abundant evidence of lateral migration of channels, and of vertical, upward, and downward, movement of channel talweg.

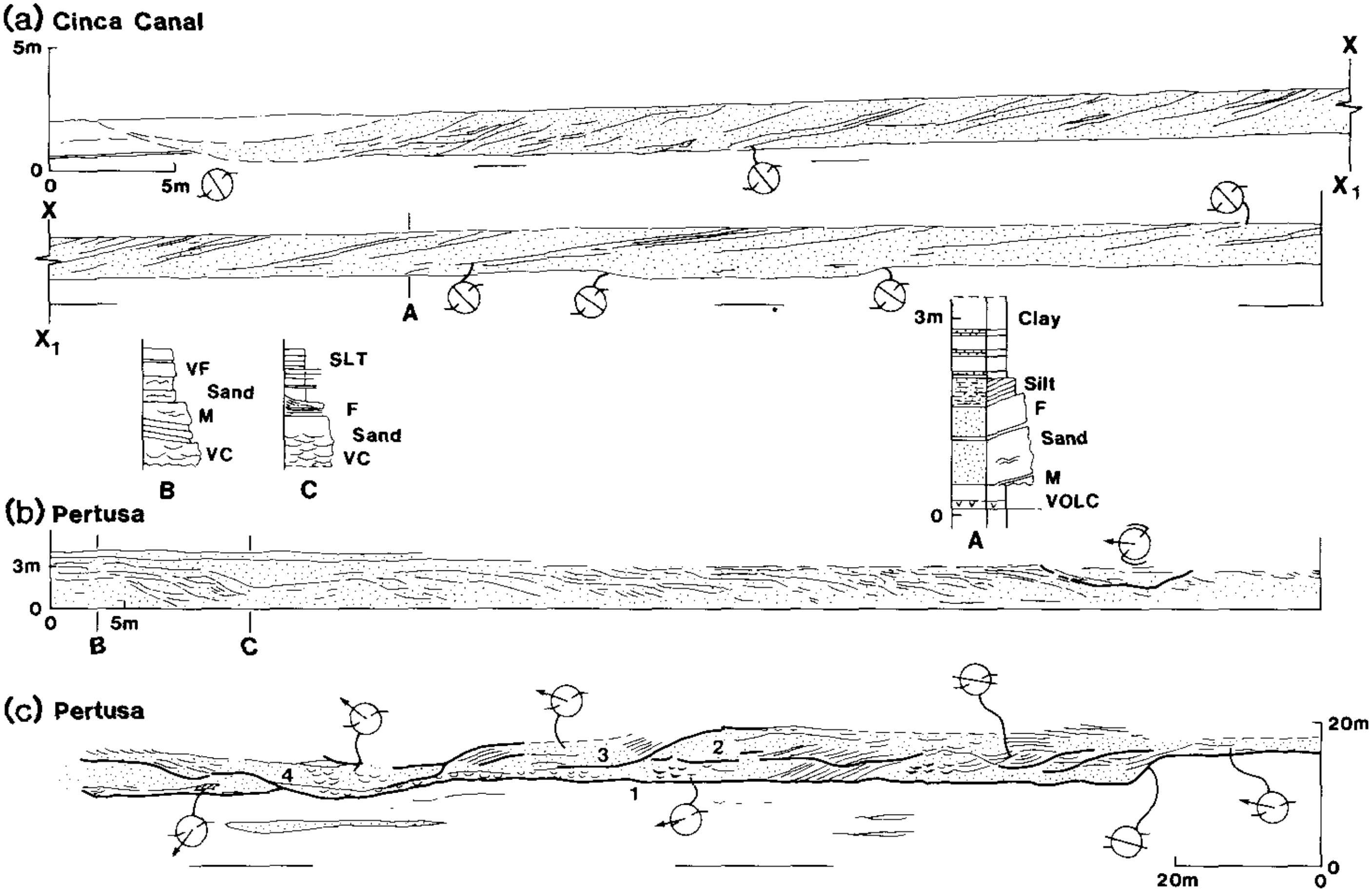
Some sheet sandstone bodies are thought to be the result of essentially *unchannelised* or sheet flow. These sheets tend to have planar contacts with the underlying alluvial mudrock, and are often a few cm or tens of cm thick. They characteristically lack evidence of channel forms as well developed bars or large bed-forms, and this is presumably because the flows were either not active or active enough, for periods long enough, to allow these typical river features to develop. Many sandstone body wings pass into sheet sandstone bodies of this unchannelised type, and must have formed in short episodes of overbank sheet-flood.

Other sheet sandstone bodies appear to be the result of *poorly channelised* flow. These are generally thin sheets that wedge out laterally, often showing width/depth ratios of 15 to 50. They sometimes have irregular bases suggesting incomplete episodes of channel incision.

5. RIVER PROCESSES OF AMALGAMATED COMPLEXES

Where sandstone-bodies consist of complexes with component ribbons and sheets that cannot be readly differentiated, without very detailed local study of relationships, then it becomes useful to be able to place them in this third category.

Figs. 8a & b represent two examples, from La Serreta and Pertusa, respectively. The same examples are illustrated in terms of their external body form in Fig. 4.


(a) Cinca Canal
5m
0
0
5m
X
X1
X
X1
A
3m
0
Clay
Silt
F
Sand
M
VOLC
A
VF
Sand
M
VC
B
SLT
F
Sand
VC
C
(b) Pertusa
3m
0
0
5m
B
C
(c) Pertusa
1
2
3
4
20m
0
20m
0

At the example chosen from La Serreta (Fig. 8a), a rather arbitrary division into 5 component sheets will help the analysis. Component sheets 1 and 2 are simple tabular sheets, and sheet 1 was deposited by a westerly flow. The first geometrical irregularity of major note involves sheet 4 which terminates abruptly towards the eastern end of the outcrop. At this point its high-angle basal scour-surface cuts down through over 2 m of alluvial mudrock and 4 m of sheet 3. This termination appears to result from a channel cut and fill sequence, which then appears to have been followed by relatively steady lateral migration of the channel in a southwesterly direction, with a SSE flow direction, leaving lateral accretion sands on an irregular scour-surface over the rest of the outcrop to the southwest. Component sheet 5 is a complex type, with features suggesting vertical and lateral accretion some of them of channel bar size and morphology.

Each of these component sheets 1 to 5 would be similar to many other sheet sandstone bodies if resting in a matrix of alluvial mudrock. However because of their amalgamation, by erosion, and the low proportion of alluvial mudrock, they together form a sandstone-body complex.

Our second example, chosen from work at Pertusa, shows another amalgamated sandstone body complex, consisting of 3 component sheets formed by easterly and southeasterly flows that overly a partially exposed ribbon, formed by a westerly flow.

The structures within the sandstone component bodies of these complexes are very similar to those formed by the river channels that constructed the distinct ribbons and sheets elsewhere. The essential difference is that, in building complexes, the erosion and migration of the channels brought them into contact with older sandstone bodies, causing amalgamation. The balance between construction of sandstone

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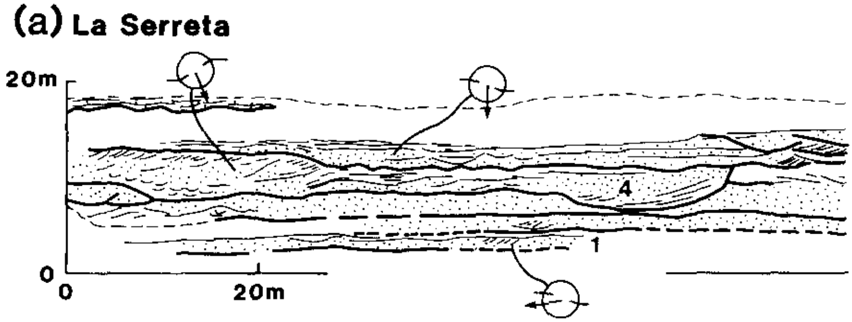
FIG. 7.—*Vertical-plane profiles across sandstone bodies with some logs through the bodies. Sandstone is stippled. Circles indicate, relative to north at top of figure, strike of planar features (diametrical lines), palaeoflow direction (arrows,) orientation of profiles (ticks on circumferences of circles). a) cut for Cinca irrigation canal, location is 16 km SSW of Huesca city, map reference 080530, b) cut for Cinca irrigation canal, 25 km SE of Huesca city, 1.4 km W of Pertusa, map reference 356544, c) gorge wall of Rio Alcanadre, immediately west of Pertusa, 25 km SE of Huesca city, map reference 378543.*

FIG. 7.—*Perfiles en secciones verticales de los cuerpos arenosos con algunas columnas. Las areniscas se representan con puntos. Los círculos indican: dirección de las formas planares (diámetros), dirección de las paleocorrientes (flechas), orientación de los perfiles (marcas en el borde de los círculos); todo ello referido al norte situado en la parte superior del círculo. a) Corte del canal de riego del Cinca, situado a 16 km al SSW de la ciudad de Huesca referencia del mapa 080530). b) Corte del canal de riego del Cinca, situado a 25 km al SE de la ciudad de Huesca, a 1,4 km al W de Pertusa (referencia del mapa 356544). c) Ladera de la garganta del río Alcanadre, inmediatamente al oeste de Pertusa, a 25 km al SE de la ciudad de Huesca (referencia del mapa 378543).*



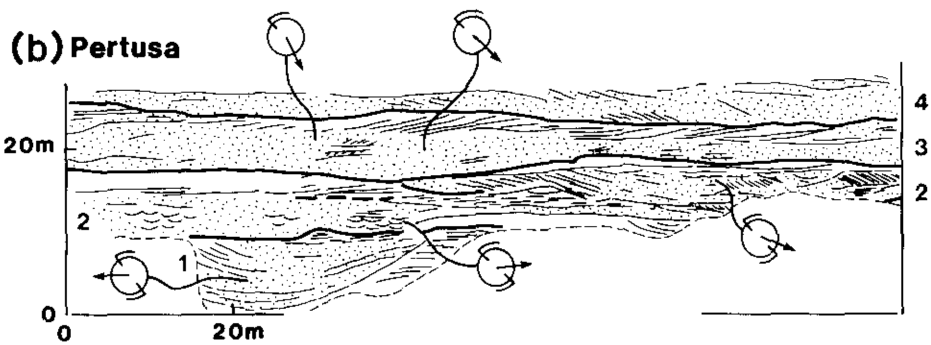


FIG. 8.—*Approximately vertical-plane profiles of sandstone bodies. Sandstone is stippled. Circles indicate, relative to north at top of circle palaeoflow directions (arrows) and orientation of profiles (ticks inside circumference indicate orientation, extensions outside circumference point towards relevant ends of profiles). a) La Serreta, b) Pertusa, details given in caption for Fig. 4.*

FIG. 8.—*Secciones verticales de los cuerpos arenosos. Las areniscas se representan con puntos. Los círculos indican las direcciones de paleocorrientes (flechas), referidos al norte situado en la parte superior del círculo, así como la orientación de los perfiles (las marcas interiores a las circunferencias indican la orientación, las extensiones hacia fuera de las circunferencias apuntan hacia las terminaciones destacables de los perfiles). a) La Serreta. b) Pertusa (para los detalles ver el pie de la Fig. 4).*

bodies, and accumulation of alluvial mudrock, was strongly biased in favour of the sandstone bodies. We shall consider possible reasons for this in the next section.

6. DISCUSSION OF ENVIRONMENTAL CONTROLS

Our object, in this discussion, is to point out the sorts of factors that may be responsible for the variety of sandstone body types that we have just described. In another paper we shall re-examine these ideas using our analysis of the time and space arrangement of the sandstone bodies in the alluvial systems already outlined (Fig. 1).

a) *Ribbons or sheet sandstone bodies?*

Our discussion of the detailed examples above has demonstrated the essential difference in river channel behaviour that distinguishes our two major types of sandstone body. Ribbons are the result of a major episode of channel incision, followed by one or many episodes of plugging of the channel, with or without well-formed in-channel bars.

In some cases the first channel was the approximate site of later channels eroded to different levels and shapes. It is possible that the 'first' channel was preceded by smaller ones whose traces were later obliterated. The characteristic feature of all ribbon forming channels is that they did not move laterally by significant amounts of channel bank erosion, during the ribbon-forming sequence of events.

In contrast, when sheet sandstone bodies were formed by channels, the sheets were constructed by lateral movement of the channels involving channel bank erosion. Some sheets (Figs. 7a and b) show evidence that this bank erosion was a steady process, so that the channel moved systematically and regularly by steps of metres, leaving lateral accretion sands behind. In other sheets (Fig. 7c), sequences of steady movement and lateral accretion were separated by avulsion jumps and new incision of the channel.

Possible factors that might influence whether a river channel was stable or unstable laterally are listed next.

1) Ephemeral, or flashy, river flow or frequent avulsion might result in lateral channel stability, simply because insufficient time was available to allow lateral channel erosion.

2) Strong downward erosion of the channel floor might inhibit lateral erosion by the channel. This downward erosion could result from local tectonic uplift of the alluvial surface or relative lowering of river base-level downstream. Incised river meanders are results of these events.

3) Increased resistance to erosion on the part of the channel bank material might create lateral stability. Differences in the petrology, cementing properties or vegetation cover might produce this effect, in response to changes in climate, hydrology or detrital supply.

The close association of both sandstone body types in single alluvial systems in the northern Ebro basin of Aragon, makes it difficult to believe that factors 2 and 3 were the dominant ones. However, systematic downstream variation in factor 1 does seem likely, and is the explanation we prefer.

b) *Separated or amalgamated sandstone bodies?*

The rate at which alluvial mudrock accumulates in a river basin will depend on many factors.

1) The rate at which water is supplied to the alluvial area.
2) The degree to which the flood waters are ponded during flood in the alluvial area.
3) The rate at which mud becomes incorporated in the river flood waters.
4) The rate at which mud deposited in the alluvial area is re-eroded by river action.

In the case of the Miocene deposits of the Aragon part of the Ebro basin, there was no through-flow of river water to the sea and all sand and mud transported into the basin was trapped as alluvium or as deposits of mud-playas within the basin. Indeed the significant quantities of lacustrine carbonate (CABRERA, COLOMBO and ROBLES, 1985) show that much of the clastic sediment from the catchment of the basin, was trapped in the alluvial systems before the basin centre was reached.

ALLEN (1978), and BRIDGE and LEEDER (1979), used quantitative models to examine factors that might control the concentration of sandstone bodies in an alluvial formation. In these models, high density (amalgamation) of sandstone bodies was caused by changing the following variables

1) increasing the width and/or depth of the individual sandstone body
2) increasing the frequency with which avulsion of the river system takes place
3) decreasing the width of the zone over which avulsion may cause re-routing of rivers
4) decreasing the subsidence rate of the alluvial surface
5) decreasing the alluvial aggradation rate
6) concentrating river paths by tectonic tilting of the alluvial surface (e.g. by half-graben growth).

We would expect factors 1) & 2) to be principally influenced by climatic changes, whereas factors 3), 4) & 6) would be principally influenced by tectonic changes. Factor 5) would, perhaps, be influenced importantly by both.

The alluvial systems of the northern Ebro basin of Aragon (Fig. 1) show a general tendency to proximal amalgamation and distal separation of the sandstone bodies. Our work confirms that the proximal sandstone bodies are, in general, thicker (factor 1), reflecting deeper rivers proximally that became shallower downstream (Friend, 1978). The other factor that we can identify is the lateral limitation, in the proximal areas, of the zones over which the rivers were free to avulse (factor 3). This limitation was caused by the presence of basin margin mountains, between the main feeder valley mouths, reflecting directly the emergence, at the surface, of southern Pyrenean thrust-sheet Mesozoic rocks (Fig. 1). This relationship is being described, in another publication, by Hirst and Nichols (in press, Special Publication of International Association of Sedimentologists, Foreland Basins Meeting 1985, University of Fribourg, Switzerland).

7. ACKNOWLEDGEMENTS

Many people in northern Spain have helped to make this work an enriching experience. On the scientific side, the support and advice of Professors Oriol Riba and Joaquín Villena, and of Dr. Cai Puigdefabregas have been invaluable. Our work has also built on the earlier field studies of Drs. M. J. Slater and R. C. Williams. Our research has been supported by the United Kingdom Natural Environment Research Council, and by a Shell Research Studentship (J.P.P.H.), and NERC Studentship (G.J.N.).

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