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Processes, facies and architecture of fluvial distributary system deposits

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Abstract

There is evidence from the stratigraphic record of examples of fluvial deposits that were the products of deposition from river systems which had decreasing discharge down-flow and transitions from proximal, channelised to distal, unconfined flow. These deposits form fan-shaped bodies several tens of kilometres in radius, and their stratigraphic architecture is aggradational, with no evidence of deep incision driven by base-level fall. The fluvial systems that generated these deposits formed under conditions for which there is no complete analogue today: an endorheic basin with a relatively arid climate adjacent to an uplifted area with higher precipitation. A conceptual model for fluvial systems of this type has therefore been built on the basis of outcrop examples and a consideration of the controls on sedimentation. Proximal areas are characterised by amalgamated coarse, pebbly and sandy channel deposits with little preservation of overbank facies. Channel dimensions are generally smaller in the medial areas, but sizes are variable: deposits are of braided, meandering and simple channels which show varying degrees of lateral migration. The channel-fills may be mud or sand, with overbank flow processes playing an important role in filling channels abandoned on the floodplain after avulsion. The proportion of overbank deposits increases distally with sheets of sand deposited as lateral and terminal splays by unconfined flow. Interconnection of sandstone bodies is poor in the distal areas because channel-fill bodies are sparse, small and are not deeply incised. The radial pattern of the sediment body forms by the repeated avulsion of channels: active channels build up lobes on the alluvial plain and rivers switch position to follow courses on lower lying areas. The term ‘fluvial distributary system’ is here used to describe a river system which has a downstream decrease in discharge and has a distal zone which is characterised either by terminal splays on to a dry alluvial plain or a lake delta during periods of lake highstand.

Keywords: Fluvial distributary system; Terminal fans; Fluvial fans; Endorheic basins; Fluvial stratigraphic architecture

Contents

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1. Introduction

Friend (1978) pointed out that some ancient river systems seem to show features that distinguish them from many modern-day river systems. He recognised three distinctive characteristics that could be recognised in ancient fluvial stratigraphic units: (1) a downstream decrease in river depth, (2) an absence of alluvial incision and (3) a convex-upwards, lobate topography of the river systems. He suggested that these features indicated deposition by a distributive river system which formed a 'terminal fan'. Subsequent work in one of the areas of Friend's original studies, the Ebro Basin, established more details of the sedimentology of two 'fluvial distributary systems' of Miocene age (Hirst and Nichols, 1986; Nichols, 1987; Friend, 1989; Hirst, 1991). The concept of terminal fans was also expanded by Kelly and Olsen (1993) with reference to some Devonian examples. In this paper we summarise the architectural characteristics of fluvial systems of this type and consider the tectonic, climatic and related base-level controls on their formation and preservation. Examples from the Miocene of the northern Ebro Basin are used to illustrate the characteristics of these systems, which are typically tens of kilometres in radius and are comprised of fluvial channel and overbank deposits which vary in relative abundance and character between proximal and distal areas. Comparison is also made with other subaerial fan deposits, including alluvial fans, fluvial fans and megafans, and the usage of different terminology considered. The term 'fluvial distributary system' is used in preference to 'terminal fan' for reasons which are discussed in later sections.

2. Characteristics of a fluvial distributary system

Conceptual models for a fluvial distributary system are shown in Figs. 1 and 2. These have been developed from earlier models presented in Friend (1978), Nichols (1987, 1989), Kelly and Olsen (1993) and Stanistreet and McCarthy (1993) with the addition of data from other sources (e.g. Graham, 1983; MacCarthy, 1990; Sadler and Kelly, 1993; Williams, 2000; Nichols, 2004, 2005; Fisher et al., 2006-this volume) and new observations in the Ebro Basin. The locations of the examples from the stratigraphic record used in this review are shown in Fig. 3.

2.1. Dimensions of the sedimentary unit

The radial distance from the apex to the distal fringe of the system is in the order of tens of kilometres: the Luna and Huesca systems in the Miocene of the Ebro Basin are respectively 40 and 60 km radius (Hirst and Nichols, 1986), the systems in the Devonian Munster

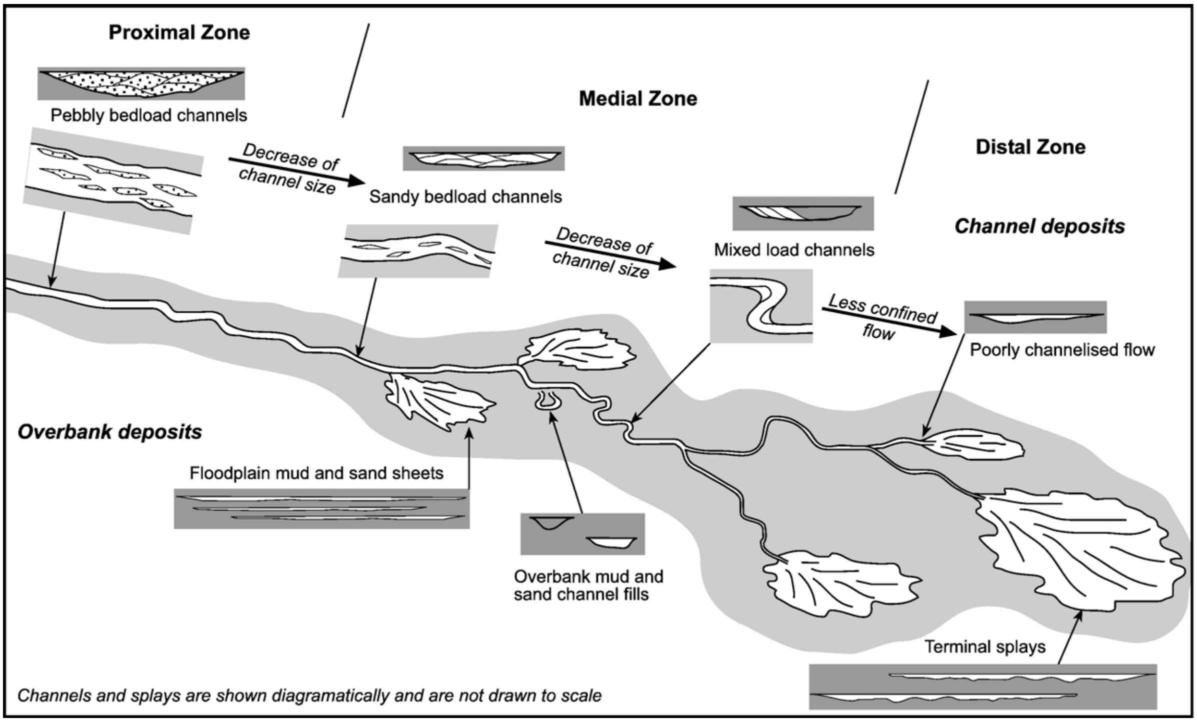

Fig. 1. Proximal to distal trends in channel and overbank processes across a fluvial distributary system: channel forms, floodplain deposits and architectural elements. The proximal to distal extent of the system is likely to be tens of kilometres.

Basin in southern Ireland are up to 120 km radius (Williams, 2000) and the system in the Wood Bay Formation of the Devonian of Spitsbergen is up to 200 km long (Friend and Moody-Stuart, 1972). The extent of a system would be determined by the size of the basin and the balance between water supply and loss due to evaporation/infiltration, so it would be possible to have deposits covering a larger area than the examples given. The thickness of the succession will be limited by the accommodation in the basin below the spill point, the level at which water flows out of the basin and it ceases to be endorheic (Bohacs et al., 2000), and the sediment supply. There is approximately 4000 m thickness of fluvial strata in the northern part of the Ebro Basin (Nichols, 1987) and the Munster Basin fill is over 6000 m thick (Graham, 1983; MacCarthy, 1990; Sadler and Kelly, 1993).

2.2. Proximal facies

The coarsest deposits occurring in the deepest channels are found in the proximal zones of the systems. These are sandy or conglomeratic facies showing clast imbrication, cross-bedding and preservation of bar structures indicating that they are the deposits of braided streams close to margin of the basin (e.g. Graham, 1983; Nichols, 1987; MacCarthy, 1990; Sadler and Kelly, 1993). The proximal channel-fills in the Luna System are reported to be up to 7 m thick (Nichols, 1987) and in the Munster Basin the channel-fill successions are at least 10 m thick (MacCarthy, 1990). In the Devonian of East Greenland, proximal zone facies in the Snehvide Formation are sandy braidplain succession of medium-grained, trough-cross bedded pebbly sandstones and fine pebble conglomerates (Friend et al., 1983). In these and other proximal zone examples, there are no associated fine-grained overbank deposits preserved, and the channel-fill facies are entirely amalgamated. This indicates that the channels were mobile, laterally migrating and reworking the adjacent floodplain deposits or repeatedly avulsing to new positions on the proximal floodplain area. The interconnectedness of the coarse facies is therefore 100% in the proximal zone. Stacks of sandstone and conglomerate can be recognized in borehole core as the deposits of the proximal parts of a fluvial distributary system, for example in the Devonian strata in the Clair Basin, West of Shetland (Nichols, 2005). The extent of the proximal zone is limited to between 5 and 10 km from the system apex in the Luna System (Nichols, 1987) whilst in the Munster Basin there are conglomeratic fluvial deposits over 40 km from the basin margin (MacCarthy, 1990; Williams, 2000).

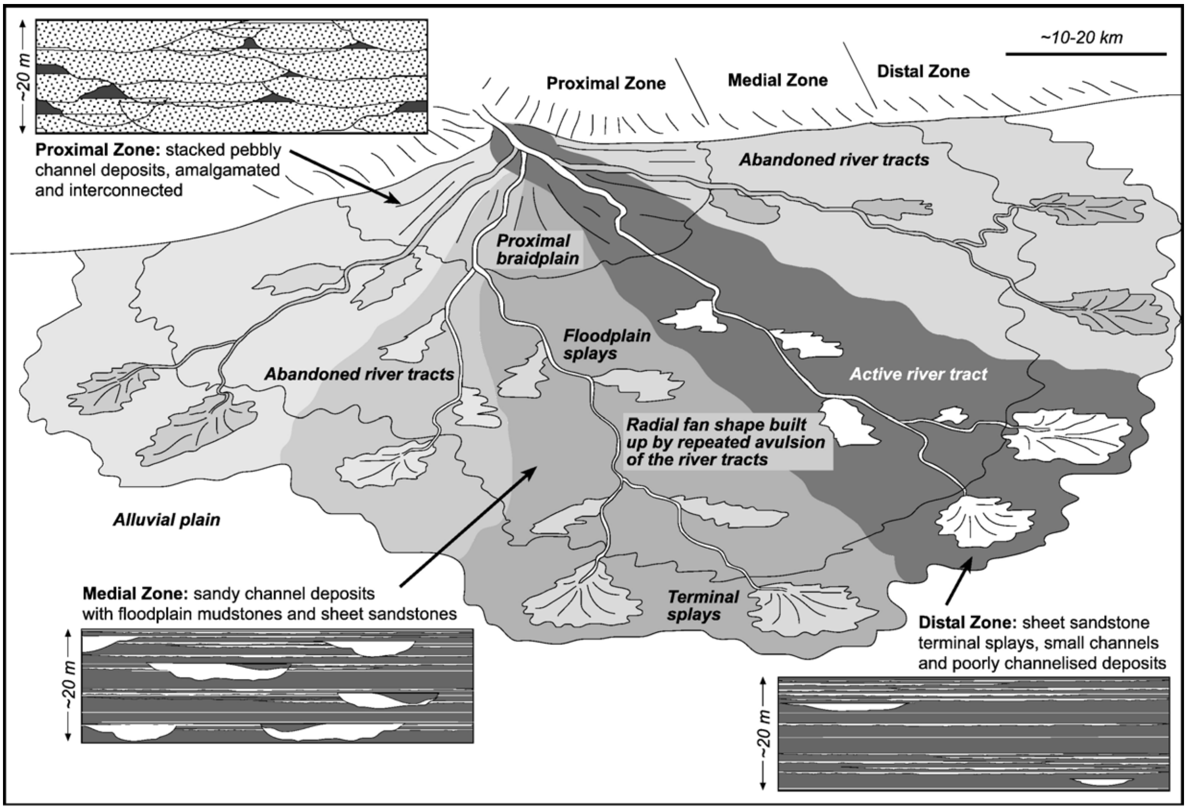

Fig. 2. The development of a fan-shaped body of sediments by repeated avulsion of the river channel and the architectural characteristics of the proximal, medial and distal zones of a fluvial distributary system. The area of deposition is likely to be tens of kilometres radius.

2.3. Medial facies

The transition from the proximal to the medial zone is marked by an increase in the proportion of overbank facies preserved and a decrease in the clast size of channel-fill facies. In the Munster Basin the channel facies are commonly trough-cross bedded sandstones and pebbly sandstones occurring in multi-storey complexes tens of metres thick (Graham, 1983; Sadler and Kelly, 1993). The bases of the channel complexes are not deeply incised into the floodplain facies and are interpreted as the deposits of laterally mobile bedload streams (Sadler and Kelly, 1993). Medial zone deposits in the Ebro Basin are rarely pebbly, and are also partly interpreted as the deposits of laterally mobile streams. However, Hirst (1991) has demonstrated that the width of the channel-fill sandstone bodies decreases downstream: at 25 to 35 km from the apex of the Huesca System 80 to 90% of the sandstone bodies have width: thickness ratios >15:1 whereas in the more distal exposures 50 to 60 km from the apex only 5 to 35% have width:thickness ratios >15:1. These data indicate that the channels tended to become more laterally stable down-system, a trend also noted by MacCarthy (1990) in the Munster Basin.

The percentage of deposits 'in-channel' was documented from measurements made of over 250 channel sandstone bodies across the Huesca System in the Ebro Basin by Hirst (1991). In the medial area, at 25 km from the calculated apex 62% of the deposits occupied channels, and this decreased to values of 30 to 40% between 40 and 45 km, and further decreased to between 10 and 15% at distances of 45 to 50 km from the apex. Similar trends have been qualitatively established in the Devonian examples from Ireland (Graham, 1983; MacCarthy, 1990; Sadler and Kelly, 1993), Spitsbergen (Friend and Moody-Stuart, 1972) and East Greenland (Friend et al., 1983).

The channel-fill bodies are enclosed within strata which are overall finer-grained, consisting mainly of mudrocks and thin sheet bodies of sandstone (Fig. 4a, b). These overbank deposits may show evidence of desiccation or soil formation. Calcareous pedogenic features are noted from the purple siltstone floodplain facies in the Munster Basin (Graham, 1983). The pale brown mudrocks which dominate the overbank facies

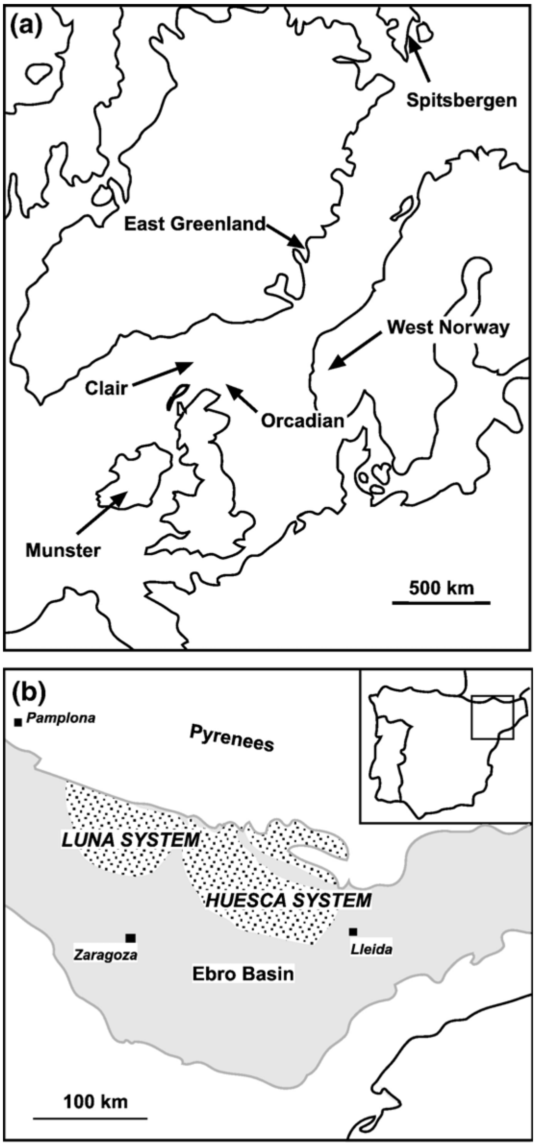

Fig. 3. Locations of examples of fluvial distributary systems from (a) the Devonian (palaeogeographic reconstruction from Friend et al., 2000) and (b) the Miocene of the Ebro Basin, Spain.

association in the Ebro Basin show relatively weakly developed palaeosol profiles (Nichols, 1987). The sandstone sheets are thin, typically only a few centimetres thick, and laterally extensive over tens of metres: they have sharp bases and show some current ripple cross-lamination. Sandstone sheets tend to occur in packages separated by metres of mudrock.

2.4. Distal facies

The distal reaches form the most distinctive elements of the fluvial distributary systems. They are characterised by a very high proportion of floodplain facies, with channel-fill deposits comprising only a few percent of the strata. In the Huesca System, the percentage, by volume, of deposits 'in-channel' was shown to be 10% or less at distances of over 50 km from the apex of the system (Hirst, 1991). In the Luna System, Nichols (1987) reported that the thickness of the channel-fills are on average less than in the medial zone, decreasing to an average of just over 2 m. Distal facies in the Munster Basin similarly display fewer and thinner channel-fills than the proximal and medial zones (Graham, 1983; Sadler and Kelly, 1993), and many of these channels are shallow and rather poorly defined.

In the Ebro Basin artificial exposures created by road and canal cuts allow the internal geometries and fills of the channels to be examined in exceptional detail (see Fig. 4). Channel scours wholly or partly filled with mudrock are seen to be relatively common: some are simple scour and fill deposits, others show evidence of lateral migration of the channel, with sand deposited on lateral accretion surfaces on the inner bank of a meander bend and a final fill with mud (Fig. 4d). Channel scours of a variety of sizes which are wholly filled with sandstone also occur (Fig. 4c) and the processes of formation of these deposits are considered in a later section.

A prominent feature of the distal zones is that much more sandstone is present as thin sheet deposits than as channel-fill facies. These sheets have sharp, sometimes erosive base and this scouring at the base of the sheets suggest local channelisation of flow (e.g. Fig. 4g; Graham, 1983). Isolated sheets may occur, but mostly they are found in packages of laterally extensive units (Fisher et al., 2006-this volume). Between the sheet sandstone beds, thick-bedded muddy and silty facies show evidence of palaeosol development (Sadler and Kelly, 1993; Fisher et al., 2006-this volume).

2.5. Distributary pattern

A characteristic of these fluvial systems is that the pattern of flow indicated by palaeocurrent data has a radial, distributive form. This was first noted by Friend (1978) and a subsequent statistical study of palaeocurrent readings from 350 palaeochannels in the Luna System by Jupp et al. (1987) demonstrated that an apex lying at the basin margin could be defined. In other examples the channel pattern may be elongate and less clearly radial, (e.g. in the Munster Basin, Williams, 2000) but the distributive character of the channels is a common feature. The implication of these patterns is that each of the systems was supplied by a river which entered the basin at a point along the margin, and then spread out onto the

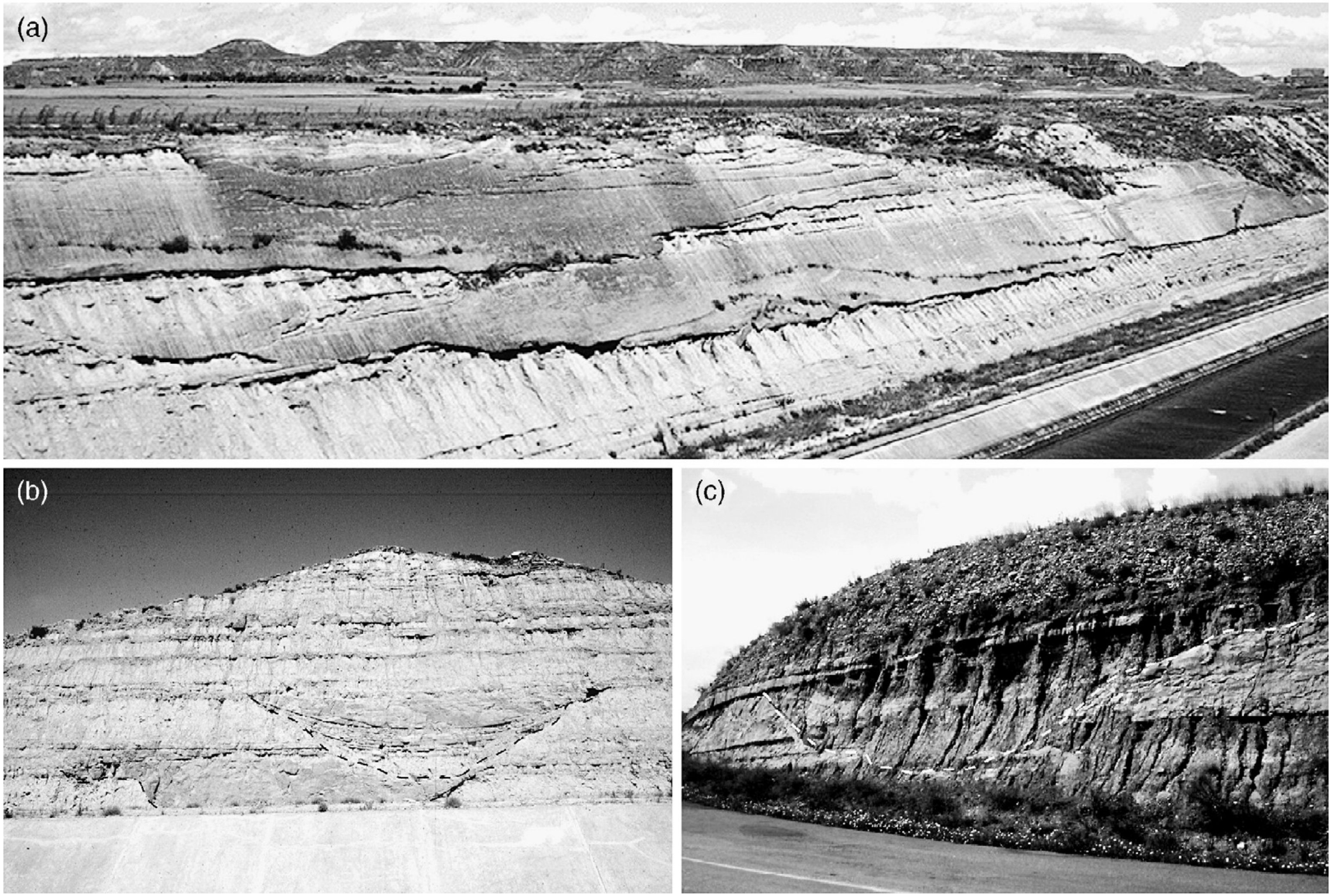

Fig. 4a-c. Examples of channel and overbank facies from the Luna and Huesca Systems, Miocene, Ebro Basin, Spain. (a) Sandstone bodies representing the fill of channels up to 10 m deep in the medial part of the Huesca System. This is in an area of the medial part of the system where channel-fill deposits represent between 30 and 40% of the succession. (b) Channel-fill sandstone bodies between 2 and 3 m thick in the medial Luna System. The fill of the lower channel is partly eroded by the later channel, which shows a complete fill of sandstone, interpreted as the result of overbank deposition (see text). (c) A channel scour 2.5 m deep filled largely with mudstone: the scour cut into sandy channel deposits (right) and overbank facies (left).

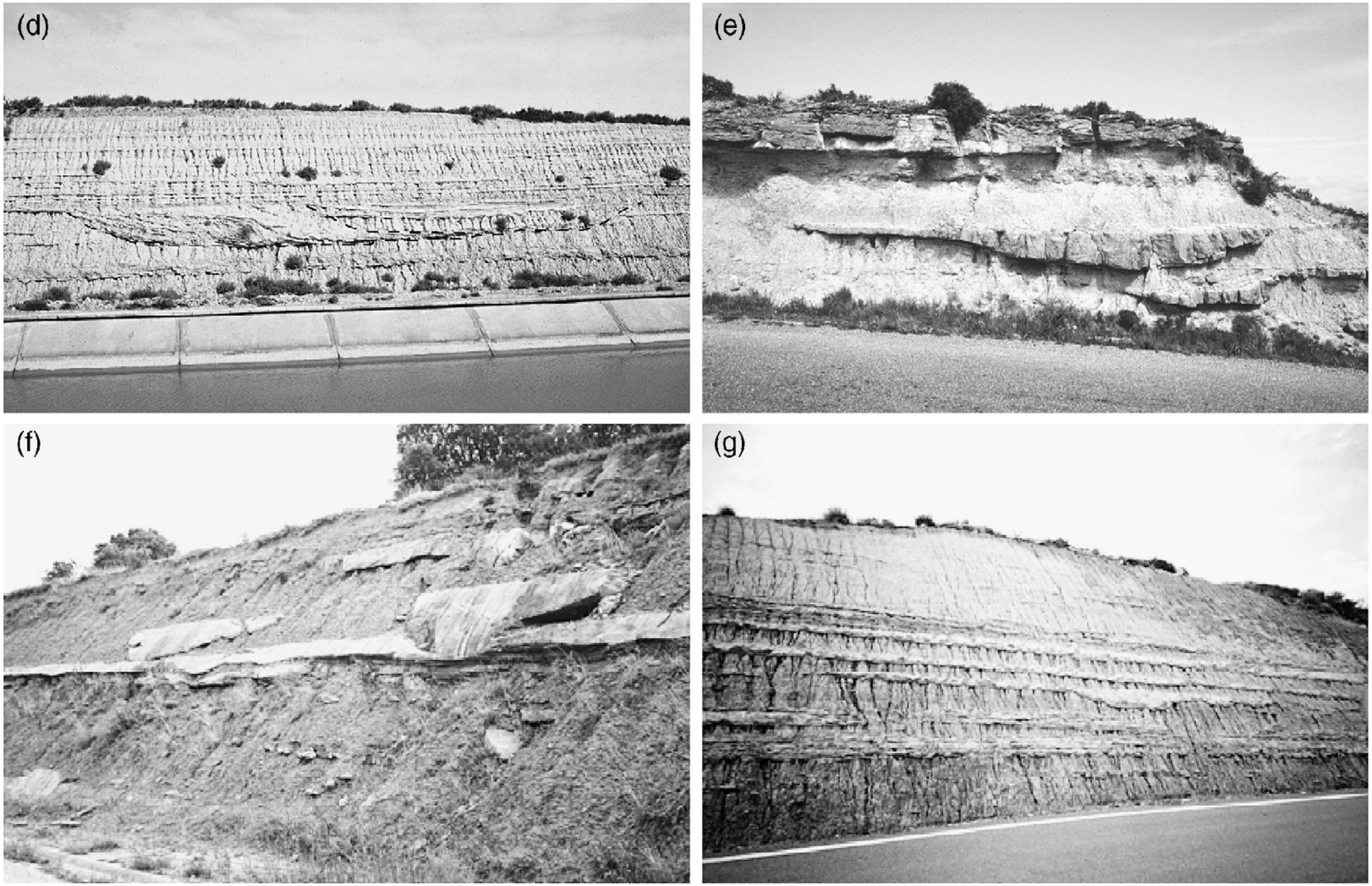

Fig. 4d-g. Examples of channel and overbank facies from the Luna and Huesca Systems, Miocene, Ebro Basin, Spain. (d) Sandstone with lateral accretion surfaces dipping to the right partially fills this 2 m deep channel in the medial to distal parts of the Huesca System: the right side of the channel-fill is a mixture of mudstone and sandstone beds. (e) A small, 1 m deep, channel scour in distal Luna System deposits, filled with sand when the channel lays abandoned on the floodplain. (f) Mudstone and a sheet sandstone incised by small channel scour less than a metre deep in the distal parts of the Huesca System. (g) Sheet sandstone bodies up to 0.5 m thick in the distal Luna System: some show erosive bases (centre), and most are composite, made up of multiple, thinner sand sheets.

alluvial plain. More than one entry point for a distributary system is indicated by Arenas et al. (2001) for the Luna System, although it is possible that each was active at different stages in the evolution of the system. In the Munster Basin there may have been several coeval entry points (Williams, 2000).

3. Fluvial channel and overbank processes in a distributary system

The fluvial channel and overbank facies described from the examples of fluvial distributary systems in the stratigraphic record can be used to determine the depositional processes which are acting in different parts of a system. These may be used to develop a conceptual model for an active fluvial distributary system (Figs. 1 and 2).

3.1. Trends in fluvial channels

The apex of the system lies at a point along a basin margin where drainage from the hinterland is funnelled into the basin (Hirst and Nichols, 1986). A gradient change as the river enters the basin promotes deposition of sediment. River channels in the proximal areas are typically bedload-dominated and may be pebbly or sandy. Cross-bedding and the preservation of bar forms suggest deposition in braided rivers (Collinson, 1996): discharge must be sufficient to carry coarse gravel, and over long enough periods for braided river bar forms to develop. The absence or limited preservation of overbank facies indicates mobile rivers repeatedly avulse or migrate to different positions near the apex. Strong currents in the channel scour the banks and inhibit the growth of vegetation which could stabilise the channel margins. The area near the apex of the system would therefore be expected to have the appearance of a braidplain, somewhat similar to a gravelly glacial outwash deposit (Boothroyd and Ashley, 1975; Boothroyd and Nummedal, 1978).

Downstream the proportion of gravel in the river channel decreases and the bedload is mainly sand deposited on mid-channel bars, with gravel limited to basal lags. The depth of the channel decreases and it may become less laterally mobile: floodplain areas are less frequently occupied by channels, allowing vegetation to have a more pronounced stabilising effect on the banks. The role of vegetation on bank stability would not have been a factor in pre-Devonian times, and may have had a limited effect in the Devonian (cf. Fraticelli et al., 2004). A progressive reduction in discharge downstream due to evaporation and infiltration of water into the floodplain occurs along with a decrease in the grain size of material carried and a decrease in the river gradient. The channel dimensions become progressively smaller, and there is a transition from bedload to mixed load character. As the outer edge of the medial zone is reached the river channel becomes sinuous, showing evidence of meandering, straight or possibly anastomosing habit (Stanistreet and McCarthy, 1993).

3.2. Discharge variations

Fluvial systems may be subject to fluctuations of discharge because of seasonal rainfall variations in the hinterland catchment area. The high rates of water loss through evaporation and soak-away in a fluvial distributary system mean that during periods of lower discharge the outer parts of the system may not receive much or any water, even if there is still some supply to the proximal zone. Evidence of discharge fluctuations is therefore to be expected, especially in the medial and distal parts of the system. A channel may experience periods of slack water during which mud will be deposited in the shallow parts of the channel: this may be preserved as drapes on bars and is particularly well displayed on the lateral accretion surfaces of meandering rivers (Fig. 4d). Total desiccation of a channel may occur, with evidence of this preserved as mudcracks on mud layers within a channel-fill succession (Nichols, 1987).

3.3. Floodplain deposition

In the proximal zone the floodplain consists of abandoned channel deposits, but in the medial zone overbank deposits are preserved. These are mostly mud deposited out of suspension during flood events, but there are also extensive sheets of sand deposited as splays from the channel margins. The thickness and extent of the sand sheets vary with the magnitude of the flood, and the bases of some show signs of scouring into the underlying sediment (Fisher et al., 2006-this volume). The sands may show parallel lamination or be current rippled, but generally they are structureless, possibly because of bioturbation or pedoturbation. Soils develop on the floodplain, but do not develop into mature profiles if rates of floodplain accumulation are relatively high. Aeolian reworking of the alluvial plain has not been recognised in the Ebro Basin, but has been noted in some Devonian basins (Kelly and Olsen, 1993; Richmond and Williams, 2000; Nichols, 2005).

3.4. Floodplain channel-fills

Sandy bedload may be preserved within a braided or meandering river if the active channel migrates laterally or the discharge decreases through time, resulting in a partial fill of the channel with sand (Fig. 4d). In-channel deposition may cause choking and trigger flooding and/or the avulsion of a river to a new position. The processes of avulsion leave a stretch of channel isolated from direct supply of sediment and water from the active channel. If the isolated, inactive channel tract is a relatively short distance from the active river, it may be filled with sand which fills the depression until it is level with the floodplain surface. Some simple sandstone channel-fills (Fig. 4e, f) are probably entirely deposits of overbank deposition from another channel, not the deposits of the confined flow which created the scour. The 'wings' which are preserved on the margins of some sandstone bodies (Friend et al., 1979) can sometimes be shown to be continuous with sand which filled the upper parts of the channel-fill body: the upper channel and the wing deposits are likely to have been formed after the channel was abandoned, and are the products of overbank flow from another, active channel. An abandoned channel that lies at a greater distance from an active channel may be filled with mud deposited out of suspension from flood events to form a 'clay plug' (Fig. 4c). The frequency of occurrence of mud-filled channels is likely to be underestimated in the stratigraphic record because it may be difficult to recognise them within a muddy overbank succession. A further possibility in the distal segments of a distributary system is a fill of a channel scour by lacustrine deposits if there is a lake level rise and the lake margin floods onto the overbank area. Therefore, although some of a channel body may be sediment that was deposited by in-channel flow, the final fill is more likely to be by unconfined flow after abandonment.

3.5. Distal zone sheets: terminal splays and floodouts

The distal reaches of the fluvial distributary systems are analogous to the floodout zones in Tooth (1999a,b). In the ephemeral rivers of arid central Australia, river channels commonly terminate in areas where the channel capacity is reduced and floodwaters spread across the alluvial surface forming terminal floodouts (Tooth, 1999a,b): these features are characterised by a transition from channelised to unchannelised flow. The floodouts in central Australia occur on a wide range of scales, from 1 km^2 to 1000 km^2, depositing sheets of fine-grained sediment. Tooth (1999a) showed that their occurrence is determined by the presence of barriers to flow, such as the presence of a build up of aeolian sands, or they may form where there is a downstream decrease in discharge. Both mechanisms are possible in the distal reaches of an aggrading fluvial system.

Features similar to terminal floodouts are also recognised in the Neales River, which is on the western side of the Lake Eyre Basin in central Australia. These are referred to as 'terminal splays' (Lang et al., 2004) and they are sheets of sand deposited by decelerating flows on the floodplain and on the dry lake bed. Their location is controlled by the incision of the river channel by base-level fall driven by falling lake level, and the river flow becomes unconfined at the edge of the dry lake bed (Lang et al., 2004). These terminal splay deposits show horizontal stratification, current ripple lamination and show subaqueous dune structures in places; the sheet sandstones of the distal zones of the ancient distributary systems such as the Munster Basin deposits (Sadler and Kelly, 1993) and Ebro Basin deposits are typically structureless, horizontally laminated or rarely ripple cross laminated.

A significant difference between either the floodouts or the terminal splays of central Australia and the sheets of sediment formed in the distal zone of the ancient fluvial distributary systems documented above, is the sediment supply. In central Australia the sediment supply is very low and the rivers are flowing very close to bedrock, which is exposed in places. In contrast, the distal fluvial distributary system deposits are documented from basins which have thick accumulations of sediment, and the preservation of both channel and overbank facies suggests higher rates of sediment supply. The ancient floodouts/terminal splays are therefore analogous in terms of processes, but the architecture of the deposits may not be comparable with the modern examples because of differences in sediment supply and other variables, such as flow magnitude.

3.6. Formation of a fan of fluvial deposits

The distributary system is built up as a series of incremental units deposited by individual rivers which flow from the apex to a point on the floodplain where their flow becomes unconfined (Fig. 2). During the lifetime of this river it will deposit sediment within the channel, on the adjacent areas of the floodplain during periods of overbank flow, and at the distal end of the channel as terminal splays onto the alluvial plain. The river may laterally migrate during this time, and local channel abandonment may occur due to meander cut-off or local readjustments of the position of the channel on the plain. The thickness of deposits will decrease away from the channel as floods deposit most of their load near the channel banks, and through time it will build up a very low amplitude lobate body on the basin floor. Areas adjacent to the fluvial sediment lobe will be at a lower elevation, and consequently avulsion of the active channel will occur, possibly at any point along the river from the apex down to the terminal splay. Repetition of this process will result in the active channel occupying different positions on the alluvial plain through time, with each avulsion redirecting the river to a nearby lower elevation course. This will eventually lead to the formation of a fan of fluvial sediments, a process recognised as the mechanism for the formation of megafans (see below, Wells and Dorr, 1987; Gohain and Parkash, 1990). At any one time, most of the system will be an inactive area, and these abandoned sectors will be subject to pedogenic modification and reworking of the surface by local run-off or aeolian activity.

3.7. Bifurcation of channels

Previous models of fluvial distributary systems have indicated that there is bifurcation of channels downstream (Friend, 1978; Nichols, 1987, 1989; Kelly and Olsen, 1993). Channel bifurcation is present in the distal zones of modern rivers which have terminal splays such as the Neales River (Lang et al., 2004) and the Markanda Fan (Parkash et al., 1983). Bifurcation of active river channels on a larger scale occurs in the Okavango Fan (Stanistreet and McCarthy, 1993), which has an almost horizontal depositional profile, but is not reported from the steeper active tracts of modern rivers. It is not possible to establish if two palaeochannels were coevally flowing, so it is not known if the fluvial distributary systems considered here would have had multiple active channels over large distances, but comparison with modern rivers suggests that it is unlikely, and more probable that bifurcation only occurred in the distal zones.

3.8. Proximal to distal extent of channels

The distance that a river will flow out into a basin in an arid setting will be determined by the balance between the rate of water supply from the drainage area and the losses along the way due to soak-away and evaporation. Sediment transport will be limited by these same factors and hence the proximal to distal extent of a distributary system will be determined by the climate in the hinterland, which governs the water supply, and the climate in the basin, which affects the rate of evaporation and the nature of the floodplain sediment, which will affect rates of infiltration. Variations in climate over both long and short time scales will result in a range of distances between the system apex and the terminal splays as the deposit builds up, and an interfingering of the proximal and medial, and medial and distal, zones is to be expected. A whole system may prograde or retrograde as the balance between supply and losses varies: this has been documented in the Luna System, Spain (Arenas et al., 2001).

4. Fluvial distributary systems and lakes

The conceptual model for fluvial distributary systems presented in Figs. 1 and 2 is valid for conditions where the river channels do not reach a basin centre lake. During periods of high discharge, unconfined flow from the terminal splays may spread out onto the alluvial plain and deposit suspended sediment out of a temporary standing body of water (Fisher et al., 2006-this volume). This body of water may be considered to be transitional to an ephemeral lake, depending on where the distinction between a temporary pond of water on an alluvial plain as a result of flooding and an ephemeral lake is drawn. If there are changes in the climate which either increases the water supply from the hinterland or reduces the evaporation in the basin (or both), then the alluvial plain will become a lake. This scenario is envisaged in the Devonian Clair Basin, in which transitions from fluvially-dominated units to lacustrine units within the vertical succession are attributed to climatic controls which determined the presence of, and extent of, a basin-centre lake (Nichols, 2005). Periods of higher lake level are also recognised in the Miocene of the Ebro Basin (Arenas et al., 2001) resulting in an interfingering of lacustrine and distal fluvial facies.

Once a lake is established in the basin the river system will no longer be terminal, and in place of terminal splays the channels will feed into a low relief delta, a 'lacustrine floodplain delta' (Blair and McPherson, 1994) such as the present day Volga Delta in the Caspian Sea (Kroonenberg et al., 1997; Overeem et al., 2003). Variations in lake level resulting in alternations in fluvial and lacustrine facies in a similar deltaic setting in the Pliocene of Azerbaijan have been recognised by Hinds et al. (2004). With lake level rise, the distal zone of a fluvial distributary system will be flooded and replaced by lake margin facies (Fisher et al., 2006-this volume), but the processes operating in the channels of medial and proximal zones will be largely unaffected. The raising of the water table will exert some influence of soil formation in the overbank areas, but otherwise the fluvial processes in the tracts of the river which are not influenced by the lake level will be the same whether the lake is present or not. A drying of the climate, a retreat of the lake shoreline and a subsequent fall in lake level will result in a return to the terminal character of the fluvial system, a state which is recognised in the Neales River in central Australia, where terminal splays are intermittently active on the former lake bed (Lang et al., 2004). This potential for fluctuation between a terminal fluvial and a lacustrine setting for the outer fringe of a fluvial distributary system is an issue which has to be taken into account when attempting to decide on appropriate terminology for these systems (see below).

5. Conditions for the formation of a fluvial distributary system: tectonic and climatic setting

Basins of internal drainage can form in a variety of tectonic settings, from extensional rift basins, such as the modern basins in the East African Rift Valley, to transtensional settings, such as the modern Dead Sea and the Devonian Orcadian Basin in Scotland, to foreland basins such as the Ebro Basin, Spain in the mid-Cenozoic. Accumulation of a thick succession of fluvial deposits would be facilitated by subsidence and a high basin margin sill, which prevents the development of an external drainage (Fig. 5). A number of the examples of fluvial distributary systems in the literature are from the 'Old Red Sandstone' (ORS) of what is now the North Atlantic area (Fig. 3a): these ORS deposits now outcrop in East Greenland, West Norway, Scotland and Ireland (Friend et al., 2000). The basins formed in the post-Caledonian phase, and lay in the middle of a large continental area created by the closure of the Iapetus Ocean. They are extensional and transtensional basins within and adjacent to the Caldeonian orogenic belt which provided the source of detritus to fill the basins with thousands of metres of clastic sediment.

During the Devonian the region where these basins formed lay close to the equator and in an intracontinental setting (Friend et al., 2000): the palaeoclimate would have been relatively hot, but the nearby mountains are likely to have been cooler areas with higher precipitation. Fluvial distributary systems can only form in basins which have a relatively warm and dry climate, where water losses through evapo-transpiration exceed the input from direct precipitation and rivers entering the basin. Desert basins are therefore the most likely settings, but only if they are adjacent to an upland area which has a much higher precipitation. A moderate supply of water is required to establish and maintain the rivers of the distributary system, and if this is not present, waterlain deposits are likely to be restricted to smaller alluvial fans at the basin margin where deposition is by debris flow or sheetflood processes (e.g. Death Valley, California). On the other hand, if an excess of water is supplied to an endorheic basin a lake will form and the river system will feed a lake delta. Favourable settings are therefore basins adjacent to, but in the rain-shadow of, mountainous areas. If the Ebro Basin was still endorheic, the modern climatic and tectonic setting may be suitable: rainfall in the Pyrenees is between 1000 and 2000 mm.a^{-1}, but the centre of the basin is semi-arid, with precipitation of around 300 mm.a^{-1} and summer temperatures reaching over 40 °C.

The supply of sediment to the distal area must exceed the rate basin-floor subsidence. This will ensure that the base-level in the basin rises as a result of basin-filling with sediment, and, consequently, the river gradient will be very low, tending to horizontal. Low gradient will

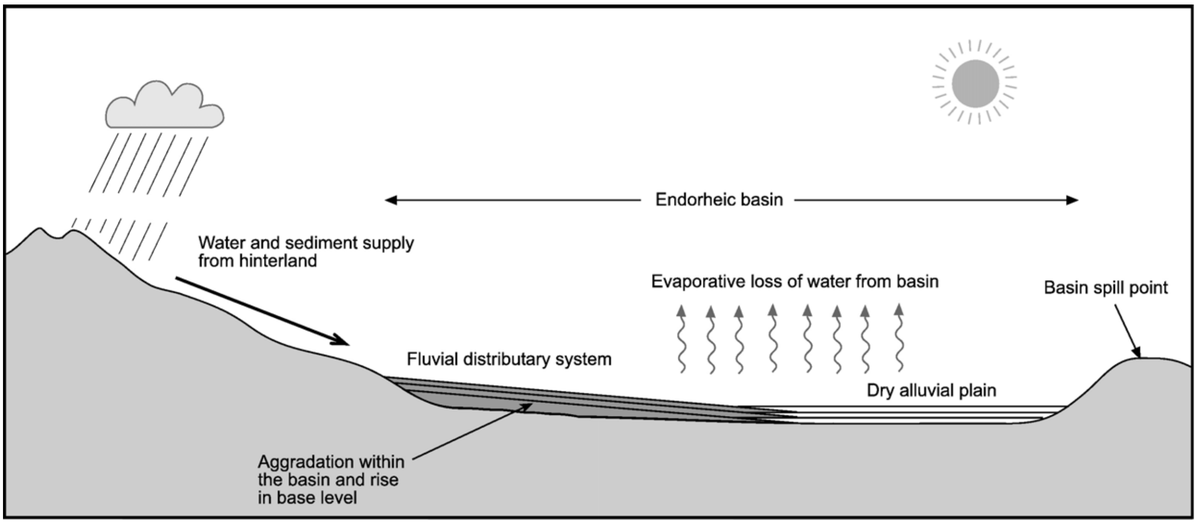

Fig. 5. Tectonic and climatic setting for the formation of fluvial distributary systems.

tend to promote avulsion because deposition around the active channel will create a lobe on the alluvial plain and the river may follow a new, steeper gradient path to the side of the lobe and thus create the fan shape that many fluvial distributary systems possess. An aggradational pattern of strata will form as sedimentary fill of the basin results in a rise in the base-level, provided that the discharge remains approximately the same and the fluvial system has the same extent into the basin.

6. Fluvial distributary systems, terminal fans, fluvial fans, megafans and lake deltas

6.1. Alluvial fans, fluvial fans, megafans, humid fans

The problem of terminology to be used in the description of fan-shaped bodies of alluvium has exercised a number of geologists and geomorphologists over the years. Blair and McPherson (1994) consider that the term 'alluvial fan' should be restricted to steep, debris flow and sheetflood dominated deposits, and draw a distinction between the processes and products of these alluvial fans and those of rivers. Such a distinction is not recognised by all workers in this field, and there are many examples of 'alluvial fans' in the literature which are the products of deposition by rivers (e.g. Nemec and Postma, 1993). Some authors refer to fans formed by the migration of channelised streams as 'fluvial fans': Collinson (1996) uses this term to encompass deposits ranging from small, steep fans as described by Nemec and Postma (1993) to the 'megafans' of the Ganges valley, such as the Kosi Fan documented by Wells and Dorr (1987) and Gohain and Parkash (1990) and the Ganga Megafan (Shukla et al., 2001). The term 'fluvial fan' or 'fluvial megafan' has been used for fluvial distributary systems, for example Arenas et al. (2001) for the Luna System in the Ebro Basin, Pennsylvanian deposits in the Paradox Basin, USA (Barbeau, 2003) and modern and Tertiary deposits in the central Andes (Horton and DeCelles, 2001). The modern 'megafans' are characterised by channels that have a through-flow of water and discharge is continuous into a channel downstream of the area of the fan: the fan morphology is a result of a change in slope promoting avulsion in a particular tract of the river. Use of the term 'humid fan' was originally coined in the context of fans of glacial outwash braidplain deposits (Boothroyd and Nummedal, 1978): recent work on the relationship between climate and processes on alluvial fans has shown that the concept of 'wet and dry fans' is oversimplistic, and sometimes misleading (Harvey and Wells, 1994; Harvey et al., 2005).

6.2. Subaerial and 'losimean' fans

Perhaps the most encompassing term is 'subaerial fan,' which Stanistreet and McCarthy (1993) use to include debris flow alluvial fans, braided river fans like the Kosi Fan, and what they term 'losimean' fans, of which the present day Okavango Fan in Botswana is their type example. The Okavango Fan is a large (150 km radius), very low gradient system with multiple distributary channels, some of which are active, others in the process of abandonment (Stanistreet and McCarthy, 1993). In the proximal reaches the rivers are sandy and meandering, becoming dominated by more confined single and anastomosing channels in the medial zone before flowing to a distal zone which is poorly channelised and dominated by unconfined flow. Discharge decreases downstream due to evaporation (and transpiration from lush vegetation in the interchannel areas) and only 2% of the input flow exits from the edge of the fan to flow in a single channel to a lake. The Okavango Fan is therefore an almost terminal system, and, as Stanistreet and McCarthy (1993) observe, there are a number of similarities with the Luna System as documented by Nichols (1987). Use of the term 'losimean fan' is limited by its definition as a fan dominated by meandering and low sinuosity rivers with a very low depositional gradient (Stanistreet and McCarthy, 1993).

6.3. Terminal fans

Kelly and Olsen (1993) use the term 'terminal fan' for fluvial distributary systems which have no surface flow into a lake or the sea. A modern case study comes from the Markanda River in India, which is an ephemeral river that ends in a series of distributary channels which form a 'terminal fan' (Parkash et al., 1983). The river loses most of its discharge before it reaches the terminal fan where it bifurcates into a series of distributary channels and subfans. There is evidence of frequent avulsion building up a lobate sheet of sandy channel and muddy overbank deposits over an area of 64 km^2, with an almost continuous layer of channel facies preserved in the top 2.5 m of the fan (Parkash et al., 1983). The Markanda Fan case study was one of only two modern examples used in Kelly and Olsen's (1993) review, the other being the Gash River Fan in Sudan (Abdullatif, 1989). As Kelly and Olsen (1993) point out, the only fan for which there is any detailed sedimentological data, the Markanda fan, is considerably smaller than most of the ancient examples they selected.

A further consideration in trying to find appropriate terminology is that the characteristics of the distal parts of the system will vary depending on the level of water in the basin centre. Under conditions where evaporative losses exceed the supply of water through direct precipitation and via the river systems, the basin centre will be a dry evaporative alluvial plain, and the channels will end in terminal splays. However, during a wetter climatic phase the lake level will rise and the distal ends of the river channels will flow directly into the water body to form a lake delta. In this state the fluvial system cannot be regarded as 'terminal', like the Markanda Fan of Parkash et al. (1983) or in the sense envisaged by Kelly and Olsen (1993). If these lake level fluctuations are relatively small, only the distal part of the fluvial system will be affected: the characteristics of channel and overbank sedimentation in proximal and medial areas will be the same whether the river is flowing into a lake or ending in a terminal splay. However, if the 'terminal fan' moniker is to be used for the whole system, it can strictly only be applied to the times when the river does not reach the lake, but this distinction cannot be determined for the proximal and medial parts of the system.

6.4. Lake deltas

In the classification of river and alluvial fan deposits suggested by Blair and McPherson (1994) the fluvial distributary systems described in this paper could be considered to be 'ephemeral-lacustrine floodplain deltas'. The drawback of using this approach is that a fluvial system prograding into a basin which is a dry alluvial plain for almost all the time, and ephemeral lakes only form away from the distal fringes of the river channels, does not really conform to the general view of a 'delta'. The term would be appropriate for wetter stages of the basin history in examples such as the Luna and Huesca Systems, but evidence for the wetter climate and the presence of a lake cannot necessarily be recognized in the bulk of the fluvial deposits.

6.5. Fluvial distributary systems

The approach preferred here is to use the term 'fluvial distributary system' to describe the form of a river system which has the shape of a 'fluvial fan', has a downstream decrease in discharge and has a distal area of either 'terminal splays', when there is no lake present, or forms a floodplain lake delta at times of high lake level. If it has a very low gradient it may also be a 'losimean fan' in the scheme of classification of subaerial fans suggested by Stanistreet and McCarthy (1993). A river pattern may be described as 'distributary' in a variety of settings, for example as part 1of a delta, but the term 'fluvial distributary system' has only been applied to the river systems with the characteristics originally defined by Friend (1978) and further described by Graham (1983), Hirst and Nichols (1986), Alonso Zarza et al. (1993) and Mather (2000).

7. The stratigraphic architecture of fluvial distributary system deposits

The short and long-term preservation potential of fluvial distributary system deposits in endorheic basins is good. To preserve thick successions of fluvial strata the area of deposition must have a long history of relative base-level rise. This condition is met in basins of internal drainage which are underfilled (Bohacs et al., 2000) and have rates of evaporation exceeding water supply. Accumulation of strata in the basin will continue until the spill point is reached, and the total thickness will be greater than the original accommodation up to the spill point as a result of subsidence due to sedimentary loading, and there may be continued tectonic subsidence in the basin. Many of the Devonian endorheic basins discussed above underwent syn-depositional subsidence due to continued tectonic activity (e.g. the Hornelen Basin in West Norway, Nilsen and McLaughlin, 1985). There is therefore the potential to accumulate many thousands of metres of fluvial deposits in these settings and many of the examples from the stratigraphic record are successions of considerable thickness.

On the basis of the conceptual model (Figs. 1 and 2) it is possible to predict the stratigraphic architecture of thick successions of fluvial distributary system deposits. In some respects, fluvial distributary systems show similarities with more conventional rivers of similar scales. There is an overall decrease in grain size downstream as the rivers undergo a transition from bedload-dominated to a mixed-load system. There is also an increase in the proportion of overbank deposits preserved. However, there are also elements of fluvial distributary systems which make them significantly different from 'normal' river deposits and these should be taken into account when constructing a palaeogeographic scenario or developing a predictive framework of reservoir characteristics.

The overall shape of the sediment body will be fan-shaped if the basin morphology allows the channels to avulse in a radial pattern across the alluvial plain. However, the degree to which a system spreads out will be governed by the basin geometry: a river feeding into one end of an elongate basin will form a narrower fan because the lateral avulsion of the channels will be limited by the sides of the basin. The proximal to distal dimensions will be largely determined by the climate in both the hinterland and the basin controlling the discharge in the rivers and the rates of evaporation.

The case studies from the Ebro Basin show that as well as the depth of the channels decreasing downstream the width of the sandstone bodies formed as channel deposits also decreases. In addition there is also a distal decrease in the percentage of in-channel component of the deposits, partly because of the smaller size of the channels, but also this is to be expected in these examples because the radial pattern spreads the channel deposits over a wider area distally. The consequence of these trends is that the degree of interconnectedness of channel sandstone bodies decreases in an exponential way from the proximal to distal areas in the Luna and Huesca Systems. The decrease in in-channel component downstream will be less extreme in systems with a less radial pattern, but nevertheless this is a characteristic feature which is important to reservoir modelling.

In simple models of fluvial sedimentation, coarse sediment is mainly deposited as bedload in the channels, and finer material from suspension on the floodplain. However, in the distal parts of fluvial distributary systems, the partition of sedimentation is not so straightforward. Evidence from the Ebro Basin shows that some of the channel scours are wholly or partly filled with mudrock (Fig. 4c, d), and that the floodplain facies association includes thin sheets of sandstone, which may locally make up a quarter of the succession. Therefore, in the distal area, more sand is to be found as sheet floodplain facies than as channel-fill. Vertical connection between sheets separated by mudrocks only occurs where they are incised by a sand-filled channel, and these are relatively uncommon. The prospects for a reservoir of interconnected sandstone sheets are therefore poor in the distal parts of a system.

Rivers which are hydrologically connected to the ocean are influenced by changes in relative sea level: a relative sea level fall results in valley incision and lateral confinement of the fluvial tract (Shanley and McCabe, 1994). In endorheic basins relative sea level has no effect on the rivers and in a relatively arid climate any basin-centre lake is likely to be relatively shallow. As noted above, fluctuations in the lake level of only a few metres may have little effect on the proximal and medial parts of the fluvial tract. Overall the base-level in an endorheic basin will rise through time, if there is no differential uplift and subsidence at the basin margin (Nichols, 2004), so the pattern of sedimentation will be aggradational. A further characteristic of a fluvial distributary system in an endorheic basin is therefore an absence of incised valley fill, a feature originally recognised by Friend (1978).

8. Conclusions

Fluvial distributary systems are a distinctive style of continental sedimentation that occur mainly in basins of internal drainage. They are characterised by a down-flow decrease in channel dimensions caused by a loss of discharge downstream due to evaporation and soak-away. They are typically fan-shaped bodies tens of kilometres in radius built up by repeated avulsion of river channels on a very low gradient alluvial plain.

Terminal splays are considered to be elements of these systems, being the areas of unchannelised flow and deposition at the distal ends of active channels which terminate on the alluvial plain. At times of lake highstand the distal zone of the system may be indundated and the river channels will feed a lacustrine delta. These entire fluvial systems cannot necessarily be called ‘terminal fans’ because at times of lake highstand the systems are not terminal. They can be considered to be a type of ‘fluvial fan’ or ‘megafan’, but differ from the type examples of megafans which have through-flowing river systems beyond the limits of the fan body. Most have the plan form of a subaerial fan, but are not necessarily fan-shaped bodies if restricted by basin topography. The term ‘fluvial distributary system’ is therefore preferred on the grounds of previous usage and avoiding the need to redefine any terminology.

Potential reservoir properties will vary considerably across the system: in the proximal zone coarse channel facies dominate and are likely to be fully interconnected; across the medial zone the size and proportion of channel sandstone decrease, but some connectivity may be provided by overbank sheet sandstones; distal areas are characterised by low concentrations of smaller channels and much of the sand deposited as unconnected sheets.

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