Fluvial Reservoirs: Using the Right Architectural Models*

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Introduction

We all know what a river looks like. Rivers typically flow from mountains down to the sea, forming a dendritic pattern of tributary streams that coalesce into a sinuous channel on a floodplain, eventually feeding a delta or estuary. Pictures of modern systems tend to inform our perception of how the deposits of a river may appear in the geological record, and hence there tends to be an assumption that the deposits of ancient systems have the following characteristics: at the large scale they are tributary; the channel-fill facies form ribbons of sandstone encased in overbank mudrock; and channel dimensions become larger as they interface with the delta or estuary. However, recent studies on both modern and ancient river systems indicate that in the majority of settings where fluvial successions form, these assumptions are either partially, or wholly, incorrect. In this article we take a look at fluvial systems and consider how modern rivers result in successions of channel and overbank facies at basin-scale in an exploration context and the resulting depositional architecture at reservoir scale.

Tributary Versus Distributive Patterns

Rivers such as the Mississippi are mainly tributary and lie in settings where tectonic subsidence and eustatic sea level rise can create accommodation in the tract leading to the sea, allowing preservation of the tributary channel pattern. However, new evidence from a global analysis of over 700 rivers in modern continental basins where sediment is accumulating shows that the large-scale river pattern is more commonly distributive (Hartley et al., 2010, Weissmann et al., 2010). These distributive fluvial systems (DFS) may feed into axial rivers, flow directly to a lake or marine coast, or terminate on an alluvial plain or erg. DFS occur in a wide range of tectonic settings, occurring at scales which reflect the basin dimensions: the largest (700 km in the case of the Pilcomayo in Bolivia and Paraguay) are found in foreland basins whereas DFS are shorter in smaller extensional and strike-slip basins. They are found in climates ranging from polar to tropical and

humid to arid and in both internally and externally-drained basins. Where the basin contains a major river draining externally to the sea (e.g., in the Brahmaputra River in India, Figure 1), the vast majority of the deposition in the basin is by the many DFS that feed into it The key differences between a DFS and a tributary river system are:

- a pattern of channels that radiates from an apex at the basin margin, in contrast to the convergent pattern of a tributary system;
- a tendency for channel size to decrease down-system due to bifurcation, infiltration and evapotranspiration, instead of the increased channel size down-flow that occurs where tributaries join a trunk channel;
- a lack of lateral confinement in a valley as DFS spread over a wide basin plain resulting in an increased floodplain to channel area ratio in more distal areas (Figure 2).

The dominance of DFS in modern aggrading basins suggests that this pattern of fluvial deposition should be widespread in the rock record. While some examples have been documented from the stratigraphic record for over 50 years (e.g., Nichols, 1987), relatively few studies have considered fluvial strata in this context. However, the fundamental differences between these distributive systems that clearly do result in deposition and tributary systems that occur widely in degradational settings means that caveats must be placed on facies models based on modern rivers. At the scale of a channel, the flow processes and products as sedimentary features will be the same, but a model of the three-dimensional architecture of channel and overbank facies cannot be constructed from tributary rivers in places where there is no net accumulation. Modern rivers which are demonstrably depositing are mainly distributive, and any attempt to understand basin-scale distribution of fluvial facies must take this into account.

Terminations of Rivers

Contrary to popular belief, not all rivers flow to the sea. Some flow into a lake, but many others simply dry up where they reach a desert or die out on an alluvial plain: these are continental basin settings that have a high potential of preservation in the rock record. 'Terminal fans' were first recognised in Devonian strata from Spitsbergen in the 1970's (Friend, 1978); they occur in arid and semi-arid areas, but also in temperate regions if basin regions if basin evaporation and infiltration exceed fluvial input and precipitation. In addition to showing distributive pattern of channel deposits, there is a marked decrease in channel dimensions and grain size down-system (Nichols and Fisher, 2007). At the distal fringes of the system, flow becomes unchannelized and terminal splays distribute water as unconfined flow forming thin sheets of fine sandstone. These distal deposits may interfinger with alluvial-plain mudrocks, ephemeral lake facies or eolian deposits – an example of the last of these being the Permian Organ Rock Formation (Cain and Mountney, 2009). A distinctive basin-scale architecture of channel and overbank facies is formed by terminal distributive systems, with a decrease in sandstone body thickness and interconnectedness down system as the rivers that deposited the sands decreased in dimensions and became more widely spaced on the floodplain. Figure 3 is a model for the distribution of channel and overbank facies based on the outcrops of Miocene strata in the Ebro Basin, northern Spain (from Nichols, 1987; Nichols and Fisher, 2007).

Ribbon Versus Sheet Architectures

In plan view a modern river is a thread of water and sediment which has a more-or-less sinuous pattern on the land surface. Models of the 3D distribution of channel and floodplain facies often reflect this pattern and populate the volume with ribbon sandstone bodies (Figure 4). In fact, to create a sandstone body with a ribbon geometry requires a set of circumstances that are quite possible, but, for the reasons explained below, probably the least likely outcome of fluvial depositional processes.

Both meandering and braided rivers migrate laterally across their floodplain, leaving behind them the deposits of point-bars or mid-channel bars. Lateral migration continues until the river avulses, abandoning the old channel and following a new pathway across the floodplain. A series of isolated lenses formed by point-bar accretion will result from rivers with relatively low sedimentation rates, but with increased aggradation rates these coalesce into sheet-like bodies formed by the lateral migration of the channel. Braided rivers also move sideways, leaving abandoned stretches of the channel containing pebbly or sandy mid-channel bar deposits as they do so; these form lenses and sheets of conglomerate or stacks of cross-bedded sandstone produced by the amalgamation of bar deposits. If avulsion occurs rapidly, the width of the sediment body will be relatively small as the channel is abandoned before extensive lateral migration occurs (Figure 5).

However, it is not just the frequency of avulsion that controls the resultant sediment body dimensions because the degree of accommodation available is also a factor (Holbrook et al., 2006). In basins where there is low accommodation available (typically as a consequence of slow subsidence), channel avulsion results in extensive reworking of the overbank facies, and a lateral amalgamation of channel deposits creates laterally extensive sheets of sandstone (Figure 6).

The nature of channel fill at the time of avulsion is also variable. If avulsion is abrupt, with all of the flow diverted into a new route, the abandoned channel will be left as an depression on the floodplain to be later filled by fine-grained flood deposits (forming clay plugs), vegetation to form peat, lacustrine deposits or even wind-blown sediment. Under these circumstances the final channel fill is likely to be almost anything other than fluvial sand. A channel can start to fill up with sands carried by the channel if the avulsion is gradual, with flow being diverted to a new pathway over year to tens of years--see Buehler et al. (2011) for a spectacular example of this process occurring in a modern river. Although partial filling by sands carried by the river can occur in this way, a complete fill is unlikely, as the flow will decrease and reduce the channel's carrying capacity before total abandonment is approached.

A true ribbon body of sandstone with dimensions similar to those of the channel can only be formed if the river shows little or no lateral migration, in a basin where there is high accommodation and where the avulsion is gradual – and even then only part of the channel fill will be sand. Under almost all other circumstances the sediment body formed from a channel will be a sheet ranging from a few times the channel width to a lateral extent of almost the whole depositional area of the fluvial system.

Conclusions

Assumptions that the rivers that deposited the fluvial strata seen in the rock record were tributary and flowed to the sea lead to conclusions about the basin-scale distribution of reservoir deposits that may be very misleading. Distributive fluvial systems are much more common in aggrading continental basins in all tectonic and climatic settings, and wherever there is net evaporation in a basin; this can include some temperate environments. The rivers may be terminal. Furthermore, any models that assume rivers mainly deposit 'ribbons' of sandstone should be used with caution as lateral migration and amalgamation of channel deposits frequently results in sheet geometries of sandstone bodies.

Acknowledgements

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Figure 1. The upper Brahmaputra River, India, where DFS terminate at an axial fluvial System.

Figure 2. The Okavango River in Botswana, with a channel bifurcation and a decrease in channel dimensions downflow.
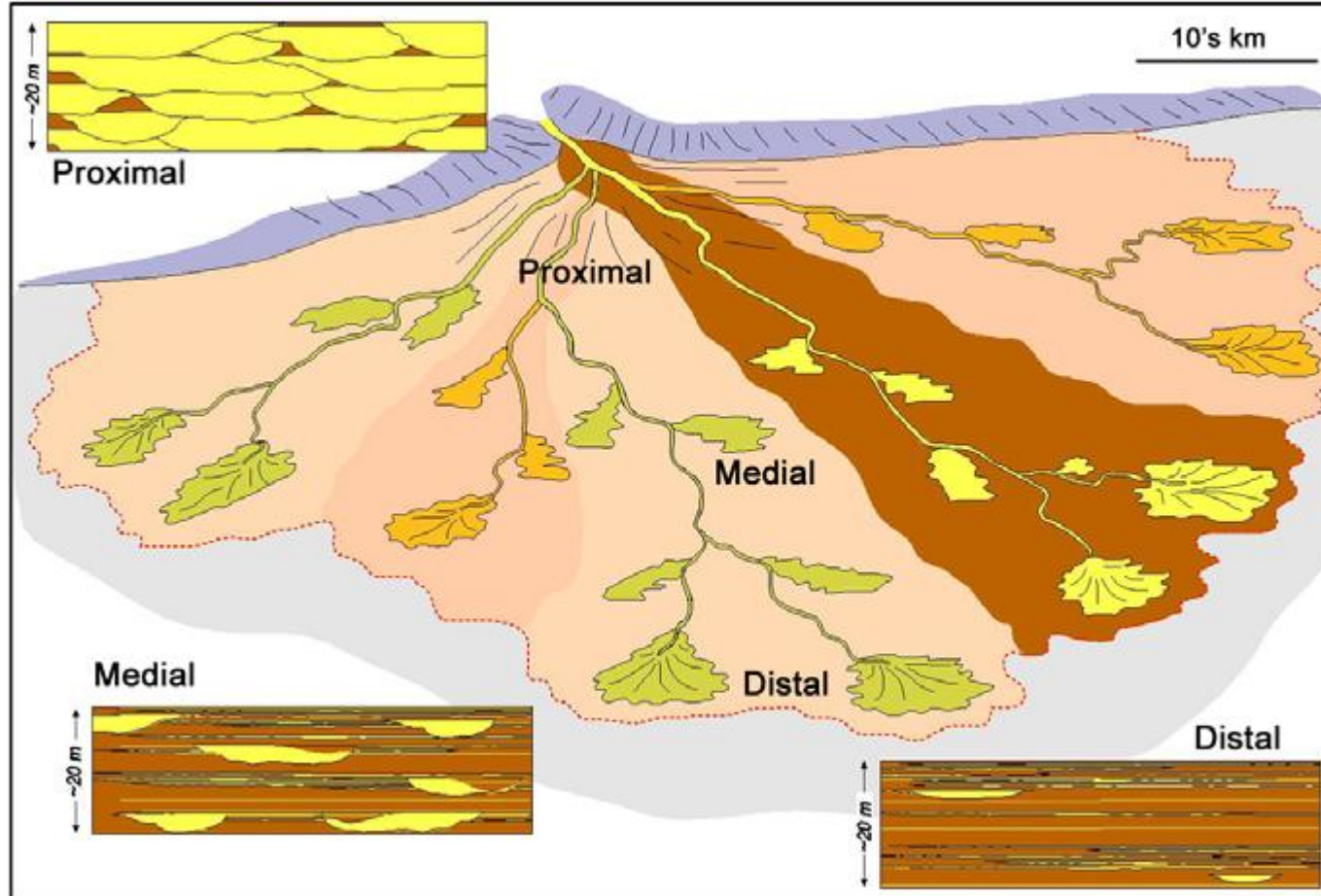
Figure 3. Model of fluvial architecture in a terminal DFS (from Nichols and Fisher, 2007).
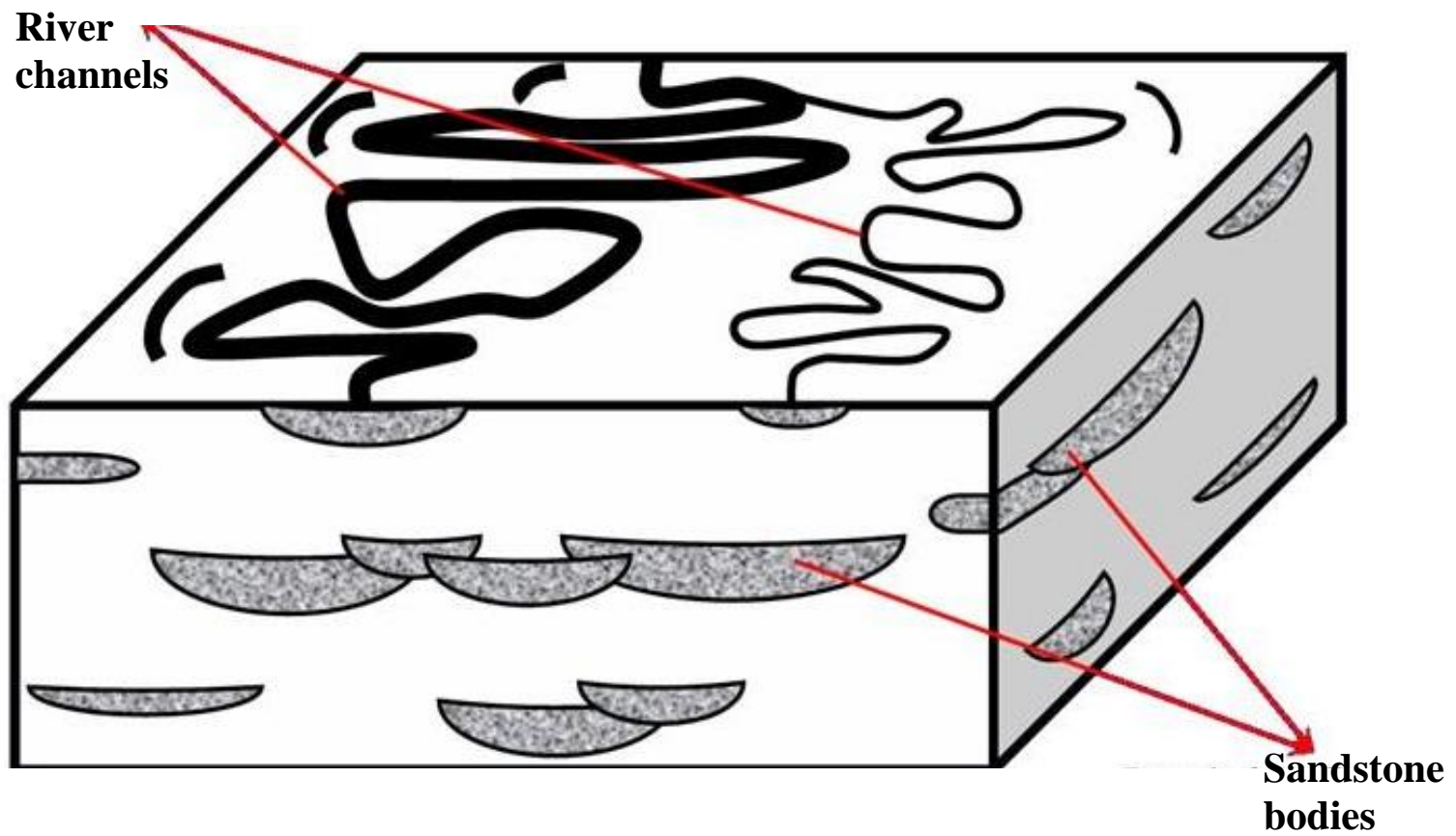
River channels

Sandstone bodies

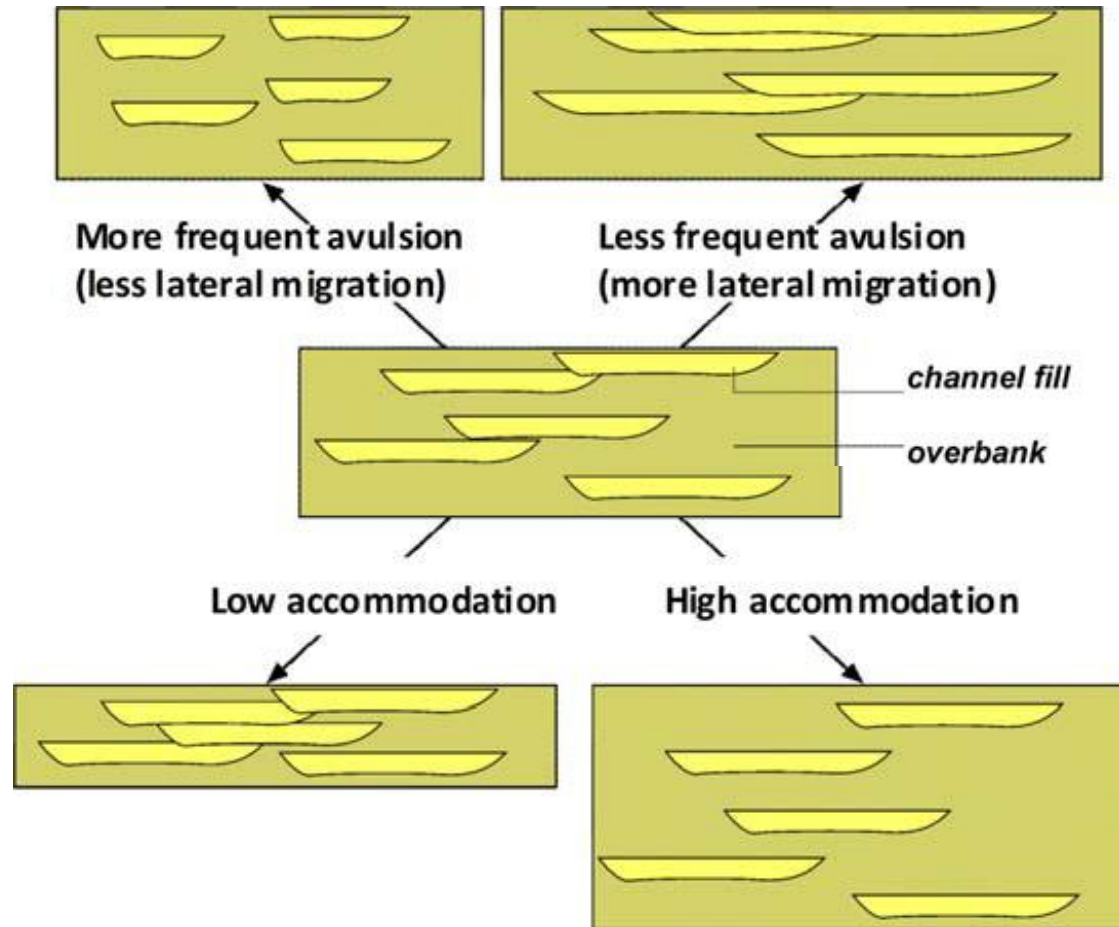Figure 4. Fluvial architecture model using a ribbon geometry.

Figure 5. Avulsion and accommodation controls on fluvial architecture.

Figure 6. Sheets of laterally amalgamated channels sandstones (Piraces, Ebro Basin, Spain).