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Fluvial Facies and their Reservoir Potential: A Concise Review

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Abstract:

This paper reviews published work on ancient and subsurface fluvial systems, and relates their depositional architecture to reservoir potential. Despite the excellent attributes of fluvial reservoir facies, exploitation of hydrocarbon fluids is often not dissociated with uncertainties that impact spatial distribution of reservoir quality (net-to-gross, porosity and permeability). The reservoir quality is generally affected by variability in depositional architecture and sedimentary attributes, particularly facies and facies associations, sandstone and mudstone geometries and dimensions, sediment texture, sandstone-mudstone ratio, sediment fabric, small-scale sedimentary structures, small-scale vertical sequences of bed thickness, and sand connectivity.

Two principal types of fluvial sandbodies were characterised based on their reservoir potential. Low-sinuosity braided channel systems are composed of sand-rich facies, and less commonly, mud drapes. These depositional mud drapes may become internal barriers to fluid flow. A striking quality of these systems are the long, straight, largely homogeneous sandbodies that form as a result of channel avulsion. These thick, tube-like and extensive sandbodies are commonly interconnected enabling lateral and vertical sweep of reservoirs. In high-sinuosity meandering channel systems, upward fining sequence dominates and causes upward decreasing permeability trend. Sandbodies within channel-fill succession in these systems have low vertical connectivity due to occurrence of mud-prone intervals that mark the onset of channel inactivity. These mud-prone intervals also reduce lateral connectivity of sandbodies beyond the limits of channel architecture. For the sequence, permeabilities are highest at the basal part where large trough-cross bedded sands are concentrated. The top of the sequence comprising ripple-bedded fine sands have lowest permeabilities. In such reservoirs, flow segregation may occur and lead to differential sweep, which will result in bypassing of oil in low-permeability ripple-bedded fine sands.

Therefore, understanding the degree of sandbody amalgamation and the effect of stratigraphic heterogeneities, arising from depositional architecture, on static connectivity of sandbodies will help to maximise hydrocarbon recovery from fluvial reservoirs. In addition to this understanding, accurate prediction of distribution of reservoir quality sandstones is key to successful fluvial reservoir development.

Keywords — fluvial, architecture, sinuosity, braided, meandering, connectivity, sweep.

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I. INTRODUCTION

A. Significance of Fluvial Reservoirs

Fluvial reservoirs account for more than 20% of the world's remaining hydrocarbon reserves [1]. Many giant oil and gas fields comprise prolific fluvial reservoirs. Ivishak Formation in Prudhoe Bay Field, Alaska; Sa, Pu, and Gao Sands in Daqing Field, China; Ness Sands in Brent Field and Statfjord Formation in Statfjord Field in the Norwegian North Sea [2]; Qishn Formation in Masila Field, Yemen [3]; Peng Lai 19-3 Oil Complex in Bohai Bay, China [4]; Cusiana Field in Colombia [5] are examples of fluvial reservoirs that have produced billion barrels of oil and several trillion cubic feet of gas. Hence, the productivity, net-to-gross ratio, reservoir quality, petrophysical properties, internal architecture, and amalgamation of small fluvial fields to a major world-class producer are among the attributes that have allured the oil and gas industry to fluvial reservoirs.

Fluvial reservoirs are widely known for their productivity in the exploitation of oil and gas due to their high net-to-gross ratio, good-to-excellent reservoir quality, relatively high recovery factor, which may exceed 60%, and so forth. Major fluvial oil and gas producers include Prudhoe Bay Field, Alaska (world's largest braided channel field and the fifteenth largest of all oil fields, [6]); Sarir Field (world's second largest fluvial field, [6]), Messla and Bu Attifel Fields, Libya; Daqing Field, China; Statfjord and Snorre Fields, Norwegian North Sea; Cooper Basin Fields, Australia; and more (Figure 1).

Despite the excellent attributes of fluvial reservoir facies, exploitation of hydrocarbon fluids is often not dissociated with several key subsurface risks and uncertainties that are associated with reservoir quality and distribution. Variability in depositional architecture and sedimentary attributes, particularly facies and facies associations, sandstone and mudstone geometries and dimensions, sediment texture, sandstone-mudstone ratio, sediment fabric, small-scale sedimentary structures, small-scale vertical sequences of bed thickness, and sand connectivity are critical factors that affect reservoir quality of fluvial reservoirs, and by extension, cause permeability contrast that often results in flow segregation.

This review is based on careful synthesis of published work on some established producing fluvial fields and field analogues, and presents critical insights into fluvial depositional architecture and its impact on sandbody geometries, dimensions and vertical and lateral stack patterns with a view to delineating attendant sedimentological attributes that affect hydrocarbon recovery. It is hoped that these insights will inform reservoir management decisions for optimal hydrocarbon recovery and extended field life.

B. Fluvial Basins and Channel Morphology

Fluvial deposits are common in rift basins e.g. Widuri field, Indonesia [7], foreland basins e.g. Ghadames-Illizi Basin, North Africa [8], and intra-cratonic basin e.g. Ourhourd Field Algeria [9]. They are also found in marginal basins, forearc basins, and retroarc basins (Figure 2). They are characterised by variable depositional patterns that cause resultant sandbodies to differ in vertical and lateral bed thickness, geometry, dimension (channel depth, channel width, sandbody area), net sand thickness, and reservoir properties (porosity, permeability, fluid saturation).

The flow in a channel influences erosion, transport, and deposition of sediments in fluvial systems. Miall ([10]) identified eight factors that control channel morphology: (1) amount of discharge and its variability, (2) grain size of sediments and variation in distribution, (3) velocity of river flow, (4) channel width, (5) channel depth, (6) channel slope, (7) bed roughness, and (8) vegetation on channel bank.

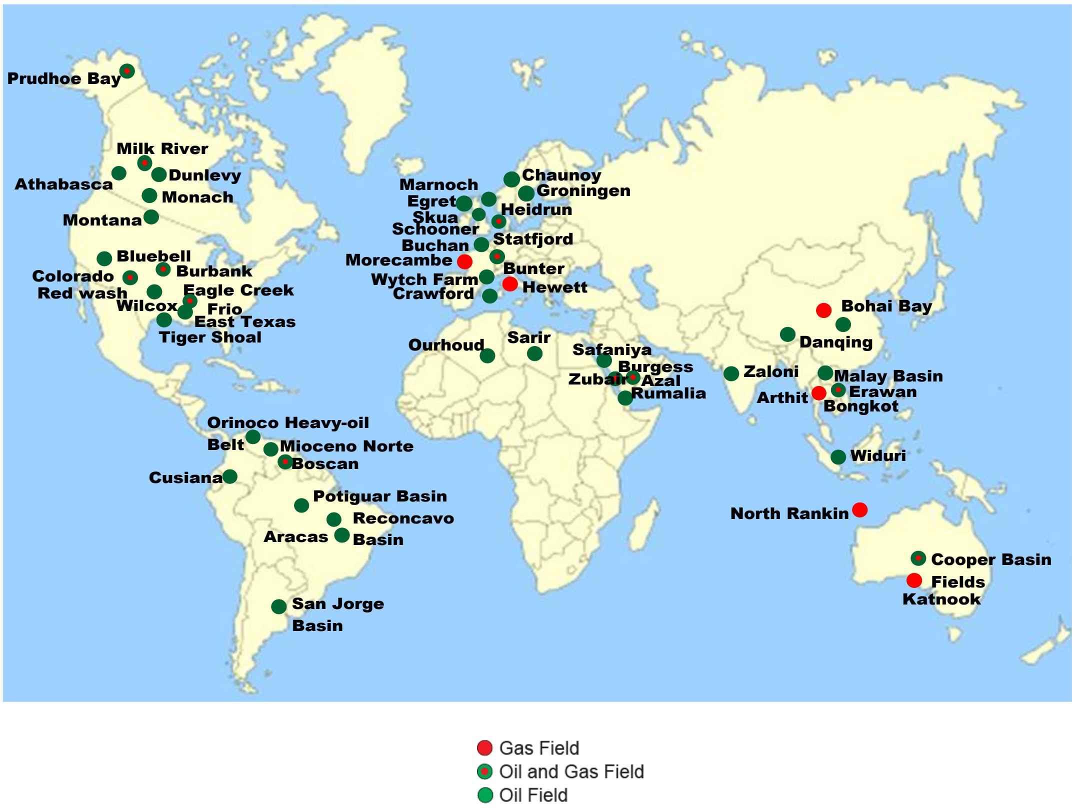

Figure 1: Distribution of world's major fluvial hydrocarbon fields [11].

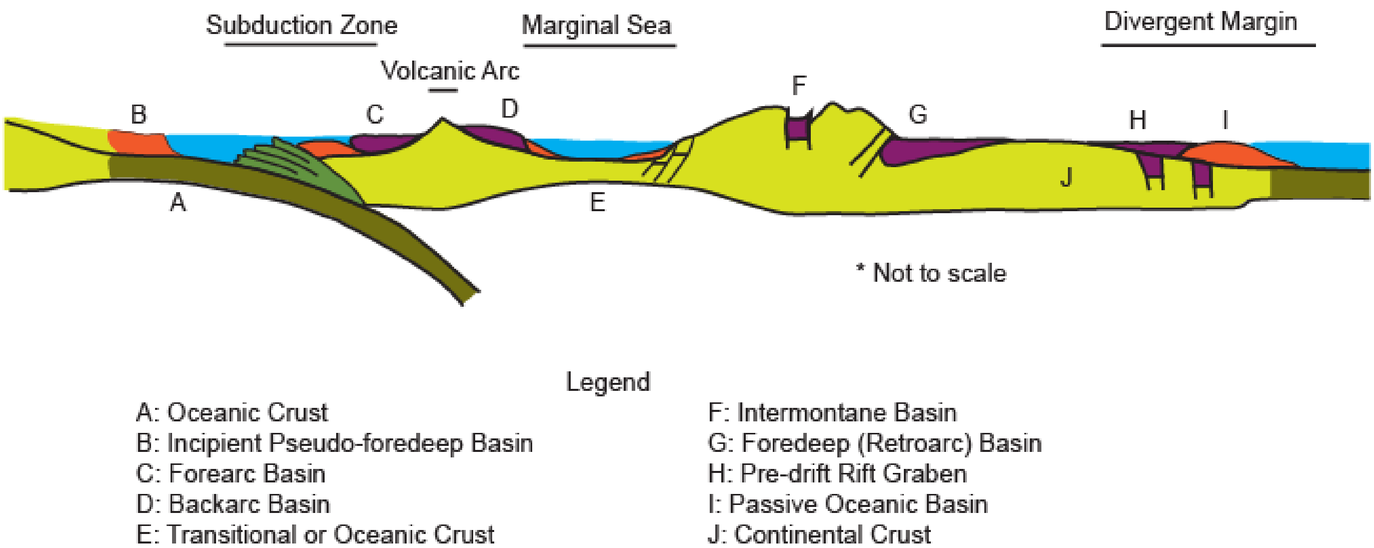

Figure 2: Tectonic setting of basins (C, D, F, G, and H) associated with fluvial deposits [11].

Fluvial channels can be classified based on their sinuosity (the tendency of a channel to deviate from a straight path [12]), braiding, and anastomosing (Figure 3). Miall ([10]) defined sinuosity as the ratio of thalweg length (i.e. the line of deepest channel) to valley length (i.e. the straight-line distance down that part of the valley over which the thalweg length is measured). Conversely, braiding develops when channel banks have the tendency to erode. Steep slopes, high sediment supply, discharge variability, abundance of bedload, and susceptibility of banks to erosion are among the factors that favour braiding [13]. A single channel, however, depending on the amount of bedload, velocity of flow, etc., may change in character from low sinuosity in upstream sections to high sinuosity in downstream reaches [10].

Table I shows a simple classification of channel types. In straight channels, water tends to flow in straight path and turbulence occurs along channel margins during flood events. Stream meandering is caused by non-uniformity in the distribution of flow velocity and turbulence within a channel bend. A river flow may separate into branches to form distributary channel pattern. The branches, then, continue their flow concurrently, but on encountering an obstacle, they weave around it to form anastomosing channel pattern [14].

Channel scouring is common in straight and braided channels, whereas channels with high sinuosity are characterised by channel deepening. Multiple channels are relatively stable with a wide variety of sinuosity but very low stream power. However, during upper-flow regime, scouring and straightening may be inadequate to provide more space to handle river flow. Consequently, flood waters may overflow the channel banks and spill out into outer areas of the channel margins [14].

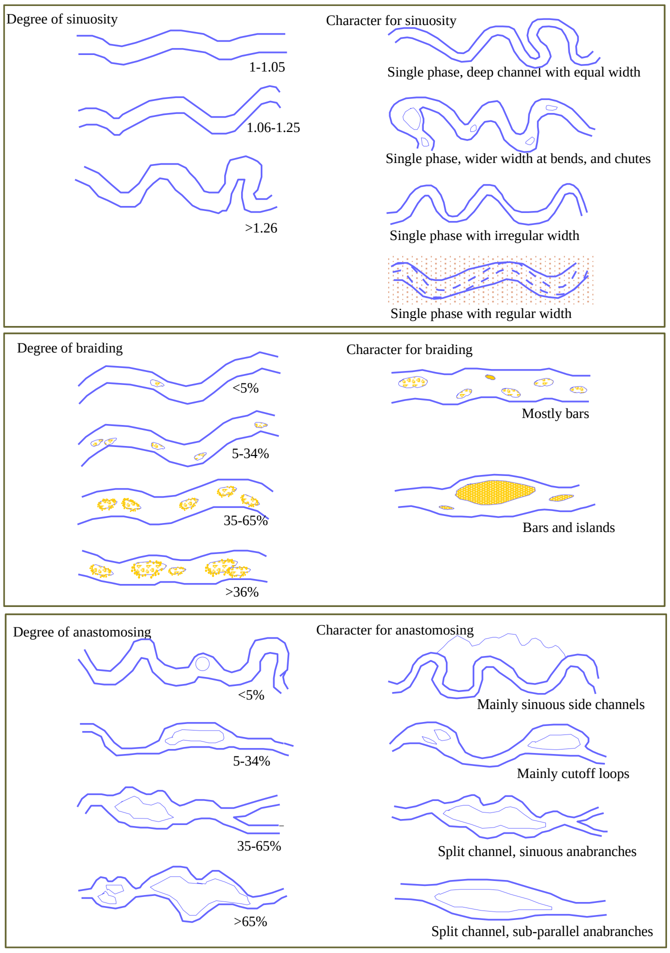

Figure 3. Classification of river channels based on their morphology [13].

TABLE I. CLASSIFICATION OF CHANNEL TYPES [11]

Degree of Sinuosity	**Channel character**	**Number of river channel**	**Dominant facies**
Low (< 1.5)	Straight	Single	Mud-rich
	Braided	Multiple	Sand-rich
High (> 1.5)	Meandering	Single	Mud-rich
	Anastomosing or Distributary	Multiple	Sand/mud-rich

C. Sediment Transport in Fluvial Systems

Fluvial deposits accumulate in a wide range of depositional settings extending from alluvial fans through river channels and terminating in proximal areas of deltas. They are preponderantly clastic sediments comprising alluvial fan deposits, river channel deposits, floodplain deposits, and deposits that accumulate in proximal areas of deltas [11].

Fluvial deposits are characterised by a wide spectrum of grain size distribution ranging from large boulders that are transported during high flood events to tremendously fine sediments such as silt and clay. The fine sediment population are transported as suspended load in river systems. They are held in suspension during upper-flow regime by fluid turbulence, and continue to be transported until they eventually settle out of suspension and become deposited [12], [13]. Modern examples of suspended-load fluvial systems are the Lower Mississippi and the Atchafalaya Rivers [14]. By contrast, coarser grain mass comprising gravels and sands are transported as bed-load sediments. The grain size and grain mass of these sediments are controlled by grain size of sediments available for transport, flow competence and flow capacity [13]. The grains are transported by rolling and saltating as they bounce on channel bed. As flow power wanes, the amount of bed-load sediments that can be transported reduces. Hence, volume of bed-load sediments decreases downstream in fluvial systems. During flood event, however, coarse bed-load sediments may be carried from the channel as floodwater overspills channel banks resulting in overbank deposition. Examples of modern bed-load river systems are Brahmaputra River and Platte River [14].

II. FLUVIAL DEPOSITIONAL FACIES AND INTERNAL ARCHITECTURE

Facies refers to a body of rock marked by a peculiar combination of lithology, physical and biological structures that contribute an aspect different from the bodies of rock above, below, and laterally adjacent [18]. The classification of fluvial depositional facies in this paper follows Galloway and Hobday classification [14], and is based on the degree of sinuosity of river system that deposited the depositional facies. On this basis, three principal depositional facies that are recognised in fluvial systems are: (1) channel-fill facies, (2) channel margin facies, and (3) floodbasin facies. These facies are discussed below in light of the associated principal architectural elements (Table II).

A. Channel-fill Facies

Channel-fill facies is the main component of a fluvial system and consists of mud-rich low-sinuosity channel-fill facies, sand-rich low-sinuosity channel-fill facies, and high-sinuosity channel-fill facies [14].

1) Mud-rich low-sinuosity channel-fill facies: The deposits of mud-rich low-sinuosity channel-fill facies consist primarily of very fine sand, silt and clay. At the base of the sequence, gravel, plant debris and mud chips may accumulate as lags, deposited on the scoured surface. Large to small-scale trough-cross stratifications generally dominate the sequence of mud-rich low-sinuosity channel-fill facies, and are common in anastomosed channel system (Figure 4).

2) Sand-rich low-sinuosity channel-fill facies: The channel-fill facies of sand-rich low-sinuosity fluvial systems is associated with braided rivers. These systems are marked by downstream-accretion deposits comprising bed-load sediments that develop as lateral, longitudinal and transverse bars (Figure 5).

TABLE II. MAIN ARCHITECTURAL ELEMENTS IN FLUVIAL DEPOSITS ([10], [19])

Element	Main facies assemblage	Sedimentary structures	Geometry and relationships
Channels (CH)	Any combination	Erosional base, massive, trough crossbeds, planar cross beds, ripples, grading	Finger, lens or sheet; concave-up erosional base; scale and shape highly variable; internal concave-up 3rd-order erosion surfaces common
Gravel bars and bedforms (GB)	Massive or crudely bedded gravel, stratified gravel	Horizontal bedding, imbrication, trough crossbeds, planar crossbeds	Lens, blanket; usually tabular bodies; commonly interbedded with SB
Sandy bedform (SB)	Very fine to very coarse sand (may be pebbly), erosional scours with intrasclasts	Solitary or grouped trough crossbeds or planar crossbeds, horizontal lamination, parting or streaming lineation, low angle crossbeds, ripple marks, crude cross-bedding, broad shallow scours including cross stratification	Lens, sheet, blanket, wedge, occurs as channel-fills, crevasse splays, minor bars
Downstream-accretion macroform (DA)	Very fine to very coarse sand (may be pebbly), erosional scours with intrasclasts	Solitary or grouped trough crossbeds or planar crossbeds, horizontal lamination, parting or streaming lineation, low angle crossbeds, ripple marks, crude cross-bedding, broad shallow scours including cross stratification	Lens resting on flat or channelized base, with convex-up 3rd-order internal erosion surfaces and upper 4th-order bounding surface
Lateral-accretion macroform (LA)	Very fine to very coarse sand, erosional scours with intrasclasts, less commonly massive or crudely bedded gravel, stratified gravel	Solitary or grouped trough crossbeds or planar crossbeds, horizontal lamination, parting or streaming lineation, low angle crossbeds, crude cross-bedding, broad shallow scours including cross stratification	Wedge, sheet, lobe; characterized by internal lateral-accretion 3rd-order surfaces
Sediment gravity flow (SG)	Massive or crudely bedded gravel. Massive matrix-supported gravel	Horizontal bedding, imbrication, grading	Lobe, sheet, typically interbedded with GB
Laminated sand sheet (LS)	Very fine to very coarse sand, may be pebbly, fine sand; minor medium to very coarse sand	horizontal lamination, parting or streaming lineation, low angle crossbeds, solitary or grouped planar crossbeds, ripple marks	Sheet, blanket
Overbank fines (OF)	Mud, silt, very fine to fine sand	Fine lamination, very small ripples, massive, desiccation cracks,	Thin to thick blankets; commonly interbedded with SB; may fill abandoned channels

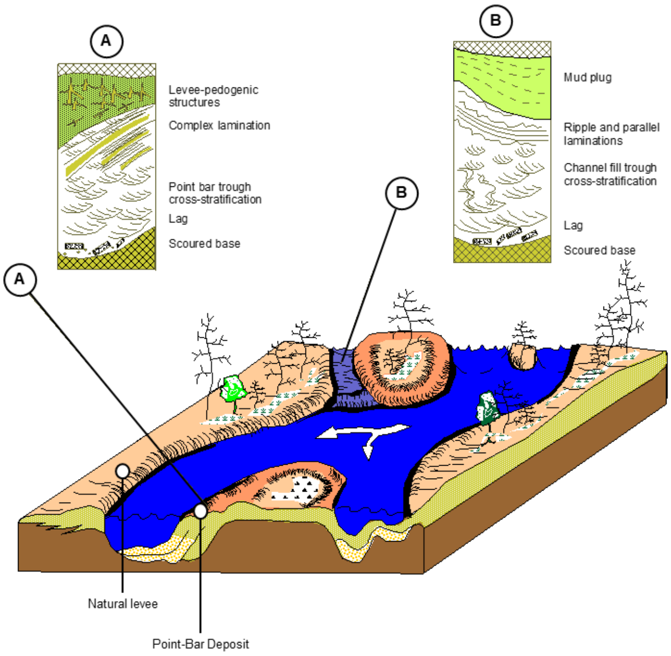

Figure 4: Depositional model and representative vertical sequences through (A) laterally accreting and (B) symmetrically-filling channel segments of an anastomosed channel system [14]. Both segments are characterised by variable sedimentary structures aside from the lag-topped scoured base.

The sequence of channel-fill facies in these channel systems comprises poor-to-moderately-sorted sand with variable proportion of conglomerate, silt and clay. Miall ([10]) recognised six varieties of sand-rich low-sinuosity channel-fill facies (Figure 6). The lithofacies 1 and 4 of the Ivishak Formation, Prudhoe Bay Field, USA, is a classic example of sand-rich low-sinuosity channel-fill facies [20].

3) High-sinuosity channel-fill facies: This channel-fill facies is found in meandering river systems (Figure 7). In meandering channel systems, sediments that are carried from outer bank of a channel bend are deposited inside another bend to form point bar deposit with characteristic upward-fining grain-size sequence [14].

During flood events, a river flow may cut directly across the surface of a point bar resulting in deposition of coarse sand on the point bar. Hence, the upward-fining sequence of a point bar may be overlain by coarser sands, forming a chute-modified point-bar. The lower portion of the sequence comprises large-to-medium-scale trough-cross stratifications and few tabular stratifications. In contrast, large-scale avalanche and tabular cross

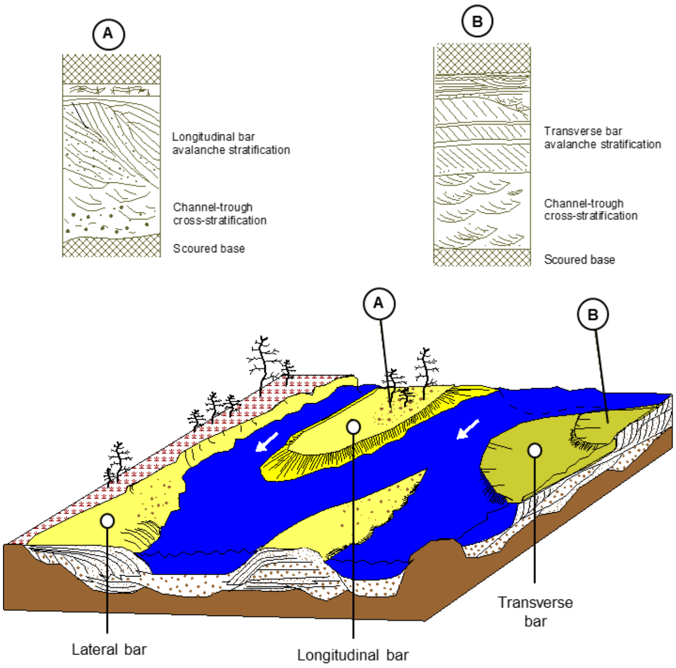

Figure 5. Depositional model and typical vertical sequences for braided channel systems [14].

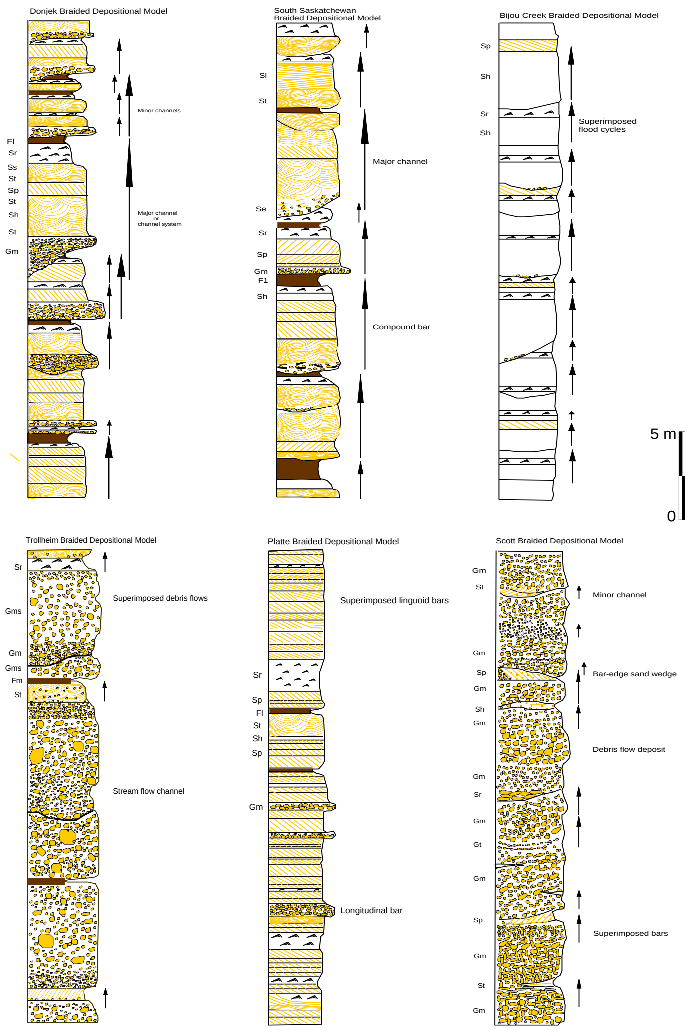

Figure 6: Schematic vertical sequences that are recognised in braided channel systems [10].

stratifications, troughs, scour-and–fills, discontinuous gravel lags, minor planar and ripple laminations occur in the upper section of the sequence. In addition, flood events may cause rivers to flow through a shorter path resulting in meander channel cut off. The channel reaches between the points where the meander neck is cut-off become abandoned and its ends may be sealed by floodplain sediments or new point-bar deposits [10], [12], [14].

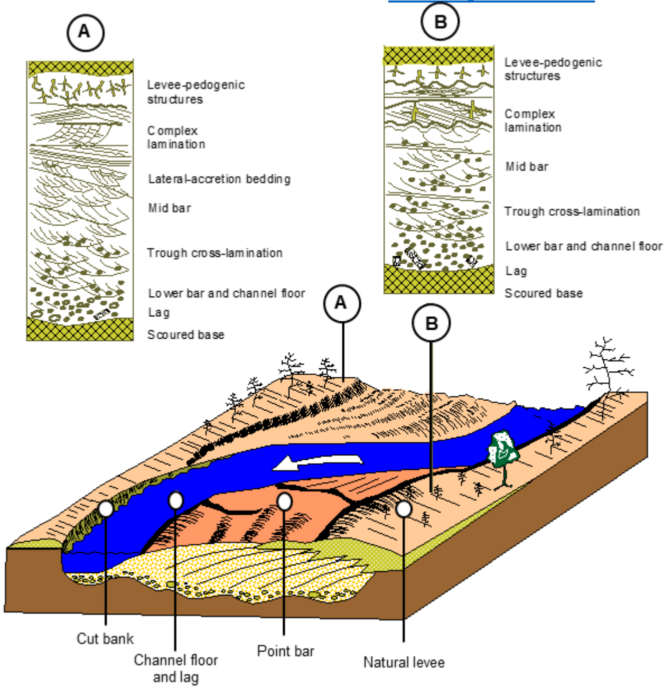

Figure 7. Schematic depositional model with representative vertical sequences through a meander-belt sandbody in a high-sinuosity channel system [14]. Unlike braided river systems, internal sedimentary structures are similar in the sub-settings within a meandering channel system.

B. Channel Margin Facies

The spillage that results when flood waters overtop channel banks leads to deposition of sediments in overbank areas. Every spillage cycle culminates in deposition of suspended-load sediments in a reducing flow competence. Hence, bed-load sediments are deposited at the proximal reaches of the channel, forming natural levee, whereas fine-grained sediments are transported farther in suspension into floodbasin. Natural levee comprises very fine sand, silt and clay, with fine ripples, climbing-ripples, wavy and planar laminations that imply deposition under conditions of lower-flow regime [13]. Associated with these sedimentary structures are abundant clay drapes, laminated mud layers and plant roots [14].

During high flood events, still, flow may follow a breach along natural levee through small channels, carrying mixed-load sediments, fine and coarser sediments, from the levee and depositing them at distal reaches to form crevasse splay deposits (Figure 8). These mixed-load deposits reflect conditions of multiple flood events, shallow flow conditions, and rapid sedimentation rates. Ripples and climbing-ripples; planar, wavy, and medium-scale trough-cross laminations; mud drapes; graded beds and scour-and-fills are sedimentary structures that dominate the internal architecture of crevasse splay deposits.

C. Floodbasin Facies

Floodbasin facies comprises suspended-load sediments that are usually deposited during waning flow. The facies assemblage is marked by low sedimentation rates and pedogenic processes. Due to reworking by organisms and plant roots, floodbasin facies lacks internal sedimentary structures.

III. CONTINUITY, CONNECTIVITY, AND PERMEABILITY HETEROGENEITY IN FLUVIAL SANDBODY

Understanding layering in facies sequence is vital for predicting continuity of sandbodies in fluvial systems. The data that provide insight into layering in rock record include high resolution sequence stratigraphic interpretation with biostratigraphic data, core and wireline log correlations, lithofacies maps, porosity and permeability plots, and more. Low-sinuosity channel systems form thick and laterally extensive braid-plain sandbodies (Figure 9) that display lens or sheet geometry [19].

Vertical accretion dominates bed-load channels in low-sinuosity braided fluvial systems. Generally, overbank materials account for less than 35% [21] thereby enabling excellent vertical connectivity of sandbodies within intervals of mud-poor channel-fill facies. The sheet sands in Westwater Canyon Member in the Morrison Formation, northwestern New Mexico, is a classic example of braid-plain sandbody that possess excellent sandbody connectivity. This sandbody extends more than 100 km wide and averages 61 km in thickness. It consists of channel sandbodies averaging 11 km wide and 15 m deep [22]. The sheet-like geometry of braided sandbodies reduces uncertainty in lateral stratigraphic heterogeneity. Thus, these sandbodies have high net-to-gross ratios, high porosity and high lateral permeability, low mud content, good lateral continuity and excellent sandbody connectivity.

By contrast, labyrinth geometry characterises sandbodies that form in high-sinuosity meandering channel systems. These channels are composed of mixed-sediment load, and are dominated by lateral accretion macroform that may display wedge, sheet or lobe geometry (Figure 10), enabling lateral stacking of sandbodies in spite of volumetrically significant overbank deposits, which can reach up to 70% [21]. However, sandbodies within channel-fill succession in high-sinuosity meandering channel systems are vertically isolated due to occurrence of thick mud-prone intervals that mark the onset of channel inactivity. These mud-prone intervals reduce lateral connectivity of sandbodies beyond the limits of channel architecture, particularly in sandbodies that are typified by wedge geometry.

Heterogeneity controls the distribution of reservoir quality in fluvial reservoirs [14], [19]. Sand-rich channel sandstones in low-sinuosity braided river systems do not have a particular permeability trend. The sandbodies lack intrachannel mud drapes, hence sandbodies are laterally continuous and internally homogeneous [21]. However, occurrence of localised small-scale upward-fining trend in channel sandstone of low-sinuosity braided river systems causes permeability heterogeneity. Thus, permeabilities in braided reservoirs are highest where sheet-flood and braid-plain sands are medium-grained and well sorted (e.g. lithofacies 3 in Ivishak Formation, Prudhoe Bay Field [20].

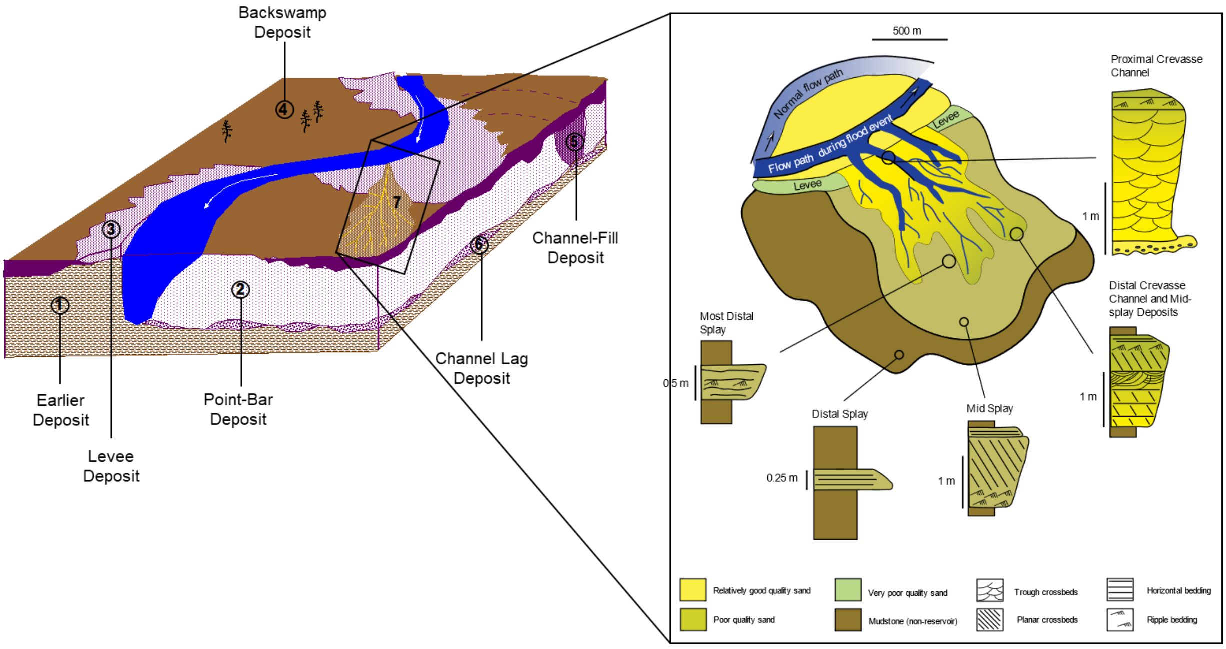

Figure 8. Schematic model of a meandering channel system illustrating main depositional areas [10], and depositional model of channel margin facies with representative vertical sequences [14]. These models illustrate variability in internal architecture, small-scale sedimentary structures, bed thickness, sandstone-mudstone ratio, vertical and lateral changes in bed thickness, and more.

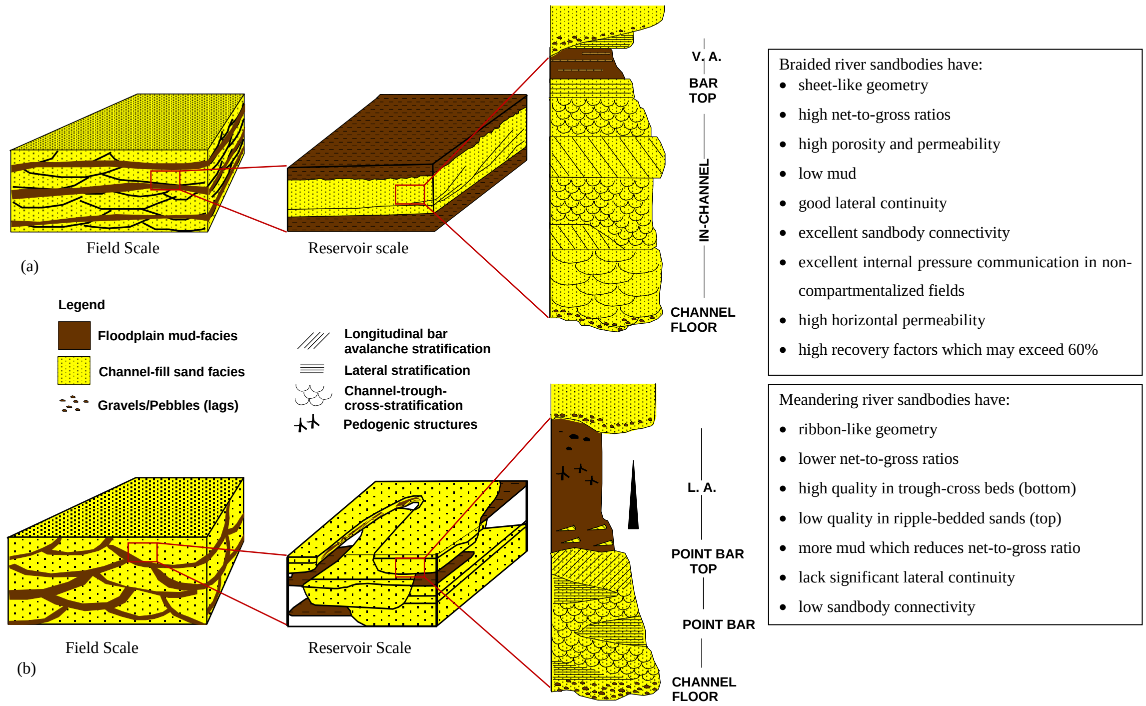

Figure 9. Schematic models of sandbody architecture and vertical sequences in (a) low-sinuosity braided channel systems and (b) high-sinuosity meandering channel systems [11]. The characteristics of the two types of sandbody architecture are summarised in the boxes. (V. A. = Vertical Accretion, L. A. = Lateral Accretion).

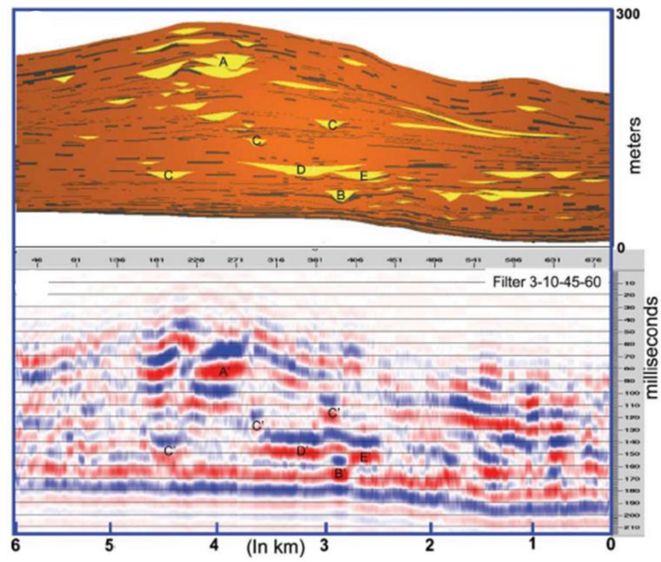

Figure 10. A seismic section showing channel distribution (A-E) in a high-sinuosity meandering channel reservoir [23]. High-sinuosity meandering channel reservoirs are characterised by chaotic or discontinuous seismic appearance due to inconsistent parallel reflections. Generally, sheet or lobe geometry improves lateral stacking of sandbodies, but wedge geometry results in low vertical connectivity within isolated sandbodies.

In high-sinuosity meandering channel systems, upward fining sequence dominates (see Figure 9, b) and results in upward decreasing permeability trend. Hence, permeabilities are highest at the base of the sequence where large trough-cross bedded sands are concentrated, and lowest in ripple-bedded fine sand, usually at the top of the sequence [21].

IV. SUMMARY AND SIGNIFICANCE

Fluvial fields vary in size from hundreds of metres to several kilometres. Fields that have low-sinuosity braided channel reservoir sandstones extend beyond ten-to-hundreds of kilometres, whereas fields with high-sinuosity meandering channel sandstone reservoirs are usually smaller in size, extending from hundreds of metres to tens of kilometres [22].

Fluvial sandbodies have different stack patterns due to their depositional complexity. The degree of stacking of channel fills and connectivity in fluvial channel systems decrease away from sediment source (Figure 11).

Ancient fluvial systems that are composed of suspended-load sediments are mud-prone with low sand percentages. Such systems have well developed levees that have low permeability. Crevasse splays that are associated with such levees are relatively impermeable. Ancient bed-load fluvial systems, by contrast, are dominated by channel and channel-margin deposits together with floodplain sandy mud and silt. The sandy floodplain and channel sediments are characterised by high permeability [14], and so, they form primary targets during hydrocarbon exploration.

In low-sinuosity straight and single channel systems, mud-rich facies dominate in contrast to low-sinuosity multiple channel systems that are composed of sand-rich facies as observed in ancient low-sinuosity braided channel systems. In these systems, discontinuous internal mud drapes exist as a result of high-bed-load/suspended-load ratio typical of these channels. These depositional mud drapes may become internal barriers to fluid flow. A striking quality of low-sinuosity braided systems are the long, straight, largely homogeneous sand bodies that form as a result of channel avulsion, and then preserved in the rock record. These thick, tube-like and extensive sand bodies (e.g. Travis Peak Formation, Texas [21] are vertically and laterally stacked resulting in channel interconnectivity, which enables lateral and vertical sweep of reservoirs. For upward-fining sequence, typical of high-sinuosity meandering channel sandstones, permeabilities are highest at the basal part of the sequence where large trough-cross bedded sands are concentrated. The ripple-bedded fine sands at the top of the sequence have lowest permeabilities. In such reservoirs, flow segregation may occur and cause differential sweep bypassing trapped oil in low-permeability ripple-bedded fine sand intervals.

Figure 10. Provenance of channel-fill facies in fluvial depositional environment (Omoniyi, 2011).

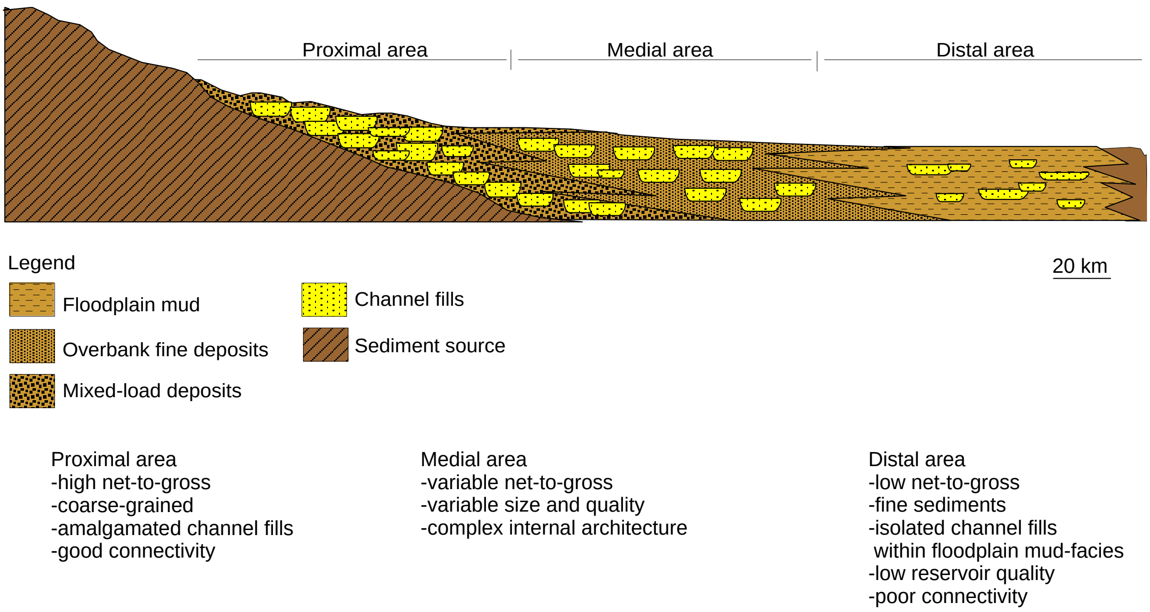

Figure 11. Provenance of channel-fill facies in fluvial depositional environment [11].

Therefore, understanding the degree of sandbody amalgamation and the effect of stratigraphic heterogeneities, arising from depositional architecture, on static connectivity will help to maximise hydrocarbon recovery from fluvial reservoirs. In addition to improving this understanding, accurate prediction of distribution of reservoir quality sandstones is key to successful fluvial reservoir development.

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