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Research Paper

Understanding Fluvial Reservoirs for Optimal Hydrocarbon Recovery

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ABSTRACT
In this review paper, we evaluated fluvial reservoirs using field analogues with the objective of reducing key uncertainty that impact their depositional architecture, and provide conceptual development concepts that deepen understanding of fluvial depositional systems, facies succession modelling, sand-body geometries, dimensions, and stacking patterns.

KEYWORDS: *fluvial reservoirs, reservoir characterisation, depositional architecture, internal geometry, sand-body connectivity.*

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I. INTRODUCTION

Many sandstone bodies that are deposited by fluvial channels form prolific reservoirs and aquifers. These reservoirs are widely known for their productivity in the exploitation of oil and gas. They have high net-to-gross, good-to-excellent reservoir quality, and high recovery factor (Davies et al., 1993). They are found in many producing fields (Figure 1) including Prudhoe Bay field in Alaska (world's largest braided fluvial field and the fifteenth largest of all oil fields), Sarir field (Martin, 1993), Messla and Bu Attifel fields in Libya, Daqing field in China, Statfjord and Snorre fields in the Norwegian North Sea, Cooper Basin fields in Australia, Masila field in Yemen, Oued Mya Basin fields in Algeria, and more (Melvin and Knight, 1984, King et al., 2003, Lavering et al., 1986, Martin, 1993, Baouche et al., 2023, Miall, 2006). These fields vary in size from hundreds of metres to several kilometres with high-sinuosity fluvial fields extending from hundreds of metres to tens of kilometres, and low-sinuosity fluvial fields extending beyond ten to hundreds of kilometres (Shepherd, 2009).

Despite the excellent reservoir quality of fluvial sandstone bodies, fluvial reservoirs are characterised by complex internal architecture that varies from one facies to another. This variable internal architecture affects geometry and dimension of sand bodies, thickness and distribution pattern of non-net lithologies, which in turn impact flow communication between wells and across reservoir intervals. The type and size of channel morphology, size range and amount of sediment load, tectonism, climate variation, and stability of channel bank are factors that affect sediment type in channel-fill sequences. The dynamic nature of fluvial channels may lead to complex internal architecture of resultant channel sandstone bodies (Omoniyi, 2021), and thus, affect their producibility.

Reservoir quality and distribution are critical to project value of a fluvial field (Omoniyi, 2011). This paper provides insight into fluvial architectural styles and development concepts that can optimise hydrocarbon recovery early on and improve recovery factor later on during the decline stage of a field. In this review, key subsurface uncertainties that are associated with each development strategy are evaluated with a view to mitigating attendant risks to hydrocarbon recovery.

II. FLUVIAL PROCESSES AND DEPOSITS

Fluvial environment extends from distal reaches of alluvial fans to proximal settings of deltaic environment (Figure 2). In fluvial settings, channel morphology is influenced by amount and variability of discharge, grain size of sediment and variation in distribution, velocity of river flow, channel width, depth and slope, bed roughness and vegetation on channel bank (Miall, 1981, 2014). Fluvial channels have tendency to deviate from a straight path. On this basis, two principal fluvial systems are recognised: (1) low-sinuosity system and (2) high-sinuosity system (Table 1, Figure 3, Figure 4). Depending on the amount of bedload and velocity of flow, a single channel may change in character from low sinuosity in the upstream areas to high sinuosity in the downstream reaches (Galloway and Hobday, 1996; Miall, 2014, 2022).

Aside from the deviation from a straight path, fluvial channels develop braiding when channel banks have tendency to erode (Friend and Sinha, R., 1993). Leeder (2011) identifies factors that favour braiding to include steep slopes, high sediment supply, discharge variability, abundance of bedload, and susceptibility of banks to erosion. In straight channels, water tends to flow in straight path. During flood events, however, turbulence occurs along channel margins and results in non-uniform distribution of flow velocity causing the stream to meander along a channel bend. Flow in a river may separate into branches to form distributary channel pattern. These branches may continue their flow concurrently until they encounter an obstacle, which causes them to weave around it to create anastomosing channel pattern. 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 (Galloway and Hobday, 1996). Consequently, flood waters may overflow channel banks and spill out into outer areas of the channel margins where they form levee deposits. During flood events, a flow may follow a breach along natural levee through small channels, carrying fine sediments that are mixed with coarse sediments of the levee and depositing them at distal reaches to form crevasse splay deposits (Van Toorenenburg et al., 2016; Burns et al., 2017; Omoniyi and Imagbe, 2025).

Fluvial deposits are primarily clastic comprising alluvial fan deposits, river channel deposits, floodplain deposits, and deposits formed in the proximal areas of deltas. These deposits are marked by a wide spectrum of grain sizes ranging from large boulders that are transported during high flood events to tremendously fine sediments such as silt and clay that are transported in suspension (Omoniyi, 2011).

III. DIMENSION OF SAND BODIES IN FLUVIAL SYSTEMS

The dimension of fluvial sand bodies varies depending on size, competence, and capacity of rivers that deposited them. Dimension of sand in large rivers such as Mississippi, Amazon, and Brahmaputra rivers among others will be larger than dimension of smaller rivers. According to Davies et al. (1993), dimension of channel sand (point bar) in high-sinuosity and low-sinuosity fluvial systems are:

$$D = \sqrt[1.54]{\frac{h_p}{64.6}}$$ for high-sinuosity fluvial system — Equation 1

$$D = \sqrt[1.85]{\frac{h_{cmax}}{12.1}}$$ for low-sinuosity fluvial system — Equation 2

h_p is height of point bar; h_{cmax} is maximum height of channel fill.

Figure 1. Selected major hydrocarbon fields composed of fluvial reservoirs.

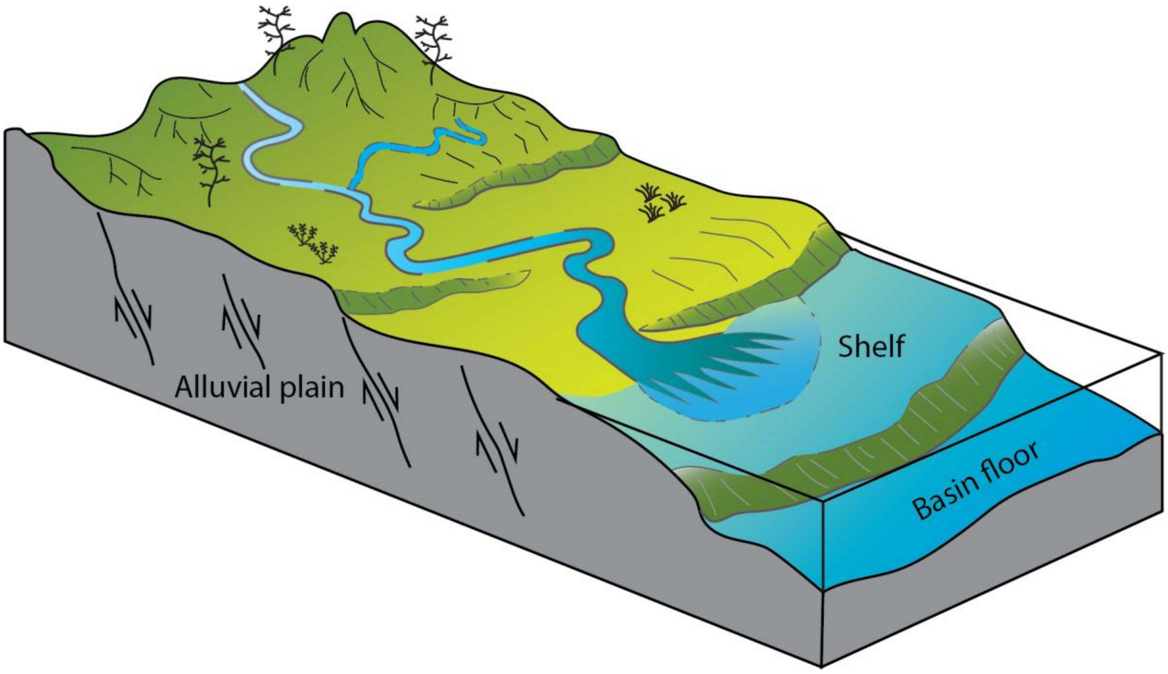

Figure 2. A cartoon of fluvial environment, extending from distal reaches of alluvial fans to proximal settings of deltaic environment.

Table 1: Channel classification based on sinuosity (Miall, 1981, 2006).

Sinuosity	Number of river channel	
	Single channel	*Multiple channels*
Low sinuosity (< 1.5)	Straight channel	Braided channel
High sinuosity (> 1.5)	Meandering channel	Anastomosing or Distributary channel

Figure 3. Charley River at Yukon, Alaska terminating into a body of braided channel. Note sand accumulation at river bends to form point-bar deposit (Source: Google images).

Figure 4. Amur River, China. Channel sands in this modern braided system forms longitudinal and transverse bars (Source: Google images).

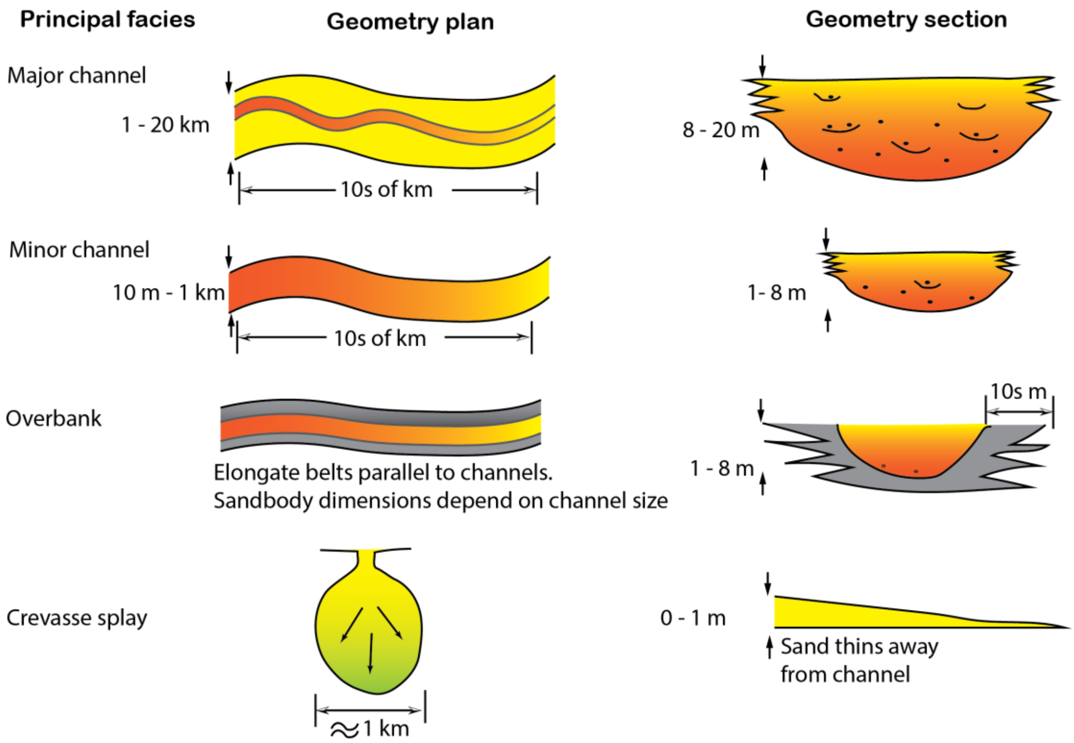

Figure 5: Dimension of sand bodies in fluvial systems (Aitken et al., 1999).

Major fluvial channels extend over 10s of kilometres with width of 1-20 km and have channel fills that are up to 20 m thick (Figure 5). By contrast, minor fluvial channels range in thickness from 10 m to 1 km and extend over 10s of km with typical channel fills that are up to 8 m thick. In these channels, deposits that accumulate outward of channel banks typically form continuous belt that extends laterally over 10s of metres with thickness of 1-8 m. Associated crevasse splay deposits, which reflect conditions of multiple flood events, shallow flow conditions, and rapid sedimentation rates, thin away from channel and rarely exceed thickness of 1 m.

IV. DISCUSSION

1. Sandbody Architecture

Fluvial sand bodies have distinct internal architecture that is controlled by their depositional complexity (Dalrymple, 2001; Jones and Glover, 2005; Miall, 2006; Pranter et al., 2014; Hudson, 2017; Stow et al., 2020; Abdel-Fattah, 2021). The shallow incision of fluvial channels into floodplain mud in low-sinuosity fluvial systems (Figure 6), typical of braided rivers, causes channel bedload sediments to spread laterally over a wide area (Omoniyi, 2023; Omoniyi et al., in press). Subsequent flows continue to switch path within the braided channel fairway and deposit their bedload sediments as lateral bar, longitudinal bar and/or transverse bar. The channel sequence comprises pebbles or gravels forming basal lags. Internal structures of these in-channel deposits include tabular and trough-cross stratification, flaser bedding, parallel horizontal lamination, lenticular bedding, ripple lamination and ripple cross lamination (Miall, 2006, 2014). The bar top in these systems may grade into vertical accretion deposit with floodplain mud capping the sequence and marking onset of channel inactivity.

Deposition in channel thalwegs gives rise to continuous laterally stacked channel sands. This stacking pattern results in development of a complex of interconnected channel sands with overall sheet geometry. The sheet sands are typically characterised by high net-to-gross and high lateral connectivity. With the passage of time, allogenic events e.g. tectonism, may cause a channel to migrate to another area on the floodplain, abandoning its fairway and depositing its bedload sediment in a new fairway. During high flow events, flow may outstrip channel banks. Such lateral flows may deposit channel sands that reach terminals of previously deposited channel sands in the now abandoned inactive channel. In this case, channel sand may directly accumulate on top of floodplain mud blanketing the abandonment topography. On the flip side, this phenomenon may develop laterally amalgamated channel sands. Based on amalgamation potential, multistorey sheets of amalgamated channel sand bodies are commonplace in braidplain systems. Thus, low-sinuosity channels are composed of thick, laterally stacked and extensive sand bodies. The multistorey channel sandstone with amalgamated stacking pattern in Statfjord Formation is a classic example (Figure 7). Campbell (1976) and

Miall and Turner-Peterson (1989) reported that the sheet sands in Westwater Canyon Member in the Morrison Formation, northwestern New Mexico, are more than 100 km wide with average thickness of 61 km. These sands were found to contain internal channel sand bodies averaging 11 km wide and 15 m deep.

High-sinuosity fluvial systems are typical of meandering rivers. In these systems, channels incise into floodplain mud and deposit its sediment load in the fairway. Confinement of subsequent sand-rich flows results in continuous deposition of sediment load with characteristic vertical stacking pattern. In such fairways, sediments that are carried from outer bank of a channel bend are deposited inside another bend, to develop a point bar sequence. This sequence is typically composed of upward-fining succession with characteristic thinning of point-bar sand into floodplain mud. In these systems, pebbles or gravels accumulate as lags on the scoured channel floor. Above the scoured base, internal structure comprises channel-trough-cross stratification, horizontal and parallel lamination, and current ripple lamination Miall, 1981, 2006). The top of point bar is commonly overlain by a thick mud plug that accumulates as lateral accretion deposit. Such floodplain deposit comprises abundance of pedogenic structures, and is thought to develop during flow stripping as fine sediments held in suspension in the mixed-load flow is transported and deposited overbank. Associated with point bar sequences are crevasse splays. These mixed-load sediments may develop over a period of multiple flood events, shallow flow conditions, and rapid sedimentation rates, which become prevalent during high flood events. During these events, flow may follow a breach along natural levee through small channels, carrying suspended load mixed with coarser sediments of the levee and depositing them at distal flow reaches to form crevasse splay deposits. Because sand bodies serve as both the storage for hydrocarbon accumulation and conduits for flow,

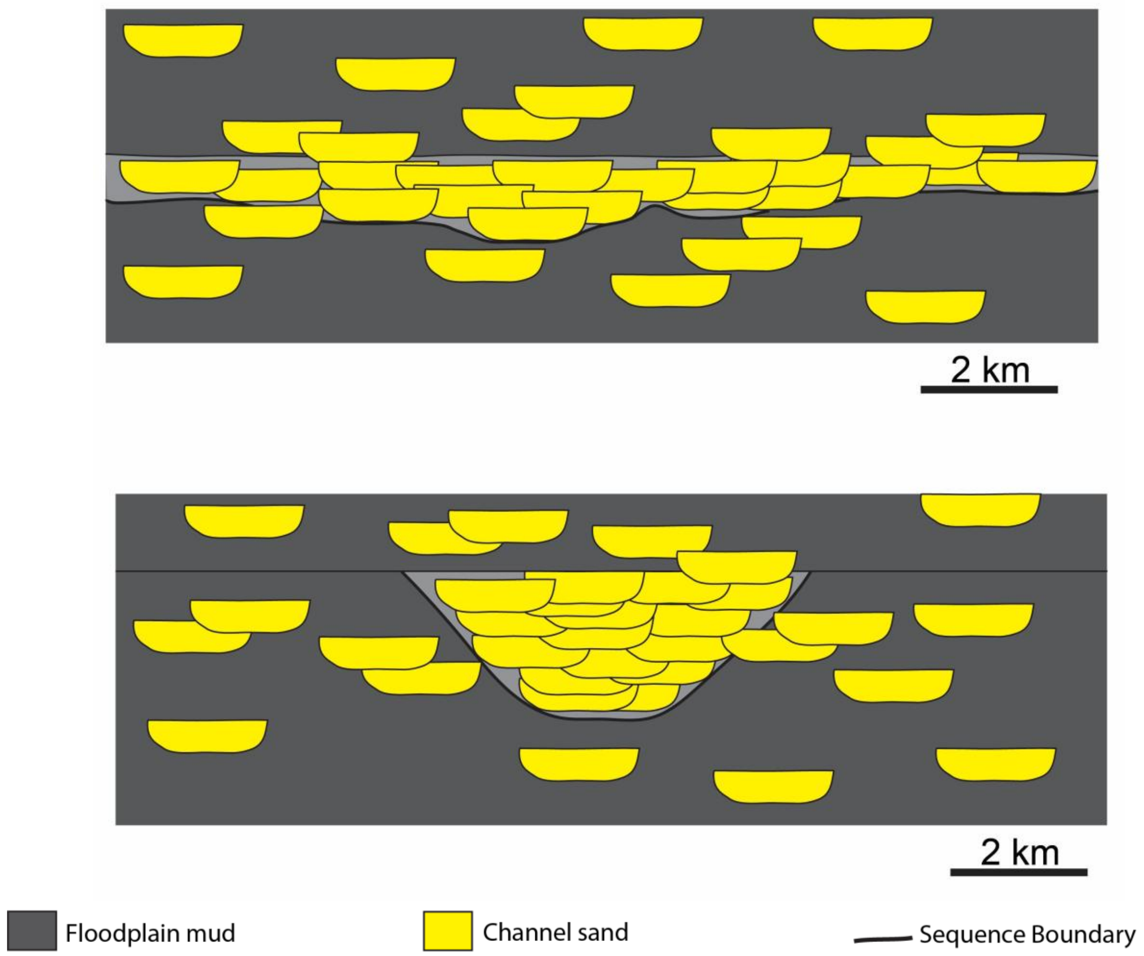

Figure 6: Schematic diagrams of shallow and deep fluvial incision: (A) shallow fluvial incision (B) deep fluvial incision (Posamentier and Allen, 1999). Widespread sheets of amalgamated channel sandstone are formed by shallow fluvial incision, extending to hundreds of kilometres. By contrast, channel-fill deposits that are associated with deep fluvial incision, typical of high-sinuosity systems, are usually not extensive but form

vertically stacked channel sandstone. Outside the primary fairway, isolated channel sands may form from sand-rich flows that outstrip channel banks, particularly during high flow events.

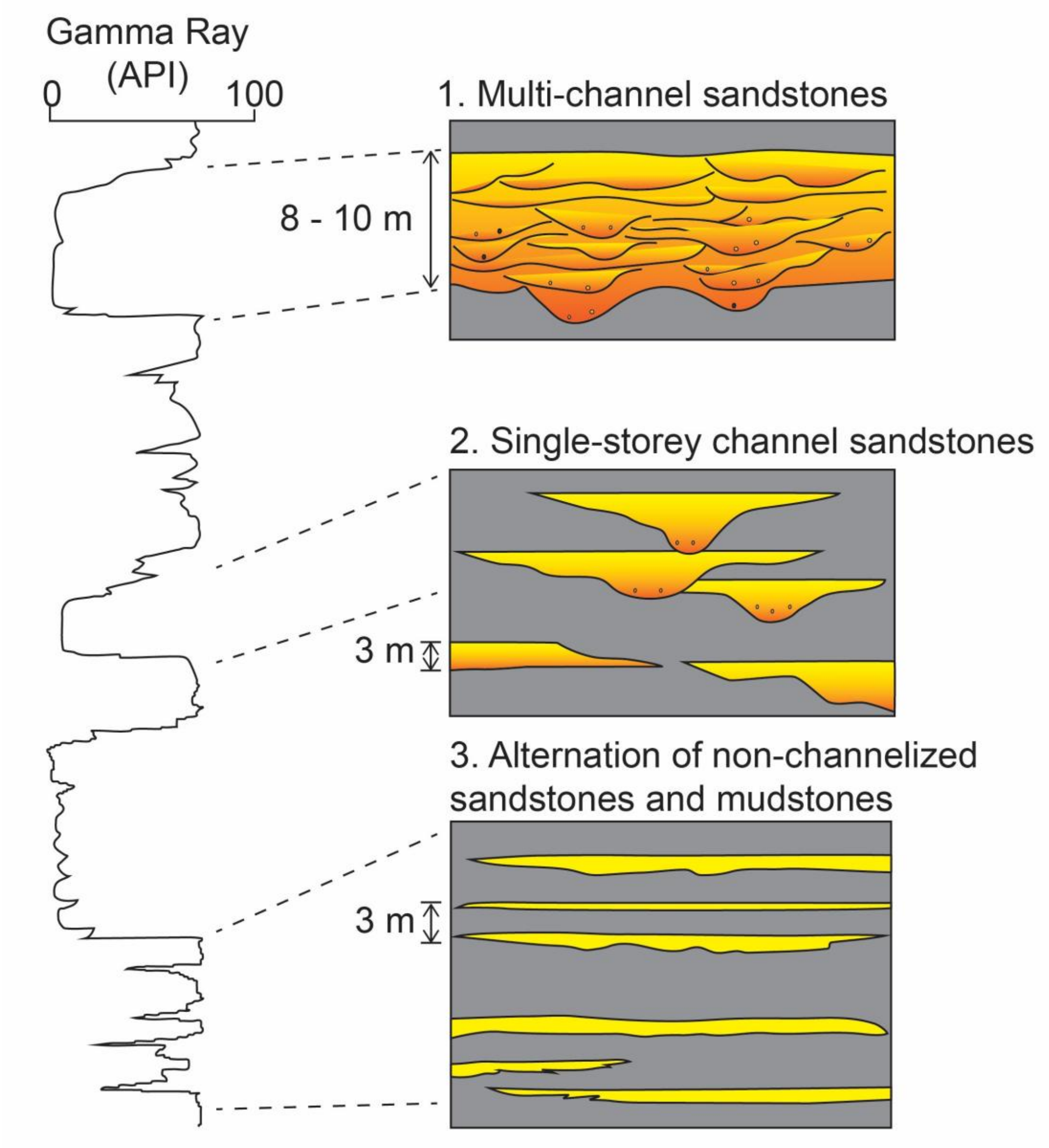

Figure 7: Facies architecture of Statfjord Formation (Van Wagoner et al., 1995).

geometries and dimension of these sand bodies will impact resource and recoverable reserve, number and location of appraisal/development wells, and well spacing.

2. Reservoir Quality (Fluid Contacts, and Fluid Systems)

Reservoirs comprising low-sinuosity channel sands have excellent quality. However, the quality of these reservoirs is significantly reduced by diagenetic modification. For example, diagenetic modification of channel lags and clay-rich rip-up clasts forms flow barriers in these reservoirs. In addition to these flow barriers, high permeability coarse sands or gravelly layers in these reservoirs may develop thief zones and thus pose a threat to production (Atkinson, 1989). A typical example is an injector in Prudhoe Bay Field, Alaska. This well penetrates a thick conglomeratic zone with permeability of 4 Darcies and shows 95% of the total injected water (Davies et al., 1993). Reservoirs comprising high-sinuosity point-bar sands, on the other hand, have lower quality attributed to high degree of variability over respective interval. In these reservoirs, trough cross-bedded sands have high quality, whereas ripple-bedded sands have lower quality. Although basal lags in some meander belt systems form potential permeability barriers within productive channel sand bodies, fine splay sands in these systems may possess better reservoir quality when mud content is low (Davies et al., 1993).

3. Permeability Variation and Sweep

Permeability varies in fluvial channel sands based on their depositional architecture. High-sinuosity channels are typified by upward fining sequence and upward decreasing permeability trend. In this sequence, permeabilities are highest at the base where large trough-cross bedded sands are concentrated; but ripple-bedded fine sands at the top have lowest permeabilities. Low-sinuosity channel sands, typical of braided sheet systems, have no particular permeability trend (Davies et al., 1993), although there may be permeability contrast that is caused by variation in grain size and sorting. Hence, permeabilities are highest where braidplain sands are medium-grained and well sorted e.g. lithofacies 3 in Ivishak Formation, Prudhoe Bay Field (Melvin and Knight, 1984). Understanding permeability trends in fluvial reservoirs is crucial to field development planning because it partly controls flood fronts. For upward decreasing permeability trends, typified by reservoirs in high-sinuosity systems, it is commonplace for gravity to move injected water downwards thereby causing it to advance faster in the lower high-permeability trough cross-bedded sands than in the upper low-permeability ripple-bedded fine sands. The gravity segregation in this case is influenced by large permeability contrast that causes early breakthrough of injected water (Figure 8). With gas flood, upper parts of the reservoirs are swept first before lower parts. This gas-depletion strategy effectively reduces chances of leaving oil behind during flooding.

4. Sandbody Connectivity and Well Configuration

Two sandbodies may be said to be well-connected when there is fluid communication between them during production. High-sinuosity fluvial systems typically display ribbon geometry with a difficult arrangement of sand pods, lenses, and channels that results in a complex labyrinth of interconnected sand bodies. As a consequence of poorly connected channel sands between oil producers and water injectors, injected water may fail to sweep oil to oil producers. In this case, it is reasonable to dedicate one water injector to one oil producer as long as the economics can be justified. Increasing well count in a poorly-drained reservoir will improve displacement efficiency and oil sweep when the wells are drilled parallel to channel orientation. With this well configuration, however, maintaining pressure support may prove difficult. By drilling production and injection wells in the channel, reservoir pressure will be significantly supported, but rapid water breakthrough and poor oil sweep may arise (Smith, 2011; personal communication). Conversely, reservoirs in low-sinuosity systems are commonly bounded by big aquifers, which will help with high initial recovery and produce efficient water drive for reservoir pressure support during production.

In fluvial reservoir development, the importance of well design cannot be overemphasized. Vertical wells are cheap to drill because they require simple technology. They are capable of penetrating more than one reservoir layer; hence they are suitable for draining oil in reservoirs with sheet geometry (Figure 9). However, these wells are susceptible to coning, early water breakthrough, and may bypass oil in isolated channel sands. Apart from these pitfalls, this well design may increase cost of production due to high well count and connection as well as maintenance during production. For development of reservoirs comprising laterally stacked channel sands, typical of low-sinuosity fluvial systems, horizontal wells are usually unsuitable because the design allows one zone to be produced at a time. Production from these sheet channel sands therefore requires nonconventional well design, which includes deviated wells, multilateral wells, smart wells, and stacked wells. These wells are characterised by increased productivity, accelerated recovery, access to remaining reserves, and reduced conning tendencies in addition to their flexibility in production and lower cost of drilling and connecting the wells.

VI. CONCLUSION

Channel sands in fluvial systems are excellent reservoirs. Despite their good-excellent reservoir quality, sedimentary heterogeneity related to depositional architecture and complexity make it difficult to evaluate fluvial reservoirs. Field development should consider internal geometry of these channel sands to design wells that will effectively drain hydrocarbon from them. The high net-to-gross, good lateral continuity, low interbedded mud, excellent sandbody connectivity, excellent internal pressure communication in non-compartmentalised fields, high horizontal permeability make low-sinuosity sheet channel sands prolific reservoirs. The reverse is the case for high-sinuosity ribbon-like channel sands with characteristic lower net-to-gross, thick interbedded mud, discontinuous channel sand and low sandbody connectivity. Water injection tends to improve oil sweep in reservoirs with laterally stacked low-sinuosity channel sands, whereas gas injection may prove more effective in sweeping oil from vertically stacked high-sinuosity channel sands to production wells.

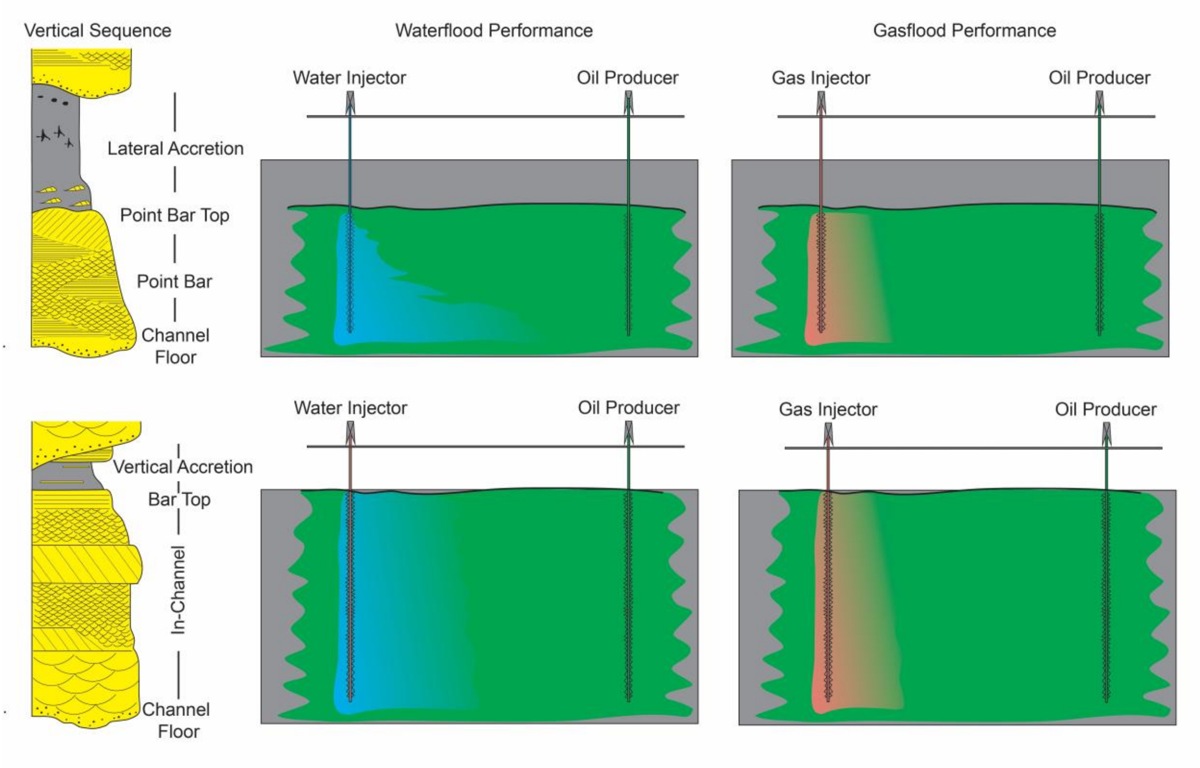

Figure 8: Cartoons of flood pattern in: (a) meandering, and (b) braided reservoirs.

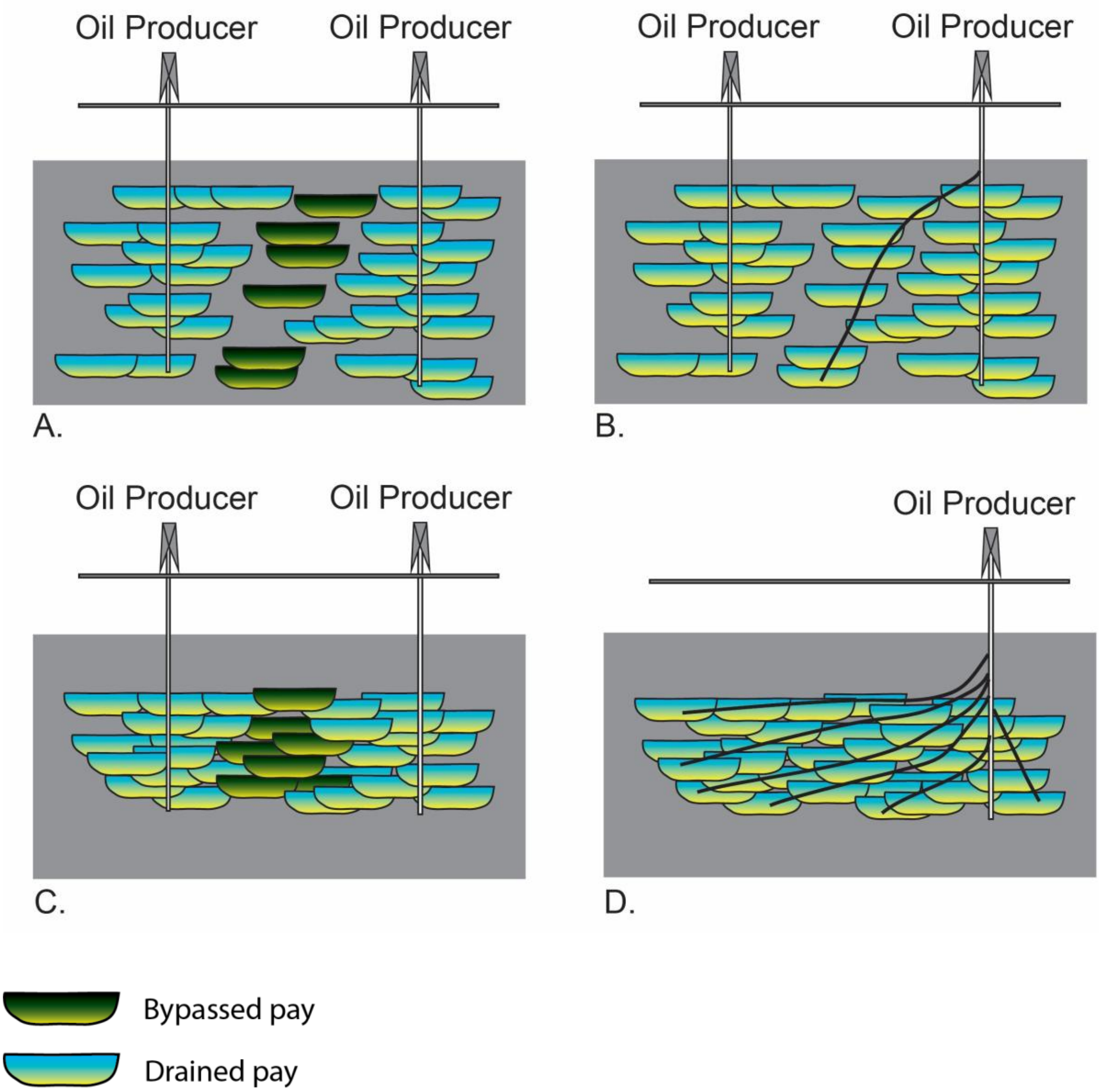

Figure 9. Well techniques for draining fluvial reservoirs. (A) Conventional vertical wells draining poorly-connected sand bodies. (B) Vertical wells and a side lateral well effectively draining sand bodies. (C) Conventional vertical wells with unswept sand bodies between them. (D) A system of multilateral wells effectively draining sheet sand bodies.

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