Sandbody architecture analysis of braided river reservoirs and their significance for remaining oil distribution: A case study based on a new outcrop in the Songliao Basin, Northeast China

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Abstract

The reservoir architecture analysis of braided rivers, especially falling-silt seam forms, has played a key role in predicting remaining oil distributions. However, no studies have used architecture analyses that document braided river outcrops and researched the tapping of the few remaining oil distributions based on outcrops in the Songliao basin, northeast China. In this paper, the architecture characteristics and remaining oil distribution of braided river reservoirs are studied using a combination of an outcrop, modern deposition and subsurface well data. The new 8–13 m thick Lower Cretaceous Quantou Formation outcrop of the Songliao basin is a braided fluvial...
succession arranged in one large fining-upward cycle. Eight facies (Gt, St, Sm, Sh, Sp, Sw, Fl and Fm), four architecture elements (CH, DA, LV, and FF), and three orders of bounding surfaces (third-, fourth-, and fifth-order) are recognized. A new distribution pattern of falling-silt seams and a braided river architecture model are presented according to the analysis of the outcrop. In the mid-channel bar, the falling-silt seams thin from the mid-bar to the bar tail following the flow direction. Each falling-silt seam is oriented tangentially to the basal surface of the mid-channel bar, and the upper falling-silt seam extends farther than the lower one. In a Daqing Oilfield exploitation block in the Songliao basin, while channels and bars are the main reservoir units, they have different remaining oil distribution patterns. For bars, water injection wells located at the mid-bar, zonal injection technology, the drilling of horizontal wells, and proper well patterns are proposed. Fourth-order bounding surfaces, single braided channels, stacking patterns, and the lateral blocking of levees and floodplains are the key factors affecting the remaining oil distribution in channels.

Keywords
Reservoir architecture, remaining oil, braided river, mid-channel bar, Songliao basin

Introduction
Over the last three decades, many studies have described the sedimentary architecture of braided river deposits based on Maill’s theory (Miall, 1985, 1988, 1996). Outcrops, well logging, ground penetrating radar, and laboratory simulations have found great application in braided river architecture research (Bridge et al., 1998; Bristow, 1993; Best et al., 2003; Cant and Walker, 1978; Liu et al., 2009; Lv et al., 2010; Jin et al., 2014). The architecture is complex due to the complicated scouring and superposition of different periods of channels and the identification of falling-silt seams. In general, the alluvial architecture of braided channel bars is complex because of a combination of lateral, vertical, upstream, and downstream accretions (Ashworth et al., 2000). Reservoirs formed in braided stream depositional environments are important worldwide, especially in the oilfields of the Songliao basin, northeast China, where braided river sandbodies play a key role, and detailed architecture analysis aids the prediction of remaining oil distribution (Falivene et al., 2006; Hou et al., 2008; Li et al., 2015; 2019; Niu et al., 2014; Xu et al., 2016). However, previous work has mainly only focused on densely spaced subsurface-well data from the Songliao basin region or outcrops in other basins in China (Chen et al., 2019; Li et al., 2015; Qin et al., 2018; Ren et al., 2018; Wen et al., 2016; Yin et al., 2013). Very little research on braided river outcrops has been carried out in the Songliao basin.

This paper describes a newly sandy braided river outcrop of the Lower Cretaceous Quantou Formation in the south Songliao basin and the recognition of the principal lithofacies and architecture elements. Combining outcrop observations with satellite images of one modern braided river, a new distribution pattern of falling-silt seams and a braided river architecture model are presented and applied to a Songliao basin exploitation block. The study’s results are significant for the understanding of braided river architecture and tapping remaining oil.
Geological setting

The Lower Cretaceous Quantou Formation is an important hydrocarbon-producing layer in the Songliao basin, northeast China. However, there are few outcrops and most of the area is covered by Quaternary sediments. The new outcrop exposing the fourth member of the Quantou Formation in the study area is located in the southern part of the basin (Figure 1). Deng (2006) and Miao (2008) publicly reported braided river sedimentation in this area, but the original outcrop they studied was damaged by engineering construction. According to previous studies, the paleoclimate was semiarid, and the paleo-provenance direction was approximately southeast during the Quantou Formation period. The outcrop is about 8–13 m thick and 100 m long. It is composed of conglomerate, sandstone and mudstone, indicative of a braided river deposits.

Data and methods

Outcrop description

The data for this study was primarily based on a detailed description of the new Songliao basin Quantou Formation outcrop, located near Siping City. Note that the outcrop is weathered, so the surface of the gray sandstone is now light red.

![Locality map of the study area with regional geological characteristics](Figure 1a)
![Aerial view of the outcrop (Google Earth)](Figure 1b)
![Section photographs](Figure 1c)

Figure 1. (a) Locality map of the study area with regional geological characteristics, (b) aerial view of the outcrop (Google Earth), and (c) section photographs.
The paleocurrent flow, from the southeast to the northwest, was mainly deduced from the morphological characteristics of the cross-beddings. Medium- to coarse-grained planar cross-bedded sandstones (Sp) were deposited mid-bar in the eastern part of the outcrop. The trend of the cross bedding layers is generally consistent with a northwest paleocurrent (Gao et al., 2013). The direction of flute cast on the basal surface of the mid-channel bar also indicates a north-westerly paleocurrent direction (Du, 2018).

**Satellite images of a modern braided river**

To better understand the morphological characteristics of the bar, the satellite images of 20 mid-channel bars in the Songhua River were analyzed. The length and width of each bar were measured, and the length/width ratios were analyzed using a scatter diagram.

**Exploitation block subsurface data**

Subsurface data, including well logs, from a Daqing Oilfield exploitation block in the Songliao basin were used to study the remaining oil distribution in mid-channel bars and channels. The block has over 300 oil production and water injection wells. A mid-channel bar is described using two well sections, and the distribution patterns of the remaining oil in channels are presented.

**The hierarchy of depositional units and bounding surfaces**

Miall’s concept of a hierarchical framework of depositional units and bounding surfaces was applied in this research (Miall, 1988, 1996), which focused on third-, fourth- and fifth-order units and bounding surfaces.

Third-order surfaces are commonly accretion surfaces inside large-scale bedforms, such as the interfaces of lateral accretion bodies and accretion bodies in channel bars. Lateral accretion bodies, a lateral accretion shale bed in a point bar, accretion bodies in a channel bar, and channel filling in the top of a channel bar, are usually defined as third-order units. In this paper, third-order surfaces mainly refer to falling-silt seams inside a mid-channel bar. Fourth-order surfaces are commonly the bounding surfaces of large macroforms. Some architecture elements, including gravel bar elements (GB), sandy bedform elements (SB), downstream accretion elements (DA), and lateral accretion elements (LA) are usually defined as fourth-order units (Miall, 1996). The lower bounding surfaces of channel-fill elements that represent the new beginning of a fluvial fining-upward cycle are commonly defined as fifth-order surfaces. These bounding surfaces are usually characterized by the erosional bases of channel-fill elements (CH) and DA elements (Table 1).

**Results and discussion**

**Lithofacies**

The conglomerate, sandstone and claystone units in the outcrop were distinguished as eight lithofacies according to clasts size, sorting, and bedding types.

**Trough cross-bedded pebbly sandstone (Gt).** This facies consists of trough cross-bedded gravels and sands and is usually the basal deposit of fining-upward cycles (Figure 2(a)). The clasts
Table 1. Hierarchy of depositional units and bounding surfaces.

| Order | Architecture element                                                                                                                                                                                                 | Bounding surface                                                                 |
|-------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| 3rd   | Accretion bodies in a channel bar, lateral accretion bodies, lateral accretion shale bed, channel filling sandbodies in the top of a channel bar                                                                               | Interfaces of the lateral accretion bodies, falling-silt seams                    |
| 4th   | Channel fill (CH), downstream accretion (DA), levee (LV), floodplain element (FF), lateral accretion (LA), gravel bar (GB), sandy bedform elements (SB)                                                              | Bounding surfaces of a channel and bar, bounding surfaces of a large macroform    |
| 5th   | Channel-fill complex                                                                                                                                                                                                   | The lower bounding surface of channel-fill complex                                |

Figure 2. Lithofacies photographs of the outcrop (the leans cap diameter is 70 mm). (a) Trough cross-bedded pebbly sandstone (Gt), (b) coarse- and middle-grained massive bedded sandstone (Sm), (c) coarse-grained trough cross-bedded sandstone (St), (d) fine- to medium-grained sandstone with flat bedding (Sh), (e) medium- to coarse-grained planar cross-bedded sandstone (Sp), (f) medium-grained wedge shaped cross bedding sandstone (Sw), (g) parallel laminated siltstone (Fl), and (h) mudstone (Fm).
comprise mostly granite (2–10 mm), gneiss (2–10 mm), quartzite (2–10 mm), and mudstone (10–50 mm) are the most clasts. These sandstone beds are cross-bedded and massive in places. It is commonly overlain by coarse-grained sandstone and underlain by siltstone and mudstone facies, which indicate the top of the underlying deposition cycle. This facies represents rapid sedimentation from a high energy flow, consistent with the lower level deposition of fluvial channels.

**Coarse- and medium-grained massive bedded sandstone (Sm).** In general, this facies consists of coarse- and medium-grained massive bedded sandstone, indicating rapid sedimentation from a high energy flow or a sufficient supply (Figure 2(b)). It mostly occurs in the lower part of a channel or a channel bar and can be interpreted as the simple filling and vertical accretion of channels or channel bars.

**Coarse-grained trough cross-bedded sandstone (St).** This facies consists of medium- to coarse-grained sandstone and usually overlies trough cross-bedded pebbly sandstone (Gt) (Figure 2(c)). The fresh surfaces are greyish white, and the sandstone grains are sub-angular to sub-rounded. Small-scale troughs and large-scale types are both evident, occurring mostly in grouped sets or, in places, solitary sets. All the above features can be interpreted as fluvial bedforms.

**Fine- to medium-grained sandstone with flat bedding (Sh).** This facies consists of fine- to medium-grained sandstone and is typically found in the central part of a channel, mid-bars and bar tails (Figure 2(d)). It is commonly no more than 1 m thick, and the upper contact is often gradational to cross-bedded sandstone in channels. However, it is thicker at the bar tail. These fine-grained sediments with sheet-like geometry indicate deposition as a bar tail or channel deposits during seasonal floods (Miall, 1996).

**Medium- to coarse-grained planar cross-bedded sandstone (Sp).** This facies consists of poorly sorted medium- to coarse-grained light-gray sandstones (Figure 2(e)). However, pebbly sandstones are found in some places. Single layers are 20–30 cm thick and up to 1 m long. It is representative bar deposits.

**Medium-grained wedge-shaped cross bedding sandstone (Sw).** This facies is uncommon and only occurs in the central part of the outcrop (Figure 2(f)). It is about 30 cm thick and consists of medium-grained wedge-shaped cross bedding sandstone. This facies is gradational with Sh on the lower boundary and St on the upper boundary. It is typical of braided river sediments, and is interpreted to represent rapid sedimentation from a high energy flow.

**Parallel laminated siltstone (Fl).** This facies mainly consists of light-gray laminated siltstone (Figure 2(g)). The lower contact of this facies is gradational with facies Sh, and its upper contact is always gradational with facies Fm. In the outcrop, this facies is less than 1 m thick, and shows lateral sheet-like bodies. It is interpreted to represent deposits in overbank areas, where most deposition is from suspension settling. The parallel lamination of this sheet-like alternating siltstone indicates widespread deposition over the upper parts of sandy channels.
**Mudstone (Fm).** This facies generally consists of red or purple mudstone with rare light-gray mudstone and white siltstone interbeds (Figure 2(h)). It is commonly massive and up to several meters thick. The lower contact of this facies is always gradational, whereas the upper contact is mostly truncated by the erosive base of trough cross-bedded pebbly sandstones. This facies is located at the top of the outcrop and represents the deposition of fines in overbank settings.

**Architectural elements**

Detailed outcrop observation showed that there are four typical architecture elements in this sandy braided river outcrop.

**Channel fill elements (CH).** Channels are common architecture elements in the profile, often appearing as 1–2 m thick complex channel sandbodies mainly characterized by facies Gt and St with some facies Sm, Sh, Sp and Sw. They can be traced laterally in excess of 50 m (Figure 3). Flow scouring is frequent at the bottom of the channels, resulting in erosional surfaces. The channel fill element is characterized by a thinning upward structure. From the bottom to the top, the rock type change from trough cross-bedded pebbly sandstone to fine- to medium-grained sandstone. The erosive basal surfaces are always infilled by facies Gt, whereas the upper contact is gradational to fine sandstone and mudstone. However, in some places, the lithofacies sequence is incomplete, and the upper part is usually absent due to a later erosional stage. The erosive contacts between the underlying facies Fm and overlying facies Gt are fifth-order bounding surfaces (Miall, 1985).

Complex channels are very common in braided river systems, suggesting the frequent shifting of channels. In Figure 3(c), channel 2–5 are complex channel sandbodies consisting of facies Gt. The scales of channel 2–5 are different from channel 1, 6, and 7 because the former are residual sediments left in the bottom of the riverbed, where a former channel was scoured by a later channel due to frequent channel diversion. Therefore, the lithological sequences in channel 2–5 are not complete or continuous.

In the middle part of the outcrop (Figure 3(d)), different forms of facies in the channels can be described in detail. Facies Gt, Sh, Sw, Sp, and St are arranged from base to top, which indicates a change in river energy from high to low. Each facies is 20–50 cm thick. Some stripes of purple mudstone are deposited in facies Gt.

**Downstream accretion element (DA).** Mid-channel bars usually show convex-up shapes. These are the main sedimentary units and are widely distributed among channels in braided river systems. These bars are commonly defined as DA elements (Miall, 1996). Studying the architecture model of a mid-channel bar is significant for remaining oil distribution research (Dang et al., 2017; Li et al., 2011; Liu et al., 2018; Yu, 2015). Channel bars are usually defined as fourth-order units and falling-silt seams are third-order bounding surfaces. However, there is little research on the occurrence of falling-silt seams.

In the eastern part of the profile, there is a mid-channel bar with three falling-silt seams (Figure 4). The 5 m thick mid-channel bar is dominated by facies Gt, St, Sm, Sp, Sh, and Fm. Its lateral extent is more than 30 meters wide, and it grades laterally gradual into braided channels, the ends of which are not seen in the profile. Only the central part and the bar tail can be described in detail. The flat base and convex-up shape represent the
vertical and downstream accretions of a flow deposit. This element forms a fining-upward cycle in the profile.

The lower contact is an erosional surface and defined as a fifth-order bounding surface similar to fluvial channels. A thickness of approximately 30 m of trough cross-bedded pebbly sandstones (facies Gt) and coarse-grained trough cross-bedded sandstone (facies St) are deposited on the base. These facies are overlain by medium- to coarse-grained planar cross-bedded sandstone (facies Sp) and medium-grained massive bedded sandstone (facies Sm). Medium-grained sandstone with flat bedding (facies Sh) is observed at the bar tail. Parallel laminated siltstone (facies Fl) is underlain by purplish-red mudstone.
Medium-grained sandstone with flat bedding (Sh) is deposited in the mid-bar, indicating rapid flow (Figure 4).

**Levee element (LV).** The levee element occurs in the upper part of the profile and is generally composed of purplish-red and grayish-white siltstones and pelitic siltstone interbedded with silty mudstone deposits (Figure 5). This element is up to 1 m thick, and horizontal bedding with some massive bedding is well developed in the study area. It represents the vertical accretion deposits of channel levees that develop between channels and floodplains.

**Floodplain element (FF).** This element, developed in the top part of the profile, predominantly consists of purplish-red mudstones with rare grey-green mudstone and siltstone (Figure 5). It is overlain by Quaternary sediments and underlain by the levee element. There are few plant fossils and root traces in the profile, indicating Lower Cretaceous oxidizing environment in a semiarid climate.

**Modern-braided-river mid-channel bar characteristics**

Satellite images of modern braided rivers can be used to observe large-scale sediment distributions and morphologies. In this study, the satellite images of 20 mid-channel bars in the Songhua River were analyzed to better understand the geometric-shape characteristics of mid-channel bars (Figure 6). For example, as seen in Figure 6(a) and (b), erosion...
predominantly occurs at the bar head, while deposition occurs at the bar tail and margins, although upstream accretion on bar heads occurs in some places (Ashworth et al., 2000; Zhang et al., 2020). This erosion can form a stage of the downstream migration of mid-channel bars, the result of turbulent flow instability occurring on erodible beds (Ashworth et al., 2000; Colombini et al., 1987; Tubino, 1991), or affected by variable channel discharges.
and the geometry of nearby bars (Rodrigues et al., 2015). Additionally, numerous cross-bar channels form during falling flow stages that dissect the mid-bars into smaller portions (Figure 6(a)) (Lunt et al., 2004; Smith et al., 2006; Weckwerth, 2018).

The length and width of each bar are presented in Table 2, and the length/width ratios are illustrated in a scatter diagram in Figure 6(h). The bars range in size from 812 m long and 283 m wide up to 4,753 m long and 1,973 m wide. The length/width ratios vary between 1.84 and 4.31, with an average ratio of 2.96. The results show that length is closely associated with width (Figure 6(h)). The relative equation is expressed as

\[ y = 0.407x - 84.675 \]

where \( y \) is width and \( x \) is length in meters. The correlation index \( R^2 = 0.8963 \).

**Distribution pattern of falling-silt seams**

A mid-channel bar consists of a bar head, mid-bar, bar margin, and bar tail (Best et al., 2003; Liu et al., 2018; Qiao et al., 2016). Based on former work and this outcrop, a distribution model of falling-silt seams was established (Figure 7). Falling-silt seams usually have a convex-up shape, like mid-channel bars, but they exhibit various morphological characteristics in different parts of the bar. At the bar head, they are not well preserved due to constant flow scouring and downstream migration (Ashworth et al., 2000; Liu et al., 2018; Qiao et al., 2016). At the mid-bar, falling-silt seams are almost flat and are at a maximum thickness. As seen in this study, the falling-silt seams thin from almost 30 cm thick in the mid-bar to 5 cm in the tail following the flow direction (Figure 4). In some

| Bar no. | Latitude     | Longitude    | Length (m) | Width (m) | Length/width |
|---------|--------------|--------------|------------|-----------|--------------|
| 1       | 45°07'23''N  | 124°53'24''E| 1359       | 469       | 2.90         |
| 2       | 45°37'29''N  | 124°59'05''E| 3166       | 1020      | 3.10         |
| 3       | 44°51'40''N  | 125°15'37''E| 830        | 401       | 2.07         |
| 4       | 44°52'08''N  | 125°10'59''E| 1017       | 312       | 3.26         |
| 5       | 44°51'57''N  | 125°12'28''E| 2840       | 1009      | 2.81         |
| 6       | 44°52'19''N  | 125°21'24''E| 4753       | 1973      | 2.41         |
| 7       | 44°53'21''N  | 125°25'49''E| 2424       | 930       | 2.61         |
| 8       | 44°56'00''N  | 125°38'28''E| 2675       | 1069      | 2.50         |
| 9       | 45°11'38''N  | 124°44'08''E| 812        | 283       | 2.87         |
| 10      | 45°21'21''N  | 124°42'38''E| 1631       | 553       | 2.95         |
| 11      | 44°56'21''N  | 125°39'45''E| 2065       | 587       | 3.52         |
| 12      | 44°53'33''N  | 125°45'45''E| 2321       | 1260      | 1.84         |
| 13      | 44°56'13''N  | 125°41'52''E| 866        | 344       | 2.52         |
| 14      | 44°53'06''N  | 125°45'57''E| 1210       | 445       | 2.72         |
| 15      | 44°46'33''N  | 125°55'05''E| 922        | 226       | 4.08         |
| 16      | 44°45'57''N  | 125°55'48''E| 1135       | 389       | 2.92         |
| 17      | 44°47'10''N  | 126°01'44''E| 2433       | 631       | 3.86         |
| 18      | 45°06'57''N  | 124°54'57''E| 1817       | 683       | 2.66         |
| 19      | 45°10'08''N  | 124°48'04''E| 1073       | 249       | 4.31         |
| 20      | 45°16'34''N  | 124°44'31''E| 1425       | 442       | 3.22         |
places, the upper seams are partially cut by cross-bar channels (Chen et al., 2015; Qiao et al., 2016). At the bar margins, the falling-silt seams are not symmetrical because of asymmetric flows in adjacent channels. Erosion and deposition are both probable. The boundary surface between the channel and the bar is not distinct. In the outcrop, at the bar tail, the upper falling-silt seam extends laterally much farther than the lower falling-silt seam (Figure 7). Each seam is tangential to the basal surface of the mid-channel bar.

For oilfields, accurately determining the dip angles and distribution ranges of falling-silt seams is difficult because exploitation block wells are not placed densely enough. However, the same falling-silt seam between two adjacent wells can be used to determine the dip angle, ranging between $0^\circ$–$3^\circ$, as shown in Figure 7 (Niu et al., 2015; Sun et al., 2014). However, for this study’s outcrop, the calculated dip is less than the true dip because the falling-silt seam is tangential to basal surface. In addition, when using this method, the distribution range is also shorter than the actual distribution range (Figure 7).

The quantitative characteristics of the falling-silt seams were described in detail. The first falling-silt seam (falling-silt seam 1 in Figure 4) is 2.3 m high and about 8 m long at the bar tail. The second falling-silt seam is 3.3 m high and about 15 m long at the bar tail. On this basis, the distribution of the first falling-silt seam at the bar tail can be expressed as

$$h = 2.26\exp(-0.059l^2)$$

where $h$ is the height from the bar base and $l$ is the extension length at the bar tail in meters.

It was deduced that the morphological characteristics, including the extension length of the falling-silt seams, are influenced by sediment supply, climate, cross-bar channels, bar migration, slope angle and base level cycle (Chen et al., 2015; Niu et al., 2015; Yu et al., 2004). Therefore, further quantitative analysis studies are required.

**Architecture model of braided river**

Based on the outcrop and former studies, an architecture model of a braided river was established (Figure 8). Eight facies (Gt, St, Sm, Sh, Sp, Sw, Fl, and Fm), four architecture elements (CH, DA, LV, and FF), and three orders of bounding surfaces are recognized.
The braided channel (CH) and mid-channel bar elements (DA) are the dominant elements and are overlain by the levee (LV) and floodplain elements (FF) (Figure 8). The channel element is characterized by laterally widespread stacked and multistory channel-fill sandbodies (Friend et al., 1979; Ghazi and Mountney, 2009). It is mainly composed of facies Gt and St, with subordinate sets of facies Sm, Sh, Sp, and Sw, all of which are arranged in fining-upward cycles. The mid-channel bar element (DA) is characterized by sets of accretion sandbodies and consists of facies Gt, St, Sm, Sp, Sh, and Fm. As for the relative sizes of channels and bars, although the Junggar basin braided river in northwest China has a “wide bar and narrow channel” distribution pattern (Qin et al., 2018), the overall size of the braided river in the outcrop cannot be assessed. The levee and floodplain elements are characterized by fine-grained sandstone and mudstone units and occur in the upper parts of the cycles.

Falling-silt seams are third-order bounding surfaces. The interfaces between two channels and channel and mid-channel bars or levees are usually defined as fourth-order bounding surfaces. Fifth-order bounding surfaces are generally the erosional bases of the channel fill (CH) and mid-channel bar elements (DA).

Falling-silt seams are sets of thinly layered deposits between accretion bodies (Figure 8). In the outcrop, they are developed in the mid-bar and bar tai. On bar margins, falling-silt seams are incomplete due to flow scouring (Liu et al., 2009). The falling-silt seams thin from the mid-bar to the bar tail following the flow direction. Each falling-silt seam is oriented tangentially to the basal surface of the mid-channel bar, and the upper falling-silt seam extends farther than the lower one.
Significance for remaining oil distribution

Determining remaining oil distribution is an important issue for oilfields during the high water-cut stage, especially in northeast China. A series of geological and engineering factors, including micro-facies, micro-structure, reservoir heterogeneity, single sandbodies, reservoir architecture, well forms, and injection-production relationships, can affect the determination of remaining oil distribution. In braided river systems, architecture analysis plays an important role in predicting the remaining oil distribution. Channels and bars are reservoir units, in which fourth- and third-order bounding surfaces are the main factors that influence the remaining oil distribution. The former surfaces that occur between channels, and channels and bars restrict the morphologies of single braided channels, channel bars and single sandbody stacking patterns (Ren and Zhao, 2015). Latter surfaces (i.e. falling-silt seams) prescribe a limit to each accretion body in a bar.

Remaining oil distribution in a mid-channel bar. This paper focused on the remaining oil distribution in a mid-channel bar. Former studies have shown that the recognition and reconstruction of mid-channel bar architecture, especially the development degree and horizontal distribution range of falling-silt seams, is valuable for predicting remaining oil distribution (Li et al., 2015; Liu et al., 2011; Sun et al., 2018; Yang et al., 2015; Zhang et al., 2013). Remaining oil generally accumulates in high development places with widely distributed falling-silt seams (Yang et al., 2015). However, many studies, even in other reservoir types, have only used subsurface data, which produce multiple multi-results, were not guided by practical outcrop models.

To combine outcrop and modern braided-river data, a Daqing Oilfield exploitation block in the Songliao basin was targeted (Figure 9). The braided river reservoir layer, P1-3, one of the most important oil layers, is on average 8.9 m thick and up to 13.1 m thick (Liu et al., 2002, 2011; Zhang et al., 2013). The 30–100 m well spacing in this block is dense enough to study the reservoir architecture and remaining oil distribution. As illustrated in Figure 9, a braided channel, mid-channel bars, a levee and floodplains with two falling-silt seams are recognized in the sedimentary micro-facies map. The reservoir architecture of the mid-channel bar established by the models and its influence on the remaining oil distribution is represented in two sections (Figure 9).

As shown in section A, two water injection wells (Wells 2 and 5) are located at the bar margins, and two production wells (Wells 3 and 4) are located at the mid-bar (Figure 9). The remaining oil is located in the top part of each accretion body (Wells 3 and 4). Remaining oil also accumulates in the lower accretion body, especially around Well 4, because no water injection well has been drilled through the lower seam and at the bar margins outside injection Wells 2 and 5, because there are no production wells in this area.

Most wells in the mid-channel bar were drilled before 2006 and only Well 4 was drilled in 2013 as a result of well pattern infilling work. The initial daily production was up 7.5 tons oil per day, which was much more than the other oil production wells in the bar. It may indicate that reservoir architecture influences the remaining oil distribution.

As shown in section B, water injection wells are located at the mid-bar (Well 10) and the bar tail (Well 8). Three production wells are located at the bar head (Well 11), the mid-bar (Well 3), and the bar tail (Well 9). The remaining oil is mostly accumulated in the bar tail and bar head outside the wells and in places between the two production wells (Wells 9 and 3).
Based on the distinctive architecture characteristics of mid-channel bars, four suggestions are presented in this study to tap the remaining oil as follows.

First, the mid-bar is characterized by vertical accretion, with good physical properties and thick falling-silt seams. It is proposed that water injection wells are drilled at the mid-bar surrounded by production wells, as shown in section B. Injection water would flow from the mid-bar to the bar margins and tail in this situation. Because the water injection/production well ratio is low, this creates economic benefit.

Second, the thick falling-silt seams at the mid-bar are natural filtration barriers that influence the efficiency of water flooding. Because the physical properties of accretion bodies vary vertically, see for example Wells 3 and 10 in section B in Figure 9, the accretion body is divided into three sections by two falling-silt seams. Consequently, zonal injection
technology should be widely applied at the mid-bar to improve the efficiency of oil displacement.

Third, drilling large angle deviated or horizontal wells is also an effective method for tapping remaining oil. Given that the length/width ratio of the mid-channel bar is on average 2.8, it is proposed that it be operated along the long axis rather than the short axis. Horizontal wells should be drilled through all the falling-silt seams to reach the lower accretion body (Figure 9).

Fourth, proper well forms and injection-production relationships play a key role. Because not all the water-injection wells are located at the mid-bar, it would be reasonable in some places to convert production wells to injection wells or injection wells to production wells; therefore, the best conversion opportunity should be studied. Additionally, adding a new well is also proposed, such as a new water injection well between Wells 9 and 3, as shown in section B.

![Figure 10. Remaining oil distribution patterns in braided channels.](image-url)
**Remaining oil distribution in braided channels.** Compared to mid-channel bars, falling-silt seams are not deposited in inner channels (Figure 10(a)) (Zhao et al., 2014). In addition, muddy interlayers do not always occur between channels (Figure 10(b) and (c)). As shown in Figure 3(b), the fourth-order bounding surfaces are not consecutive due to strong channel scouring in the middle part of the profile, which will affect the remaining oil distribution. As shown in Figure 4, there are no distinct falling-silt seams or other muddy interlayers between the braided channels and bar margins, which indicates a good connection between the two units (Figure 10(d)). Therefore, the injected water is pushed forward as a whole, and the degree of water flooding is even in the single braided channel (Figure 10(a)) (Xu et al., 2016; Zhao et al., 2014). This results in little remaining oil accumulating in the top parts of two injection and production wells. The stacking patterns of single braided channels can also affect remaining oil distribution (Sun et al., 2018). Figure 10 presents four different patterns and characteristics of remaining oil distributions (Figure 10(e) to (h)). However, it should be noted that stacking pattern analysis needs to be considered together with well forms and injection-production relationships, and laterally interlayered levee and floodplain elements can disconnect injection and production wells (Figure 10(i) and (j)). For example, as shown in ‘Data and methods’ section (Figure 9), three oil production and two water injection wells are presented. Based on the production and absorption profiles of Wells 15 and 16, these two wells did not have good injection-production relationships, and remaining oil was mainly located in the sandbody of Well 15. That indicated the bounding surfaces between channel and levee elements blocked injected water.

To summarize, considering only the architecture characteristics of braided river reservoirs and the blocking effects of varied order surfaces is not sufficient because the work of exploiting remaining oil is systematic and requires a comprehensive consideration of a number of geological and engineering factors.

**Conclusions**

The Songliao basin Quantou Formation outcrop is a conglomerate, sandstone, and mudstone succession of eight lithofacies (Gt, St, Sm, Sh, Sp, Sw, Fl, and Fm) with fining-upward cycles. Four typical architecture elements, including channel fill (CH), downstream accretion (DA), levee (LV), and floodplain (FF) are recognized. These elements are interpreted within a framework of six orders of bounding surfaces. A new distribution pattern of falling-silt seams and a braided river architecture model were established according to the outcrop. In the mid-channel bar, the falling-silt seams thin from the mid-bar to the bar tail following the flow direction. Each falling-silt seam is oriented tangentially to the basal surface of the mid-channel bar, and the upper falling-silt seam extends farther than the lower one. Architecture analysis is a powerful tool for predicting remaining oil distribution. While channels and bars present the main reservoir units, they have different remaining oil distribution patterns. For channel bars, water injection wells at the mid-bar, zonal injection technology, horizontal wells, and proper well patterns are proposed to achieve maximum economic benefit. For channels, fourth-order bounding surfaces, the stacking patterns of single braided channels, and the lateral blocking of levees and floodplains are the key factors that affect the remaining oil distribution.

This paper proposes an architecture model for braided rivers and provides a falling-silt seam pattern significant for oilfield exploitation. However, former studies have shown that mid-channel bars and falling-silt seams have different geometrical forms. Therefore, this
study highlights the following adaptability conditions. First, mid-channel bars and falling-silt seams show a convex-up shape. Second, the Quantou Formation sediments at the outcrop were deposited in a semiarid paleoclimate, which is considered to influence the formation of channel bars. Third, the results of this paper may be adaptable to channels and bars that have similar lithological association sequences.

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**References**

Ashworth PJ, Best JL, Roden JE, et al. (2000) Morphological evolution and dynamics of a large, sand braid-bar, Jamuna River, Bangladesh. *Sedimentology* 47(3): 533–555.

Best JL, Ashworth PJ, Bristow CS, et al. (2003) Three-dimensional sedimentary architecture of a large, mid-channel sand braid bar, Jamuna River, Bangladesh. *Journal of Sedimentary Research* 73(4): 516–530.

Bridge J, Collier R and Alexander J (1998) Large-scale structure of Calamus river deposits (Nebraska, USA). *Sedimentology* 45(6): 977–986.

Bristow CS (1993) Sedimentary structures exposed in bar tops in the Brahmaputra River, Bangladesh. *Geological Society of London* 75(1): 277–289.

Cant DJ and Walker RG (1978) Fluvial processes and facies sequences in the sandy braided South Saskatchewan river. *Sedimentology* 25(5): 625–648.

Chen DY, Wang F, Chen HD, et al. (2019) Characterization of braided river reservoir architecture of the upper paleozoic He 8 member on Fugu Tianshengqiao outcrop, Eastern Ordos basin. *Oil & Gas Geology* 40(2): 335–345.

Chen YK, Wu SH, Wang YJ, et al. (2015) Distribution patterns of the fall-silt seams in the channel bar of the perennial sandy braided river: An approach. *Sedimentary Geology and Tethyan Geology* 35(1): 96–102.

Colombini M, Seminara G and Tubino M (1987) Finite-amplitude alternate bars. *Journal of Fluid Mechanics* 181(1): 213–232.

Dang SG, Yan JL, Wang W, et al. (2017) Quantitative characterization of braided river reservoir architecture interface in Bohai Sea. *Special Oil and Gas Reservoirs* 24(4): 88–93.

Deng YB (2006) *Relations between sedimentary microfacies and lithologic trap of Fuyu reservoir in South Songliao Basin*. Master’s Thesis, Jilin University, China.
Du YS (2018) Discussion on paleocurrent analysis. *Journal of Palaeogeography (Chinese Edition)* 20(5): 925–926.

Falivene O, Arbuès P, Howell J, et al. (2006) Hierarchical geo-cellular facies modelling of a turbidite reservoir analogue from the eocene of the Ainsa basin. *Marine and Petroleum Geology* 23(6): 679–701.

Friend PF, Slater MJ and Williams RC (1979) Vertical and lateral building of river sandstone bodies, Ebro basin, Spain. *Journal of the Geological Society* 136(1): 39–46.

Gao C, Xu XY and Liu ZY (2013) The working method of measuring the occurrence of cross bedding to find the paleocurrent direction. *Western Resources* 3: 116–118.

Ghazi S and Mountney NP (2009) Facies and architectural element analysis of a meandering fluvial succession: The Permian Warchha sandstone, salt range, Pakistan. *Sedimentary Geology* 221(1–4): 99–126.

Hou JG, Liu YM, Xu F, et al. (2008) Architecture of braided fluvial sandbody and origin for petrolierous difference of the Guantao formation of neogene in Kongdian oilfield of Huanghua depression. *Journal of Palaeogeography* 10(5): 459–464.

Jin ZK, Yang YX, Shang JL, et al. (2014) Sandbody architecture and quantitative parameters of single channel sandbodies of braided river: Cases from outcrops of braided river in Fukang, Liulin and Yanan areas. *Natural Gas Geoscience* 25(5): 311–317.

Li HY, Gao Y, Wang YJ, et al. (2015) Intercalation pattern and its impact on development of braided river reservoirs: A case of Fengcheng oilfield, Junggar basin, NW China. *Petroleum Exploration and Development* 42(3): 397–373.

Li SM, Song XM, Jiang YW, et al. (2011) Architecture and remaining oil distribution of the sandy braided river reservoir in the Gaoshangpu oilfield. *Petroleum Exploration and Development* 38(4): 474–482.

Li ZD, Pang H, Xu JZ, et al. (2019) Case study of sandbody architecture and quantitative parameters of the far source sandy braided river: Saertu oilfield, Daqing. *Journal of Petroleum Science and Engineering* 181: 106249–106210.

Liu B, Zhao HQ, Li GY, et al. (2002) Sand body identification of braided river reservoir: An example from the P1-3 west of Lamadian-Saertu oilfield, Daqing, China. *Acta Petrolei Sinica* 23(2): 43–47.

Liu H, Lin CY, Zhang XG, et al. (2018) Reservoir architecture and remaining oil distribution in braided river of Guantao formation, Kongdian oilfield. *Journal of Jilin University (Earth Science Edition)* 48(3): 665–677.

Liu YM, Hou JG, Song BQ, et al. (2011) Characterization of interleavers within braided-river thick sandstones: A case study on the Lamadian oilfield in Daqing. *Acta Petrolei Sinica* 32(5): 836–841.

Liu YM, Hou JG, Wang LM, et al. (2009) Architecture analysis of braided river reservoir. *Journal of China University of Petroleum* 33(1): 7–11.

Lunt IA, Bridge JS and Tye RS (2004) A quantitative, three-dimensional depositional model of gravely braided Rivers. *Sedimentology* 51(3): 377–414.

Lv MS, Chen KY, Xue LQ, et al. (2010) Hierarchy analysis for flow units division of low-permeability reservoir: A case study in Xifeng oilfield. *Energy Exploration & Exploitation* 28(2): 71–86.

Miall AD (1985) Architectural-element analysis: A new method of facies analysis applied to fluvial deposits. *Earth-Science Reviews* 22(4): 261–308.

Miall AD (1988) Architectural elements and bounding surfaces in fluvial deposits: Anatomy of the Kayenta formation (lower Jurassic), southwest Colorado. *Sedimentary Geology* 55(3–4): 233–262.

Miall AD (1996) *The Geology of Fluvial Deposits*. Berlin Heidelberg: Springer Verlag, pp.75–178.

Miao CS (2008) *Study on the relation of diageneisis and lithologic trap of Fuyu reservoir in Fuxin Area, Southern of Songliao Basin*. Master’s Thesis, Jilin University, China.
Niu B, Gao XJ, Zhao YC, et al. (2015) Architecture characterization and modeling of channel bar in paleo-braided river: A case study of dense well pattern area of Sazhong in Daqing oilfield. *Acta Petrolei Sinica* 36(1): 89–100.

Qiao YP, Shao XJ, Jie JT, et al. (2016) Architecture analysis and controlling factor on far source sandy braided river reservoir – A case study of Qinhuangdao32-6 oilfield. *Petroleum Geology and Recovery Efficiency* 23(1): 46–52.

Qin GS, Hu WR, Song XM, et al. (2018) Gravel braided river architecture and inter-layers distribution: A case study of Jurassic Badaowan formation outcrop in the northwest of Junggar basin. *Journal of China University of Mining & Technology* 47(5): 1008–1020.

Ren XX, Hou JG, Liu YM, et al. (2018) Architectural characterization and a distribution model of lithology near the boundary surfaces of different orders in a sandy braided river – A case study from the Jurassic sandy braided-river outcrops in the Datong Basin, Shanxi Province. *Petroleum Science Bulletin* 3(3): 245–261.

Ren XX and Zhao W (2015) Architecture analysis of braided river sand body and the distribution of remaining oil in guan 80 region of Dagang oil field. *Petrochemical Industry Technology* 6: 102–103.

Rodrigues S, Mosselman E, Claude N, et al. (2015) Alternate bars in a sandy gravel bed river: Generation, migration and interactions with superimposed dunes. *Earth Surface Processes and Landforms* 40(5): 610–628.

Smith GHS, Ashworth PJ, Best JL, et al. (2006) The sedimentology and alluvial architecture of the sandy braided South Saskatchewan river. *Sedimentology* 53(2): 413–434.

Sun MS, Liu CY, Feng CJ, et al. (2018) Main controlling factors and predictive models for the study of the characteristics of remaining oil distribution during the high water-cut stage in Fuyu oilfield. *Energy Exploration & Exploitation* 36(1): 97–113.

Sun TJ, Mu LX, Wu XH, et al. (2014) A quantitative method for architectural characterization of sandy braided-river reservoirs: Taking Hegli oilfield of Muglad basin in Sudan as an example. *Acta Petrolei Sinica* 35(4): 715–724.

Tubino M (1991) Growth of alternate bars in unsteady flow. *Water Resources Research* 27(1): 37–52.

Weckwerth P (2018) Fluvial responses to the Weichselian ice sheet advances and retreats: implications for understanding river paleohydrology and pattern changes in Central Poland. *International Journal of Earth Sciences* 107(4): 1407–1429.

Wen LF, Wu SH and Yue DL (2016) New distribution pattern of mudstone interlayer within battue bar reservoir of braided river: A case study of field outcrops in Wuguantun. *Petroleum Geology and Engineering* 30(4): 5–7.

Xu L, Hou GT, Dai CM, et al. (2016) New insights into reservoir architecture of Fuyu oil layer in Southern Songliao basin based on analyses of water-flooding characteristics. *Energy Exploration & Exploitation* 34(1): 61–76.

Xu ZB, Shen CS, Chen YK, et al. (2016) Architecture characterization for sandy braided river reservoir and controlling factors of remaining oil distribution: A case study of P oilfield (neogene), Bohai offshore, *China. Acta Sedimentologica Sinica* 34(2): 375–385.

Yang SC, Zhao XD, Zhong SY, et al. (2015) Inner heterogeneity within braided bar of braided river reservoir and its influence on remaining oil distribution. *Journal of Central South University (Science and Technology)* 46(3): 1066–1074.

Yin SL, Wu SH, Chen GY, et al. (2013) A study on intercalation of sand-gravel braided river deposit based on outcrop section. *Journal of Southwest Petroleum University (Science & Technology Edition)* 36(4): 29–36.

Yu H (2015) Fine-characterization of the internal configurations for the braided river reservoirs and remaining oil. *Petroleum Geology and Oilfield Development in Daqing* 34(4): 73–77.

Yu XH, Ma XX, Mu LX, et al. (2004). *Geological Model and Interface Analysis of Braided River Reservoir*. Beijing: Petroleum Industry Press, pp.25–99.
Zhang CM, Yin TJ, Zhao L, et al. (2013) Reservoir architectural analysis of braided channel. *Geological Science and Technology Information* 32(4): 7–13.

Zhang K, Wu SH, Feng WJ, et al. (2020) Bar dynamics in a sandy braided river: Insights from sediment numerical simulations. *Sedimentary Geology* 396: 105557–105515.

Zhao L, Wang JC, Chen L, et al. (2014) Influences of sandstone superimposed structure and architecture on waterflooding mechanisms: a case study of Kumkol oilfield in the South Turgay basin, Kazakhstan. *Petroleum Exploration and Development* 41(1): 96–94.