

Formation Mechanism and Sedimentary Pattern of Abandoned Channels

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Abstract: Accurately identifying and quantitatively describing abandoned channels in meandering rivers are of great significance for improving hydrocarbon recovery. By using modern deposition analogy, field outcrop analysis, a dense well spacing, core observations and a review of the literature, this paper studied the formation process and space–time amalgamation of abandoned channels in meandering river. The results reveal that formation mechanisms of abandoned channels include chute cutoff patterns (shoal–cutting, ditch–scouring and embayment–eroding patterns) and neck cutoff patterns. The chute cutoff pattern forms a gradually abandoned channel, while the neck cutoff pattern forms a suddenly abandoned channel. From upstream to downstream, the sedimentary pattern of the abandoned channel transforms from a chute cutoff pattern to a neck cutoff pattern, where the main controlling factors transition from the grain size and gradient to the flow and vegetation. An abandoned channel formed by a chute cutoff pattern consists mainly of siltstone, fine sandstone and thin gravel layers, which form a lithological–physical barrier. The abandoned channel formed by a neck cutoff pattern consists mainly of mudstone and argillaceous siltstone, forming a lithological barrier. Based on the amalgamation and structure of the reservoir architectural elements, the abandoned channel can be divided into three planar sedimentary patterns (crescent, semilune and horseshoe) for a single channel and five vertical sedimentary patterns for composite channels.

Key words: abandoned channel, cutoff pattern, formation mechanism, sedimentary pattern, meandering river

1 Introduction

Fluvial sedimentary systems are an important hydrocarbon reservoir in eastern China, and among meandering river reservoirs, they are the most typical (Yu, 1997). In the late stage of high water – cut development, the remaining hydrocarbon is difficult to trap because of the influence of the distribution and architecture of the abandoned channel (Zhao, 2002). Abandoned channels are the most common geomorphic feature of meandering rivers, and it is important to study the formation mechanism, development characteristics and amalgamation configuration of the abandoned channels.

Fisk (1947) first provided a qualitative oxbow model based on observations along the lower Mississippi River (Bridge et al., 1986). Hickin (1974) pointed out that the ratio of bend curvature to channel width affects the development characteristics of abandoned channels. Brierley (1991) emphasized the variability of chute channel typologies for the Squamish River and distinguished them

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into high-energy and low-energy channels (Brierley, 1991). Nicoll and Hickin (2010) proposed that the bend curvature of the confined meandering river is larger than that of the freely meandering river. At present, many studies on abandoned channels have focused on morphology (Zinger et al., 2011), evolutionary processes and internal architecture (Peakall et al., 2007; Liu et al., 2018) described by outcrop (Micheli and Larsen 2011), flume experiments (Braudrick et al., 2009) and numerical modeling (Yue et al., 2005). Abandoned channels are a testimony of channel movement, and they are represented as depressions at the position of a formerly active channel. However, a study on detailed plane and vertical amalgamations of abandoned channels has never been mentioned.

Therefore, the main aims of this paper are: (i) to investigate the main planform patterns of abandoned channels; and (ii) to systematically analyze the formation mechanisms (type morphology and sedimentary process) and architectural characteristics (internal variability of channel-fill deposits) of abandoned channels. This study attempted to establish planar and vertical sedimentary patterns for different types of abandoned channels to analyze how they influence reservoir connectivity and to provide guidance for tapping the remaining hydrocarbon in the subsurface.

2 Methods

To effectively describe the development characteristics of abandoned channels on multiple scales, we used satellite images archived by Google Earth to measure macroscopic abandoned channels of the Songhua River and other rivers and to identify the controls on the production of oxbow lakes by meander cutoff (67 reaches were documented by means of more than 1000 sets of digitized aerial photographs spanning nearly fifteen years to measure channel morphology with temporal changes). Field outcrop data published in the literature are used as analogies for the sedimentary architectural assemblage, and a dense well spacing with an average 110 m spacing is used to reconstruct the mesoscale geometry of the abandoned channel and to dynamically verify the well injection-production relationship. The type and amalgamation of abandoned channels can be easily recognized and separated by the significant differences in the well logging responses. The cores from three wells are described in terms of sediment texture, lithologic characteristics and sedimentary rhythm by careful observation, and then, the density and scale of the lateral accretion interlayer are determined.

3 Results

3.1 Cutoff pattern of abandoned channels

Cutoff is a fundamental process in the evolution of meandering rivers. Abandoned channels are some of the most widespread and distinctive landforms within the floodplain environment. A quantitative theory has not been formulated to explain how abandoned channels are filled because the controls on the process have not been studied widely nor interpreted physically. Fisk (1947) reported that a meandering river being abandoned by cutoff is determined first by its diversion angle, the angle between the active channel flow and the abandoned channel entrance (Constantine et al., 2010). Allen (1964) proposed that channel-fill deposits form as a result of vertical aggradation in abandoned channels, such as a cutoff meander loop or a gradual shoaling channel that is slowly abandoned (Allen., 1964). In channels isolated by meander neck cutoffs, the bulk of sediment filling is introduced by overbank floods and is therefore relatively fine grained. The filling in a gradual abandoned channel represents a net accumulation from undergoing alternate scouring during flood stages and deposition during falling stages, and the channel continues to operate until completely filled. Consequently, the filling is relatively coarse grained and texturally similar to the normal bed load in a stream. The cutoff incidents shorten the meandering river's length and produce abandoned channels, which are characterized by a substantial topographic slope and continuous scouring over a long-term period. This paper mainly discusses two cutoff processes that are commonly recognized: chute cutoff, a process that occurs when floods incise a floodplain and turn the floodplain into the dominant conveyor of river discharge, and neck cutoff, a process that results from bank collapse after migration of a meander bend (Gay et al., 1998).

3.1.1 Formation mechanism and internal architecture of chute cutoff

Most sedimentary records of chute channels that formed in the upriver edges of the meander neck are provided for the modern Amite River and some ancient examples (McGowen and Garner 1970).

Furthermore, depending on the environmental context and different mechanisms along meandering rivers, chute cutoff may occur due to the enlargement of swales, headcut extensions during locally induced flooding, or the downstream extension of an embayment during multiple flood periods (Constantine et al., 2010). Consequently, the natural chute cutoffs are divided into shoal-cutting pattern, ditch-scouring pattern and embayment-eroding pattern according to the scouring position and chute cutoff development processes (Li et al., 2013; Fig.1). The erosion of a point bar results from deviation of the hydrodynamic axis during flooding, which forms a sandbody similar to the middle - channel bar. This process is called shoal-cutting (Luchi et al., 2010; Fig.2a). The shoal-cutting pattern commonly occurs in a low water stage with limited sand (especially when the ratio of the bend curvature radius to the river mean width is between 2 and 3), and there is a high rate of lateral migration in the bend (Hickin and Nanson 1975). According to statistical data from 67 reaches of the Songhua River and other rivers, we found that shoal-cutting is most likely to occur when the diversion angle is approximately 50° . Meanwhile, the shoal-cutting pattern is well developed during flood periods, and it is always accompanied by other cutoff patterns. However, due to poor stability, the shoal-cutting pattern is easily modified in later flood stages.

In most sandy meandering rivers, the ditch-scouring pattern is an indispensable component that occurs most frequently in rapidly extending bends. The development of a ditch-scouring pattern is thought to have heralded a decrease in the sinuosity of the main active channels triggered by a climate-driven increase in water discharge (Nanson and Croke 1992). One of the scrolled chutes will gradually connect downstream after iterative water flow scouring (Fig.2b). The ditch-scouring pattern is the main way of meandering river cutoff, which mainly consists of two stages (Bridge and Demicco 2011). First, the upper part of a point bar is scoured during one or more floods, forming a number of scroll bars and scroll sloughs with different incising degrees. Then, the distributary of the main channel scours along the relatively deeper scroll slough and accomplishes the process of cutoff. Furthermore, ditch-scouring cutoff could be formed by migrating headcut erosion during the water-falling stage (Grenfell et al., 2014). In addition, Constantine (2010) pointed out that bedload aggrades most rapidly at channel entrances with high diversion angles, resulting in faster plug bar growth and ditch-scouring channel disconnection.

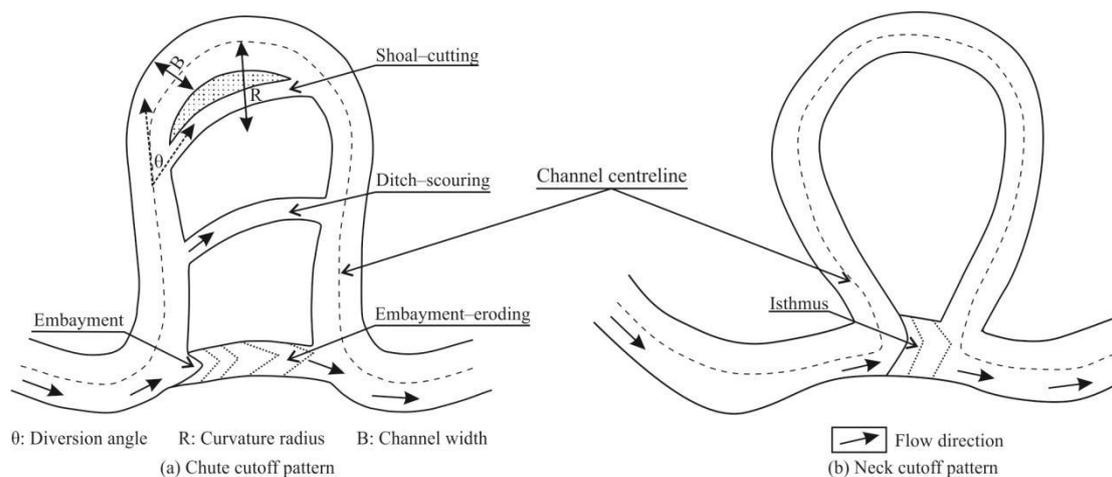


Fig. 1. Schematic illustrating the cutoff patterns in the abandoned channel.

The last chute cutoff pattern is called embayment-eroding pattern. During a long period of erosion caused by water flow, the bank constantly collapses and moves back, forming an embayment-shaped cove that finishes the embayment-eroding process (Fig.2c). The main reason for its formation is a sharp increase in flow during the flood period. This pattern generally develops in the area where the hydrodynamic axis starts drawing near the concave bank, which depends on the water level (Hauer and Habersack 2009). The development of embayment-eroding pattern is controlled by the flood scale, rock composition and vegetation coverage of the point bar.

Due to differences in sedimentary filling architecture in abandoned channels formed by different cutoff patterns, the shielding conditions and seepage characteristics of subsurface reservoirs are complicated. An abandoned channel formed by a chute cutoff pattern is still connected with the flow of

the main active channel. The obvious difference in sedimentary characteristics between the abandoned channel and the active channel is that the abandoned channel predominantly receives a finer suspended load than the active channel due to gravitational differentiation of sediments, as well as the shallowing and narrowing effect of the plug bar formed at the channel entrance (Miall, 1985). The planform of the abandoned channel shows asymmetry; the slope of the upstream and downstream channels is quite different, generally between 15 and 30°, and the width and thickness of the abandoned channel are approximately 2/3 of those of the active channel. The abandoned channel deposits have an upward fining trend in grain size, where the upper part developed overbank deposit fill embedded with a small number of plant rhizomes, the middle part is filled with relatively coarse-grained deposits, and the bottom part is similar to the active channel, which has a scouring-and-filling structure with imbricated gravel that indicates the direction of flow (Fig.3a; Fig.3b). Some of the coarse-grained sediments in the abandoned channel are derived from the active channel, partly from point bars or bank collapse (Bartholdy and Billi 2002). The sediment grain size and sandbody thickness in the chute cutoff channel are larger than those in the neck cutoff channel; therefore, the former predominantly forms a physical-lithological barrier.

3.1.2 Formation mechanism and Internal architecture of neck cutoff

With the curvature radius of the meandering river gradually increasing, a narrow isthmus is formed in the neck of the meander bend. The neck cutoff process will occur after the narrow isthmus is destroyed by an extraordinary flood, which suddenly forms an abandoned channel (Fig.2d). Generally, the neck cutoff pattern appears at the edge of the upper entrance of the point bar (Jackson, 1976); this pattern is mainly developed downstream, where the topographic slope is small and vegetation is relatively dense. Usually, the rate of channel migration depends on flow, bank resisting force, viscous force, vegetation cover, topographic slope, bend radius and channel width (Schumm and Khan 1971). The abandoned channel formed by the neck cutoff pattern is disconnected from the active channels, which causes it to only receive suspended loads during floods (Lewis and Lewin 1983). Repeated flood pulses of varying magnitudes and sediment delivery alternate with finer-grained material and organic matter and ultimately stack into laminated fill. The thickness of sediments in the abandoned channel is smaller than that in the active channel. The abandoned channel has an annular symmetry, and the slope is generally between 3 and 10°. Deposits in the neck cutoff channel also have an upward fining trend in grain size, and the upper part and middle part have overbank deposits embedded with a small number of plant rhizomes, and parallel bedding is mainly developed (Nemec and Postma 1993). In addition, the bottom filling of the neck cutoff channel is the same as that of the chute cutoff channel (Fig.3c; Fig.3d). The organic mud sediments may be deposited after large floods, and the gravel cluttered at the channel bottom may result from the migration of sediments during high-magnitude flood events. The lithology type of this abandoned channel predominantly consists of mudstone or argillaceous siltstone with very low porosity and permeability; thus, it mainly forms a lithological barrier.

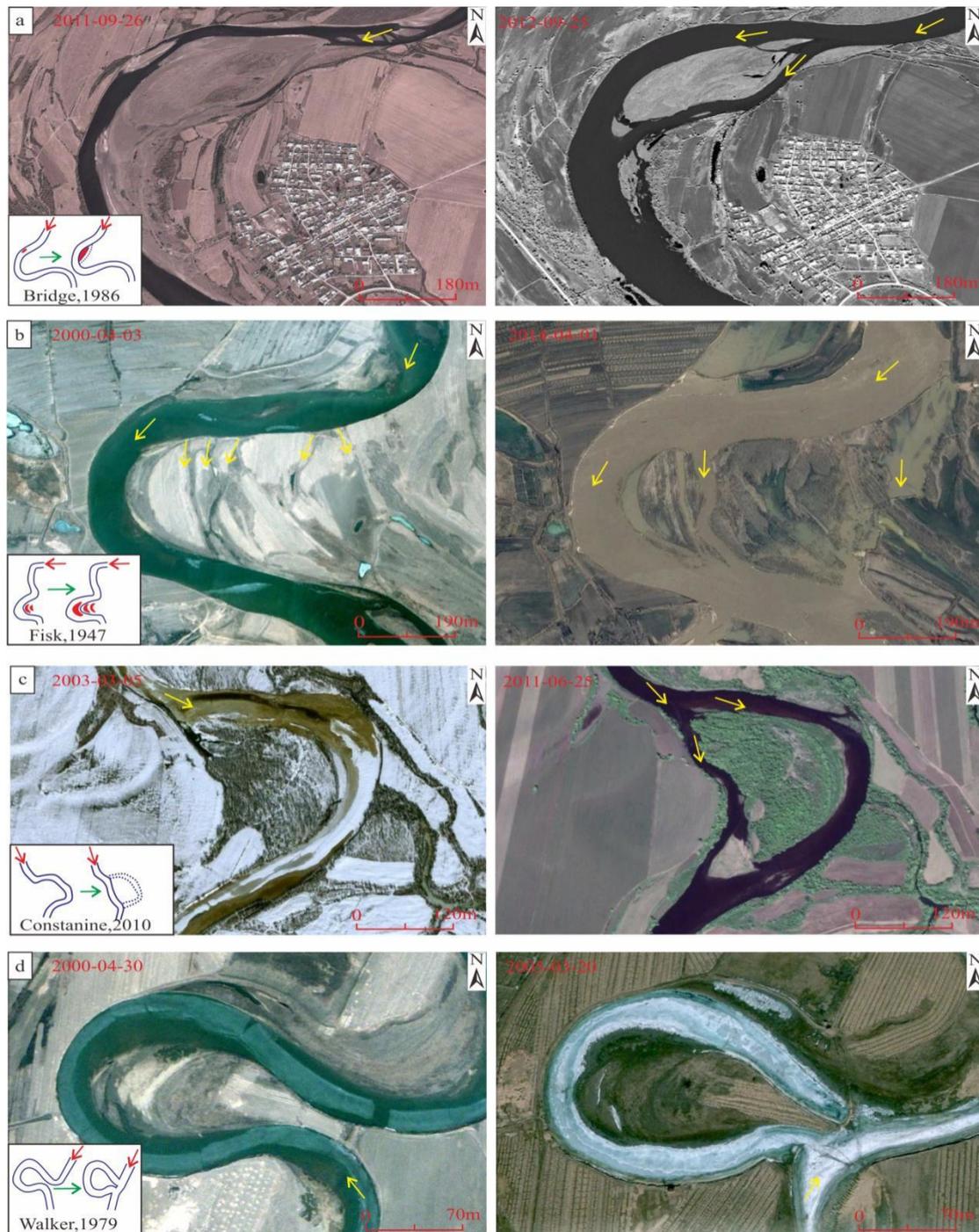


Fig. 2. Formation process and cutoff pattern of the abandoned channel in the Songhua River.

3.2 Sedimentary evolution process of abandoned channels

The process of sedimentary evolution in abandoned channels is continuous, and the migration rate of the abandoned channel depends on the force ratio: eroding force (stream power and channel slope)/resisting force (bank height and bank vegetation) (Lawler, 1993). In a single meandering river, the sinuosity gradually increase from upstream to downstream, while the topographic slope and sediment grain size gradually decrease, and the cutoff pattern changes from chute to neck (Zhang et al., 2013). Gogoi and Goswami (2014) showed that the chute cutoff pattern often occurs upstream (strong water energy and weak bank adhesion) and that the neck cutoff pattern occurs downstream (water stability and flourishing vegetation) and summarized the characteristics of channel migration in the Subansiri River at different stages (Fig.4). Sixty-seven reaches of the Songhua River and other rivers

show that chute cutoffs and neck cutoffs are both present in the majority of meandering rivers. However, different reaches mainly developed one cutoff pattern. In summary, the controlling factors of cutoffs are diversion angle, climate, lithology, topographic slope, flow, grain size, vegetation and so on. Grenfell et al. (2012) proposed that the influence of flow, gradient, grain size and vegetation coverage is particularly important, and the statistics of 799 cutoff reaches found in the Strickland River in Papua New Guinea, the lower Paraguay River in Paraguay/Argentina, and the Beni River in Bolivia (Table 1) showed that the chute cutoff pattern is mainly controlled by the flow and gradient and that the neck cutoff pattern is controlled by grain size and vegetation. Specifically, under conditions of increasing water discharge, the ability of a channel to enlarge its capacity and improve its hydraulic efficiency is the main factor controlling changes in fluvial style, and the sinuosity of the river decreases (Straffin and Blum 2002).

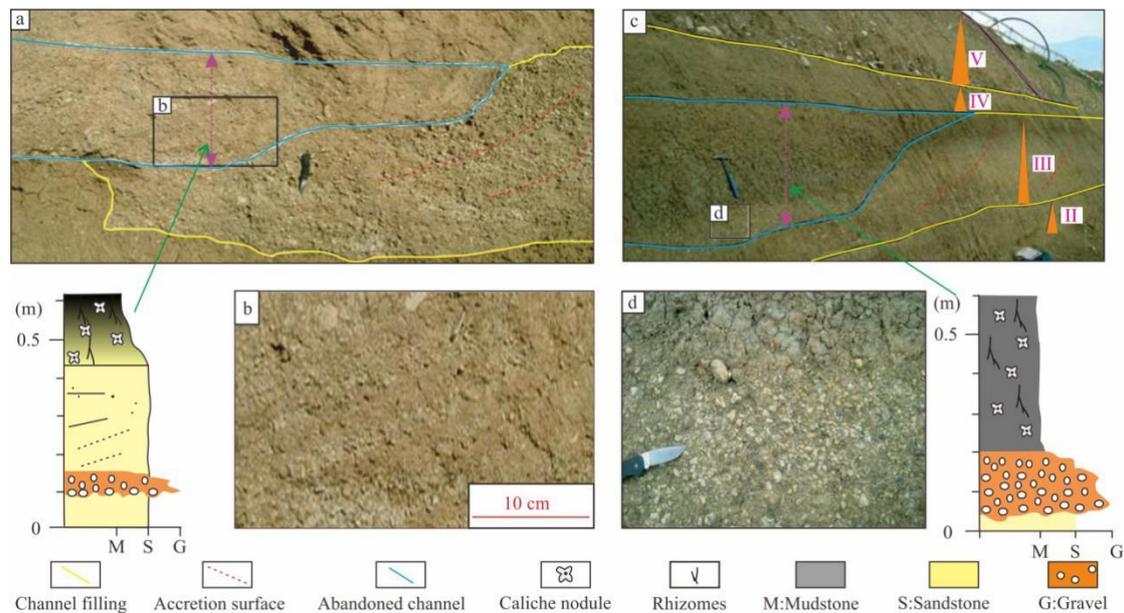


Fig. 3. Difference in sedimentary fill of different abandoned channels (modified after Ghinassi, 2011).

Table 1. Modern river-related data statistics (modified after Grenfell et al., 2012).

| River name | Flow (Mm^3y^{-1}) | Topographic Slope($^{\circ}$) | Median particle size(mm) | Mean curvature (frequency) | Cutoff pattern | Controlling factor |
|-----------------|-------------------------------------|---------------------------------|--------------------------|----------------------------|----------------|-----------------------|
| Stricking river | 98144 | 0.0002 | 0.2 | 2.55(66) | Chute cutoff | Flow-gradient |
| Paraguay river | 101836 | 0.00003 | 0.25 | 2.95(50) | Chute cutoff | Flow-gradient |
| Beni river | 64693 | 0.0002 | 0.1 | 2.16(69) | Neck cutoff | Grain size-vegetation |

In conclusion, three stages are generally distinguished during meandering river cutoff: (i) cutoff initiation and diversion formation; (ii) plug bar formation and the start of channel narrowing and shallowing; and (iii) disconnection and complete abandonment. The abandoned channel is 'disconnected' from the network of active channels, and the former channel is transformed into a floodplain oxbow lake that only receives suspended load during floods (Toonen et al, 2012).

3.3 Sedimentary pattern of abandoned channels

Field and flume research shows that the sedimentary pattern of an abandoned channel is controlled by many factors, such as sedimentation rate, slope, flow energy, and the ratio of sediment discharge to

sedimentation rate (Billi et al, 2018). The change in stacking style is controlled by basin geometry, subsidence rate, the controls on sandbody thickness and the influence of local versus regional avulsion (Heller and Paola 1996). Mackey and Bridge (1995) first constructed an elaborate three-dimensional model of river architecture from upstream to downstream. Van Dijk et al. (2013) confirmed that the stability of the bank increases and the chute cutoff decreases with increasing silt deposits in the meandering river, and the sinuosity of the channel decreases. As a result, sedimentary patterns that can be applied to reservoir prediction must undergo analogy analysis based on the sedimentary context and genetic type (Li et al., 2017).

This paper analyzes more than 1000 aerial photographs from the Yangtze River, the Yellow River and the Songhua River using Google Earth to change hue, shape, texture and shadow. Three sedimentary patterns of single abandoned channels in different reaches have been found. A crescent (9.7%) pattern occurs in upstream reaches, and the abandoned channel is characterized by low sinuosity and small amplitude, which means that the topographic slope is large and the erosional resistance of the bank is poor. A semilune (72.3%) pattern occurs in the middle reaches, where a chute cutoff channel is mainly developed with a moderate sinuosity and a gradual increase in amplitude, indicating seasonal flow discharge and a medium-to coarse-grained sediment fill. A horseshoe (14.2%) pattern occurs in downstream reaches, where a neck cutoff channel is mainly developed with a high sinuosity and relatively large amplitude, which means that the flow discharge is very stable and the bank is highly resistant to erosion (Fig. 5a). A planar sedimentary pattern in a single abandoned channel reveals that (i) the abandoned channel mainly developed a semilune pattern, followed by a horseshoe and a crescent pattern in turn; (ii) the shoal-cutting pattern is always accompanied by the other three cutoff patterns; (iii) the neck cutoff pattern is well developed in the reaches where the topographic slope is small and vegetation is dense; and (iv) with the evolution of the meandering river (Fig.5b), the grain size of sediments decreases, and while the topographic slope decreases, the sinuosity of the meander bend increases, and the development pattern of the abandoned channel changes from a crescent to a semilune pattern and finally forms horseshoe pattern (Fig.5c).

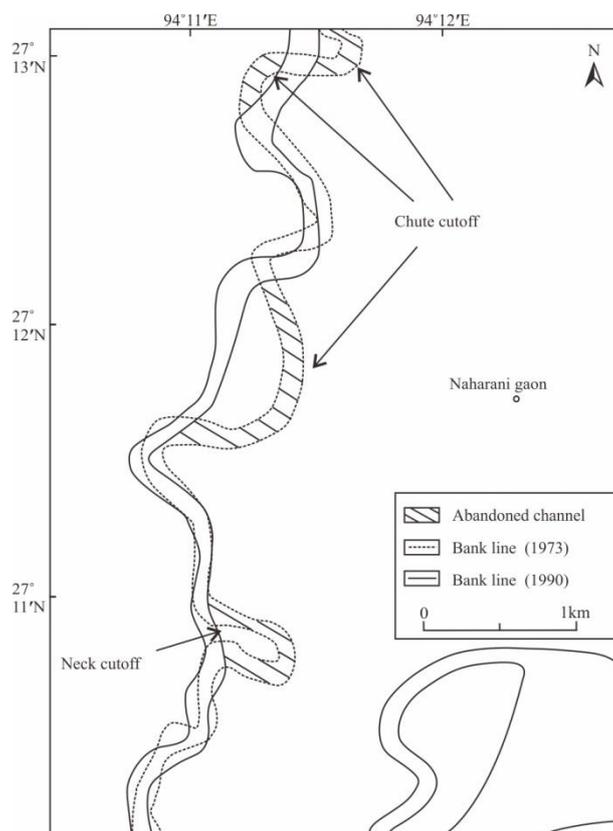


Fig. 4. Bank line evolution comparison between two years in the Subansiri River

(modified after Gogoi and Goswami 2014).

The amalgamation of the composite abandoned channels determines the connectivity of the reservoir. According to the contact relationship, the vertical stacking pattern of the composite abandoned channels can be divided into five types (Fig.5d; Fig.5e). L1(11 samples) patterns are formed in an unconfined and flat sedimentary context, where two single meander bends continuously swing towards each other, and the main types are ditch-scouring, embayment-eroding and neck cutoff patterns. L1 mainly represents the oscillation of different river channels over a long period that tend to be in contact after the cutoff process, and the majority of the contact part is infilled with mud or fine-grained sediment. As a result, the neck cutoff channel and embayment-eroding cutoff channel are not connected, and only the bottom of the ditch-scouring cutoff channel is connected because the two point bars for both meander bends are shielded by a low-permeability barrier. L2(19 samples) patterns are formed in an unconfined and small slope sedimentary context, where the abandoned channel and the point bar of another channel tend to make contact when two single meander bends swing in the same direction. The main types are embayment-eroding and neck cutoff patterns, which create a connected stacking pattern, and the active channel incises the adjacent meander bend, thus connecting the coarse-grained sediment at the bottom and the two point bars. Another stacking pattern occurs when the active channel only incises the muddy deposits in the upper part of the adjacent abandoned channel. Hence, the two point bars of single meander bends are not connected. L3(24 samples) patterns are formed in a confined and small slope sedimentary context, where the two point bars that formed at different stages are connected when the later active channel incises the preexisting point bar. The main types are ditch-scouring and shoal-cutting patterns, which have coarse-grained sediment at the bottom of the channel and thin laminated muddy deposits at the upper part of the channel. The degree of reservoir connectivity depends on the rhythm and lithology of the abandoned channel fill, so the reservoir connectivity gradually increases with increasing discharge from the later channel flow. L4(8 samples) patterns are formed in an unconfined and flat sedimentary context, where the active channel tends to make contact when two single meander bends swing in the opposite direction. The main types are embayment-eroding and ditch-scouring patterns, and thus, the two point bars are connected regardless of whether the patterns are chute cutoff or neck cutoff, most of which are the result of multiple periods of oscillation of the same channel. and L5(5 samples) patterns are formed in a confined and flat sedimentary context, where a single meander bend is in the process of swinging, and the main types are shoal-cutting and ditch-cutting patterns, with the formation of a multistage cutoff. While only a single pattern or two patterns exist, point bars that formed at different stages are connected because of the coarse-grained deposits at the bottom of the active channel with a small incision.

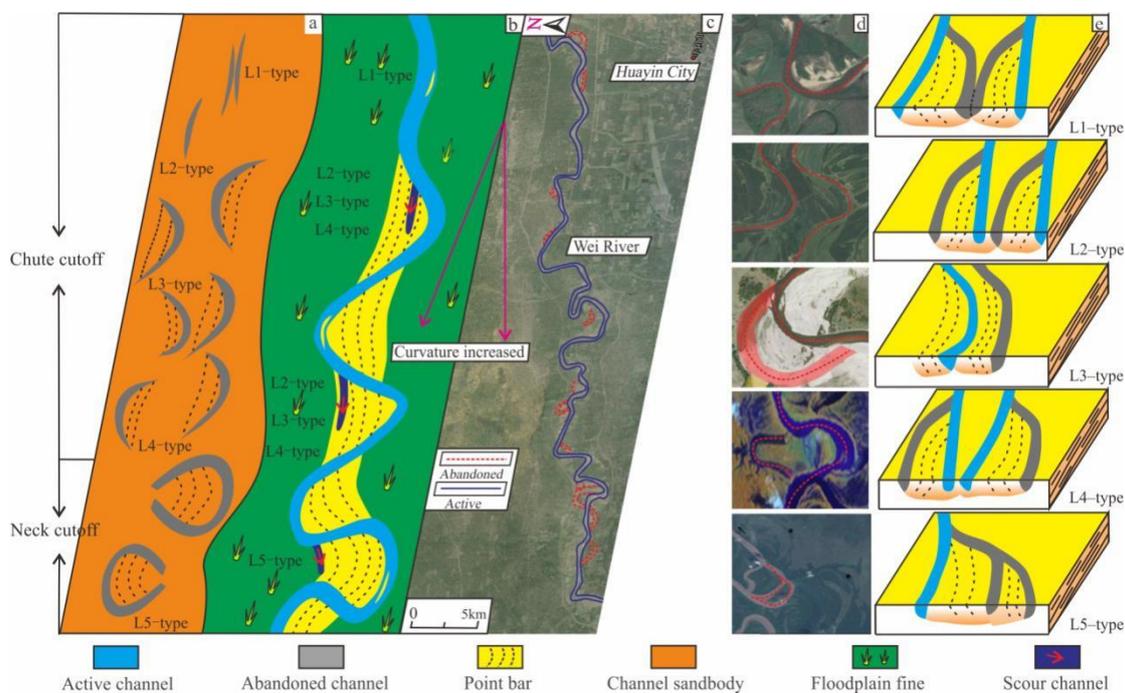


Fig. 5. Sedimentary pattern of abandoned channels.

(a) Planar amalgamation pattern of a single abandoned channel; (b) Formation mechanism of different abandoned channels; (c) Modern fluvial sedimentary of Wei River in Huayin City; (d) Planar amalgamation pattern of composite abandoned channels of the Songhua River; (e) Vertical amalgamation pattern of composite abandoned channels.

3.4 Influence of abandoned channels on oilfield water flooding

The methods of sandbody isopach mapping, sandbody top contour mapping, geochemistry records and well logging microfacies analysis amalgamation were adopted (Song et al., 2017), and we found that the abandoned channel of the meandering river is laterally associated with the point bar, which is the convex bank boundary at the point bar (Li et al., 2016). Meanwhile, the geometric characteristics of the abandoned channel can also be described according to Leeder's empirical formula (Leeder, 1973). The shape and combined well logging characteristics of the abandoned channel are quite different from those of the point bar deposits and the overbank deposits (Fig.6). Therefore, the combined planar and vertical patterns of the abandoned channel can be comprehensively described based on core, well logging, seismic and dynamic data and can be compared with modern deposits and field outcrops (Shan et al., 2008).

To further analyze the influence of the abandoned channel on oilfield development in the high water-cut stage, a dense well spacing was selected. The wells are situated in the northern part of the Daqing Placanticline. The Lamadian Oilfield, a gas cap reservoir controlled by a short axis anticline with a northeast trend, connects to the northern part of the Saertu Oilfield with a gentle slope in the east and a steep slope in the west. The current well spacing is 30–150 m after three infill adjustments. The SIII group of the northwest block in the Lamadian Oilfield is a typical hydrocarbon reservoir of meandering rivers.

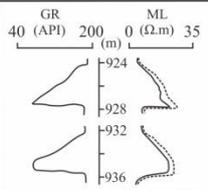
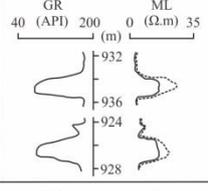
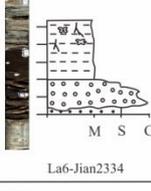
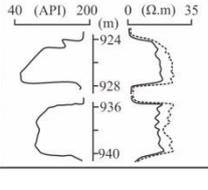
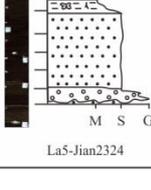
| Channel type | Sedimentary filling | Sedimentary structure | Stacking style | Logging curve | Lithologic section |
|----------------------|---|---|----------------|--|---|
| Chute cutoff channel | The upper part is fine grained embedded with plant rhizomes The middle part is fine grained embedded with coarse grained deposits The lower is gravel and coarse grained deposits | Scouring and filling Imbricate structure Ripple cross-laminated | Pagoda shape |  |  |
| Neck cutoff channel | The upper and middle part is filled by overbank deposits embedded with plant rhizomes The lower is gravel and coarse grained deposits | Scouring and filling Imbricate structure Trough cross-stratification Horizontal lamination | Finger shape |  |  |
| Active channel | The upper part is thin laminated fine grained deposits The middle part is filled by massive medium grained deposits The lower is gravel and coarse grained deposits | Scouring and filling Imbricate structure Trough cross-stratification Parallel-lamination | Box shape |  |  |

Fig. 6. Characteristic difference between the abandoned channel and active channel.

According to the spatial amalgamation and data identification of the abandoned channel mentioned above, this paper analyzes three reservoir units: SIII3, SIII4+5 and SIII6+7. Twenty-six single meandering rivers and 67 abandoned channels were identified, 43 of which were chute cutoff and 24 of which were neck cutoff (Fig.7a). Based on the classification of vertical stacking patterns for the composite abandoned channels, L2-type and L4-type patterns were the most common, whereas L1-type, L3-type and L5-type patterns were less developed. The neck cutoff channel appeared only in L1-type and L2-type patterns, but all five types of stacking patterns developed the chute cutoff channel.

Ultimately, two major effects on the sedimentary patterns of abandoned channels in the high water-cut stage were summarized. First, the production well or the injection well are drilled in the abandoned channel. If the cutoff patterns of the abandoned channels are neck cutoff types, the remaining hydrocarbon will be accumulated on either side of the abandoned channel. For example, the liquid

quantity of injection well La7–242 gradually decreases with an increase in injection pressure (Fig.7b; Fig.7e). Thus, it is best to use volume fracturing to produce the remaining hydrocarbon.

In addition, if these cutoff patterns of the abandoned channels are chute type, the remaining hydrocarbon will have accumulated as a result of top lateral accretion interlayer shielding, as the daily oil production of production well La3–PS232 was approximately 1 t (Fig.7c; Fig.7e). This well is surrounded by two injection wells (La3–232 and La3–PS2322), and because the two injection wells in SIII4+5 are drilled in the abandoned channel (Fig.8a; Fig.8b), the effect of water flooding is poor, and it is suitable to use horizontal wells for producing the remaining hydrocarbon. Second, the production well and the injection well are drilled in point bars on both sides of an abandoned channel, and the shielding effect of the abandoned channel is related to the above 5 vertical sedimentary patterns. For example, the daily oil production of production well La6–2401 decreased from 4 t in the early stage to 0.5 t at the present stage (Fig.7d; Fig.7e), and an abandoned channel with a neck cutoff pattern was developed between production well La6–2401 and injection well La6–2415. To reduce the influence of the injector–producer relationship in the imperfect well pattern, infill the production well or the injection well is an appropriate way to produce the remaining hydrocarbon.

4 Discussion

Although abandoned channels are common characteristics of meandering rivers, a detailed description of their sedimentary patterns is summarized in the literature (Brierley, 1991). Brierley (1991) pointed out that high–energy meandering rivers show a lower width/depth (W/D) ratio and coarser filling, whereas low–energy meandering rivers show a higher W/D ratio and finer filling. The sedimentary pattern of meandering rivers is strictly controlled by the interaction between climate, tectonic and sea–level changes (Blum and Törnqvist 2000). An increase in flow discharge and topographic slope can cause a decrease in curvature radius, and cohesive banks and dense vegetation effectively limited channel enlargement. However, during floods, newly abandoned channels may be formed where gradient advantages exist. The formation and preservation of abandoned channels are controlled by diversion angle and incident flood, where the former has certain particularity and the latter is caused by disequilibrium between the sediment transport capacity and sediment supply. Whether an abandoned channel will form and evolve according to predetermined stages largely depends on site specific conditions and context (Toonen et al., 2012).

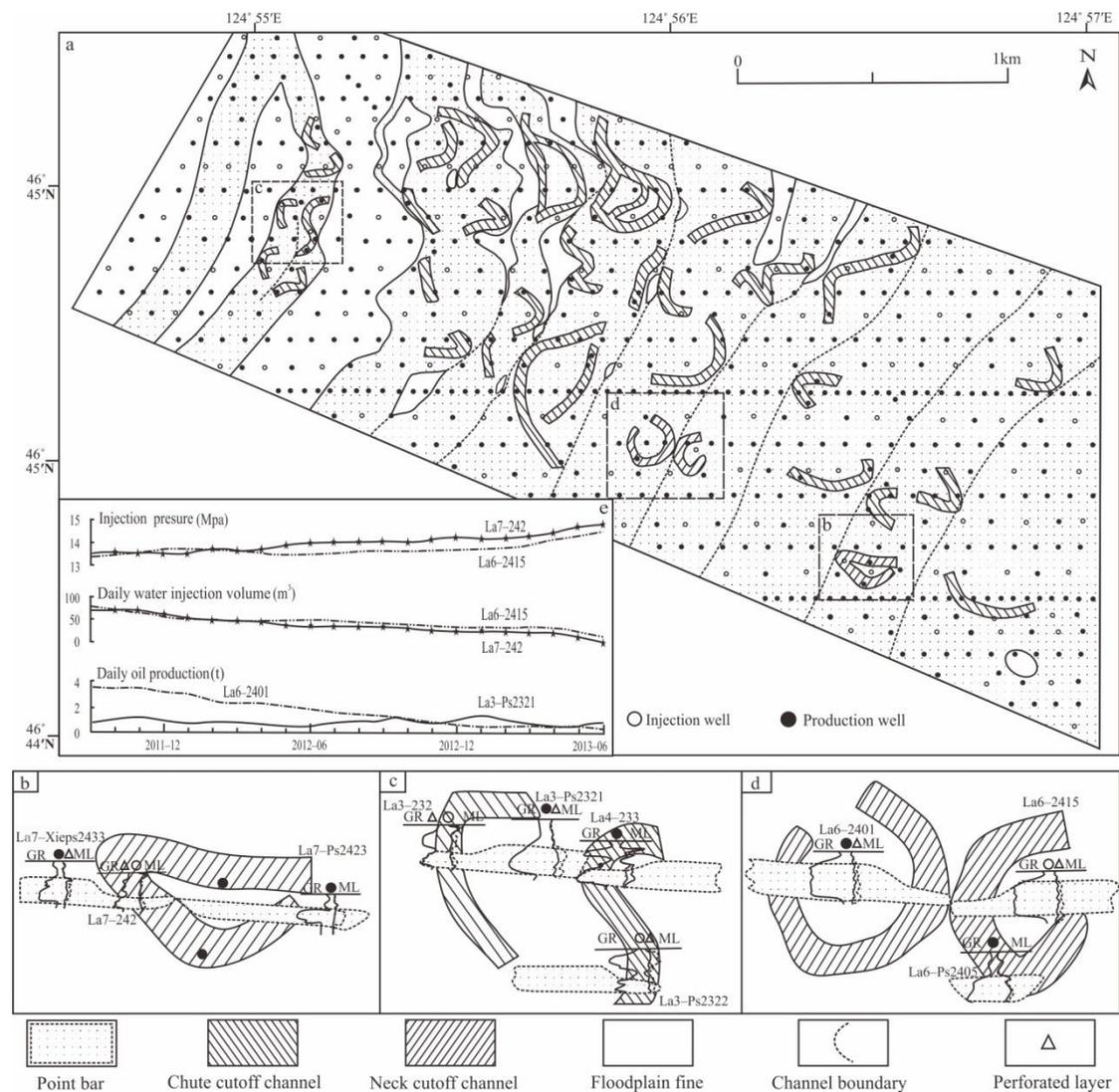


Fig. 7. Reservoir connectivity and interlayer characteristics of developed well blocks.

This paper summarizes the limited modern deposition and developed well blocks and is biased to all meandering rivers. Our patterns for abandoned channels build on the literature, outcrop data and developed well blocks and modern deposits. The patterns have yet to be applied to other parts of our study area, and the results of this paper should be applied only a specific sedimentary environment.

5 Conclusions

(1) The filling process of abandoned channels in meandering rivers is essentially divided into two stages: the transitional stage in which the active channel is connected to the abandoned channel and the disconnected stage in which the abandoned channel is completely formed. An event causing the initial diversion of the main active channel, which cuts off the meandering river or cause alluvial bifurcation–abandonment, triggers the beginning of the transitional stage, leading to plug bar formation at the entrance, and finally, the disconnected stage is a product of flooding events.

(2) The cutoff patterns of abandoned channels can be classified into two major categories: chute cutoff (shoal–cutting, ditch–scouring and embayment–eroding patterns) and neck cutoff. With the sedimentary evolution of a meandering river from upstream to downstream, the sedimentary pattern for

a meander bend transforms from chute cutoff into neck cutoff, and the active control factors change from the grain size and gradient to the flow and vegetation. The chute cutoff pattern forms a gradually developing lithological–physical barrier in the abandoned channel, and the neck cutoff pattern forms a sudden lithological barrier in the abandoned channel.

(3) Three planar sedimentary patterns of single abandoned channels and five vertical sedimentary patterns of composite abandoned channels were established and influence oilfield water–flooding in the high water–cut stage.

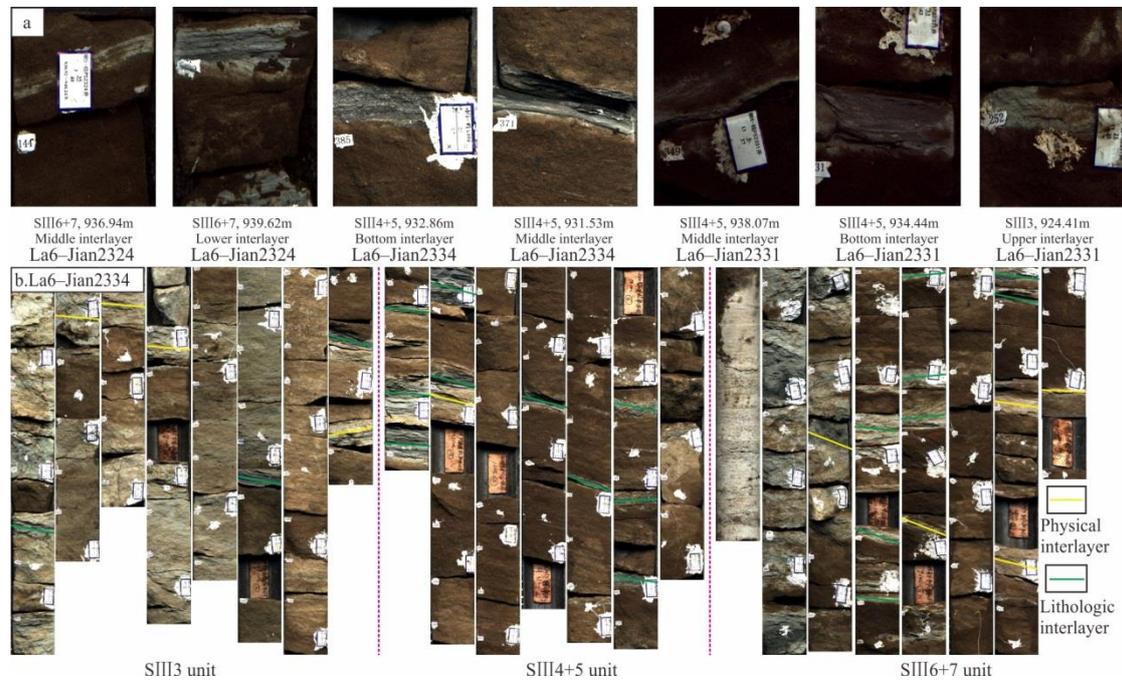


Fig. 8. Interlayer characteristics of abandoned channels.

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