Reconstruction of meander-bend migration from associated channel-belt architecture recorded in successions of ancient meandering rivers: A case study from the Cretaceous Songliao Basin, China

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Abstract
Identification of the diverse channel patterns of meander-bend migration is essential when reconstructing the historical evolution of sedimentary processes in meandering rivers. However, reconstruction of the spatio-temporal evolution of ancient meandering fluvial deposits for hydrocarbon exploration is difficult due to the limited research on the patterns and styles of meander-bend migration. To reconstruct the geomorphologic and sedimentary evolution of subsurface meandering palaeochannels, this study proposes an approach based on combining meander-bend planforms and cross-sectional architectural elements of clastic sedimentary successions of ancient meandering rivers. The research was applied to meandering fluvial deposits of the lower Cretaceous Quantou Formation in the north-eastern Songliao Basin, China. High-resolution satellite images of modern meandering rivers were used to classify and evaluate the meander-bend planform transformations of expansion, rotation and contraction (also known as bend tightening, i.e. narrowing of the neck of the meander-bend showing a tendency towards neck tightening or cut-off). Major meander-bend transformations were related to cross-sectional bedding architecture (i.e. bed dipping or bounding surface), which was identified through well-log and core characteristics, to construct the migration patterns of subsurface meander-belt deposits. Integration of well-log and core analysis from a dense array of wells allowed the stratigraphic architecture of ancient meandering rivers and stacking patterns of fluvial sandbodies to be characterised. Furthermore, major reservoir architectural elements and bounding surfaces of meandering channels were identified. Ultimately, the 3D meandering fluvial architecture was represented on 2D vertical sections so that, planform transformations and the evolutionary processes of point bars and meander bends could be elucidated. Reconstruction of meander-bend migration is of practical value for deciphering ancient fluvial systems and the development of subsurface fluvial reservoir models.

Keywords
ancient meandering river, meander-bend migration, palaeochannel, reconstruction, Songliao Basin

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1 | INTRODUCTION

As one of the most ubiquitous global dynamic ecosystems, meandering rivers are important for ecological health, natural resources, economic wealth and human well-being (Grill et al., 2019; Güneralp et al., 2012; Lin et al., 2017; Shan et al., 2018a; Xu et al., 2016). Channel planform change on modern meandering rivers (MMRs) shapes planetary surfaces (Carling et al., 2016), and successions of ancient meandering rivers (AMRs) document signals of palaeoclimate and palaeogeography (Lin et al., 2017; Sun & Wang, 2009; Wang et al., 2017). Interpretation and reconstruction of AMRs plays an important part in identifying palaeo-environment and palaeoclimate (Foreman & Straub, 2017; Hazelwood & Stetler, 2019; Ielpi & Lapôtre, 2019; Morecroft et al., 2019; Yang et al., 2020) and is also a significant component of hydrocarbon exploration and exploitation (Lin et al., 2018a, 2018b; Mu et al., 2015; Parquer et al., 2020; Shan et al., 2015a; Willis et al., 2015; Wu et al., 2012; Yue et al., 2007). However, due to the extremely complex characteristics of hydrocarbon reservoir architecture (Fustic et al., 2019; Meirovitz et al., 2016; Qiao et al., 2019; Ru et al., 2016; Singh et al., 2016), limited underground data (Shan et al., 2015c) and diversity of channel-bend transformations (i.e. expansion, translation, rotation or a combination thereof) (Chen et al., 2017; Ghinassi & Ielpi, 2015; Ghinassi et al., 2014; Hooke et al., 2011; Ielpi & Ghinassi, 2014; Johnston & Holbrook, 2018; Lin et al., 2017; Seminara, 2006), reconstruction of the evolutionary process of AMRs is a major challenge (Willis & Sech, 2018a). Developments in fluvial sedimentology, reservoir architecture, well-log geology and numerical simulation mean that the reconstruction of AMRs is increasingly attracting global attention (Fustic et al., 2019; Ghinassi & Ielpi, 2015; Ghinassi et al., 2016, 2018; Hossain & Imranuzzaman, 2019; Hritz & Wilkinson, 2006; Ielpi & Ghinassi, 2014, 2015; Parquer et al., 2017; Qiao et al., 2019; Santos & Owen, 2016; Shan et al., 2018a; Shibata et al., 2018; Yan et al., 2020).

This study aims to provide a novel approach to reconstruct the meander-bend planform changes from channel-belt architecture recorded in the successions of AMRs. This approach, emphasising the corresponding relationships between channel planform transformation and 3D fluvial architecture (Chen et al., 2017; Lin et al., 2017, 2018b), is demonstrated through a case study of subsurface meandering fluvial successions in the Cretaceous Songliao Basin, China. Wells drilled as part of the China Cretaceous Continental Scientific Drilling Project (Songke nos 1 and 2) (Hou et al., 2018; Wang et al., 2019a, 2019b; Zhao et al., 2017), have shown that the third member of the Quantou Formation is dominated by meandering fluvial successions (Feng et al., 2010; Guo et al., 2004; Li et al., 2019; Shan et al., 2018a; Shu et al., 2003; Wang et al., 2007, 2013, 2019a). To study the third member in detail, an area with a dense well pattern (ca 100 m well spacing) and considerable well-log data was selected in the Daqing Oilfield, in the north-eastern Songliao Basin. The stratigraphic framework of the subsurface sequence was reconstructed through a comprehensive analysis of well logs and cores and used to interpret the depositional styles and planform changes of the AMRs. Architectural elements and the stacking patterns of sandbodies were identified through reservoir architectural analysis. Also, time-lapse satellite images of MMRs were employed to illustrate meander-bend transformations and to identify the migration patterns corresponding to specific architectural elements. The results contribute to reconstructing meander-bend migration patterns and demonstrating relationships between complex channel morphodynamics, reservoir architectural hierarchy, planform transformations and corresponding stacking patterns of fluvial channel sandbodies, so as to reconstruct the evolutionary process of AMRs. Finally, the consistency (i.e. a river course evolving in line with the previous migration pattern) and transformation (i.e. a river course evolving from one migration pattern to another) of river evolution is discussed.

2 | GEOLOGICAL SETTING

The Songliao Basin, which is diamond-shaped and surrounded by large-scale fault blocks, holds the largest and most important petroliferous resources of the Mesozoic and Cenozoic continental sedimentary basins in north-eastern China, covering an area of 26 × 10^4 km^2 (Feng et al., 2010; Li et al., 2017, 2019; Shan et al., 2018a). The tectonic evolution of the basin comprises four stages: mantle upwelling, rift, post-rift thermal subsidence and structural inversion (Feng et al., 2010; Shan et al., 2018a) (Figure 1A). The basin is extensively filled with continental clastic successions of alluvial-fluvial, fluvial-deltaic and fluvial-lacustrine deposits from Jurassic to Neogene age (Shan et al., 2018a; Shu et al., 2003). Layer 19 is the third member of the Quantou Formation, which is the uppermost unit of the Lower Cretaceous and is further divided into Layer 19-1 and Layer 19-2 (Figure 1B). The formation is part of

FIGURE 1 Structural map of the Songliao Basin and study area, showing the tectonic units, stratigraphic characteristics and well locations. (A) Structural divisions of Songliao Basin showing the six first-order tectonic units and 32 s-order tectonic units; seismic section a–a′ is shown in Figure S1. (B) Stratigraphic characteristics and depositional systems of Cretaceous formations in Songliao Basin (modified from Shan et al., 2018a). (C) Tectonic units in the study area and location of 52 wells in the central downwarp; the 11 cross-sections marked on the map provided the stratigraphic framework for the sedimentary sequence.
the Yangdachengzi reservoirs in the central downwarp of the Daqing Oilfield, northern Songliao Basin (Shan et al., 2015a, 2015b), and Layer 19 is one of the major oil-producing reservoirs (Bai et al., 2012; Shan et al., 2013, 2015b, 2015c; Wang et al., 2013). The Quantou Formation was formed in the transitional stage from rifting to post-rift subsidence of the Songliao Basin and the depositional environment was dominated by large-scale fluvial-deltaic sedimentary systems (Figure S1). Member 3 is dominated by greenish-grey, dark greenish-grey, brownish-grey, greyish-brown mudstone and silty mudstone, with interbedded greenish-grey fine-grained sandstone. During this period, meandering fluvial successions were developed by rivers draining from south-west to north-east (Guo et al., 2004; Shan et al., 2013, 2018a; Wang et al., 2019a).

3  | DATA AND METHODS

3.1  | Data sets

Data sets used in this study comprised cores and logs from tightly spaced wells, including 52 wells (Wells X-1 to X-52) with a spacing of 19–180 m. Lithologic characteristics were identified in cores and well logs for Layer 19-1 and 19-2. High-resolution time-lapse satellite images, obtained from Google Earth and Rivermap database (http://www.rivermap.cn/), were used to characterise meander-bend transformation. Meander-bend images were selected on the basis that: (a) they showed typical meander-bend morphology; (b) multi-temporal remote sensing images were available for the same meander bend; and (c) they had high-resolution spatial resolution, from 0.59 to 19.10 m/pixel. Overall, nine specific meanders in eight rivers were chosen to illustrate the major migration pattern classifications adopted in this study, including the Murray River in Australia, Mamore River in Bolivia, Negro River and Colorado River in Argentina, Guaviare River in Colombia, Raidak River and Ganga River in India and Yellow River in China.

3.2  | Well-log analysis and correlation

Four types of well-log curves were employed to interpret subsurface lithologic characteristics and facies, spontaneous potential (SP), gamma ray (GR), deep resistivity (RLLD) and shallow resistivity (RLLS), of which GR logs provide the best quality information. Variations in well-log characteristics are associated with grain size and bounding surfaces, so different log shapes are considered as proxies for various facies associations, sandbody stacking patterns and depositional environments (Nazeer et al., 2016; Slatt, 2006). In the context of meandering fluvial environments, the amplitude, shape and cut-off style of well-log curves are relevant (See Figure 2 for detail). High and low amplitude well-log curves reflect coarse and fine grain size, respectively (Figure 2A), and vertical changes in grain size determine log shape. Six types of log shape were defined, bell, funnel, block, symmetrical, serrated and irregular, corresponding to the depositional processes of retrogradation, progradation, aggradation, progradation and retrogradation, aggradation and aggradation, respectively. The width of the log response reflects sediment thickness, with narrow and wide responses interpreted as thin and thick sandbodies, respectively (Figure 2A). The cut-off style of the GR log was used to describe abrupt changes in log response that are related to sharp lithological breaks associated with unconformities and sequence boundaries (Krassay, 1998) and can reflect sandbody vertical stacking patterns (Qiao et al., 2019; Shan et al., 2015b). The GR logs were qualitatively classified as type I, II, III and IV, according to the cut-off degree (Figure 2B). These correspond to sandbody contacts categorised as isolated, contacted, embedded and scoured stacking patterns (Figure 2B).

To carry out stratigraphic correlations and interpretations, 11 well-to-well cross-sections (see lines L1–L3, T4–T9 and S10–S11 in Figure 1C) were examined, including longitudinal cross-sections L1–L3 (parallel to average palaeoflow direction) extending from south-west to north-east, transverse cross-sections T4–T9 (perpendicular to palaeoflow direction) extending from north-west to south-east and oblique cross-sections S10–S11 extending west-east and south-north. The cross-sections were used to establish the sequence stratigraphic framework (Li et al., 2012; Shan et al., 2015c, 2018b; Xu et al., 2014) for the study area. A pseudo-3D fence diagram was produced to examine the 3D stratigraphic framework (Figure S2).

3.3  | Facies associations and mapping

Based on the comprehensive analysis of cores, well logs and well-to-well correlations (thickness data are available in Table S1), four sets of sediment thickness contour maps were created, including reservoir thickness, reservoir-sand thickness, maximum sandbody thickness and sandstone fraction. The contour maps were used to illustrate the position of depocenters and the scale and distribution of reservoir sandbodies. Planform facies associations were then mapped through critical well-log analysis and correlation. Additionally, fluvial reservoir sandbodies, here mainly those of point bar and abandoned channel deposits, natural levee deposits and overflow deposits (i.e. crevasse splay and floodplain deposits). The stacking patterns of sandbodies show the contacts in different depositional units, which
Figure 2 Schematic diagram showing the direct correlation between facies, stacking patterns of sandbodies and well-log characters relative to the sedimentological relationship. (A) Well-log amplitude, shape (GR—gamma ray, SP—spontaneous potential). (B) Well-log (GR) cut-off style. (C) Sandbody vertical stacking patterns.
helps evaluate the quality of connectivity of reservoir sandbodies. Contacts are also important references for evaluating reservoir flow units, which are zones with vertically and laterally continuous reservoirs that have similar geological and petrophysical properties that affect the flow of fluids (Chen, 2019; Ebanks, 1987). The stacking patterns of sandbodies also reflect their relative age—for example, a sandbody that crosscuts another was formed later than the one it crosscuts—which allows the evolutionary history of fluvial sandbodies to be reconstructed. Closely spaced stacking patterns can indicate vertical and lateral connectivity of reservoir sandbodies. The basic classification of sandbodies into isolated, embedded and contacted relationships can be used as a proxy for overall connectivity (Table 1 and Figure 2). In Layer 19, stacking patterns were grouped into three categories, isolated (IS), superimposed (SS) and adjacent (AS), and 14 subsets, as shown in Table 1. Finally, stratigraphic correlation and interpretation was used to illustrate the vertical and planform distribution of sandbodies and reservoir architecture.

3.4 Architectural hierarchy

The principles of hierarchical classification of bounding surfaces and depositional units that were used here are mostly based on previous studies (Miall, 1985, 2006; Lin et al., 2018a; Shiers et al., 2018; Viseras et al., 2018). Specifically, classes of architectural elements applicable to units of different scales are arranged hierarchically as bed, interbed, inclined bed, bed-set, point bar increment, point bar, channel, channel belts and channel systems, corresponding to the seven orders of bounding surfaces as shown in Figure 3. The most important architectural elements identified in this study are the interbed, inclined bed and channel. Additionally, based on the planform facies associations, the study area was subdivided into nine migration zone sub-regions, numbered from Z1 to Z9, see Table 2. The migration zones were used to enhance reconstruction of the planform migration patterns of subsurface meander-belt deposits.

4 MEANDER-BEND MIGRATION PATTERNS

4.1 Classification of meander-bend migration patterns

The migration dynamics of meandering rivers has been of public concern in recent decades due to its economic and social consequences, and it is also of fundamental interest to fluvial geomorphologists and sedimentologists due to its complexity and role in river evolution (Brice, 1964, 1974; Daniel, 1971; Davis, 1903; Gueneraldp & Marston, 2012; Hickin, 1974; Lane, 1957; Seminara, 2006). Classification of river migration patterns has a long history of research and debate (Brice, 1964, 1974; Gurnell et al., 1994; Hooke, 1984; Lin et al., 2018c; Seminara, 2009). The classification scheme for meander-bend migration patterns of MMRs (Lin et al., 2017, 2018b) used in this study has six major individual patterns and three complex patterns (Table 3). The terminology used here is mostly based on Lin et al. (2018b) and available in Table 3. The characteristics of the six major migration modes are displayed in Figure 4. In SE and SC modes, the bend apex is maintained in a central position, half-way between the upstream and downstream bend inflection points; the former increasingly erodes the outer bank, showing a symmetrical and expansional shape (Figure 4A and A'). When a meander-bend expands to a certain extent, contraction (or bend tightening) processes begin and the migration pattern transforms from SE to SC mode (Figure 4B and B'). The DRE and URE modes both involve progressive migration of the bend towards the outer bank; DRE moves the bend apex downstream, demonstrating the development of down-river rotation and expansion (Figure 4C and C'); the URE moves the bend apex upstream, with a tendency to up-river rotation and expansion (Figure 4E and E'). The DRC and URC modes both develop a form of meander-bend tightening with a neck cut-off trend. The DRC comprises downstream bend shifts, exhibiting a down-river rotation trend (Figure 4D and D'); the URC comprises upstream bend shifts, manifesting a tendency of up-river rotation (Figure 4F and F').

The complexity of migration patterns is illustrated in Figure 4 with examples of SE-C, SC-URC and SC-DRC modes. In Figure 4G, the upstream meander shows the evolution from SE to SC, while the downstream channel transforms from SE to SC to URC. The URC mode in the image taken on 7 April 2011 (Figure 4G-2) can be inferred as a neck cut-off, which is confirmed in the later image taken on 5 April 2014 (Figure 4G-3). In Figure 4H, the river channel initially evolves in URC mode (Figure 4H-1); after the cut-off process, the meander planform changes first adopts SC mode (Figure 4H-2) then DRC mode (Figure 4H-3). In Figure 4I, the meander transforms from an initial SC mode (Figure 4I-1) to URC mode (Figure 4I-2), and after the neck cut-off, it evolves to the SE mode (Figure 4I-3).

4.2 Recognition of meander-bend migration patterns

To reveal the meander-bend planform evolution of subsurface fluvial successions, it is important to identify migration patterns in well-to-well cross-sections. The relationship between
the channel planform evolution of MMRs and the subsurface reservoir architecture of AMRs has been discussed in many previous studies (Ghinassi et al., 2014, 2018; Ielpi & Ghinassi, 2014; Lin et al., 2018b; Shan et al., 2018a). The fundamental relationship between morphological evolution and the internal architecture of meandering river deposits is

| Stacking patterns | Abbreviation | Illustration | Contacts and major connectivity | Temporal and spatial relationships |
|-------------------|--------------|--------------|-------------------------------|-----------------------------------|
| Isolated styles   |              |              |                               |                                   |
| Contemporaneous channel sandbody isolated mode | IS-1 | Channel to channel | Isolated, disconnected | Sandbodies develop in different positions in the same period |
| Non-contemporaneous channel sandbody isolated mode | IS-2 | Channel to channel | Isolated, disconnected | Sandbodies develop in different positions in different periods |
| Contemporaneous levee sandbody isolated mode | IS-3 | Levee to levee | Isolated, disconnected | Sandbodies develop in different positions in the same period |
| Non-contemporaneous levee sandbody isolated mode | IS-4 | Levee to levee | Isolated, disconnected | Sandbodies develop in different positions in different periods |
| Contemporaneous overflow sandbody isolated mode | IS-5 | Overflow to overflow | Isolated, disconnected | Sandbodies develop in different positions in the same period |
| Non-contemporaneous overflow sandbody isolated mode | IS-6 | Overflow to overflow | Isolated, disconnected | Sandbodies develop in different positions in different periods |
| Superimposed styles |              |              |                               |                                   |
| Channel sandbody superimposed mode | SS-1 | Channel to channel | Embedded, vertical and lateral connectivity | Upper channel sandbody incises lower sandbody |
| Channel–levee sandbody superimposed mode | SS-2 | Channel to levee | Embedded, vertical and lateral connectivity | Channel sandbody incises levee sandbody |
| Channel–overflow sandbody superimposed mode | SS-3 | Channel to overflow | Embedded, lateral connectivity | Channel sandbody incises overflow sandbody |
| Levee–overflow sandbody superimposed mode | SS-4 | Levee to overflow | Embedded, lateral connectivity | Levee sandbody incises overflow sandbody |
| Adjacent styles   |              |              |                               |                                   |
| Channel sandbody adjacent mode | AS-1 | Channel to channel | Contacted, lateral connectivity | Channel sandbodies adjacent to each other |
| Channel–levee sandbody adjacent mode | AS-2 | Channel to levee | Contacted, lateral connectivity | Channel sandbody adjacent to levee sandbody |
| Channel–overflow sandbody adjacent mode | AS-3 | Channel to overflow | Contacted, lateral connectivity | Channel sandbody adjacent to overflow sandbody |
| Levee–overflow sandbody adjacent mode | AS-4 | Levee to overflow | Contacted, lateral connectivity | Levee sandbody adjacent to overflow sandbody |

Legend: Floodplain deposits; Channel sandbodies; Levee sandbodies; Overflow sandbodies.
indicated in the change in dip azimuth and angle of inclined beds, including the first-order to fourth-order bounding surfaces (Figure 3). When a meander bend transforms from one pattern to another, the inclined bed dip tends to change as conceptually summarised in Figure 5 (Ghinassi et al., 2014, 2016; Ielpi & Ghinassi, 2014; Shan et al., 2018a; Willis & Tang, 2010). For example, when the meander bend develops from stage 1 to 2 (Figure 5A), there is a change in dip of second-order and fourth-order surfaces (sections a–a′ and b–b′ of Figure 5A). As the meander bend migrates downstream in DRE mode (Figure 5D), the dip of the second-order surface tends to increase towards the bend apex (from stages 1 to 2 or stages 3–4 in section b–b′ of Figure 5A). When the meander bend transforms from DRE mode to URE (from stage 2 to 3 of Figure 5A), there is a decrease in the dip of second-order (i.e. inclined bed interface or interbed interface) surfaces (sections a–a′ and b–b′ of Figure 5A).

In an individual meander-bend migration, changes in the dip and spacing of inclined beds in the transverse section (parallel to the direction of bend apex migration) and the symmetry and convergence of e beds dipping in the longitudinal section (parallel to the river axis) help differentiate migration patterns. In the case of SE mode, the transverse section commonly records increasing dip of inclined beds towards the outer bank (section a–a′ of Figure 5B) while the longitudinal section generally documents symmetrical
| Migration pattern                | Abbreviation | Illustration | Transformation | Geometry | Bend apex migration |
|---------------------------------|--------------|--------------|----------------|----------|---------------------|
| Individual                      |              |              |                |          |                     |
| Symmetrical expansion           | SE           | ![Symmetrical expansion Illustration](image) | Symmetrical | Transversely away from the channel-bend axis |
| Upstream rotation and expansion | URE          | ![Upstream rotation and expansion Illustration](image) | Expansion, extending the meander bend towards the outer bank | Asymmetric | Towards the upstream |
| Downstream rotation & expansion | DRE          | ![Downstream rotation & expansion Illustration](image) | Asymmetric | Towards the downstream |
| Symmetrical contraction         | SC           | ![Symmetrical contraction Illustration](image) | Contraction, narrowing the meander-bend neck and showing a neck cut-off tendency | Symmetrical | Transversely away from the channel-bend axis |
| Upstream rotation and contraction | URC         | ![Upstream rotation and contraction Illustration](image) | Asymmetric | Towards the upstream |

(Continues)
### TABLE 3 (Continued)

| Migration pattern | Abbreviation | Illustration | Transformation | Geometry | Bend apex migration |
|-------------------|--------------|--------------|----------------|----------|---------------------|
| Downstream rotation and contraction | DRC | ![DRC Illustration](image) | Asymmetric | Towards the downstream |

**Complex**

| Symmetrical expansion–contraction | SE–C | ![SE–C Illustration](image) | From expansion to contraction | Symmetrical | Transversely away from the channel-bend axis |
|----------------------------------|------|-----------------------------|-------------------------------|------------|---------------------------------------------|

| Upstream rotation and expansion–contraction | URE–C | ![URE–C Illustration](image) | From expansion to contraction | Asymmetric | Towards the upstream |
|-----------------------------------------------|--------|-------------------------------|-----------------------------|------------|---------------------|

| Downstream rotation and expansion–contraction | DRE–C | ![DRE–C Illustration](image) | From expansion to contraction | Asymmetric | Towards the downstream |
|-----------------------------------------------|--------|-------------------------------|-----------------------------|------------|---------------------|

**FIGURE 4** Major meander-bend transformations adopted in this study. Yellow arrows in (A) to (I) and blue arrows in (A’) to (I’) indicate the direction of river flow; different combinations of red arrows in (A’) to (I’) symbolise specific migration modes. Images obtained from Google Earth are in the WGS84 reference coordinate system, with a spatial resolution of 0.59 to 19.10 m/pixel. Plates (A) to (I) show historical images of investigated meander channels. The original satellite images were subject to false colour image processing to enhance the visual appearance. Plates (A’) to (I’) show incremental growth of specific migration modes. (A) SE mode, Murray River, Australia (140°36′8.58″E, 34°17′48.96″S). (B) SC mode, Mamore River, Bolivia (65°01′44.47″W, 16°49′25.53″S). (C) DREM mode, Negro River, Argentina (65°59′50.50″W, 39°15′47.53″S). (D) DRC mode, Guaviare River, Colombia (69°54′29.96″W, 03°28′34.11″N) (E) URE mode, Colorado River, Argentina (74°52′6.83″W, 8°02′8.30″S). (F) URC mode, Raidak River, India (89°38′45.25978″E, 26°21′41.24989″N). (G) SE to SC to URC mode, Ganga River, India (78°38′44.96″E, 29°11′19.08″N). (H) URC to SC to DRC mode, Yellow River, China (110°50′12.38″E, 40°17′6.53″N). (I) SC to DRC mode, Mamore River, Bolivia (64°47′2.92″W, 17°06′14.38″S).
bed-set geometry (section b–b’ of Figure 5B). The URE mode usually preserves the gently decreasing dip of inclined beds towards the outer bank in the transverse section (section a–a’ of Figure 5C). In the longitudinal section, the upstream portion of the point bar displays a steeper bed-set dip than the downstream (section b–b’ of Figure 5C). In contrast, the DRE mode generally increases the dip of inclined beds from the inner to the outer bank (section a–a’ of Figure 5D), while the upstream portion of the point bar shows gentler dipping inclined beds parallel to the
longitudinal river axis (section b–b’ of Figure 5D). For the contraction patterns (i.e. SC, DRC and URC), SC tends to present as increasing dip of the second-order surface in the transverse section (section a–a’ of Figure 5E); although the longitudinal section shows a similar symmetrical shape of bedsets, the bedding tends to be abruptly cut towards both ends (section b–b’ of Figure 5E). The transverse section appearance of the URC mode is similar to the URE mode (section a–a’ of Figure 5F); however, in the longitudinal section, the dipping inclined beds generate down-lapping geometries in the upstream direction (section b–b’ of Figure 5F). The DRC mode shows similar characteristics with the DRE mode in the transverse section (section a–a’ of Figure 5G); distinctively, along the river axis, the dipping inclined beds generate down-lapping geometries downstream (section b–b’ of Figure 5G).
To reconstruct subsurface channel planforms in a dense well pattern, it is important to identify the architectural elements and bounding surfaces from cores and well-log facies. Unlike reconstructions based on outcrop architecture, it is difficult to recognise changes in dip and spacing of the inclined bed interface in the subsurface condition. Characteristics and

| Rank of surface | Definition | Example process | Depositional units | Instantaneous sedimentation rate (m/ka) | Characteristics in borehole cores and outcrops | Characteristics in gamma-ray (GR) well logs |
|-----------------|------------|-----------------|-------------------|-----------------------------------------|-----------------------------------------------|-------------------------------------------|
| First order     | Represent cross-bed set bounding surfaces and record boundaries within microform and meso form deposits | Bedform migration | Ripple (microform), Diurnal, dune increment, or reactivation surface | $10^7$ | Bed set surface, can be recognised by truncation or wedgeout of cross-bed foresets | Surface not usually recognised from the GR log, no obvious change in the amplitude of the curve |
| Second order    | Coset bounding surfaces; these indicate changes in flow conditions, or a change in flow direction, but no significant time break | Bedform migration | Dune (mesoform) | $10^4$ | Interbed or inclined bed coset surface; lithofacies above and below the surface are different, but the surface is usually not marked by significant bedding truncations or other evidence of erosion | GR log curve differs in shape above and below the surface, inflection point of the curve indicates surface location |
| Third order     | Cross-cutting erosion surfaces within macroforms that dip at a low angle and may truncate underlying crossbedding at a low angle | Seasonal events, 10-year flood | Macroform growth increment | $10^{2-3}$ | Increment surface, dipping 5–20° in direction of accretion; these surfaces indicate stage changes, but no significant change in sedimentary style or bedform orientation within the macroform | Usually not recognised from the GR log, no obvious change in the amplitude of the curve |
| Fourth order    | Represent the upper bounding surfaces of macroforms, or surfaces of lateral or downstream accretion | 100-year flood, channel and bar migration | Macroform, e.g., point bar, levee, splay immature palaeosol | $10^{2-3}$ | Point bar surface, convex-up macroform top, minor channel scour, flat surface bounding floodplain elements | GR log curve differs in shape above and below the surface, inflection point of the curve indicates surface location |
| Fifth order     | Bounding major sand sheets, e.g., broad channels and channel-fill complexes, or palaeosol horizons within floodplain sequences | Long term geomorphic processes, e.g., channel avulsion | Channel, delta lobe, mature palaeosol | $10^{5-1}$ | Channel surface, flat to concave-up channel base, or basal bounding surfaces of fan trenches and lobes | GR log curve differs in shape above and below the surface, inflection point of the curve indicates surface location |
| Sixth order     | Groups of channels or palaeovalleys, stratigraphic units such as members or submembers | Fifth-order (Milankovitch) cycles, response to fault pulse | Channel belt, alluvial fan, minor sequence | $10^{-1}$ | Channel-belt surface, flat, regionally extensive, or base of incised valley | — |
| Seventh order   | Enclose the major lithosomes representing discrete allogetic events | Fourth-order (Milankovitch) cycles, response to fault pulse | Major depositional system, fan tract, sequence | $10^{-1-2}$ | Channel system surface, sequence boundary, flat, regionally extensive, or base of incised valley | — |
diagnostic criteria for the different hierarchies of surfaces used in the subsurface data sets (borehole cores or outcrops) for this study are provided in Table 4. It can be difficult to differentiate between some surfaces in well logs and cores, such as third, fourth and fifth-order surfaces (Miall, 2006).

However, in the closely spaced wells used in the study, it was possible to identify and differentiate clear interbed interfaces through continuous well-to-well cross-sectional correlation and analysis. Figure 6 shows how meander-bend migration behaviour was reconstructed from analysis of adjacent wells (Well X-9, X-10, X-11, X-12, X-13, X-15 and X-19), using Layer 19-1 as an example. First, lithologic characteristics and well-log facies were used to determine the depositional environment at each well location, then planform facies associations were mapped based on well-to-well correlation and analysis. Point bar deposits and abandoned channel fills were identified from facies associations and distribution. Thus, in Figure 6A, the boundary of the point bar could be inferred to end at well locations X-9, X-11 and X-15. Based on individual well-log analysis, abandoned channel fills were divided into different stages; the initial and final centrelines (i.e. medial line or axis of the river channel) are outlined in Figure 6A. The depth and orientation of underground surfaces and beds were determined by image logging and core-based orientation techniques supported the PetroChina Daqing Oilfield Company. At each well location, the interface and attitude of inclined beds and bedsets was measured on cores in the boreholes. In the absence of high-resolution seismic profiles, the core orientation of a single well and borehole is not enough to interpret the architectural distribution around the well, making it difficult to reconstruct the whole underground space. However, it was possible to map continuous interbed interfaces and dip changes using pseudo-3D fence diagrams of fluvial architecture based on multiple tightly spaced well-to-well cross-sections and borehole cores (Figure 6B). Using Walther’s law of facies and stratigraphic continuity of the target interval, interbeds and inclined beds in areas of no data between wells were speculated (termed as speculative interbed or inclined bed, and so forth) based on the well-to-well reservoir architectural analysis. The interbeds and inclined beds of Layer 19-1 in Well X-10 dip towards Well X-9, and cores in Well X-11 show interbeds dipping towards wells X-12 and X-9, and on X-13. Additionally, Well X-12 documents a steeper bed-set dip towards Well X-10 than Well X-15. Ultimately, the meander bend in the downstream part was interpreted as migrating from the location of Well X-10 to X-9, and the upstream bend developing from the location of Well X-19 to X-15. The planform transformations were identified as URE and DRE modes. The evolutionary process of meander bends was outlined from initial to final centrelines (Figure 6C) through linear interpolation (Ruiu et al., 2016; Shan et al., 2018a) which was conducted by the Blend tool in CorelDRAW and Matlab software (relevant code and function are available through the software).

5 | STRATIGRAPHIC AND RESERVOIR ARCHITECTURE

5.1 | Lithologic characteristics and well-log facies

The lithologic characteristics of the target Layer 19 are primarily characterised by oil-bearing brown sandstones, siltstones and grey basal conglomerates. Integrated with the characteristics of well-log shapes and cores, six well-log facies and depositional units were recognised. Well-log facies adopted here follow the classification scheme of previous works (Li et al., 2019; Lin et al., 2018a; Shan et al., 2015c), including point bar deposits, abandoned channel deposits, natural levee deposits, crevasse splay deposits, floodplain deposits and oxbow lake deposits. Examples of core lithologic characteristics and well-log facies were shown in Wells X-8, X-17, X-29, X-35, X-41 and X-50 of Layer 19 (Figure 7).

5.1.1 | Point bar deposits

In Well X-17 of Layer 19-1, cores obtained at a depth of 435.5 m reveal dark brown tabular and cross-laminated siltstone with interbedded greenish-grey argillaceous siltstone (Figure 7B), showing a fining-upward trend. The GR and SP logs show a wide bell shape, while the RLLD and RLLS logs both show a narrow bell shape. The GR logs present a high amplitude type III response. These log characteristics show fining-upward and thinning-upward trends and retrogradation processes, which further indicate the embedded stacking pattern of sandbodies in point bar deposits (Figure 7B).

5.1.2 | Abandoned channel deposits

In Well X-35 of Layer 19-1, cores obtained at a depth of 444.1 m show grey massive medium to coarse-grained gravelly
### Point bar deposits in well X-17

| Layer | Depth (m) | Sand bodies | Lithologic schematic diagram | Core | Stacking pattern | Cycles |
|-------|-----------|-------------|--------------------------------|------|------------------|--------|
| 18    | 430       |             |                                |      |                  |        |
| 19−2  | 440       |             |                                |      |                  |        |
| 19−1  |           |             |                                |      |                  |        |
| 20    |           |             |                                |      |                  |        |

### Abandoned channel deposits in well X-35

| Layer | Depth (m) | Sand bodies | Lithologic schematic diagram | Core | Stacking pattern | Cycles |
|-------|-----------|-------------|--------------------------------|------|------------------|--------|
| 18    | 440       |             |                                |      |                  |        |
| 19−2  | 450       |             |                                |      |                  |        |
| 19−1  |           |             |                                |      |                  |        |
| 20    |           |             |                                |      |                  |        |

### Natural levee deposits in well X-41

| Layer | Depth (m) | Sand bodies | Lithologic schematic diagram | Core | Stacking pattern | Cycles |
|-------|-----------|-------------|--------------------------------|------|------------------|--------|
| 18    | 430       |             |                                |      |                  |        |
| 19−2  | 440       |             |                                |      |                  |        |
| 19−1  |           |             |                                |      |                  |        |
| 20    |           |             |                                |      |                  |        |

### Crevasse splay deposits in well X-29

| Layer | Depth (m) | Sand bodies | Lithologic schematic diagram | Core | Stacking pattern | Cycles |
|-------|-----------|-------------|--------------------------------|------|------------------|--------|
| 18    | 440       |             |                                |      |                  |        |
| 19−2  | 450       |             |                                |      |                  |        |
| 19−1  |           |             |                                |      |                  |        |
| 20    |           |             |                                |      |                  |        |

### Floodplain deposits in well X-50

| Layer | Depth (m) | Sand bodies | Lithologic schematic diagram | Core | Stacking pattern | Cycles |
|-------|-----------|-------------|--------------------------------|------|------------------|--------|
| 18    | 450       |             |                                |      |                  |        |
| 19−2  | 460       |             |                                |      |                  |        |
| 19−1  |           |             |                                |      |                  |        |
| 20    |           |             |                                |      |                  |        |

### Oxbow lake deposits in well X-8

| Layer | Depth (m) | Sand bodies | Lithologic schematic diagram | Core | Stacking pattern | Cycles |
|-------|-----------|-------------|--------------------------------|------|------------------|--------|
| 18    | 430       |             |                                |      |                  |        |
| 19−2  | 440       |             |                                |      |                  |        |
| 19−1  |           |             |                                |      |                  |        |
| 20    |           |             |                                |      |                  |        |
sandstone with interbedded brown siltstone at the base and dark massive silty mudstone at the top, showing a fining-upward trend (Figure 7C). The GR logs display a wide bell-shaped response, while the SP, RLLD and RLLS logs show a narrow bell shape. The GR logs present a high amplitude type IV response. These log characteristics imply fining-upward and thinning-upward trends and retrogradation processes, which further indicates the scoured channel stacking pattern of sandbodies in abandoned channel deposits (Figure 7C).

5.1.3 | Natural levee deposits

In Well X-41 of Layer 19-2, cores obtained at a depth of 435.0 m present brown horizontally bedded and tabular cross-laminated siltstone (Figure 7D), showing a fining-upward trend. All well logs display a block-shaped and bell-shaped response, with the RLLD and RLLS logs showing a narrow bell shape and the GR logs showing a high amplitude type IV. These log characteristics show fining-upward and thinning-upward trends and retrogradation processes, which indicate the scoured stacking pattern of sandbodies in natural levee deposits (Figure 7D).

5.1.4 | Crevasse splay deposits

In Well X-29 of Layer 19-1, cores obtained at a depth of 447.2 m show brownish-yellow wedge-shaped cross-laminated sandstone (Figure 7E), illustrating a coarsening-upward trend. The well logs show a narrow funnel-shaped response. The GR logs display a low amplitude type III response. These log characteristics indicate coarsening-upward and thickening-upward trends and progradation processes, which implies the embedded stacking pattern of sandbodies in crevasse splay deposits (Figure 7E).

5.1.5 | Floodplain deposits

In Well X-50 of Layer 19-1, cores obtained at a depth of 460.7 m show dark brown ripple cross-laminated siltstone interbedded with fine-grained siltstone and mudstone (Figure 7F), displaying a fining-upward trend. All well logs demonstrate a narrow serrated shape. The GR logs show a low amplitude type II response. These log characteristics show fining-upward and thinning-upward trends and aggradation processes, which indicate the contacted stacking pattern of sandbodies in floodplain deposits (Figure 7F).

5.1.6 | Oxbow lake deposits

In Well X-8 of Layer 19-1, cores obtained at a depth of 435.6 m are dominated by dark massive horizontally bedded silty mudstone, fine-grained siltstone and mudstone (Figure 7G). All well logs show narrow irregular shapes. The GR logs show a low amplitude type I response. These log characteristics indicate the isolated stacking pattern of sandbodies in oxbow lake deposits.

5.2 | Stratigraphic correlations and facies associations

Well-to-well stratigraphic correlations were conducted to explore the facies associations of point bar, abandoned channel, crevasse splay, natural levee, oxbow lake and floodplain deposits. Longitudinal cross-sections L1–L3 reveal good continuity of the channel sandbodies of Layer 19-2 and development of floodplain deposits of Layer 19-1 (Figure 8). Transverse cross-sections T4–T9 demonstrate major boundary surfaces of different depositional units (Figure 9). Oblique cross-sections S10–S11 further aid identification of lateral and vertical changes in architectural elements and boundary-surface types (Figure 10). The platform distribution of facies associations was illustrated by integrating the stratigraphic correlations with the contour map analysis (i.e. reservoir thickness, reservoir-sand thickness, maximum sandbody thickness and sandstone fraction, see Figures 11 and 12, and Figures S3–S8 for details). The results show that point bar, abandoned channel, floodplain and crevasse splay are well developed in the meandering fluvial depositional stages of Layer 19. In the stage represented by Layer 19-1, two meander belts are preserved that flowed through the study area from the south-west, and have estimated widths in the range 80–300 m (Figure 13). In the stage represented by Layer 19-2, the two meander
belts still run to the north-east and have width estimates ranging from 50 to 250 m (Figure 14).

5.3 | Stratigraphic sandbody correlations and interpretation

The vertical distribution of reservoir sandbodies is represented by well-to-well sandbody correlations and interpretation. Stacking patterns are dominated by IS-2, IS-6 and SS-1 modes (Figure 8) in cross-sections L1–L3. Individual sandbodies are 1–5 m thick and extend laterally for 120–350 m, showing longitudinal connectivity. Transverse cross-sections T5–T9 document isolated sandbodies arranged stacking patterns of IS-1, IS-2 and IS-6 modes (Figure 9). Due to the presence of overbank fine-grained sediments, the boundaries of channel sandbodies are easier to determine. Sandbody thickness is in the range 1–5 m and lateral extension is 30–350 m, showing lateral connectivity. Modes IS-1, IS-2 and IS-6 are the major stacking patterns in the oblique cross-sections S10–S11 (Figure 10), showing relatively poor connectivity of sandbodies.

The planform distribution of reservoir sandbodies shows that they are sheet-like and strip-like and oriented south-east and north-west. Two stages of composite sandbodies can be identified in Layer 19-1 and Layer 19-2, corresponding to two meandering palaeochannel stages. In Layer 19-1, sandbodies in Wells X-2, X-26 and X-32 showed the broadest coverage. Sandbody width ranged from 80 to 225 m in the first stage and 70–230 m in the second stage (Figure S9). In Layer 19-2, sandbodies in Wells X-22, X-34 and X-40 displayed the broadest coverage. Sandbody width ranged from 75 to 300 m in the first stage and from 75 to 760 m in the second stage (Figure S10).

6 | RECONSTRUCTION OF MEANDER-BEND MIGRATION

Based on the stratigraphic correlations and interpretation of sandbodies, second to fifth-order bounding surfaces were identified and the principal meander-bend transformations depicted, as shown in Figure 15. Accordingly, the 3D architecture was used to reconstruct migration zones for Layers 19-1 and 19-2 that are represented as 2D vertical sections in Figure 16.

6.1 | Meander-bend migration of Layer 19-1

The architectural elements of migration zone Z1 of Layer 1 are outlined in Figure 15A and the migration pattern, corresponding to DRE mode, in Figure 16A. Well X-34 records abandoned channel fills in the lower interval, with channel sandbodies in the upper interval, and mud at the top; the upper inclined beds dip towards Wells X-32 and X-33. The upper interval of Well X-35 shows development of abandoned channel fills; the interbeds and speculative inclined beds of Well X-34 in upper Layer 19-1 dip increasingly towards Wells X-33 and X-35, and the interbeds between Wells X-31 and X-33 dip towards each other. These characteristics indicate that the meander bend migrated from the location of Wells X-34 to X-33, X-35 and further to Well X-32, indicating an up-river migration. Well X-47 records floodplain deposits in the lower interval and channel sandbodies in the upper, with speculative inclined beds dipping towards Wells X-33 and X-35, and the interbeds between Wells X-31 and X-33 dip towards each other. These features indicate
FIGURE 9 Stratigraphic correlations and interpretation of the reservoir architecture of north-west to south-east cross-sections T4–T9 of Layer 19 in Member 3 of the Quantou Formation.
the meander bend migrated from the location of Wells X-47 to X-45, towards Well X-50. No sandbody was found in well X-50, suggesting the channel did not migrate through that location. Well X-48 records channel sandbodies in the lower interval, abandoned channel fills in the upper interval, and mud in the top interval; Well X-46 records channel sandbodies with interbeds dipping increasingly towards Wells X-34 and X-44; Well X-44 records abandoned channel fills. This indicates the meander bend migrated from the location of Well X-46 to Well X-44.

The architectural elements of migration zone Z2 of Layer 1 are outlined in Figure 15B, corresponding to URE and URC modes in Figure 16A. Well X-33 documents a transition from floodplain deposits at the base to abandoned channel fills in the upper interval, with interbeds dipping increasingly towards Wells X-34 and X-31; speculative inclined beds of Wells X-34 and X-46 dip towards Well X-32, indicating meander-bend migration from the location of Wells X-33 to X-31, X-34, and further to Well X-35 (see Z1), with an up-river migration trend. Well X-36 documents floodplain deposits, indicating that meander-bend migration ended between Wells X-35 and X-36. Interbeds and inclined beds of Well X-32 dip towards Well X-31. The floodplain deposits recorded in Wells X-23 and X-29 determine the channel boundary.

The architectural elements of migration zone Z3 of Layer 1 are shown in Figure 15C, corresponding to URE and URC modes in Figure 16A. Well X-23 documents floodplain deposits in the lower interval and overflow sandbodies in the upper interval. Wells X-24 and X-26 record channel sandbodies with interbeds and speculative inclined beds dipping towards Well X-23, indicating meander-bend migration from the location of Wells X-26 and X-24 to Well X-23. Floodplain deposits documented in Wells X-29 and X-31 and channel sandbodies recorded in Well X-24 indicate that the speculative channel boundary is between Wells X-24, X-29 and X-31. Interbeds and speculative inclined beds documented in Well X-24 dip towards Well X-29, showing an up-river migration trend.

The architectural elements of migration zone Z4 of Layer 1 are shown in Figure 15D, corresponding to DRE and DRC modes in Figure 16A. Interbeds and speculative inclined beds recorded in Wells X-2 and X-3 dip increasingly towards Well X-20, indicating meander-bend migration toward Well X-20. Wells X-20 and X-21 document interbeds and speculative inclined beds dipping towards Well X-22 and further to Wells X-23 and X-24, showing a down-river migration trend. Floodplain deposits, documented in Wells X-4, X-5, X-15, X-16, X-19, X-29 and X-23, determine the channel boundary. Interbeds of channel sandbodies in the upper interval of Well X-18 dip towards Well X-15.

The architectural elements of migration zone Z5 of Layer 1 are shown in Figure 15E, corresponding to DRE and URE modes in Figure 16A. Well X-1 records increasing interbeds towards Well X-2, indicating meander-bend migration from the location of Well X-1 to Well X-2, and further to Well X-3 (see Z4). Well X-17 (see Figures 11 and 12) documents channel sandbodies; Wells X-4 and X-5 record overflow sandbodies in the upper interval; Well X-16 records floodplain deposits, indicating that the meander bend migrated through Well X-17 and terminated between Wells X-17, X-4 and X-16.
The architectural elements of migration zone Z6 of Layer 1 are shown in Figure 15F, corresponding to DRE and URE modes in Figure 16A. Wells X-52 and X-51 record channel sandbodies in the lower interval with interbeds dipping towards Well X-50. Wells X-52 and X-49 record abandoned channel fills and overflow sandbodies, respectively; Well X-41 records floodplain deposits, putting the channel boundary between Wells X-52 and X-49 and suggesting meander-bend migration from the location of Wells X-52 to X-51. Additionally, the channel sandbodies and floodplain deposits limit the channel boundary to between Wells X-42 and X-41. Interbeds developed in the lower interval dip towards Well X-43. As the meander bend migrated from the location of Wells X-46 to X-44 (see Z1), it shows a downriver migration trend. Both Wells X-43 and X-44 document mud in the top interval, while Well X-42 documents channel sandbodies in the upper interval, indicating that the meander bend might have changed course from the location of Well X-44 to Well X-42. Interbeds and speculative inclined beds of Well X-37 dip towards Wells X-39 and X-36; Well
X-40 records channel sandbodies in the top interval, showing an up-river trend.

The architectural elements of migration zone Z7 of Layer 1 are shown in Figure 15G, corresponding to SE and URC modes in Figure 16A. Well X-37 records channel sandbodies with interbeds and speculative inclined beds dipping towards Wells X-30, X-36 and X-39; overflow sandbodies recorded in the lower part of Well X-36 indicate the channel boundary, suggesting migration of the meander bend from the location of Wells X-41 and X-37 to Wells X-30, X-36 and X-39. Well X-40 documents channel sandbodies and Well X-39 documents abandoned channel fills in the upper interval of Layer 1, indicating meander-bend migration through Wells X-40 and X-39, showing an up-river migration trend. Interbeds and speculative inclined beds between Wells X-30 and X-38 dip towards Well X-30 and further towards Well X-29. The floodplain deposits of Well X-29 indicate the location of the channel boundary is between Wells X-29 and X-30. Well X-30
records the approximately symmetrical geometry of the interbeds, which dip towards the locations of Wells X-37 and X-28.

The architectural elements of migration zone Z8 of Layer 1 are shown in Figure 15H, corresponding to DRE and DRC modes in Figure 16A. Interbeds and speculative inclined beds recorded in oblique cross-section S10 dip from Well X-29 towards Wells X-28 and X-27. Well X-29 mainly documents floodplain deposits. Well X-28 records channel sandbodies with interbeds and speculative inclined beds dipping increasingly towards Well X-26 and further towards Well X-13, indicating a down-river migration trend.

The architectural elements of migration zone Z9 of Layer 1 are shown in Figure 15I, corresponding to DRE mode in Figure 16A. The floodplain deposits recorded in Wells X-19, X-16, X-15, X-5, X-7 and X-9 determine the meander-belt boundary. Well X-11 documents interbeds dipping towards Wells X-12 and X-9, and further towards X-13. Additionally, Well X-12 records a steeper bed-set dip towards Well X-10 than Well X-15, indicating a down-river migration trend.

6.2 | Meander-bend migration of Layer 19-2

The architectural elements of migration zone Z1 of Layer 2 are outlined in Figure 15A, corresponding to URE and DRE
modes in Figure 16B. Well X-34 records mud at the base and channel sandbodies in the upper interval. Interbeds and speculative inclined beds in Wells X-32 and X-33 document the increasing dip angle towards Well X-34. Interbeds between Wells X-34 and X-35 dip towards each other. Interbeds in Well X-31 dip increasingly towards Well X-33. These changes indicate that the meander bend migrated from the location of Wells X-32 and X-35 to X-33 and X-34; inclined beds near the upstream location of Well X-46 display a steeper bed-set dip than those downstream, indicating an up-river migration trend. In the upstream part, Wells X-44 and X-46 record abandoned channel fills in the upper interval with speculative inclined beds dipping towards Well X-44. Interbeds in Well X-43 dip increasingly towards Well X-44, suggesting that the meander bend migrated from the location of Wells X-43 and X-46 to X-44 and indicating a down-river migration trend.

The architectural elements of migration zone Z2 of Layer 2 are displayed in Figure 15B, corresponding to URC and DRE modes in Figure 16B. Well X-35 records channel sandbodies and mud in the lower and upper intervals, respectively, with inclined beds dipping towards Well X-36, indicating that

FIGURE 14 Planform facies associations of Layer 19-2 in Member 3 of Quantou Formation. (A) Comprehensive interpretation of four contour maps of: (a) reservoir thickness; (b) reservoir-sand thickness; (c) maximum sandbody thickness; and (d) sandstone fraction (see Figure 12 and Figures S4, S6 and S8 for details). (B) Planform distribution of facies associations of Layer 19-2
FIGURE 15  Spatial analysis of the architectural elements and boundary surfaces associated with the hierarchy and classification schemes in Figure 3. Not to scale. (A) Migration zone Z1. (B) Migration zone Z2. (C) Migration zone Z3. (D) Migration zone Z4. (E) Migration zone Z5. (F) Migration zone Z6. (G) Migration zone Z7. (H) Migration zone Z8. (I) Migration zone Z9
the meander bend migrated towards Well X-36. However, channel sandbodies are seen in the upper interval of Wells X-34 and X-32 with interbeds and inclined beds dipping towards Well X-32, suggesting the development of speculative abandoned channel fills and a neck cut-off, which also supports DRC mode in Z2 of Layer 19-1. Additionally, interbeds and inclined beds of Wells X-32 and X-31 dip increasingly towards Well X-23, indicating a down-river migration trend.

The architectural elements of migration zone Z3 of Layer 2 are shown in Figure 15C, corresponding to SE mode in Figure 16B. Interbeds and speculative inclined beds between Wells X-22 and X-31 dip towards Well X-23, while speculative inclined beds between Wells X-23 and X-24 dip towards Well X-23 in the lower interval and towards Well 24 in the upper interval, indicating that the meander bend first migrated towards Well X-23 and then towards Well X-24. Wells X-22 and X-29 record interbeds and speculative inclined beds dipping towards Well X-24; Well X-26 documents channel sandbodies in the lower interval and abandoned channel fills in the upper interval, with speculative inclined beds dipping towards Well X-24, suggesting channel migration from the location of Well X-26 to X-24.

The architectural elements of migration zone Z4 of Layer 2 are shown in Figure 15D, corresponding to DRE and URC modes in Figure 16B. Wells X-4, X-5, X-15, X-16, X-19, X-29 and X-23 record a transition from floodplain deposits in Layer 19-1 to channel sandbodies in Layer 19-2, with increasing dip of interbeds and speculative inclined beds towards Well X-16, indicating a down-river migration trend. Additionally, interbeds and speculative inclined beds of Well X-20 and X-22 dip increasingly towards Well X-21, suggesting an up-river migration trend.

The architectural elements of migration zone Z5 of Layer 2 are displayed in Figure 15E, corresponding to URE mode in Figure 16B. Wells X-1 and X-2 record channel sandbodies with inclined beds dipping towards Well X-3, which documents abandoned channel fills in the lower interval. Wells X-1, X-2 and X-3 document mud in the upper interval, suggesting river channel abandonment. Although, interbeds recorded in Wells X-4 and X-16 dip increasingly towards Wells X-5 and X-7, indicating an up-river migration trend.

The architectural elements of migration zone Z6 of Layer 2 are illustrated in Figure 15F, corresponding to DRE, URE and DRC modes in Figure 16B. Interbeds and speculative inclined beds of Well X-52 dip towards Wells X-51 and X-50. Well X-50 records channel sandbodies in the lower interval with interbeds and inclined beds dipping towards Wells X-45 and X-43,
indicating that the meander bend migrated towards Wells X-45 and X-43 and had a down-river migration trend. Wells X-42 and X-41 record levee sandbodies and abandoned channel fills in the upper interval, respectively, with speculative inclined beds dipping towards Well X-41 and further dipping at a low angle towards Well X-49, indicating an up-river migration trend. Individual channel sandbody and floodplain deposits developed in Wells X-35 and X-39 determines the channel boundary. Speculative inclined beds dip towards Well X-37 from Wells X-36 and X-39, and further towards Wells X-41 and X-40.

The architectural elements of migration zone Z7 of Layer 2 are displayed in Figure 15G, corresponding to URE and DRE modes in Figure 16B. The meander bend migrated from the location of Wells X-37 and X-39 to Wells X-41 and X-40 (see Z6), illustrating an up-river migration trend. Well X-30 records channel sandbodies in the upper interval, with interbeds and speculative inclined beds dipping towards Wells X-28 and X-29, showing a down-river migration trend.

The architectural elements of migration zone Z8 of Layer 2 are outlined in Figure 15H, corresponding to DRE modes in Figure 16B. Well X-29 records channel sandbodies with interbeds dipping towards Wells X-24, X-19 and X-28. Wells X-28 and X-27 document channel sandbodies in the lower interval with bedsets dipping towards Well X-27. However, Well X-27 records floodplain deposits in the upper interval, and Wells X-29 and X-28 record channel sandbodies in the upper interval with bedsets dipping towards Well X-28. These characteristics indicate that the meander bend migrated from the location of Well X-28 to Well X-27 in the earlier stage, then possibly was subject to avulsion and migrated from the location of Well X-29 to Well X-28 in the later stage. Well X-24 possibly records a similar process. Well X-26 records channel sandbodies with interbeds and speculative inclined beds dipping increasingly towards Well X-13.

The architectural elements of migration zone Z9 of Layer 2 are shown in Figure 15I, corresponding to DRE mode in Figure 16B. Floodplain deposits recorded in Wells X-19, X-16, X-5 and X-10 determine the location of the meander-belt boundary. As the inclined beds dip towards Well X-13 from Well X-26 (see Z8) and Well X-13 records channel sandbodies in the lower interval and abandoned channel fills in the upper interval, the meander bend appears to have migrated through Well X-13. The interbeds documented in Well X-12 dip towards Well X-11 and further towards X-9, indicating a down-river migration trend from Well X-26 to Wells X-12 and X-11.

7 | DISCUSSION

7.1 | Reconstruction of AMRs

The detailed anatomy of meander-bend migration can aid in the reconstruction of AMRs. The stacking patterns of individual sandbodies can be inferred from comprehensive well-log facies and, when integrated with the distribution of architectural elements, meander-bend transformation and evolution can be reconstructed. This case study is exclusively relevant to subsurface data sets of cores and well logs, where reconstructing meandering-channel evolution is more challenging in the absence of 3D seismic data. However, it provides an approach that extracts the greatest amount of information from limited data sets, allowing the evolution of ancient channels to be reconstructed. Hence, this approach could be applied to palaeochannel reconstruction of outcrop analogues, using information on river channel migration, spatio-temporal variation of point bar geometry and facies, and outcrop orientation (Ghinassi et al., 2018; Willis, 1989).

In the proposed method, different river migration styles are demonstrated based on MMRs in a way that is inspired by previous qualitative transformation patterns (Ghinassi et al., 2014; Gilvear et al., 2000; Hooke, 1980, 1995). The idea of reconstructing palaeochannels from river depositional architectures has been demonstrated in previous studies using outcrops (Fustic et al., 2018; Ghinassi & Ielpi, 2015; Ielpi et al., 2018; Miall, 1994; Owen et al., 2017; Santos & Owen, 2016; Shibata et al., 2018; Viseras et al., 2018), numerical and physical simulations (David et al., 2018; Eke et al., 2014; Okazaki et al., 2013; Parquer et al., 2017, 2020; Van De Lageweg et al., 2016; Willis, 1989; Yan et al., 2018), remote sensing (Biswas et al., 2019; Khan et al., 2018; Monegaglia et al., 2018; Rossetti, 2010) and subsurface strata (Ielpi & Ghinassi, 2015; Lin et al., 2017; Lunt et al., 2013; Qiao et al., 2019; Shan et al., 2018a; Shibata et al., 2018; Zhang et al., 2013). Multiple, equally likely reconstructions can be obtained from groups of architectural elements, making it difficult to reconstruct palaeochannels planform morphology and evolutionary history.

Different river migration styles result in different dip azimuth and angle of inclined beds, and this can be used to aid identification of planform morphology of AMRs. Combining meander-bend migration patterns in each migration zone (Figure 16) allows the morphology of the whole ancient meander belt to be reconstructed. As shown in Figures 16 and 17, the meander-bend migration patterns represented in Layer 19-1 and Layer 19-2 are primarily characterised by DRE and URE mode migration. Accordingly, the complex fluvial meander-belt evolution in Layer 19 has been interpreted as shown in Figure 18. From the initial to the final channel centrelines, four primary evolution stages of river course are mapped (Figures S11 and S12).

7.2 | Consistency and transformation of river evolution

River evolution demonstrates a certain consistency and transformation and plays a significant part in sculpturing
the landscape, leading to complex modern and ancient fluvial systems. However, deciphering the consistency and transformation of surface and subsurface fluvial evolutionary processes is challenging in terms of morphology, sedimentology and hydrodynamics (Ma et al., 2020; Nienhuis et al., 2020; Parquer et al., 2017; Seminara, 2009; Zuecco et al., 2019), unlike studies focused on MMRs which are readily observable and accessible. The meander-bend transformations illustrated in Figure 4, based on MMRs, show consistency in evolution of the migration pattern in the simple case of one migration mode (Figure 4A through F). However, where meander-bend migration transforms from one mode to another, as in the cases of the Ganga River, India (Figure 4G), Yellow River (Figure 4H), China and Mamore River, Bolivia (Figure 4I), the pattern of evolution is more complex. When looking at subsurface deposits of AMRs, the record of fluvial evolution is buried and invisible, making it more difficult to determine the consistency and transformation mode. This study presents an alternative method of elucidating evolution of AMRs, based on reconstructing the meander-bend migration patterns (Figures 16 and 17). In the reconstructed meander-bend migration of Layer 19, there was some consistency in migration modes in some zones over the evolutionary period; river courses maintained DRE mode in the downstream migration zones Z2, Z4, Z7 and Z9, and upstream zones Z1, Z5, Z6 and Z8.
and URE mode was maintained in the downstream zone Z3. In contrast, other migration zones changed from one migration pattern to another, as shown in Z1 (DRE to URE), Z2 (URE to URC), Z3 (URE to URC), Z4 (DRC to URC), Z6 (DRE to DRC) and Z7 (URC to URE).

The consistency and transformation of river migration might directly affect the connectivity of river channel sandbodies. The vertical and planform distribution of Layer 19 sandbodies (Figures S9 and S10) shows that migration zones with consistency of river migration have remarkable vertical and lateral connectivity of reservoir sandbodies. Different kinds of migration patterns enrich fluvial morphology, which is influenced by numerous factors, including water discharges, bank strength or bank resistance to erosion, stream power, slope and climate. Different depositional environments develop diverse river morphologies. Investigation of present day waterways could illuminate how ancient rivers helped to set the stage for life on land (Ielpi & Lapôtre, 2019). In turn, past river courses contribute to the evolution of modern and future rivers and ecosystems. Therefore, it is important to identify which kind of migration pattern tends to be dominant under different conditions, to discover what factors determine the consistency and transformation of migration patterns, and to discuss whether migration patterns can provide new insights into the transition and coexistence of different fluvial systems.

**FIGURE 18** Reconstruction of the ancient meandering belt of Layer 19-1 to Layer 19-2 in Member 3 of the Quantou Formation
7.3 | Implications for characterisation of reservoir architecture

Traditionally, the complex internal architectures and great channel heterogeneity of meandering palaeochannels render it difficult to decipher reservoir architectural characteristics (Ghinassi et al., 2014, 2016; Shan et al., 2015b; Willis & Sech, 2018b; Wu et al., 2008, 2012; Yin et al., 2008; Yue et al., 2008). Reconstruction of the migration process of palaeochannels generally relies on speculation from the characteristics of reservoir sandbody distribution. Fluvial morphology can inform understanding of ancient fluvial deposits and planform transformations, but it is often overlooked and under-recognised in data sets of ancient successions (Durkin et al., 2018). An example is considered here to illustrate this issue.

The original result of Zhang et al. (2013) as shown in Figure 19A distinguished different channel sandbodies formed in different periods of river evolution (stages 1–11). In the interpretation of reservoir architectural elements and flow units, it is important to reconstruct the historical evolution of the river in order to classify sandbodies into different stages. However, inaccuracies in interpretation might occur as shown in Figure 19B, putting reservoir sandbodies formed in different meander-bend evolutionary stages into the same stage or reconstructing the meandering channel without consideration of migration patterns. For example, stage 2 in location a is matched with stage 2 in location a′, leading to a positive assessment (i.e. the connectivity of reservoir sandbodies is good) of flow units between locations a and a′. However, the contemporaneous sandbodies (sandbodies developed in the same period, see Table 1) are those in locations a and b, as shown in Figure 19C. Using the information in Figure 19C, more accurate meander-bend evolutionary stages can be established, as shown in Figure 19D. The evolutionary history of river courses can be inferred from

FIGURE 19 | Reservoir characterisation and reconstruction of meandering palaeochannels. (A) Original results of architectural elements and distribution of point bar sandbodies. (B) Interpreted palaeochannel evolution corresponding to (A), meander-bend migrations supervised by matching non-contemporaneous channels into a contemporaneous stage (e.g. stage 2 in location a is matched with stage 2 in location a′). (C) Reinterpretation of architectural elements and distribution of point bar sandbodies. (D) Interpreted palaeochannel evolution corresponding to (C) based on migration patterns (e.g. stage 2 in location a is matched with stage 2 in location b).
simple geometric considerations, but information on consistency and transformation of river migration and evolution will be lost, leading to inaccurate reservoir characterisation and evaluation. In this sense, evaluation of migration patterns would be of relevance to sedimentologists concerned with the reconstruction of meandering rivers, as well as petroleum geologists applying well logs and cores for the construction of fluvial reservoir models.

8 | CONCLUSIONS

1. Different channel migration patterns of MMRs are identified using representative modern river meanders, illustrating individual channel behaviours and complex migration styles. On this basis, meander-bend migration patterns are used for coupling channel planform transformation with the subsurface cross-sectional characteristics of meandering rivers.

2. The reservoir stratigraphic framework of Layer 19 in Member 3 of the Cretaceous Quantou Formation is reconstructed through comprehensive correlations and interpretation of facies associations and spatial distribution under a dense well pattern. Different well-log facies characteristics of Layer 19 are classified into six types.

3. Following the comprehensive interpretation of sandbody stacking characteristics and architectural analysis, the spatio-temporal combinations of point bar and internal elements of Layers 19-1 and 19-2 are identified and assessed. Connectivity of channel sandbodies implies favourable reservoir potentiality and is shown to be related to the consistency of meander-bend migration.

4. The reconstructed channel migration architectures in Layer 19 demonstrate the geomorphic and depositional process of AMRs in the Quantou Formation. The proposed migration patterns demonstrate insight into reservoir architecture and palaeochannel reconstruction and could contribute to the identification of residual oil.

5. Analysis of migration patterns allows the consistency and transformation of river migration in varying depositional environments to be determined. Characterisation of MMRs and reconstruction of AMRs contributes to an understanding of the dynamic evolution and morphodynamic diversity of rivers that can aid evaluation and prediction of ancient and future river activity.

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DATA AVAILABILITY STATEMENT

The stratigraphic thickness data and relevant figures that support the findings of this study are provided in the supplementary material.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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