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ORIGINAL PAPER

Architecture mode, sedimentary evolution and controlling factors of deepwater turbidity channels: A case study of the M Oilfield in West Africa

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Abstract Turbidity channels have been considered as one of the important types of deepwater reservoir, and the study of their architecture plays a key role in efficient development of an oil field. To better understand the reservoir architecture of the lower Congo Basin M oilfield, semi-quantitative–quantitative study on turbidity channel depositional architecture patterns in the middle to lower slopes was conducted with the aid of abundant high quality materials (core, outcrop, logging and seismic data), employing seismic stratigraphy, seismic sedimentology and sedimentary petrography methods. Then, its sedimentary evolution was analyzed accordingly. The results indicated that in the study area, grade 3 to grade 5 architecture units were single channel, complex channel and channel systems, respectively. Single channel sinuosity is negatively correlated with the slope, as internal grains became finer and thickness became thinner from bottom to top, axis to edge. The migration type of a single channel within one complex channel can be lateral migration and along paleocurrent migration horizontally, and lateral, indented and swing stacking in section view. Based on external morphological characteristics and boundaries, channel systems are comprised of a weakly confining type and a non-confining type. The O73 channel system can be divided into four complex channels named S1–S4, from bottom to top, with gradually less incision and more accretion. The study in this article will promote deeper understanding of turbidity channel theory, guide 3D geological modeling in reservoir development and contribute to efficient development of such reservoirs.

Keywords Reservoir architecture · Turbidity channel · Sedimentary evolution · Deep water · Shallow seismic · Controlling factors

1 Introduction

Deep water channels are considered one of the significant types of reservoir, sometimes containing rich oil and gas resources. There have been studies abroad on their depositional architecture, mainly focusing on architecture element recognition and description through core and other observations. Achievements have been made by independent oil companies (IOCs) and institutions, with the assistance of the rapid development of deepwater drilling, geophysics theory and sonar scanning, on sedimentary configuration of deepwater turbidite channels. Domestic researchers are doing similar studies using deepwater sediments in the South China Sea area. These studies and related achievements contribute a lot to reducing risks in early-stage deepwater exploration (Heiniö and Davies 2007; Posamentier and Kolla 2003; Slatt 2006; Menard 1955; Li et al. 2008; Wang et al. 2009; Deng et al. 2008; Lü et al. 2008). For continental slope areas in the Lower Congo Basin, West Africa, there have been studies of deepwater channel sedimentary patterns and the factors controlling them in terms of sedimentology and sequence stratigraphy.

However, with the gradual development of more deepwater oilfields, plenty of dynamic data reveal complex superimposition of single sand bodies inside channel systems and various high-heterogeneity rock types in single

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sand bodies. This impedes further and more effective development of deepwater oilfields. Therefore, it is necessary to analyze configurations of both complex and single sand bodies to clarify single sand body distribution patterns, quantitative scales, superimposition and lithology inside single sand bodies.

We took the deepwater M oilfield in West Africa as an example to study semi-quantitative–quantitative sedimentary configuration patterns and their spatial evolution in this article. Based on abundant drilling, core and high-quality seismic data, the study was carried out at three different levels, including channel system, complex channel and single channel levels, employing methods such as core description, log recognition and seismic attribute slices. The study in this article may promote turbidite channel theory understanding and benefit 3-D geomodeling, making it useful in developing this type oilfield more efficiently.

2 Geological background

The M oilfield is one of the most favorable exploration and development petroliferous basins located in the lower Congo Basin, with typical passive continental margin characteristics (Liu and Li 2009; Xiong et al. 2005; Kolla et al. 2001). The research zone lies in the middle–lower slope, between compressive and extensional zones, 186 km away from Luanda, Angola. The architecture is not severely impaired by Cretaceous gypsum activities, and the main target layer is Oligocene. Its sedimentary type is considered to be a deep water turbidite channel system under a regressive background with a water depth of 1400–1800 m (Fig. 1). There are 18 wells in the research zone of the Oligocene O73 reservoir, and they are characterized by a core depth of 168 m; average well distance more than 1000 m; dominant seismic frequency of 35 Hz; and sand recognition 15–20 m. The Pleistocene layer of the near-seabed area has turbidite channel sediments under a regressive background as well. The provenance is from the Eastern Congo River. The dominant seismic frequency reaches 65 Hz, and vertical sand recognition is 6 m. Therefore, it is reasonable to make an analogy between the target layer (deep zone) and the near-seabed layer (shallow zone), due to the similar turbidite channel sediments. The basic data used in this article include core data, logging data, high-density seismic acquisition, and shallow channel high-quality seismic data (single channel sand recognizable) and onsite outcrop measurement data. These types of information can be crosschecked and used in complementary manners in geological research models, e.g., the combination of shallow channel high-frequency seismic data and onsite outcrop data serves to complement the limited deepwater seismic resolution, making full-scale analysis of channel architecture type and scale possible; core data provide complementary information for research into inner filling models. Comprehensive use of available information is a key method to study sedimentary architecture.

3 Turbidite channels hierarchical division

Several criteria were proposed for the hierarchical division of turbidite channel architecture. For example, Mutti and Normark proposed a five-turbidite-facies scheme in 1987, mainly based on the genetic type of sand bodies. Later, a seven-turbidite-facies scheme was put forward by Zhao et al. (2012a, b) and Lin et al. (2013). In this division, they gave more thought to hydrodynamic characteristics, sedimentation and contact relations of the formation of channel sand bodies. In this article, we adopted the seven-turbidite-facies scheme to study sedimentary architecture patterns on three levels, which are single channel, complex channel and channel system levels, to demonstrate the influence on reservoir distribution from macro perspectives (Table 1).

There are certain genetic connections between units of channels at different levels (Zhao et al. 2012a, b). The channel system is characterized by complex channels of different periods, while the formation of complex channels is subject to the migration patterns of single channels. There are differences in the scale of architectural units at different levels, thereby influencing the data type required for study. The architectural units of large-scale channel systems are recognized mainly through seismic data (comprising of seismic facies and seismic reflection structures), while that of the intermediate scale (complex channel) can be recognized also through seismic data (strata slicing). With regard to the small scale (single channels), drilling data (coring and well logging data) and high-resolution 3D seismic data near sea bottom are applied. The relations among various hierarchies are shown in Fig. 2, and higher level sedimentary characteristics are usually subjected to the perturbation and sedimentology of lower level architectural units.

4 Sedimentary architectural patterns of turbidite channel

It is the best to study the architectural patterns through detailed investigation of each hierarchy's characteristics and its origin. Nevertheless, considering the impact of reservoir distribution on real well development and production, we did the research from a 3-level perspective, and this was the channel system, complex channel and single

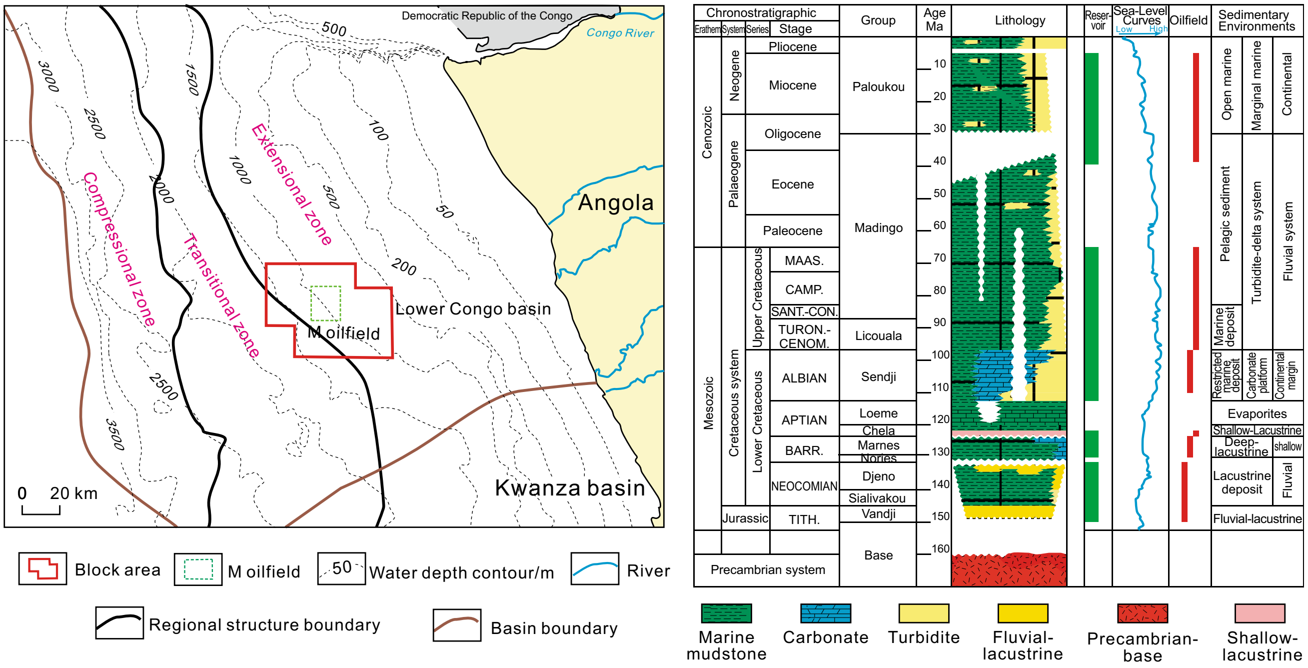

Fig. 1 Location and comprehensive stratigraphic column of study area

Table 1 Comparison of different schemes of hierarchical division of sedimentary configuration of turbidity channels (Lin et al. 2013, revised)

Mutti and Normark (1987)	Lamb (2003)	Lin et al. (2013)
1 Basin filling, fan complex	6 Complete set of strata	7 Submarine fan complex
2 Single fan	5 Composition of several 4-level configurational units, which are distinguishable	6 Single submarine fan
3 Fan development stage	4 Sedimentation products of various sedimentary environments and patterns of flow	5 Channel system 4 Complex channel
4 Natural levee microrelief of channel	3 Products under the same genetic mechanism	3 Single channel
5 Lithofacies, bedding microrelief	2 Single sedimentation unit	2 Sedimentation unit inside single channel (e.g., Bouma sequence)
	1 Further segmentation of a single sedimentation unit	1 Rhythmical layers inside the sedimentation unit

channel levels. We believed that the channel system influenced the vertical development layer selection, while the scale of the complex channel and the relations of its inner single channels played a key role in determining well spacing.

4.1 Hierarchical architectural patterns of single channels

Single channels are formed by repeated gravity-flow deposits along one channel over a period of time, a major origin unit in turbidite channels. So it is important to study the architectural patterns and internal filling features in order to understand reservoir development.

4.1.1 Geometrical morphology characteristics

Elements of the geometrical channel morphology usually include the channel widths, depth, sinuosity, arc, length of curve, wave length (Wood and Mize-Spansky 2009). Based on studies of modern and ancient submarine fans, scholars found that due to the combined effects of ancient sedimentary environments, tectonic subsidence and eustatic sea level changes, there were telling differences in the

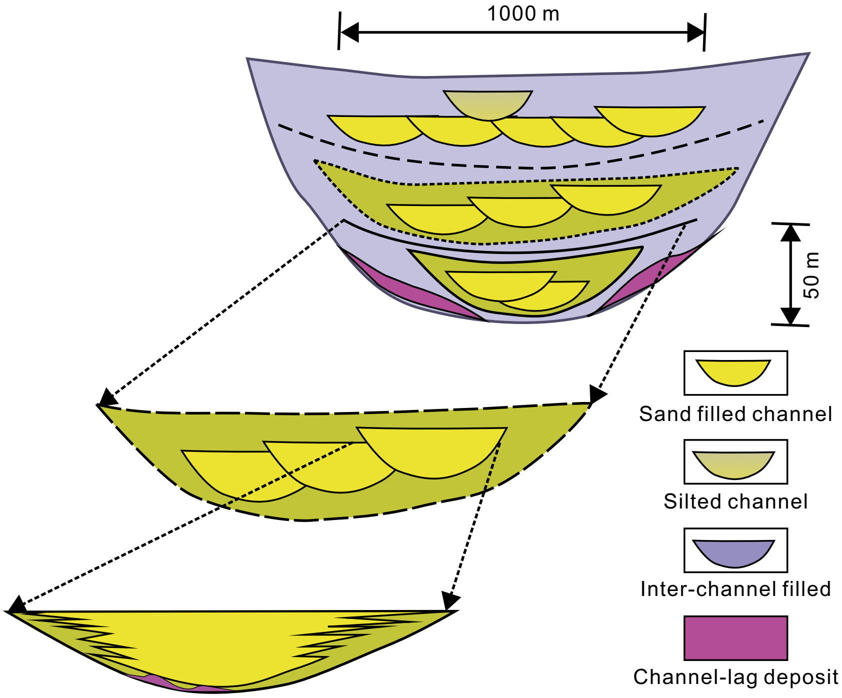

Fig. 2 Configuration unit sedimentary pattern of turbidity channels

geometrical morphology characteristics of turbidite channels. Because of the relative small scale of single channels (min. depth being 10 meters), while dominant frequency of M oilfield seismic data is 40 Hz, it is very difficult to recognize a single channel. However, the M oilfield near-seabed area high-frequency seismic data show a dominant frequency of 70 Hz and similar sedimentary background and type, which makes a critical complement to single channel studies. Since it is hard to extract ideal single channels from real oilfield seismic data, we analyze geometrical morphology and characteristics of single channels with the aid of shallow high-frequency seismic data. It has been found that in seismic profiles, single channels are U or V shaped, presenting medium-strong amplitude inner side, parallel or wave-like reflection, and good consistency as depicted by Fig. 3.

Sinuosity is one essential parameter in the study ($k = h_a/l_a$, k being sinuosity, while h_a being the winding length and l_a being the valley length, see Fig. 3a). It is measured through samples extracted from shallow seismic data. Statistical analysis revealed that the sinuosity distribution of single channels ranges between 1.0 and 5.4, averaging 1.87. As a result, single channels are classified as low-sinuosity channels and high-sinuosity channels. The average sinuosity of low-sinuosity channels was 1.2, while that of high-sinuosity channels was 1.8. Such difference is due to various geological factors (Wynn et al. 2007; Deptuck et al. 2003; Peakall et al. 2000) and may have much to do with the gradient of the ancient continental slope. Against the backdrop of similar sedimentary origin and sedimentation background, we considered the channels located near the sea bottom due to their being less impacted by tectonic movement. Then, analysis of the relationship between single channel sinuosity and topographic slope ($\theta = \arctan(h/l)$, θ being slope, h being the width, l being the length, see Fig. 4a) was done, which shows a negative correlation between the two and a correlation coefficient of 0.8. See Fig. 4b for image. As the slope becomes steep, the downcutting enhances while lateral migration weakens. Whereas when the slope is gentle, provenance supply drops off and sedimentation becomes finer, enabling weaker downcutting and increased lateral migration. Thus, high-sinuosity single channels are formed. This analysis can also support estimating paleotopography slope based on the current single channel sinuosity. As for single channel width and depth (thickness), they are obtained from shallow high-frequency seismic data coupled with outcrop measurements, on account of sparse well distribution and difficulty to determine single sand body boundaries from such well spacing. The result shows that in the study area, the depth of single channels (d) ranged between 10 and 35 m, and width (w) generally between 150 and 450 m (Fig. 3b).

4.1.2 *Lithofacies filling model*

Lithofacies directly reflect the nature of the sedimentary environment. Different lithofacies have different genetic

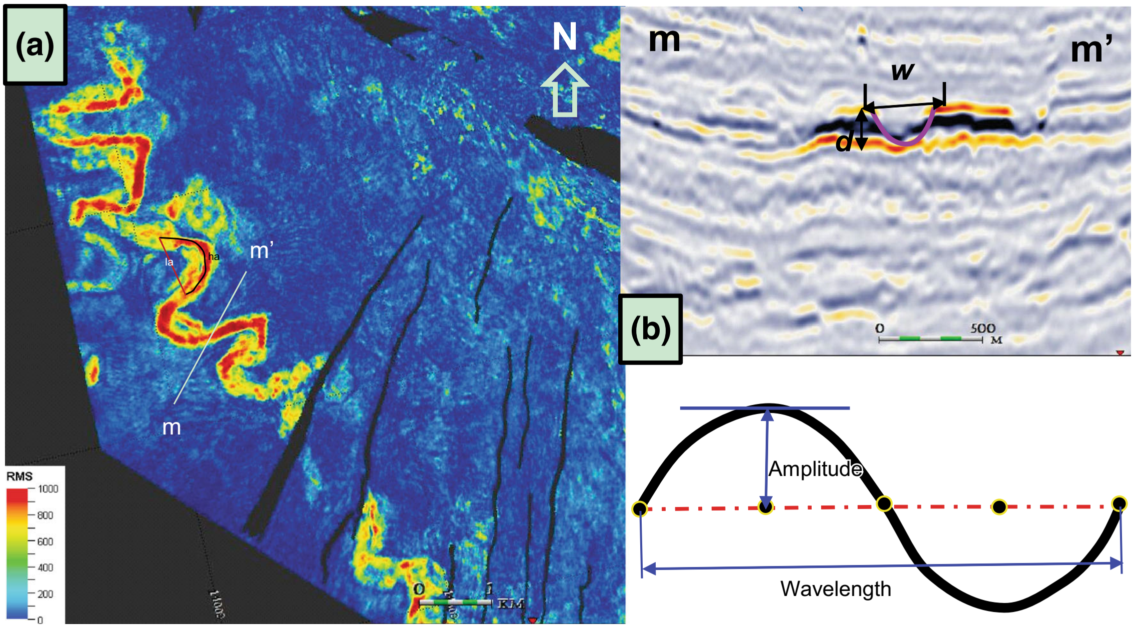

Fig. 3 Geometric elements of turbidity channels (the shallow seismic data in the study area)

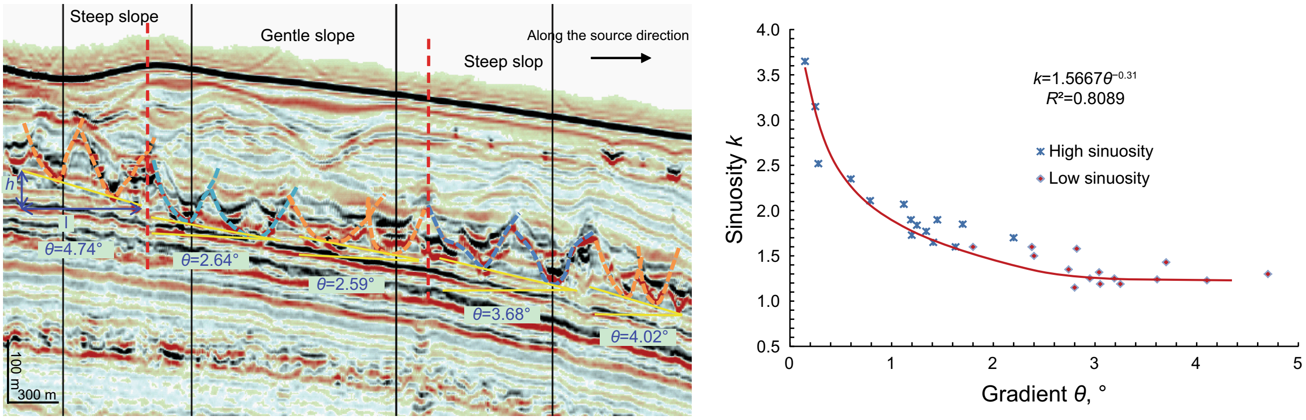

Fig. 4 Correlation of tortuosity and slope gradient (the shallow seismic data in the study area)

mechanisms, indicating different permeable capacity (Bouma 1985; Habgood et al. 2003). Therefore, exact identification of lithofacies types is required for studies on the genetic mechanism of turbidite channels and analysis on permeable discrepancy. The coring data show that obvious turbidite channel sedimentary characteristics can be found in the M oilfield. Lithologically, turbidite channels in the area are mainly composed of massive sandstones, mixed with a little fine-grained sediment. Based on sedimentary tectonics, they have Bouma sequence features and are mostly blocky structure. Cross and parallel beddings can be seen on the top. Erosive bases are generally developed, mixed with retention sediments (mudstone fragments) at the bottom of the channel. Multiple washings can be seen in the main body of the channel (secondary erosion). Mudstone interlayers and argillaceous slumps can also be seen on some sites. Floating gravels are visible inside the massive sandstones (Fig. 5). The sand bodies are generally fining upward. That is, lithofacies inside the channel, from bottom upward, form a configuration pattern of retention sediment ~ massive gravelly coarse sandstones (which may contain mud-sized grain) ~ massive middle-fine sandstone ~ interlaced bedded sandstone ~ fine-grained sediment, with sand bodies becoming thinner from bottom to top.

The specific sedimentary sequences inside the channels produce corresponding logging responses. Single channel responses for individual wells are as follows. Natural gammas are mainly bell-wise and nearly box shaped, while the resistivity curve is slightly funnel shaped (Zhao et al. 2010). Finally, based on such information from field outcrops, cores of the target stratum, etc., the internal filling

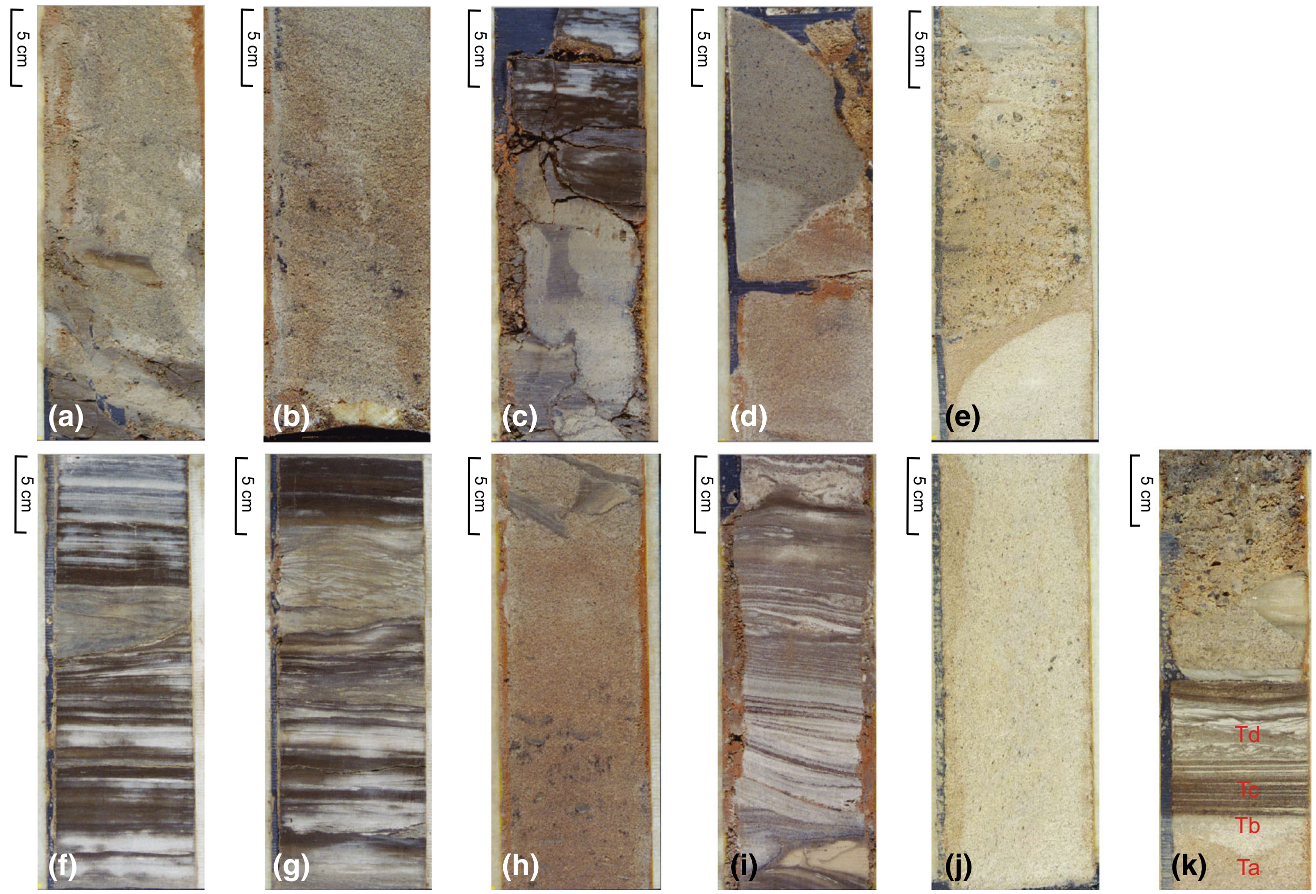

Fig. 5 Internal lithofacies characteristics of single channels in the M oilfield, West Africa (well position as shown in Fig. 9). From *top left* **a** massive gravelly coarse sandstone, well-1A, 3196.25 m; **b** massive mud-sized grain—coarse sandstone, well-1A, 3197.16 m; **c** retention sediments at the bottom, well-1A, 3199.06 m; **d** massive gravelly coarse sand facies, well-2B, 3202.29 m; **e** massive sandstone (see the erosion surface), well-2B, 3213.03 m; **f** thin-layer muddy silt facies, well-1A, 3205.0 m; **g** corrugated-bedding siltstone, well-1A, 3206.12 m; **h** massive gravelly medium-coarse sand facies (floating boulder clays on the top), well-2B, 3202.08 m; **i** corrugated-bedding siltstone, well-2G, 3209.26 m; **j** massive medium-fine-grained sand facies, well-2B, 3213.67 m; **k** Bouma sequence, well-2B, 3217 m

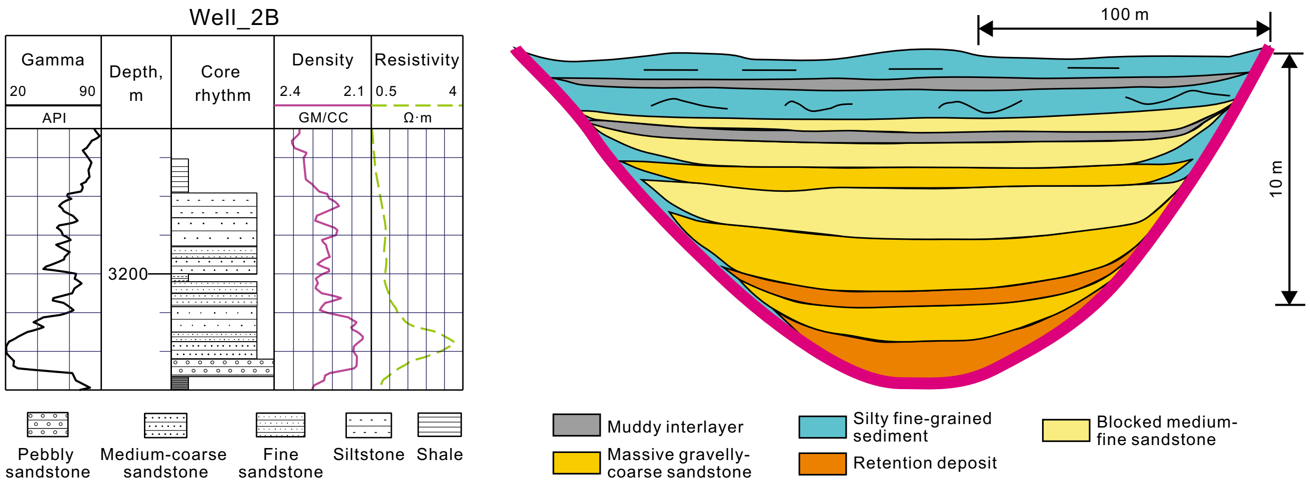

Fig. 6 Logging and lithofacies characteristics of single channel (well position as shown in Fig. 9)

patterns of single channels are summarized (Fig. 6). The inner part of single channels is filled in "bundles," with sand bodies becoming thinner and finer from axis to the edge. Vertically, retention gravels are usually deposited at the bottom of the channel. Sand bodies of the channel change progressively, mixed with thin muddy or clay layers. From the bottom upward, the pattern of sand tends to be thinner and finer. The sedimentary tectonics of thin sand-shale interbed at the top of the channel form parallel bedding-corrugated bedding.

4.2 Hierarchical architecture patterns of complex channels

A complex channel consists of single channels that are laterally or vertically superimposed, mainly controlled by an autogenetic cycle. It is a medium-sized architectural unit (Mutti and Normark 1987; Kane et al. 2007; Abreu et al. 2003; Anka et al. 2009). We studied the internal architectural patterns using both shallow high-frequency and deep well-to-seismic integration data.

4.2.1 Horizontal migration pattern

By drawing the RMS amplitude attributes slice of channel deposits in the M oilfield, we can see that there are two migration types in single channels: in lateral and paleocurrent direction (Zhao et al. 2012a, b) from the channel plan view. So we built the migration pattern of single channels inside the complex channel according to the seismic response features, as shown in Fig. 7. Lateral migration causes sand body distribution more continuous, which expands the connected range of sand bodies. With migration in the paleocurrent direction, since the single channels are vertically superposed, the sand bodies show great heterogeneity in the vertical direction. In plan view, channels migrate along the provenance direction, presenting wide stripes for sand bodies (Liu et al. 2013). The width of complex channels ranges between 300 and 1500 m in the study area. Due to different migration patterns of different channel segments, there are ambiguous relations between the width and depth for complex channels in our study. Another important factor to describe migration patterns in complex channels is sinuosity, which is due to single channel migration. It is measured to be 1.0–1.8, averaging at 1.3 in our study, using the central line in the boundary area of the complex channel as baseline. This is much smaller than that of single channels.

4.2.2 Profile migration pattern

The profile migration patterns of complex channels are also subjected to single channel migrations. As we know, the profile migration pattern of single channels can be classified into lateral and vertical migrations (Labourdette 2007; Hubbard et al. 2009). The lateral migration causes single channels joining together in the lateral direction horizontally, so the sand body thickness of complex channels is very close to that of a single channel (Fig. 8a). As such, the vertical heterogeneity is relatively weak. Also, the vertical migration can be categorized into two types: indented and swing (Fig. 8b, c), causing channels to superimpose in the vertical direction. The thicknesses of sand bodies are generally larger than the depth of single channels. Moreover, as retention slump-block deposits (inferior filter beds) usually occur at the bottom of the channel, the vertical heterogeneity of such compound sand bodies is relatively strong. Results show that the depths of complex channels in the study area lie between 20 and 185 m. As affected by profile migration features and the lithological changes inside, there are obvious well-seismic response characteristics in the boundary regions. The mudstone content rises at the boundary, making the sand body thinner, mostly manifested by weakened amplitude intensity. In addition, the lateral migration of channels can create imbricate responses on the seismic profile (Fig. 8).

4.3 Hierarchical architecture pattern of channel systems

The channel system (canyon or large incised waterway) is regarded as a large-scale unit, superimposed by various complex channels (Xie et al. 2012; Yu et al. 2012). Affected by erosive power, the reservoir architecture models of the same deepwater turbidity channel system differ greatly in different deposit locations. Spatial structure characteristics can be represented by the seismic information. Researchers categorize channel systems into restricted (with incised valley), weakly restricted (with incised valley) and non-restricted (without incised valley) according to geomorphic features (Hubbard et al. 2009; Zhao et al. 2012a, b; Lin et al. 2013; Clark and Pickering 1996; Deptuck et al. 2003; Sun et al. 2014; Chen et al. 2015).

Different superimposition patterns of complex channels lead to different architectures inside the channel system. Inside restricted channel systems, deeply incised indented and swing complex channels are the major part and barely develop large natural levees. With weakly restricted channel system, there are deeply incised indented and swing complex channels combined with weakly incised horizontal migration patterns, with deposit overflow along incised valleys, developing large natural levees on both sides. Non-restricted channel system features weakly incised indented and swing channels, along with horizontal migration patterns. There are occasional deeply incised channels at the bottom of non-restricted channel systems,

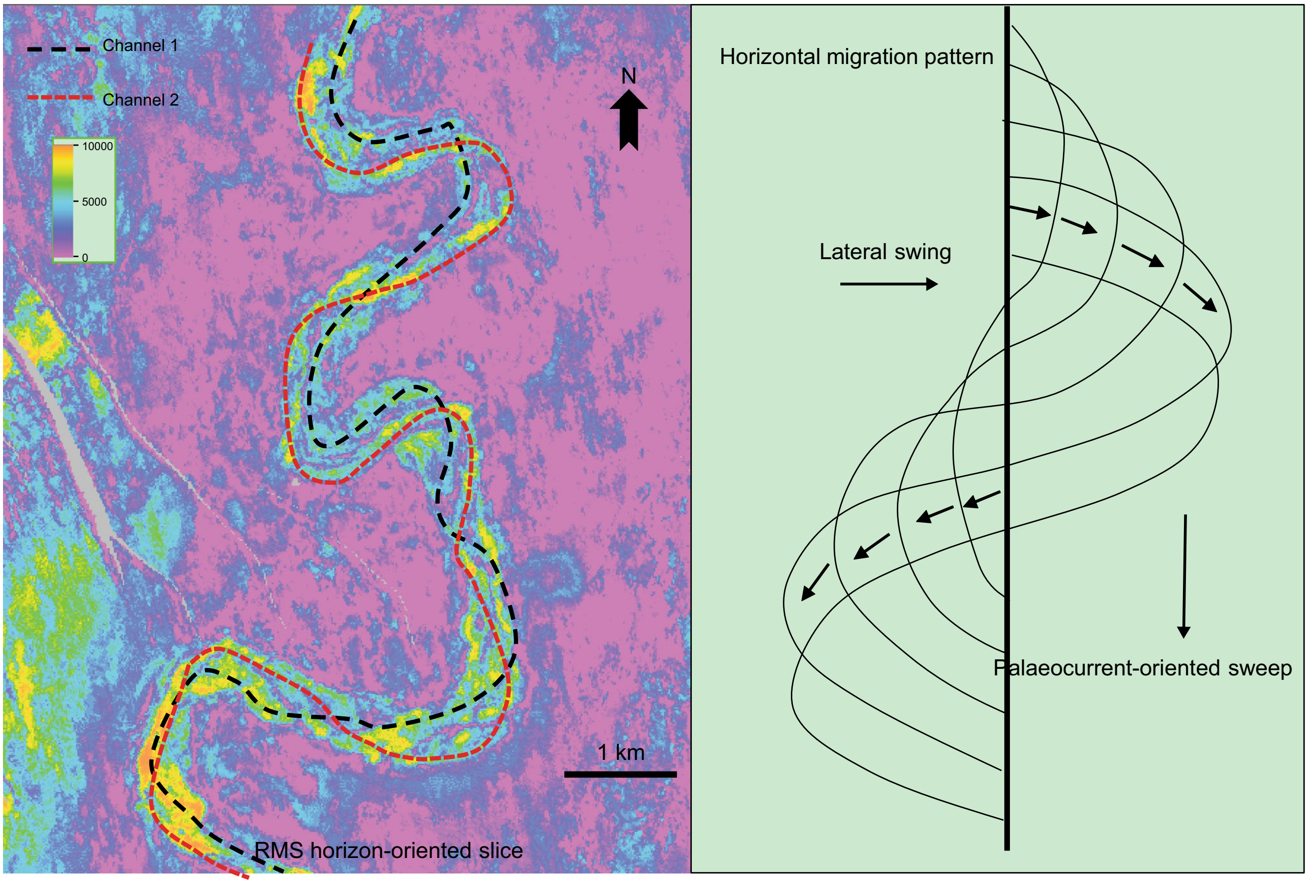

Fig. 7 Plane migration patterns of single channel based on layer slicing in M oilfield (slice position as shown in Fig. 1)

with no evident natural levee development. Especially in the late stage of channel system development, it is difficult to distinguish between fine-particle-filled channel deposits and natural levee deposits. To sum up, the spatial patterns of channel system vary significantly due to deposition patterns of complex channels.

Weakly restricted and non-restricted channel systems are considered as major categories developed in the O73 oilfield in the study area, and their seismic response characteristics are shown in Fig. 9. There show certain evolution trends in the plane. The closer it is to the provenance direction, the stronger the channels incision. Weakly restricted channel systems have distinct incised sections, and wedges (large natural levee deposit) are developed on both sides. The further it is from the provenance direction, the weaker the incision, and the stronger the aggradation and lateral migration. Non-restricted channel systems develop with no evident boundary features (without developing large incised valleys). Typical vertical evolution patterns can be found inside non-restricted channel systems, depicted in four stages. Great incision in the early-stage deposits and large incise valleys are developed. But in later stages, because of rising sea level, incision abates while aggradation and lateral migration enhances, resulting in inconspicuous incised valleys. Results show widths of 1000–3000 m and depth of 80–280 m for the O73 channel system, a large-scale one.

5 Sedimentary evolution of turbidity channels

It is through analyzing the evolution of channel systems that we understand the deposition processes and architectural genesis. More importantly, it will strengthen the credibility of inter-well prediction for the architectural characterization based on well-log and seismic data under wide spacing.

5.1 Sedimentary evolution characteristics

Through well-to-seismic calibration, we make a comprehensive explanation of S1-S4 (Fig. 9) complex channel sediments in the O73 channel system of the M oilfield. Seismic attributes demonstrating sand body distributions, such as RMS amplitude, were extracted (Fig. 10). Combined with core data, we have managed to explain evolution characteristics of each stage (Fig. 11).

The O73 reservoir of the M oilfield shows noticeable sequence sedimentary characteristics. The early

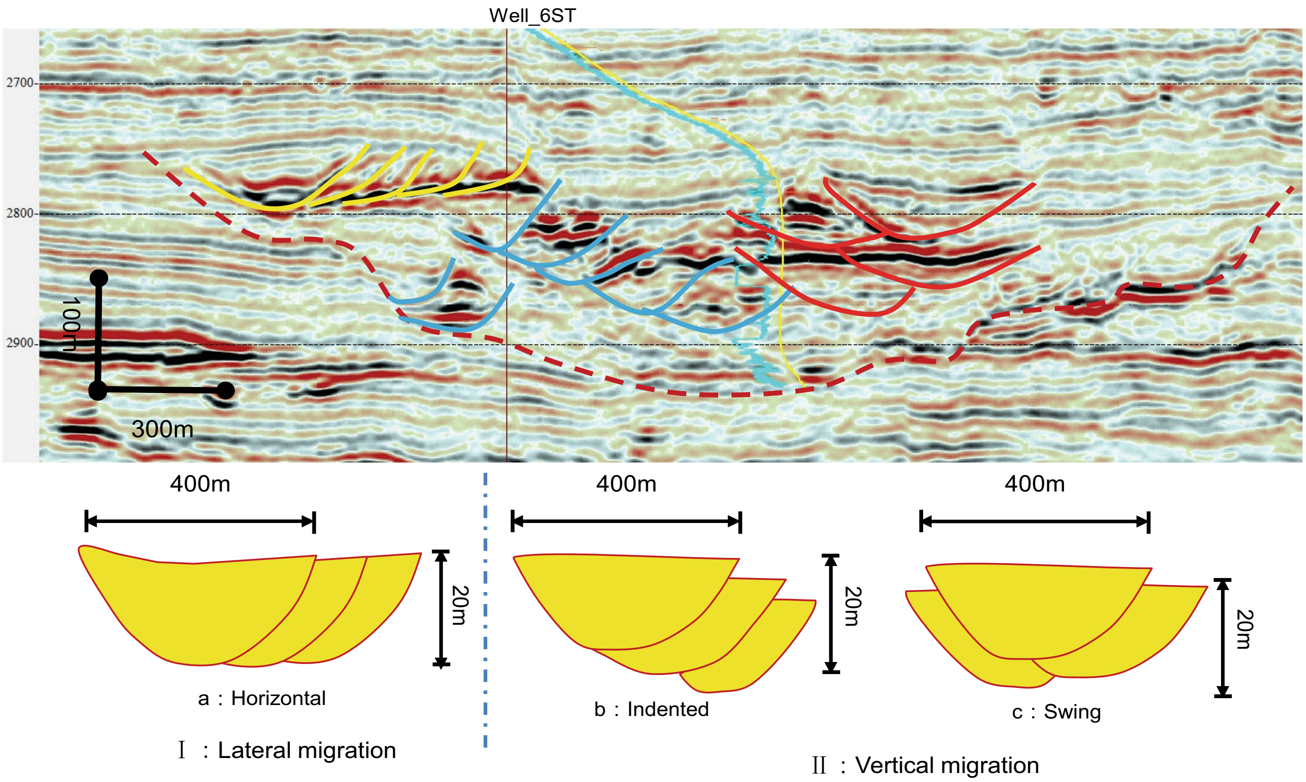

Fig. 8 Profile migration patterns and vertical evolution of single channels of zone O73 in the M oilfield

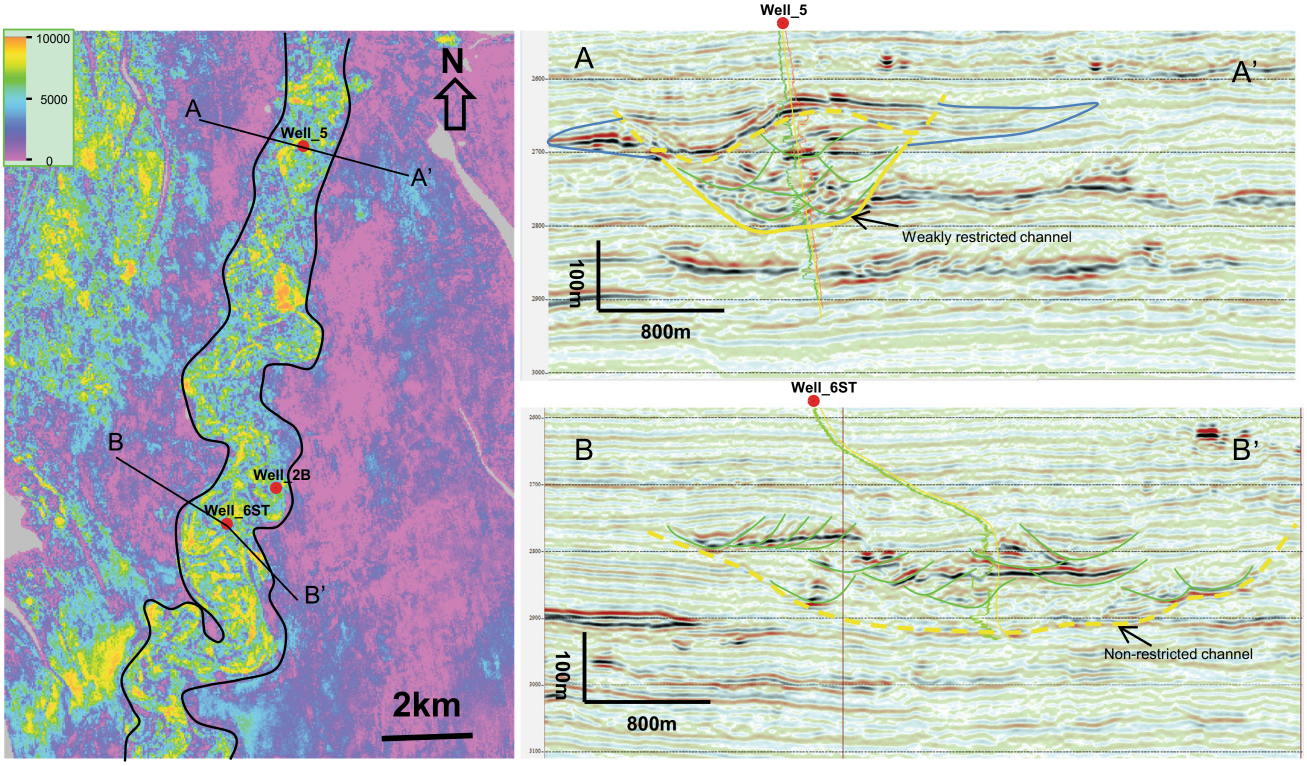

Fig. 9 Plane evolution relation of the O73 channel system (slice position as shown in Fig. 1)

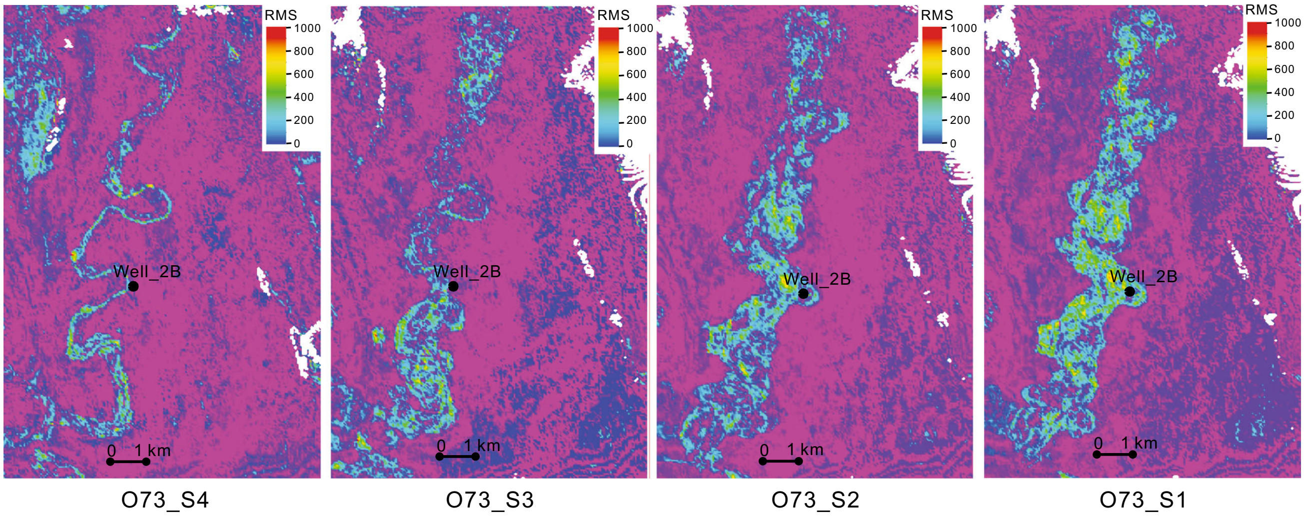

Fig. 10 Plane characteristics of O73 channel system in the M oilfield (slice position as shown in Fig. 9)

sedimentary stage (S1) belongs to deepwater stratified sediments. It shows distinct restricted characteristics with abundant supply and strong erosive power, widely distributed in the riverbed at the bottom of the large submarine canyon of the O73 reservoir. Well-2B coring shows that the lowermost part of the sequence mainly consists of a coarse sandstone stratigraphic unit, which often contains coarse to boulder-level conglomerates and mudstone fragments. It can be deduced that its high sedimentary energy enables it to downcut the older conglomerate layer and clastic layer. The middle part of the sequence is a mixed sedimentary unit of thicker coarse sand and medium sand, probably high-density turbidite sediment, and it progressively changed into a finer-grained Tb and Tc type low-density turbidite layer in an upward direction. The uppermost part is a mudstone layer, indicating gradually waning energy.

During the S2 stage, sediment supply is still sufficient, but the sea level began to rise forming a slightly restricted channel. Here the single channel shows lateral migration, as a weakly restricted channel, and thus widely distributed. As shown in Fig. 11, the S2 sequence channel sediment presented a transition trend from the main channel axis to the edge, with muddy interlayers gradually developing in the edge. Core analysis indicates that the lithology of S2 is mainly thick massive sandstone, partially interbedded with thin mudstone layers. The top layer gradually changed to siltstone and mudstone layers, with occasional ripple bedding, showing gradual abandonment characteristics.

During the S3 stage, the sea level continued to rise, and sediment supply started to decrease. Channel sediments show distinct non-restricted characteristics. Lateral migration and vertical downcutting are both strong for single channels, as well as high sinuosity. The channel on the planar graph (Fig. 10) is very clear. Superposition of multi-period channel sand bodies results in expanded distribution of sand bodies. For well-2B, the meander section of the outer S3 sequence channel complex was drilled, so the core only represents a partial sedimentary filling sequence. There is a layer of gravelly sediments (about 4 m in thickness) at the bottom of the coring section, which is covered by a hard sand clastic layer (about 2 m in thickness) and then comes a 6-m-thick muddy siltstone (the top sediment of the S3 sequence is draped by the mudstone layer). For well-2G, drilling of the meander section of the interior S3 sequence channel revealed that S3 sequence channel intensively eroded S2 sequence sediments (Fig. 11e), which is possibly related to weak consolidation of the early channel sediment and the supply channel formed due to the negative topography on the edge of the channel.

The S4 sequence is the last layer of the O73 channel system, belonging to the sediment shrinkage stage when the sea level reached a peak. The channel is still highly sinuous, but the scale is much smaller than that of the S3 sequence. The downcutting depth decreases, with strengthened lateral restriction. Core analysis indicates that the bottom of the sequence is well-sorted medium-fine massive sandstone, with good consistency in seismic response within the whole oil field (Fig. 10). It is the final product of channel filling, and there will be the abandonment stage of the O73 channel system afterward.

5.2 Sedimentary controlling factors and their evolution

5.2.1 Sedimentary controlling factors

Deepwater detrital deposits are controlled by autogenetic cycles and allogenetic cycles. The controlling factors

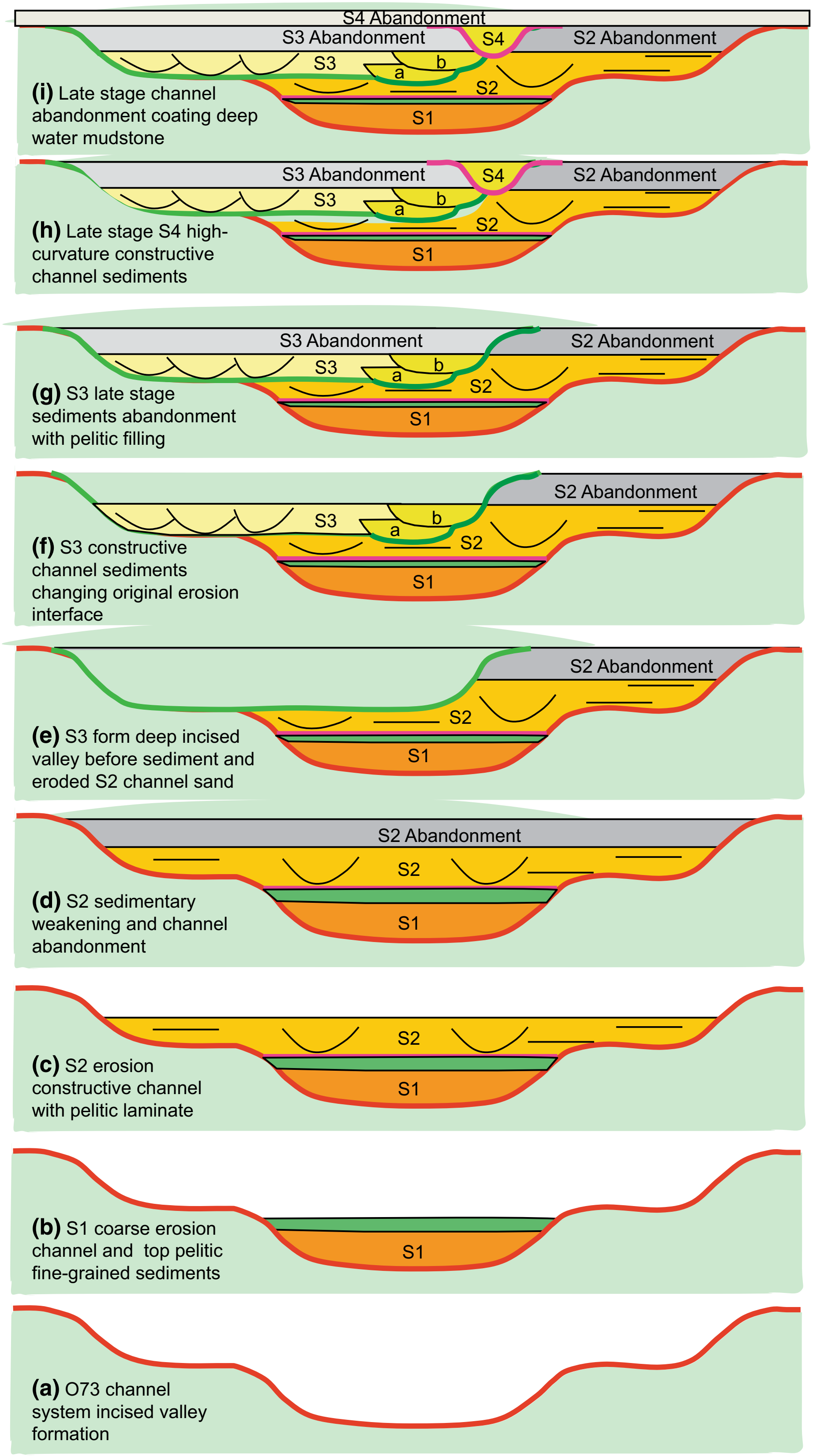

Fig. 11 Vertical evolutionary model of O73 channel system in the M oilfield

include eustacy, basin tectonic movement, sediment types and supply rates. Moreover, events such as earthquakes and tsunamis may also allow the clastic particles to reach the deep sea after traversing the continental shelf and slope valley, forming deepwater sediments (Stow et al. 1996; Shanmugam 2008). The combination of many controlling factors causes the difference in the erosive power of channels, resulting in the complex and diverse superposed relationship of sand bodies. These controlling factors include the provenance distance, provenance types, climate in the provenance area, sea level eustacy, topographic slope. Under normal circumstances, the closer to the provenance, the greater the topographic slope and the more sea level drops, the more abundant the sediment supply, the greater the load density, the higher the deposit velocity, and the stronger the erosive power (He et al. 2011; Zhuo et al. 2013; Li et al. 2011). These factors carry various weights in influencing channel systems, and they correspond to various types of channel systems. For instance, fast sedimentary flow and powerful erosion in steep slopes favor restricted or weakly restricted channel systems, whereas non-restricted channel systems are often observed in gentle slope areas. Likewise, when sea level falls, there is ample sediment supply and all kinds of channel systems can form. Otherwise, in times of rising sea level where sedimentary supply is scarce, turbidite channel systems are seldom developed. Furthermore, allogenetic cycles are more evident in high sea level periods while autogenetic cycles dominate in low sea level periods (Posamentier and Kolla 2003; Prather 2003). For the O73 channel system of the M oilfield, eustacy, tectonic movement and topographic slope play a key controlling role in reservoir architecture and distribution, and abundant sediment from the Congo River thanks to the moist climate in the Oligocene is also another vital factor in turbidite channel formation (Booth et al. 2003; Violet et al. 2005; Beydoun et al. 2002). Tectonic movements such as differential uplift keep modifying both the macro- and micro-topography, which alters the energy of gravitational flow, and then alters development location and distribution of deepwater sedimentary units. From a macro-perspective, the differential uplift of the Congo Basin in the Angola area causes the sedimentary center to move north. Meanwhile, from a micro-perspective, tectonics like salt diapir accompanied by partial salt rock movement also greatly affects deepwater channel systems (Anka et al. 2009; Broucke et al. 2004; Kolla 2007; Pirmez and Imran 2003). Eustacy influences the development of deepwater channel systems too. Deepwater sediments in West Africa developed in the Upper Cretaceous when global sea level fell. At that time, the scale of deepwater channel systems expanded as sea level fell and they advanced toward the sea. Furthermore, the planar features of deepwater channels turned from wide and thin to narrow and thick. Because of the contemporaneous falling sea level and continent uplifting, it reduces the distance between provenance and deepwater sedimentary supply, which is beneficial to form sediments. Therefore, the above analysis indicates that sediment type of the O73 channel system is subjected to controlling factors including sediment supply, deepwater gravitational flow and density.

5.2.2 *Evolution discussion*

Although models of the development of the channel system are affected by multiple factors, they follow certain evolutionary trends (Posamentier and Kolla 2003; Prather 2003; Liu et al. 2008). Horizontally, the development is mainly manifested as the evolution of different channel system types; and vertically, the development is primarily represented by the evolution of its internal complex channels.

Horizontally, along the provenance direction, there are certain trends in changes on account of differences in erosion of sediments. As the root of the channel system is nearer to the sediment source, large size, high flow rate and strong erosive power, large incised valleys can be formed and restricted channel systems that focus on transporting sediments were mainly developed, leading to a large amount of fragmental flow, turbidite and slump sediments developed in it. In the middle of the channel system, sediments become finer with decreased flow rate, resulting in weakened downcutting and strengthened aggradation, so the weakly restricted channel system (e.g., O73 channel system as shown in Fig. 9) is mainly developed at this point, in which channels with some degree of bending are developed and filled with an amount of fragmental flow and slump substances. While at the distal end of the channel system, the supply energy wanes and sediments are of the smallest size and lowest flow rate. At this point, the sediments downcutting capacity is weak, but the lateral migration capacity is strong, developing non-restricted channel systems mainly in which the single channels are mostly moderately to highly bent.

Vertically, influenced by eustacy and delivery rate of sediments, the development of internal complex channels inside the channel system also follows evolutionary trends. In the early development period of the channel system (S1 stage), high flow rate and abundant supply of sediments with strong erosion mostly contribute to form deep downcutting complex channels. They, as erosive channels, mainly transport sediments. In the middle development period of the channel system (S2 stage), the sea level begins to rise. The sediment supply is still rich, but the slowing flow rate leads to its slightly weakened downcutting capacity and strengthened aggradation, with mixed development of aggradational channels and erosion channels mainly under the effect of sedimentation. In the middle to late development period of the channel system (S3 stage), with the continual rise of the sea level, the sediment supply falls gradually (except in tsunamis, earthquakes and other unexpected events). The channel's downcutting capacity weakens, but the lateral accretion capacity becomes increasingly stronger, with aggrading highly sinuous channels mainly developed. In the late development period of the channel system (S4 stage), the sea level reached a high level and the sediment supply was the weakest, pointing to a sediment shrinkage stage where only a small number of highly sinuous aggraded channels and even isolated mudstone-filled single channels were developed.

6 Conclusions

1. The study is focused on the Tier 3–5 architectural unit of the reservoir in the study area. The channel sinuosity is controlled by continental shelf slope, a key factor to influence sinuosity, and there exists negative relations between single channel sinuosity and slope gradient. Affected by an autogenetic cycle of sedimentation, lithofacies inside the channel, from bottom up, form a configuration pattern of retention sediment ~ massive gravelly coarse sandstones (which may contain mud-sized grains) ~ massive middle-fine sandstone ~ interlaced bedded sandstone ~ fine-grained sediment, with sand bodies becoming thinner and finer from axis to the edge.
2. In plan view, two types of migration are found for single channels inside the complex channel—lateral migration and paleocurrent migration. From the profile, there are lateral, indented and swing migrations. Lateral migration is horizontal, with the thickness of sand bodies similar to that of single channel. While for indented and swing patterns, the thickness of sand bodies is basically larger than that of a single channel. There are weakly restricted and non-restricted channel systems in this area. From the provenance direction and vertical direction, the channel system tends to evolve from weakly restricted to non-restricted.
3. From bottom upward, the O73 channel system of the M oilfield can be subdivided into four phases of complex channel sedimentation S1–S4. The downcutting capacity of the channel weakens while the vertical and lateral migration strengthened gradually. Provenance and paleotopography slope are main factors to control sedimentary evolution.

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