Acta Geologica Sinica (English Edition), 2019, 93(6): 1909–1921

Gradual Evolution from Fluvial Dominated to Tide Dominated Deltas and Channel Type Transformation: A Case Study of MPE3 Block in the Orinoco Heavy Oil Belt of the Eastern Venezuelan Basin

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Abstract: Based on the data of core description and sporopollen analysis, the gradual evolution of deltas in vertical direction and transition of channel types in the MPE3 block of the eastern Venezuela Basin have been surveyed by seismic phase and well logging facies interpretation. The results show that due to the great sea level rise, the sedimentary system of the Miocene Oficina Formation in the MPE3 block shifted from the distal-source sandy braided river delta to tide-affected delta, and eventually to tide-dominated delta. Vertically, during the early stage of sedimentation of Oficina Formation, the distributary channels of the delta were dominated by braided river channels. While in the later stage, as the tidal effect was gradually intensified, the channel changed from braided channel to meandering channel. On plane, as a result of differential transgression, sedimentary framework and distribution of sand bodies vary across the study area. Compared with the eastern part, the western part has more braided channels, larger channel bars, less developments of distributary bay and higher ratio of sand to mud. Whereas the braided channels in the south are larger than those in the north. It is the first time we pointed out the impact of marine transgression differences on the sedimentary facies distribution and river type transition in the study area. Factors like the structural and paleogeomorphological change, sea level variation, supply of sediments have strong influence on the evolution of sedimentary system and distribution of sandbodies. It is predicted that the major sandbody is more developed in the central south, which can guide the subsequent horizontal well development.

Key words: Orinoco heavy oil belt, Miocene Oficina Formation, braided river-dominated delta, tide-dominated delta, river type transition

Citation: Huang et al., 2019. Gradual Evolution from Fluvial Dominated to Tide Dominated Deltas and Channel Type Transformation: A Case Study of MPE3 Block in the Orinoco Heavy Oil Belt of the Eastern Venezuelan Basin. Acta Geologica Sinica (English Edition), 93(6): 1909–1921. DOI: 10.1111/1755-6724.13859

1 Introduction

The Orinoco heavy oil belt of the petroliferous Eastern Venezuelan Basin, is located at the north part of the Orinoco River drainage area. The river flows from southwest to northeast and enters the Atlantic Ocean to form the Orinoco Delta nowadays. The heavy oil belt is divided into four zones from west to east: Boyaca, Junin, Ayacucho and Carabobo. As a typical marine delta, the Orinoco Delta has exhibited the development of thick sandstone deposits since Miocene and the depositional process was impacted by the complex mutual flow action among the river, tide and wave (Gamero, 1996; Martinius et al., 2012). Tectonic movements have resulted in complicated depositional process in the whole Orinoco heavy oil belt since the Miocene (Soto et al., 2011; Deville et al., 2015).

There are different viewpoints on the depositional setting in the heavy oil belt where the flow current direction and hydrodynamic conditions changed drastically in the Miocene. For example, according to the study on the Orinoco sediments, Eisma et al. (1978) pointed that tide-dominated delta has been prevailing in this area since the Miocene. However, Muller (1959) and Laraque et al. (2013) proposed that fluvial environment (mainly braided- and meandering- river) was developed in the area. Due to the impact of fluvial and ocean currents, the depositional environment of the heavy oil belt in the southern part is fluvial-deltaic setting; but a large tide-dominated delta controlled by the Guiyana ocean currents was prevailing in the east (Wilson et al., 2017).

Marine transgression and tectonic movements also played important roles in the deposition environment during the Miocene. The tectonic movements near the southern Caribbean Sea varied dramatically and indicated that tectonic movement is one of the major factors on sedimentary environment (Pindell, 2009). With the tectonic evolution process, transgression is the controlling factor for crustal tension which resulted in basin cracking (Croce 1996; Pindell, 2009) and tidal effect. In particular,

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to the far north of the Orinoco Delta, estuarine bay deposits dominated by tidal effect and sea level fluctuation were developed according to the field observations near the Trinidad (Chen, 2014). On the basis of sporopollen data, Martinius (2012) conducted research on the sedimentary process in the mid-western part of the Orinoco heavy oil belt and found that the deposits of this area were formed in a complex depositional environment because of marine transgression.

Based on the studies from previous researchers, the MPE3 area which is located in mid-east of Carabobo area was investigated for its sedimentary facies. The MPE3 is one of an important development block in the Orinoco heavy oil belt. As a result of regional differential transgression, sedimentary framework and distribution of sandbodies varied with the regions in the study area. Combined with cores, wire-line logging and seismic data, the evolution process of delta under the background of transgression has been examined to find out the major controls of sedimentary evolution and transformation of channel type, distribution law of major sandbodies. It is found that the depositional environment varied gradually from braided river delta to tidal-influenced delta, and then to tide-dominated delta, as a result of transgression enhancement. The sedimentary evolution model was constructed and the depositional processes under the transgression setting were clarified. At the same time, according to the concept of meander-braided transition, we also found this kind of channel transition process, i.e., the transition from the braided river channel to the meandering river channel. Finally, we clarified that tectonic and palaeogeomorphological changes, sea level changes, climate and provenance supply have important effects on sedimentary system evolution and sand-body distribution, and then predicted the distribution of favorable reservoir sandbodies in the MPE3 block.

2 Geological Setting

Located in the eastern part of Venezuela in South America, the Eastern Venezuelan Basin is bounded by the El Pilar strike-slip fault in the north, the Precambrian of the Guyana Shield in the south, the Atlantic coastal continental shelf in the east, and the Elbauer Ridge in the west (Garciacaro et al., 2011; Soto and Mann, 2011). The Eastern Venezuela Basin is a foreland basin developed on the Mesozoic and Cenozoic, with little Paleozoic sediments (Beltran et al., 1996; Callec et al., 2010; Parra et al., 2011). Its tectonic evolution can be divided into three stages (Aymard et al., 1990; Svanes et al., 2004; Guzmán and Fisher, 2006; Sánchez et al., 2011; Parra et al., 2011), that is, the rifting stage (Late Permian-Jurassic period, passive continental margin stage (Cretaceous-Eocene), and foreland basin stage (Oligocene-present). The Orinoco heavy oil belt is located in the western part of the Orinoco Delta, with proved oil-bearing area of 5.4×10^4 km^2, oil geological reserves of about 2000×10^8 t and recoverable oil reserves of about 500×10^8 t. The study area (MPE3 block) is located in the middle eastern part of Carabobo (Fig. 1).

Due to dramatic changes in fluvial and tidal hydrodynamics, there are some controversies in the genesis, morphology and distribution of sandbodies in this area. Eisma et al. (1978) pointed out that the area mainly had tide-influenced or tide-dominated deltas according to the research on sediments in the Orinoco heavy oil belt. Martinius et al. (2012) studied the sedimentary characteristics in the central and western parts in the heavy oil belt, and thought that affected by the tides the area had a complex sedimentary system according to the research on sporopollen. Mulle (1959) and Laraque et al. (2013) believed that there developed the braided and meandering river sedimentary environments in this area. Surveying the Trinidad outcrop of the Orinoco Delta, Chen et al (2014). suggested from field observation that the sedimentation in this area was controlled by tidal action and dramatic changes in sea level. Therefore the sedimentary pattern was more complicated. Due to differences in research periods and location, the researchers have divides or contradiction in the understandings on the sedimentary environment of the Orinoco Delta.

In the MPE3 Block, the major oil-bearing horizon is the Miocene Oficina Formation, which can be divided into the Morichal Member, the Yabo Member, the Jobo Member and the Pilon Member upwardly (Muller, 1959; Eisma et al., 1978; Martinius et al., 2012; Zhang et al., 2012; Laraque, et al., 2013; Chen, et al., 2014; Chen et al., 2016; Huang et al., 2017). In this study, the Morichal -Jobo Members were taken as the research objects, of which the major oil producing layer, Morichal Member is further subdivided into four sand layer groups of O-13, O-12, O-11 and O-11s upwardly. There are 2 sand layer groups of Jobo (inf) and Jobo (sb) in the Jobo Member (Fig. 1).

3 Samples and Methods

Wireline logs from 32 drilled wells were collected. Among these wells, cores with picutres and samples, and laboratory test data, such as the lithology, physical property were collected from 2 wells. Electrical well-logging data acquisition and processing were completed by Schlumberger. Wire-line log GR (Gamma-ray) curves of each well was adopted to do the research on sedimentary facies and sequence stratigraphy. 3D seismic data with the dominant frequency of 40–60 Hz were also available and covered the entire study area.

The sedimentary characteristics of target intervals were studied, by using knowledge of the tectonic background and sedimentary environment, as well as data from coring, sampling and logging. In addition, the theories of high-resolution sequence stratigraphy was adopted in this research. Methods of seismic facies identification and analysis of seismic attributes were used to clarify the configuration and distribution of sandbodies.

4 Results

4.1 Sedimentary characteristics

4.1.1 Types of sedimentary facies

Zonocostites ramonae and Fungal hyphae are relatively enriched in the sporopollen assemblages, which mainly reflect the paleontological assemblages from delta to

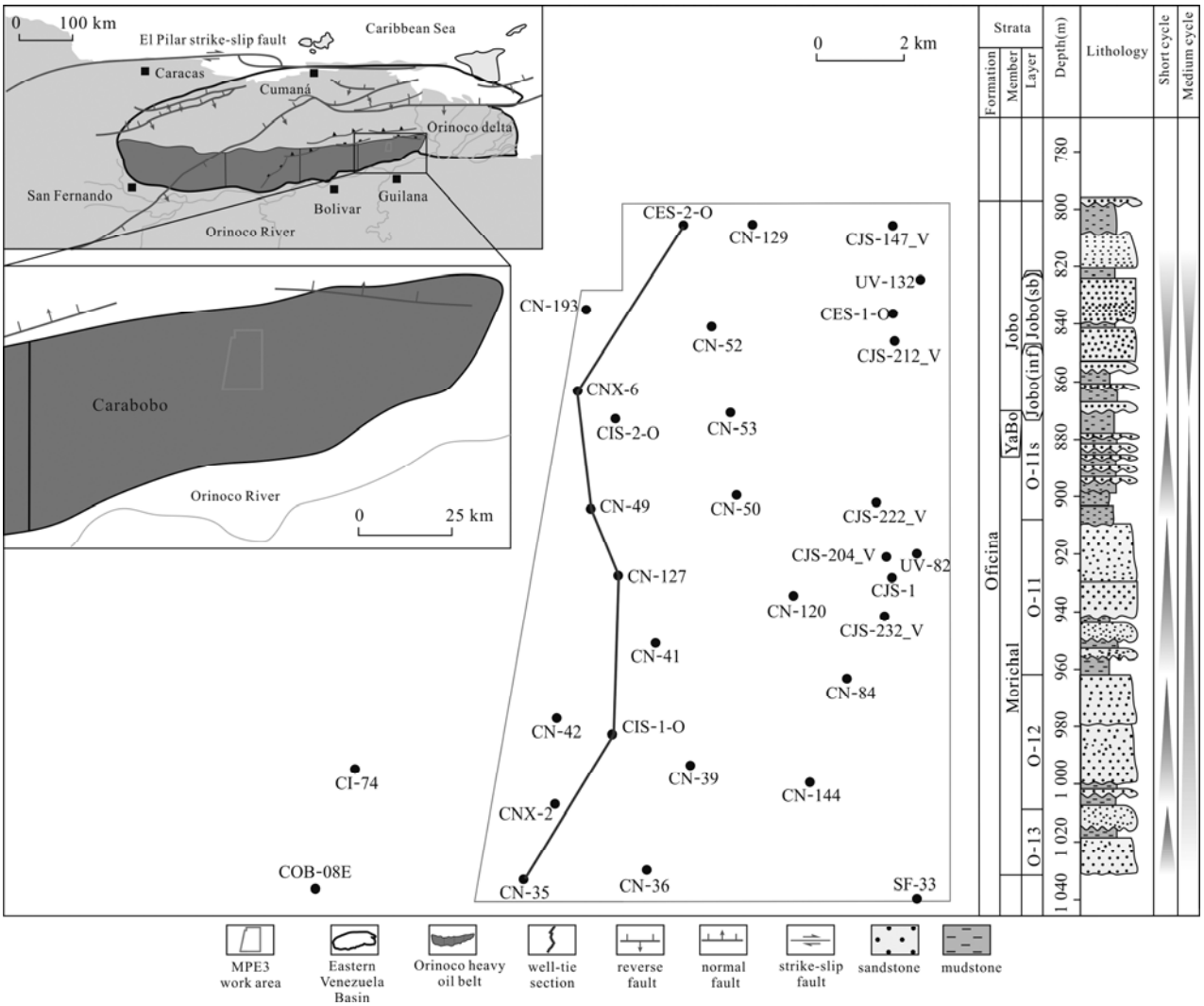

Fig. 1. Regional structural background of Orinoco heavy oil belt and location map of the study area.

coastal zone which were impacted by tidal currents (Martinius et al., 2012). In accordance with the criteria proposed by Maill (1977), the target horizon in this study is the Oficina Formation, which is dominated by the combination of sandstone and mudstone, and has 12 types of lithological combinations identified, including mudstone-argillaceous siltstone (Figs. 2a–2d), siltstone to fine sandstone-fine sandstone (Figs. 2e–2h), medium to fine sandstone-medium sandstone (Figs. 2i–2n), and pebbled sandstone - coarse sandstone (Figs. 2o–2p).

The medium-fine sandstone is mostly developed among sandstones, which can interbed with thin siltstone and mudstone, or contain pebbles (Fig. 2o) or coarse sandstone with muddy masses (Fig. 2p). The medium-fine sandstone is loose and mainly made up of relatively pure unconsolidated sandstone, and medium-good in sorting (Figs. 2e–2n), with part of them showing poor sorting due to the influence of mud. The grains are sub-angular to sub-roundness and of medium compositional maturity. Overall, the sorting, roundness, and compositional maturity get better gradually upwardly (Chen et al., 2016), reflecting that the influence of hydrodynamics gradually became stronger. The fine sandstone and mudstone are mostly characterized by mixed lithologies of sand and mud (Figs. 2a–2f). Microscopic observation and statistics show that the mineral composition is mainly quartz (with the average content of above 90%), and the clay minerals are mainly kaolinite (accounting for more than 70% of the total clay minerals). The sedimentary structures include bedding structures, scouring structures, and biological structures. The bedding structures mainly consist of trough and tabular cross beddings (Figs. 2k and 2m), massive bedding (Figs. 2l), parellel bedding (Fig. 2h), ripple bedding or laminae (Figs. 2a, 2c and 2e), deformation bedding (Fig. 2f), and horizontal lamination (Figs. 2b and 2d). Among them, the trough and tabular cross beddings are most developed in the O-12–O-13 sand groups. Scouring surfaces are seen occasionally at the bottom of sandstone, accompanied by a small amount of clay boulder. Also, evident wormholes and bioturbation markers (Fig. 2g) , muddy masses, and thin argillaceous strips can be frequently observed (Figs. 2o and 2p). There are few fossils in the study area. In the mudstone and silty mudstone, charcoal, plant leaves and plant root fossils are

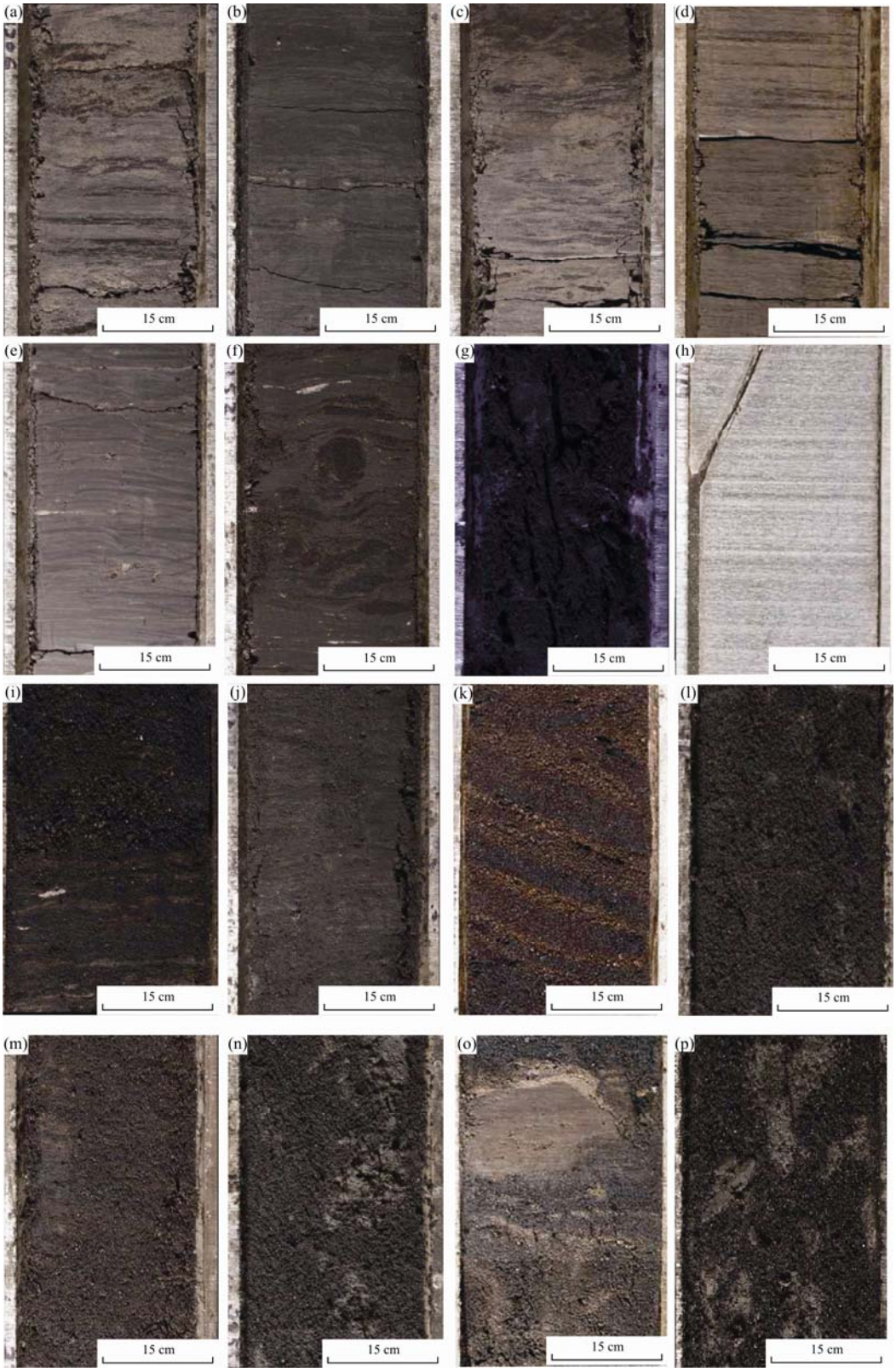

Fig. 2. Core photos of typical lithologies in Well CES-2-0.

(a) 1007.7 m, laminated silty mudstone; (b) 963.8 m, horizontally laminated argillaceous siltstone-fine sandstone; (c) 1007.4 m, laminated mudstone mixed with siltstone; (d) 910.2m, horizontally laminated shaly siltstone sandstone; (e) 958.9m, shaly siltstone-fine sandstone with ripples; (f) 960.7 m, argillaceous siltstone to fine sandstone with deformation beddings; (g) 964.7 m, bioturbated fine sandstone; (h) 835.1m, parallel bedding fine sandstone; (i) 966.2 m, medium-fine sandstone with argillaceous laminae; (j) 952.2 m, sandstone with thin argillaceous strips; (k) 927.3m, planar cross bedding fine sandstone and medium grain-sized sandstone; (l) 987.6 m, massive medium sandstone; (m)994.6 m, sandstone with trough/ tabular cross beddings; (n) 991.8 m, medium sandstone with gravel; (o) 882.3m, coarse sandstone with muddy masses and thin argillaceous strips; (p) 993.6 m, coarse sandstone with muddy masses.

found locally. The relative enrichment of Zonocostites ramonae and Fungal hyphae in the sporopollen combination mainly reflects paleontological combination from delta to the shoreline.

The quartz content in the sandstone and mudstone in the study area is high, showing the characteristics of sediments distant from the provenance (Mahnaz et al., 2017). Various sedimentary structures and ancient organism indicate relatively shallow sedimentary background (Martinius et al., 2012); while the lithofacies and logging curves show large sets of thick sandstone intercalated with mudstone in the major oil-bearing interval of the Morichal Member, indicating a process of gradual transgression upwardly with obvious characteristics of delta buildup by influx of rivers to the sea (Chen et al., 2016).

4.1.2 Typical sedimentary sequences

By combining core observation with early research results (Zhang et al.,2012;Chen et al., 2016), it is inferred that the Oficina Formation is mainly composed of marine delta deposits affected by rivers and tides. The main sandbody is sandy braided (distributary) channel (referred to as a braided river) far from provenance, meandering (distributary) channel (referred to as meandering channel) and distributary channel controlled by tidal zone (referred to as tide-dominated distributary channel). Sedimentary sequences of the three different types of sedimentary facies were established, respectively representing sedimentary characteristics of braided river-dominated delta (Fig. 3a), tide-influenced braided river delta (Fig. 3b) and tide-dominated delta (Figs. 3c and 3d).

In the braided river-dominated delta, there is the development of thick-massive medium to coarse sandstone intercalated with thin mudstone generally in normal grading, with rich trough and tabular cross beddings indicating unidirectional current. The sandstone layers take on a box shape on log curves, suggesting the development of braided river channels and bars (Fig. 3a). For the braided river-dominated delta in the study area, apart from the development of braided river channel, channel bar, meandering channel and point bar, there is also the development of interdistributary bay between distributary channels, composed of gray-grey black mudstone and silty mudstone intercalated with medium-thin argillaceous siltstone with occasional calcareous and ferrous nodules. This implies fine sediments carried by floods, slow water flow rate, and slow deposition of sediments. The thickness of single layer in interdistributary bay facies is 0.3–3.0 m, and there are massive and not obvious horizontal beddings in the mudstone. The sandstone at the bottom of channel is largely medium and fine sandstone, which gradually transited to siltstone, silty mudstone or mudstone upward. The braided river delta affected by the tide is dominated by medium-thick sandstone and interbeddings of sandstone and mudstone. Mudstone is more developed at the top. Overall, it is dominated by normal grading. The channels here begin to be meandering, and channels of braided river and meandering river also get smaller in scale (Fig. 3b). There are two typical sedimentary sequences in the tide-dominated delta, one is the typical normal grading sequence (Fig. 3c) representing the alternate occurrence of distributary channel and estuary bar vertically and gradually decreasing scale of sandbody upwardly. The other is the lower normal grading and upper reverse grading sequences, generally showing characteristics of reverse cycle (Fig. 3d). Specially, the distributary channel, more strongly affected by the tide, has much lower sand to mud ratio and more evident normal grading. The cores have dual clay layers, more apparent wormholes and bioturbation signs, and more visible meandering characteristics of river channel.

4.1.3 Seismic reflection characteristics and description

Adopted the methods proposed by Siringan (1993), and Wood and Mize-Spansky (2009), the 3D seismic data volume in the study area is divided into three seismic facies (Fig. 4) according to the superposition style and intensity of events including superimposed filling facies (Figs. 4a–4c) and lateral accretion facies (Figs. 4d–4f) and sheet waveform facies (Figs. 4g–4i).

Superimposed filling facies has obvious incision at the boundary, strong polarity at the bottom, weak polarity inside, and chaotic filling (Figs. 4a and 4b). The events stack upwardly, and individual events have strong polarity and good continuity. Seismic facies of this type mainly occurs in the O-13–O-12 sand group, with obvious interactive incision of fluvial channels inside. The bottom of the O-13 sand layer group shows obvious morphology of incision valley. This type of seismic facies mainly reflects vertical accretion characteristics of sandbodies during the migration of braided distributary channel and channel bar in delta plain (Fig. 4c).

The lateral accretion facies has incision and denudation of bottom boundary which is not obvious as it is, overall uniform reflection polarity, the significant reduction of upward polarity of event, more evident lateral superposition migration, and stronger polarity and better continuity of single reflection event (Figs. 4d and 4e). The seismic facies of this type mainly appears in O-11–O-11s sand group, and is more developed in the transitional zones between delta plain and front of tide-influenced or tide-dominated delta. The main types of sandbodies are meandering distributary channels and tide-dominated distributary channels (Tang et al, 2016), reflecting lateral accretion characteristic of sandbodies resulted from the lateral and directional migration of meandering river channel and tide-dominated distributary channel (Fig. 4f).

The sheet waveform facies has inapparent reflection of the top and bottom boundaries, quite strong internal reflection polarity and better continuity and smaller migration amplitude of events (Figs. 4g and 4h). This type of seismic facies is mainly seen in the Yabo–Jobo Interval dominated by the tide-dominated delta front, where the main types of sandbodies are tide-dominated estuary bars and sheet sands, with progradation characteristics (Fig. 4i).

4.2 Laws of sedimentary evolution and river type transform

According to fluvial patterns (Miall, 1977;Schumm, 1985), meandering-braided transition could be generated

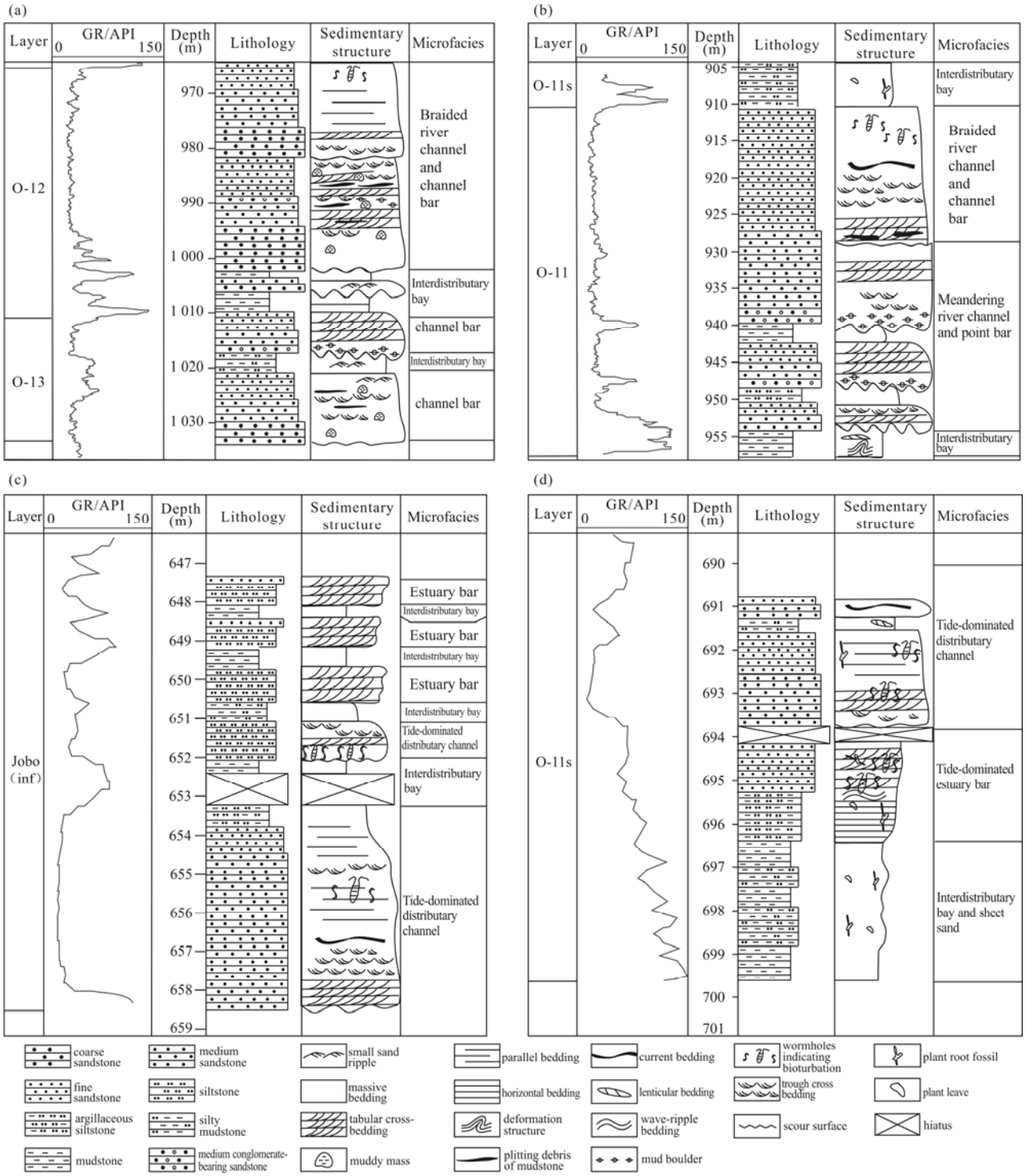

Fig. 3. Sedimentary sequence characteristics of different types of deltas in the study area (GR-Natural gamma).
(a) Well CES-2-0, sedimentary sequence characteristics of braided river-dominated delta; (b) Well CES-2-0, sedimentary sequence characteristics of tide-influenced braided river delta; (c) Well COB-08E, sedimentary sequence characteristics of tide-dominated delta; (d) Well COB-08E, sedimentary sequence characteristics of tide-dominated delta.

(Li et al., 2017a). Vertically, the evolution of sedimentary facies of the Oficina Formation, which is a whole ascending-decreasing cycle upwardly in the study area, is controlled by the datum cycle (Fig. 1). Correspondingly, the sedimentary facies transforms from braided river-dominated delta in the O-13 and O-12 sand groups to tide-influenced braided river delta in the O-11 groups, ultimately to the tide-dominated delta in the O-11s, Yabo and Jobo sand groups (Fig. 5). The evolution process of sedimentary environments and facies belts results in

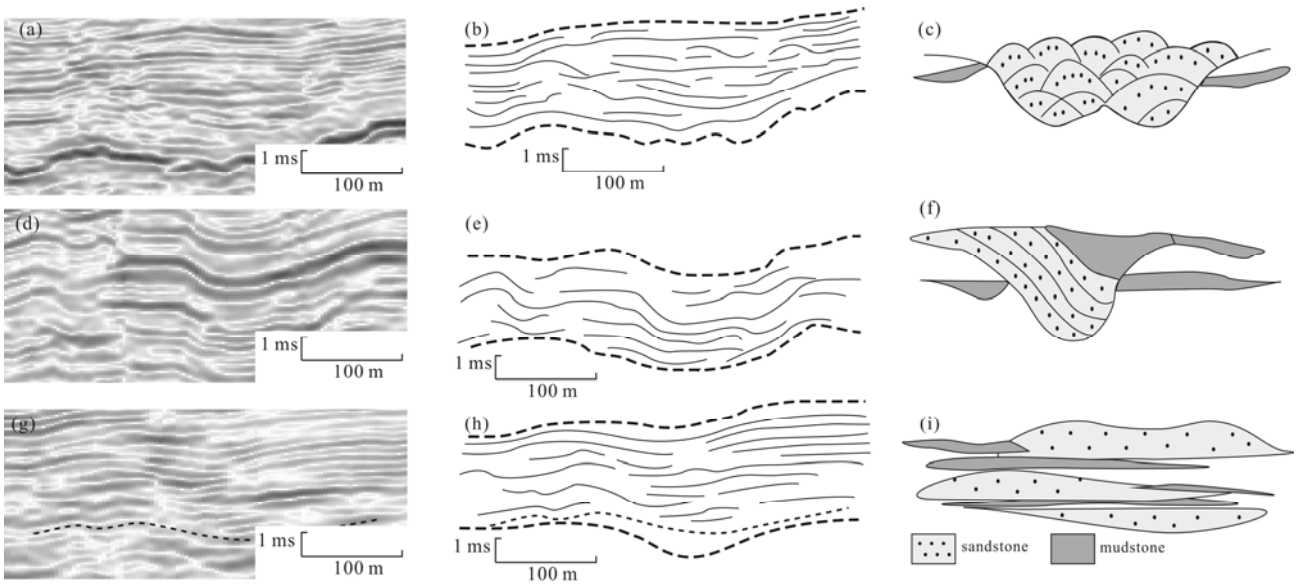

Fig. 4. Sedimentary interpretation and sandbody configuration pattern of typical seismic facies.
(a) Original seismic profile of superimposed filling facies; (b) interpreted seismic profile of superimposed filling facies; (c) sandbody configuration pattern of superimposed filling facies; (d) original seismic profile of lateral accretion filling; (e) interpreted seismic profile of lateral accretion filling; (f) sandbody configuration pattern of lateral accretion filling; (g) original seismic profile of sheet waveform facies; (h) interpreted seismic profile of sheet waveform facies; (i) sandbody configuration pattern of sheet waveform facies.

different channel types and distribution of sand bars. In the sedimentary evolution process, types of distributary channel and sandbodies also change gradually, from the dominance of braided river channel (Fig. 5a), then to the braided and meandering channels (Fig. 5b), and finally to mostly meandering channel (Fig. 5c). The characteristics of logging curves of well-tie profile from north to south also reflect the transition from braided channel to meandering channel (Fig. 6). The logging curve of the formation below initial flooding surface (IFS) shows characteristics of thick box shape, indicating well development of braided river channel with mud in sand feature. In contrast, the logging curves of middle and upper formations above initial flooding surface (IFS) are characterized by bell shape, indicating that the better development of meandering channel with interbeded sand and mud or sand in mud feature.

4.2.1 Distal-provenance sandy braided river-dominated delta

The O-13 and O-12 sand groups in the lower part of the Morichal Member of the Oficina Formation are deposits of distal-provenance sandy braided river-dominated delta, in which the predominant sandbodies include braided channel, channel bar, estuary bar (Fig. 5a). In this period, the sea level was relatively low, fluvial incision was strong and delta plain was well developed, dominated by braided river channels. The channel bar was developed in fluvial channels. The sedimentary sequence shows the characteristics of typical channel deposits, with many sets of braided channel sandbodies stacking over each other. Due to the strong erosion of a large number of braided channels, a large amount of clay boulder and splitting debris of mudstone appear in the sedimentary sequence. The sandbodies are distributed in the southwest-northeast direction on plane. Compared with the east, the braided channel is more developed in the west. The channel bar is larger and more contiguous, but the distributary estuary is relatively undeveloped, and the sand to mud ratio is higher. Compared to the north, the braided channel in the south is larger. During this period, the delta front pushed seawards by ocean currents and waves parallel to coastline. The estuary bars in the delta front are tongue-shaped and large in scale.

4.2.2 Tide-influenced braided river delta

In the upper O-11 sand group of the Morichal Member, it shows the development of deposits of tide-influenced braided river delta. During this period, the impact of transgression gradually increased. Due to the support and alteration of tidal water, the distributary channel gradually became meandering, especially in the offshore area of the northern part in the study area. The meandering channel was more developed in the east (Fig. 5b). The southwestern area still maintained the characteristics of well-developed braided channel and channel bar. The wormholes and bioturbation phenomena in the northern coastal area reflecting the impact of transgression increased significantly. The distributary channels in the north and east became meandering gradually, and there occurred deposits of meandering channels and point bar in the east. The distributary estuary was more developed. Compared with braided river-dominated delta, as the tidal action gradually enhanced, the damage to the delta strengthen, leading to a significant decrease in sand to mud ratio, which can be seen from sedimentary sequence of Well CIS-1-0 and CES-2-0. The delta front was not only affected by waves but also influenced by tides with the gradual strengthening of transgression. Therefore, it resulted in the formation of slightly finger-like estuary

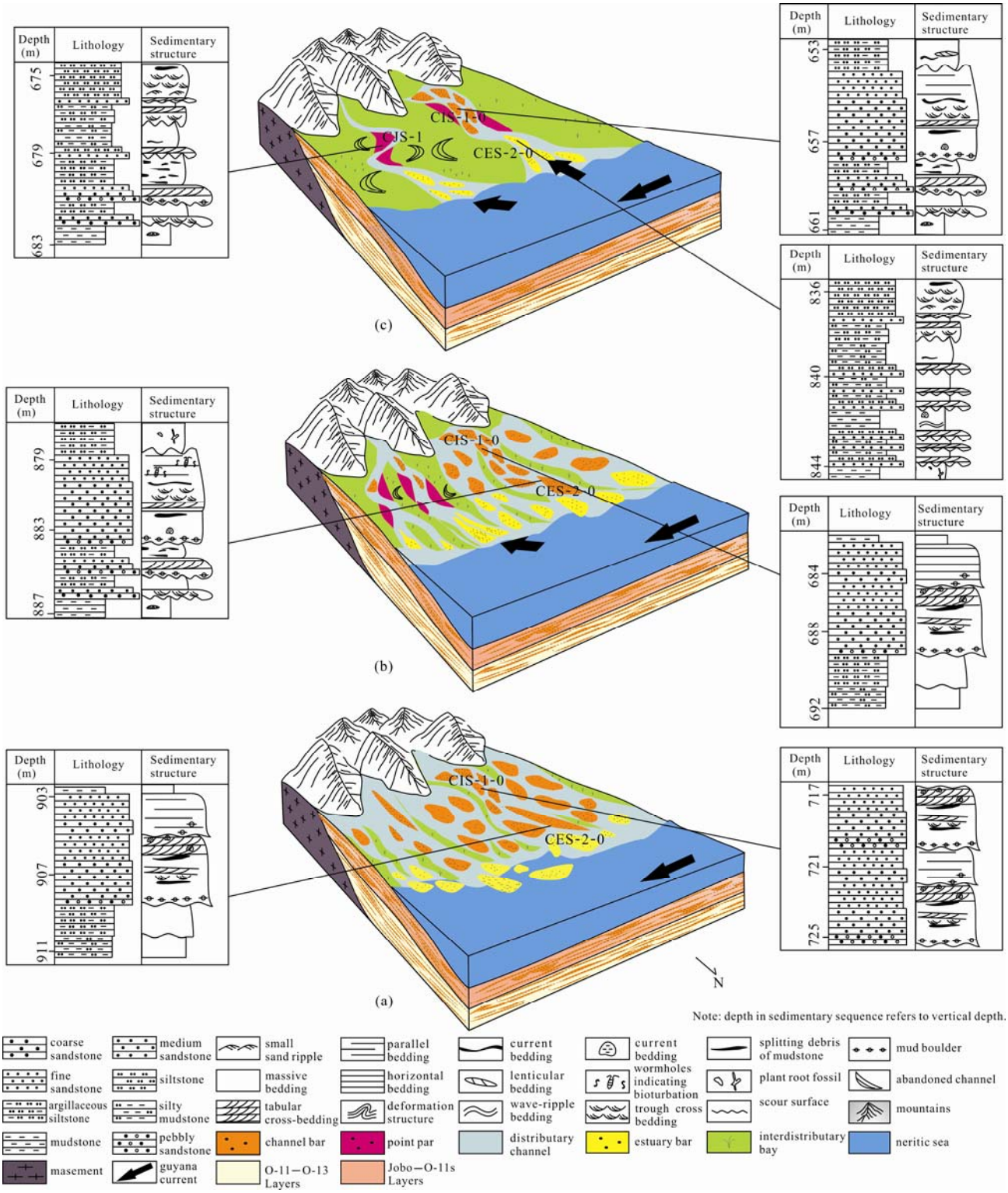

Fig. 5. Sedimentary evolution pattern in the study area.
(a) Sedimentary pattern of sandy braided river-dominated delta; (b) sedimentary pattern of tide-influenced braided river delta; (c) sedimentary pattern of tide-dominated delta.

bars and reduced scale of estuary bars due to transgression.

4.2.3 Tide-dominated delta

The tide-dominated delta deposits mainly occur in the O-11s sand group and the Jobo Member, and the sedimentary background was in transgression and highstand system tracts near maximum flooding surface. The delta sandbody was strongly altered by strong tidal action in high level stage. On one hand, this made the

distributary channel more meandering and point bar in meandering river more developed. On the other hand, the strong tidal action caused estuary bar to turn into finger-shaped sand bar in smaller scale (Fig. 5c). There were interbeddings of sand and mud in the sedimentary sequence, with sand to mud ratio and vertical thickness of sandbody reducing significantly. The southwestern region was characterized by coexistence of braided river and meandering river. The southeastern part showed sedimentary characteristics of typical meandering channel, with better development of abandoned channel. The northern offshore area with lower sand to mud ratio and more obvious thin interbeds of sand and mud, shows the characteristics of superposition of estuary bar and thin sheet sand. There the delta front estuary bars are more obviously altered by the tide, and in elongated finger shape perpendicular to coastline.

4.3 Analysis of influencing factors and prediction of favourable sandbody

4.3.1 Impact of sea level changes

Sea level changes can be demonstrated by sedimentary markers, paleontological signs (Ke et al.,2018) and topographical signs. According to the species analysis of sporopollen, the sea level in the study area has been rising after Late Miocene, and this understanding was consistent with the understanding of regional sea level changes by Svanes et al. (2004). Thick mudstone indicates the maximum flooding surface (Croce, 1996). The increase of kaolinite and decrease of illite can serve as the sign of transgression (Clayton et al., 1999; Rosenthal, 2012; Mourelle et al., 2015).The transgression had two effects on the deposition of sediment: (1) the supporting action of seawater broke the balance between gravity and carrying force of original sediment and the influence on sedimentation changed mainly from buoyancy to friction, thereby resulting in extensive sedimentation in the estuary area; (2) the transgression caused variations in the salinity of upstream fluvial water, destroying the relatively stable state and making fine-grained materials deposited. If the transgression continued and its force exceeded the deposition of the rivers, the original sedimentary system would be destroyed.

With the rapid rise of sea level, the maximum transgression was reached during the deposition period of the O-11s sand group Yabo Member, and then gradually began to retreat (Fig. 6). The distributary channels of the O-11s sand group become smaller and lower in sand to mud ratio from south to north, and show bell shape on logging curves. The Yabo Member, a set of thin interbeds of mud and sand, was the product in the maximum flooding period. The thickness of mudstone gradually increases from south to north, reflecting that the area near sea in the north is more strongly affected by transgression. In the deposition period of the Jobo Member, sea level fluctuated, the sea level kept at relatively high position, the sandstone was also relatively developed, but the sandbodies in distributary channel facies were much smaller compared with those in the Morichal Member. The combination of seismic RMS properties and drilling data indirectly reflects distribution differences of sandstone and mudstone on the plane, and also indicates that transgression was more severe in the northern and eastern regions, which resulted in distribution differences of sedimentary systems on the plane.

4.3.2 Impact of structural and paleo-geomorphological changes

As a worldclass foreland petroliferous basin, tectonic movements after the Late Miocene have certain impact on its regional deposition. Structural changes in the study area determined the paleo-geomorphology, and paleo-geomorphology restricted the accommodation of the basin, thus affecting volume distribution of sediments and differentiation of sedimentary facies, which in turn controlled distribution and law of sedimentary system combination vertically (Wu et al., 2014; Yin et al, 2018). During the depositional period of the Morichal Member, the paleo-geomorphic features can be divided into three stages (Fig. 7), the stage of obvious progradation in lowstand system tract (Fig. 7a), the influencing stage of weaker transgression (Fig. 7b), and the stage of intense transgression (Fig. 7c). In the stage of obvious progradation in lowstand system tract, there was an uplift developed in the central of western part of the study area. It led to different tectonic patterns in the east and west of the area, with the eastern part lower in terrain. Although in the stages of weaker transgression and strong transgression, the geomorphological difference became smaller, but the geomorphology in the east and west still differed. The local uplift in the west could obstruct transgression, therefore the eastern part was more susceptible to influence of transgression.

Different stages show different controlling effects on progradation unit of delta. The stage of obvious progradation in low system tract corresponded to the depositional period of the O-13–O-12 sand group. At this time, with sufficient fluvial supply, the distal-provenance sandy braided river delta was developed. The seawater began to invade but the tidal influence was not far, and the horizontal development was also limited (Fig. 7a). The influencing stage of weaker transgression corresponded to the sedimentary period of the O-11 sand group, which was the major development stage of tide-influenced delta. The western part of the study area was uplifted locally, resulting in faster velocity of water feeding into the sea. At the same time, the sea level rise during this period led to significant support and reformation of delta front tide. Especially in the eastern part, affected by continuous transgression, the braided channel began to be meandering (Fig. 7b). The stage of strong transgression corresponded to the depositional period of the O-11s sand group-the Jobo Member. During this period, the transgression rapidly expanded, and the delta was strongly affected by the tide. The eastern and western distributary channels were all obviously meandering (Fig. 7c).

4.3.3 Influence of provenance supply

The coastline receded seawards in the depositional period of the major oil producing layer of the Morichal Member, the sea level was close to the slope break and can reach the east side of the Trinidad Tobago area (Martinius

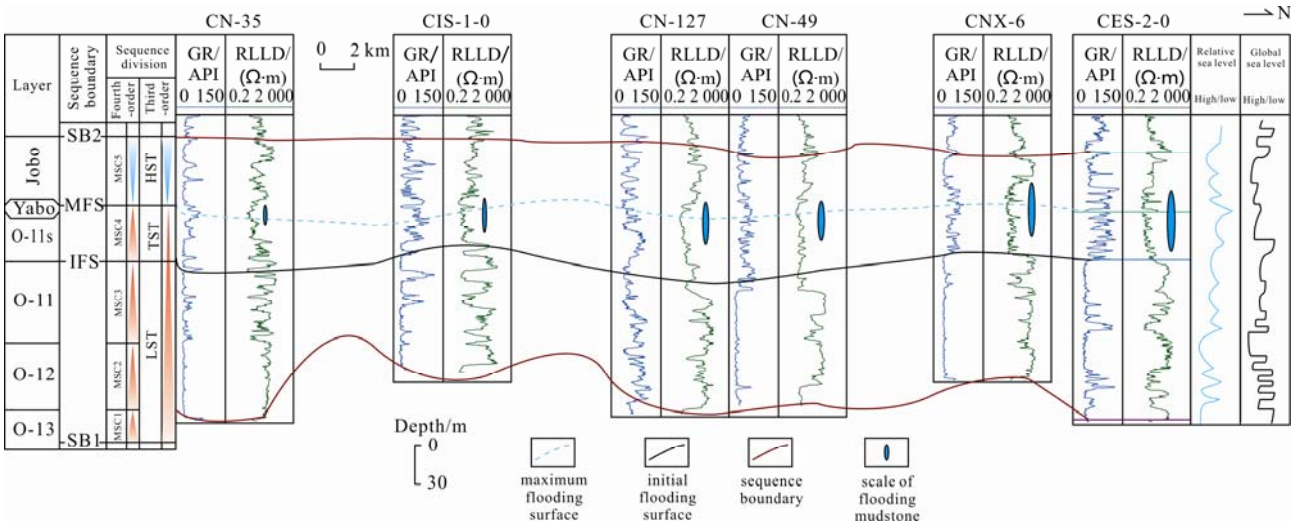

Fig. 6. Well-tie section for stratigraphic correlation and flooding surface identification (see section location in Fig. 1).

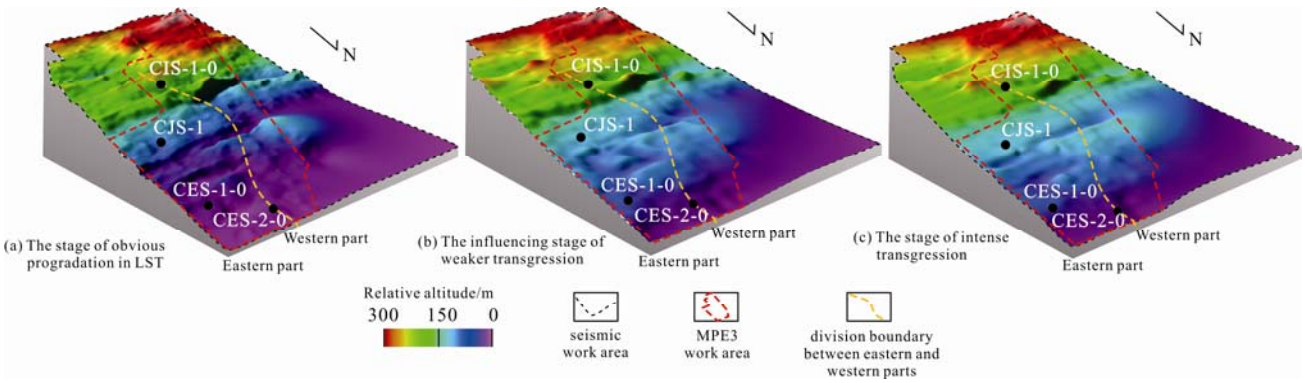

Fig. 7. Evolution map of paleotopography in the study area.

et al, 2012; Deville et al, 2015). However, in the depositional periods of the Yabo Member, the Jobo Member, and the Pilon Member, the sea level gradually rose, being in the inter glacial period, and the sea level was far from the slope break of continental shelf and rapidly invaded landwards. The change of paleo-climate brought about change in sea level, and in turn affects the evolution of sedimentary environment and process of river type conversion (Pindell et al, 2009). Díaz et al. (1996) pointed out that the provenance in the study area was mainly from the southwestern Guyana Shield by studying sedimentary records of the Miocene in Orinoco. Goldstein et al. (1997) concluded through the study on Sm-Nd isotope that there was a small amount of oceanic crust source material from the east in the Late Miocene-Pliocene in the Orinoco Delta. The more sufficient the provenance supply, the larger the sedimentary scale, and the higher the proportion of coarse debris deposits thickness will be. The closer the provenance is, the coarser the sediments and the worse the sorting of the sediments will be (Callec et al, 2010). In the lower part of the Oficina Formation, the sandbody of braided channel is larger in scale and higher in sand to mud ratio, and the sediments are poorer in sorting than those in the upper part, indicating that the provenance supply in this period was abundant. This is proved by the morphological distribution of the RMS attribute in the O-12 sand group (Fig. 8). As the provenance became farther and the sediment supply was weakened, the sandbody of the O-11s sand group decreased in scale and sand to mud ratio and gets better in sediment sorting, marking the shift from distributary channel sediments to meandering channel sediments. As the sea level rose, the provenance carried by tidal water formed the deposits of estuary bar influenced by tide. This is confirmed by the relatively isolated distribution of low-valued RMS attribute of the O-11s sand group (Fig. 9).

4.3.4 Prediction of favorable sandbody

Based on above mentioned understandings to sedimentary environment, law of sedimentary evolution and sedimentary pattern, by using drilling and seismic data, favorable sandbody distribution of major sand group O-12 and O-11 in the study area were predicted with geologic statistical inversion method (Figs. 10 and 11). The inversion results of reservoir show that the O-12 sand group has more well-developed reservoir and thicker sandbody, showing characteristics of predominant sandbody of braided river-dominated delta. However, the O-11 sand group, subject to transgression, is different in sedimentary environment, showing the characteristics of

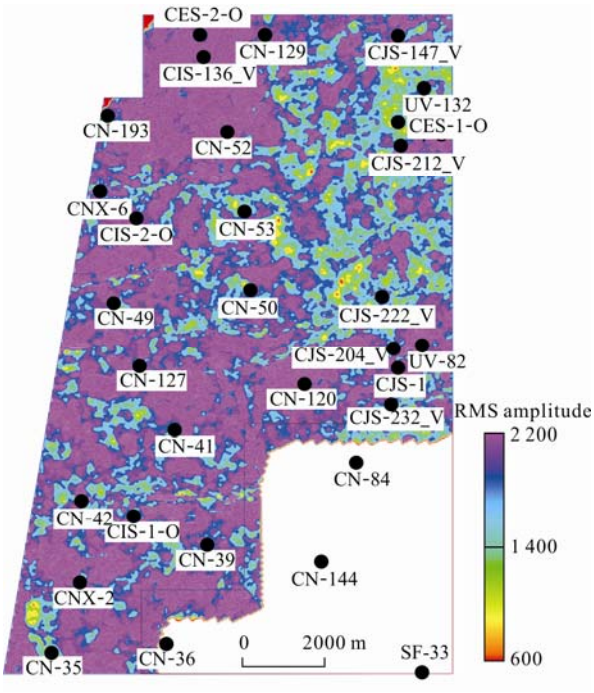

Fig. 8. Distribution of seismic RMS properties of O-12 sand group with high sand content.

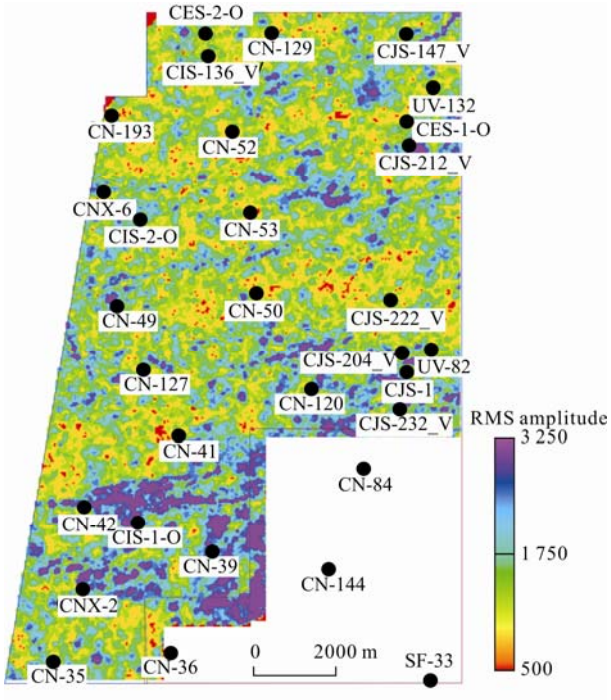

Fig. 9. Distribution of seismic RMS properties of O-11s sand group with low sand content.

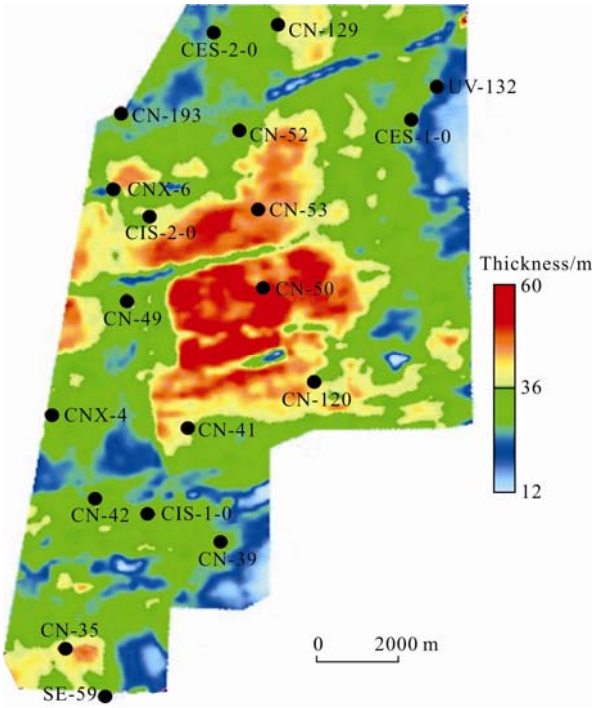

Fig. 10. Thickness distribution map of O-12 sand group from inversion.

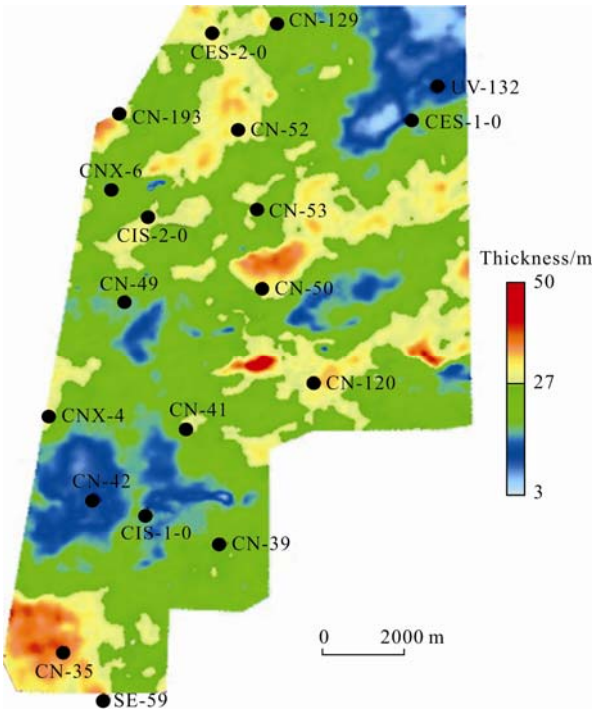

Fig. 11. Thickness distribution map of O-11 sand group from inversion.

delta sandbody affected by tides. The inversion results of reservoir are consistent with the understandings on sedimentary evolution and channel type transform. The southern and central study area are richer in favorable reservoir sandbodies, the subsequent development by horizontal well should pay attention to reservoir changes caused by evolution of sedimentary facies belt in the study area.

5 Discussion

The formation and evolution of marine deltas are

mainly related to the interaction between rivers and oceans, including transgression intensity (e.g. Yu et al., 2017), fluvial action intensity and variation characteristics (e.g. Li et al., 2017a), delta types (e.g. Coleman and Gagliano, 1964; Li et al., 2017b), and coastal paleotopography and ring. Environmental changes (such as Cao et al., 2013; Wang et al., 2015; Feng et al., 2015; Li et al, 2019) play an important role. Many researchers have recognized that transgression in this area has an important impact on the river delta system, but the extent of the impact has been uncertain in different geological periods, especially since the Miocene. In view of local differential uplifting since the Miocene, it is inferred that hydrodynamic change caused by local tectonic uplift is a control of depositional pattern. The seismic data was used to obtain relative attitude data. It is difficult for us to clarify the real height of the ancient uplift. In this paper, a model of continuous gradual evolution for delta has been established. However, limited to the available data, it has still not been quantitatively characterized. In addition, the oil and gas reservoirs in the study area are very developed, but there are still great differences in different layers. Although we have made a preliminary study on the favorable reservoir prediction, this part of the content is limited by the data, and is not deep enough. We can only look forward to further study.

6 Conclusion

(1) In Early-Middle Miocene, the sedimentary environment of the MPE3 Block of the Orinoco heavy oil belt in the Eastern Venezuelan Basin was the fluvio-marine transitional depositional environment, the sedimentary facies was the distal-provenance sandy braided river delta controlled by rivers and tide, and the major sandbodies were the deposits in braided channel, meandering channel, and estuary bar. Due to the large-scale rise in sea level, the sedimentary system changed from the braided river-dominated delta to tide-influenced delta, and eventually evolved into tide-dominated delta.

(2) Controlled by transformation of structure and sedimentation, the type and sedimentary pattern of distributary channels of delta changed from braided river to meandering river. The distribution of estuarine bars transformed from the river-dominated tongue-shaped bars to tide-dominated finger-shaped bars. The main sandbodies in the study area are originated from braided river channel, channel bar, meandering river channel, point bar and estuary bar.

(3) Based on tectonic setting of the East Venezuela foreland basin, it is pointed out that the influencing factors of sedimentary environment, facies evolution and channel type conversion in the study area are structural and paleo-geomorphic changes, sea level fluctuation, and provenance supply differences.

(4) Based on the understanding to sedimentary facies evolution, the favorable reservoir sandbodies were predicted with geologic statistical inversion method. The results show that the distribution of favorable sandbodies is evidently constrained by delta evolution and river type conversion. The central south of the study area has more favorable sandbodies, and subsequent development by horizontal well should pay attention to reservoir variations caused by sedimentary facies evolution in the study area.

Acknowledgments

This work was supported by the Important National Science Technology Specific Projects (number 2016ZX05031-001).

Manuscript received Aug. 1, 2018
accepted Dec. 20, 2018
associate EIC XIAO Yitian
edited by LIU Lian

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