Sedimentological characteristics and controlling factors on fluvial styles of the Guantao Formation, Kongdian Oilfield, China

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MS received 3 March 2017; revised 3 May 2018; accepted 8 May 2018;
published online 1 February 2019

The Kongdian Oilfield is located in eastern China. More than 30 years have passed since the oil field was discovered in 1979. The majority of the oil is produced from reservoirs of the Guantao Formation (Miocene). A detailed description and interpretation of core, well-logging and 3-D seismic stratigraphic slices data was carried out to analyze sedimentological characteristics of the Guantao Formation and two fluvial styles have been identified encompassing braided channel and meandering channel. Seven main facies associations were defined: (i) upward-fining channel, (ii) braided channel with mid-channel bar, (iii) meandering channel with point bar, (iv) levee, (v) floodplain, (vi) minor channel, (vii) swamp. Vertical changes in fluvial styles of the Guantao Formation were recognized by variations in preserved thickness, channels stacking pattern, regional paleoflow directions, and channel/floodplain ratios. The fluvial succession is 50–70 m thick in the lower Guantao Formation, composed of braided channels and high channel/floodplain ratio. The alluvial succession is 60 m in thickness in the upper Guantao Formation, the dominant fluvial styles change to meandering channels and channel/floodplain ratio reduces. The main factor that may have affected the fluvial style is the base-level changes. With the rise of the base level the fluvial style is believed to have changed from braided channels to meandering channels.

Keywords. Sedimentological characteristics; facies associations; Guantao Formation; fluvial styles; controlling factor; evolutionary model.

1. Introduction

The evolution of a river is a complex process and numerous works have been carried out to analyze variations of alluvial styles at several scales (Miall 1977, 1985, 1993; Bridge 1985, 1993, 2000; Ethridge *et al.* 1998; Jiao and Yan 2005; Allen and Fielding 2007; Smith *et al.* 2010). Many studies showed that variations of fluvial styles are related

to factors such as tectonics, climate, the location of the river (Arche and López-Gómez 1999; Catuneanu and Elango 2001; Marenssi *et al.* 2005; Huerta *et al.* 2011). Until now, there are few studies describing the sedimentary characteristics of the Guantao Formation in the Kongdian Oilfield. The existing literature based on the analysis of core, well log and seismic data show that mainly braided channels deposits are developed in the

Figure 1. Map of the study area and geological survey of the Kongdian oilfield in the Huanghua depression.

lower Guantao Formation, Kongdian Oilfield (Hou *et al.* 2008; Wu *et al.* 2010; Chen *et al.* 2012). What were the fluvial styles in the upper Guantao Formation? What is the reason that led to change of dominant fluvial styles? With these questions, detailed description of the core data, well logging, 3-D seismic data and correlations of well-logs were used to analyze different fluvial styles and main forcing factor on variations of fluvial styles of the Guantao Formation in study area.

2. Geological setting

The Kongdian Oilfield is located in the mid-south area of Huanghua depression which is a significant Cenozoic tectonic unit broadly NE–SW oriented, located in the middle of the Bohai Gulf basin, Eastern China (figure 1). The Huanghua depression contains approximately 5000 m of Cenozoic alluvial, fluvial, and lacustrine strata. The Huanghua depression underwent multistage extension and subsidence interpreted through the analysis of the tectonic-sequence surface, syn-sedimentary fault's activity and the back-stripping of the subsidence history (Li *et al.* 2009). The bottom interface of Miocene Guantao Formation is a regional post-rifting unconformity surface and divides the basin's Cenozoic evolution into rifting and post-rifting stage. The rifting stage had multiple sedimentary cycles and very thick lacustrine sediments (3500–4000 m) formed during this period and several seawater intrusions occurred during this period as

well (Qi *et al.* 1994). In the filling sequence of the rifting stage, the bottom interface of the first member of Shahejie Formation is also a regional recognizable angle (20° – 35°) disconformity surface in the whole basin and divides the rifting stage into two extensional stages. The geometry feature and property of the fault system shows that the tectonic deformation of the study area was controlled by the NW–SE extending stress field in the rifting extensional stage I and the extending stress field turned to NS in the extensional stage II (Qi *et al.* 2010; Ye *et al.* 2013). The multistage extension and subsidence process is closely related to the change of the regional extending stress field orientation which was controlled by the tectonic events of the surrounding plates, especially the accelerated westward subduction from the Pacific plate to the Eurasia plate (Li *et al.* 2011). In the post-rifting stage, the middle and north area of Huanghua depression underwent stable subsidence at early stage and accelerated subsidence at late stage. In the Miocene, the Guantao Formation which was deposited during the stable subsidence period is composed of coarse clastic sediments dominated by fluvial facies (He *et al.* 2008) and the depth of the Guantao Formation ranges between 1350 and 1500 m in study area (figure 2). The southwestern Cangxian paleo-uplift were considered to be main source areas of Guantao Formation in Kongdian oilfield through the cluster analysis of the heavy mineral associations and ZTR index analysis (Sun *et al.* 2006) (figure 3).

Figure 2. Comprehensive geology column of study area. The study interval, highlighted by a black box, is located in the Guantao Formation.

Figure 3. Direction of sediment supply in Kongdian Oilfield obtained from the study of heavy mineral assemblage types and ZTR.

Table 1. Basic data of wells used in the study.

Strata		Core length (m)						
		Well KJ1	Well K31	Well K60	Well K61	Well K1024	Well K1042	Well K1050
Member	GU	17	53	32	18	50	28	8
	GL	32	73	17	42	33	—	30
Total		49	126	49	60	83	28	38

Figure 4. Photographs of lithofacies from the study area.

3. Methodology

An integrated data set from Kongdian oilfield was used to address the goals of this study including 7 wells with cores, more than 150 wells of logging and a 3D seismic data set acquired over an area approximately 5.5×5 km. These wells are listed in table 1. The cores used are from the Guantao Formation. The total length of the cores is 433 m. Some core photographs are also used in the study of depositional environments. Descriptive content based on the core includes grain size, colour, sedimentary structures and so on. Spontaneous potential (SP) and gamma-ray (GR) log are used as auxiliary tools to identify facies. 3D seismic stratal slices are also used to predict the plane distribution of fluvial deposits which improves seismic-surface display mainly by making slices linearly between geologic time-equivalent seismic-reference events (Zeng *et al.* 1998a,b). Successive reference horizons (top and bottom interfaces of Guantao Formation) were spaced at 110 m sec intervals and stratal slices were generated at 2 m

sec intervals. Reconnaissance horizon slicing was accomplished using multiple reference horizons, each having been chosen for its reflection continuity. Each horizon slice represented an amplitude extraction from a level at a fixed interval below or above the reference horizon. On stratal slices, Channel belts fills are defined by strongly positive (red) amplitudes that indicate well-developed sandstones. Weakly positive amplitude denotes thin or shaly sandstones and negative amplitude (blue) corresponds to mudstones. Through the comprehensive analysis and classification of information from core, logging, and seismic data, facies in the study area were identified and the depositional environment was deduced.

4. Lithofacies, facies associations and fluvial styles

4.1 Lithofacies

Eight lithofacies are defined based principally on grain size and sedimentary structures in the

Table 2. *Facies classification and descriptions of the Guantao Formation from the study area.*

Lithofacies	Description	Interpretation
Gc: Clast-supported conglomerate	This lithofacies consists of clast-supported normally graded conglomerate. Bone clasts that form thick, poorly sorted clast-supported beds with interstitial sand	Bedload deposition in the environment of rapid flow-speed-reduction. This lithofacies contain lag deposits from rapidly waning flow
Sp: Planar cross-bedded sandstone	Light green medium to fine sand, well sorted with relatively high angle (25–30°) cross stratification, covered by Sr, Mm. This type of lithofacies is very common in this area (32.2%). Basal erosion surface has been observed frequently	Generally deposited in the lower part of sand bodies with overlying mud rock bedload deposits from linear or slightly sinuous dunes forming in the deep or fast-flowing part of the channel
St: Trough cross-bedded sandstone	Light green medium sand with cross-bedded troughs, well sorted, generally observed in the lower parts of sand bodies	Interpreted as the product of the migration of sinuous-crested dunes in the deep part of the channel
Sm: Massive sandstone	Massive, poorly sorted to weakly graded, light grey, medium to fine sandstone. Occasionally contains carbonaceous floating pebbles	Deposited in the channel by rapidly waning fluvial flows
Fm: Massive siltstone	Massive grey green siltstone or sandy siltstone, poorly sorted, often interbedded with mudstone and rarely observed in channels. It has a relatively flat base	Deposition occurred in rapidly waning flows farther from the channel where flows were not sufficiently powerful to scour the floodplain substrate
Fr: Ripple cross-laminated siltstone	Light grey or dark grey, ripple laminated siltstone, well sorted, occasionally contains fine to very fine sandstone. Slightly erosional base can be observed. The top surface is often eroded by the new elements in the upper part. Sometimes observed as an independent strip sand body (<1 m) in mudstone	This lithofacies is interpretable as bedload deposition in unidirectional flows or abandoned channel fills
Mm: Massive mudstone	Grey-green or brown mudstone, massive or weakly bedded, up to several centimetres in thickness, abandoned channel or floodplain	This lithofacies is created by suspension deposition, formed in the upper parts of channel sand bodies or in floodplain
Mc: Carbonaceous mudstone	Carbonaceous mudstone. Mudstone with a high carbon content, massive or horizontally bedded	This lithofacies is interpreted to have formed from peat swamps in a warm and humid climate

Kongdian Oilfield. These are divided into four main groups based on grain size: conglomerates (G), sandstones (S), siltstones (F), and mudstones (M). Photographic examples and descriptive characteristics of each lithofacies are respectively presented in figure 4 and table 2.

4.2 Facies associations

Eight lithofacies have been grouped into seven facies associations. These seven facies associations

represent the predominant depositional forms in fluvial environments of the Guantao Formation and major changes in the lithofacies and facies associations of the Guantao Formation were recognized in the study area (figures 5 and 9).

4.2.1 FA1: Upward-fining channel

Upward-fining channel is common in the Kongdian Oilfield (figure 5A). Gc frequently appears at the bottom of the single channel sand bodies

Figure 5. Photograph of core and typical vertical log of facies associations.

vertically, covered by Sm, Sp. The upper part contains Sr and Fr, and Fm. The bottom conglomerate is characterized by imbricate arrangement. The grain size of the channel sand bodies is fining-upward. Upward-fining channel fills commonly show fining-upward successions and this feature can be observed from the core and logging curve. Several scour interfaces may exist in channel sand bodies reflecting multistage paleo-flood events (Allen 1983). This group of facies may be traction-load deposits laid down within the active channel.

4.2.2 FA2: Braided channel with mid-channel bar

Braided channel with mid-channel bar is another important facies association in this area, with coarse grain size clastic. Thin clast-supported conglomerate is at the basal part, and the middle and upper part is planar cross bedded coarse to medium sandstone with slight fining in grade. More than one thin muddy layer can be observed in the mid-channel bar (figure 5B). This facies association is occasionally in contact with rippled sandstone above an erosional surface. Almost unchanged

granularity vertically in sandstone of this element reflects the rapid filling deposition in the channel. It is frequently developed in the member GL. These deposits were laid down by channelized, predominantly unidirectional flows (figure 12) in which sediment was transported chiefly as bedload, producing macroscale bedforms (Allen 1983; Bridge 1985; Miall 1985; Liao *et al.* 1998).

Facies analysis on stratal slices can reduce the ambiguity and it also helps to predict the plane distribution of sediments. Amplitude band commonly occur in the reservoir body outline. The amplitude image of GL shows several wide reservoirs that are typically more than 2000 m wide which are reflected as strongly positive amplitude bands (figure 6). These reservoirs are interpreted as wandering channel (braided channel) sandstones which is a kind of channel sandstones typically with large coverage area. Several scattered irregular areas with strongly positive amplitude can be observed on stratal slice of GL and these areas are interpreted as mid-channel bars in braided channel combining the analysis of well data. The deposits of mid-channel bar is thick and the spontaneous potential curves show box-shaped signature.

Figure 6. Typical stratal slice and sedimentary interpretation of GL in Kongdian oilfield.

Figure 7. Typical stratal slice and sedimentary interpretation of GU in Kongdian oilfield.

4.2.3 FA3: Meandering channel with point bar

FA3 is a common facies association in GU. Planar cross bedded medium-fine sand deposited in the lower part of sand bodies. The upper part is the deposition of rippled fine sandstone or siltstone. The grain size of the sand body is fining upward. A number of erosion surfaces can be observed inside the sand body reflecting multiple reactivation events. The thickness of a single story is related to the duration of the flood and

the sediment loads that floodwater carried. The story is 2–3m thick and has a low dip angle ($<5^\circ$) in this area (figure 5C). Complex paleocurrent directions reflected that these channels probably deposited in the meandering river system (figure 12). The main flow of the channel is directed away from the inner bank, as on the inside of a meander, surface flow impinges on the outer bank, leading to an active cut bank erosion, and traction-load deposited in the inner bank (Miall 1985).

Figure 8. Photographs of carbonaceous floating pebbles from the swamp in the GU.

The amplitude image of GU shows several relatively narrow reservoirs that are typically 300–800 m wide (figure 7). The amplitude bands in the GU sands which have a channel-like form are thought to represent successive positions of the meandering belt as it migrated laterally prior to abandonment. Sinuous channels interpreted as abandoned channels following periods of point-bar deposition can be observed on thick sandstone belts in GU. Amplitude images show sinuous trends of the abandoned channels. These abandoned channels commonly are moderate to high sinuosity, 50–100 m wide. The channels locally oscillate laterally and cut back locally across preexisting point bars and resulting in complex internal reservoir architecture.

4.2.4 FA4: Levee

The grain size of levee deposits is fine, mostly siltstone and sandstone. The sedimentary structures are mainly massive and ripple lamination. This facies association is interbedded with channel or floodplain vertically (figure 5D). This type of deposition may develop on both sides of the river. The levee deposits are not often preserved due to the erosion of the frequently migrating river. This element is rarely observed in the lower part of member GL, and frequently observed in the member GU (figure 7). These over bank deposits is product of splaying processes where the mass over bank flooding produced sheet-like deposits and built the levee (Allen 1983; Miall 1985; Fielding 1986).

4.2.5 FA5: Floodplain

Floodplain deposits formed in low-energy environment during flood period are particularly important components of GU meandering rivers

characterized by broad floodplains (48.5%). The floodplain deposits are mainly massive mudstone with internally developed silty thin layers, and can be up to tens of metres thick (figure 5D). Relatively coarse-grained braided rivers of GL have channel systems that tend to occupy most of the river floodplain, so that floodplain are small in area and their deposits constitute a minor component of the fluvial assemblage (figure 6).

4.2.6 FA6: Minor channel in floodplain

These channel-like sedimentary bodies are filled by thin planar cross-bedded sandstones or trough cross-bedded sandstones basal covered by thick massive siltstone or mudstone. These fine particles reflected the insufficient supply of sediments adjacent to active channels (figure 5D). These small-scale channel fills were interpreted as the fill of the minor channel segment in floodplain.

4.2.7 FA7: Swamp

The dark grey carbonaceous mudstone is the main lithofacies of swamp deposits, weakly bedded, (figure 5E). Carbonaceous floating pebbles (3–5 cm), observed in channel fills occasionally (figure 8), were derived from cannibalization of swamp deposits. These deposits are probably formed in a low-lying area in the flood plain where the water gathered easily and plants are easy to grow.

4.3 Fluvial styles

The stratigraphic record of the Guantao Formation in the Kongdian Oilfield consists of a 120 m thick succession with two distinctive fluvial packages (figures 9–11). The lower package is a

Figure 9. Fluvial lithofacies assemblages and vertical profiles of coring wells in study area.

coarse-grained succession dominated by braided channels sand bodies ($W/Th > 100$) (figures 9 and 10). The braided fluvial style is characterized by very thick sandstone, up to 70 m or more. This fluvial style was observed in the member GL which contains a medium-fine grained succession of sandstones (70% in vertical logs and 83% in cores). The thick sand body, which is often separated by thin layers of fine grained deposit, is actually multiple stacked mid-channel bar sand bodies in the channel with paleocurrents directed to the NE and NNE (figure 12) (Straub *et al.* 2009). There is no obvious sequence of grain size variation in the sand body and the coarsest deposits are not necessarily confined to the bottom. The scale of the levee may be very small in the braided river sedimentary system so that silty and muddy deposits are relatively rare, reflecting the probable lack of suspended sediment in the ancient braided river in this area.

The only small amount of suspended sediment could well be quickly scoured away by the frequent migration of the channel. The upper package of member GU contains a fine grained succession of mudstones (45% in vertical logs and 48.5% in cores) with isolated, relatively narrow ($W/Th < 70$) high-sinuosity fluvial channels (Gibling 2006). Compared with the GL, floodplain is preserved relatively well with the content of 48.5% in this member (figure 9). Sand body is connected with the underlying floodplain mudstone through scour surface (figure 10). The scour surface, in turn, are followed by the lithofacies Sp, St and Fr. The upper part of the sequence is massive mudstone of floodplain. The thickness of complete vertical sequence of a meandering channel ranges between 5 and 10 m in this area. These sand bodies are mainly point bar sand bodies in the channel with complex paleocurrent directions (figure 12). Thin layer of siltstone or mudstone between the small rhythms

Figure 11. Model of three different rivers identified in the Guantao Formation study area.

Figure 12. Paleocurrent directions in the upper (A) and lower (B) Guantao Formation obtained from the study of diplog.

Figure 13. Sequence stratigraphic interpretation of seismic profiles in the Cangxian–Kongdian area of the Huanghua depression.

deposited reflected the deposits in the normal water period (Yue 2006). Levee may be better preserved in the inner bank but poorly preserved in the cut bank due to the lateral erosion of the channel.

5. Discussion

5.1 Forcing factor

To determine the influence of forcing factor on fluvial style transformation of the Guantao Formation, this research has been carried out regarding the potential factor base level changes.

The Guantao Formation is composed of lower LST mainly consists of multi-storey, large-scale channel sandstones which are related to low rates of base-level rise (figure 13). In contrast, the upper part of the Guantao Formation is a TST comprises single-storey strata with relatively small-scale channels, which were probably associated with more rapid rates of base-level rise. In the study area, the Guantao Formation is unconformably underlain by the Dongying Formation without incised valley. The evidence from oil-field show that the change of scale and styles of channel most likely reflected the changes of base-level rise. The sediments were deposited in an overall fining-upward and transgressive sequence.

Figure 14. Paleogeographic reconstruction of the Guantao Formation.

Variation in base level must be related to continuous tectonic subsidence and uplift of the Bohai Gulf basin during the post-rift stage.

Greater content of fine particles in stratigraphic section are interpreted as a relative lower altitude and further source area caused by the extension and subsidence of the basin. The large scale of sand bodies and high sandstones content of the lower part of Guantao Formation reflect the adequate sediment supply and the closer source area at the early post-rift stage. With the further development of tectonic movement, decrease in sediment supply capacity resulted into finer grain size and the less sandstone proportion (51.5%) of the upper part of Guantao Formation.

Besides, analysis of sporopollen and mudstone in the Kongdian area indicates that the transition from wet to semi-arid climate in the Guantao Formation is also a potential influence factor of fluvial style transformation (Li *et al.* 2011).

5.2 Sedimentary evolution model

The depositional model of the early sedimentary stage fluvial system of Guantao Formation is best represented by a wide channel belt, internally showing a braided morphology of minor channels. The position of the active channel belt vary through time as the channel belt aggrades. Average rates of vertical accretion were high throughout lower Guantao time for the large number of major channels preservation within the section. The close vertical spacing and large width of channel is interpreted to be the product of lower subsidence rate which gave opportunity for rivers to laterally migrate and expand. The complex internal arrangement of sandstone lenses within the GL channel sequences resulted from the rapid switching of channels and the downstream migration of low relief barforms. High degrees of channel belt

interconnectedness would suggest relatively high rates of average sediment accumulation and the channels were actively transporting much coarser grained material. Braided channel-fill sequences typically terminate upward either with deposition of fine silt and mud or laterally extensive irregular scour surface. As for GU, the isolated channel-belt within a fine-grained succession of mudstones reflects deposition by relatively small, sinuous rivers that deposited sand in point bars. The channel migrated laterally within its channel belt and produced truncated point-bar. A relatively high rate of subsidence is interpreted during the deposition of the meandering channel belt as levees are better preserved compared to GL. Overbank flooding produced splays attached to some channel fills forming a levee. Channelized deposits represent a relatively low proportion of the stratigraphic sections and floodplain deposits are common (figure 14).

6. Conclusion

1. Based on stratigraphic analysis of Guantao Formation, eight lithofacies and seven lithofacies associations have been defined and regional sedimentary evolution model have been established in different periods. The Guantao Formation of Kongdian oilfield is a 120 m thick fluvial succession composed of braided, meandering channels with vertically variable preservation of floodplain environments. The lower part of the study area is characterized by braided channels with mid-channel bar and the fluvial succession is 50–70 m in thickness. Braided channels have characteristics as follows: in general, multistorey channels cut frequently and superpose each other, with conglomerate bed of detention at the bottom. From bottom to top, sand

body becomes thinner and sand grain size gets finer. The upper part of the study area is characterized by meandering channels with point bar and the fluvial succession is about 60 m in thickness. Meandering channels have isolated channel-belt, truncated point-bar and a relatively high proportion of floodplain deposits.

2. The transformation in the fluvial styles of the Guantao Formation permits interpretation of two main sedimentary scenarios during the Early Miocene in the Kongdian oilfield: an early, low base-level setting and a late, high base-level setting. Continuous tectonic subsidence and uplift of the Bohai Gulf basin at the post-rift stage controlled the variation in base level and fluvial styles.

Acknowledgements

The author wishes to thank Prof. Lin from the School of Geosciences (Chinese University of Petroleum) sufficient guidance in the project. The Kongdian project was entirely funded by the China National Petroleum Corporation, which is gratefully acknowledged. Special thanks to Zhang Xianguo, Wang Hongwei, Fu Xiaoliang, Liu Xiaochen, Li jia, Wang Chunwei, Zhang Jianxing and Li Shujing for assistance in the project.

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Corresponding editor: PARTHA PRATIM CHAKRABORTY