Sedimentology and Mechanism of a Lacustrine Syn-rift Fan Delta System: a Case Study of the Paleogene Gaobei Slope Belt, Bohai Bay Basin, China

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Abstract

Fan delta systems have long been studied as a kind of good hydrocarbon reservoirs. Although many models have been raised according to their local conditions, there still exists some controversies regarding the formations of the ones developed in continental syn-rift settings. Taking Paleogene Es₃²⁺³ of Gaobei Slope Belt as an example, this paper conducted a comprehensive geological study and a forward depositional modeling. The results show that the sediment within the study area came mainly from the northeastern Baigezhuang uplift and the northwestern Xinanzhuang uplift over a short distance. The sedimentary system is characterized by subaerial debris flow, subaerial braided channels, subaqueous distributary channels, front sand bars and front sand sheets. Furthermore, the study area is a balance-filled basin that experienced a 3rd order normal regression followed by a transgression during the development of the study interval. The results also show that, a stable subsidence rate with small-magnitude climate changes would be a plausible explain for the entire sequence of the fan delta system in the study area. The tectonic subsidence was indeed the dominant driving force to a continental syn-rift fan delta system, although the climate, sediment supply or lake level might bring some lower order (e.g., 4th and

5th order) superimpositions. This paper proposed a likely model for fan deltas developed in continental syn-rift settings, which is expected to gain some insights into the forming mechanism and provide some supports for the reservoir characterization of similar and correlative sedimentary systems.

Keywords: Gaobei Slope Belt; syn-rift settings; depositional model; autoretreat; fan delta

0 Introduction

Since the conception of fan delta was first put forward by Holmes in the 1960s, more and more attention has been paid to it. Galloway (1976) studied the modern sediments and stratigraphic framework of Copper River and proposed a classical facies model of fan delta, which is still widely cited. As an important kind of hydrocarbon reservoir, fan delta has been studied by many geologists during the subsequent several decades. Colella (1988) studied the Pliocene-Holocene sequences of a Gilbert fan delta of Crati basin in Italy, and he suggested that tectonism can control sedimentation processes, which represents large fracture events and multi-time risings and subsidences. Eyles and Eyles (1989) studied the outcrop of the ice-contact fan in Wrangell and White River in southern Alaska and described the characteristics of fan deltas that were close to active volcanoes and influenced by glaciers. Many other case studies also proposed models for some specific settings (Billi et al., 1991; Burns et al., 1997; Chough et al., 1990; Cole and Stanley, 1995; Crews and Ethridge, 1993; Hwang et al., 1995; López-Blanco et al., 2000; Postma, 1990; Saez et al., 2007). While as the advent of sequence stratigraphy, an increasing number of basin filling cases of both marine and non-marine environments are analyzed and characterized under sequence stratigraphic frameworks, highlighting bounding surfaces and controls of allogenic factors (lake level, tectonic, climate, sediment supply, etc.) (e.g., Vail et al., 1977; Mitchum and Van Wagoner et al., 1991; Posamentier and Allen, 1993; Catuneanu, 2002, 2009, 2013; Zecchin and Catuneanu, 2013, 2015; Li et al., 2018). The same is true for fan delta system researches (Zhu et al., 2008; Jiang et al., 2013;

Feng et al., 2013; Zhu et al., 2014; Lin et al., 2018).

For the fan deltas developed in normal faults controlled syn-rift basins, there are some valuable researches for both marine and lacustrine environments (e.g., Scholz et al., 1990; Gawthorpe et al., 2017). However, there is still a lack of a specific model highlighting the interplay among the allo genetic controls (tectonic subsidence, sediment supply, eustacy, climate, etc.) and the forming processes of these sedimentary systems, especially in continental lacustrine environments, in which climate may play a significant role rather than the eustacy.

As a syn-rift fan delta succession developed in a half-graben lacustrine basin, the 3rd member of Shahejie Formation (E_{s3}) of the Paleogene Gaobei Slope Belt is a main oil-bearing interval of the entire Nanpu Sag and has great petroleum significance. In recent years, many studies have been carried out on this region (Feng et al., 2016; Jiang et al., 2013; Lu et al., 2018; Zhang et al., 2017), while there are still many controversies concerning the developing mechanisms of the fan delta successions.

Taking the Paleogene Gaobei Slope Belt as an example, this paper aims at: i) conducting provenance and sedimentological analysis of the deposits in the study area; ii) analyzing the spatial and temporal distribution of the depositional systems; and iii) quantitatively modeling the basin filling process under certain controlling factors to gain some insights into the formation mechanism of a continental syn-rift fan delta system.

1 Geological background

Bohai Bay Basin is a Meso-Cenozoic rift basin developed within the North China Platform. It covers a total area of 20×10^4 km² and is bounded to the east by the Jiaoliao Ridge and to the west by the Shanxitai Syncline (Fig. 1a). Nanpu Sag, lying in the northern part of the Bohai Bay Basin, is characterized by graben valley structures (Fig. 1b). The Gaobei slope belt is located in the northern part of Nanpu Sag (Fig. 1b) (Zhang et al., 2008). As a hanging-wall side, it is bounded by the Xinanzhuang normal fault to the northwest and by the Baigezhuang normal fault to

the northeast. While as a foot-wall side, it is bounded to the south by the Gaobei normal fault (Fig. 1b) (Guo et al., 2012; Jiang et al., 2013).

The strata developed in this study region include the Quaternary Pingyuan Formation (Q), the Neogene Minghuazhen Formation (Nm), the Guantao Formation (Ng), the Paleogene Dongying Formation (Ed) and the Shahejie Formation (Es) from top to bottom (Table 1). The Shahejie Formation can also be divided into Es₁, Es₂, Es₃ and Es₄ from top to bottom. Es₃ contains five Submembers, Es₃¹, Es₃², Es₃³, Es₃⁴, and Es₃⁵ (Zhu and Ge, 2001; Zhu et al., 2011; Zuo et al., 2011) (Fig. 2). Among them, the Es₃² and the Es₃³ are usually called Es₃²⁺³ Submember as a whole, being the target interval of this paper (Fig. 2 dashed-lined red box).

Fig. 1 Tectonic maps of Study area. (a): Structural position of Nanpu sag; (b): Geological background of Nanpu Sag (modified after Yuan et al., 2014, Guo et al., 2013); (c): The enhanced map of Gaobei area showing locations of the main wells.

The Paleogene tectonic evolution of the Bohai Bay Basin can be divided into three tectonic episodes, namely Synrift Episode 1, Synrift Episode 2 and Synrift Episode 3. Synrift Episode 1, corresponding to the development of Es₃⁵ and Es₃⁴, is the initial stage of a rifting tectonic movement, during when the Xinanzhuang Fault and Baigezhuang Fault started to become active and control the sedimentation of the hanging-wall Gaobei area. Synrift Episode 2, corresponding to the development of

Es₃³ and Es₃², is the main stage of the tectonic movement, which is characterized by rapid faulting processes and fast subsidence of the Gaobei area. Synrift Episode 3, corresponding to the development of Es₃¹, is the final stage of the rifting movement, during when the above two faults gradually became silent and the subsidence slowed down.

According to the local exploration and development traditions, the Es₃²⁺³ Submember can be subdivided into three sandgroups, namely (from bottom to top) Sg 1, Sg 2 and Sg 3.

Fig. 2 Regional stratigraphic sequence of the study area (modified after Yuan et al., 2014)

2 Materials and methods

Core observation and description of this study were based on core samples (longer than 200 m) mainly obtained from W06, W07, W08, W08-3, W08-5, W11,

W13-26, W15-21, W17-1, W19, W23 and W23-1 in the Paleogene Gaobei Slope Belt, Bohai Bay Basin. The corresponding well logging data to these wells were also used in this study. All of these underground data, which were acquired from the PetroChina Jidong Oilfield Co., are available for researchers who meet the criteria of the PetroChina Jidong Oilfield Co. for access to confidential data. A forward 2-D quantitative depositional simulation was implemented with Sedpak v5.1, which is an Ubuntu-based program developed by the research team of the University of South Carolina (Strobel et al., 1989; Kendall et al., 1991; Zhu et al., 2013; Wang et al., 2017).

2.1 Provenance, petrologic and facies analysis

In this study, compositional maturity, mudstone color index and heavy mineral approaches were adopted to determine paleocurrent directions in the study interval. The detailed method of compositional maturity was shown in Appendix 1, in which I_c was used to represent the compositional maturity of sandstone samples in the contour map (Fig. 3a). The detailed method of mudstone color analysis could be seen in Appendix 2, in which r was used to represent the degree of oxidation-reduction in the contour map (Fig. 3b). The detailed method of the heavy mineral analysis could be seen in Appendix 3, in which ZTR index was used to represent the degree of corrosion resistance and stability in the contour map (Fig. 3c).

Statistical analysis of thin sections of core samples was used to determine the lithologic component of the Es_3^{2+3} Submember. Using cumulative probability curves of granularity (referred to Visser, 1969), the depositional environment and the hydrodynamic conditions of the Es_3^{2+3} Submember were comprehensively analyzed.

Based on the core observation and description, as well as the petrologic analysis above, lithofacies within the Es_3^{2+3} Submember were classified and interpreted first. Then, along with correlated well logging signatures, the single-well microfacies were identified by the assemblies and combined characteristics of different types of lithofacies. Finally, under the constraints of these single wells, coupled with provenance features and seismic attributes, the distribution of the sedimentary facies

were mapped under a seismic-well based sequence stratigraphic framework.

2.2 Quantitative simulation

Quantitative simulations of the basin filling processes of Gaobei Slope Belt were implemented by inputting parameters derived from geological interpretations and modern analogs and empirical studies (Nemec, 1990; Blair and McPherson, 1994; Zhang et al., 2017; Dong et al., 2010a and 2010b). The back-stripping method was used to estimate the subsidence and sediment supply rate. Since the basin was balanced-filled during the deposition of the study interval (Zhang et al., 2017), the water supply always offset the difference of between the subsidence and the sediment supply. According to the specific situation of the study area (details see the following discussion part), several scenarios were set. Many simulation runs were conducted with parameter adjustment before the results matching the observed section.

3 Provenance of sandstone

3.1 Compositional maturity

As shown in Fig. 3a, the value of I_c is less than 0.2 to the northwest of Well W26, which is located in the northwestern part of the study area. Similarly, it is also less than 0.2 to the northeast of Well W04, which is in the northeastern part of the research region. However, the value of I_c is between 0.3 and 0.4 near Well W08-6 in the central part of the study area and ranges between 0.4 and 0.5 around Well W16 in the southern part of the research area. Furthermore, it reaches values higher than 0.5 near Well W23 in the southwestern part of the study area.

That is, the compositional maturity of sandstones from the Es_3^{2+3} Submember is lower in the northeast and northwest than in the southwestern part of the study region. Specifically, the sediment in the study area came from northeast and northwest during the depositional period of the Es_3^{2+3} Submember.

3.2 Mudstone color index

According to the formula for calculating the value of r and Table 3 (Appendix 2), no matter how high the degree of oxidation of sedimentary rock is, the value of r always varies from -100 to 100. If $r < 0$, it indicates a reducing sedimentary environment. In contrast, if $r > 0$, it shows an oxidizing sedimentary environment. The value of r hints at oxidizability (Huo, 2012; Zhao et al., 2009). In other words, the lower values indicate that the environment possessed a higher reduction level and is farther from its source region.

As Fig. 3b shows, the mudstones in the Es_3^{2+3} Submember are chiefly of minus index (gray to greenish), showing a northwards increasing trend. The trend indicates that the sediment mainly came from the northwest and northeast during the depositional period of the Es_3^{2+3} Submember in the research area. In addition, the two source areas were near Xinanzhuang fault and Baigezhuang fault, respectively.

3.3 Heavy mineral analysis

The ZTR index is less than 10 to the northwest of Well W26 in the northwestern part of the study area. Similarly, it is also less than 10 to the northeast of Well W12 in the northeastern part of the study area. It ranges from 10 to 20 near Well W11 in the central portion of the area, ranges from 20 to 30 near the Well W08-6 in the southern region, and reaches values higher than 40 near the Well W23 in the southwest of study area (Fig. 3c).

In short, the sandstones of the Es_3^{2+3} Submember have lower maturity in the northwest and northeast than in the southwest.

4 Petrology

According to the component analysis (following the approach of Zeng and Xia, 1986), the relative percentage of quartz feldspar and rock fragment are 28%, 35.5%, and 36.5% respectively. Therefore, the rocks have a relatively low content of quartz and high contents of feldspar and detritus (Fig. 4; Fig. 5).

Fig. 3 Contour maps of the study region suggesting that the sediment within the study area came mainly from the northeastern Baigezhuang uplift and the northwestern Xinzhuang uplift. a) Contours of the compositional maturity of the Es_3^{2+3} Submember; b) Contours of mudstone color index values in the Es_3^{2+3} Submember; c) Contours of ZTR values in the Es_3^{2+3} Submember

Fig. 4 Triangular figure showing sandstone types occurring within the Es_3^{2+3} Submember. The abundances of quartz are relatively low, showing that the fan delta was close to the source area of the bedrock and underwent transportation of a short distance.

Fig. 5 Photomicrographs of samples from the Es₃²⁺³ Submember.

A: W17-1, 3305.59m; B: W17-1, 3305.59m; C: W19, 3560.32m; D: W19, 3560.32m; E: W08-3, 4074.62m;
F: W06, 3199.86m

Examination of the cumulative probability curves of particle sizes from the study area shows that the curves take on various patterns, such as the two-stage pattern, the three-stage pattern, the complex two-stage pattern and the broad gentle arc (Fig. 6a, b and c). Also, the strongly inclined two-stage type (Fig. 6d,e) and the weakly inclined two-stage style also developed (Fig. 6f,g). These curves indicate the possible existence of both high-energy subaqueous distributary channels and low-energy sand bar/sand sheet environments.

Fig. 6 The cumulative probability curves of particle sizes: a) two-stage pattern; b) the three-stage pattern; c) the complex two-stage patterns; d, e) the strongly inclined two-stage type; f,g) the weakly inclined two-stage style

5 Facies and architecture

5.1 Lithofacies

The lithofacies of the sedimentary rocks are richly varied in the target interval. Through the lithofacies analysis of the Es₃²⁺³ Submember of the Gaobei slope belt, 10 lithofacies types have been recognized based on grain size and structures (Tab.1; Fig. 7). They could be classified into 3 categories. The first one, containing Gms, Gm and Gt, indicates mainly debris flows to lag deposits and minor channel fills. The second one, containing St, Sp, Sl and Sr, is characterized by relatively coarse to fine grain sized sandstones and reveals mainly lower flow regimes. The third one, containing Fe, Fsc, and Fm, is characterized by fine grain sizes. Also, the most frequent associations of these lithofacies are shown in Fig. 8.

Tab. 1 The types of lithofacies in the Es₃²⁺³ Submember

Code	Lithology	Sedimentary structures
Gms	Cobble, or pebble conglomerate	Massive, matrix-supported
Gm	Conglomerate	Massive or crudely bedded
Gt	Conglomerate	Trough cross bedding
St	Pebbly, coarse to medium sandstone	Trough cross bedding
Sp	Coarse to medium sandstone	High angle bedding (>10°)
Sl	Medium to fine sandstone	Low angle bedding (<10°)
Sr	Fine sandstone	Ripple cross lamination
Fe	Siltstone to muddy siltstone	Lenticular bedding, ripple cross lamination
Fsc	Muddy siltstone	Ripple cross lamination
Fm	Mudstone	Massive bedding

Fig. 7 Core samples of the lithofacies.

a: Gms, W15-21, 3075m; b: Gm, W08, 3890m; c: Gt, W17-1, 3306m;
d: St, W23, 3907.5m; e: Sp, W07, 3983.5m; f: Sl, W23-1, 3828.5m; g: Sr, W07, 3983.9m; h: Fe, W23-1,
3836m; i: Fsc, W23-1, 3825.5m; j: Fm, W08, 3916m.

Fig. 8 Some specific combinations of the lithofacies in the Es_3^{2+3} Submember. SDF:

Subaerial Debris Flow; SBC: Subaerial Braided Channel; SDC: Subaqueous Distributary Channel;

FSB: Front Sand Bar; FSS: Front Sand Sheet. Lithofacies codes see Tab. 1.

5.2 Sedimentary facies

According to the lithofacies and the lithofacies associations, we interpret that a fan delta sedimentary system is responsible for the sediments developed in the study interval.

5.2.1 Fan delta plain

Massive, poor-rounded, poorly-sorted and matrix supported cobble or pebble conglomerates with no fossils are interpreted as subaerial debris flow deposits (Fig. 8; Fig. 9). While well-sorted, poor-rounded, matrix supported conglomerates, with basal erosional surfaces or with basal erosional surfaces and mud gravels are interpreted as subaerial braided channel fill deposits (Fig. 8; Fig. 9). Sedimentary structures of these braided channel include trough cross beddings and high-angle beddings, and fossils are rarely founded either. There are also some brown colored, massive or horizontal bedding mudstones that are interpreted as flood plain deposits.

Fig. 9 Core and seismic characteristics of the fan-delta environment. SDF: Subaerial Debris Flow; SBC: Subaerial Braided Channel; SDC: Subaqueous Distributary Channel; FSB: Front Sand Bar; FSS: Front Sand Sheet. Lithofacies codes see Tab. 1.

5.2.2 Fan delta front

Fan delta front belongs to the subaqueous part of the fan-delta. Unlike the redish brown to brown in fan delta plain, the mudstone color in fan delta front mainly ranges from gray to brown. Fine conglomerates, pebbly sandstones, sandstones and siltstones with many kinds of sedimentary structures are also well developed in this

environment. Massive conglomerates with basal erosional surfaces, trough cross-bedding conglomerates, pebbly sandstones or sandstones, and parallel bedding to high-angle bedding sandstones are interpreted as subaqueous distributary channels (Fig. 8; Fig. 9). The combination of ripple cross-bedding siltstones to sandstones, low-angle bedding sandstones, and fine conglomerate to sandstones with massive or trough cross beddings, which usually show reverse rhythm as a whole, are interpreted as front sand bars (Fig. 8; Fig. 9). Thin layer, ripple crossbedding fine sandstones to siltstones interbedded with gray colored mudstones are interpreted as front sand sheets (Fig. 8; Fig. 9). On seismic profile, the fan delta is characterized by low-moderate frequency, moderate-high amplitude, moderate to high continuity with wedge shaped geometry (Fig. 9). In particular, subaqueous distributary channels can further be classified into 5 types (Fig. 10, Details see Appendix 4).

Fig. 10 Typical stacking types of subaqueous distributary channels

5.2.3 Prodelta

Predelta is another subfacies belonging to the subaqueous part of the fan delta. It is characterized by massive greenish gray to dark gray mudstones. Thin layers of muddy siltstones or siltstones are also developed among these mudstones.

5.3 Facies association and distribution

Within the Es_3^{2+3} Submember, fan deltas are the main sedimentary facies developed in the Gaobei slope belt. Moreover, fan delta front subfacies was predominant in the study interval. In Sg 1, the thickness of sand bodies vary mostly in the range of 10 to 20 meters, and it was distributed from the northeast and northwest to the southwest (Fig. 11a). The fan delta developed from the northeast and northwest to the southwest (Fig. 11d). In Sg 2, the thickness of the sand bodies increased compared to Sg 1, reaching more than 30 meters (Fig. 11b).

As the fan body became broader and progressed continually from the northeast

and northwest to the southwest, the subaerial parts were widely developed (Fig. 11d). In Sg 3, the fan delta, which was dominated by a transgressive sedimentary systems tract, decreased in size and retreated from the southwest to the center of the research area. During this period, the scale of the sand bodies was also reduced relative to that of Sg 2 (Fig. 11c,f).

Fig. 11 Maps of RMS amplitudes and corresponding sedimentary facies. RMS: Root Mean Square; SBC: Subaerial Braided Channel; SDC: Subaqueous Distributary Channel; FDF: Fan Delta Front; FDP: Fan Delta Plain; FSB: Front Sand Bar; FSS: Front Sand Sheet; IFA: Inter-Fan Area; LM: Lake Mud; PR: Provenance; Sg: Sandgroup.

Fig. 12 Cross section of sedimentary facies projected on a seismic profile (location see Fig. 1). SBC: Subaerial Braided Channel; SDC: Subaqueous Distributary Channel; FDF: Fan Delta Front; FDP: Fan Delta Plain; FSB: Front Sand Bar; FSS: Front Sand Sheet; IFA: Inter-Fan Area; LM: Lake Mud; PR: Provenance; Sg: Sandgroup; MRS: Maximum Regression Surface; TST: Transgressive Systems Tract; RST: Regressive Systems Tract. Lithofacies codes see Tab. 1.

6 Quantitative simulation

The duration of the deposition of the study interval was around 2 ma according to previous studies (Zhang et al., 2017). Thus we assumed the duration is 2 ma and the simulation time was set from -2 ma to 0 ma. Also, considering the lake level was dominantly controlled by the climate (open flowing basin connected to the regional water system), a new “lake level” was employed to represent the collective effect of the climate and the real lake level change. Several scenarios for simulation were set, and many runs were implemented until the simulating result fit the observed profile well. These scenarios are:

Scenario 1: the subsidence and sediment supply rate are constant, while the lake level is adjustable for fitting;

Scenario 2: the subsidence rate and lake level are constant, while the sediment supply rate is adjustable for fitting;

Scenario 3: the sediment supply rate and lake level are constant, while the subsidence rate is adjustable for fitting.

Reference scenario: keep all of the subsidence rate, sediment supply rate and lake level constant through the entire simulation duration.

According to the simulation results, Scenario 1 to Scenario 3 can all match the measured data very well after some parameter adjustments. Interestingly, although not exactly the same, the reference scenario simulation did resemble the measured data very well, too. We should remember that it was a scenario with all constant or fixed allogenic controls. The reference scenario shows a progradation trend and a coarsening-upward facies pattern first with the shoreline moving towards the basin side. Then it shows a consequent retrogradation trend and a fining-upward facies pattern with the shoreline moving towards the land side (Fig. 13).

Fig. 13 Sedpak simulation of the reference scenario. a) Chronostratigraphic diagram (aka Wheeler Diagram); b) Facies cross-section highlighting the shoreline trajectory. The sediment source direction was set only from the left side, and the sediment supply rate was set at

0.0075km²/ka for sand and shale constantly; the subsidence rate was set -0.7m/ka for the depocenter constantly; the lake level was set constant at -6m; the time step was set at 0.03ma (overall 67 steps for the total 2 ma); the isostasy effects were not included.

7 Discussions

Fan deltas are widely developed in continental rift settings. Similar to other sedimentary systems, the formation of fan deltas is a function of accommodation and sediment supply. Yet the accommodation is a package of several separate allo genetic factors including lake level, subsidence, climate, etc. (Catuneanu and Zecchin, 2013; Zecchin and Catuneanu, 2013, 2015; Li et al., 2015).

Baigezhuang fault in the NW and Xinanzhuang fault in the NE are the two controlling margin faults as shown in Fig. 1. The faulting activities during the deposition of Es₃ member were quite active. As mentioned in the geological background, the depositional period of the study interval belongs to the Syn-rift Episode 2 characterized by rapid faulting movement. In contrast, the coeval paleo-climate was steady (Zhang et al., 2017), which could be treated as a constant in a higher order (3rd) with probable fluctuations in lower orders (4th or lower). The coeval sediment supplies from NW and NE were abundant and quite proximal to the loading area, which is indicated by the maturity analysis. Primarily as a function of climate, the sediment supply is controlled by the climate to a great extent. Thus the sediment supply rate also could be treated as a constant. Due to the nature of the continental lakes, the lake level is not correlative to the global sea level. On the contrary, the lake level of the study area is more related to the regional hydraulic system, which was also dominantly controlled by the climate. Hence, tectonism and climate are the two ultimate factors that control the forming of the sedimentary sequences in the study area. While the former one may account more in such a rifting setting according to previous literatures (Strecker and Marrett, 1999; Withjack et al., 2002; Jackson et al., 2005; Zecchin et al., 2006; Ji et al., 2012; Wang et al., 2017).

According to the simulation results, making the allo genetic factors fluctuating in

some specific pattern to fit the real-world measured data is not very hard. However, keeping these factors constant to get some similar results is somewhat difficult. In the study interval, constant lake level, subsidence and sediment supply rate indeed made a stacking pattern similar to the measured data on a macro scale. They have both a regressive systems tract (RST) followed by a transgressive systems tract (TST), although there exist many differences in smaller scales. This indicates that, in larger scales, the fan delta system of the study area may form in a relatively stable environment that the depositional trend change was mainly because of the autoretreat effect (see Muto and Steel, 2001 and 2002) rather than significant fluctuations of sediment supply rate, climate or lake level. Certainly, the smaller scaled architectures could be attributed to the small-magnitude fluctuations of climate, tectonic subsidence, sediment supply or lake level change (the latter two are actually climate-controlled or closely related to the climate). Thus a stable subsidence rate with small-magnitude climate changes would be a plausible explain for the entire sequence of the fan delta system of the study area.

Rapid subsidence caused a rapid increase of the water depth of the fault-controlled continental rift lake basin. The forming period of Sg1 recorded the deepest level of the water body, while the water depth was decreasing (regression) since the sediment supply surpassed the subsidence rate. However, as the expanding of the fan delta surface area, the same sediment supply rate could not support the regression process any longer. This was the transition from regression to transgression, which was recorded by Sg 2 and Sg 3 (Fig. 14).

Fig. 14 The depositional model of the target interval. SBC: Subaerial Braided Channel; SDC: Subaqueous Distributary Channel; FDF: Fan Delta Front; FDP: Fan Delta Plain; FSB: Front Sand Bar; FSS: Front Sand Sheet; IFA: Inter-Fan Area; LM: Lake Mud; PR: Provenance

8 Conclusions

(1) Analysis of compositional maturity, mudstone color index values and heavy minerals suggests that the sediment within the study area came mainly from the northeastern Baigezhuang uplift and the northwestern Xinanzhuang uplift. According to the mudstone index values, the study area experienced a weak reducing environment, corresponding to a shallow or semi-deep lake. The proportion of stable components is low, suggesting that the sediments were adjacent to the source area and were transported over a short distance.

(2) Furthermore, a fan delta system is interpreted in the Es_3^{2+3} Submember. 10 lithofacies types have been recognized based on grain size and structures. These lithofacies types can further constitute several associations, including subaerial debris flow, subaerial braided channel, subaqueous distributary channel, front sand bar and

front sand sheet, etc.

(3) The fan bodies moved forward to the center of the basin during the formation of Sg 1 and Sg 2, which comprises the higher leveled regression systems tract (RST). The fan bodies retreated to the edge of the basin during the Sg 3, which comprise the higher leveled transgression systems tract (TST). Stable tectonic subsidence was indeed the dominant driving force to a continental syn-rift fan delta system, although the climate, sediment supply or lake level might bring some lower order (e.g., 4th and 5th order) superimpositions.

Acknowledgment

Financial support was provided by the Fundamental Research Funds for the Central Universities and the QUST Initial Fund for Young Scholars. The authors also acknowledge Dr. Phil Moore from U. of S Carolina and Prof. Zhu Hongtao from China University of Geosciences for their supports on the Sedpak simulation software.

Appendix

1. In this study, $I_c = Q / (F + R)$ (I_c represents the compositional maturity; Q, F, and R are on behalf of the content of quartz, feldspar and rock debris respectively).
2. The degree of oxidation-reduction that the color of mudstones reflects was calculated, depending on the following formula.

$$r = \left(\sum_{i=1}^n h_i \times r_i \right) / h$$

r color index of Mudstone in each stratum; unite: %

h_i The thickness of mudstone layers which have the same color in the correlative strata; unit: m

r_i Color index of each color; unit: %

h Thickness of the mudstone strata, $h = \sum_{i=1}^n h_i$ unit:m

Appendix Table 1 Color index of sedimentary rocks (modified after Huo, 2012 and Zhao, et al., 2009)

Color	Black	Dark gray	Gray	Gray green	Hoar	Yellow	Chocolate brown	Tawny	Red
Code	12	13	14	8	0	4, 5	9,10	15	1,2,3,11
r _i %	-100	-75	-50	-25	0	25	50	75	100

3. The ZTR index refers to a ratio that is given by [the content of stable heavy minerals / the content of transparent heavy minerals] x 100%. The stable heavy minerals include zircon, tourmaline, and rutile, and the transparent heavy minerals include zircon, tourmaline, rutile, staurolite, garnet, sphene, biotite, epidote, and barite.

4. Typical sedimentary sequences of the subaqueous distributary channels

Type 1 Normal Graded bedding- large cross bedding type

This type is characterized by fine conglomerate with granularity graded bedding at the bottom, and grades upwards to sandy sediments with cross-bedding. This kind is of positive rhythm (Fig. 10a).

Type 2 Reverse rhythm- positive rhythm pattern

This type of sequences usually consists of a reverse graded sedimentary unit at the bottom and an overlying positive grading sedimentary unit. There are sandstones with cross beddings at the top (Fig. 10b).

Type 3 Multi-channel overlapping and scouring pattern

This type is a composite and represents the overlapping of several phases.

Previous phases of channel deposition were reworked by the strong flow of later phases of deposition. In every single phase, the bottom of deposit usually contains boulder clay and other characteristics typical of scouring surfaces (Fig. 10c).

Type 4 Large cross bedding- low-angle bedding pattern

Trough cross bedding mostly appears in the lower parts of channel deposits and turns into graded bedding in the upper parts (Fig. 10d).

Type 5 Multiple channels overlay by a single sand bar or channel fill

This pattern is characterized by a single channel fill and sand bar overlying multiple channels. Large cross bedding can be seen at the bottom of the channel fill (Fig. 10e).

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