The Architecture of Braided Deltas in Modern Daihai Lake, Northern China: Implications for 3-D Sedimentation Models of Rift Lakes*

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Abstract

Daihai Lake, a modern lacustrine rift basin, located in the Inner Mongolia, Northern China, serves as an important modern analog for understanding processes and architecture of deltaic sedimentation in an active rift setting. Two of the largest deltas (Muhuahe Delta and Tianchenghe Delta) on the margins of Daihai Lake were surveyed to compare and contrast stacking patterns using photographs, field and sediment sampling. The Tianchenghe Delta on border fault has much steeper offshore gradients than the Muhuahe Delta on the axial shoaling margin where the trend of faults is orthogonal to the shoreline, resulting in a relatively narrow sandy dominated shelf and typical sigmoid progradation configuration. In contrast, the Muhuahe Delta on shoaling margin has a broad, sandy shelf and shingled progradation configuration which is strongly influenced by coastal currents.

This research presents preliminary results of an integrated study using sedimentary logs and core data collected from 49 trenches in the two deltas. Grid spacing of trenches is approximately 200 m over most of the study area, allowing for reasonably detailed mapping of spatial sedimentary facies. Two 3-D sedimentation models, which employ chronostratigraphic correlation technique, were generated utilizing the Schlumberger proprietary simulation software Petrel. The chronostratigraphic sedimentation models predict and represent the architectures and sand-body continuity of sediments, which can be applied in reservoir characterization of braided deltas in rift lakes.

Introduction

Lacustrine rift basins, which contain some of the most prolific hydrocarbon source rocks and reservoirs located in the eastern part of China, were formed during the Mesozoic and Cenozoic eras. Large volumes of oil and gas were generated from the organic-rich shale and contained in effective reservoirs in the basin (Anjos et al., 2000; Biswas, 1982; Katz, 1990; Liu, 1986; Tiercelin, 1991). Effective petroleum exploration in these ancient lacustrine rift basins require geologists to predict the distribution of depositional facies and internal character of reservoirs (Jiang et al., 2007; Qiang and McCabe, 1998; Zhu et al., 2005). However, accurate prediction of these reservoirs is difficult because of the abrupt vertical and lateral facies changes in rift lake deposits caused by tectonic activity and topography (Soreghan et al., 1999). Based on studies of modern rift lakes, prediction models for the depositional processes and distribution of various sand-dominated deltaic sedimentations can be developed. Analogous deltaic sedimentation in rift lake basins with comparable geological settings have been studied extensively around the world, most notably in the Eastern Africa (Cohen, 1990; Crossley, 1984; Johnson et al., 1995; Scholz and Rosendahl, 1990; Soreghan et al., 1999; Wells et al., 1999), Eastern China (Li et al., 1982; Yu, 1995; Zha, 1984), and in Lake Baikal (Hans Nelson et al., 1999; Hutchinson et al., 1992). These kind of basins usually include coarse-grained deltas, such as fan deltas and braided deltas (McPherson et al., 1987, 1988; Nemec and Steel, 1988; Orton, 1988; Yu, 1997, 1995, 1994), which are analogs for the potential syn-rift hydrocarbon reservoirs. Sedimentation patterns in rift lake basins have been investigated for a long time. The investigation includes facies stacking, paleoclimatic conditions and paleotectonic activities, each of which has led to important advance in our understanding of sedimentary processes and sediments distribution in lacustrine environment (Barr, 1987; Blair and McPherson, 1998, 2008; Cohen et al., 1986; Coleman, 1982; Fisher et al., 2008; Groshong, 1989; Johnson et al., 1995; Konate, 1994; Qiu, 1992; Seidel, 2008; Suydam, 1997; Xia et al., 2004).

Daihai Lake, the focus of this study, is a modern extensional basin filled with coarse-grained sediments (Wang, 1991). Due to its typical geological characteristics of a rift basin, the lake is regarded as one of the best modern analogs of a lacustrine rift basin in Eastern China. The drainage basin part is subdivided into thirteen major river catchments. In the rift tectonic setting, nine fan deltas on a border fault in the northwest region of the lake have much steeper offshore gradients than the three braided deltas on axial and southeastern shoaling margins. The two deltas studied here, Muhuahe Delta and Tianchenghe Delta, were selected on the basis of tectonic setting and distribution along the shoaling margins of the lake. These two deltas exhibit significant differences in tectonic, sedimentation and limnological settings.

Over the past decade, major progress has been achieved on classifications of deltaic system, making it possible to develop new and improved depositional facies. However, little was known about the spatial facies architecture and lithologic variability of the deltas in lacustrine rift basin. Thus, the objectives of this study are (1) to identify the specific lithofacies types based on texture and lithologic character of sediments; (2) to compare and contrast the depositional processes, morphology and sedimentary facies of the deltas in different tectonic setting, drainages, and sediment discharge rates; (3) to establish the framework of sand bodies for reservoir prediction, and delineate their spatial extent. Therefore, the results of this study are applicable to a variety of lacustrine rift reservoirs in East China or other areas.

Geographic and Geological Setting

Daihai Lake is located in Liangcheng County (40° 29′ 27″ - 40° 37′ 06″ N, 112° 33′ 31″ - 112° 46′ 40″ E). In the part north of the lake, Manhan Mountain with the maximum elevation 2288 m and strike 60° is the footwall block of the northern border fault system (Figure 1). Matou Mountain in the south of the lake with the maximum elevation about 1600 m comprises hills. The basin covers an area of 653.3 with catchments of 2289 . Daihai Lake is 86.5 , with the lake level elevation at 1218 m and a maximum depth of 16.05 m. The lake is in a delicate state of hydrologic balance, with all of the annual water loss occurring through evaporation, resulting in water salinity of 4 g/l.

Daihai Lake was formed during late Pliocene to early Pleistocene (Li, 1972). A series of northeastern faults which confined the grabens had developed in southern Inner Mongolia due to the Himalayan movement. The rift system, which consists of Daihai Lake, Huangqihai Lake and Erhai Lake, is 150 km long and 15 km to 20 km wide (Figure 1B). The structural framework of Daihai Lake rift basin was principally controlled by northeastern and southeastern faults. Due to the different intensity of faulting, the hanging-wall block north of the lake exhibits steeper slope gradients than in the south. In addition, basalt south of lake indicates that the fault systems were active before Daihai Lake formed.

Archean and Cenozoic Formations were exposed around the basin (Figure 1C), with a lack of Palaeozoic and Mesozoic rocks. Adjacent to the main basin border fault in the northwest, rift-related highlands rise and consist of Archean granite gneiss, while the mountain ranges in the southeast are composed of Tertiary basalt (Liu, 1965). The ephemeral rivers of the drainage have built modern alluvial fans at the front of mountains and deltas along the margin of the lake, with thicknesses ranging from 100 m to 240 m.

Data and Methods

This study includes two aspects, field study primarily for sample and data collection, and laboratory experiments mainly for determination and interpretation. The field program entailed trenching, sedimentary structures identification, profiles description, sampling, and photographing at selected locations in the two deltas. The laboratory work involved lithofacies and architectural elements analysis, and establishing a depositional model.

In order to determine the sedimentary features in the two deltas, 32 trenches in Tianchenghe Delta and 17 trenches in Muhuahe Delta were dug with shovels. The intervals of trenches are approximately 300 m to 500 m, in response to the topographic variation, water table change, and solidness of sediments. The colors and grain sizes of the sediments, sedimentary structures, and lithofacies were described for each profile. The sand bodies' shapes and their lateral extensions were identified in terms of the bounding surfaces hierarchy. The geometry of the deltas, and switching and migration of distributary channels were observed by remote sensing imagery.

The laboratory work mainly determined grain size, identified bounding surfaces, and established spatial depositional models. The grain size distribution curves from a number of samples were obtained by using a Marlvern laser particle size analyzer. Depositional models of deltas were established by integrated columns and bounding surfaces.

Sedimentation

The depositional system consists largely of braided fluvial-delta facies, which are distributed along the margins along Daihai Lake (Figure 2). The deltas along the margin of Daihai Lake contain gravels to very fine-gained sediments of quartz, feldspar, debris and abundant micas that characterize their terrestrial sources. The general color of sediments is white to dark grey of sands and silts, and dark grey to black of mud. The concave-up cross-stratified, trough and planar cross-stratified, and massive were dominant sedimentary structure types of the measured trenches. To establish the spatial distribution of sand bodies and to reconstruct depositional evolution of these deltaic systems, the lithofacies were identified and grouped into assemblages; architectural elements were determined based on bounding surfaces.

The sediments in the two deltas were subdivided into fourteen different lithofacies, which include three gravel lithofacies, six sandy lithofacies and five clayey lithofacies, based on lithologic characters, primary sedimentary structures and geometry (Miall, 1977, 1978b). The lithofacies survey provides insight into the depositional processes on the basis of the sedimentary structures that can be interpreted in terms of the hydrodynamic regimes (Postma, 1990; Simons et al., 1965). Each lithofacies, summarized in Table 1, has been described, interpreted and classified from the coarsest (gravel) to the finest (mud) and a code (Table 1) modified from Miall (1978, 1996) and Postma (1990) has been assigned to each lithofacies.

Application of the bounding surfaces concept allows the subdivision of a clastic succession into a hierarchy of architectural elements ("packets of genetically related strata" termed by Allen, 1983). An architectural element is lithosome characterized by its geometry and scale, represents a particular process or suite of processes occurring within a depositional system (Miall, 1988). Based on distinctive lithofacies assemblages, bounding surfaces (or geometries) and internal stratification, nine kinds of architectural elements have been defined in the deltas of Daihai Lake. The architectural elements fall into two main groups depending on the rank of their bounding surfaces. The architectural elements within fifth-order surfaces comprise: (1) gravelly braided channel (GC), (2) sandy braided channel (SC), and (3) distributary channel (DC). The architectural elements within fourth-order surfaces comprise: (1) ephemeral flood sediments (EF), (2) downstream accreting macroforms (DA), (3) overbank fines (OF), (4) laminated sand sheet (LS),

(5) flood sheet flow deposit (FS), and (6) wave sand sheet (WS) (Figure 3). The channel elements may include component DA, LS units with smaller-scale.

The Muhuahe Delta is located in the east of Daihai Lake. Sediments in this delta are fine and well-rounded as a result of the longest distance (more than 50 km) of source rock. The Muhuahe River is a braided river with moderate sinuosity. Fine to coarse sands with trough cross bedding, planar cross bedding and mixed bedding are common in channels on delta plains. Silt or muddy-silt layers with wave ripples are prevailing in delta fronts. Sedimentary successions of Muhuahe Delta were coarsening upward with some fining upward channel sedimentation. Erosional surfaces and lag sediments were common in channel sedimentation. The wave ripples in delta fronts suggest that coastal waves reworked the sediments and formed distal bars along shoreline with good connectivity. However, during 1988 to 1993 evaporation in Daihai Lake was low while discharge of Muhuahe River was high. The Muhuahe Delta was bird foot-like because of the greater of stream action than wave action. Subsequently, with the high rate of evaporation and strong wave action, the Muhuahe Delta was cuspate-like. Thus, when the evaporation decreased, the delta was fluvial-dominated with distributary mouth bars in delta fronts due to the strong stream action. In contrast, the delta was wave-dominated with distal bars along shoreline as evaporation increased.

Tianchenghe Delta is located on the south side of Daihai Lake. The grain sizes of these deltas is coarser than that of Muhuahe Delta due to the shorter distance of sediment supply of 15 km to 30 km. The average gradient of the southern depositional slope is 2° to 3°. The feed river of the delta is an ephemeral stream with a large range of grain size distribution, and they dried up in arid seasons. Braided distributary channels with gravel, gravelly-sand and coarse-sand were common in the delta plain. Pebbles in channels show moderate rounding with diameters of 0.05 m to 0.1 m. Massive bedding, planar cross bedding and trough cross bedding were the main sedimentary structures in the sediments. Fine silt and mud sedimentation were developed in the delta front. The silt sedimentation was characterized by ripples and laminations. Tianchenghe Delta also has large scale channels with moderate sinuosity. Sedimentary successions in channels were fining upward with erosional surfaces and lag sediments. Sedimentation of delta front was characterized by interbeds of mud layers and fine-sand layers with ripples. The dark gray mud layer at the bottom of sedimentary sequence indicates the coarsening upward sequence of delta front. Sand bodies were widespread in the delta front with good connectivity due to the gentle slope gradients.

Spatial Depositional Model

Near-shore morphology and sediment patterns vary significantly between the two deltas. Slope gradients of the Tianchenghe Delta located at the south border fault are steeper than the ones of the Muhuahe Delta situated on the axial shoaling margin. Although both exhibit a well-defined lobe at the lake-ward margin, the width and spatial extension of these deltas are different due to re-sedimentation by the wind-generated waves of Daihai Lake. The Muhuahe Delta has a more extensive subaerial delta than the

Tianchenghe Delta, partly because it is situated at the northeastern gentle slope margin with a larger terminal splay, but also due to its higher sediment discharge. As a result, much of the coarse bed load from the Muhuahe River was deposited on the delta plain, leaving a predominantly fine-grained suspended load at the further delta front. By contrast, the relative highly confined space for subaerial deposition, together with the narrow shelf and steeper slope gradients, provides the setting for rapid dispersal of coarse sediments in the steep slope offshore from the Tianchenghe River. Combining vertical logs and cross profiles it was possible to reconstruct spatial depositional variations and 3-D models of the deltas (Figure 4).

Sedimentary facies of Muhuahe Delta mainly represent a braided delta which is characterized by a broad sandy shelf and are strongly affected by waves. The notable projection of this delta into Daihai Lake, given a fetch and wave regime, results in an asymmetric braided-delta front with a windward west side and leeward east side. Sedimentary successions in channels were fining-upward with erosional surfaces and lag sediments. Sedimentation of the delta front was characterized by interbeds of mud layers and fine-sand layers with ripples. The dark gray mud layer at the bottom of sedimentary sequence indicates the coarsening upward sequence of the delta front. Silty sand bodies were widespread in the delta front with good connectivity due to gentle slope gradients. Rather than resisting wave energy, sediment is variably eroded and redistributed along the delta front as a function of the variable wave energy and grain size. The coarse-grained to gravelly facies predominantly accumulated in the delta plain as a result of rapid fall-out of the coarsest suspended load carried by the ephemeral stream, whereas the mud beds were mainly deposited in the delta front and partly transported lake-ward to form the deeper lake tracts.

As a modern deposit, the Muhuahe Delta provides a complete exposure of a scale that is generally impossible to measure from ancient outcrops. In order to determine the sediment filling patterns and sand body skeletons in the deltas, cross sections (longitudinal sections along the axis of the delta and transverse section through the delta plain) were correlated with vertical sedimentological logs at selected locations on the delta lobes (Figure 5). Sections (A) to (C), whose locations are shown in Figure 5, extend from proximal to distal delta with the length ranging from 2.5 km to 3.7 km. These profiles reflect the fact that sedimentological distinctions between the different parts of the delta are based on the changes of lithofacies and element assemblages' characteristics. Collectively, the elements are characterized by coarse-grained beds in a proximal delta, whereas fine-grained beds are found in the distal delta. The decrease in architectural elements thicknesses is shown in basin-ward directions away from the source, suggesting that the delta has a lobate shape. The pre-existing sand bodies were frequently cut by switched and migrated channels with 100 m to 200 m lateral extent in proximal delta, resulting in significant amalgamation of elements and well connectivity of sand bodies both horizontally and vertically. The architectural elements in distal lobe (delta front) are characterized by fine-grained lithofacies with ripples and laminas, and predominantly represent sheet-like or lenticular shape, which is interpreted as results from the spreading and deceleration of unconfined sheet-flood events over a continually wider area (Fisher et al., 2008).

Section (E) is a transverse profile through the delta plain, which mainly reflects the lateral extension and connectivity of architectural elements. Sandy architectural elements are predominant in the center of delta near the feed channel. These elements are commonly relatively thick and superimposed, whereas the lateral extension are limited. Channels in the profile are characterized by coarse-grained lithofacies and obvious incision at the bases. Flanks of section (E) primarily comprise FS, OF, LS, WS, in which sand bodies are more than 200 m in lateral extent. Individual sand bodies in the delta front are commonly separated by thin veneers of silt and clay.

Discussion

The formation of Daihai Lake and evolution of depositional systems were driven by various complicated geological agents. The tectonic controls on depositional systems were mainly characterized by gradients of slope and mainly manifested in the following aspects of the delta: external geometry, sedimentary sequences and profile configuration (Figure 6). Deltas on steep slopes, which cover small areas, are elongate due to the restricted depositional region and persistent stream action. However, deltas on gentle slopes, which cover large areas, are in general lobate as a result of the relative open depositional region and along-slope currents. In Daihai Lake, Tianchenghe Delta is lobate, and the Muhuahe Delta is cuspate which was reworked by coastal waves.

The sedimentary sequences of deltas on steep slopes are characterized by thick sand layers interbedded with thin veneers of mud. With the decrease of slope gradients, deltas consist of more mud and less sand sediments. Therefore, thick mud interbedded with thin sand layers are the main characteristics in deltas on the gentle slope. Meanwhile, deltas on steep slopes have coarser grain size and a lager scale of sedimentary structures than the ones on gentle slopes. The sinuosity of distributary channels in deltas on gentle slopes is larger than deltas on steep slopes. The incised distributary channels in deltas on gentle slopes are deeper due to the persistent stream action. The profile configurations of deltas on steep slopes are sigmoid with foreset and bottomset. Topset are gradually predominant along with the decrease of slope gradients. Shingle foreset were developed on the gentle slopes.

Conclusions

1) Based on characteristic lithology, primary sedimentary structures and geometry, the sedimentation in the two deltas has been divided into three groups of lithofacies: gravelly lithofacies (Gm, Gi, Gp), sandy lithofacies (Sp, St, Sm, Sh, Sr, Sw) and five clayey lithofacies (Fr, Fc, Fm, M1, M2).The architectural elements are grouped into “architectural elements in fifth-order surfaces” comprising gravel-braided Channel (GC), sandy-braided channel (SC) and distributary channel (DC); other elements are defined under the “architectural elements in fourth-order surfaces”, including ephemeral flood sediments (EF), downstream accreting macroforms (DA), overbank fines (OF), laminated sand sheet (LS), flood sheet flow deposit (FS) and wave sand sheet (WS).

2) The spatial depositional model of the deltas demonstrate the various sediment compositions which are controlled by structural

setting, slope gradients, and the amount and type of sediment discharge by rivers. The tectonic setting dominates the overall distribution of sedimentary facies. Nevertheless, high-frequency processes driven by winds, waves, and changes in lake level could affect the sedimentary characteristics.

3) The architectural elements are characterized by coarse-grained beds in the proximal delta, representing significant amalgamation of elements and well connectivity of sandbodies. In contrast, the architectural elements in the distal lobe (delta front) are characterized by fine-grained lithofacies with ripples and laminas, and predominantly represent sheet-like or lenticular shape.

4) The Tianchenghe Delta on the border fault has much steeper offshore gradients than the Muhuahe Delta on the axial shoaling margin where the trend of faults is orthogonal to the shoreline, resulting in a relative narrow sandy dominated shelf and typical sigmoid progradation configuration. The Muhuahe Delta on the shoaling margin has a broad, sandy shelf and shingled progradation configuration which are strongly influenced by coastal currents.

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Zhu, G.Y., Q. Jin, J.X. Dai, S.H. Zhang, L.Y. Zhang, and Y.L. Zhang, 2005, A Composite Hydrocarbon-Generation System: An Important Concept for Source Rock Evaluation and Hydrocarbon Prediction in Rift Lacustrine Basin (in Chinese with English abstract): Chinese Journal of Geology, v. 40, p. 133-144.

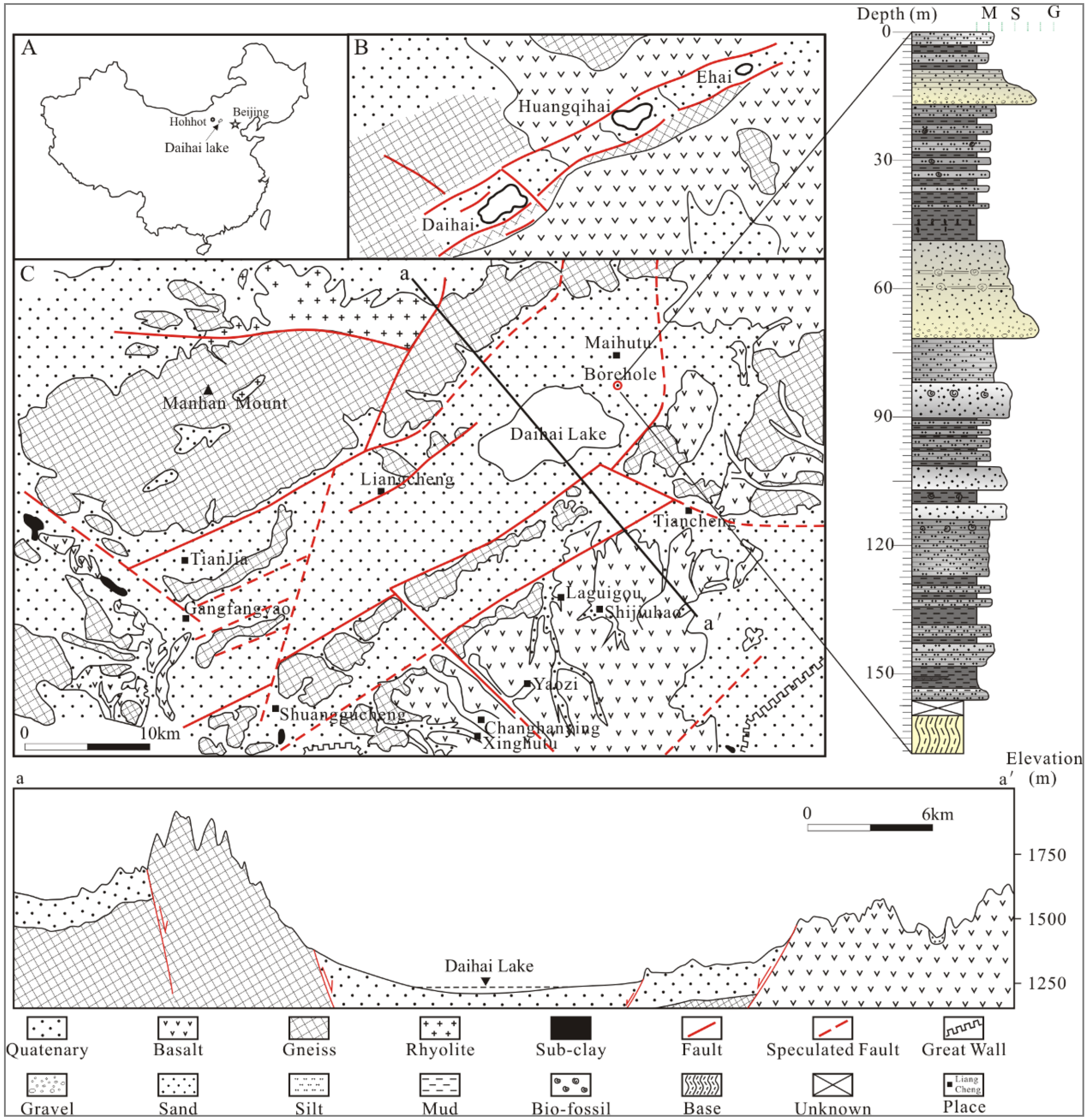


Figure 1. Geologic map of Daihai Lake area in Northern China showing regional geological setting, lithologic column of borehole (Li, 1972), and regional cross section.

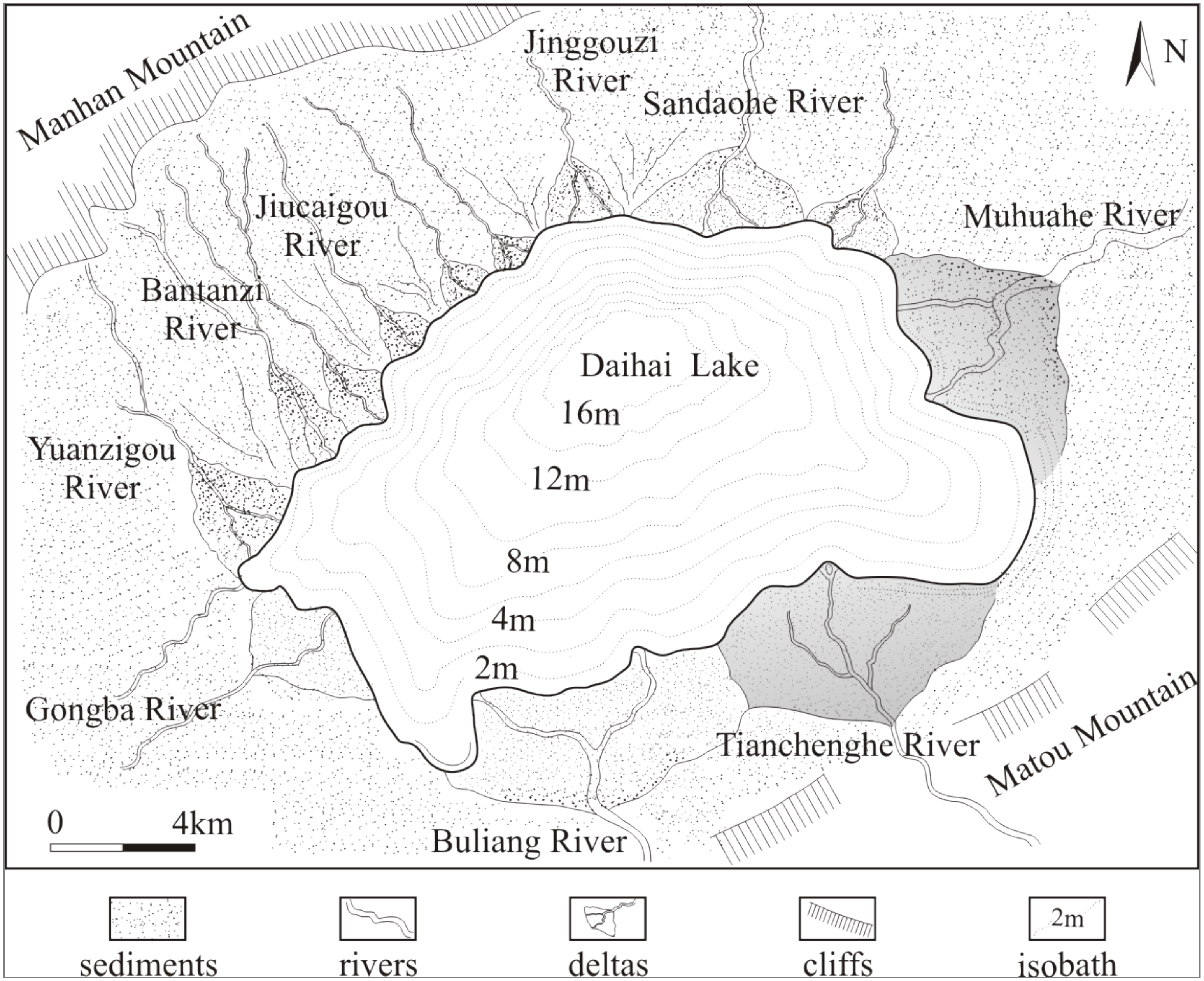


Figure 2. Distribution of fluvial-delta systems in Daihai Lake basin. Thirteen primary ephemeral rivers developed deltas around Daihai Lake. The two shadowed deltas are the objectives of this research: Muhuahe Delta and Tianchenghe Delta.

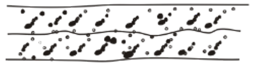
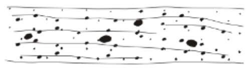
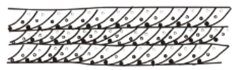
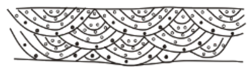
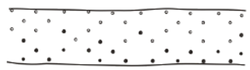
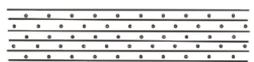
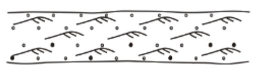
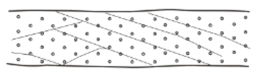
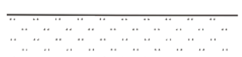
Code	Depiction	Grain Size	Sedimentary Structure Description	Interpretation
Gravelly lithofacies assemblages				
Gm		Massive, gravel	Structureless	Longitudinal gravel bars, lag deposits in channel
Gi		Crudely bedded gravel	Imbrication	Longitudinal bars
Gp		Gravel stratified	Horizontal bedding, planar cross-beds	Linguid bars or deltaic growth
Sandy lithofacies assemblages				
Sp		Sand, medium to very coarse, may be pebbly	Solitary or grouped planar cross-beds Megaripple bedding	Transverse bars, point bars (low flow regime)
St		Sand, medium to very coarse, may be pebbly	Solitary or grouped planar cross-beds	Dunes or minor channel fills, lower flow regime
Sm		Sand, medium to very coarse, may be pebbly	Massive	Rapid deposits, collapse, highly concentrated stream flows
Sh		Sand, fine to medium	Flat bedding or Parallel bedding	Planar bed flow, high flow regime
Sr		Sand, fine to medium	Ripple cross lamination	Current ripple
Sw		Sand, medium to very fine, may be silt	Oscillation cross bedding	Winnowing, lake beach deposits
Clayey lithofacies assemblages				
Fr		Silt, may be fine sand	1.Wave ripple marks 2.Current ripple marks	1.Delta front or beach deposits 2.Overbank or swamp deposits
Fc		Silt, or mudy silt	Thin interlayer of mixed bedding consist of wavy, lenticular and flaser bedding	Deltaic front deposit
Fm		Silt, may be fine sand	None or massive	Overbank or drape deposits
M_1		Mud, may be silt	Light color	Overbank deposit
M_2		Mud	Dark color	Prodelta

Table 1. Description and interpretation of deltaic lithofacies in Daihai Lake. The classification scheme is modified from Miall (1977, 1988, 2003).

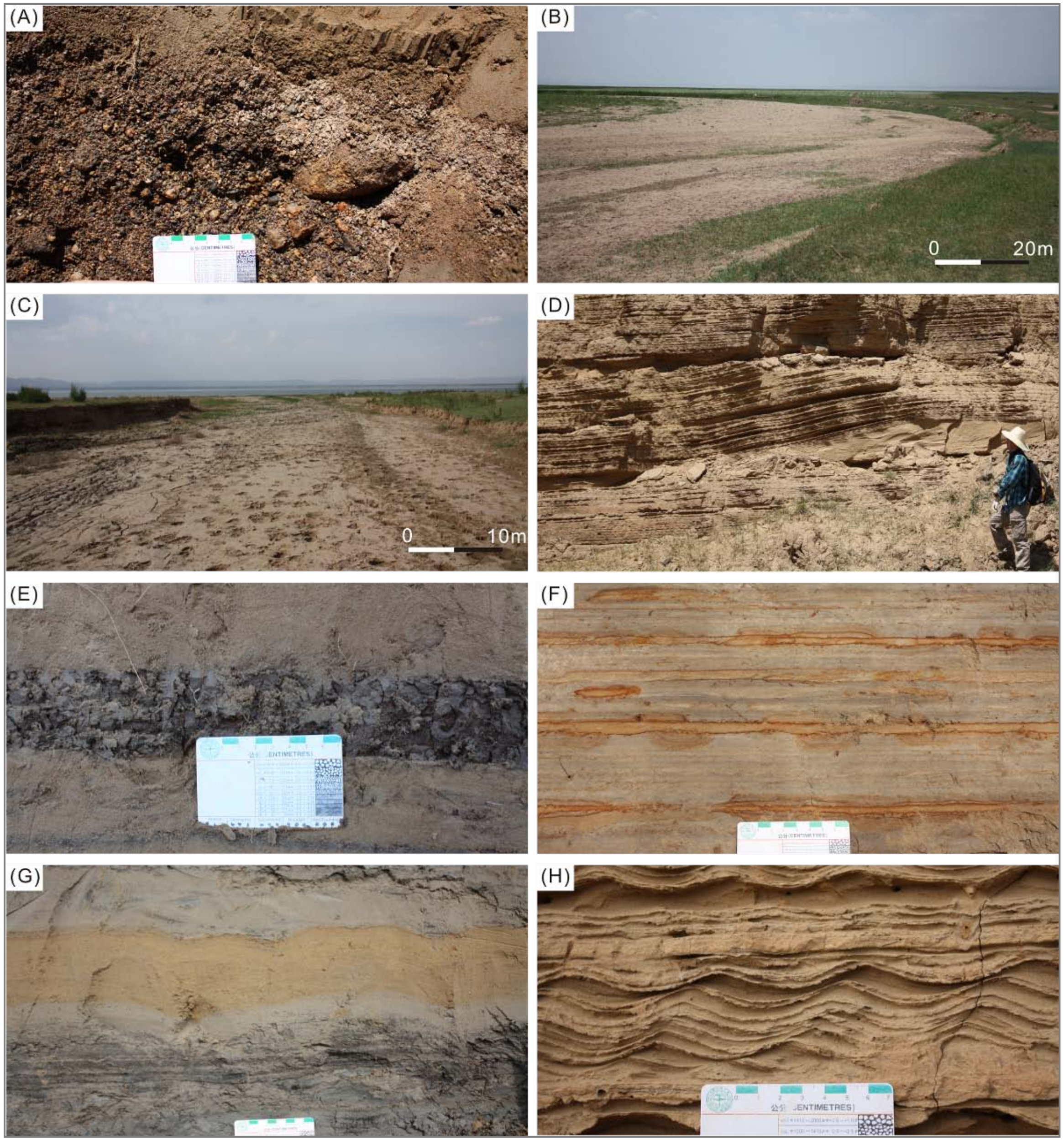


Figure 3. Architectural elements in Muhuahe Delta and Tianchenghe Delta. (A) Gravelly braided channel; (B) Sandy braided channel; (C) Distributary channel; (D) Downstream accreting macroforms; (E) Ephemeral flood sediments; (F) Laminated sand sheet; (G) Overbank fills; (H) Wave sand sheet.

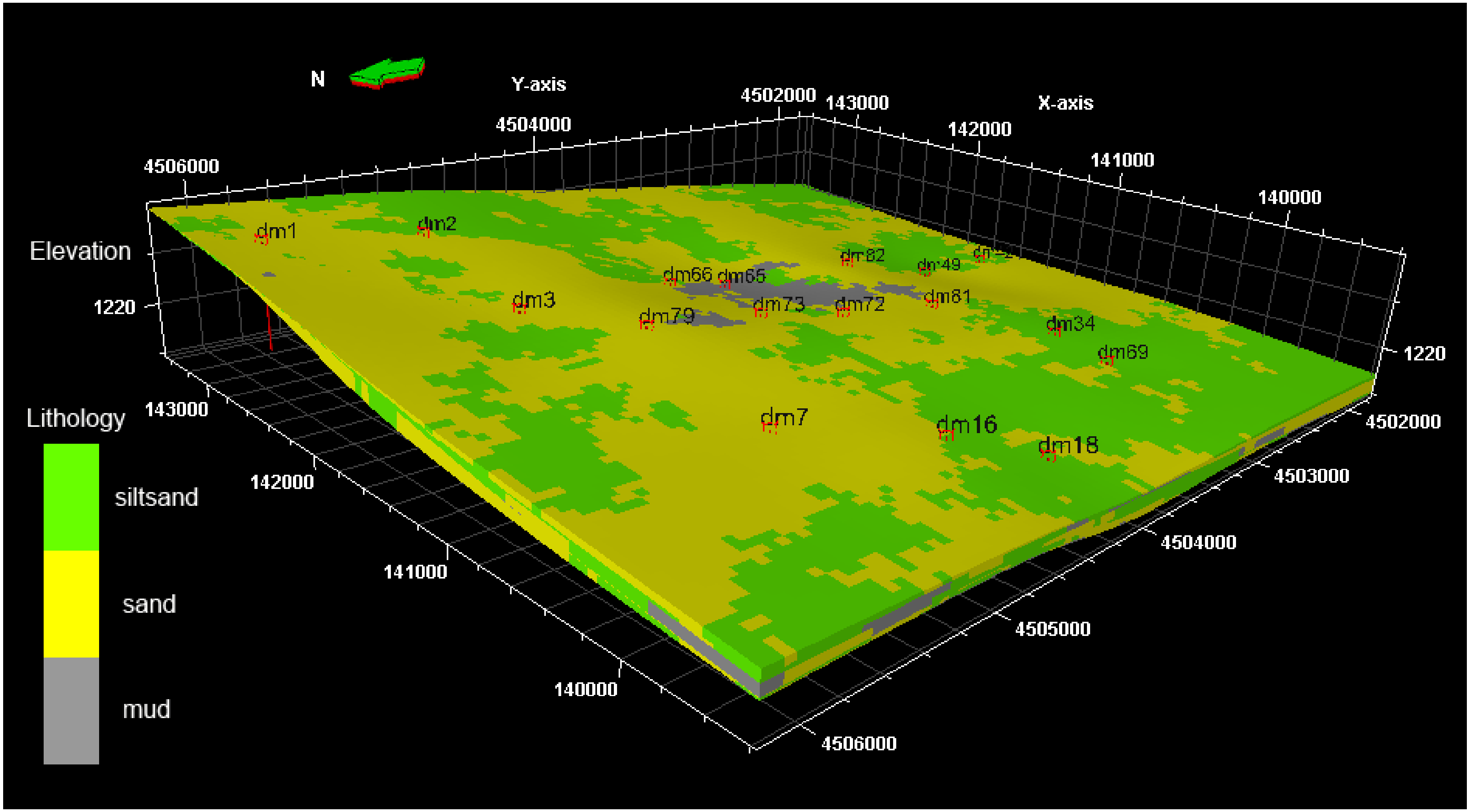


Figure 4. Spatial depositional model of Muhuahe Delta showing the progradation and distribution of sedimentary facies. The data was collected from seventeen trenches dug on Muhuahe Delta.

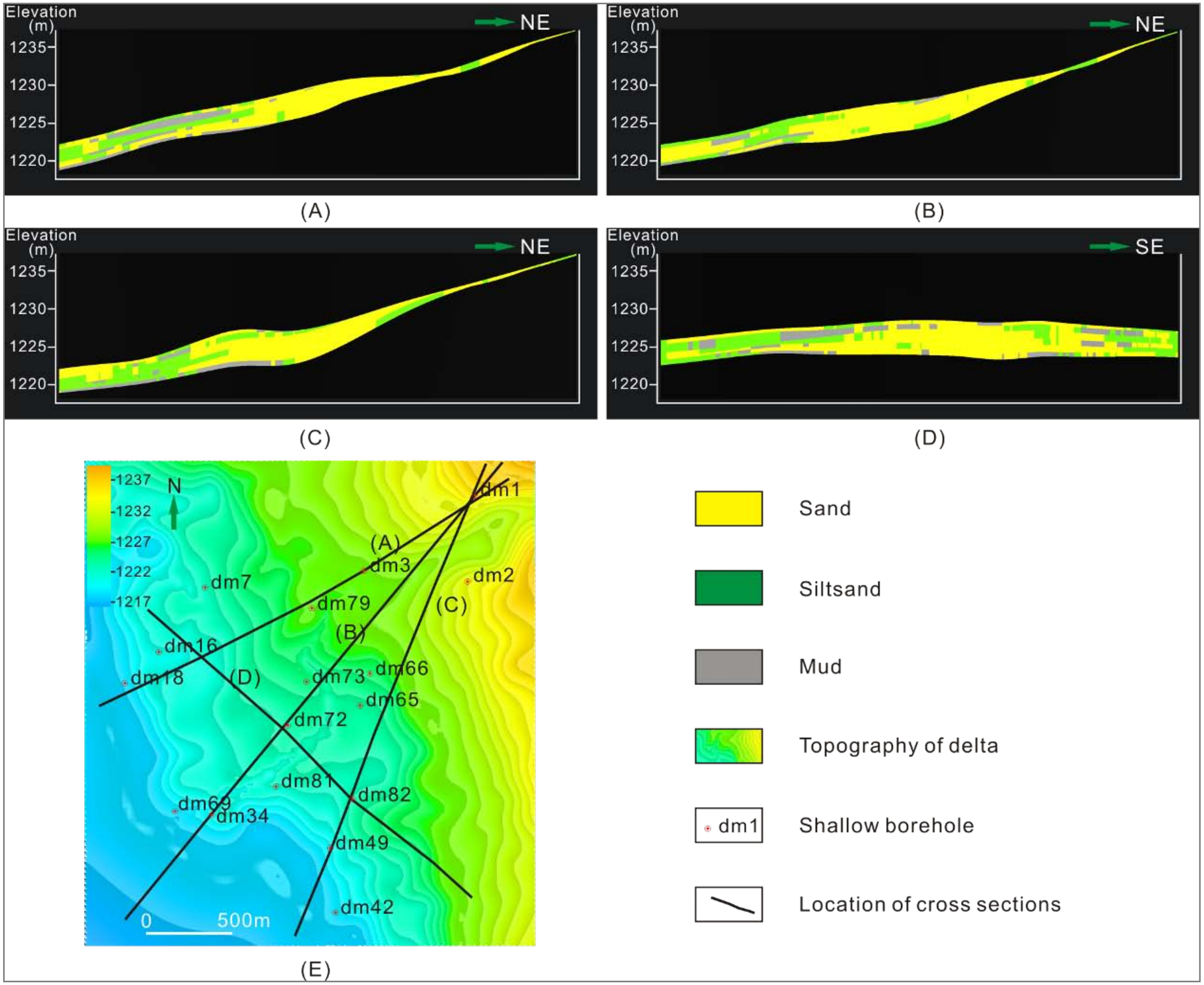


Figure 5. Topography and facies cross sections from the three-dimensional model of Muhuahe Delta. Note the architecture of facies in the longitudinal sections (A), (B) and (C) and transverse section (D). Distal bars were developed in the delta front (E).

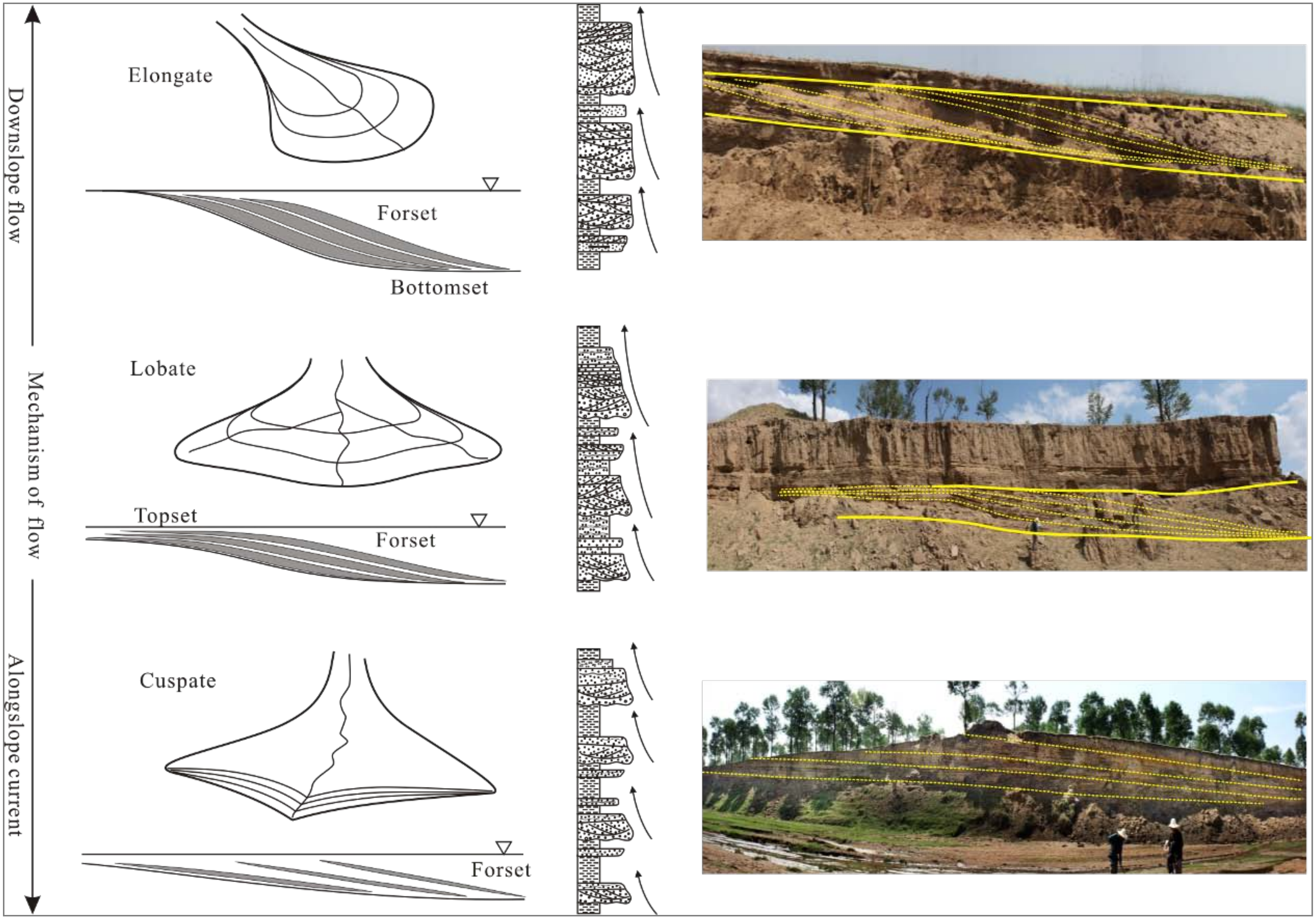


Figure 6. Tectonic controls on depositional systems and interaction between down-slope flows and along-slope currents.