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Sequence Stratigraphy of Fluvial Facies: A New Type Representative from Wenliu Area, Bohai Bay Basin, China

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Additional information is available at the end of the chapter

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Abstract

The application of sequence stratigraphy to the fluvial portion of sedimentary basin fills is most challenging, especially where the fluvial deposits under analysis are isolated or far away from coeval shorelines and marine influences. Taking the Wenliu Area as an example, this chapter aims at addressing researches about another type of river. High-resolution stratigraphic analysis of the lower second member of the Shahejie Formation of the W79 Block of Bohai Bay Basin (China) has revealed that the study area, previously interpreted as a shallow water delta system, actually originated in a subaerial setting with a distributional pattern. The base level fluctuations are mainly controlled by the regional tectonic setting. Active subsidence stages tend to make base level rising semi-cycles, while relative stable stages tend to make base level falling semi-cycles.

Keywords: fluvial, sequence stratigraphy, Bohai Bay Basin

1. Introduction

At the end of 1980s, Vail proposed the theory of sequence stratigraphy. At present, this theory has become a powerful new method to study sedimentary strata. Since Posamentier and Vail et al. in 1988 established the first non-marine (alluvial) sequence stratigraphy model [1], people began to pay attention to the difference between allo genetic cycles and authigenic cycles in fluvial depositional system. The eustasy, the tectonism, the climate, and other factors beyond the river power system are defined as allo genetic factors. The factor of the system itself caused by sediment cycles is called authigenic factor, such as

the lateral migration of the channels. People can explain the interaction of the allogenic controls (accommodation space and sediment supply) which have controlled the formation the fluvial sequence. Many authors have put forward their respective models [1–15]. But till now, there is still not a widely accepted model as a passive continental margin model of sequence stratigraphy.

Fluvial deposits are among the best understandable depositional systems. However, the associated sequence stratigraphy application in fluvial systems is one of the most challenging topic, especially when the river sediments are isolated or away from the shorelines and the sea, such as the overfilled continental sedimentary basins which have only the continental strata record preserved, or in the case that the data availability is limited to the continental basin. In the latter case, all efforts should be made to expand the range of observation scale, if possible, to study the relationships between the rivers and the age of the coastal and marine systems. However, the modern stratigraphy is enough in order to provide a genetic stratigraphic analysis of the stratigraphic record, from the scale of a single depositional system to the scale of the whole basin [16].

All siliciclastic detritus is transported by fluvial system from some point. Debris is eroded from mountain source area and is carried into basins, forming alluvial fans, coastal plains, deltas, fan deltas, as well as fluvial deposition itself. Recognizing fluvial depositional settings and reconstructing local fluvial styles are the main works of a sedimentologist. Three conventional examples [16] of fluvial styles are shown in **Figure 1**, while there may be some other types beside the conventional ones [19].

Taking the Wenliu Area as an example, this chapter aims at addressing researches about another type of river.

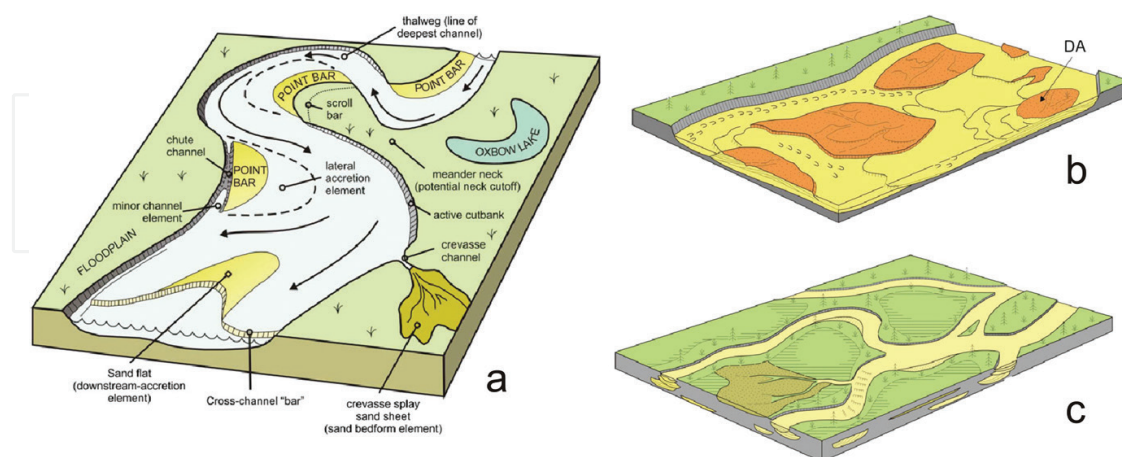


Figure 1. (a) A model for a meandering river, based on the South Saskatchewan River, Canada [17]; (b) a model for a sandy-braided river, based on the South Saskatchewan River, Canada [17]; (c) a model for an anastomosed river in a humid environment. Based on the work of Smith and Smith [18] in Banff National Park Canada.

2. Distributive fluvial deposition

The new river type we are going to propose is a kind of river that resembles distributive fluvial system (DFS) very much. DFS was firstly raised by Weissmann et al. [20]. Weissmann et al. have discussed that many aggradational depositional systems are dominated by distributive landscapes in both subaerial and subaqueous settings. The term “distributary fluvial systems” (DFS) addressed a key question in the earth sciences, i.e., that the most of the current fluvial facies models have a limited relevance in the interpretation of the ancient deposits.

Weissmann et al. [20] also pointed out that many of the DFSs have been impacted by significant Quaternary climatic fluctuations and the deposits will represent the Quaternary sedimentary features of the history. From the regional to the local scale, the distributive fluvial systems display characteristics including: (1) deposition in the alluvial system becomes diving into the basin, (2) the radiation pattern of channels from a vertex, (3) a broadly fan-shaped deposit that is convex upward across the DFS and concave upward down-fan, and (4) an intersection point above which the alluvial system is held in an incised valley and below which it spreads out across an active depositional lobe (if the river is presently incised into its DFS). The observed DFS geometry and graphic style in these different basins are very different. In the open DFSs, the river is not confined in a valley, nor is able to transfer on the surface of DFS. The tearing process is dominated by node tearing near the DFS vertex or intersection. These rivers seem to have significant differences from the valley, because the floodplain material can be easily deposited and saved in the open fan. The DFS rivers observed in many sedimentary basins are now wholly or partially cut into the DFS. The incision takes two main forms: (1) incision of the proximal DFS controlled by sediment supply and discharge control due to climate change [21, 22, 23] or tectonic tilting [21, 22], or (2) incision driven by basic level decline (whether is the ocean, lakes, or by river capture) [24].

3. Sequence stratigraphic model of fluvial facies

Fluvial sedimentation is the result of several allogenic factors, including sea level, environmental energy flux, source area tectonic movement, and basin subsidence [3, 4] (**Figure 2**). The relative importance of these factors is hard to determine, although related stratigraphic criteria can be derived from field studies and from experimental work [25]. The tectonism, the relative sea level fluctuations, and the climatic controls may be interpreted from the changes through geologic time in the directions of tectonic tilting during the deposition and from the variations of the landscape gradients. They can also be interpreted from the variations in the depths of burial, as inferred from the analyses of paleocurrent directions, architectural elements, fluvial styles, and late diagenetic clay minerals, coupled with isotopic geochemistry and petrographic studies of framework and early diagenetic constituents [26–28].

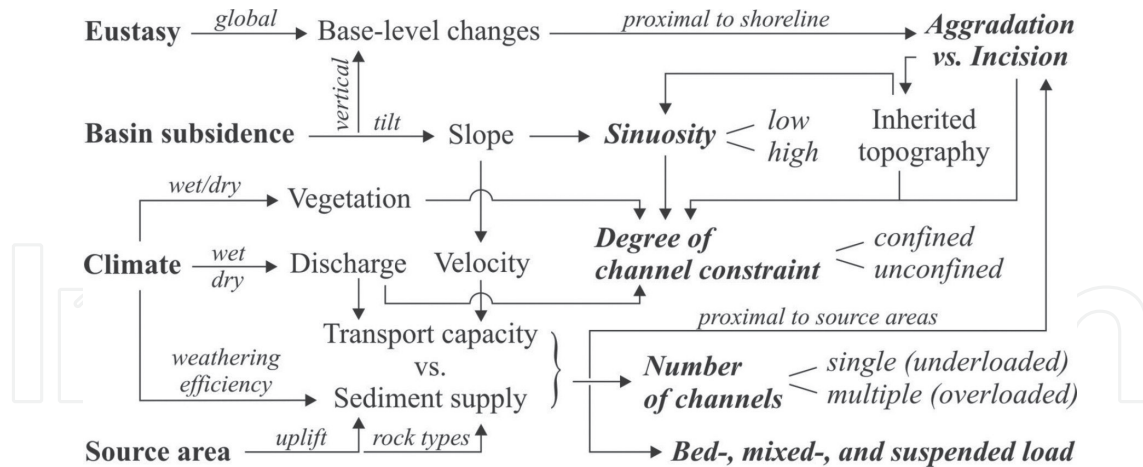


Figure 2. Allogenic controls on fluvial sedimentation [16].

The base level control on fluvial cyclicity represents the bulk of the first-generation sequence stratigraphic models, which assume a direct correlation between rising and falling base level on one hand, and fluvial aggradation and downcutting on the other hand [1, 29, 30]. The predictable relationship between fluvial processes and base level changes reflects a most likely scenario, but exceptions do exist [16]. This relationship is valid for the downstream reaches of fluvial systems, where rivers respond to “downstream controls” (i.e., interplay of sea level changes, basin subsidence, and fluctuations in environmental energy flux induced by climate change). In such settings, which may be characterized by either low or high accommodation space in the Leckie and Boyd’s [31] scheme of fluvial stratigraphy, the fluvial deposits may be integrated within the standard lowstand, transgressive, and highstand systems tracts.

Wright and Marriott [2] believe that lowstand system tracts are mainly composed of amalgamated channel deposits. The thick transgressive systems tracts are characterized by the deposits of floodplains that are mainly wrapped with isolated channel sand bodies. The upward highstand systems tracts are characterized by higher density sandstones and paleosol deposits, representing good stratigraphic markers. Shanley and McCabe [4] considered that fluvial strata can be traced to marine strata from the same period. Laterally amalgamated fluvial sheet sandstone can overlap the unconformities. In the upper alluvial parts, amalgamated channel deposits turn into relative isolated and fine-grained sediments interbedded with meandering channel deposits. This sedimentary feature shows the tidal influence from the ocean. Catuneanu [16] made a summary of these two representative models (**Figure 3**). Thus, the fluvial sequence boundaries are placed at the bottom of base level cycles. Incised valleys form when the base level falls, while lowstand systems tracts occur at the beginning of base level rise [32].

Holbrook et al. [11] introduced the useful buttresses and buffer concepts to explain longitudinal changes in fluvial facies and building upstream coastline. One is some fixed point of control on the river equilibrium profile in the ocean basin. It is a base level (sea level) in the main river inland basin. The reaction buffer space with and below the current gradient profile

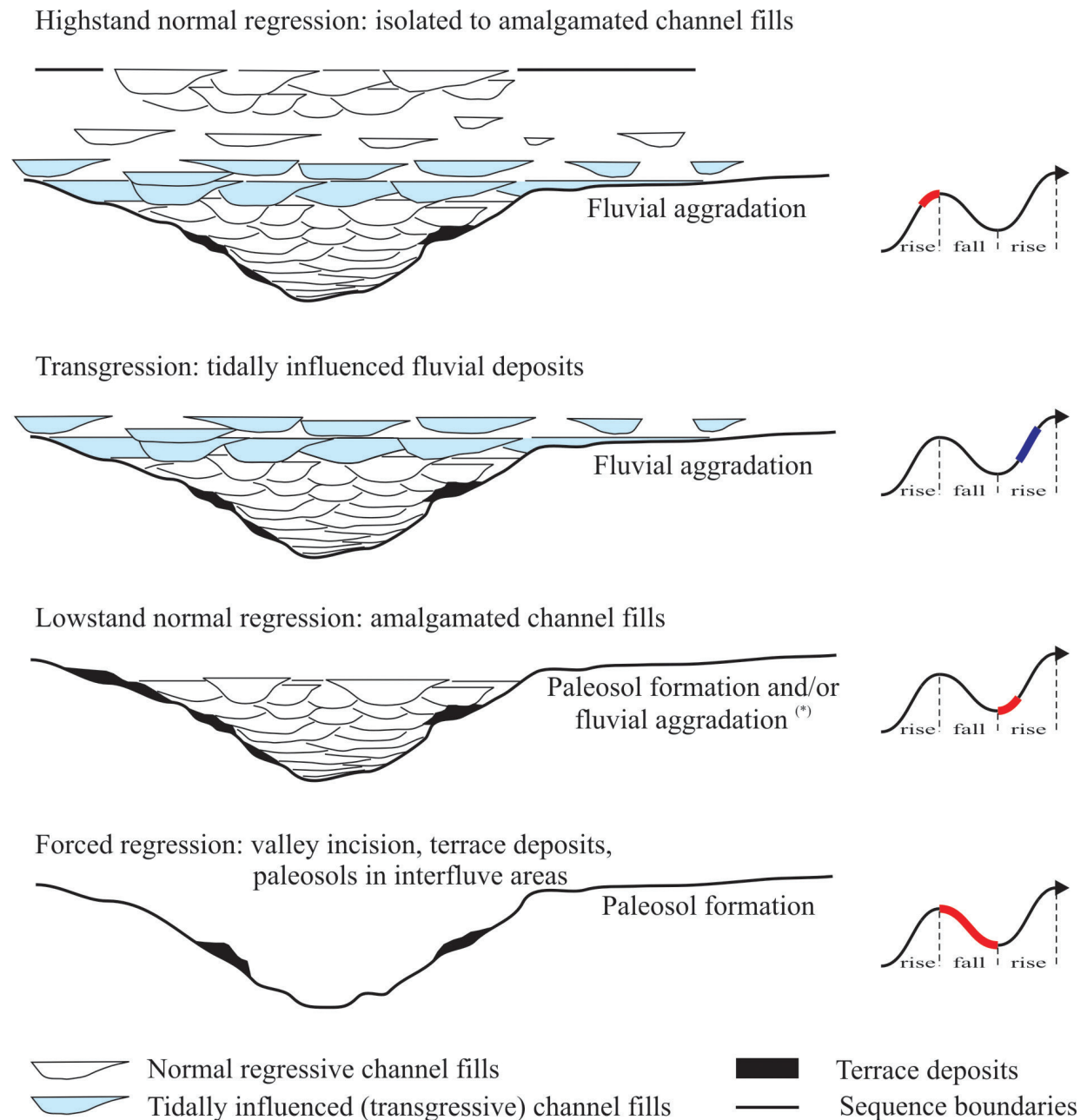


Figure 3. Stratigraphic model of fluvial facies modified from [16].

as the representative of the file may not exist an upstream control, such as tectonic or climatic change, the influence of river flow, and sediment. The tectonic uplift may increase the gradient distribution and the upper buffer zone. The decreasing of the buttresses, such as in the fall of sea level, may lead to the river system incision, but if the sea level fall blow newly exposed continental shelf as a similar slope, the river profile, there may be little change in the style of the river. In this case, the river system will change into to a new dynamic balance due to new water and sediment flux rate. In the accommodation between the upper and lower areas of the buffer zone, a representative (potential) of the river system to save space is available.

The ratio between channel and floodplain architectural elements during stages of positive accommodation depends on the rates of base level rise. Rapid base level rise leads to increased floodplain aggradation, which results in overall finer-grained successions. Slowly rising base level creates little accommodation available in overbank areas. At the same time, the channel stack in reducing accommodation time may be accompanied by frequent avulsion, which contributes to the spread of excessive lateral sediment [33]. Channel amalgamation under conditions of low accommodation is usually the case with the lowstand and late highstand systems tracts. As the late highstand amalgamated channel fills have a low preservation potential due to the subsequent erosion associated with the subaerial unconformity, the fluvial portion of the depositional sequence commonly displays a fining-upward profile (**Figure 3**). These general principles of fluvial stratigraphy, which relate the stacking patterns of fluvial architectural elements to changes in base level and available accommodation, have also been documented in the case of fan delta systems, which are governed by similar process/response relationships between fluvial processes within alluvial fans and the base level fluctuations of the standing bodies of water into which they prograde [34].

4. Methodology

4.1. Sequence stratigraphic analysis

Geophysical borehole logs represent various rock properties, which can be used for stratigraphic interpretation. The most common type of log, often used for local stratigraphic correlation, is summarized in **Figure 4**. As technology improves, some new types of well logs are being developed. For example, the new micro-resistivity logs combine the methods of conventional resistivity and dipmeter measurements to produce high-resolution images that simulate the sedimentological details of an actual core. This “virtual” core allowed in the details of mm scale visualization, including sediment bedding, cross-bedding, and biological noises. Well logs have both merits and disadvantages compared with outcrops. Geophysical logging in the outcrop of the advantage is that they provide continuous information from the inheritance of relatively thick, often in a range of kilometers. This type of configuration file (log curve) allows one to see the trend in different scales, from single element sedimentary deposition system in the size of the whole basin, to fill. For this reason, data provided by well logs may be considered more complete relative to the discontinuous information that may be extracted from the study of outcrops. Therefore, comparative study of underground relation and formation can usually scale far greater than from the outcrop research. On the other hand, nothing can replace the study of the actual rocks; hence, the wealth of details that can be obtained from outcrop facies analysis cannot be matched by well-log analysis, no matter how closely spaced the boreholes may be [35].

The surface of log interpretation is largely speculative, under the condition of practical rock data. The core data provide the most clear “ground truth information” [36]. Therefore, the

Log	Property measured	Unit	Geological uses
Spontaneous potential	Natural electric potential (compared to drilling mud)	Millivolts	Lithology (in some cases), correlation, curve shape analysis, identification of porous zones
Resistivity	Resistance to electric current flow	Ohm-metres	Identification of coals, bentonites, fluid evaluation
Gamma-ray	Natural radioactivity-related to K, Th, U	API units	Lithology (shaliness), correlation, curve shape analysis
Sonic	Velocity of compressional sound wave	Microseconds/metre	Identification of porous zones, coal, tightly cemented zones.
Caliper	Size of hole	Centimetres	Evaluate hole conditions and reliability of other logs
Neutron	Concentrations of hydrogen (water and hydrocarbons) in pores	Percent porosity	Identification of porous zones, cross-plots with sonic, density logs for empirical separation of lithologies
Density	Bulk density (electron density) includes pore fluid in measurement	Kilograms per cubic metre (gm/cm ³)	Identification of some lithologies such as anhydrite, halite, non-porous carbonates
Dipmeter	Orientation of dipping surfaces by resistivity changes	Degrees (and direction)	Structural analysis, stratigraphic analysis

Figure 4. Types of well logs, properties they measure, and their use for geological interpretations (after [17, 18, 35]).

geophysical data including logging and seismic can only provide indirect information on the solid and fluid phases in the underground that must be calibrated and the interpretation accuracy of verification to verify the geological data of rock [16]. The integration of all available data sets (e.g., outcrop, core, logging, and cuttings, therefore, the seismic) is the best way to correctly identify the stratigraphic contact.

The seismic data can also be used to produce seismic stratigraphic interpretation in the two kinds of materials at the interface of different acoustic characteristics. This can be described by acoustic impedance and is given by the product of density and velocity. The larger is the difference in acoustic impedance between two lithologies, and the stronger is the reflection. Various subsurface layers can be recorded by seismic traces through geophones that receive the reflections. The impedance contrasts control the nature of each wavelet. Such seismograms are time seismic sections. The seismic section generally follows the empirical Faust formula of seismic wave velocity, depth, and age proof [37]:

$$V = 46.5(ZT)^{1/6} \text{m/s}, \quad (1)$$

V is seismic velocity, Z is buried depth, and T is geological age.

Continuous seismic reflection is a “time line” hypothesis; in the basin, it is of great significance to analyze and research the sequence stratigraphy. Seismic records are also complicated by multiples and diffractions. Multiples may be strong enough to obscure deep reflections, but they are now relatively easy to remove by processing. The diffraction from the steep inclined surface is the scripture, such as fault, channel profit, and the erosion of relief unconformity. They are useful indicators of other components showing a steep reflection event but may be confused by the migration. The seismic record can be considerably improved, and interpretation facilitated by the use of two special techniques, the construction of synthetic seismograms, and the use of vertical seismic profiling (VSP) [38].

Synthetic seismograms are generated by the conversion of sonic and density data reflection coefficients. VSP is the recording and analysis of seismic signals received from a geophone lowered downhole. The well is reduced to be recorded on the surface of the signal, when they return to the surface of the detector to incrementally shift. Still, the shortest wavelength signal to each half the length of the T detector was analyzed. Each location has a new record. The synthesis and VSP data is very valuable for calibration of seismic records. For example, they enable a detailed record of seismic velocities to produce depth-corrected cross-sections. However, the VSP technique is far better for various reasons. It can, for example, can be used to calculate the total depth of expansion (TD) of synthetic seismic records, and not. Synthesis methods rely on logging data A, only reflect the conditions close to the hole. In the case of poor hole conditions or seismic reflectors having a very small horizontal extent (less than one Fresnel zone), the synthetic method may not provide a record typical of the area.

In this chapter, the method of stratigraphic analysis we used is an integrated well-seismic correlation. The Wenliu Area possesses abundant available materials, including a 3D seismic database (covering an area of about 35 km²), more than 340 drilling wells and logging data (including core data of over 330 m from 8 cored wells of the area), and plentiful analysis test data. Thus, it is possible to launch a detailed sequence stratigraphic study.

With the 3D seismic database, regional reflection surfaces were traced to the target area. With the correlation of synthetic seismogram and VSP logging data, the relationship between seismic travel time and well depth was established. More than 10 seismic well sections were interpreted and main structures (especially faults) were identified. A more precise analysis was conducted with logging data beyond this. Wavelet transformation and Maximum Entropy Spectral (MEM) analysis with gamma-ray data were also used to enhance the accuracy of the sequence identification.

4.2. Facies mapping

Logging data are used for stratigraphic and lithologic interpretation, while they can also be used directly in facies mapping. Lithologic information may yield different combinations of logs in the CRO field reconnaissance. These relationships can be converted into a computer algorithm and the log data are digitized and stored in the data bank, a powerful automatic mapping technology. Digital log data can also be displayed and manipulated using interactive computer graphics routines, a facility which can easily compare formation related purposes. Well service company invested a lot of money on design and marketing automation processing and display used in basin analysis and petroleum development techniques, but these techniques suffer from the limited resolution of the physical location is very special. The techniques cannot be used without much initial careful calibration to local petrographic and groundwater conditions.

In addition to logging method as the foundation, extensive additional technique has been developed for underground rock physics for many years, the core and sample data check. These methods have several goals: such as stratigraphic correlation, provenance, reconstructions of

paleogeography, regional stratigraphic trends, and tectonic history. Some of these techniques provide a numerical study of the age information. Others are useful or relevant local or regional origin but do not necessarily provide such age information. The grain size, grain shape, and the debris of a stratigraphic unit depend on the initial nature of the clastic source. Yet, after transportation, deposition, and burial process, the debris may experience many metamorphic processes, so that the features of the original source blurred. The analysis of basin detrital composition depends on these main factors: (1) source area geological structure; (2) source area of the climate and terrain; (3) transport process of debris diffusion and mixing mode brings; (4) chemical and mechanical wear, winnowing, transport, and deposition; and (5) diagenetic changes during burial of deposits.

The seismic data can also be used for basin mapping. The seismic reflector, the amplitude, and the continuity of seismic facies are the three elements, becoming more and more important to improve the processing and visualization of seismic sections. The concept of seismic facies is the most effective application in the main data including 2D cross-section, but the stratigraphic and sedimentological interpretation is not easy in two-dimensional settings. This problem is not too serious when 3-D data is available, because the nature of the whole volume of 3-D data could be a visual system to provide guidance for the real world. The calibration between the seismic attributes and the lithofacies is specific for each basin to a considerable extent.

The channel environment 3D interpretation of sedimentary system is the most spectacular one, especially in the alluvial and in the submarine fan depositional settings, in the channel-levee complexes and crevasse splays, and finally in the coastal plains [39].

In this chapter, the methods to the facies analysis and mapping we used are traditional mapping approach. One of the first step in the facies analysis of a clastic reservoir is the description and interpretation of available conventional cores. Core description was based on 10 cores taken from 7 cored wells of the target interval of the Wenliu Area. The color, the sedimentary structures, and the grain size of deposits were analyzed (the grain size analysis was based on a LS130 Coulter laser micro-granulometer). Sedimentary source analysis was also conducted with heavy mineral combination analysis, which calculates the ratio of stable transparent heavy minerals (mainly zircon and tourmaline) to the entire transparent heavy minerals (zircon, tourmaline, garnet, barite, epidote, etc.). Sedimentary facies were interpreted based on the analysis above. Finally, based on the detailed stratigraphic framework and counted sand body data, the lithofacies paleogeographic characteristics were analyzed, and along with the interpreted types of facies, a depositional model was established and the possible distribution of sedimentary facies was predicted both laterally and vertically.

5. Geological background of the Wenliu Area

The Bohai Bay Basin is located in the eastern China continental margin. It is a composite sedimentary basin formed in the Mesozoic and Cenozoic periods and the Proterozoic to the

Paleozoic period, covering an area of 195,000 square kilometers in the Bohai Sea and the coastal areas. Various reservoir systems and reservoir rock types are well developed in the basin, and the Eocene Shahejie Formation is the major hydrocarbon bearing layer series (Figure 5a) [40]. Some new studies show that the formation and evolution of the Bohai Bay Basin was induced by both the thermal power of bottom of the lithosphere and plate boundary activity due to regional stress field. The dynamic process of the Cenozoic basin in the Bohai Bay Basin is related to the thermal activity of the lithosphere in eastern China. It is also related to the regional stress field controlled by the tectonic activity at the plate boundaries and belongs to the superimposition of many regional geological processes [41, 42]. The Bohai Bay Basin is a Meso-Cenozoic sedimentary basin superimposed on the Paleozoic basement. During previous geological times the basin was part of the North China craton. The upper Proterozoic and the lower Paleozoic sequences are constituted of marine sediments, including the upper Proterozoic strata of the Jixian system, the Changcheng system and Qingbaikou system, which are mainly composed of micritic limestones, quartz sandstones, and shales. The sedimentary cover is not only distributed in the lower part of the basin, but widely distributed around the basin. The lower Paleozoic sequence is made up of Cambrian and Ordovician carbonates, with shales, siltstones, and sandstones. The upper Paleozoic sequence is made up of Carboniferous and Permian strata, with paralic and continental clastic rocks and some coal seams. The Mesozoic strata range in age from the Triassic to the Cretaceous. They are composed of tuffaceous sandstones, conglomerates, mudstones, and coals (Figure 6).

The Dongpu Depression, located in the south margin of Bohai Bay Basin, is an oil-rich sedimentary depression. It is a 16-km long and 70-km wide NNE fault depression that covers an area of approximately 5300 km² (Figure 5a). The Dongpu Depression formed from the Huabei Movement in the late Paleogene. The evolution of the depression reveals an evident tectonic component and shows periodic features [43]. It is bounded by the

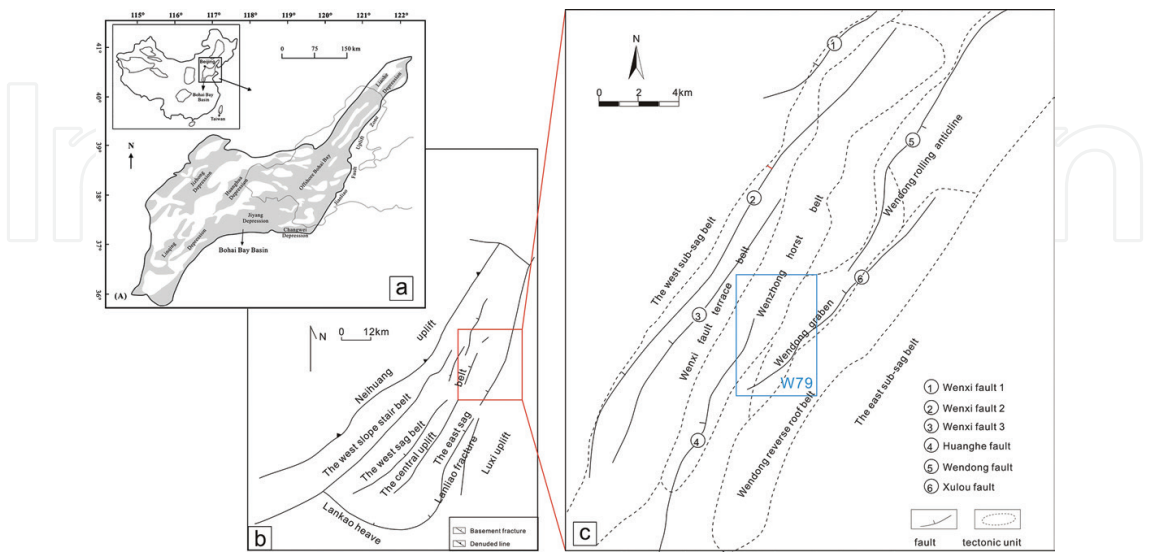


Figure 5. (a) Location of the Bohai Bay Basin (after [40]). (b) Location of the Dongpu Sag. (c) Location of Wenliu Area showing the main structures (after [19]).

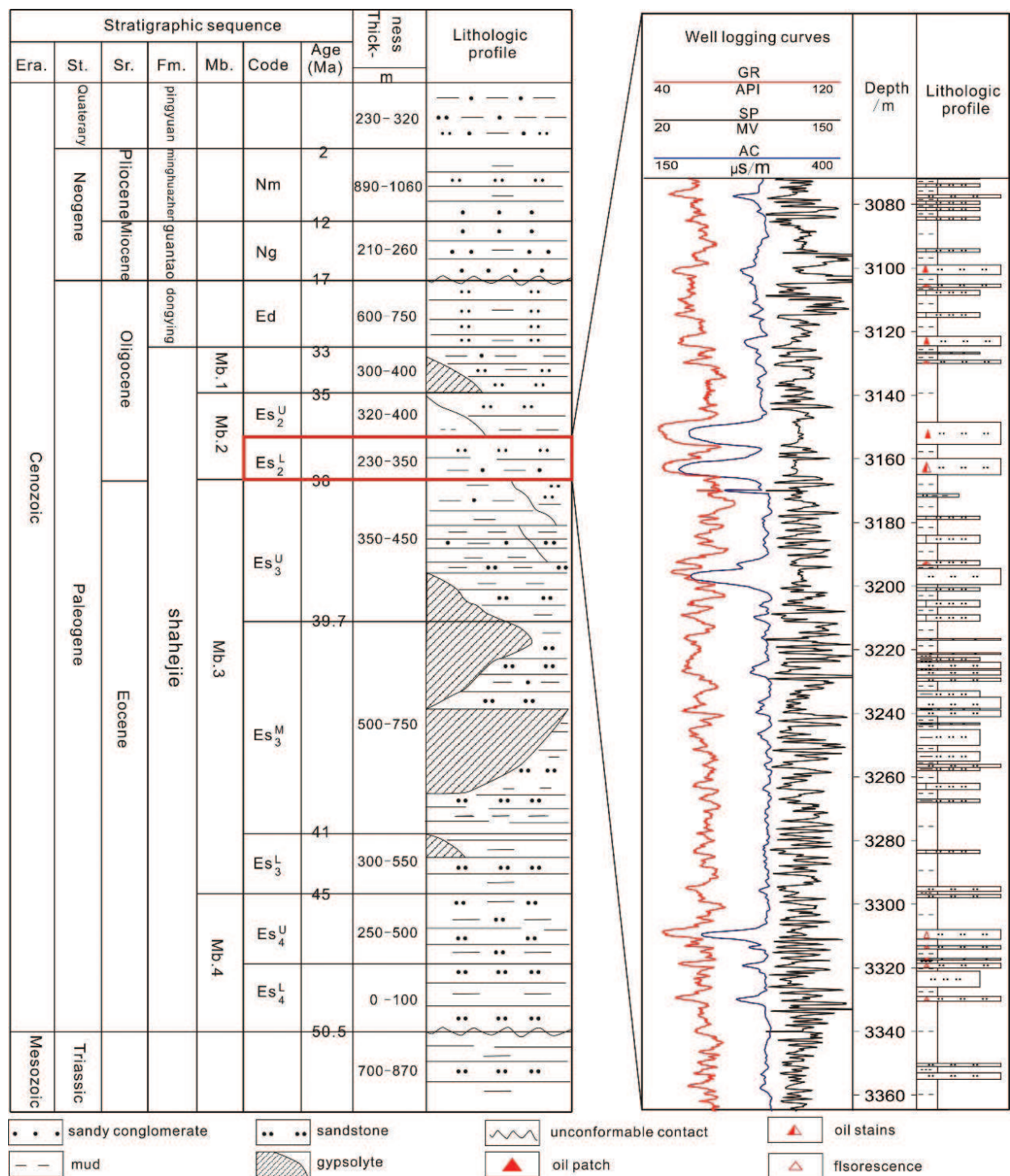


Figure 6. Stratigraphy in Dongpu Depression, Bohai Bay Basin (left), enhancing the lower second member of Shahejie FM. In Well W167 of Wenliu Area (right). St, system; Sr, series; Fm, formation; Mb, member (after [19]).

Luxi Uplift on the east, the Lankao Uplift on the south, and the Neihuang Uplift on the west. Its north margin is the Maling Fault, which is also the south margin of the Linqing Depression. The Lanling, Changyuan, and Huanghe basement rift faults controlled the early evolution of the Dongpu Depression and changed it from a broom fault depression

to a double-break fault depression. During the early Paleogene, the Tan-Lu Faults changed from transpression to dextral lateral strike-slip faults, altering the regional stress field from a shear-extrusion field to a shear-tensile field. Differential subsidence also occurred during this period. The regional shear-tensile effects caused the Central Uplift rise, then induced gravitational sliding and salt rock intrusion, and finally molded the present appearance of the Dongpu Depression [44].

The Wenliu Oilfield, located in Henan Province, is on the northern part of the central uplift of the Dongpu Depression. Bounded by two large sag belts (i.e., the West and the East Sub-sag Belt), the Wenliu Oilfield is a complicated fault zone that is characterized by horst and graben structures [44]. It is also of the NNE direction and is approximately 20 km long and 16 km wide, covering an area of more than 2000 km² (**Figure 5b**).

The W79 Block, one of the most important blocks of the Wenliu Area, has already entered the middle to late stage of the developing period. The Paleogene lower second member of the Shahejie Formation (Es_2^L , lowermost Oligocene succession, ranging from approximately 2700 m to 3000 m) of this block, originally described as a shallow water delta system deposit, is the main oil-bearing interval of this area (the oil-bearing area is nearly 13.4 km²) and has plentiful remaining petroleum resources. However, because of its complicated sedimentary features, many studies [41, 44–47] concerning sequence stratigraphy and sedimentary facies models are still under scientific debate. Hence, this paper aims to provide an analysis of the sequence stratigraphic and sedimentary characteristics of the Es_2^L , Paleogene Shahejie Formation of the W79 Block based on abundant well logging data, 3D seismic data, and core data under the principles of high-resolution sequence stratigraphy and sedimentology (**Figure 5c**).

6. Sedimentary model of Wenliu Area

The reservoir properties depend on tectonism, eustasy, sediment flux, biological process, climate, and other allogenic and authigenic factors. At the basin scale, these factors mainly determine the formation of systems tracts [48], while at smaller scales, they influence colors, shapes, structures, and internal architectures of the sedimentary bodies. It is at these smaller scales that reservoir characterization (especially lithological and lithofacies analysis) becomes significant.

According to core observation and description as well as well logging analysis, this chapter concludes that the lithology of the target area is characterized by mudstones, sandy mudstones, muddy siltstones, shaley siltstones, and sandstones. The main color of the sandstones is light brown, whereas the main color of the mudstones is red to purple. Statistics shows that mudstone is the dominant lithology of the target interval (more than 63%), with the other components showing relatively smaller percentages (siltstone 14.5%, muddy siltstone 5%, limy siltstone 5%, and sandstone 12.5%). Shapes of grain size cumulative curves plotted on log-probability paper could reveal environmental characteristics. The plots of grain size as

cumulative curves of the target interval show that suspension population occupies a large proportion (generally larger than 30%). Saltation population is dominant and its segment is relatively steep. The truncation points between these two populations are usually bigger than 3 (ϕ value). Traction population is usually missing within the target interval (**Figure 7**).

The ratio of stable transparent heavy mineral assemblage (mainly zircon and tourmaline) to the entire transparent heavy mineral amount (zircon, tourmaline, garnet, barite, epidote, etc.) indicates that the sourcelands are on NNW direction.

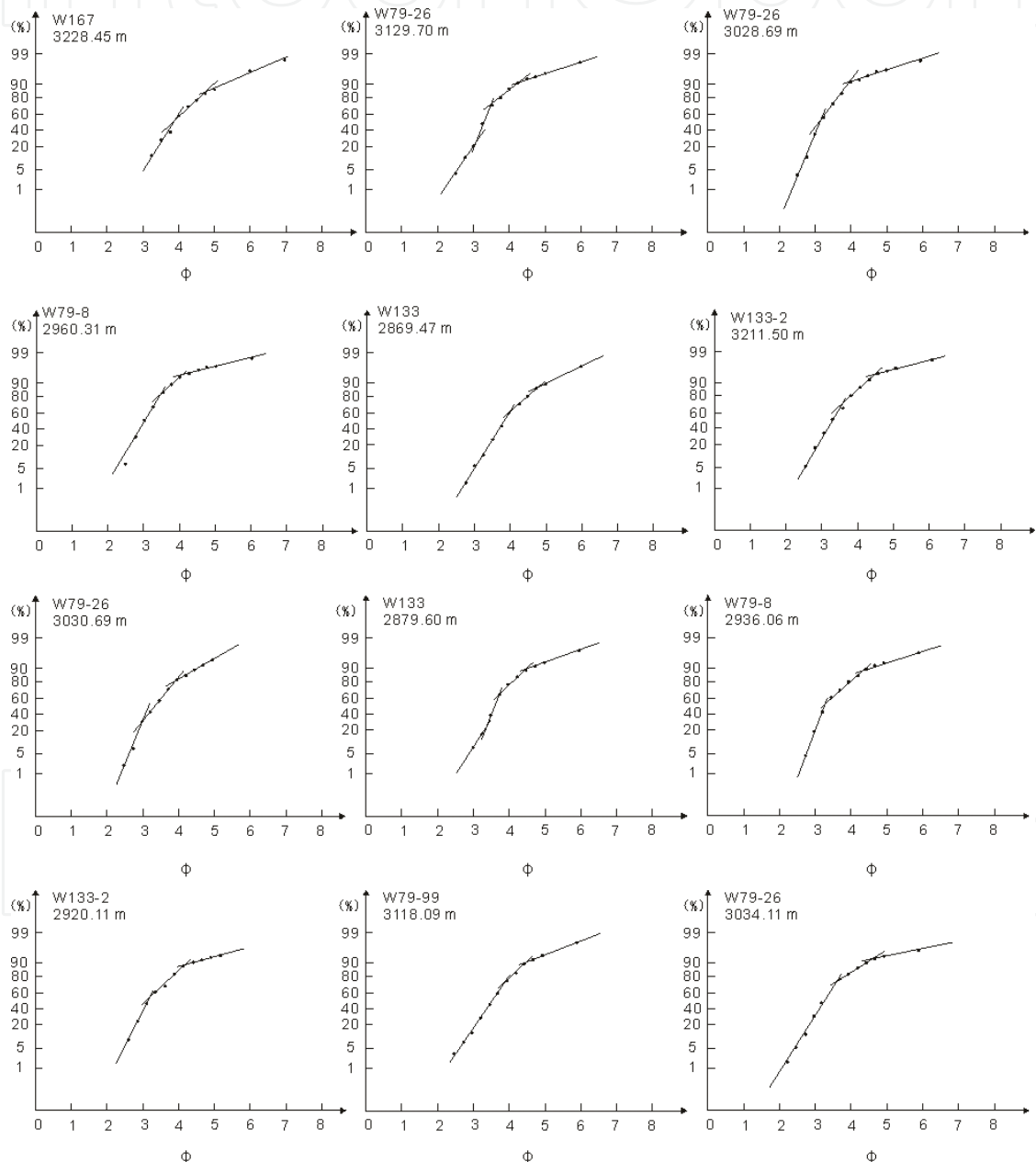


Figure 7. Grain size cumulative probability plots of target interval in Wenliu Oilfield (after [19]).

6.1. Lithofacies characteristics

The lithofacies characteristic analysis is also very important for depositional environment analysis [49–52]. The lithofacies recognition and categorization is based on lithology, grain size, physical and biogenic sedimentary structures, and stratification from core observation and description. Seventeen lithofacies have been recognized within the study interval, including from fine-grained sandstones of parallel bedding to mudstones of

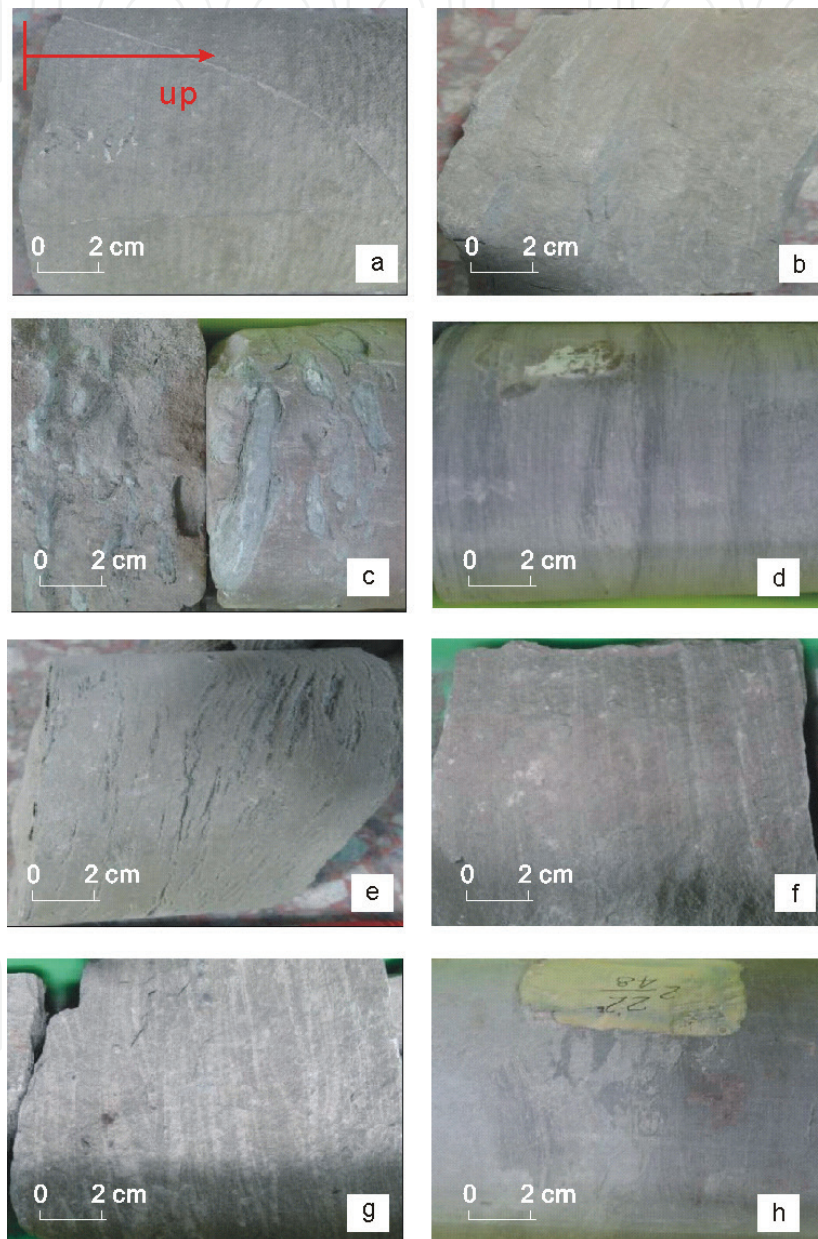
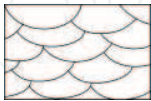

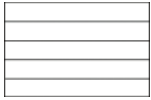
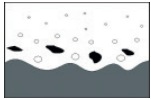
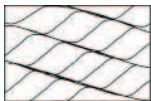

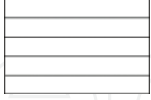
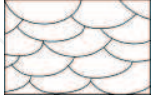
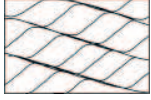
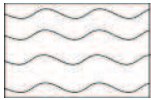


Figure 8. Typical lithofacies of the W79 block for the target interval: (a) parallel bedding sandstone; (b) trough cross-bedding sandstone; (c) scouring structured sandstone with mud gravels; (d) ripple cross-bedding siltstone; (e) wavy cross-bedding siltstone; (f) parallel bedding siltstone; (g) ripple cross-bedding muddy siltstone; (h) flasher structured mudstone (after [19]).

lenticular structures (**Figure 8**). The codes, features and interpretation are summarized in **Table 1**.

According to the reddish-brown mud of subaerial oxidizing features and the grain size cumulative plots revealing typical channel deposit features (**Figure 7**), along with the specific

ID	Lithology	Structure and texture	Interpretation	Schematic representation
St	Sandstone	Trough cross-bedding	Channel lower part, curved bounding surfaces, originates by migration of 3-D bedforms, high energy	
SLa	Sandstone	Low-angle cross bedding	Low-angle foreset lamina of single direction (generally lower than 10°), high-energy	
Sp	Sandstone	Parallel bedding	Parallel and acclinic, stable and high energy	
Ss	Sandstone	Scouring	Channel bottom, erosional bounding surface, usually mingled with mud gravels, high energy	
SSr	Siltstone	Ripple cross-bedding	Superimposition of one ripple on another as the ripples migrate, abundant sediment supply (especially suspension population)	
SSLa	Siltstone	low-angle cross bedding	Low-angle foreset lamina of single direction (generally lower than 10°)	
SSp	Siltstone	Parallel bedding	Parallel and acclinic, result of suspension settling of fine-size sediment	
SSt	Siltstone	Trough cross bedding	Curved bounding surfaces, originates by migration of 3-D bedforms	
MSSr	Muddy siltstone	Ripple cross bedding	Superimposition of one ripple on another as the ripples migrate, abundant suspension sediment supply	
MSSw	Muddy siltstone	Wavy bedding	Wavy lamina, parallel to the bounding surface as a whole, abundant sediment supply of clay and silt	

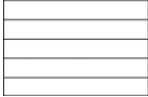

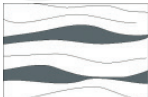
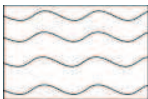
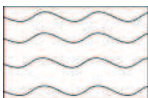


ID	Lithology	Structure and texture	Interpretation	Schematic representation
MSSp	Muddy siltstone	Parallel bedding	Parallel and acclinic, result of suspension settling of fine-size sediment or precipitation from solution, low energy	
MSSla	Muddy siltstone	Low-angle cross bedding	Low-angle bounding surfaces, originates by migration of planar bedforms, low energy	
SMf	Silty mudstone	Flaser bedding	Fluctuating depositional conditions marked by periods of current activity, mud < sand	
SMw	Silty mudstone	Wavy bedding	Wavy lamina, parallel to the bounding surface as a whole, abundant sediment supply of clay and silt	
Mw	Mudstone	Wavy bedding	Wavy lamina, parallel to the bounding surface as a whole, abundant sediment supply of clay	
Mm	Mudstone	Massive bedding	Contain few or no visible internal lamina, overbank or abandoned channel deposits	
MI	Mudstone	Lenticular bedding	Fluctuating depositional conditions marked by periods of current activity, mud > sand	

Table 1. Lithofacies of the target interval succession (after [19]).

associations of the lithofacies as reconstructed from the core descriptions, a meandering river fan is interpreted to be responsible for the sedimentation.

6.2. Meandering river fan

The target interval of the Dongpu Depression was formed under a rift contraction basin environment far from the source and with an abundant sediment supply. Single well core section shows that channel and overbank deposits are two main sequence types of the sedimentary strata. The channel deposits generally have complete sequences and are relatively isolated. The overbank deposits are mainly composed of reddish-brown shale that could indicate the exposed and oxidic environment (together with the lack of subaqueous paleontological fossils, it may be revealed as subaerial sedimentary environment) (**Figure 9**). Lithofacies paleogeographic mapping shows many meandering channels distributed along

the basin margin like a large fan-shaped river system, which shows distributive characteristics quite different of those of a fan delta system (**Figure 10**).

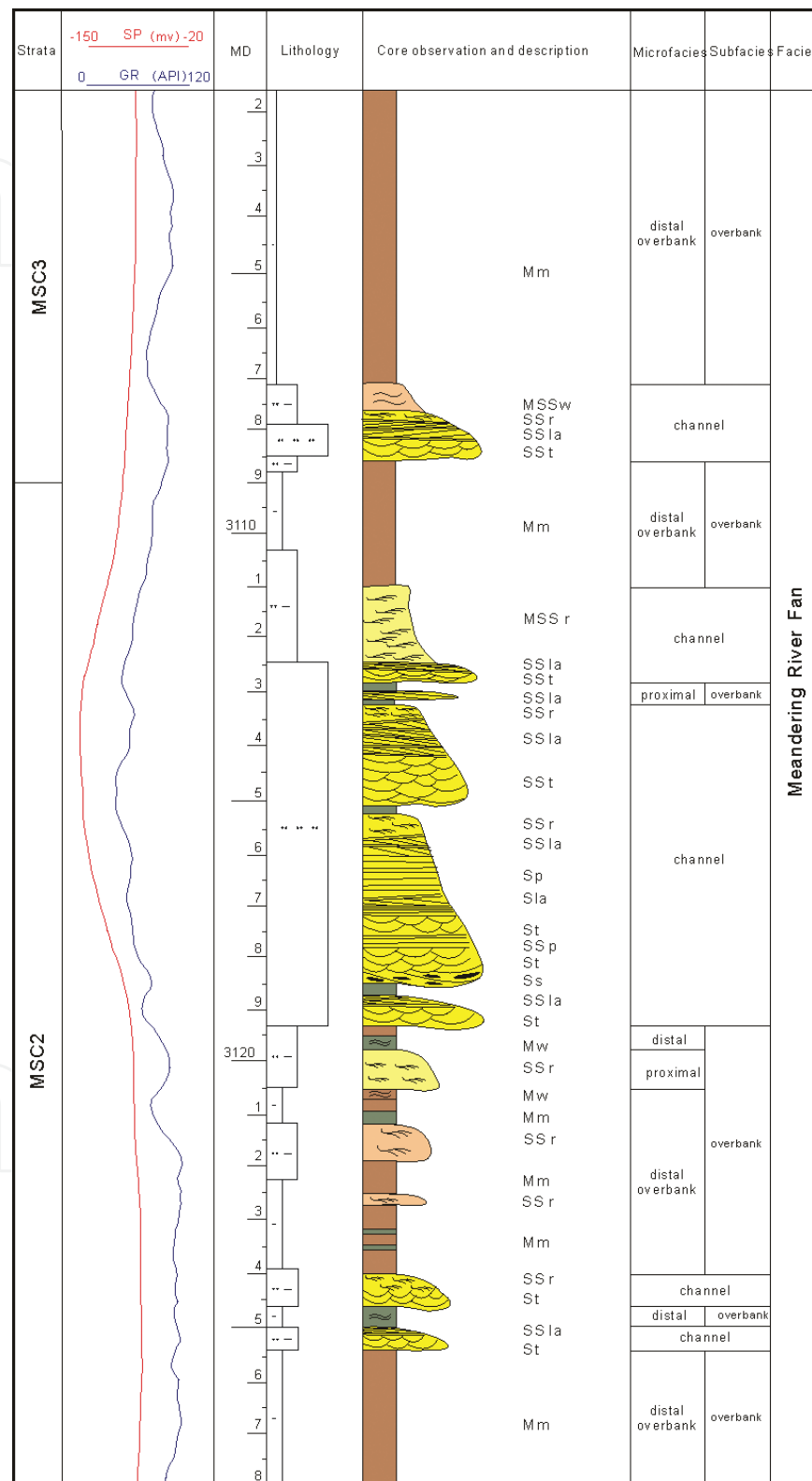


Figure 9. Single well facies (W133-12 Well) (after [19]).

This special depositional system is interpreted to be a meandering river fan, mainly composed of three subfacies (i.e., channel fill subfacies, overbank subfacies, and river flood lake subfa-
cies) (**Figure 10**). In the study area, back-stepping and forward-stepping types both exist, revealing $A/S > 1$ and $A/S < 1$, respectively, and their logging curve (gamma ray) reflections are generally of toothed boxes or bell shapes (see **Table 2**).

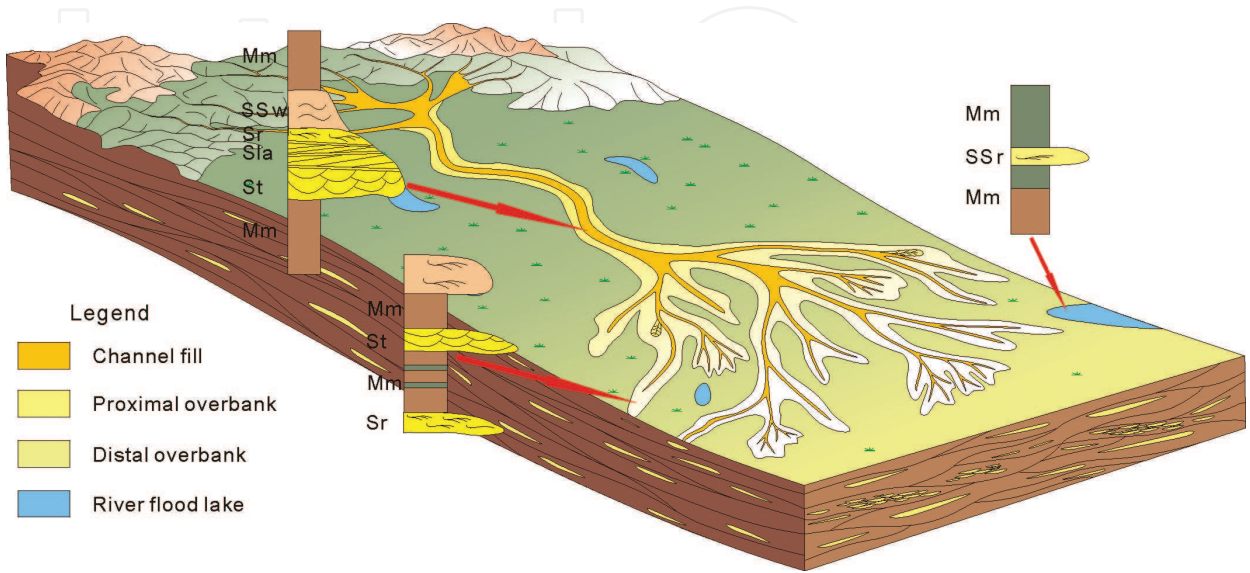


Figure 10. Sedimentary facies model of the target interval in Dongpu Depression (after [19]).

	Meandering river fan	Shallow water delta
Settings	Mainly subaerial	Subaqueous and subaerial
Paleo-climate	Humid; oxidizing environment (major part) to slightly reductive environment (some small parts)	Relatively humid; reductive environment to slightly oxidizing environment
Subaqueous paleontological fossils	Rare	Relatively abundant
Wave or tide forces	No	Yes
Sediment supply	Sufficient	Sufficient
Deposits between distributive/distributary channels	Mud	Mud or sand sheet
Distance between distributive/distributary channels	Relatively large	Small to medium
Sequence and cyclicity	Mainly positive cycles	Both positive and negative cycles
Subfacies	Channel fill subfacies, overbank subfacies and river flood lake subfacies	Delta plain subfacies, delta front subfacies, and pro-delta subfacies

Table 2. Comparison of meandering river fan and shallow water delta (after [19]).

The channel fill subfacies are mainly composed of sand-rich channel deposition. From bottom to top, Ss, St, Sla, and Sr constitute the main lithofacies and show a fining-upward cycle. The grain size is relatively coarse, and the sandbody connectivity is therefore high. The overbank subfacies contain two parts. The proximal overbank is next to the channel and is one of the most important reservoir types due to its good physical properties (i.e., after channel fill). The common lithofacies of the proximal overbank include Sla, SSla, and SSr. The distal overbank is distributed between channels and is mainly composed of purple to red mudstone. The common lithofacies include MSSw, SMw, and Mm. The river flood lake subfacies form near the distal overbank, recording stand water, and are mainly composed of grayish-green mudstone. The common lithofacies of this subfacies contain Mw, Mm, and Ml.

7. Sequence stratigraphy

7.1. Sequence stratigraphic surfaces

The identification of sequence stratigraphic surfaces and classification of depositional trends is the core component of high-resolution stratigraphic correlation and division. Integrated seismic and well analyses show that two major sequence stratigraphic surfaces collaboratively limit the target interval.

SB1, the top surface of the target interval, has strong and continuous reflection in the seismic section (**Figure 11a**). It is a regional parallel unconformity and is characterized by overlying thick and continuous shale of Es_2^U . Its features on the well logging curves are high GR (gamma ray), AC/DT (acoustic) and SP (spontaneous potential) values and a low R25 (2.5 m resistivity) value. Below this surface, tooth-shaped AC/DT and GR curves become the main characteristics, revealing a frequent sand mud inter-bedding (**Figure 11b1**).

SB2, the bottom surface of the target interval, also has strong and continuous reflection in the seismic section (**Figure 11a**). It is also a parallel unconformity characterized by a stable mudstone layer of the underlying Es_3^U . Its features on well logging curves are high GR, AC, SP, and R25 values (**Figure 6**). The most obvious characteristic is the in the SP curve, approximately 10 m above the surface, in which the curve has a v-shaped low value zone (**Figure 11b2**).

7.2. Facies associations under sequence stratigraphic frame

Based on core observations as well as integrated seismic and well analyses, more than 58 short-term base level cycles could be recognized in the target interval of the W79 Block. Genetic sequence stacking patterns can be used to define genetic sequence sets, showing base level rises and falls [1]. Thus, these short-term patterns could be combined into six middle-term base level cycles (from bottom to top—MSC1 and MSC6). In a similar way, given the regional setting, these six middle-term base level cycles could be further

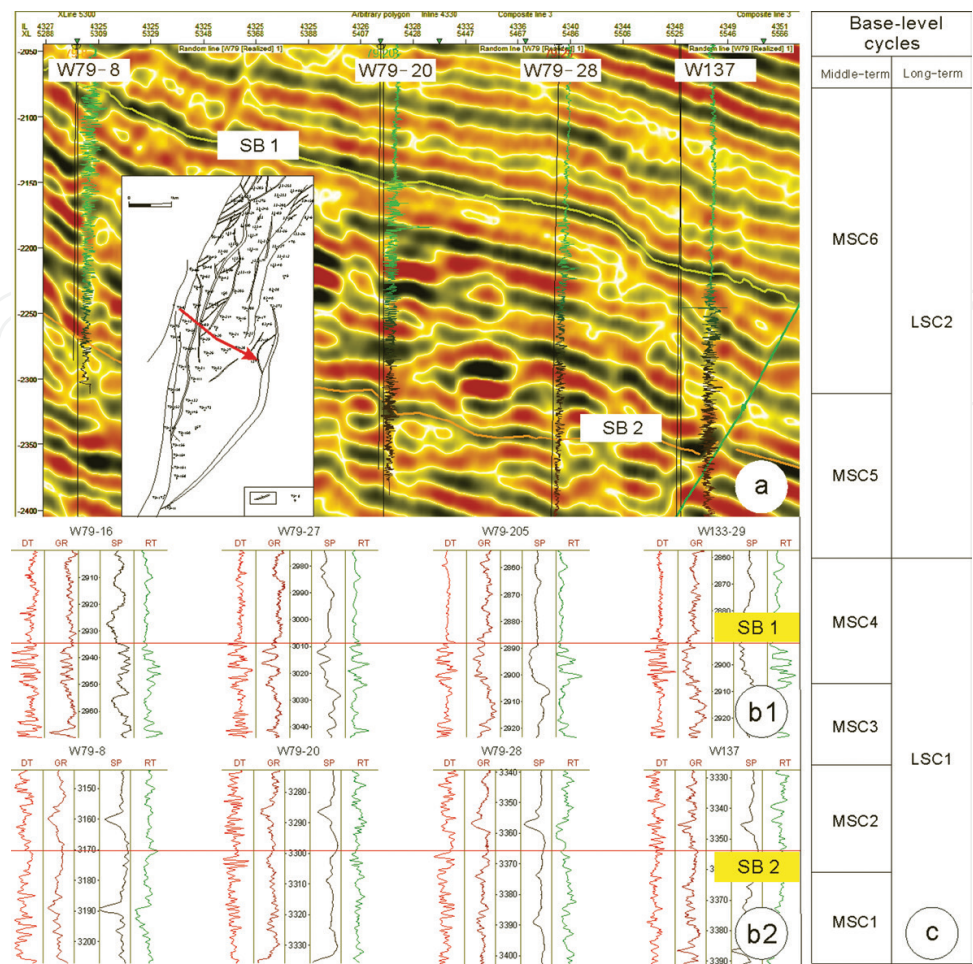


Figure 11. Identification of main sequence stratigraphic surfaces and stratigraphic division framework (after [19]).

combined into two long-term base level cycles (from bottom to top—LSC1 and LSC2) (Figure 11c). Under this high-resolution sequence stratigraphic frame, according to the practice of oilfield development, a 58-small-layer plan was accepted for paleogeographic mapping (Figure 12) and for other subsequent studies. Precise paleogeographic mapping shows that the vertical facies distribution and association have strong regulations on the long-term base level cyclic scale.

LSC1, the first long-term base level cycle, composed of MSC1 to MSC4, approximately 90 m to 120 m long, is the lower part of the target interval and is limited by the SB2 at the bottom. At the lower part of this long-term base level cycle, proximal overbank deposition and distal overbank deposition are most commonly found, whereas channel fill deposition could sporadically be found. In contrast, at the upper part of this long-term base level cycle, apart from proximal and distal overbank, channel fill deposition is also commonly found and the connectivity of the sandbody is relatively higher than that of the lower part of LSC1, which has no or isolated channel fill deposition. The ratio of channel fill to overbank increases from bottom to top, and the sedimentary stratigraphy shows an

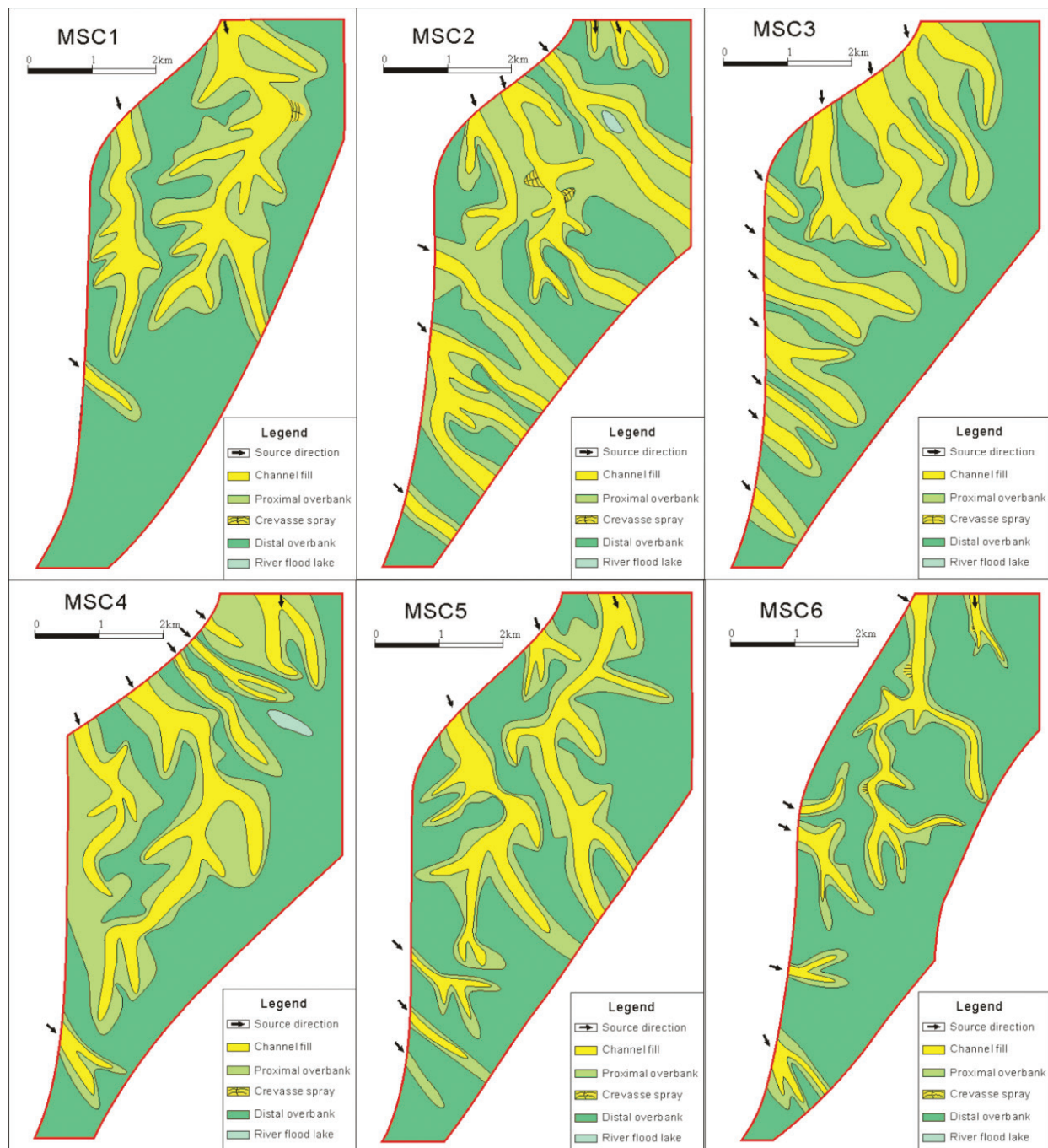


Figure 12. Sedimentary facies maps of the middle-term base level cycles of the target interval of W79 Block (after [19]).

overall coarsening-upward trend, revealing that the environment varied from a relatively higher accommodation condition to a relatively lower accommodation condition. This vertical change indicates that the entire LSC1 was formed during base level falling or an A/S decreasing period and is, in fact, a semi-cycle of the long-term scale. The vertical characteristic of LSC1 might reveal a relatively stable tectonic setting where subsidence tends to be slow and the depositional process is stable with abundant sediment supply.

LSC2, the second long-term base level cycle, composed of MSC5 to MSC6, approximately 150 to 190 m long, is the upper part of the target interval and is limited by SB1 at the top. In the lower part of this long-term base level cycle, similar to that of the upper part of LSC1, channel fill deposition is commonly found apart from the proximal and distal overbank deposition, and the connectivity of the sandbody is relatively high. In contrast, in the upper part of this long-term base level cycle, proximal overbank deposition, and distal overbank deposition are most commonly found, whereas channel fill deposition is sporadically found. The sedimentary stratigraphy shows an overall upward-fining trend, revealing that the environment varied from a relatively lower accommodation condition to a relatively higher accommodation condition. Similar to LSC1, the entire LSC2 was also a semi-cycle of the long-term scale, whereas it was formed during a base level rising or A/S increasing period. The vertical characteristics of LSC2 might reveal an active tectonic setting where subsidence tends to be fast and the base level rises rapidly, which makes the ratio of the channel to overbank change from high to low.

8. Discussions and conclusions

Through the regional correlation of the lithofacies within different depositional systems, this chapter proposes a high-resolution stratigraphic framework, including 2 long-term base level cycles, 6 middle-term base level cycles, and more than 58 short-term base level cycles.

The base level fluctuations are mainly controlled by the regional tectonic setting. Active subsidence stages tend to make base level rising semi-cycles, while relative stable stages tend to make base level falling semi-cycles.

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