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Sub-Layer Correlation of Quantou Ⅳ Formation of the Lower Cretaceous in Haituozi Area of Songliao Basin

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Abstract

Fluvial-flood plain facies are developed at lower-mid Quantou Ⅳ Formation, and delta front - shallow lake facies are developed at the upper formation in Haituozi area of Southern Songliao Basin. Channel sand bodies are good oil and gas reservoirs, but the distribution of sand is not clear, which has become a key factor restricting oil and gas development. No less than 100 wells data of logging, some data of drilling, cores and testing are collected and used in correlation, firstly 5 roughly provenance direction and 5 crosscutting provenance direction sections were selected in the area, with high resolution sequence stratigraphic analysis, Quantou Ⅳ Formation is subdivided into 4 sequences (corresponding to the fifth order cycle sequence, are respectively called cycle A, B, C and D), sequence stratigraphic framework were established. Then the similarity of facies association characteristics in base level change, consistency of reservoir fluid properties, isochronous maximum flooding surface in a certain area, different stages of overlay channels are took full account in the operation of sub-layer correlation. In the end 3 sub-layers are divided from cycle A , 3 sub-layers divided from cycle B, 5 sub-layers from cycle C, and cycles D corresponds to a sub-layer, Quantou Ⅳ Formation is divided into 12 sub-layers, which lays good foundation for the production and development.

Key words: High resolution sequence stratigraphy; Sub-layer correlation; Songliao basin; Haituozi area; Quantou Ⅳ Formation

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INTRODUCTION

Research on stratigraphic division and correlation, stratigraphic development characteristics in the isochronous stratigraphic unit is one of the most basic research contents in sedimentology (Qian *et al*., 1994; Holland *et al*., 2000). Geological features of sedimentary data record is the basis for comparison. Because of different research angles, the early stratigraphic correlation methods commonly include lithostratigraphic correlation, lithofacies correlation, paleontology lithofacies correlation, geochemical characteristics correlation, magnetostratigraphic correlation, and so on, these methods are good ways to solve large-scale chronostratigraphic comparison and correlation.

To meet the higher economic requirements, high-resolution stratigraphic division and correlation within the scope of the target block become particularly important, such as the detailed exploration and development of oil and gas, coal, geothermal and other sedimentary mineral, in particular for their production design, dynamic analysis and production management. China's geologists have summarized "comparison method of cycles of contrast, hierarchical control", "the principle of similar lithology, thickness ratio of roughly equal" in lake delta depositional system, "comparison method of ancient soils, sliced and other elevation" in the river sedimentary system under the China's oil exploration and development practices (Zhao, 1988; Wang *et al*., 2001; Wen *et al*., 2010), these methods are based on a marker bed, have good applicability at some extent and conditions, and have widely used in stratigraphic division and correlation of oil exploration and development.

Since Cross proposed the high-resolution sequence stratigraphy, a large number of researchers start high-resolution sequence stratigraphy research using the data of core, log, logging, seismic and so on, and the theory applied to the prediction and stratigraphic comparison and division of continental reservoir of coal, oil and gas, uranium and other reservoir (Li *et al*., 2008; Chen and Zhang, 2005; Zheng *et al*., 2003; Bourquin *et al*., 1998). Especially in the fluvial facies, establishing high-resolution stratigraphic framework, analyzing stratigraphic features, summarizing deposition variation, discussing the role of base-level changes control on reservoir development, predicting conducive accumulation conditions achieve good applications (Zhang *et al*., 2009; Yu *et al*., 2005; Wang *et al*., 2005; Zheng *et al*., 2004; Liu *et al*., 2002; Tang, 2008). Geologists have been troubled by the problem of fluvial facies reservoir sub-layer correlation, but some scholars (Wang *et al*., 2005; Qu *et al*., 2008; Yuan and Shen, 2007; Deng *et al*., 1997; Kjemperud *et al*., 2008; Bourquin *et al*., 2006; Cross, 2000) use the theory of high-resolution sequence stratigraphy to fluvial sand and finer comparison study of body cell, also made a useful theoretical exploration and practices.

In this paper, no less than 100 wells' log data and some data of cores, drilling, well testing are collected and analyzed, and based on these, high-resolution continental sequence stratigraphic framework of the study area is established (corresponding to the fifth order sequence), in the end with the application of sub-layer correlation methods, Quantou Ⅳ Formation（also called Fuyu oil layer in the oilfield） is fine divided and correlated within the frame, significant application results are achieved.

1. GEOLOGICAL BACKGROUND

Haituozi area is located in southern Songliao Basin (Figure 1), across two major tectonic units—the western slope and the central depression, and it is a major discovery area of oil and gas exploration in Jilin Oilfield in recent years. During the period of Quantou Ⅳ formation of the Lower Cretaceous deposition, the climate is arid, the basin tectonic subsidence is relatively stable, terrain is flat, large fluvial systems are well developed in the margin of the basin and flow into the depression center, which led to formation of a wide range of fluvial deposits throughout the basin. Combined with previous knowledge of sedimentary facies of the area (Zhao *et al*., 2008; Gong, 2010), and through a large number of core observation and experimental analysis, this study suggests that the deposition provenance of Quantou Ⅳ formation of Haituozi area mainly came from the southwest. Alluvial fluvial (low-sinuosity rivers) - flood plains are mainly developed in early and mid period, and delta front - shallow lake sedimentation are mainly developed in later period. The channel sand and the delta front sand bodies are major oil and gas reservoirs. After years of exploration practice, the reservoir of Quantou Ⅳ Formation in Haituozi area has been in the rolling development stage, fine prediction the distribution and characterization of reservoir sand is becoming increasingly important for the reservoir and further potential increasing reserves evaluation.

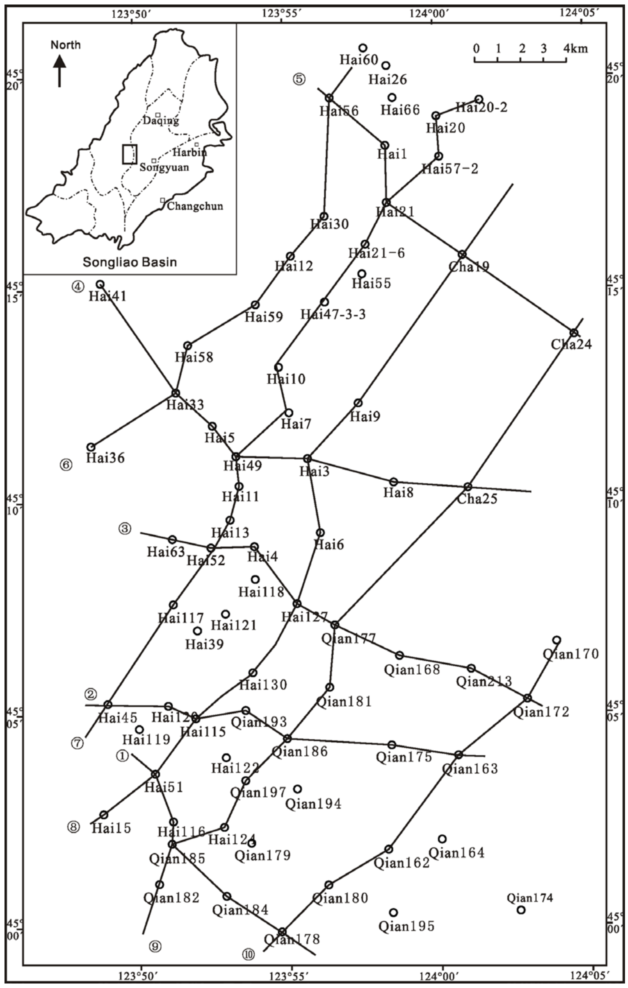

Figure 1
The Locations of Haituozi Area, Wells, and Cross Sections

2. THE ESTABLISHMENT OF HIGH-RESOLUTION SEQUENCE STRATIGRAPHIC FRAMEWORK

Based on the principles and research methods of high-resolution sequence stratigraphy (Deng *et al*., 2003), combined with the recognition of "Turnaround Surface" —base-level rise and fall (Wang, 2008), Quantou Ⅳ Formation is divided into four short-term cycles, and the interfaces of 4 sand groups are roughly the same with short-term cycle top and bottom and blooding surface, but the exact division of the interface may be different. Four short-term cycles are named A, B, C and D from bottom to top (Figure 2). The characteristics of each sycle and its interfaces of each cycle are analyzed below, typical interface drilling and logging response are shown in Figure 3.

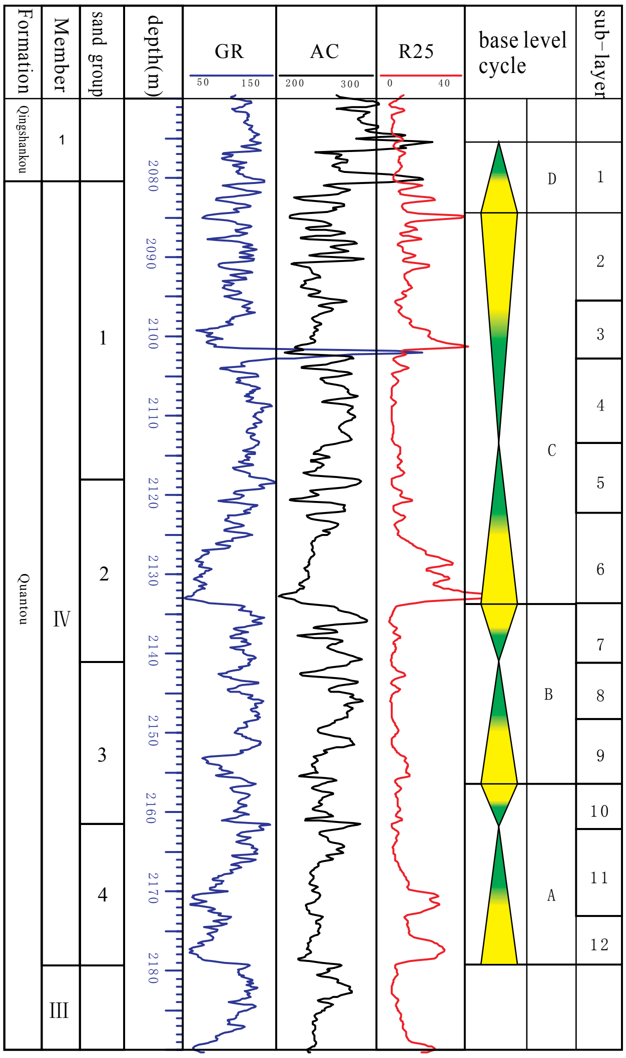

Figure 2
Sequence Stratigraphy and Sub-Layer Correlation of Quantou Ⅳ Formation in Haituozi Area(Well Hai 116)

Rising half cycle of A: the Bottom Boundary Surface is roughly equivalent to sand group 4 bottom interface (the interface of Quantou Ⅳ formation and Quantou Ⅲ formation), more data of drilling and logging shows that it is the bottom interface of thick channel sand or Multi-stage stacked sand (mutant side), part is progradation to retrogradation turnaround surface (Figure 3), characteristic is not obvious on the seismic profiles; top interface is surface of thicker sediment of floodplain mudstone. Purple, gray-green mudstone are mainly developed, with interbeds of siltstone and fine sandstone. The whole half cycle performances retrogradation characteristics. Stratigraphic thickness is small, generally 20 to 30 meters.

Falling half cycle of A: The bottom boundary is Rising half cycle A's bottom interface, roughly equivalent to the bottom boundary of sand group 3. Top interface is retrogradation to progradation turnaround surface, which is sand group 3's internal interface. Characteristics are not obvious in seismic profile. In half cycle mudstone colors are mostly purple red, a small amount are light gray.The whole half cycle performances trogradation characteristics, stratigraphic thickness is about 20m.

Rising half cycle of B: Bottom interface is the top interface of falling half cycle A. Top interface is the surface of thicker floodplain mudstone sediment. Red, light gray mudstone are mainly developed with fine sandstone and siltstone. the whole half cycle performances retrogradation characteristics, and the thickness is approximately 20m.

Falling half cycle of B: Top interface, sand group 3's internal interface, is bottom interface of thick channel sand or multi-stage retrogradation stacked sand in drills and well logging performance, part is progradation to retrogradation turnaround surface (Figure 3).A set of approximately 5 m sand body or the floodplain mudstone sediment is developed. The mudstone colors mostly are purple, red, light grey. The whole half cycle performances trogradation characteristics, the thickness is about 15m.

Rising half cycle of C: bottom interface is half-cycle B's top interface, top interface are usually turnaround surface, mostly floodplain deposition. Mudstone colors are light gray, red. The whole half cycle performances retrogradation characteristics.

Falling half cycle of C: the bottom interface is half cycle C's top interface. The top interface is the same as sand group 1's top interface, which is the turnaround surface of trogradation and retrogradation or bottom interface of a set stacking retrogradation sand from drilling and logging performance. Mudstone has significantly different colors, upper side are red, gray-green, but lower side are gray, dark gray (Figure 3). In the seismic profile, the interface should be the weak reflection interface under regional marker T_2, and locally onlap phenomenon may be found on the reflection interface. C's falling half cycle is transition from floodplain to deltafront, the sedimentary characteristics is from trogradation to accretion, the thickness is heavy, usually around 30m, falling half cycle of C is asymmetric with Rising half cycle of C.

Rising half cycle of D: the bottom interface is cycle C's top interface. The top surface is flooding surface of semi-deep lake mudstone, the GR curve base value change occurs at the interface, seismic reflection profiles are strong axis, mostly are oil shale deposition section, with comparative in all the region. The upper part is source rocks, the lower is reservoir, with the most favorable source-reservoir-seal assemblage, so half-cycle D's sand strata is usually hydrocarbon reservoir, which is the most favorable lithology trap layer. The thickness is generally 10 ~ 20 m.

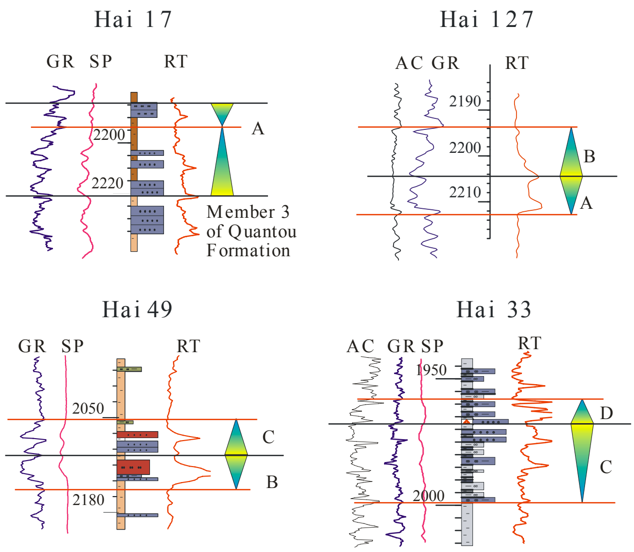

Figure 3
Response Characteristics of Cycle Boundary on Drilling and Logging

With the principles and methods of high-resolution sequence comparison, the sequence stratigraphy of backbone profile contrast on the basis of a single well sequence. Ten sections (5 roughly provenance direction and 5 crosscutting provenance direction) are selected in Haituozi area, the hemicycle level stratigraphic correlation is carried out, hemicycle level sequence stratigraphy of nearly 100 wells in the region is established at last.

3. SUB-LAYER CORRELATION IN THE FRAMEWORK

3.1 Main Problems of Previous Sub-Layer Division

Main problems of previous division of Quantou Ⅳ Formation in Haituozi area are: 1) Divide oil group (similar to the fifth level cycles in this study) firstly, the division mostly has the isochronal geology significance at this time, then thickness correlation are carried out in each oil group based on the relations of mudstone and sandstone-lithological correlation (contrast sandstone to sandstone, mudstone to mudstone). 2) Short-term cycles are identified using sequence stratigraphy approach, but the existence of autocyclicity is ignored. For instance the fining-upward distributary channel rhythm is mistaken for base level rising half cycle, and correlate to another river channel or rising half-cycles around; or the coarsening-upward crevasse fan is mistaken for base level falling half cycle, and correlate to another crevasse fan/ crevasse channel or falling half-cycles. The above two methods result pure lithological correlation, rock layer equal thickness correlation or anisochronous correlation. On this wrong basis, wrong analysis and forecasting of the reservoir distribution and reservoir characteristics are made, and it is not conducive to guide the later period development and production.

3.2 The Principles of Sub-Layer Correlation in the Study

At early and mid-major Quantou Ⅳ Formation deposition period alluvial river - floodplain sedimentation are mainly developed in Haituozi area, and at later period shallow lake delta sedimentation are mainly developed. Especially the banded distribution of early sand body sedimentation, sand lateral changes quickly, poor connectivity, the river burst diversion, frequent variation of sedimentary facies, characteristic of stratigraphic division and correlation is not obvious, the lack of obvious division contrast symbol, all of these cause some difficulties for the division contrast work. To solve this problem, this research takes the high resolution sequence stratigraphy theory as the instruction, and establishes a regional high-resolution sequence stratigraphic framework based on various geological data such as core, logging, seismic and oil testing data. In the actual operation of sub-layer correlation, the predecessors have recognized the significance of comprehensive use of various information to increase the accuracy and reliability of crrelation (Yuan and Shen, 2007; Qiu *et al*., 1987). The comparative study, according to the actual data, in the high-resolution sequence stratigraphic framework, similarity of facies association characteristics in base level change, consistency of reservoir fluid properties, isochronous maximum flooding surface in a certain area, different stags of overlay channels are took full account in the operation of sub-layer correlation.

3.2.1 Similarity of Facies Association Characteristics in Base Level Change

Regarding the fluvial deposits, the short-term autocyclicity is obvious (Yuan and Shen, 2007; Huang *et al*., 2006), autocyclicity is the combined result of rivers' own water body power and the sediment source supply, usually it only controls the internal structure of sedimentary facies and proportion of each facies, less relations with base-level cycles change (Deng *et al*., 2007), there is no comparative with each other; The fluvial deposits are controlled by the role of climatic change and small-scale regional tectonic activity (Lou and Zhao, 1991; Amorosi *et al*., 2008; Nádor *et al*., 2007), its depositional cycle is the reflection of base level change, which controls the formation of stacking pattern, formed contrast stratigraphic unit. The faster base-level changes, the more obvious depositional cycle reflection on the stratum. Combined with previous knowledge of sedimentary facies in this area (Zhao *et al*., 2008), based on core observation and experimental analysis, log-phase recognition, this paper analyzes microfacies firstly, especially the characteristic change of microfacies association, that is the change of stratum stacking pattern which reflect deposits allocycles (Liu *et al*., 2002), different microfacies development position in the base-level cycle is different, the horizontal development of sedimentary microfacies and the vertical evolution of the facies sequence is result of base-level cycles (five cycles) change, when contrast it has the similarity. The relationship of facies association characteristics and short-term base level change provides the basis for correlation, this method is the most direct application high-resolution sequence stratigraphy theory to the sub-layer correlation (Figure 4-A).

3.2.2 Isochronous Maximum Flooding Surface in a Certain Area

Mudstone section formed at maximum flooding period is stratum response of base-level rise and fall. If there is no such flooding surface in fluvial environment in a certain unit of geological time, it is autocyclicity sediment and has no comparative; only flooding can connect the mutual isolated river to form a flood plain mudstone, it is isochronal surface in a certain area. In different wells, as long as the upper and lower surfaces is isochronal, respectively, the rock layer under the control of two flooding surface is also isochronal (Hu *et al*., 2010). Mudstone formed during maximum flooding period generally are darker, relatively pure, thicker, and easy to distinguish on the lithology and logging properties, in a certain area it is a good “marker bed”, with good contrast (Figure 4-B).

3.2.3 Consistency of Reservoir Fluid Properties

Reservoir’s fluid information has important meaning to sub-layer correlation (Yuan and Shen, 2007). The oil, gas and water have good differentiation in the reservoir. In the conventional oil or gas reservoir, the same oil or gas reservoir has the oil-gas interface and the water-oil interface, the gas located at the highest spot, the oil layer next, and the water level must be located at the lowest spot; the layers which have different oil-gas or water-oil interface must have the stable compartment separated. Based on this law, making fully use of well tests data and production test data provided another kind operation method for the sub-layer correction (Figure 4-C).

3.2.4 Different Stages of Superimposed Channels

Channel deposit includes two kinds, the isolated channel deposition (intermittent superimposed channel) and the superimposed channel deposition (continuous superimposed and erosional superimposed). The former is easy to identify, the latter is that the channel formed at later period directly superimposed or erosional superimposed on the channel formed at early period, if not thoroughly washed, there are still fine-grained sediments between two sedimentary unit measured from the power curve, on the other hand if erode strongly, two period channels are completely superimposed and it is not easy to identify from cores and logs, so it is not easy to separate (Bridge and Tye, 2000). General “split layer” is used in the previous division and correlation of this kind channel (Wen *et al*., 2010). However, this phenomenon generally occurs in the transition period of base-level cycles falling to rising (Kjemperud *et al*., 2008), the smaller the A/S value for low curvature of meandering river, the more prone to erosion superimposed. Accordingly, analysis of the channel development position of base-level cycles can better determine whether there is superimposed channel, the different periods of channel sand are better distinguished according to the changes in response to a variety of logging curves (Figure 4-D).

3.3 Application

The overall thickness of Quantou Ⅳ Formation in Haituozi area is 100-120m, and it distributes relatively stable in the region. From bottom to top, the mudstone colors change from red to mottled, light gray, which responses relative rise sedimentary base level cycle. In the lower part (A, B, Rising half cycle of C), river - flood plain facies are major developed, in the upper part (Falling half cycle of C, Rising half cycle of D), delta front - Bin shallow lacustrine deposits are major developed. The bottom is interface of of Quantou Ⅲ and Ⅳ Formation, lithology is more consistent, thick layer of river sand or multi- period stacked sand bodies of this section are responded by drilling and logging, so sub-layer correlation of this section should give full consideration of different stages of superimposed channels; Up floodplain and lacustrine sedimentary is more developed, isochronous maximum flooding surface in a certain area should be considered; upper delta front is deposited, because of the distribution of big range of micro–facies, Similarity of facies association characteristics in base level change, especially vertical evolution of river channel, crevasse-splay / crevasse channel deposits should be considered; top boundary is a flooding surface, response the semi-deep lake mudstone, which is oil shale development segment, the GR curve base value changes the interface up and down, strong axis reflection in seismic profile, is a good marker bed; Meanwhile, making full use of the well tests data and production data of oil fields, considering the consistency of reservoir fluid properties, the sub-layer correlation of Haituozi area is carried out.

Took full advantage of established 10 short sequence cycles skeleton profile of the region (Figure 1), made full use of the above summary of the principle, and combined with the traditional correlation approach, 3 sub-layers are divided from cycle A , 3 sub-layers divided from cycle B, 5 sub-layers from cycle C, cycles D corresponds to a sub-layer, and finally Quantou Ⅳ Formation is divided into 12 sub-layers (Figure 5).

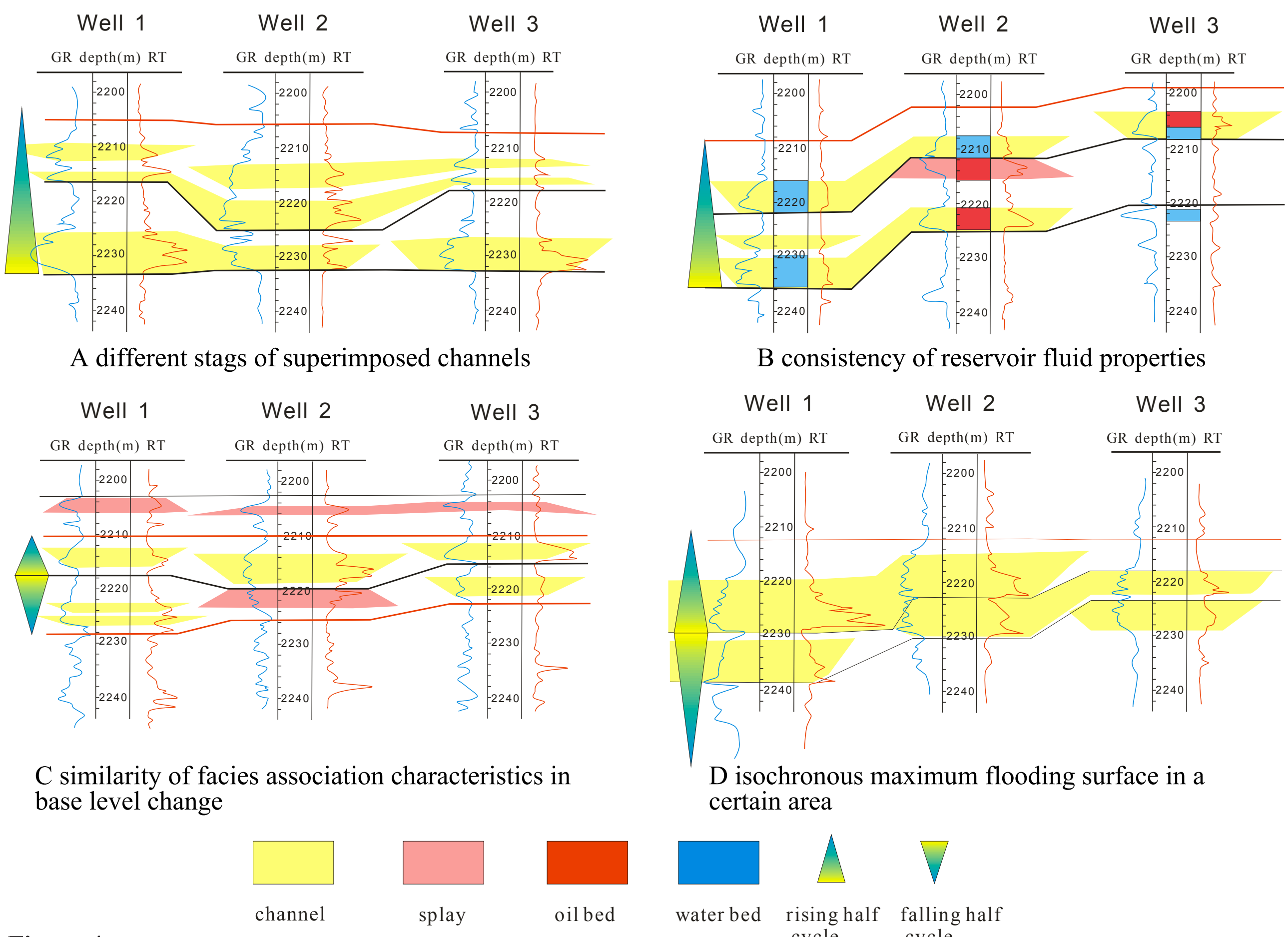

Figure 4
Sub-Layer Correlation in High-Resolution Sequence Stratigraphic Framework

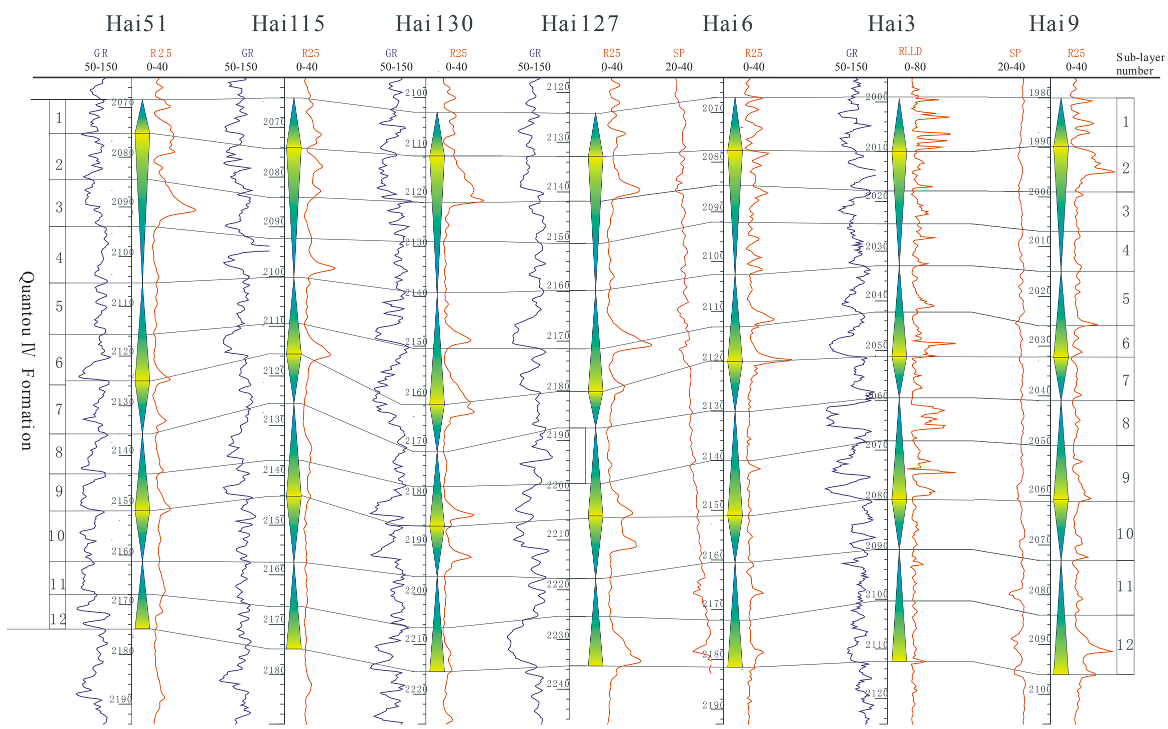

Figure 5
Correlation Section of Well Hai51-Hai9 in Haituozi Area(⑧ in Figure 1)

CONCLUSIONS

The theory of high resolution sequence stratigraphy has good guidance and applicability to carry out stratigraphic division and correlation for fluvial - Delta deposition. The above practices not only take into account the development of autocyclicity , but also consider the impact of short-term allocycles, essentially the sub-layer correlation in this study is the comparison of the allocycles, which constraints the autocyclicity in the stratigraphic framework. Integrated sub-layer correlation method had a very good practical application for the further analysis of the sedimentary microfacies vertical evolution and distribution, judgment of accumulation type, analysis of reservoir control factors, prediction of reservoir favorable target, the results proved the reasonableness of the division plan. The application of this method is most instructive for the similar areas whose data is relatively mature.

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