# Depositional Architecture-based Correlation Techniques for Deltaic and Fluvial Reservoirs in Lacustrine Basins*

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## Abstract

Most reservoirs in oil and gas fields of Eastern China are composed of predominately lacustrine deltaic and fluvial deposits, which exhibit complex reservoir architectures (cake-layer, jigsaw puzzle, labyrinthine or shingled). The recognition of various reservoirs involves making a well correlation where data are limited to a few, widely spaced cores and well logs. The geologists are therefore required to infer the reservoir extensional character in lateral by various means. Depositional architecture-based techniques of different facies zone for Deltaic and Fluvial system, represent genetic interpretations of reservoirs depending upon their certain sedimentary environments and architectures, are available to help the geologists make a reliable geological correlation. In certain sedimentary environments or facies zone, the individual sedimentary units or sand bodies can exhibit their specific architectural characteristics (geometry, length scale and vertical variation).

As a generalization, reservoirs with deltaic deposits commonly consist of basin-ward dipping and off-lapping clinoform prograding strata. Reservoirs with fluvial deposits show rapid facies variation and various architectures (lateral accretion, downstream accretion and overbank fills). This study is such one exercise whereby different geological correlation techniques based on various depositional facies zones of reservoirs were discussed for their potential impact on hydrocarbon development. Shihezi Formation (Middle Permian) in Sulige oil field (Ordos Basin) and Badaowan Formation (Lower Jurassic) in Cainan oil field (Junggar Basin) have been correlated using well logs and core data. The deposits of Meandering river were identified in Shihezi Formation with core characteristics (erosional surfaces, trough and planar cross-beddings) and log patterns (bell shape of logs); and fan deltaic deposits in Badaowan Formation with massive conglomerates and cylinder gamma-ray curve. Combined with the thickness of sand bodies, net-to-gross and conceptual guides derived from geometries observed in basin margin outcrops, the Shihezi Formation was correlated as labyrinthine (channel complexes with point bars and clay plugs); and the Badaowan Formation was correlated as shingled geometry with inclined sedimentary bodies (prograding configuration) instead of lithostratigraphic correlation as cake-layer. The correlations for Badaowan Formation, which were verified by production data, exhibited improvement of development efficiency by 12.5%.

## Introduction

The most of oil fields in eastern China have been coming into high water-cut stage with increasingly injection-production contradictions (Li, 2004; Zhong et al, 2007; Yu et al, 2008, 2012). The methods of conventional characterization for reservoir heterogeneity, like lithostratigraphic correlation for layer-cake reservoir, are not meeting the demand of waterflood development demand, especially deltaic and fluvial reservoir in the lacustrine basins with various sedimentary facies. Heterogeneities and architectures of reservoirs are the major concern to development and production engineers and geologists (Miall, 1988). During production in oil fields, geologists have to interpret and correlate the sand bodies within reservoirs with the limited subsurface data. However, in certain sedimentary environments, the individual sand-bodies can show their specific features of geometry and scale. Weber and van Geuns (1990) proposed a very useful and simple classification of reservoir geometries (layer-cake, jigsaw puzzle, and labyrinth reservoir types). Reservoirs with channel systems (jigsaw puzzle) and delta systems (shingled) show rapid facies variation, exhibit a high degree of complexity, and may be continuous over short ranges only (Tyler and Finley, 1992). Hence, the extent to which a detailed correlation can be made will depend upon the sedimentary environments of sand-bodies.

The core significance of reservoir characterization is to identify genetic features and predict distribution of reservoirs in temporal and spatial. As a review for the prospective of petroleum development, reservoir correlations are generally conducted under the genetic sand body's scale, even single sand body, which are limited by extension of depositional setting or facies zone. Geological model for reservoirs are built from the integrated information of sedimentary environments, depositional processes, geometry and scale. Recent studies have demonstrated the architectural configuration (scale and geometry of sand body and interlayer) of delta and fluvial systems, and proposed the correlation methods for these reservoirs (Miall, 1988; Ainsworth, 1999; Yu, et al, 2011). Nevertheless, geologists have yet to know how the reservoirs can be identified and predicted correctly using subsurface data alone. The problems with reservoir characterization in plane and vertical profile are acute in lacustrine setting, such as fluvial, delta, and fan system. As different depositional systems, even the different facies belt of the same depositional system, the analytic and mapping method on plane and section for reservoir characterization or correlation techniques of sand-body should be different. In this case, the correct reservoir architectures and extensions could be obtained, and better to approach the reality of sub-surface geology. For these reservoir rocks of deltaic and fluvial system, information that is much more accurate is need on three dimensional geometry, spatial scale, and reservoir architecture. This kind of information can be obtained by various studies focusing on modern sediments and ancient outcrops.

During the initial period of reservoir development, some geologists correlated reservoirs (sand bodies) by lithostratigraphic technique in two-dimension cross sections. This lack of sand body correlation as basic principle and of reservoir evaluation function, namely, there are not genetic interpretation, sand body prediction and guide the role of oilfield development. Usually problems and illusion are as follows: 1) Overlong sand bodies with similar well log patterns or totally isolated sand bodies; 2) Each well almost drilled in the center of sand bodies; 3) Violation of sand body geometry features, concave usually is fining upwards in grain size and bell shape of logging, conversely, but convex is coarsening upwards in grain size and funnel shape of logging; 4) Why the same thickness and grading sand body extend with same distance? 5) Do not reflect the sedimentary environment and changes of base level (Figure 1). This paper represents an aim to illustrate the procedures of reservoir correlation and compare the differences between lithostratigraphic and chronostratigraphic correlation techniques based on the clastic reservoir behavior of genetic sand body in facies zone scale of fluvial and deltaic systems.

## Principles for Vertical Reservoir Correlation of Genetic Sand Bodies

The geological studies of reservoirs consist of core analyses and various petrophysical studies made from well logs. In order to enhance hydrocarbon recovery, the sand body correlations have to reflect the heterogeneities or extension of reservoirs in vertical and plane scale. Geologists have to use stratigraphic and facies analysis to interpret the reservoir's geometry based on an understanding of its depositional environment or facies extension. In order to enhance hydrocarbon recovery, the correlations have to reflect the heterogeneities of reservoirs in vertical and plane scale. However, reservoir formed within different depositional system represents various architectures, and even show diverse scale within the same depositional system. Hence, the reservoir correlations have to obey the following principles.

**Facies and Architectures**. The facies characteristics of specific depositional system present the corresponding geometry, cycle, scale (ratio of width and length) and its within stacking pattern of sand body or base level changes in vertical. Size grading and cycle should be clarified in different order before reservoir correlation. The size grading represents the grain size changing within sand body in vertical, which reflects sedimentary process and geometry of sand body. For instance, fining upward generally indicates the concave up geometry of sand body, which developed by lateral accretion of fluvial. In addition, the coarsening upward suggests convex which formed by downstream accretion or aggradation of delta. Nevertheless, the sedimentary cycle always show base level changes and stacking patterns of genetic sand bodies. For fluvial system, the sand bodies could not be correlated through lithostatigraphic mean due to their facies change and limited scale in spatial (Figure 2). Geologists have to identify the sedimentary type (meandering or braided) of genetic sand bodies by size-grading, sedimentary structures, color, fossils and well log patterns. Finally, the reasonable correlations have been made after the scale (width or extension) of sand bodies in lateral quantitatively or semi-quantitatively have been determined through mapping extensions and changes of depositional facies zone in plan.

**Sedimentary Sequence**. Sedimentary sequence commonly consists of a series of facies, which is a genetic unit for a depositional system. For the reservoir correlation, sedimentary sequence reflects the genetic mechanism and chronostratigraphy of integrated sand bodies. Sand bodies of delta front or distributary mouth bar developed by progradation along the structure dip orientation. The common geometric configuration for them are the shingle or sigmoid. However, these kinds of reservoirs are generally forced a layer-cake correlation through the depositional system casually. As the single sand body or package of sand bodies scale in production geology, geologists need to employ different correlation means for the corresponding genetic units and predict the anisotropy of the reservoir.

**A/S Change and Stacking Pattern**. Recent studies have made efforts to understand the effects of relative sea level or base level changes in sediments at a scale close to the hydrocarbon reservoirs. This high-resolution sequence stratigraphy involves determining sedimentary sequences from core, log, and outcrop studies (Shepherd, 2009). Sequence stratigraphic analysis is a significant step to build a stratigraphic scheme for a reservoir. The sequences are also the containers for the assemblages of the various macroforms, which control the property and patterns within the reservoir. However, the ratio of accommodation and sediment supply changes is an indicator for parasequences, which have distinctive stratigraphic stacking patterns. The stacking pattern can be progradational, aggradational, or retrogradational depending upon the balance between accommodation and sediment supply. Once geologists have recognized the specific stacking pattern, they can predict the facies changes of parasequences laterally (basinward or landward).

**Markers**. For any depositional system, markers are never absolute. As a view of sequence stratigraphy, most of them are boundary surfaces. In order to understand stratigraphic features at the reservoir scale, the key stratal surfaces in wells have to be determined before reservoir correlation. Generally, major flooding surfaces are determined through vertical facies profile in the individual wells. Flooding events are established by inferring marked shifts in water depths from the more shoreward facies upward to the more basinal facies in cores and logs (Van Wagoner et al, 1990). However, at the reservoir scale, certain intervals can be identified as marker. These beds with distinctive features can be correlated with a high degree of confidence between wells. Coal beds for instance which formed over long periods can be considered as approximate time line separating individual depositional successions. Nevertheless, at the localized or sand body scale, flooding surfaces may extend limit even showing shingle or stacked features.

## Principles for Plane Reservoir Characterization

Plane reservoir characterization is significant for production by predicting the scale and configuration horizontally. Generally, there are two different methods to analyze the plane reservoir features: 1) plane distribution of sedimentary parameters (isograms), and 2) plane distribution of various genetic units (depositional facies or facies zone). The former one emphasizes selecting and statistic of sedimentary parameters, spatial anisotropy and integration. However, the later one relies on the understanding of geological model in different subenvironments. During the processing of characterization, geologists have to pay attention to sedimentary parameters, quantitative geological database, plane and vertical consistency.

**Sedimentary Parameters**. Sandstone content (ratio of sandstone and formation in which sandstone is not includes silt, and thickness of each single sandstone layer is more than 1 meter) and sand thickness are two major aspects indicating reservoir characteristics. In larger scale (interval thickness more than 30 m), sandstone content reflects distribution of depositional facies for a certain interval or geological time. In small scale (interval thickness less than 30 m), sand thickness map represents the changes of genetic units within depositional facies. It must be pointed that sedimentary environment should be considered before reservoir characterization for geologist's responsibility. In general, turning position of paleotopography is the enrichment of sandstone for any sedimentary environments, neither the highest nor the lowest position in structure. For instance, the point bar is the thickest part of sandstone for meandering fluvial system, and shelf break is the one in passive margin basin.

**Parameter Statistic**. In order to predict distribution of reservoir correctly, geologists have to select proper statistic methods for the sedimentary parameters. First, some geologists calculate the sandstone content with siltstone, which can be as reservoir. However, siltstone does not reflect the specific depositional system due to it belongs to mudstone. Hence, siltstone should be excluded when calculating sandstone content. Second, cut off for thickness of each single sand body should be set up when evaluating the thickness of sandstone within an interval (Figure 3). For example, there are two wells with the same thickness of interval and gross thickness of sandstone. One of the wells consists of one layer with the thickness of 30 m, but the other comprise of 30 layers with the average thickness of 1m. In case the quality of these two wells can not be distinguished by sandstone content and gross thickness of sandstone, such as sandstone content is ratio of sandstone and formation which sandstone is not include silt but sandstone thickness is more than 1 meter.

**Quantitative Geological Database**. Geological models or analogues derived from outcrops and subsurface studies are vital for reservoir characterization. Modern sedimentology showing more detailed information about the plane distribution of each depositional system provides a path of quantitative geological database for subsurface reservoirs. In order to predict plane distribution of sand bodies subsurface, ratio of width and thickness of sand bodies within reservoir should be calculated by log data.

**Plane and Vertical Consistency**. Consistency of reservoirs includes two aspects, which are genetic extent and consistency in space. Therefore, geologists should revise the procedure of doing cross-well section and plane reservoir characterization individually. The cross-well section and plane characterization should be conducted simultaneously, which represents a mutual verification and correction. For the deltaic system, reservoir in delta front should be correlated shingle as the progradation along orientation of sediment supply (Figure 4).

## Cainan Oil Field as Case

The Cainan oil field, the subject of this research, lies within the Junggar Basin, northwestern China. The main reservoir intervals lie within the delta-lacustrine in Badaowan Formation of Jurassic. The major reservoir facies are interpreted to be fan delta system depend upon cores, wells and seismic data. This study focuses on the first Member of Badaowan Formation, which was characterized by the previously discussed methods.

**Identification of Markers**. The first Member of Badaowan Formation was fan deltaic front facies, which mainly consists of subaqueous distributary channels and distributary mouth bars (braided diara). Intra-layers and inter-layers of non-reservoir were identified by the combination of well logs and cores observation. In the vertical profile, the objective was subdivided into four packages and seven genetic sand bodies (Figure 5).

**Cross Well Correlation**. The interval consists of conglomerates, gravelly sandstone, and medium sandstone totally showing coarsening upward feature of grain sizing and cycle. The genetic sand bodies and packages with rising base level cycles indicate progradation of the fan delta front (Figure 6). Coal bed at the top of the interval was interpreted to be a regional marker, and was flattened in study area. The correlation of reservoir shows that the genetic sand bodies with good continuity extend 500 m to 1,000 m along the orientation of sediment supply. In proximate area, sand bodies dip basin-ward with relatively low angle. In distal area, increasing number of genetic sand bodies show progradation structure.

**Plane Distribution**. The plane facies distribution of the first Member of Badaowan Formation was generated based on the sandstone content, well analysis and cross well correlation. In delta plain, feeder channel with small scale of bars present low sandstone content due to bypassing on the relatively steep slope. However, in delta front, larger scale of distributary mouth bars and more distributary channels spread widely with higher sandstone content (Figure 7).

**Production Verification**. In order to verify the reliability of depositional architecture-based correlation technique of depositional facies zone for reservoir characterization, well package of D1048 was selected to analyze (Figure 8). D1048 was injection well, while D1049 and D220 were production wells. Perforations were conducted at the upper intervals within these three wells. In the initial production period, well D1049 and D220 were water-free produced. Since 2008, tracers (Er, Sm) from well D1048 have been detected in well D1049, but there was no tracer in well D220. The results suggested that the reservoirs within these well should be correlated by chronostratigraphy method instead of lithostratigraphy. After changing the correlation method and injection position, the efficiency of recovery has been increased by 12%.

## Conclusions

1. Depositional genesis of reservoirs (sand bodies) is the precondition of reservoir correlation. Sand bodies with different geometry, scale, and stacking pattern were developed in corresponding sedimentary environments. Key factors of controlling changes of different depositional facies zone and sand bodies were the differences paleotopography and base level change.

2. The methods and principles of reservoir correlation are various for different sedimentary genetic or vertical stacking patterns of sand bodies. Even different depositional facies zones within the same depositional system have the specific strategies or methods for sand body inter-well correlation. Therefore, Inter-well reservoir characterization should be conducted which based on the changes of depositional facies zone, and combined with vertical succession sequences, depositional processes, stacking patterns of sand bodies or base level changes.

3. Sand body statistical content and method for mapping of reservoir characterization are different in various depositional scales. However, formation thickness was more than 30m, sandstone content should employed ratio of sandstone thickness and formation thickness for mapping; and if the thickness was less than 30m, the content should directly use sandstone isopach mapping without silts (thickness of each single sand body more than 1 m).

4. Constraining by quantitative geological database, plane reservoir distribution can be conducted by selecting proper statistic and spatial consistency, which approach the goal of addressing the conflicts between injection and production.

## Acknowledgement

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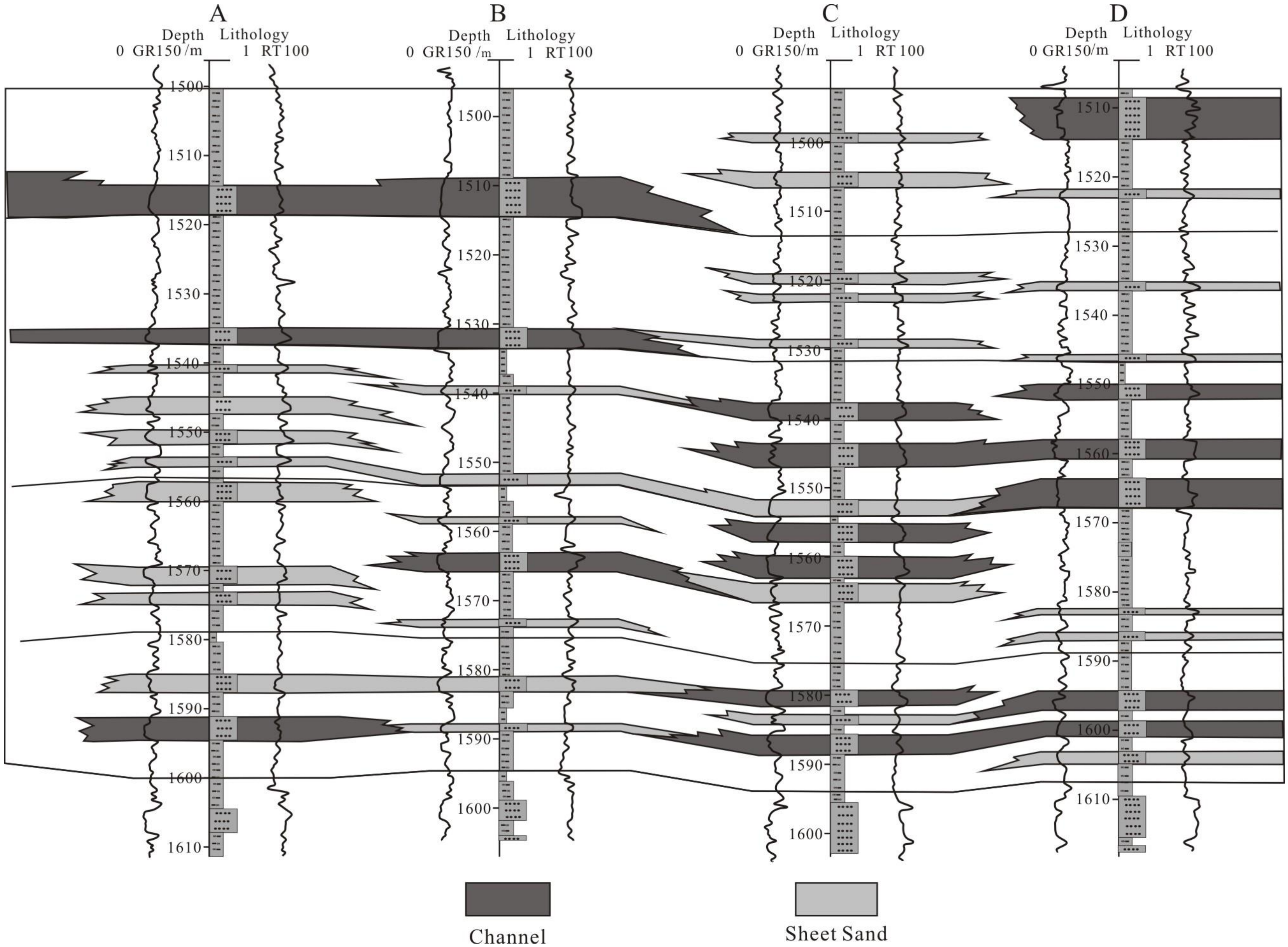



Figure 1. Layer-cake correlation for deltaic reservoir. Note that this correlation presents some improper information of reservoir architecture and inter-well prediction. For instance, the sand bodies with different thickness show the same lateral extension, and were correlated without any structure dip.

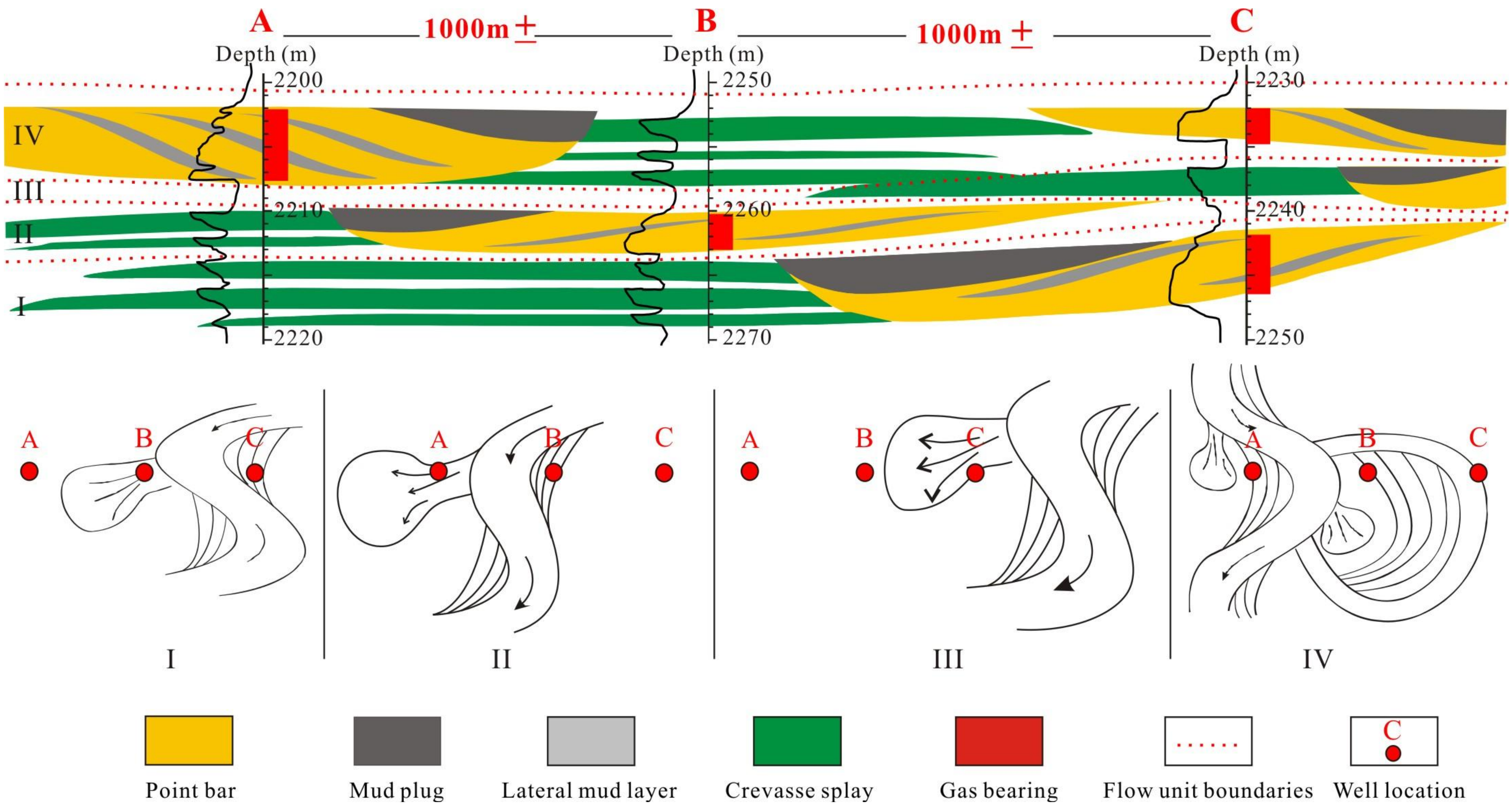



Figure 2. Correlation and plane distribution of fluvial reservoir in Shihezi Formation, Ordos Basin. Architectures were identified by log patterns, and plane view of channel systems were predicted by correlation.

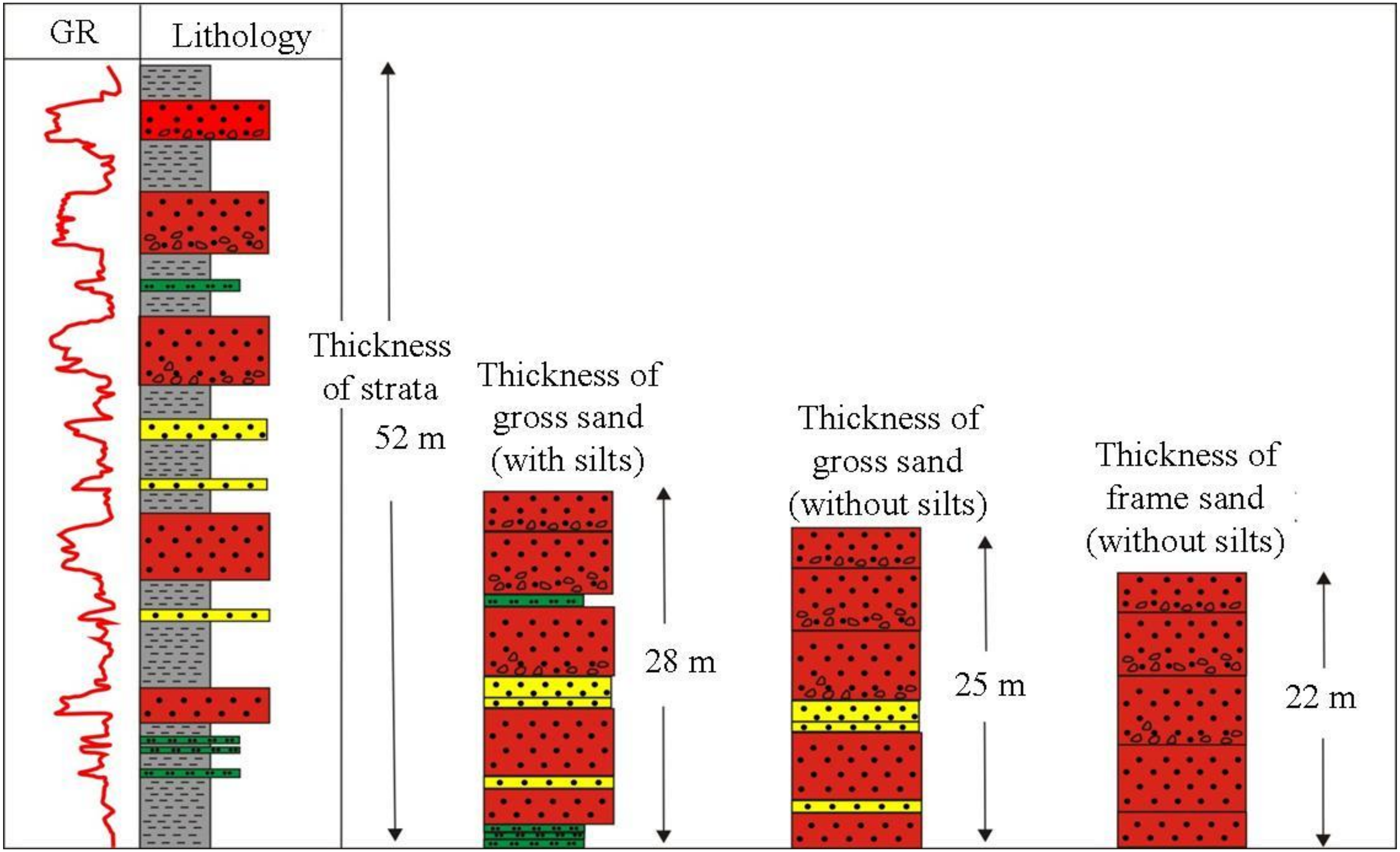



Figure 3. Different parameter statistic methods of sandstone content in vertical. Note that only thickness of gross sand without silts represents depositional systems. Thickness of frame sand without silts indicates distribution of reservoirs.

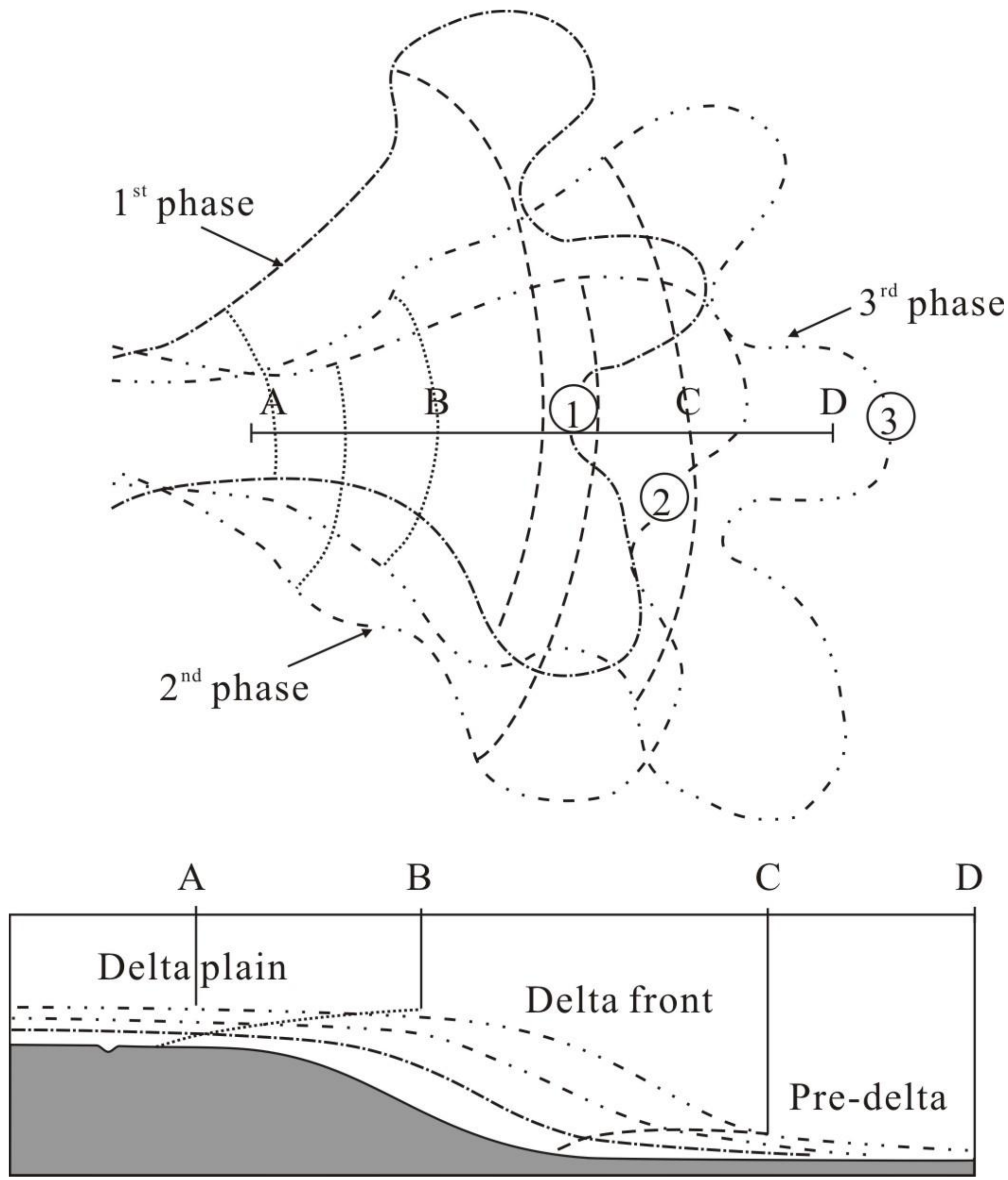



Figure 4. Schematic diagram of delta system illustrating plane and vertical consistency.

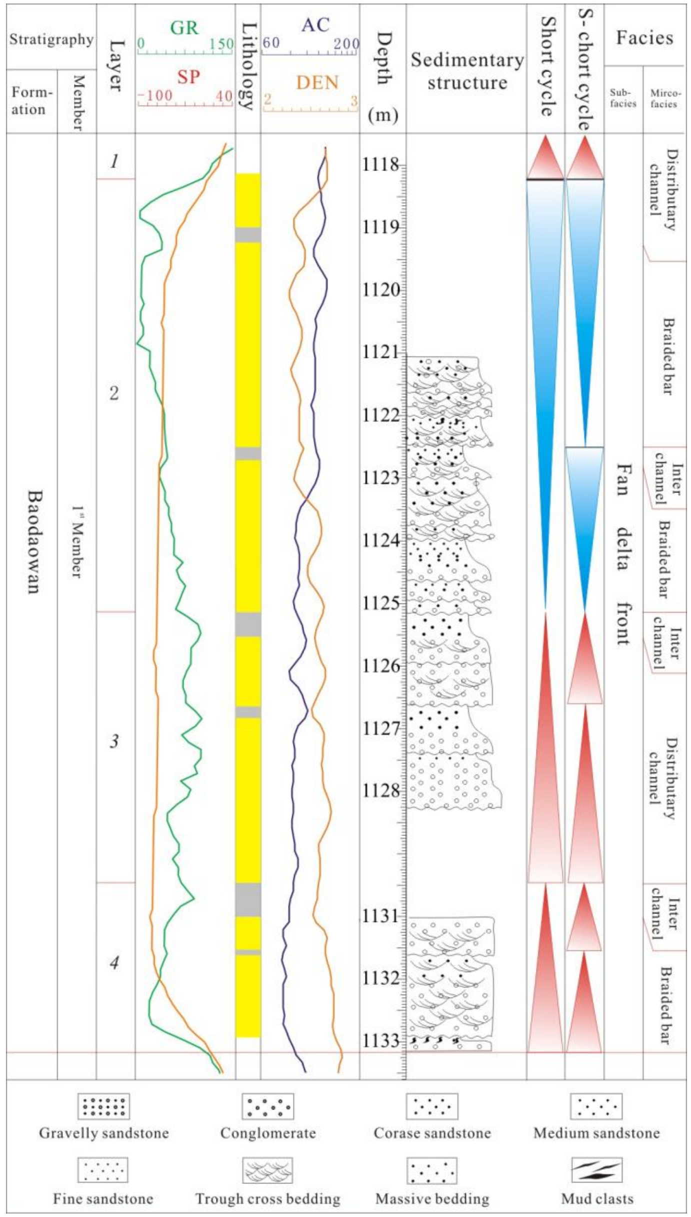



Figure 5. Integrated column of Badaowan Formation showing lithology, well log patterns, and sedimentary cycles.

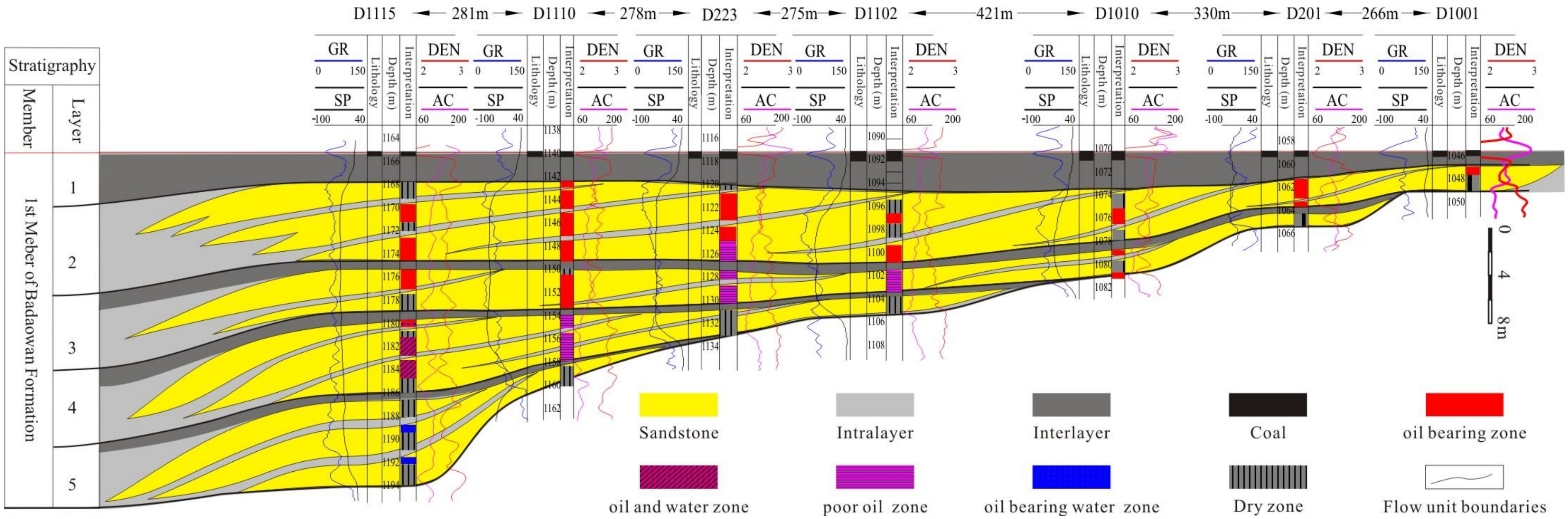



Figure 6. Correlation panel of fan delta reservoir showing progradation along structure dip. Note that coal bed at the top was flattened as a regional marker.

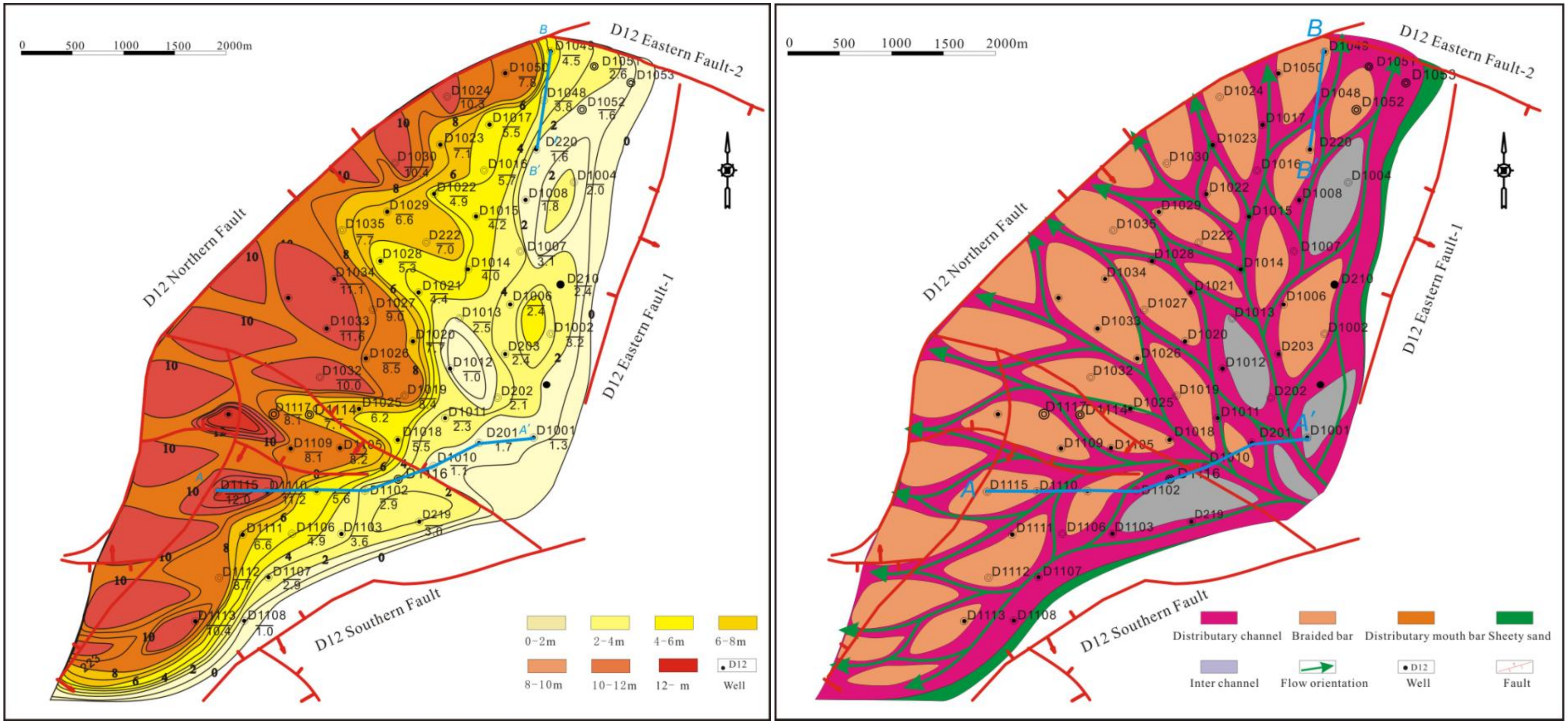
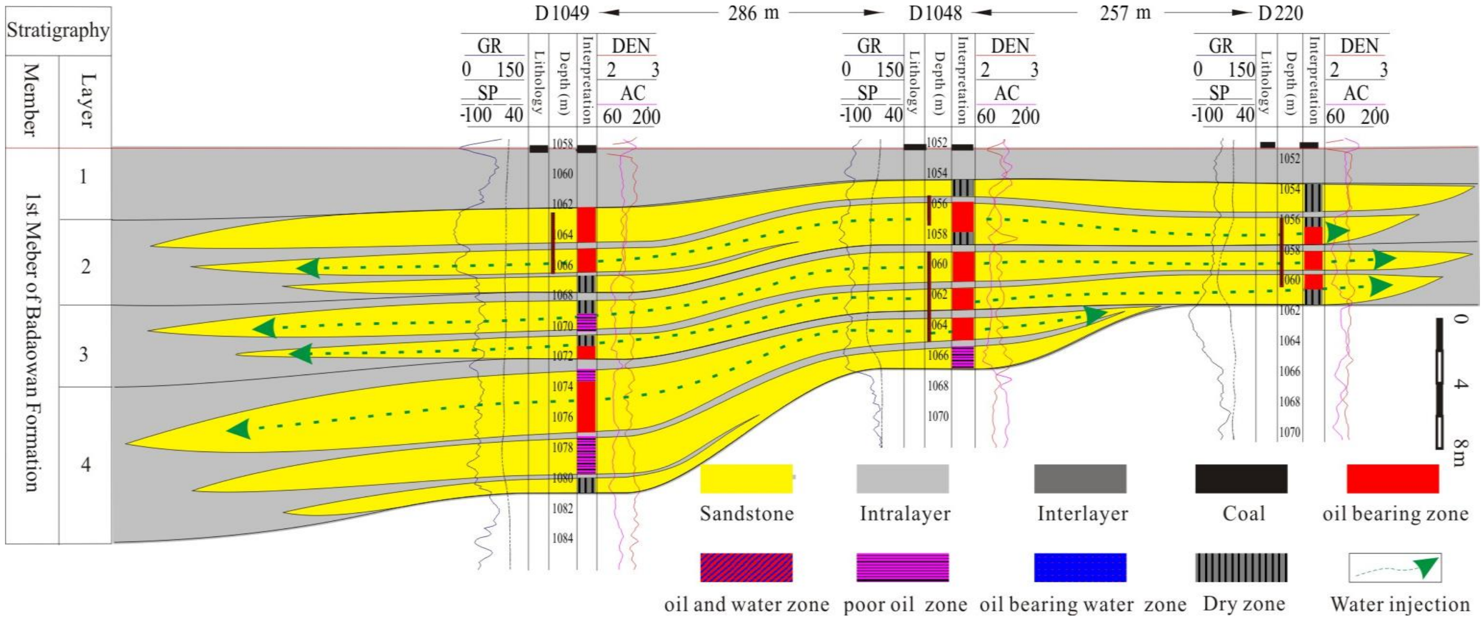



Figure 7. Isolith of sandstone content (A) and facies distribution (B) of fan delta system in Badaowan Formation, Junggar basin.



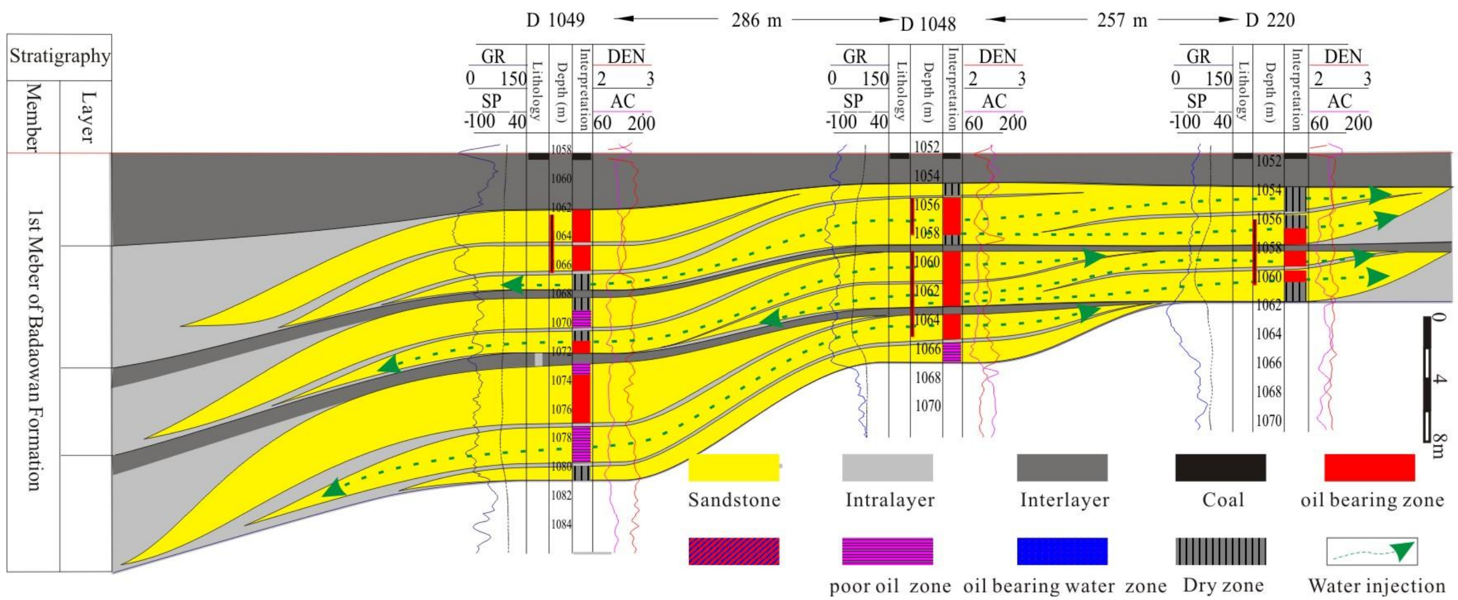




Figure 8. Correlation of wells in Cainan oil field illustrating the difference between (A) cake-layer correlation (lithostratigraphic) and (B) depositional architecture-based correlation (chronostratigraphic).