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Along-Strike Reservoir Development of Steep-Slope Depositional Systems: Case Study from Liushagang Formation in the Weixinan Sag, Beibuwan Basin, South China Sea

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Abstract: Seismic, core, drilling, logging, and thin-section data are considered to analyze the reservoir diversity in the east, middle, and west fan of the Liushagang Formation in the steep-slope zone of the Weixinan Sag, Beibuwan Basin. Three factors primarily affect the reservoir differences for steep-slope systems: (1) Sedimentary factors mostly control reservoir scales and characteristics and the drainage system and microfacies. Massive high-quality reservoirs have shallow burial depths. Channel development and sediment supply favor the formation of these reservoirs. The sedimentary microfacies suggest fan delta plain distributary channels. (2) Lithofacies factors primarily control reservoir types and evolution. The diagenesis of high-quality reservoirs is weak, and a weak compaction–cementation diagenetic facies and medium compaction–dissolution diagenetic facies were developed. (3) Sandstone thickness factors primarily control the oil-bearing properties of reservoirs. The average porosity and permeability of high-quality reservoirs are large, the critical sandstone thickness is small, the average sandstone thickness is large, and the oil-bearing capacity is high. Furthermore, the reservoir prediction models are summarized as fan delta and nearshore subaqueous fan models. The high-quality reservoir of the fan delta model is in the fan delta plain, and the lithology is medium–coarse sandstone. The organic acid + meteoric freshwater two-stage dissolution is developed, various dissolved pores are formed, and a Type I reservoir is developed. The high-quality reservoir of the nearshore subaqueous fan model is in the middle fan, and the lithology is primarily medium–fine sandstone. Only organic acid dissolution, dissolution pores, and Type I–II reservoirs are developed. Regarding reservoir differences and models, the high-quality reservoir of the steep-slope system is shallow and large-scale, and the reservoir is a fan delta plain distributary channel microfacies. Weak diagenetic evolution, good physical properties, thick sandstone, and good oil-bearing properties developed a Type I reservoir. The study of reservoir control factors of the northern steep-slope zone was undertaken in order to guide high-quality reservoir predictions. Further, it provides a reference for high-quality reservoir distribution and a prediction model for the steep-slope system.

Keywords: Weixinan Sag; reservoir diversity; Liushagang Formation; northern steep-slope

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Citation: Liu, S.; Zhu, H.; Liu, Q.; Zhou, Z.; Chen, J. Along-Strike Reservoir Development of Steep-Slope Depositional Systems: Case Study from Liushagang Formation in the Weixinan Sag, Beibuwan Basin, South China Sea. *Energies* **2023**, *16*, 804. https://doi.org/10.3390/en16020804

Academic Editors: Yuming Liu and Bo Zhang

Received: 23 November 2022
Revised: 29 December 2022
Accepted: 6 January 2023
Published: 10 January 2023

1. Introduction

Since the concept was first proposed in the 1960s, the fan delta depositional system has received increasing attention. With the development of research, studying the fan delta has gradually deepened from the initial study of sediment characteristics and outcrops to the sedimentary model and fan delta reservoirs [1–6]. With the gradual deepening of studies on the fan delta depositional system, we found that the fan delta depositional system is widely developed in the continental lacustrine basins in the early stage of structural development and belongs to a type of accumulation of coarse debris [7–11]. Furthermore, the nearshore subaqueous fan comes from the deep-water fan, primarily manifesting as a submarine fan, with coarse-grained sediment and developed in the lowstand system tract [12–15]. Research on the nearshore subaqueous fan depositional system is becoming increasingly hot and can be divided into inner, middle, and outer fans and shows different characteristics according to the lithology, grain size, and structure [16–19]. The fan delta and the nearshore subaqueous fan have similar sedimentation; however, as an unconventional reservoir, some reservoir diversity problems of the nearshore subaqueous fan and fan delta exist [20–25]. Based on the different sedimentary reservoir factors [26–29], this is a comprehensive study on the reservoir diversity in the northern steep-slope zone of the Weixinan Sag, Beibuwan Basin.

The Beibuwan Basin is a Cenozoic-faulted sedimentary basin under the background of a Mesozoic regional uplift. After more than 40 years of exploration and development, the Weixinan Sag of the Beibuwan Basin is currently proven to be a hydrocarbon-rich sag [30–32]. Located on the northwest edge of the Beibuwan Basin, Weixinan Sag is a primary battlefield for oil exploration and development in the western South China Sea. The production situation of existing oil fields is challenging, and an urgent need exists to find large-scale, high-quality reserves. Studies have defined the sedimentary system and characteristics of the steep northern slope of the Liushagang Formation in the Weixinan Sag. The Weixinan Sag was in the early stage of tectonic evolution during the Liushagang Formation and developed a fan delta and nearshore subaqueous fan sedimentary system [33]. However, different areas in the northern steep-slope zone of the No. 1 fault in the Weixinan Sag are affected by large differences in burial depth, differences in the overall sedimentary environment, and varying oil and gas reservoir types [34–36]. There are still many problems in the prediction of high-quality reservoirs in the northern steep-slope zone. The specific influencing factors and the distribution law of high-quality reservoirs are still unclear.

Fan delta and nearshore subaqueous fan deposits are developed in the Liushagang Formation of the steep-slope belt to the north of the study area. Under the constraints of general sedimentary facies, a series of high-quality reservoir distribution problems exist in the northern steep-slope zone of the Weixinan Sag in the Beibuwan Basin. In this contribution, we choose the slope belt of a faulted lacustrine basin to dissect the high-quality reservoir and origin. (1) The abundant data show differences in reservoir development in the northern steep-slope zone's western, central, and eastern areas. (2) Through the reservoir differences of different areas in the northern steep-slope zone, the reasons for controlling the reservoir differences are clarified, and it is considered that the sedimentary, lithofacies and sandstone thickness factors jointly control the reservoir differences. (3) By studying the controlling factors of high-quality reservoirs in different areas, two high-quality reservoir development models, a fan delta model and a nearshore subaqueous fan model, are summarized to provide a corresponding basis for studying high-quality reservoir distribution.

2. Geological Setting

The Beibuwan Basin to the north of Hainan Island, south of Guangxi, and connected with the Yinggehai Basin in the west, is the primary petroleum-bearing basin north of the south China Sea, with an area of approximately 39,000 km^2 (Figure 1A). The entire basin contains eight sags and three uplifts. The Weixinan Sag northwest of the Beibuwan Basin has an area of 3000 km^2 (Figure 1B). It is bounded by the Yuegui Uplift to the northwest, the Weixinan Uplift to the southwest, and the Qixi Uplift to the east and southeast. The Weixinan Sag is surrounded by mountains to the north and south and connects the east to the west. The Weixinan Sag can be divided into three subsags: the A subsag to the north, the B subsag in the middle, and the C subsag to the west [37–39]. In the Cenozoic era, the Weixinan Sag experienced complex tectonic evolution activities and can be divided into two stages of tectonic evolution: the rifting stage (the Changliu Formation to the Weizhou Formation) and the depression stage (the Weizhou Formation to the Wanglougang Formation) [40–43]. The fault activity is noticeable during the rifting period, and faults control the basin's development. However, during the depression period, the fault activity weakened or disappeared, and sedimentation controlled the basin development. Faults are widely developed in the Weixinan Sag. The No. 1 fault system is developed in the northern boundary area, and the No. 2 fault system is in the basin's center (comprising many en-echelon faults) (Figure 1C).

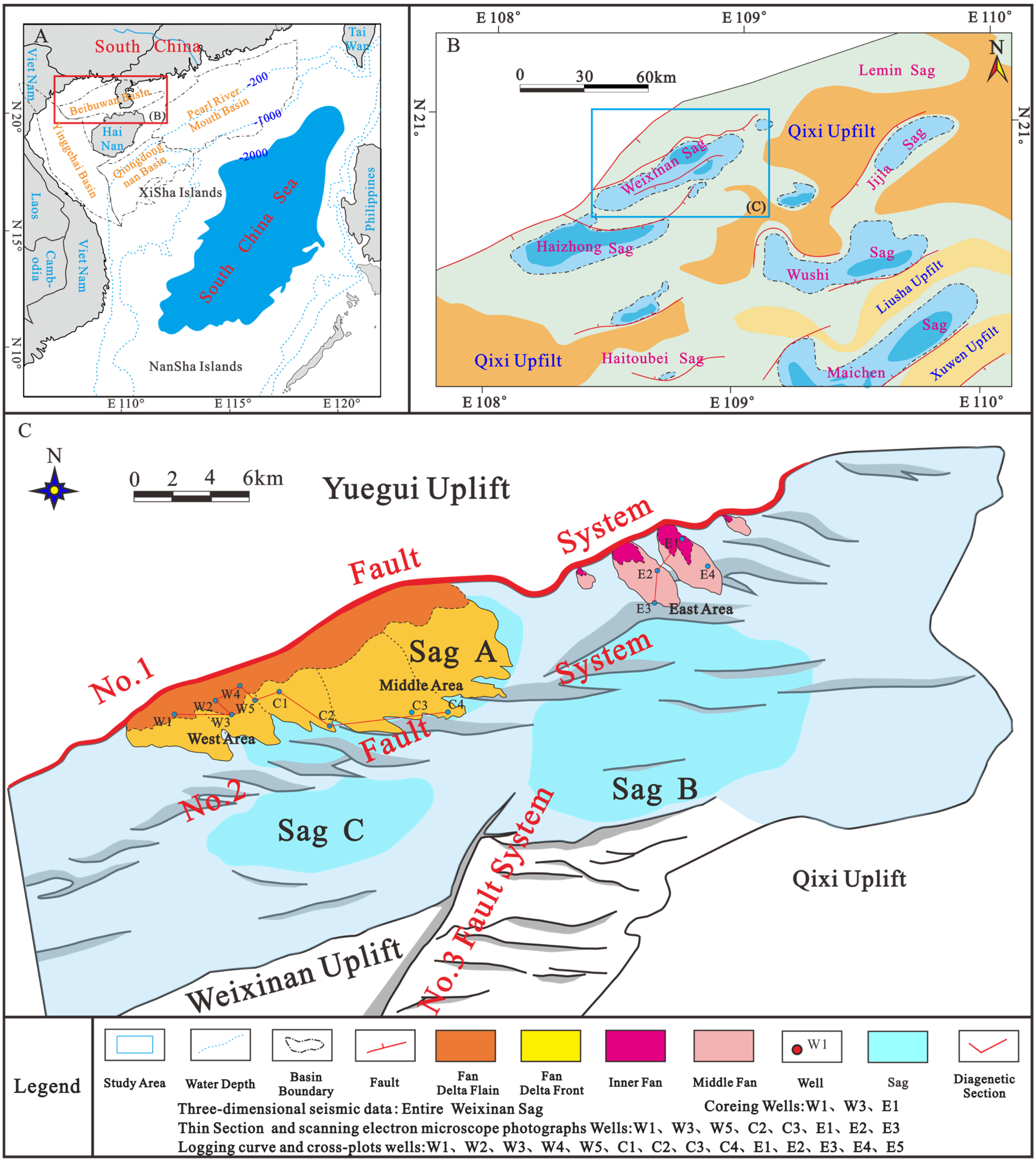

Figure 1. (**A**). Location map of sedimentary basins in the south China Sea. (**B**). Location map of the Weixinan Sag and other sags in the Beibuwan Basin. The Beibuwan Basin is shown in (**A**). (**C**). The division of the specific depositional system of the Liushagang Formation in the northern steep-slope zone in the Weixinan Sag. The Weixinan Sag is shown in (**B**).

The entire Cenozoic strata are presented in the Weixinan Sag, with a thickness of 6700 m, including continental sedimentary strata in the Paleogene and marine sedimentary strata in the Neogene and Quaternary.

From the bottom to the top, the Changliu, Liushagang, and Weizhou Formations are developed in the Paleogene, and continental sediments, such as lake and delta facies, are primarily developed (Figure 2). The Changliu Formation (65.5–55.8 Ma) is typically less than 300 m. The lithology is brownish-red and purplish-red sandy mudstone, mudstone, sandy conglomerate, and pebbly sandstone. Alluvial fluvial facies deposits are developed. In the early rifting stage, the Liushagang Formation's strata (55.8–35 Ma) have a thickness of approximately 2000 m [38,41]. Sequence stratigraphy analysis shows that the Liushagang Formation can be divided into three members. The lower sequence is the Liushagang Formation's third member, the middle sequence is the second member, and the upper sequence is the first member. In the Liushagang Formation's third member (T90–T86), the lake level was low, and the lithology was pebbly sandstone mixed with thin mudstone. A set of fan delta and shore shallow lake deposits developed. In the Liushagang Formation's second member (T86–T83), the lake level rose, and the lithology was dark mudstone, oil shale, and thin sandstone, and a set of lacustrine deposits developed. In the Liushagang Formation's first member (T83–T80), the lake level dropped again. The lithology is medium–fine sandstone mixed with mudstone, and a set of braided river delta deposits developed [38,44–46]. The thickness of the Weizhou Formation (35–23 Ma) is large and the maximum is over 3000 m. The lithology is the interbedding of sandstone, conglomerate, and mudstone, and the meandering river delta depositional system developed (Figure 2). The study area is in the eastern, central, and western areas of the A subsag northwest of the No.1 fault system. A set of fan delta sedimentary systems from the Yuegui Uplift developed.

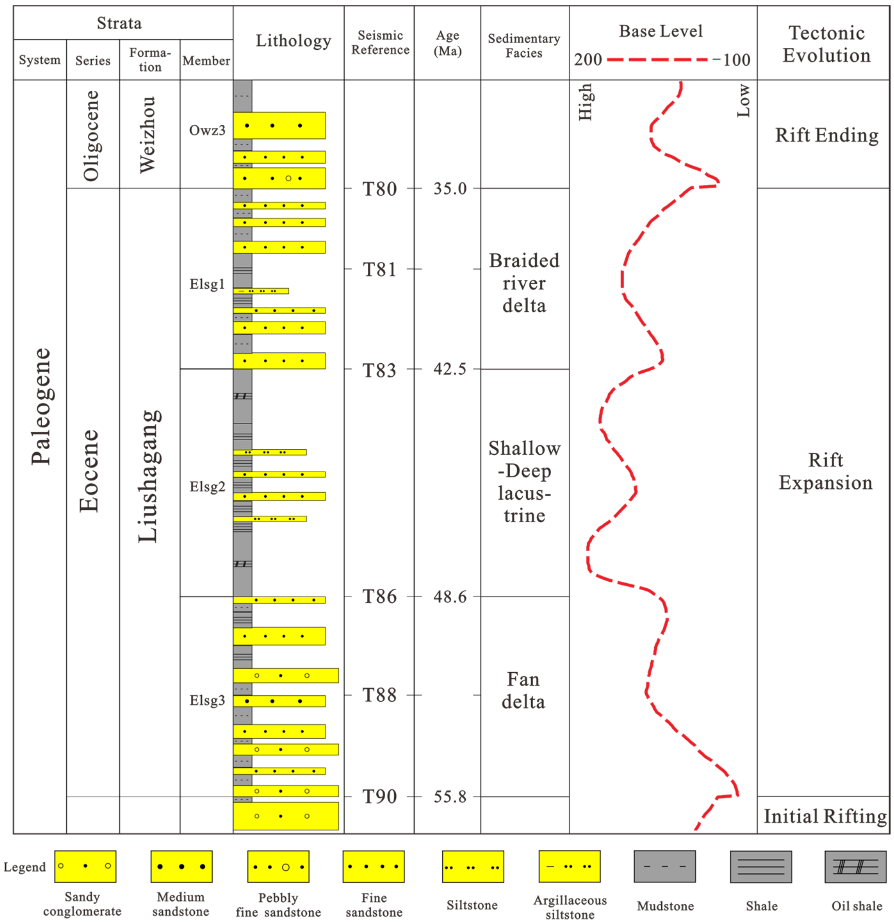

Figure 2. Stratigraphic evolution histogram of the Weixinan Sag, Beibuwan Basin.

3. Materials and Methods

Much three-dimensional seismic, core, logging, and thin-section data from identification, analysis, and testing are used to analyze the reservoir diversity in the northern steep-slope zone of the Weixinan Sag. All data are from the CNOOC Hainan Branch.

The three-dimensional seismic data cover 500 km^2 of the entire northern steep-slope zone, and the dominant seismic frequency is 30–35 Hz. The data are used for sequence stratigraphic analysis, restoring paleogeomorphology and the drainage system, and studying the scale of the sedimentary channel and system in the northern steep-slope zone of the Weixinan Sag to distinguish the differences between the west, middle, and east areas [47]. Therefore, based on the identification of denudation areas, denudation/downlap areas, and downlap areas, the source and sink areas should be considered in the restoration process. The specific steps include: (1) eliminating the subsidence difference caused by post-rifting tectonic movement; (2) dividing the source-to-sink systems; (3) recovering the denudation volume in the denudation/downlap area of each source-to-sink system; (4) calculating the denudation volume in the denudation area of each source-to-sink system; and (5) restoring the geomorphology.

This area has 3 coring wells (Wells W1, W3, E1), and the overall coring length of the Liushagang Formation section is more than 50 m. The analysis of typical core photos is used for the lithologic discrimination and fine description of different sedimentary microfacies to analyze the oil–gas properties of high-quality reservoirs. The Liushagang Formation has more than 10 wells drilled. The statistics of lithology combination and sand content for several wells are used for analyzing the sedimentary microfacies and the statistics of reservoir sandstone thickness, clarifying the critical sandstone thickness for reservoirs.

Fourteen wells in the Liushagang Formation were identified by thin sections and scanned by an electron microscope (Wells W1, W3, W5, C2, C3, E1, E2, E3) to analyze the reservoir mineral type, reservoir type, reservoir diagenesis, and reservoir diagenetic facies distribution (Wells W1, W2, W3, W4, W5, C1, C2, C3, C4, E1, E2, E3, E4, E5).

A few wells were analyzed for reservoir oil–gas properties, porosity, and permeability. By combining various data using the theories of sedimentology, sequence stratigraphy, and sedimentary reservoirs, this study summarizes the control factors of the differences between high-quality reservoirs in the study area and predicts the development model of high-quality reservoirs.

4. Results and Interpretations

Analysis of the exploration data on Weixinan Sag confirms noticeable differences between the reservoirs in the western, central, and eastern areas of the northern steep-slope zone of Weixinan Sag, including the following three sections:

4.1. Catchment-Fan Systems along the Steep-Slope Zone

(1) Drainage system

By combining 3D seismic data and denudation restoration, we restored the Wanshan Uplift's landform and drainage system [47]. The western and central areas have a large source area and adequate material supply. The short-axis steep-slope source-to-sink and drainage systems are developed. It is a composite drainage system, and the entire source area is connected, showing a composite linear source.

The eastern source area is small, and the material supply is inadequate. The short-axis slope source-to-sink system is developed, and the drainage system is undeveloped. It is a single drainage system, and the entire source area is isolated, showing a single-point source (Figure 3).

(2) Supply flux

Four aspects of the supply flux are counted: channel (slope), valley (width, depth, and area), fault (activity), and sedimentary system (burial depth, sedimentary area, thickness, and extension length). The differences between the west, middle, and east areas are compared (Figure 4 and Table 1).

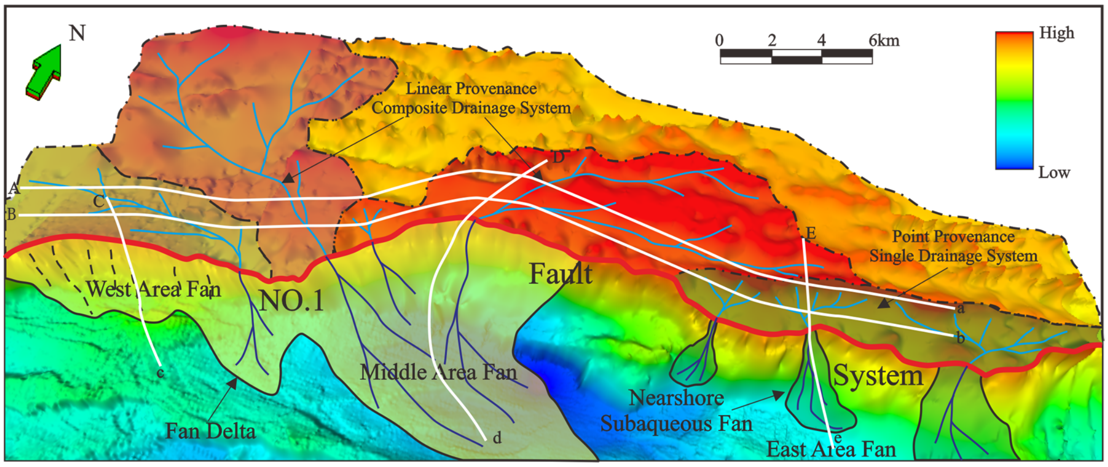

Figure 3. Distribution map of paleogeomorphology and drainage system in different areas of the northern steep-slope zone of the Weixinan Sag (The Aa, Bb, Cc, Dd and Ee are seismic section).

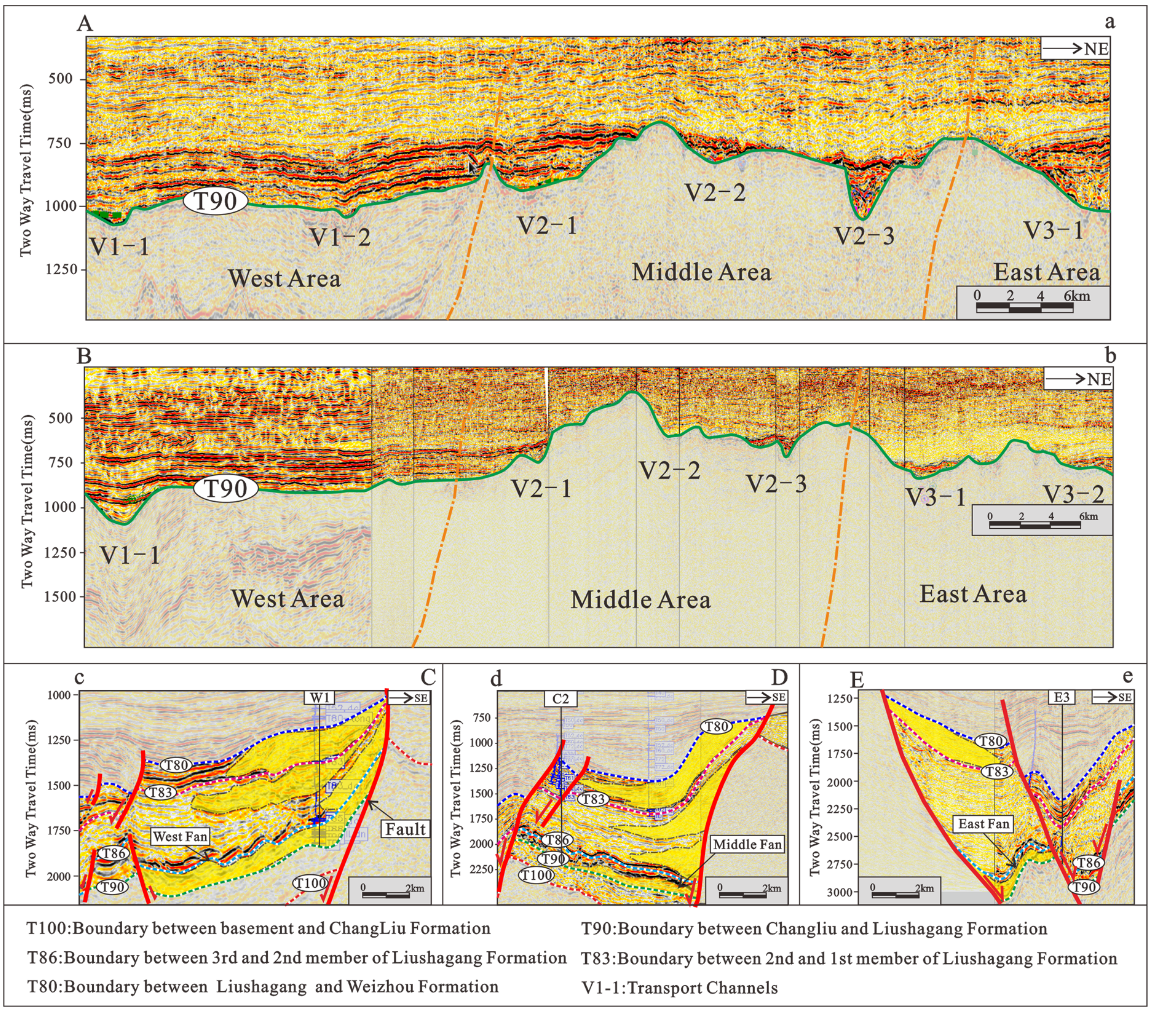

Figure 4. Interpreted seismic section Aa and Bb (SW–NE) of the gully and interpreted seismic section Cc, Dd, and Ee (NW–SE) of the sedimentary system in the northern steep-slope zone of the Weixinan Sag, Beibuwan Basin (the location of the section is shown in Figure 3).

Table 1. The channel information of the west, middle, and east areas in the northern steep-slope zone of the Weixinan Sag.

Area	Number	Channel		Valley		Fault	Deposition System			
		Slpoe/°	Depth/m	Width/m	Area/m^2	Activity/m/Ma	Deposition Depth/ms	Deposition Area/m^2	Thickness/m	Extend/m
West Area	V1-1	4	0.2	4	0.6	500	1850–2150	200	0.6	15.5
	V1-2	3	0.15	3	0.5	550				
Middle Area	V2-1	6	0.2	4	0.7	300	2000–2250	300	0.45	25
	V2-2	7	0.2	6	0.65	200				
	V2-3	8	0.3	4	0.8	150				
East Area	V3-1	8	0.25	3	0.5	700	2750–3000	125	0.3	10
	V3-2	7	0.23	2.5	0.4	610				

The western area is characterized by a small slope, medium gully, strong fault activity, shallow burial depth of the sedimentary system, and medium-scale development. The central area is characterized by a medium slope, large gully, medium fault activity, medium burial depth of the sedimentary system, and large-scale development. The eastern area is characterized by a large slope, small gully, strong fault activity, large burial depth of the sedimentary system, and small-scale development.

The drainage system in the western area is developed, the sediment supply is large, and the reservoir scale is medium to large. The central area is far from the fault, the sediment supply is weak, and the reservoir scale is large. The eastern area has an undeveloped drainage system, a small sediment supply, and a small reservoir scale. (Figure 4 and Table 1).

(3) Sedimentary facies

Different sedimentary facies represent different sedimentary environments and control the reservoir types [6,10,13,14,26,27]. Fan delta and nearshore subaqueous fan depositional systems are developed in the study area.

In the Liushagang Formation of well W1 in the west, fan delta plain distributary channel microfacies are developed. A large set of thick sandstone developed between 2100 and 2200 m (Figure 5). The core shows that the lithology is grayish-brown massive oil-bearing medium sandstone. The reservoir's thin section at 2118.1 m shows that the content of matrix and muddy is low, and many primary and secondary pores are developed (Figure 5). It is a suitable reservoir type.

The fan delta front underwater distributary bay microfacies are developed in the middle area. The overall lithology is fine, the content of muddy and matrix is high, the primary porosity is reduced, and the secondary porosity is increased, making it a medium reservoir type.

During the Liushagang Formation of well E1 in the east, the middle fan branch channel microfacies are developed (Figure 5). The core at 3049.37 m shows that the lithology is gray, massive siltstone. The reservoir's thin section at 3062 m shows that the matrix and muddy content is high, and the proportion of primary pores is reduced and undeveloped. The proportion of secondary pores is high, and a small amount is developed, making it a poor reservoir type (Figure 5).

Fan delta plain distributary channel microfacies are developed in the west and are the primary reservoirs. Fan delta front distributary bay microfacies are developed in the central area, making them medium reservoirs. In the eastern area, nearshore subaqueous fan and middle fan branch channel microfacies are developed, making it the worst reservoir.

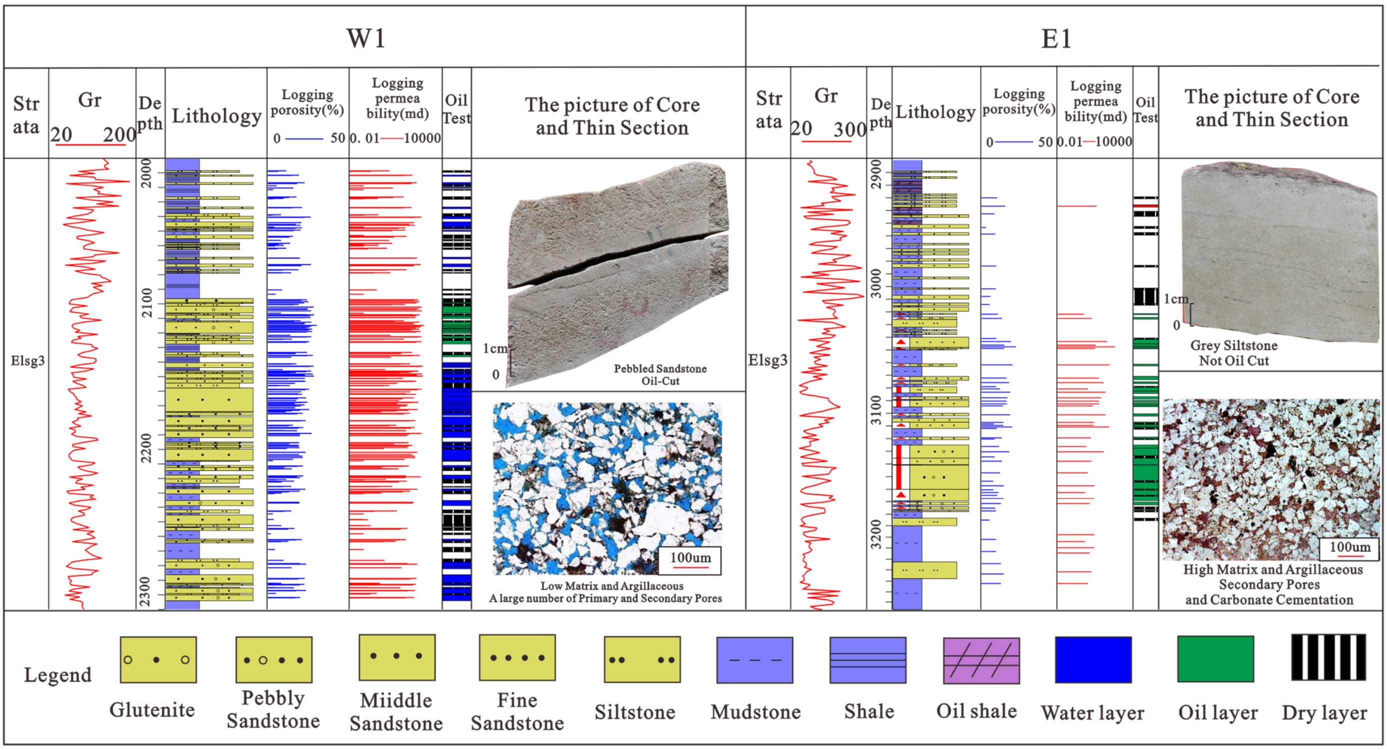

Figure 5. Single-well cores, logging, and reservoir thin sections in the west and east areas (well W1 (the well location is shown in Figure 1C) in the west, with good physical properties, and well E1 (the well location is shown in Figure 1C) in the east, with poor physical properties).

4.2. Diagenetic Processes and Facies

(1) Diagenesis type

Various reservoir diagenesis types exist [48,49]. This study clarifies the differences between diagenesis in the east, middle, and west areas regarding compaction, cementation, and dissolution and guides the study of diagenetic facies. Through the analysis of typical well thin sections in the northern steep-slope zone of the Liushagang Formation, the west area is shallow buried and has weak compaction, and the detrital grains contact is primarily the point contact (Figure 6A); interstitial materials are argillaceous cementation (Figures 6F and 7A), and carbonate and siderite cementation also developed. The primary pores are well developed, two-stage acid corrosion of meteoric freshwater + organic acid is developed, and the corrosion pores are developed (Figure 6G).

The middle area is moderately buried and moderately compacted, and the detrital grains are the line contact (Figure 6B); the interstitial materials are cemented by argillaceous, carbonate, and clay minerals (Figures 6F and 7B), and the primary and secondary pores are developed. The late organic acid dissolution is primary, and the dissolution pores are medium (Figure 6H).

The east area is deeply buried, strongly compacted, and the detrital grain contact is concave–convex (Figure 6C). The interstitial materials are cemented by argillaceous and carbonate minerals (Figures 6F and 7C), and the secondary pores are primary. The dissolution of meteoric freshwater is limited, and the dissolution of late organic acids is primary, and the dissolution pores are small (Figure 6I).

(2) Diagenetic facies

Different diagenetic facies control different reservoir types and predict high-quality reservoir development [27,28,50]. Diagenetic facies types were divided by thin section observation, logging curve classification, and cross-plots of different logging curves. Five types of diagenetic facies occur in the study area: Type I is weak compacted and cemented diagenetic facies, Type II is medium compaction and dissolution diagenetic facies, Type III is strong compaction and medium dissolution diagenetic facies, Type IV is compaction and argillaceous filling diagenetic facies, and Type V is dense compaction diagenetic facies.

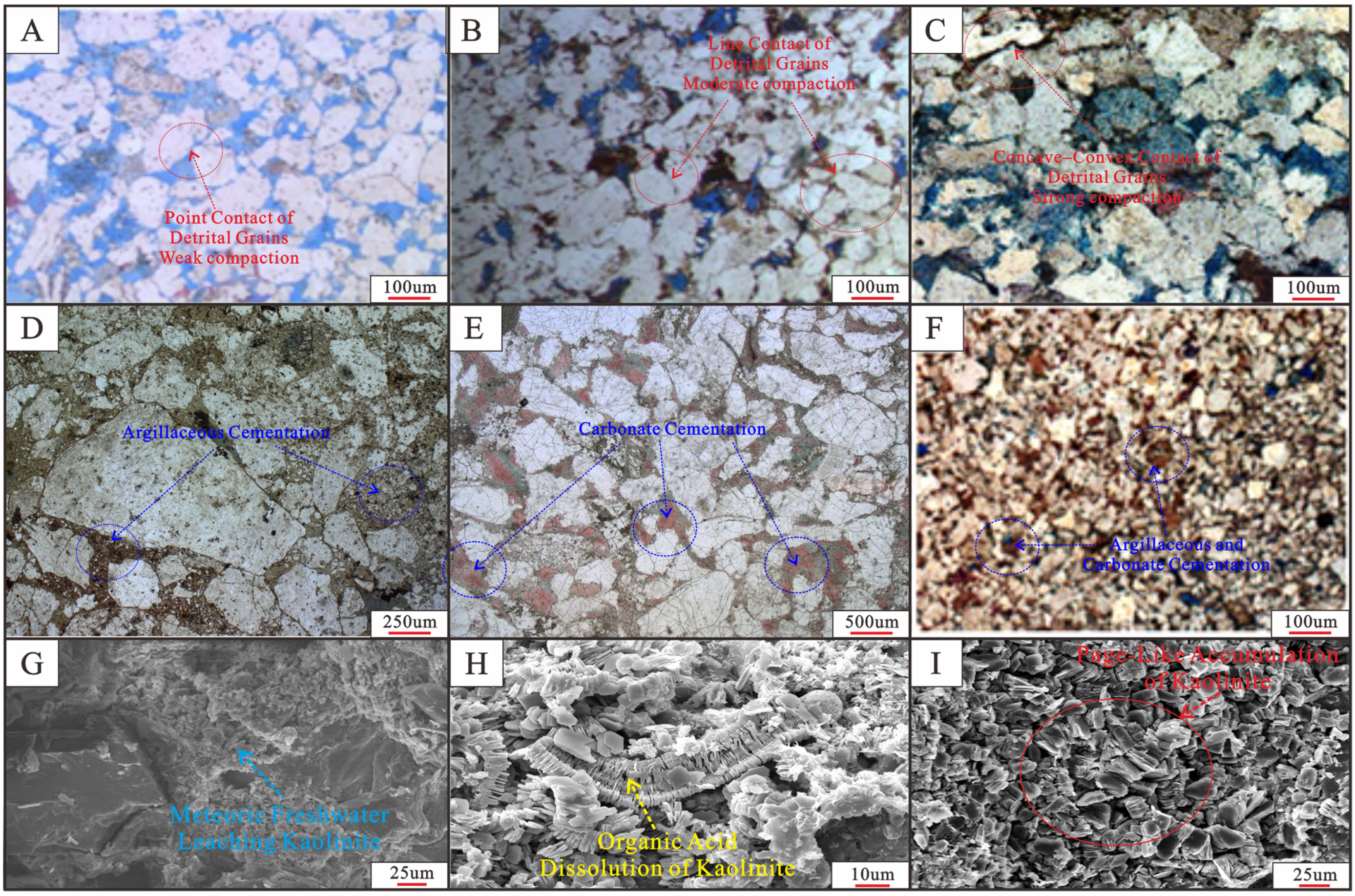

Figure 6. The thin section and scanning electron microscope photographs of the diagenesis of a typical well in the northern steep-slope zone of the Weixinan Sag. (**A**). Well W5, 2053.2 m, the point contact of detrital grains. (**B**). Well C3, 3158.44 m, the line contact of detrital grains. (**C**). Well E3, 3566.74 m, the concave–convex contact of detrital grains. (**D**). Well W3, 1935.9 m, the argillaceous cementation. (**E**). Well C3, 3229.31 m, the carbonate cementation. (**F**). Well E3, 3571.82 m, the argillaceous and carbonate cementation. (**G**). Well W1, 2152.65 m, the early meteoric freshwater leaching kaolinite. (**H**). Well C2, 2677.16 m, the late organic acid dissolution of kaolinite. (**I**). Well E2, 3047.85 m, the page-like accumulation of kaolinite and typical late dissolution.

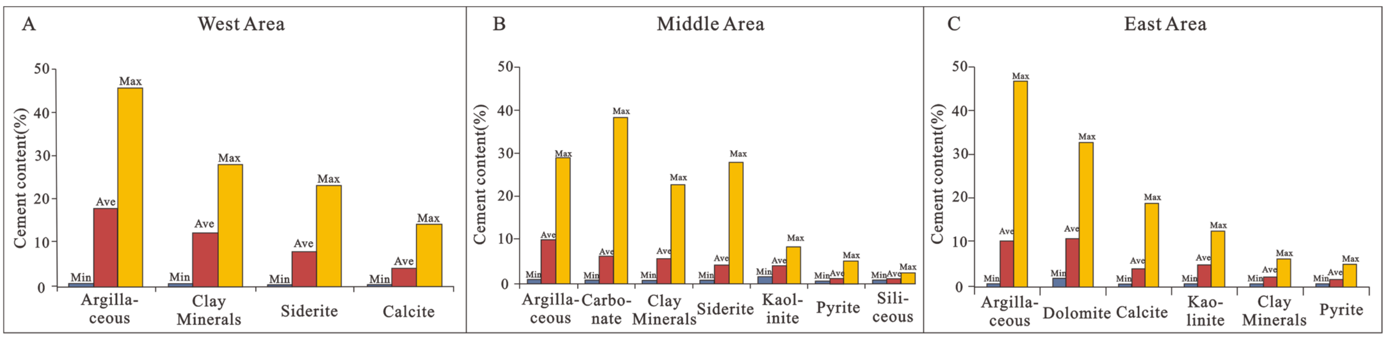

Figure 7. The cement types and contents of west area (**A**), Middle area (**B**) and East area (**C**) of the Liushagang Formation in the northern steep-slope zone of the Weixinan Sag.

We mainly used two methods to divide diagenetic facies:

1. Typical thin sections and quantitative statistics

Through thin-section observation of typical wells, we have summarized the characteristics of five types of diagenetic facies: Type I, weak compacted and cemented diagenetic facies (weak compacted, many primary pores are developed, porosity > 20%); Type II, medium compaction and dissolution diagenetic facies (the primary and secondary pores are developed, the porosity ranges from 15% to 20%); Type III, strong compaction and medium dissolution diagenetic facies (strong compacted, the secondary pores are developed, the porosity ranges from 10% to 15%); Type IV, compaction and argillaceous filling diagenetic facies (strong compacted, the content of matrix and muddy is high, the porosity ranges from 6% to 10%); and Type V, dense compaction diagenetic facies (strong cementation, a small amount of secondary pores are developed, porosity < 6%).

2. Logging curve and cross-plot identification (GR, RD, DEN, CNC, AC)

The range of logging curve values of different diagenetic facies types can be determined through the cross-plots of logging curves. In combination with AC, CNC, DEN, RD, and GR logging curves, we divided the diagenetic facies in the study area (Table 2).

Table 2. Typical logging curves of reservoir diagenetic facies.

Diagenetic Facies Type	AC/(um/S)	CNC/(*v*/*v*)	DEN/(g/m^3)	RD/(Ω/m)	GR/(API)
Type I weak compacted and cemented diagenetic facies	100–130	0.3–0.5	2.0–2.3	0.7–6	40–60
Type II medium compaction and dissolution diagenetic facies	70–90	0.1–0.2	2.3–2.5	5–20	50–75
Type III strong compaction and medium dissolution diagenetic facies	60–70	0.05–0.15	2.4–2.6	20–45	70–85
Type IV is compaction and argillaceous filling diagenetic facies	70–90	0.1–0.2	2.3–2.5	5–20	80–95
Type V is dense compaction diagenetic facies	60–70	0.05–0.15	2.4–2.6	20–45	90–110

1. Type I weak compaction and weak cementation facies: high GR, AC, and CNC and low RD and DEN.
2. Type II medium compaction medium dissolution facies: high GR, AC, and CNC and low RD and DEN.
3. Type III strong compaction medium strong dissolution facies: high GR, AC, and CNC and low RD and DEN.
4. Type IV compaction argillaceous filling facies: low GR, CNC, and AC and high RD and DEN.
5. Type V tight cementation facies: low GR, CNC, and AC and high RD and DEN (Table 2).

Combined with various diagenetic facies, we studied the diagenetic facies in different areas by connecting wells. The west area primarily develops thick massive pebbly sandstone with Type I weak compaction and cementation diagenetic facies, Type IV compaction argillaceous filling diagenetic facies at the root, and Type V dense cementation diagenetic facies at the thin-front sandstone (Figure 8).

The middle area is dominated by Type II medium compaction and dissolution diagenetic facies and Type III strong compaction and medium dissolution diagenetic facies. Unlike the west area, Type V tight cemented diagenetic facies are more developed (Figure 8).

The east area is dominated by Type III strong compaction and medium dissolution diagenetic facies of an underwater distributary channel sandstone reservoir (Figure 9). The thin layer primarily comprises Type V dense cemented diagenetic facies.

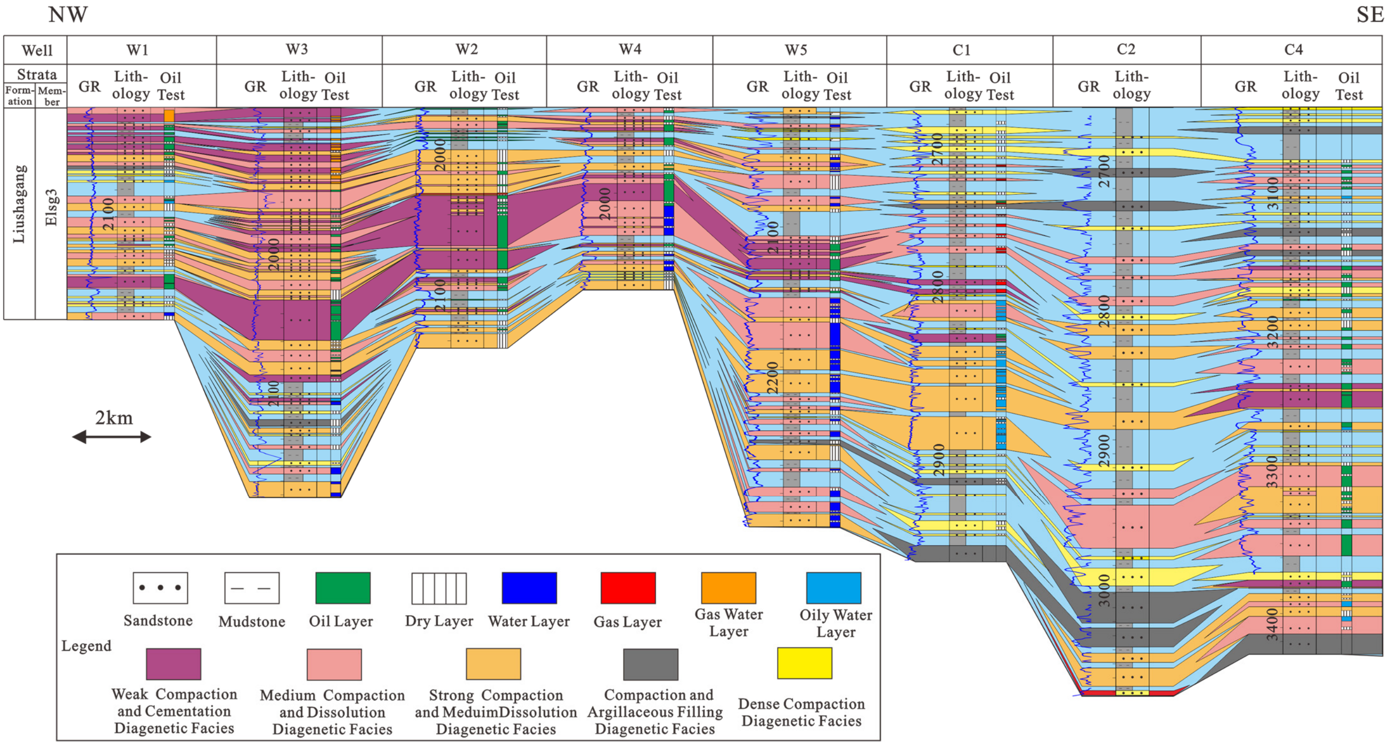

Figure 8. The diagenetic facies correlation section from wells W1 to C4 showing the diagenetic evolution of the west and middle areas in the Weixinan Sag (the section location is shown in Figure 1).

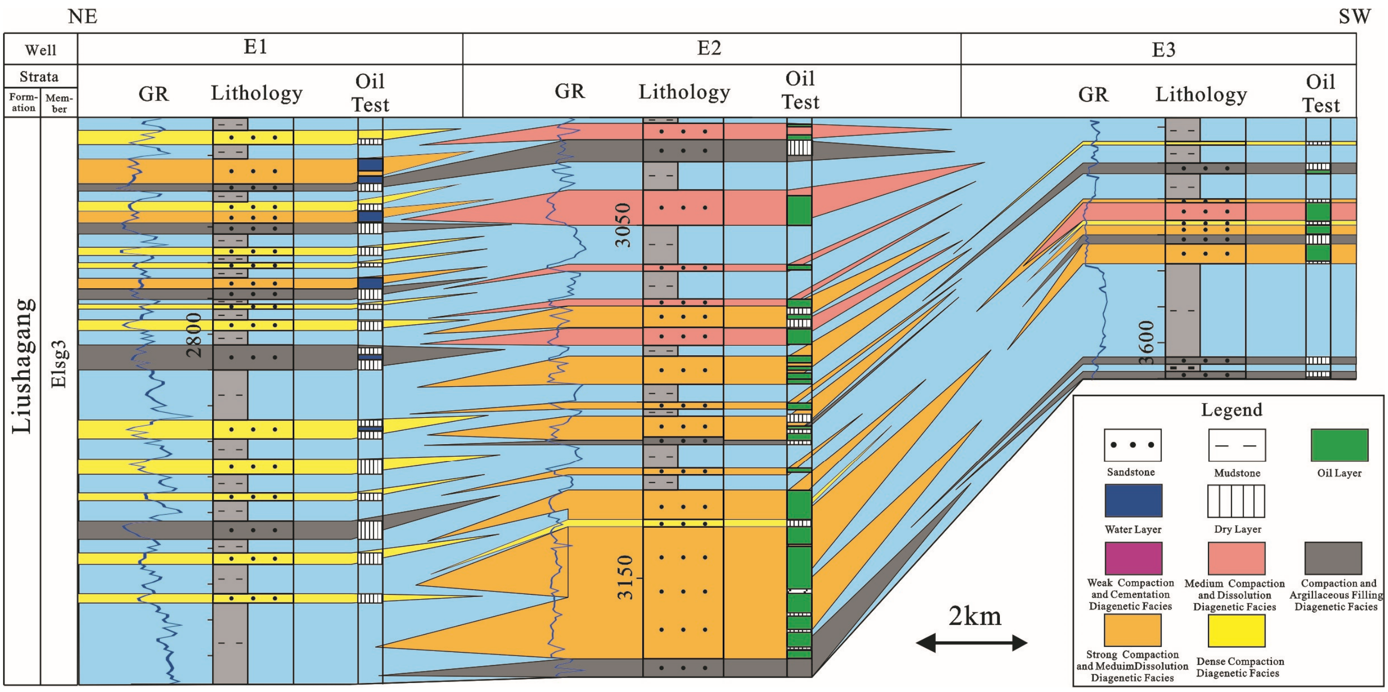

Figure 9. The diagenetic facies correlation section from wells E1 to E3 showing the diagenetic evolution of the east area in the Weixinan Sag (the section location is shown in Figure 1).

4.3. Porosity, Permeability, and Oil Saturation

(1) Porosity and permeability

Through physical property statistics, the physical property characteristics of the three areas in the steep-slope zone of the Weixinan Sag are as follows.

The porosity of the western area ranges from 0.6% to 28.5%, averaging 15.1% (Figure 10A). The permeability is between 0.01 and 4481 mD, averaging 184.4 mD (Figure 10B). The porosity of the central area ranges from 0.3% to 25.6%, averaging 12.7% (Figure 10A), and the permeability is between 0.01 and 2335 mD, averaging 62.1 mD (Figure 10B). The porosity of the eastern area ranges from 1.7% to 13.6%, averaging 8.8% (Figure 10A), and the permeability is between 0.06 and10.2 mD, averaging 0.97 mD (Figure 10B).

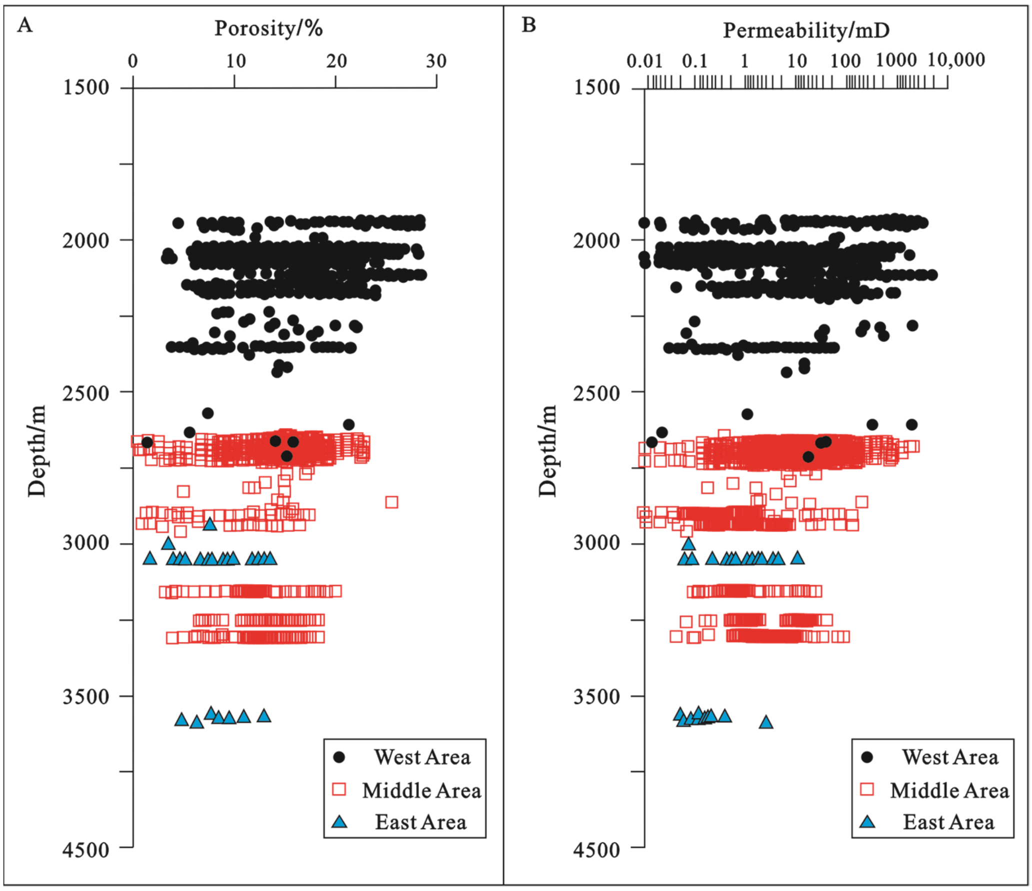

Figure 10. The relationship between (**A**) porosity and (**B**) permeability and depth in the western, central, and eastern areas.

Further, we divided these reservoirs into different types by adopting the following criteria:

1. Type I conventional reservoir: porosity > 12% and permeability > 10 mD;
2. Type II low permeability reservoir: porosity range from 6% to 12% and the permeability is between 1 and 10 mD;
3. Type III tight reservoir: porosity < 6%, permeability < 1 mD (Table 3).

Table 3. The reservoir classification standards table.

Reservoir Type	Porosity/(%)	Permeability/(mD)
Type I Conventional Reservoirs	>12%	>10 mD
Type II Low Permeability Reservoirs	6–12%	1 mD–10 mD
Type III Tight Reservoirs	<6%	<1 mD

(2) Oil saturation

First, the reservoir grade controls the reservoir's oil–gas properties, and we clarified the relationship between different reservoirs and oil saturation. The western region primarily developed Type I conventional reservoirs, with oil saturation from 35 to 90%. In the central area, Type II low permeability reservoirs are developed, with Type III tight reservoirs developed around them. The oil saturation is 20–68%. In the eastern region, the range of Type I conventional reservoirs is small, and most areas develop Type II low permeability reservoirs and Type III tight reservoirs with oil saturation of 10–45%. (Figure 11).

Sandstone thickness is another crucial factor controlling oil saturation. In the northern steep-slope zone of the Weixinan Sag, the critical sandstone thickness (the oil saturation in most areas exceeding the critical thickness is more than 50%) in different areas is determined from the statistical analysis of sandstone thickness and oil saturation in the western, central, and eastern areas. The critical sandstone thickness in the west area is the smallest at approximately 3 m, while that in the middle area is medium at approximately 5 m and that in the east area is the largest at approximately 8 m (Figure 12A,B).

Simultaneously, we studied the distribution of the average sandstone thickness in different areas. The sandstone thickness in the west is the largest (average sandstone thickness 40 m), and the sandstone thickness in the middle area is medium (average sandstone thickness 25 m). The sandstone thickness in the east is the thinnest (average sandstone thickness < 20 m) (Figure 13).

The critical sandstone thickness in the western region is small, the average sandstone thickness is large, and the oil-bearing property is the best. The critical sandstone thickness in the central region is medium, the average sandstone thickness is medium, and the oil-bearing property is medium. The critical sandstone thickness in the eastern region is large, the average sandstone thickness is small, and the physical property is the worst.

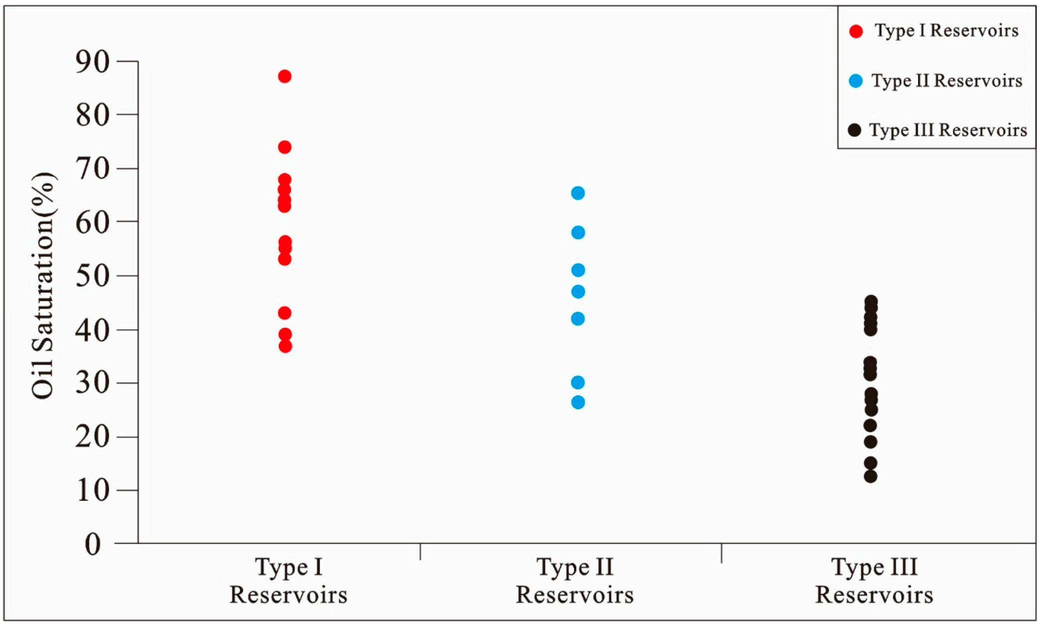

Figure 11. The oil saturation characteristics of different reservoirs.

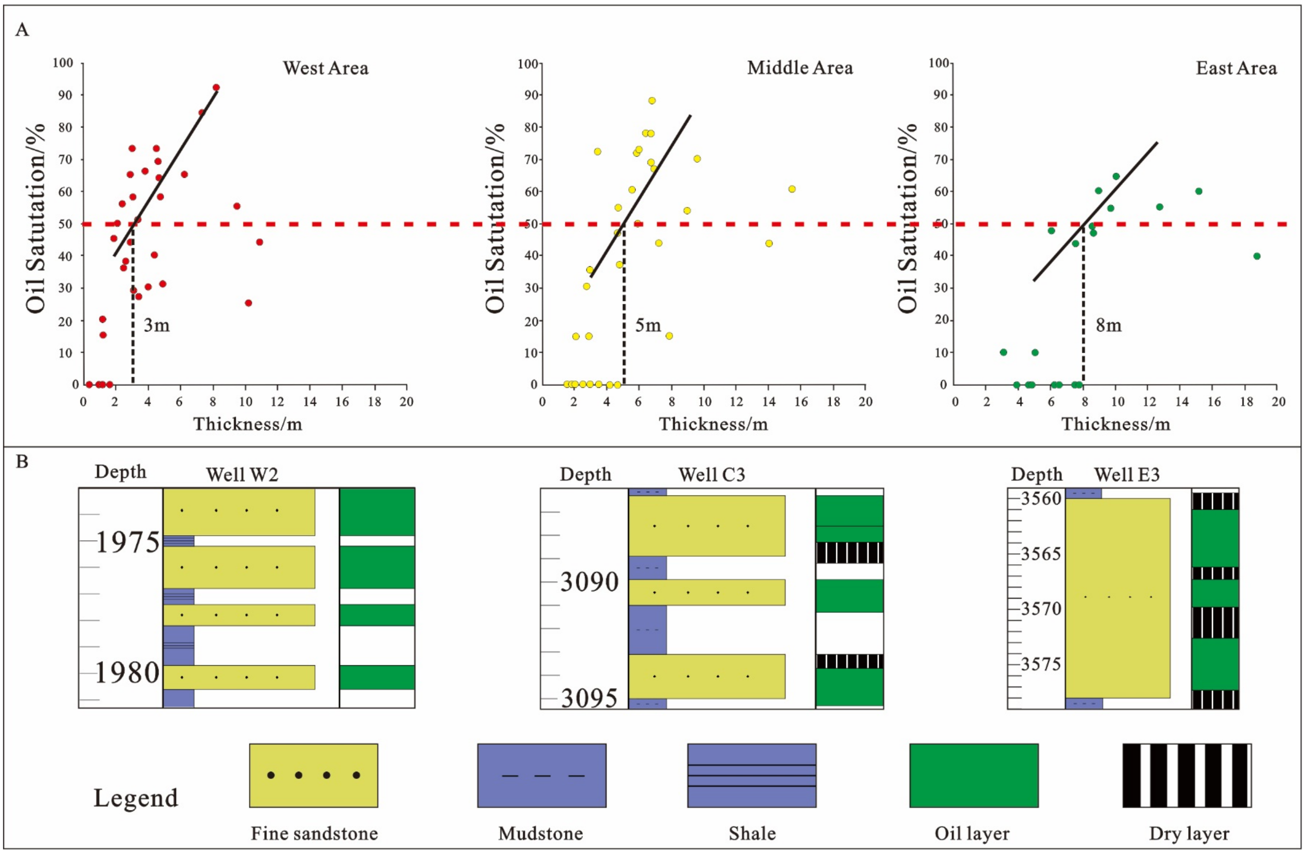

Figure 12. (**A**) Statistical relationship between critical sandstone thickness and oil saturation in different areas of the northern steep-slope zone of the Weixinan Sag. (**B**) Sandstone thickness and oil–gas bearing analysis of typical well logging in different areas.

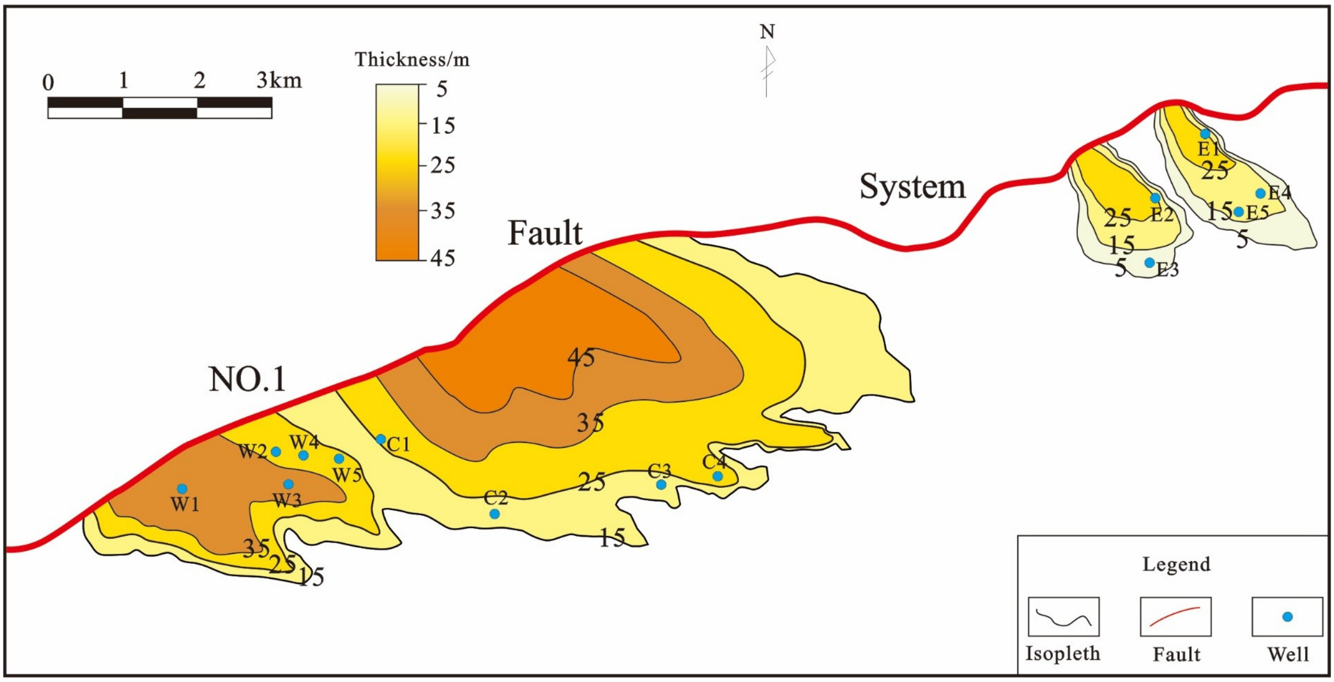

Figure 13. Average sandstone thickness in different areas of the Liushagang Formation in the northern steep-slope zone of the Weixinan Sag (with an average of 40 m in the west, 25 m in the middle, and 20 m in the east).

5. Discussion

Combined with the reservoir differences in different areas, the control factors and models of high-quality reservoirs were studied, and finally, the distribution of high-quality reservoirs was predicted.

5.1. Factors Controlling Reservoir Quality

For the steep-slope sedimentary system, comparing the reservoir differences in the western, central, and eastern areas of the Weixinan Sag, macro-to-micro-reservoir control factors are summarized. It is considered that sedimentary, lithofacies and sandstone thickness factors jointly control the differences between reservoirs.

Sedimentary factors are macroscopic aspects of reservoir development. Different sedimentary environments control different reservoir scales and types, primarily including the drainage system and sedimentary microfacies. The dominant sedimentary characteristics of the steep-slope sedimentary system are, to a considerable extent, shallow burial depth, adequate material supply, large reservoir scale, and the development of microfacies in the distributary channel of fan delta plain.

Lithofacies factors play a decisive role in high-quality reservoirs, primarily controlling high-quality reservoirs from microscopic distribution, including diagenesis and diagenetic evolution. The dominant lithofacies characteristics of high-quality reservoirs in the steep-slope sedimentary system are weak diagenesis and diagenetic evolution, developing Type I reservoirs.

The sandstone thickness factor controls the reservoir's oil-bearing property, including porosity, permeability, and oil saturation. The dominant sandstone thickness characteristics of the steep-slope sedimentary system are larger average sandstone thickness, smaller critical sandstone thickness, and higher oil-bearing properties.

5.2. Models of High-Quality Reservoirs

In combination with the reservoir differences and controlling factors in different areas, high-quality reservoir prediction models for different sedimentary systems were established. Fan delta sedimentary systems were developed in the western and central areas, and fan delta reservoir prediction modes were developed.

The characteristics of the fan delta reservoir model are as follows. It is a Type I reservoir in the fan delta plain. The lithology is medium–coarse sandstone containing a small amount of gravel. The two-stage acid fluid of organic acid + meteoric freshwater is active, the dissolution is strong, and the dissolved material migrates out of the system. Intergranular, intragranular, and matrix dissolved pores are developed, and the physical properties are the best. The Type II reservoir is in the fan delta front, the lithology is medium–fine sandstone, and argillaceous fine sandstone can be seen in the outer front area. The clay matrix and debris contents are high, and only organic acid dissolution is developed. The Type III reservoir is in the pre-delta, comprising mudstone, fine grain size, poor sorting, high shale content, compaction, and mostly tight layers (Figure 14A).

The nearshore subaqueous fan sedimentary system in the eastern areas belongs to the nearshore subaqueous fan prediction model. The reservoir characteristics of this model are as follows. The Type I reservoir is located in the middle fan and is dominated by medium–fine sandstone, with only organic acid fluid, intergranular, intragranular, and matrix dissolution pores developing. The physical properties are the best. The Type II reservoir is located in the inner and middle fan edge and is dominated by medium–fine sandstone and argillaceous fine sandstone. Organic acid fluid dissolution is weakened, argillaceous and mica contents are high, authigenic clay mineral content is high, and clay mineral intercrystalline pore development and the physical properties are moderate. The Type III reservoir is in the outer fan area, primarily mudstone, with a fine grain size, poor sorting, high shale content, compaction, and mostly dense layers (Figure 14B).

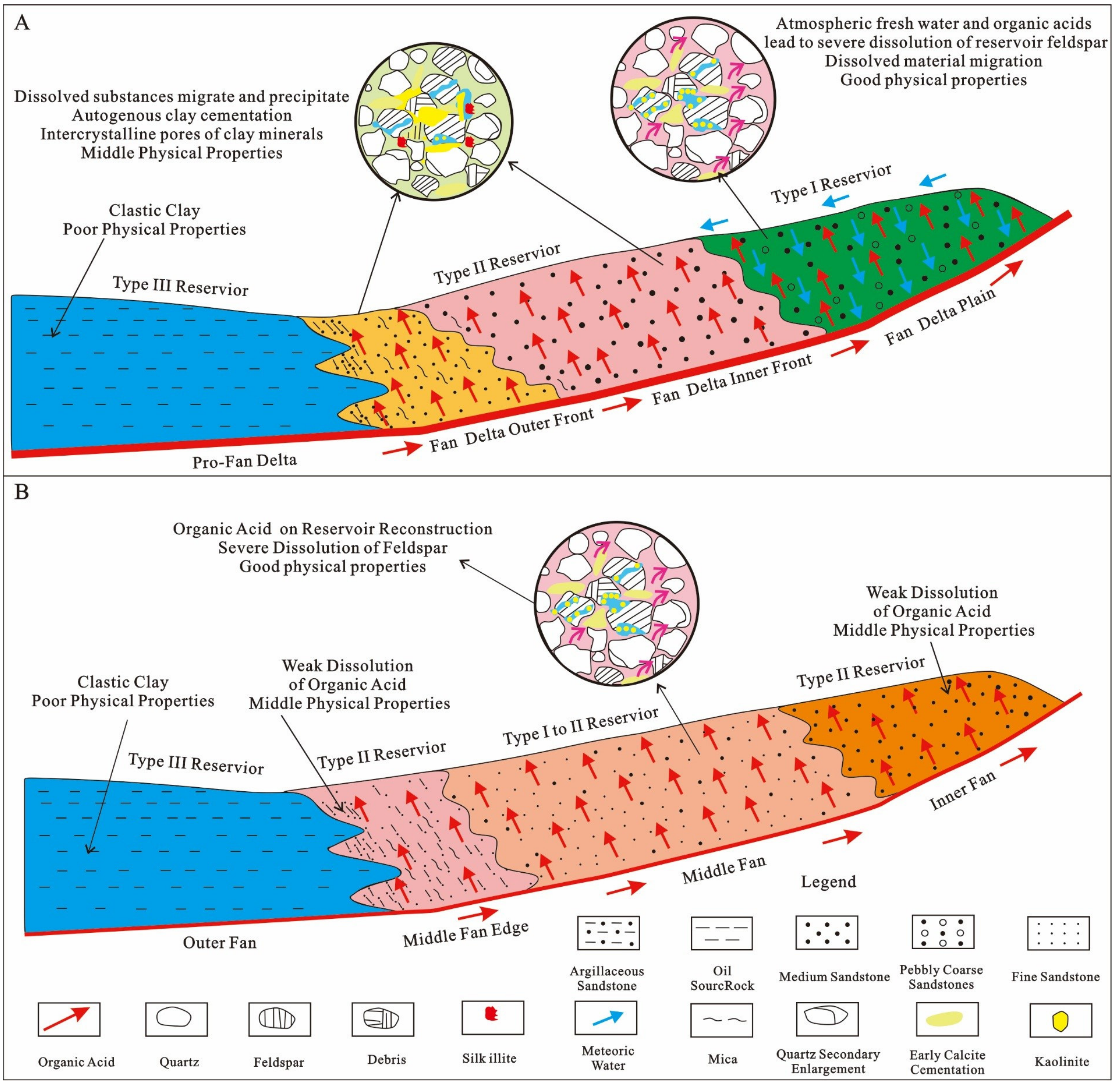

Figure 14. Reservoir prediction model of the (**A**) fan delta and (**B**) nearshore subaqueous fan in the Weixinan Sag.

5.3. Implications for Reservoir Development along the Steep-Slope Zone

Through the main controlling factors and development models of reservoirs in different areas, we predicted the distribution characteristics of high-quality reservoirs in the study area. In the western area, sweet spot reservoirs are distributed surrounded by wells W1 and W3, and Type I conventional reservoirs and Type II low permeability reservoirs are developed around them. A small number of Type III tight reservoirs is distributed in the edge area, mainly developing oil layers and dry layers.

In the central area, well C3 in the sweet spot reservoir's distribution area is small. The Type I conventional reservoir and Type II low permeability reservoir are widely distributed, and the Type III tight reservoir is slight. It develops oil, oil–water, and dry layers.

In the eastern area, with well E5 and E3 as the center, sweet spot reservoirs and Type I conventional reservoirs are developed around them, and Type II low permeability reservoirs are developed around them. Type II low permeability reservoirs account for the largest proportion, and Type III tight reservoirs are less distributed in the marginal area, developing oil, water, and dry layers (Figure 15).

The shallowly buried western area is dominated by Type I reservoirs with high oil-bearing properties, the moderately buried central area is dominated by Type II reservoirs with medium oil-bearing properties, and the deep-buried eastern area is dominated by Type II and III reservoirs with low oil-bearing properties.

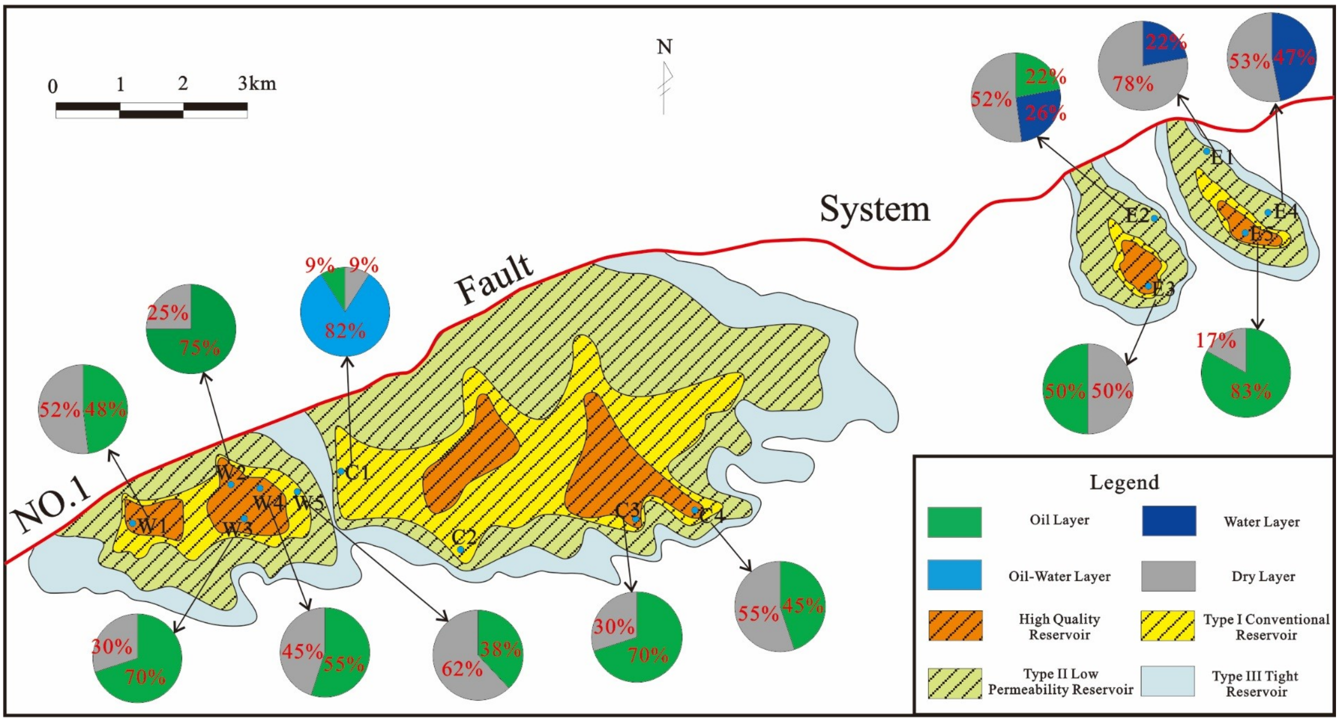

Figure 15. The high-quality reservoirs in the northern steep-slope zone of the Weixinan Sag.

6. Conclusions

1. The Liushagang Formation in the Weixinan Sag of Beibuwan Basin develops a steep-slope sedimentary system with different reservoir characteristics in the west, middle, and east areas. Integrating the reservoir variety in different areas, we summarize the controlling factors and development models for high-quality reservoirs and finally predict the location of high-quality reservoirs.

2. Combined with the reservoir differences between the western, central, and eastern areas, the macro-to-micro-reservoir controlling factors of the steep-slope system are defined. Sedimentary, lithofacies, and sandstone thickness factors jointly control the reservoir differences. The sedimentary factor is a prerequisite for affecting reservoirs, controlling their scale, material source, and type. Lithofacies factors play a decisive role in high-quality reservoirs. Different lithofacies control the diagenesis and diagenetic evolution of reservoirs. Sandstone thickness plays a significant role in the exploration of high-quality reservoirs, with different sandstone thicknesses controlling the oil-bearing properties. High-quality reservoirs in the steep-slope systems are characterized by shallow burial depths, adequate material supply, weak diagenesis, shallow diagenetic evolution, large sandstone thickness, and developing Type I reservoirs.

3. The reservoir prediction models for fan delta and nearshore subaqueous fans are summarized. The high-reservoir for the fan delta model is the fan delta plain. Organic acid + meteoric freshwater dissolution is developed, all types of dissolved pores are developed, and it has the best physical properties. The high-reservoir of the nearshore subaqueous fan model in the middle fan develops only organic acid dissolution, all types of dissolved pores develop, and the physical properties are moderate.

Author Contributions: Conceptualization, investigation, and data curation, S.L., Z.Z. and J.C.; methodology, H.Z. and Q.L.; formal analysis, validation, software, resources, and visualization, S.L.; writing—original draft preparation, S.L.; writing—review and editing, S.L. and H.Z.; supervision, H.Z.; project administration and funding acquisition, H.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Major Outsourcing Projects of China National Offshore Oil Corporation (Hainan) (Grant Nos. CCL2020ZJFN0343).

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding authors. The data are not publicly available due to confidentiality restrictions.

Acknowledgments: We thank the CNOOC (Hainan) for the release of all the data. We thank the two anonymous reviewers for reviewing this manuscript and the editorial department for editorial handling and helpful comments.

Conflicts of Interest: The authors declare no conflict of interest.

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