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RESEARCH ARTICLE

Comprehensive Provenance Analysis of the Es3^3 Sub - Member in the Eastern Shichang Sub - Sag, Nanpu Sag, Bohai Bay Basin

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Abstract

The eastern part of the Shichang Sub-sag in the Nanpu Sag is influenced by multiple provenance systems. However, there are divergent opinions regarding the directions of sediment supply and the relative contributions of different provenances to this area, which have led to controversies over the types of slope-breaks, the depositional models, and the sand-body distribution under different provenance regimes. These uncertainties have severely constrained the exploration of lithologic hydrocarbon reservoirs in the western slope area of the sub-sag. The provenance systems and the distribution range of sand bodies were clarified through Dickinson ternary diagrams, seismic reflection characteristics, as well as analyzing rock clastic grain components, heavy mineral assemblages, and sandbody distribution patterns. Research revealed that there are two main provenance areas supplying the Es3^3 submember in the eastern Shichang Subsag: one originating from the northeast and the other from the east. The ZTR index and sandbody distribution patterns indicate that the northeastern provenance exerts a widespread influence over the eastern Shichang Sub-sag and serves as the dominant sediment-supply area, whereas the eastern provenance has a comparatively limited impact. The northeastern provenance in the eastern part of the Shichang Sub-sag controls the fan-delta sand bodies on the western slope, which are favorable zones for lithologic reservoir development, whereas the eastern provenance controls the fan-delta front sand bodies in the eastern sector, which are favorable zones for structural reservoir development. Provenance system determination in the eastern Shichang Subsag provides a reference for studying sedimentary systems and sandbody distribution under varying slope-break types and provenance controls, and additionally provides guidance for reserve growth and production enhancement efforts in the eastern Shichang Sub-sag.

Keywords: provenance, detrital grain, comprehensive, sedimentary facies, Es3^3 submember, Shichang Subsag.

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1 Introduction

Provenance refers to the material source of sediments, and provenance analysis aims to reconstruct the pre - depositional history of sediments, thereby revealing the evolution of the Earth's lithosphere [1]. As early as the 20th century, scholars inferred the nature, location, and transport pathways of source areas by analyzing the internal chemical composition differences of stable detrital minerals and integrating the regional tectonic background. Since the mid - 20th century, provenance analysis has evolved from determining source areas based on terrigenous clastic sedimentological characteristics to integrated studies of lithofacies paleogeography combining sandstone texture, structure, and mineral composition; scholars such as Dickinson [2], Crook [3], and Morton [4] established a series of discriminant models for determining provenance directions through quantitative statistical analysis of sandstone detrital components and detrital mineral microchemistry, building on the foundational sedimentological framework laid out by Blatt et al. [5]. Among these, the ternary diagrams and related models based on detrital components by Dickinson [2] and Bhatia [6, 7] are the most widely applied and influential, establishing new provenance analysis models that have significantly improved their accuracy and reliability. By the end of the 20th century, with the rapid development of geological techniques and theories, various analytical methods had been progressively refined and applied in provenance analysis research [1]. In particular, systematic understanding of the processes controlling heavy mineral assemblage composition — including sediment transport, hydraulic sorting, and diagenetic dissolution — was significantly deepened during this period [8]. Entering the 21st century, provenance analysis has evolved into a comprehensive research field integrating multiple techniques and methods, with the research focus shifting towards high - precision mineral chemical analysis, particularly using the chemical composition of detrital heavy minerals (such as garnet, tourmaline, rutile, etc.) to trace source rock types, metamorphic grades, and source area attributes [9–14], overcoming the limitations of whole - rock geochemistry. The application of high - resolution instrumental techniques has become increasingly widespread. On one hand, multi - proxy approaches integrating tectono - stratigraphic analysis, source - to - sink system reconstruction, and detrital zircon U-Pb geochronology combined with rare earth element (REE) geochemistry have been widely applied to decipher provenance evolution in rift lacustrine basins [15–17]. On the other hand, integrated sedimentological and geochemical analyses of clastic reservoirs have been applied to reconstruct transport - deposition processes and paleogeographic frameworks in lacustrine rift basins [18, 19]. The understanding of mineral stability differences and diagenetic effects has also deepened, by systematically evaluating the preservation potential of different heavy minerals during burial to eliminate the interference of different heavy minerals with the original provenance, and combining light detrital mineral petrology to quartz - feldspar -rock (QFR) ternary diagrams for tectonic background discrimination [20, 21]. Currently, multiple methods for determining sediment provenance - such as heavy mineral analysis, Dickinson discriminant ternary diagrams, and geochemical element tracing have been widely applied in provenance system studies of various sedimentary basins, and significant results have been achieved in precisely identifying source rock attributes, tracing sediment transport pathways and directions, and reconstructing paleogeographic patterns [22–27].

The Nanpu Sag in the Bohai Bay Basin is a typical continental rift basin, and the eastern Shichang Subsag is located in the northeastern part of the Nanpu Sag. The Paleogene $Es3^3$ submember in the study area has proven reserves of tens of millions of tons, and the anticlinal structural belt in the central part and the fault - nose structural belt in the northern part have achieved favorable exploration and development results. Previous researchers have conducted extensive studies on the sedimentary facies types and sandbody distribution of the $Es3^3$ submember in the eastern Shichang Subsag and have obtained numerous results. Regarding sedimentary facies, microfacies types, and their assemblages, a relatively consistent understanding has been reached, it is generally considered that the eastern Shichang Subsag is a fan delta - lacustrine sedimentary environment influenced by multiple provenances. However, significant disagreements exist regarding the understanding of the provenance systems, provenance directions, provenance influence ranges, sandbody distribution characteristics, and facies boundaries. Lei et al. [28], through source rock type and heavy mineral assemblage analysis, concluded that the main provenance lies in the southeast and the secondary provenance is located in the northeast; Liu et al. [29], through quantitative heavy mineral analysis, suggested that high - temperature metamorphic

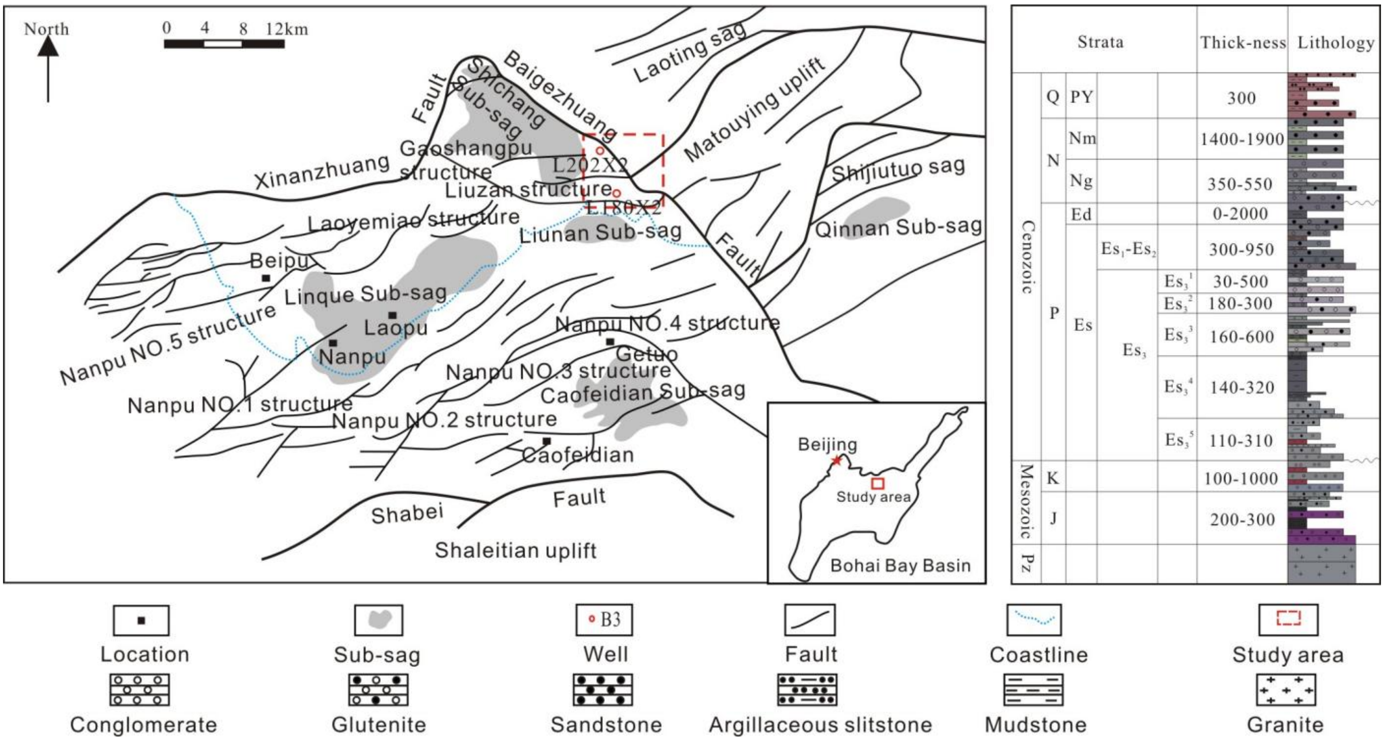

Figure 1. Tectonic location map of the eastern part of Shichang Subsag.

detrital zircons with fir - tree structure originated from a detrital dispersal system derived from an ancient orogenic belt - type provenance area, and the provenance originates from the uplifted block of the Baigezhuang Fault; Lu et al. [30] and Zhang et al. [31] considered that the fan delta provenance in the eastern Shichang Subsag mainly comes from the northeast direction. Differences in the supply directions of provenances and the relative contribution levels of different provenances to various structural positions in the eastern Shichang Subsag area have led to controversies about slope - break types in the eastern Shichang Subsag, particularly in the western slope area, as well as sedimentary patterns and sandbody distribution controlled by different provenance systems.

With the deepening of exploration and development, the lithologic reservoirs in the western slope of the eastern Shichang Subsag have gradually become a key zone for increasing reserves and production. As a result, the unclear understanding of the distribution direction and scale of sand bodies in the slope area constrains the exploration of lithologic reservoirs in the slope zone. This study clarifies the provenance systems of the Paleogene Es3^3 submember in the eastern Shichang Subsag and the influence range of each provenance through analysis of rock detrital grain components, seismic reflection characteristics, and heavy mineral composition, and analyzes the differences in the influence ranges of different provenances, providing an important reference basis for the detailed division of sedimentary facies and the precise delineation of facies boundaries in the study area, while also holding significant guiding significance for promoting the exploration of lithologic reservoirs in the western slope area of the study region.

2 Geologic Settings

Structurally, the eastern Shichang Subsag of the Nanpu Sag belongs to the foreland of the Yanshan Fold Belt, located in the northeastern part of the Nanpu Sag, Huanghua Depression, Bohai Bay Basin. To the northeast, it is bounded by the Baigezhuang Fault, adjacent to the Baigezhuang Uplift and Matouying Uplift; to the south, it is bounded by the Gaoliu Fault, connecting with the Nanpu Sag; to the west, it neighbors the Gaoshangpu area, wedged between the intersection of the Baigezhuang Fault and Gaoliu Fault (Figure 1). It is a syndepositional faulted anticlinal structure gradually developed on the basis of a Mesozoic uplift, with its margins evolving into nosed structure groups developed along the hanging wall of the Baigezhuang Fault.

The tectonic evolution of the eastern Shichang Subsag underwent four stages: fault-depression formation stage, fault-depression development stage, fault-depression expansion stage, and depression stage. During the Early Cretaceous of the Late Yanshanian, rifting occurred in the study area, forming the Baigezhuang Fault that controlled the structural and sedimentary evolution of the region. Since the Cenozoic, from the depositional period of Es35 to Es31 in the Early Oligocene, primarily controlled by the Baigezhuang Fault, the study area exhibited a northwest - trending half-graben distribution and onlapped towards the southwest. By the end of Es1 deposition, tectonic inversion occurred in the study area, resulting in a regional unconformity where the Ed3 member overlies the Es1 member. During the late Es1 deposition, fault - depression activity rapidly weakened, and the entire area uplifted, leading to erosion. During the rifting period of the Dongying Formation, activity along the Baigezhuang Fault weakened while the southern Gaoliu Fault became intensely active, causing the rift center to migrate southward. The tectonic movement at the end of the Dongying period resulted in folding, uplift, and subsequent erosion across the area; during the Guantao period, accompanied by the overall subsidence of the entire Bohai Bay Basin, the study area entered the depression depositional stage [32–37].

3 Samples and Methods

3.1 Samples

This study focuses on the provenance analysis of the Paleogene Es3^3 submember in the eastern Shichang Subsag of the Nanpu Sag. The fundamental data and samples used in this research were provided by the Exploration and Development Research Institute, Jidong Oilfield Company, PetroChina, under a collaborative research agreement. The authors have no commercial or financial interests in the data provider. All sample analysis and testing work were completed at Experimental Centre of Exploration and Development Research Institute of Liaohe Oilfield Company, China. The research comprehensively utilized seismic data, logging data, drilling cores, thin sections, and laboratory analysis data from 15 cored wells in the eastern Shichang Subsag of the Nanpu Sag to conduct the study.

3.2 Methods

Focusing on the core objective of provenance analysis, this study systematically collected and analyzed 62 core samples from 15 cored wells in the Es3^3 submember. The obtained experimental data include: (1) heavy mineral analysis data: providing contents of 31 types of heavy minerals including rutile, zircon, tourmaline, garnet, sphene, apatite, anatase, leucoxene, magnetite, hematite - limonite, ilmenite, hornblende, pyroxene, epidote, biotite, chlorite, cassiterite, staurolite, brookite, pyrrhotite, zoisite, chloritoid, kyanite, chamosite, pyrite, magnesite, barite, hematite, celestite, glauconite, and limonite, which serve as key evidence for discriminating source rock properties and provenance directions of sedimentary provenance areas; (2) quantitative detrital component statistics: obtaining relative percentage contents of quartz, feldspar (K - feldspar, plagioclase), and various rock fragments (igneous, metamorphic, sedimentary rock fragments) in sandstone samples, which are used to evaluate sandstone compositional maturity and indicate source rock types. Simultaneously, the research also conducted detailed observations of thin section identification data from the aforementioned core samples under microscopy. Microscopic examination focused on recording mineral composition of detrital grains, textural characteristics (grain size, sorting, roundness), the types of interstitial materials (cements, matrix), and diagenetic phenomena, providing microscopic-scale verification and supplementation for the detrital component statistical data, serving as indispensable petrological direct evidence for provenance analysis.

4 Results

4.1 Seismic Reflection Characteristics

Paleotopography and paleogeomorphology influence the later development and distribution of the basin to some extent [38, 39]. Through the analysis of paleotopography and sediment distribution patterns, the variation trend of ancient landforms can be clarified, paleo - denudation areas, slope areas, and depression areas can be divided; moreover, clastic composition characteristics and sandbody distribution patterns provide important constraints on sediment source areas and depositional systems [40, 41]. Therefore, the characteristics of paleo - gullies and basin boundary fault structures in provenance system studies can be used to determine the locations of source areas.

Through seismic profile analysis of the hanging wall of the Baigezhuang Fault in the eastern Shichang Subsag (Figure 2), three distinct incised channels are identified developing towards the hanging wall direction of the Baigezhuang Fault, corresponding to the well areas of L202x1, L158x1 G62, and L24x1 L180x2

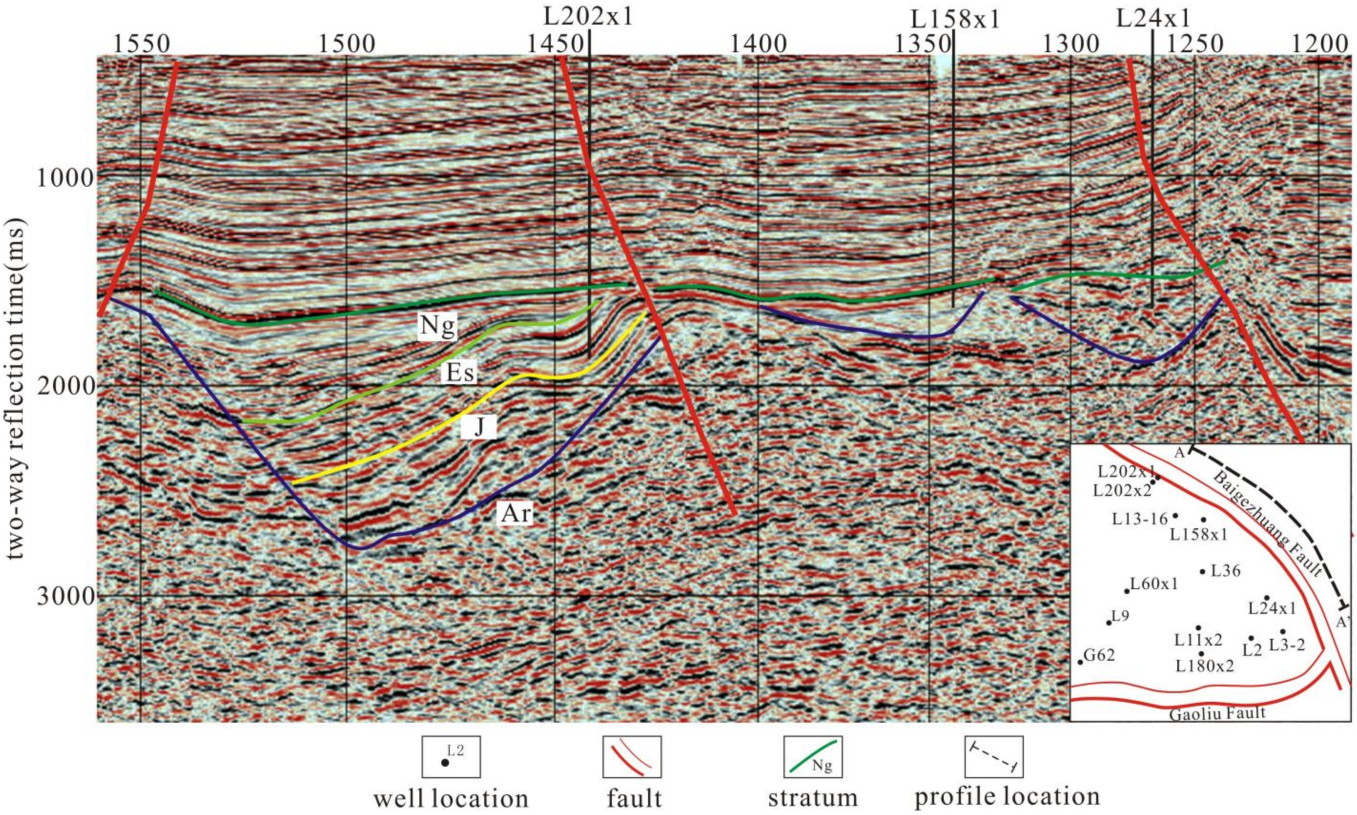

Figure 2. Seismic reflection characteristics of channels perpendicular to the provenance direction.

respectively; the direction along the channels can be roughly determined as the provenance injection direction. From the scale of the channels on the seismic profiles, the northern channel is incised deeper and wider than the southern channel, indicating that the provenance supply from the northern L202x1 well area is more abundant and has a greater influence on the study area. Previous studies have also demonstrated that variations in activity along different segments of the Baigezhuang Fault during the Shahejie Formation period controlled the depocenters and subsidence centers in the eastern Shichang Subsag of the hanging wall [42]. The distribution and scale of the channels further corroborate this previous viewpoint.

Table 1. Heavy mineral composition of the Es3 submember in the eastern part of Shichang Subsag.

Zone	Well	Heavy mineral content and ZTR index (%)								
		Rutile	Zircon	Tourmaline	Garnet	Magnetite	Hematite-limonite	Epidote	Biotite	ZTR
Zone I	L2	0.93	16.66	3.76	36.56	23.81	17.60	0.55	1.55	21.35
	L3x2	1.43	15.21	2.50	36.20	36.54	7.21	0.57	0.23	19.14
	L11x2	0.95	28.99	1.83	38.71	17.99	8.96	0.32	2.33	31.76
	L24	1.10	33.56	1.26	34.97	16.85	10.62	1.24	0.26	35.92
	L180x2	1.30	17.60	1.80	36.30	36.10	1.50	0.00	0.20	20.70
Zone II	L160x1	0.83	18.20	1.63	27.58	21.60	8.15	4.50	3.90	20.66
	L9	0.28	27.86	2.66	18.80	10.51	0.45	27.18	0.27	30.80
	L13-16	0.37	16.77	1.18	19.41	22.05	8.37	31.40	0.49	18.31
	L36	0.45	15.56	0.91	12.67	45.58	5.88	17.82	1.86	16.92
	L60x1	1.23	18.62	0.84	13.96	41.48	6.06	11.92	0.30	20.69
Zone III	L158x1	0.00	6.90	1.12	14.40	25.98	0.00	29.12	0.72	8.02
	L201	0.34	17.26	1.03	11.53	27.98	6.69	34.58	0.31	18.63
	G35	0.66	16.10	0.87	18.01	32.38	5.91	24.99	0.21	17.64
	G62	0.41	12.82	1.29	12.55	26.43	7.19	38.25	0.26	14.52
Zone IV	L202x2	0.47	11.84	0.44	12.96	2.77	30.18	25.01	1.94	12.75

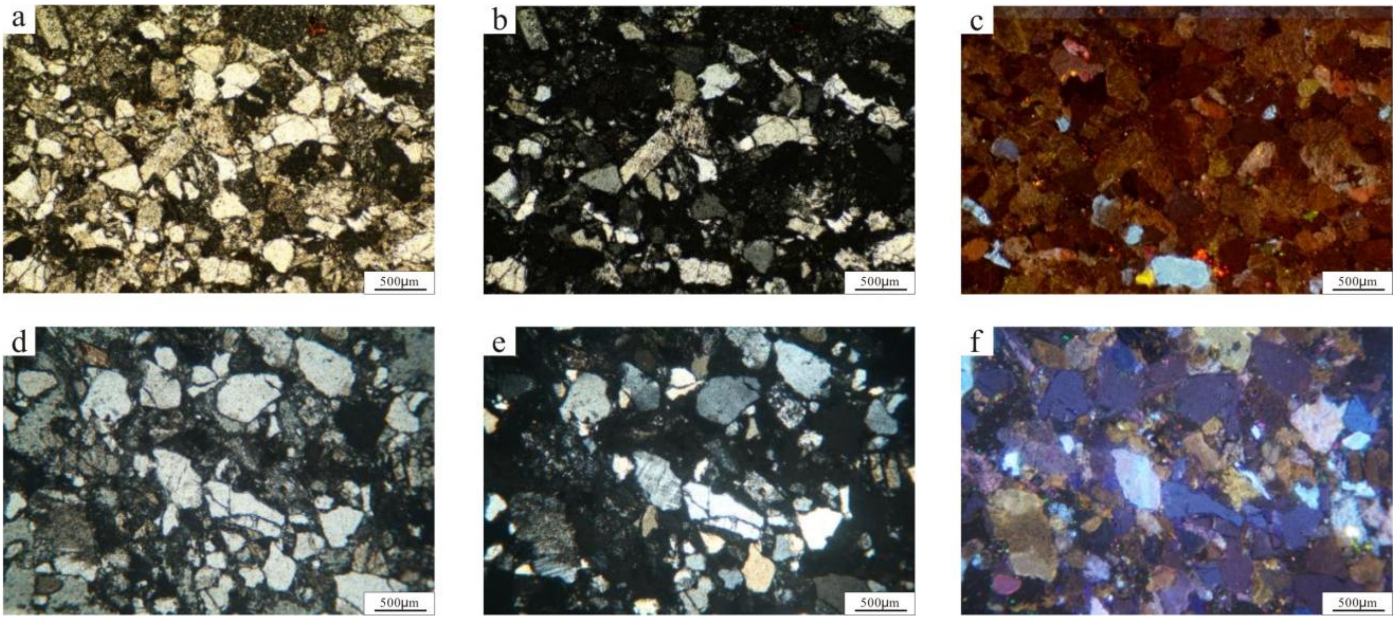

Figure 3. Microscopic characteristics of clastic rocks in the Es3^3 submember of the eastern part of Shichang Subsag. (a) well L202x3,3886.96 m, (PPL); (b) well L202x3,3886.96 m, (XPL); (c) well L202x3,3886.96 m, (CL); (d) well L1-25,2888.24 m, (PPL); (e) well L1-25,2888.24 m, (XPL); (f) well L1-25,2888.24 m, (CL). (XPL: Cross Polarized Light; PPL: Plane Polarized Light; CL: Cathodoluminescence)

4.2 Petrological Characteristics

Through microscopic characteristic analysis and cathodoluminescence detection of sandstone detrital samples from cored wells (Figure 3), it is observed that various grains in the Eocene Es3^3 submember of the eastern Shichang Subsag maintain good integrity. The effectiveness of detrital component analysis and tectonic discrimination methods — including QFL ternary diagrams and heavy mineral assemblage identification — fundamentally depends on the preservation state of primary detrital minerals, unaffected by significant diagenesis, secondary alterations, or later metamorphism [2, 43–45]. Such integrated multi-proxy approaches combining sandstone petrography, heavy mineral assemblages, and source-to-sink analysis have been successfully applied in rift basins to constrain provenance evolution and sediment dispersal [46]. The samples in this study satisfy these prerequisites, ensuring the reliability of subsequent provenance interpretations.

4.3 Heavy Mineral Characteristics

Heavy minerals refer to transparent or opaque minerals with a specific gravity greater than 2.86g/cm^3 in terrigenous clastic sedimentary rocks (especially sandstones and siltstones), generally present in small amounts not exceeding 1%. Owing to their relative resistance to weathering and strong stability, heavy minerals in sandstones are capable of preserving more information about the source rocks [47, 48]. Therefore, heavy mineral analysis holds an important position in provenance research.

Different source rock types have different mineral compositions, and contemporaneously deposited detritus usually exhibits identical or similar heavy mineral assemblage characteristics; whereas detritus deposited during different periods, due to variations in provenance and source rocks, also shows differences in heavy mineral assemblage characteristics. A statistical analysis of heavy mineral data from the Es3^3 submember in 15 cored wells in the eastern Shichang Subsag indicates that the Es3^3 submember contains 31 types of heavy minerals, with relatively high abundances of rutile, zircon, tourmaline, garnet, magnetite, hematite - limonite, epidote, and biotite (Table 1). Based on the two characteristics of stability and transparency of heavy minerals, the 8 types of heavy minerals with relatively high proportions among the 31 types of heavy minerals are classified, and three types of heavy mineral assemblages in the study area are defined: (1) the first type is stable transparent heavy minerals, including rutile, zircon, tourmaline, and garnet; (2) the second type is opaque heavy minerals, including magnetite and hematite - limonite; (3) the third type is unstable transparent heavy minerals, including epidote and biotite. By analyzing the planar characteristics of the columnar diagram of the three types of heavy mineral assemblages (Figure 4), the eastern part of the Shichang Subsag can be divided into three zones: (1) Zone I is the eastern L24x1~L180x2 well area, where transparent heavy minerals are predominant, and unstable transparent heavy minerals are either absent or present in extremely small quantities; (2) Zone II is the northeastern to western slope L158x1~G62 well area, where the heavy mineral assemblage comprises minerals from all the above three types, and the biggest difference between Zone II and Zone I is the presence of a large amount of epidote; (3) Zone III is the L202x2 well area. From the perspective of heavy mineral assemblages, the heavy mineral types in Zone III are similar to those in Zone II, but there are differences in the relative abundances of the second - type heavy minerals, specifically, magnetite and hematite - limonite. Therefore, it is inferred that there are differences in provenance or parent rocks between Zone II and Zone III.

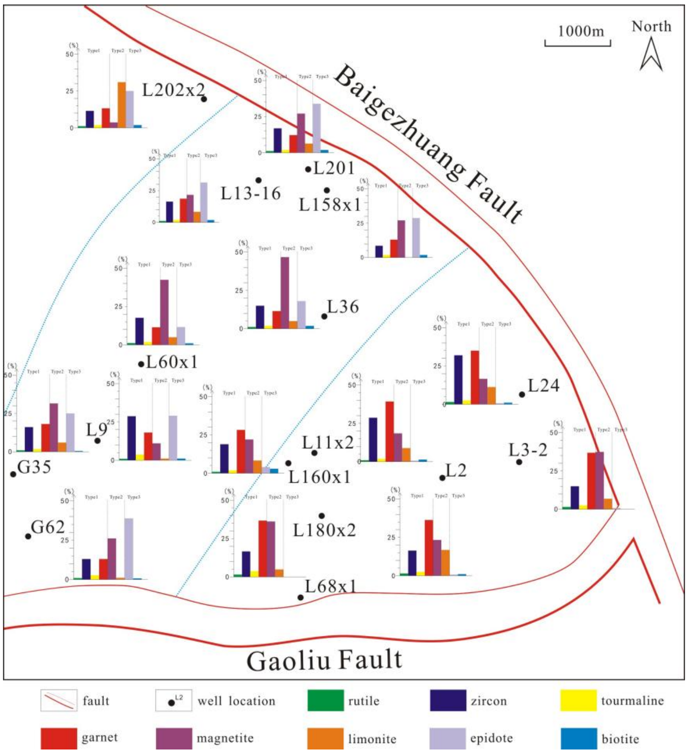

Figure 4. Chart of Heavy Mineral Association Characteristics in the Es3^3 Submember of the Eastern Part of Shichang Subsag.

The ZTR index is the percentage of three stable heavy minerals, zircon, rutile, and tourmaline, in the total amount of transparent heavy minerals. The larger the ZTR index value, the higher the mineral maturity and the greater the distance from the provenance area. As a stability coefficient for heavy minerals, the ZTR index serves as an important indicator for assessing mineral maturity, mainly controlled by transportation distance and paleoclimate, and is one of the key parameters to reveal the provenance direction. The ZTR index in the eastern part of the Shichang Subsag varies significantly (8.02%~35.92%, with an average of 20.52%), generally exhibiting a distribution pattern with alternating high and low values from west to east. It is worth noting that the ZTR values of wells L202x2, L158x1, and L3-2 near the downthrown side of the Baigezhuang Fault are relatively low, generally displaying a trend of gradual increase from northeast to southwest.

Frequency distribution characteristics of heavy minerals: Through the statistical analysis of the frequency distribution of heavy minerals in the Es3^3 of the eastern area of the Shichang Subsag, it was found that different well combinations would yield different results. If the heavy mineral data from both Zone I and Zone II wells are statistically combined, the frequency distribution of zircon, garnet, epidote and magnetite shows a bimodal characteristic, indicating that they may be composed of multiple causes and controlled by multiple sources or multiple parent rocks. However, based on the results of the regional division of heavy mineral composition characteristics, when the frequency distribution of heavy minerals is statistically analyzed for wells within the same area, the frequency distribution of zircon, garnet, epidote and magnetite shows a unimodal characteristic, indicating that it is of single origin and comes from the same type of parent rock or is controlled by a single source. This also supports the correctness of the analysis results of heavy mineral composition characteristics for the determination of source.

4.4 Sandbody Distribution Patterns and Sedimentary Facies Analysis

Clastic materials are mainly transported by hydrodynamic forces during their transportation. As the hydrodynamic force gradually weakens, larger clastic materials are gradually unloaded, while lighter silt and muddy sediments are transported by weaker currents to more distant areas for deposition. Consequently, along the paleocurrent direction, the content of glutenite gradually declines, and the muddy content gradually rises. In provenance analysis, the systematic combination of heavy mineral assemblage variations and grain - size proxies — including the planar variation trend of the percentage of gravel - bearing sandstone — provides robust indicators for determining the advancing direction of the paleo - provenance [49].

Statistical analysis of drilling, logging, and analytical testing data from 15 wells in the eastern Shichang Subsag reveals distinct vertical variations in sand-body distribution within the $Es3^3$ submember. The upper and middle intervals are dominated by thick, positive-cycle sand bodies, whereas the basal interval consists of a thick reverse-cycle sand body with considerable lateral thickness variations across the study area. In contrast, the middle and lower intervals are characterized by thin box-shaped, finger-shaped, and tooth-shaped sand bodies interbedded with thin mudstone layers. Planar sand bodies are distributed in a fan - shaped to strip - like manner from the downthrown side of the Baigezhuang Fault to the southwestern part of the study area (Figure 5), and the sandstone content shows a decreasing trend. The high - value areas are distributed in a strip along the Baigezhuang Fault. In the well areas of L202x2, L158x1∼G62, and L24x1∼L180x2 near the downthrown side of the Baigezhuang Fault, the sandstone content is high, mainly between 35% and 45%. The well areas of L202x2 and L158x1∼G62 are relatively concentrated high - value zones for sandstone percentage in the northern part of the study area, with a northeast - southwest distribution, which is associated with the sedimentary background of a provenance from the northeast; the high - value areas eventually converge in the western slope area of the study area, serving as the main sediment supply for the western slope; the well area of L24x1∼L180x2 is another high - value zone for sandstone percentage in the eastern part of the study area, extending in a northeast - southwest direction along the L24x1∼L2∼L180x2 trend, and acting as the main sediment supply in the eastern part of the study area.

Based on the aforementioned analysis of the provenance system in the eastern part of the Shichang Subsag, combined with the single - well facies, logging facies, seismic facies, and previous knowledge of the sedimentary facies in the study area, it is considered that the study area is a fan delta-lake facies sedimentary environment controlled by two major provenances (Figure 5). Among these, the NE - SW-oriented provenance in the L158x1 well area is the dominant one, which governs the development, distribution, and scale of lithologic oil reservoirs in the western slope of the study area; the influence area of the provenance in the NE - SW direction of the L24 well area is predominantly located in the eastern part of the study area, and it controls the eastern fault-nose oil reservoirs.

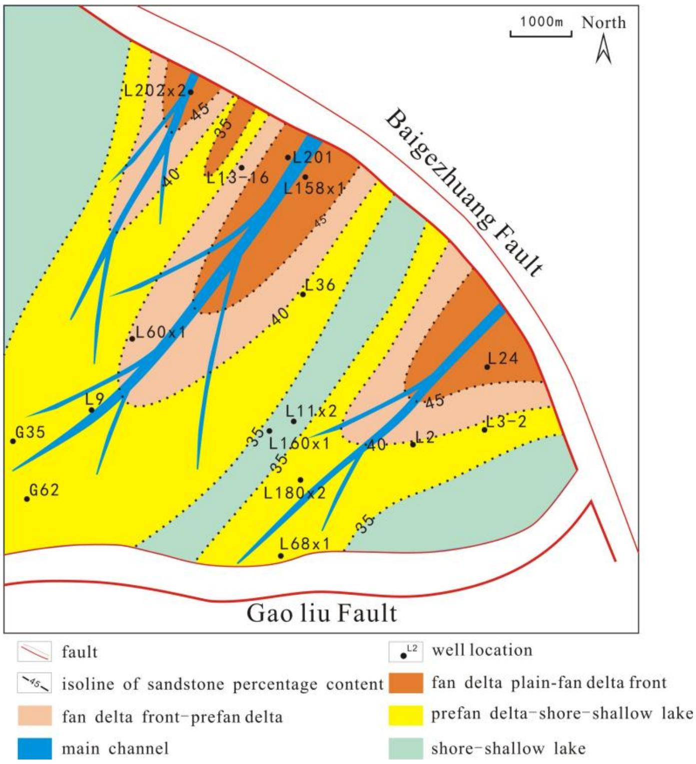

Figure 5. Isoline Map of Sandstone Percentage Content and Sedimentary Facies Map of the $Es3^3$ Submember in the Eastern Part of Shichang Subsag.

5 Discussion

5.1 Evolution of Fault-depressed Basins

During the Late Eocene, influenced by the gradual subduction of the paleo - Kula Plate beneath the island arc along the eastern margin of Asia, the regional stress field in the eastern Shichang Subsag shifted from the original NW - directed compression to NW - directed extension; the previously formed Baigezhuang Fault began sinistral strike - slip movement. Under the combined effects of the stress field and the early - formed faults, the eastern Shichang Subsag entered a period of intense fault-depression extension; accompanied by this geological setting of fault - depression extension, several thousand meters of strata were deposited throughout the entire area [50].

By identifying and statistically analyzing the quartz, feldspar, and rock fragment contents in 62 samples from the $Es3^3$ submember in the eastern Shichang Subsag, the QFL and QmFLt diagrams were selected as templates to plot the statistical results. From the distribution of plotted points on Dickinson's QFL and QmFLt triangular diagrams, it is evident that the majority of data points concentrate within the island arc dissection zone, with a few scattered into the

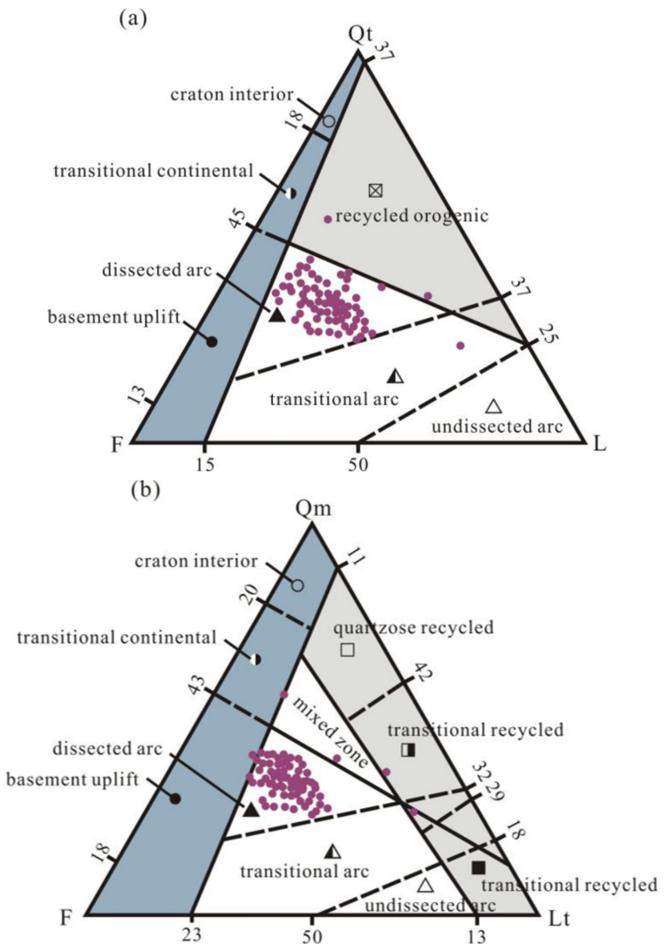

Figure 6. Dickinson's Triangular Diagram Comparison Chart for the Es3^3 Submember in the Eastern Part of Shichang Subsag.

recycled orogenic belt and island arc transitional zone (Figure 6). This indicates that during the depositional period of the Es3^3 submember in the eastern Shichang Subsag, the tectonic setting of the provenance area primarily belonged to the island arc dissection zone, reflecting relatively intense tectonic activity in the study area during this period. This is consistent with the tectonic background in which the eastern Shichang Subsag was in the peak period of fault-depression extension during the Eocene.

5.2 Hydrocarbon Exploration

Through the analysis of reservoir characteristics, two oil reservoirs, the central anticline and the back fault-nose in the study area, have been discovered on the northern provenance passage, which are respectively located in the L36 well area and the L158x1 well area, and both have been put into development. Therefore, the next exploration focus should be on the western slope. In terms of tectonic setting, the western slope has a single tectonic background, and the entire Cenozoic is characterized by slope - type paleogeomorphic structures. Therefore, the exploration of lithologic oil reservoirs in the slope area and structural oil reservoirs under the lithologic background should be the focus of the next exploration in the western slope. The drilling of pre - exploration well L9 in the western slope encountered thick oil layers in the Es3^3 submember, further demonstrating the exploration and evaluation potential of the entire western slope.

The eastern part of the study area is close to the provenance, and the sand bodies are poorly sorted. Based on the analysis of drilled wells, the Es3^3 submember of Well L24 close to the provenance is mainly composed of glutenite and gravel - bearing inequigranular sandstone, with coarse grain size and poor physical properties, indicating that this well is located in the fan delta plain - front position. Well L68x1, which is far from the provenance, has finer grain size, and its single - well natural productivity is low, which can only reach industrial productivity after fracturing, indicating that this well is located in the fan delta front - prefan delta position. Therefore, the main body of the fan delta front between Well L24 and Well L68x1, controlled by the eastern provenance, is the focus of next exploration and evaluation.

6 Conclusions

(1) Based on a comprehensive analysis incorporating Dickinson's triangular diagram method, reflection characteristics of incised channels in seismic profiles, analysis of rock clast grain composition, analysis of heavy mineral associations, and distribution patterns of sand bodies, it is believed that there are two main provenance areas in the eastern part of the Shichang Subsag: the northeastern - sourced and eastern - sourced areas.

(2) Based on the comprehensive research on the provenance system, the tectonic setting of the provenance areas in the eastern part of the Shichang Subsag is predominantly characterized by the island - arc incised zone. The area is mainly controlled by the northeastern provenance, and the influence range of the eastern provenance is relatively small. This has resolved the disputes in recent years regarding the understanding of the provenance in the western slope of the study area.

(3) Through studying the influence ranges of different provenances on the eastern part of the Shichang Subsag and combining with the existing distribution

characteristics of oil reservoirs, it is considered that the northeastern provenance controls the development of lithologic oil reservoirs in the western slope, and the lithologic oil reservoirs in the western slope are the direction for the next exploration. The eastern provenance controls the eastern part of the study area, and the sand bodies in the eastern fan - delta front constitute the key exploration zones for the next step.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

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Ethical Approval and Consent to Participate

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