

Article

Sediment-Routing Reorganization and Associated Sedimentary Responses Across the Es3–Es2 Syn-Rift Stage Transition in the Qinan Sag, Bohai Bay Basin, China

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Abstract

Transitions within the syn-rift stage provide a key window for examining sediment-routing changes and associated sedimentary responses in lacustrine rift basins. In the Bohai Bay Basin, the interval from the third member (Es3) to the second member (Es2) of the Eocene Shahejie Formation records a transition from early strong rifting toward relatively stable rifting. The Qinan Sag, a secondary sag along the Qikou Sag margin, was sensitive to this transition. Using cores, well logs, three-dimensional (3D) seismic data, and heavy-mineral data, this study reconstructs the source configuration, palaeogeomorphology, depositional-system evolution, and Es3–Es2 source-related sediment-dispersal domains. The results show that the supply pattern shifted from coeval supply by a southern regional source and northern and western local sources during Es3 to southern regional-source dominance during Es2. Accordingly, Es3 contains strongly differentiated braided-delta, fan-delta, and subaqueous-fan assemblages. Es2 contains weakly differentiated shallow-water delta and beach-bar assemblages. Three source-related sediment-dispersal domains coexisted during Es3. During Es2, the northern domain was no longer identified, and the western gentle-slope belt evolved into a high-sand-ratio beach-bar belt. This reorganization was mainly controlled by the combined effects of source-configuration changes, geomorphic segmentation, and contrasting slope–A/S conditions (A/S = accommodation/sediment supply). Supply-pattern simplification and weakened geomorphic segmentation shifted sediment routing after basin entry from multiple, dispersed pathways to dominant-source-controlled focused routing. Moderate-to-steep slopes and higher relative A/S proxy values during Es3 favoured discrete, segmented sandy-deposit preservation; gentle slopes and lower relative A/S proxy values during Es2 promoted focused routing and preservation of sandy deposits along the dominant direction, with local shallow-water enrichment. Across the Es3–Es2 syn-rift stage transition, regional-source-related sediment routing showed stronger persistence; local-source-related routing more often weakened or terminated, with corresponding areas tending to show shallow-water redistribution and enrichment signals.



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Keywords: lacustrine rift basin; syn-rift stage transition; sediment-routing reorganization; sedimentary responses; palaeogeomorphology; accommodation/sediment-supply conditions; Qinan Sag; Bohai Bay Basin; Shahejie Formation

1. Introduction

Lacustrine rift basins are sensitive to changes driven by rifting activity [1–4]. In particular, during the transition from strong rifting toward relatively stable rifting, basin

boundary conditions commonly become less continuous and uniform, and instead show more pronounced stage-dependent and spatially variable changes [1,5,6]. These changes are commonly recorded by adjustments in depositional-system assemblages, sandstone distribution, and sediment-routing patterns [7–10]. Transitions within the syn-rift stage therefore provide a key context for understanding sedimentary responses, sediment-routing changes, and their controlling mechanisms in lacustrine rift basins.

Research on sedimentary filling in lacustrine rift basins has gradually shifted from the identification of depositional facies and sandstone distribution toward the analysis of coupled relationships among source areas, routing pathways, transient sediment storage, and final sedimentary responses within source-to-sink and sediment-routing frameworks [11–13]. Classic lake-basin type models define overfilled, balanced-fill, and underfilled lake basins according to the balance between potential accommodation, mainly controlled by tectonics, and sediment-plus-water supply, mainly linked to climate [14,15]. This framework places source-to-sink and sediment-routing analyses within a broader lake-basin boundary-condition context. Nevertheless, how such boundary-condition changes are translated into stage-dependent sediment-routing reorganization and associated sedimentary responses during transitions within the syn-rift stage remains insufficiently understood.

The Bohai Bay Basin is a typical continental lacustrine rift basin in eastern China, and its Paleogene succession records a relatively complete history of multistage rift evolution [16–19]. Sedimentary responses differ markedly among different rift stages [5,20,21]. In the Qinan Sag, the interval from the third member (Es3) to the second member (Es2) of the Shahejie Formation corresponds to a key transition from early strong rifting toward relatively stable rifting [21]. Previous studies have improved understanding of the evolution of depositional patterns in this area during rifting [22–25], and seismic geomorphological data have been used to characterize sediment-dispersal features [26]. However, an integrated understanding of the linkage between depositional-system evolution and sediment-routing reorganization across this syn-rift stage transition remains limited.

Based on integrated analysis of multiple datasets, this study aims to clarify the controls on sediment-routing reorganization and associated sedimentary responses across the Es3–Es2 syn-rift stage transition in the Qinan Sag. To address this objective, we reconstruct changes in source configuration, palaeogeomorphology, depositional systems, and sediment-routing patterns from Es3 to Es2 in the Qinan Sag. The main sedimentary characteristics across the syn-rift stage transition and the reorganization of source-related sediment-dispersal domains are identified, and a corresponding spatiotemporal evolutionary model is developed. The roles of source-configuration changes, geomorphic segmentation, slope conditions, and relative accommodation/sediment-supply (A/S) conditions in sediment routing, sandy-sediment preservation, and local enrichment are further examined. A conceptual framework is proposed to explain differences in sedimentary responses during transitions within the syn-rift stage. The results provide a reference for interpreting sediment-routing reorganization and sedimentary responses during transitions within the syn-rift stage in lacustrine rift basins.

2. Geological Setting

The Bohai Bay Basin is located in the eastern North China Craton and represents a typical Mesozoic–Cenozoic superimposed basin in eastern China. It is bounded by the Yanshan Fold Belt to the north, the Taihang Mountains to the west, the Liaojiang Uplift to the east, and the Luxi Uplift to the south, and is one of the most important petroliferous basins in China (Figure 1a) [16,17,27]. The basin contains several first-order structural units. Among them, the Huanghua Depression is located in the central part of the basin (Figure 1a) and is a typical continental rift structural unit [27–29]. The Huanghua Depression developed on a

Figure 1 consists of three panels: (a) Regional map of China showing the Bohai Bay area. (b) Detailed map of the Bohai Bay area showing the Yanshan fold belt, Bohai Bay Sea, and various geological features. (c) Detailed map of the Bohai Bay area showing the Yanshan fold belt, Bohai Bay Sea, and various geological features.

Panel (a) shows the location of the Bohai Bay area within China. The map includes labels for the Bohai Bay, Bohai Sea, and various geological features. A scale bar indicates 0 to 200 km. A north arrow is present.

Panel (b) is a detailed map of the Bohai Bay area. It shows the Yanshan fold belt, Bohai Bay Sea, and various geological features. A scale bar indicates 0 to 20 km. A north arrow is present.

Panel (c) is a detailed map of the Bohai Bay area. It shows the Yanshan fold belt, Bohai Bay Sea, and various geological features. A scale bar indicates 0 to 5 km. A north arrow is present.

three third-order sequences, corresponding, from top to bottom, to the first member (Es1), second member (Es2), and third member (Es3) of the Shahejie Formation (Figure 2). The depositional evolution of the Shahejie Formation corresponds to early and stable rifting stages within the Paleogene syn-rift stage under episodic tectonism (Figure 2). Differential uplift and subsidence related to Paleogene tectonic activity produced a regional angular unconformity between Es3 and Es2 [35]. A regional unconformity between Es2 and Es1 is widely developed in the Bohai Bay Basin [41].

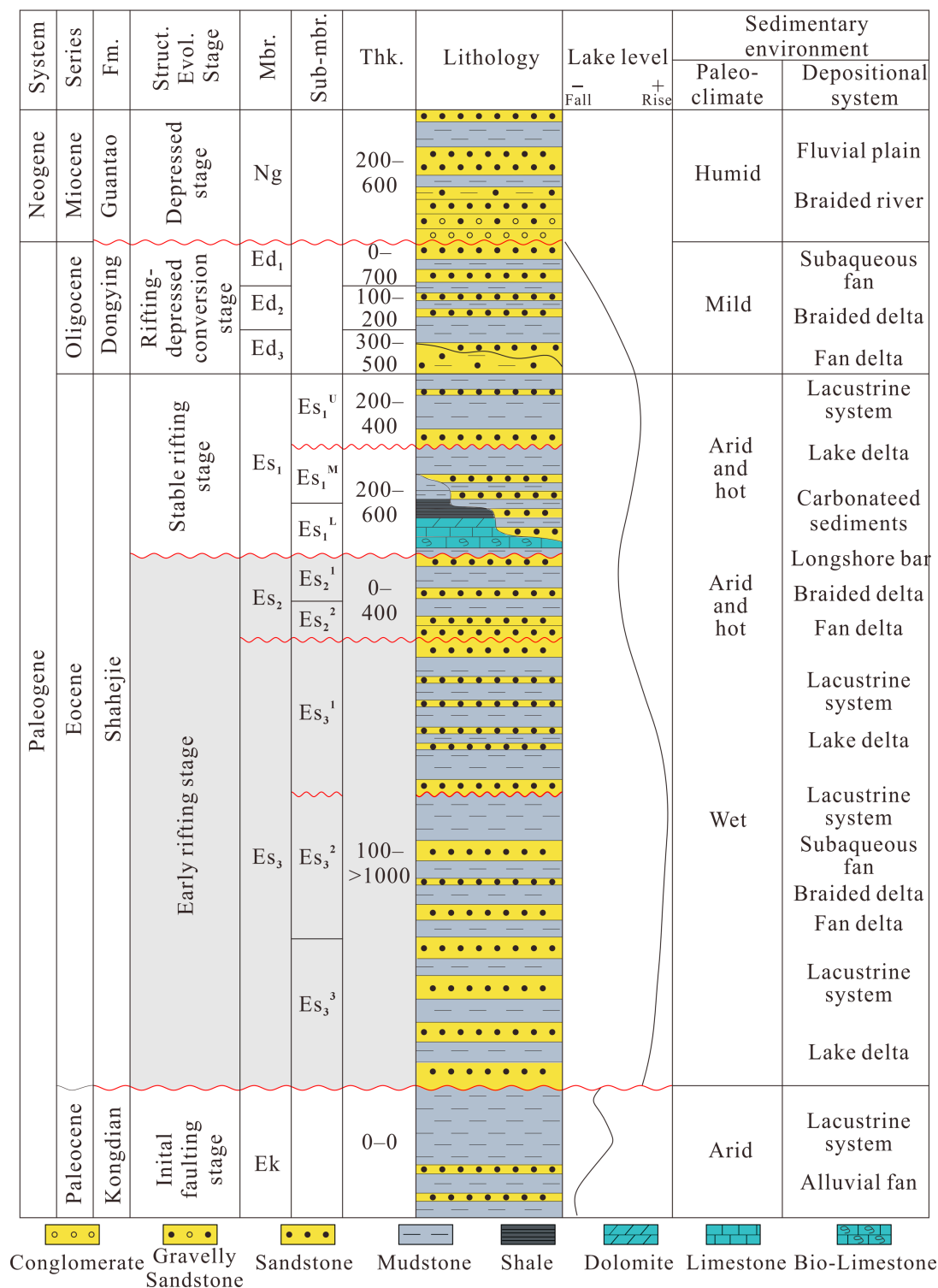


Figure 2. Paleogene stratigraphic column of the Qikou Sag, Bohai Bay Basin, partly based on [21,38,42,43]. Red wavy lines indicate unconformities.

3. Data and Methods

3.1. Data

The core, well-log, mud-logging, and three-dimensional (3D) seismic data used in this study were provided by the Dagang Oilfield Branch of PetroChina Company Limited (Tianjin, China). The well-log curves include gamma ray (GR), spontaneous potential (SP), acoustic transit time (AC), true resistivity (RT), and density logs. The well-log data were acquired and processed by China Petroleum Logging Co., Ltd. (Xi'an, China). Heavy-mineral analyses were jointly completed by the Dagang Oilfield Branch of PetroChina (Tianjin, China), the Exploration and Development Research Institute of PetroChina Huabei Oilfield Company (Cangzhou, China), the State Key Laboratory of Petroleum Resources and Prospecting at China University of Petroleum (Beijing, China), and the Laboratory Center of the PetroChina Research Institute of Petroleum Exploration and Development (Beijing, China). For heavy-mineral analysis, samples were disaggregated, cleaned, and sieved to obtain the sand-sized fraction. Heavy and light mineral fractions were separated using sodium polytungstate heavy liquid. The recovered heavy-mineral fraction was then washed, dried, and mounted for identification, classification, and grain counting under a microscope, allowing the relative abundances of different mineral types to be calculated. The heavy-mineral dataset comprises 309 samples from 16 wells. The study area comprises the 3D seismic-covered region south of the Nandagang Buried Hill (Figure 1c), with an area of approximately 500 km². The target intervals are Es3 and Es2. The 3D seismic data have a frequency bandwidth of 10–70 Hz and a dominant frequency of approximately 25 Hz. A total of 17 cored wells (Figure 1c) were used for core observation and description in the target intervals, with a cumulative core length of approximately 270 m.

3.2. Methods

In this study, source configuration during Es3 and Es2 was constrained through integrated palaeogeomorphological and heavy-mineral analyses. Provenance directions were identified using the zircon–tourmaline–rutile (ZTR) index and heavy-mineral assemblages [44–46]. Palaeogeomorphological reconstruction was performed using the impression method [47,48], with the regionally stable limestone surface at the base of Es1 in the Qikou Sag used as the stratigraphic marker and correlation datum. The Es2 palaeogeomorphology was reconstructed using the base of Es1 as the datum. The Es3 palaeogeomorphology was reconstructed using the erosion-restored base of Es2 as the datum. Because erosion occurred to varying degrees in different directions within the study area, eroded areas were restored mainly using depth-domain 3D seismic profiles, in combination with reflection characteristics and the trend-surface method [49]. Time–depth conversion of the 3D seismic data was based on the time–depth relationship provided by Dagang Oilfield. Depositional systems were identified by integrating cores, well logs, 3D seismic reflection characteristics, and seismic root-mean-square (RMS) amplitude attributes [50,51]. Detailed core observations and descriptions were used to identify lithofacies, interpret associated depositional processes, and establish lithofacies associations [52]. These associations were then combined with well-log responses to further identify depositional systems and their major depositional facies types [53,54].

The sand ratio, relative A/S proxy, slope gradient, and fault growth index used for the subsequent interpretive framework were extracted from representative data points with clear depositional-unit assignments, complete well-log data, and reliable correlation with seismic and palaeogeomorphological interpretations. The sand ratio was calculated as the ratio of sandstone thickness to total stratigraphic thickness in the corresponding interval at each data point. It was used as a stratigraphic proxy for the relative enrichment of sandy sediments in different depositional units, rather than as a direct measure of sediment-flux

partitioning, such as $Q_{\text{sand}}/Q_{\text{s}}$. Slope gradient was extracted from the palaeogeomorphological reconstruction at each data-point location and was used to characterize the slope background of different depositional units. The relative A/S proxy was expressed as the mudstone-thickness/sandstone-thickness ratio within the same stratigraphic interval, and was used to compare the relative background of muddy versus sandy preservation among different sediment-dispersal domains within the accommodation–sediment-supply framework [55,56]. The fault growth index was calculated as $F = T_d/T_u$ [57], where T_d and T_u are the stratigraphic thicknesses on the downthrown and upthrown sides of the fault, respectively. This index was used to characterize fault activity intensity. These representative data points are mainly distributed in slope belts controlled by synsedimentary faults and in adjacent subaqueous depositional areas. They were used to compare relative differences in sandy-sediment preservation and enrichment among different source-related sediment-dispersal domains.

On the basis of previous studies [22–25,58], we integrated cores, well logs, mud-logging data, seismic data, and palaeogeomorphological reconstructions to examine changes in source configuration, depositional systems, and sediment routing between Es3 and Es2 in the Qinan Sag.

4. Results

4.1. Sequence Stratigraphic Framework

4.1.1. Second-Order Sequence Boundaries

The sequence stratigraphic framework of Es2 and Es3 was established using mappable stratigraphic surfaces and their diagnostic seismic reflection characteristics [59,60]. The Shahejie Formation is bounded by two second-order sequence boundaries: the upper Ed/Es boundary and the lower basal Es boundary. The Ed/Es boundary corresponds to a sandstone–mudstone lithological transition (Figure 2). On seismic sections, this boundary is marked by laterally continuous, medium- to strong-amplitude reflections in the sag area and slope belts, with local truncation along the sag margin (Figure 3a). The basement in the study area is dominated by Mesozoic strata. On seismic sections, the basal Es boundary is expressed by an abrupt change from weak to strong reflections in the sag area and inner slope belt. In the outer slope belt and along the sag margin, this boundary is commonly defined by pronounced onlap (Figure 3). In wells, the basal Es boundary is marked by a lithological transition between grey mudstone and brownish-red to purplish-red mudstone (Figure 3), providing a diagnostic criterion for distinguishing the Shahejie Formation from the underlying basement.

4.1.2. Third-Order Sequence Boundaries

Within this second-order sequence, third-order sequence boundaries were identified by their characteristic third-order unconformities and correlative conformities [59,61,62]. The basal Es1 surface is a regionally persistent marker horizon within the Shahejie Formation. On seismic sections, it is characterized by strong-amplitude, highly continuous reflections (Figure 3). In wells, this surface corresponds to a widely developed carbonate interval and is commonly marked by a pronounced decrease in gamma-ray values (Figure 3).

The basal Es2 surface is generally expressed as a medium- to weak-amplitude reflection with moderate continuity in the sag area. In the slope belts and along the sag margin, this surface is less distinct because of the masking effect of strong carbonate reflections and the relatively short duration of Es2 deposition [40]. On seismic sections, it is commonly identified by subtle truncation and locally by polarity reversal (Figure 3). In wells, the basal Es2 surface corresponds to an increase in gamma-ray values and can be identified as a sandstone–mudstone lithological transition surface (Figure 3).

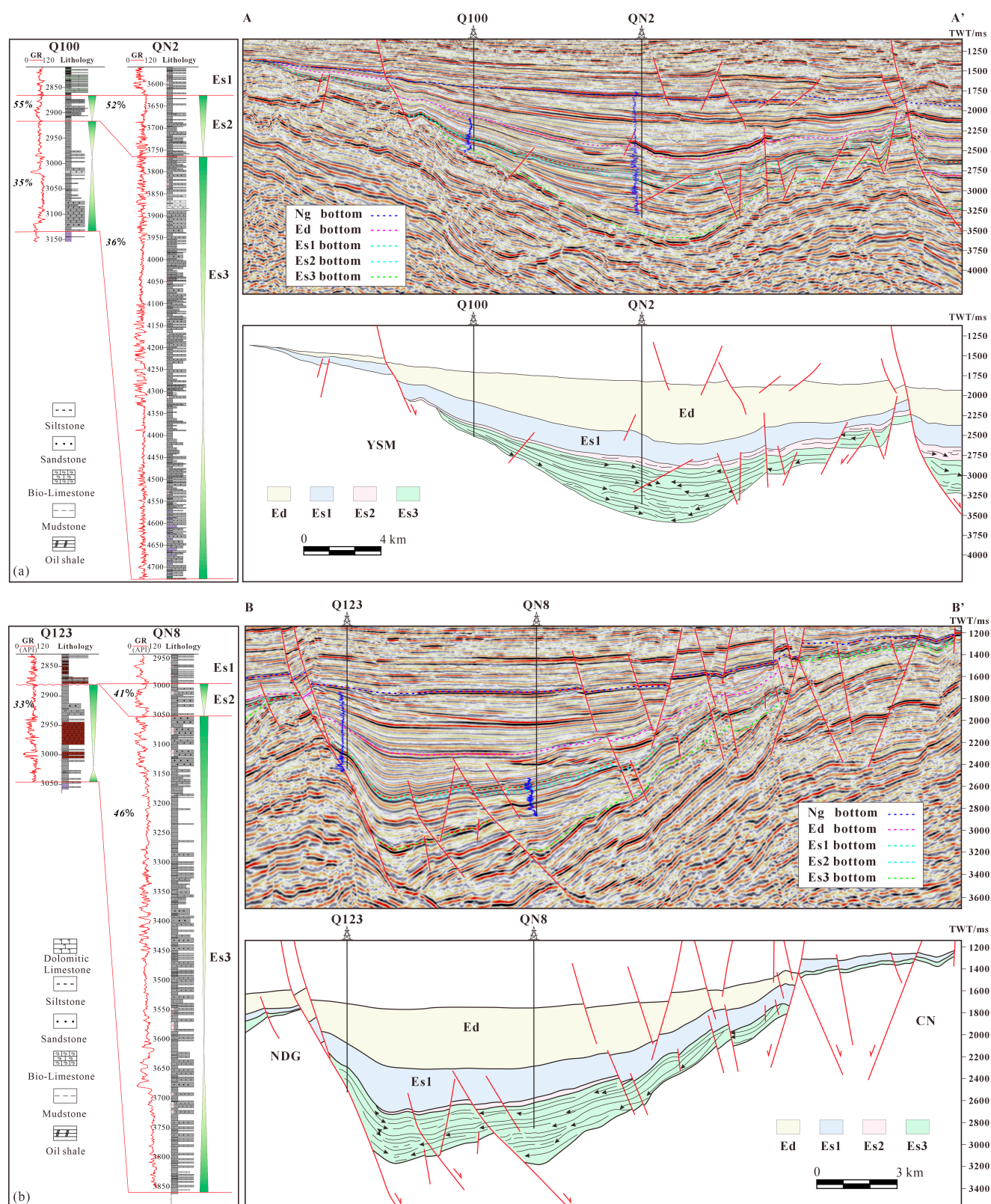


Figure 3. Representative seismic sections across the Qinan Sag and their stratigraphic-structural interpretations. (a) NEE-trending seismic section AA' and its interpretation. (b) SE-trending seismic section BB' and its interpretation. The section locations are shown in Figure 1c. The left panels show GR logs, lithology, and third-order sequence correlations of representative wells. Percentage values shown beside the wells indicate the sand ratio within the corresponding third-order sequence.

Together with the second-order sequence boundaries described in Section 4.1.1, these two sequence surfaces divide the Shahejie Formation into three third-order sequences from top to bottom, corresponding to Es1, Es2, and Es3. Their durations are approximately 3.9 Ma, 1.5 Ma, and 4.8 Ma, respectively [40]. Es2 corresponds to an incomplete falling base-level phase. Es3 represents a complete third-order cycle composed of rising and falling base-level phases. A maximum flooding surface can be further identified within Es3. This surface is traceable in both seismic sections and wells (Figure 3), and commonly corresponds to the interval with the most developed mudstone or the highest gamma-ray value. This sequence framework provides the stratigraphic basis for subsequent analyses of source configuration, palaeogeomorphology, depositional systems, and sediment routing.

4.2. Provenance and Palaeogeomorphology

4.2.1. Heavy-Mineral Assemblages

Heavy-mineral compositions differ markedly between Es3 and Es2. In Es3, several heavy minerals, including zircon, garnet, and pyrite, are commonly present, resulting in relatively complex assemblages. Authigenic heavy minerals are more abundant in Es3 (Table 1). In Es2, stable heavy minerals such as zircon and anatase are dominant, and authigenic heavy minerals are markedly less abundant, indicating greater enrichment of stable components (Table 1). Overall, the assemblages changed from multicomponent assemblages in Es3 to stable-heavy-mineral-dominated assemblages in Es2.

Table 1. Heavy-mineral compositions and abundance classes of Es3 and Es2 in the Qinan Sag. (1) Heavy minerals are grouped by stability into stable, relatively stable, unstable, and authigenic heavy minerals. They are also classified by average abundance into major components (>10%), minor components (0.10%–10.0%), and trace components (0.01%–<0.10%). (2) Values in the table represent the average abundance (%) of each mineral across all valid samples from the corresponding stratigraphic interval. (3) The trace-component column lists only minerals with average abundances of 0.01%–<0.10%; minerals with average abundances < 0.01% are not listed. (4) Leucosene, anatase, hematite–limonite, and magnetite are included in the main heavy-mineral assemblages used for provenance discrimination in this study, but their abundance classes in this table depend on their average abundances in the corresponding stratigraphic interval.

Heavy-Mineral Group	Interval	Major Components (>10%)	Minor Components (0.10%–10.0%)	Trace Components (0.01%–<0.10%)
Stable heavy minerals	Es3	Zircon (41.97)	Hematite–limonite (8.48), Tourmaline (5.52), Anatase (5.22), Leucosene (3.84), Rutile (1.22), Magnetite (5.04), Brookite (0.25)	Corundum (0.02)
	Es2	Zircon (47.87), Anatase (11.73)	Leucosene (8.11), Tourmaline (6.93), Magnetite (2.81), Rutile (1.44) Brookite (0.84), Hematite–limonite (0.60)	—
Relatively stable heavy minerals	Es3	Garnet (24.03)	Epidote (0.83), Apatite (0.34), Titanite (0.25)	Chloritoid (0.04), Staurolite (0.04)
	Es2	Garnet (18.04)	Epidote (0.14), Titanite (0.11)	Staurolite (0.02), Apatite (0.01), Chloritoid (0.01)
Unstable heavy minerals	Es3	—	Amphibole (1.39), Biotite/muscovite (0.68)	Pyroxene (0.02)
	Es2	—	Biotite/muscovite (0.32), Chlorite (0.18), Amphibole (0.14)	Pyroxene (0.02)
Authigenic heavy minerals	Es3	Pyrite (16.47)	Siderite (5.50), Barite (3.54), Magnesite (1.16)	—
	Es2	—	Pyrite (4.93), Anhydrite (0.87), Magnesite (0.78), Barite (0.20)	Glauconite (0.02)

Representative wells further show zonal differentiation in the main heavy-mineral assemblages of Es3. In the western YSM-side wells, the assemblages are garnet-dominated, with subordinate zircon. In the southwestern Well Z21, the assemblage is characterized by zircon, garnet, and epidote, with relatively high magnetite content. In the northern NDG-side wells, zircon is dominant and garnet is subordinate. In the southern CN-side wells, the assemblages are characterized by zircon enrichment. The ZTR index in Es3 shows spatial variation from low values (26%–41%) to moderate values (59%–83%) and high values (72%–94%) (Figure 4a). The main heavy-mineral assemblages in Es2 are simpler. The western YSM-side wells are dominated by low-ZTR garnet–zircon assemblages (34%–51%), and the southern CN-side wells are characterized by high-ZTR zircon-dominated assemblages (86%–96%) (Figure 4b). The main heavy-mineral assemblages and ZTR indices show stronger differentiation in Es3, while Es2 is characterized by concentrated high-ZTR assemblages.

4.2.2. Palaeogeomorphology and Provenance Interpretation

Both Es3 and Es2 show a general geomorphic pattern with low-lying areas in the east, but the distribution of geomorphic highs differs between the two intervals (Figure 4). During Es3, the palaeogeomorphology was characterized by low areas in the east and high areas to the north, west, and south, corresponding to the NDG, YSM, and CN sides. Clear sediment-input pathways are indicated along these three sides. Sediment dispersal was multidirectional and spatially dispersed (Figure 4a). During Es2, geomorphic highs were mainly distributed along the western YSM side and southern CN side; the eastern part remained the main low area, and the northern NDG side was lower than the western and southern highs. No clear sediment-input pathways are indicated along the northern NDG side or western YSM side. Sediment dispersal became more focused (Figure 4b). The Es3 palaeogeomorphology shows a relief of approximately 650 m, slope gradients of approximately 0.7–2.7°, and a mean elevation of approximately 179 m relative to the datum surface (Figure 4a). The Es2 palaeogeomorphology shows a relief of approximately 160 m, slope gradients of 0.18–1.4°, and a mean elevation of approximately 36 m relative to the datum surface (Figure 4b). Overall, Es3 was characterized by stronger structural relief and a pronounced stepped palaeogeomorphology, especially across the transition from the slope belts to the sag area (Figure 4a). During Es2, relief decreased and the slope morphology became gentler (Figure 4b).

4.3. Lithofacies Associations and Depositional Successions

4.3.1. Lithofacies Associations

Core observations and well data show that the sedimentary rocks of Es3 and Es2 in the study area are dominated by sandstone and mudstone. Conglomerate occurs locally, and limestone is minor (Figures 5–8). From Es3 to Es2, the clastic deposits show an overall fining trend. Es3 is dominated by fine sandstone, followed by pebbly sandstone and conglomerate. Es2 consists mainly of fine sandstone and silty to fine sandstone, with little conglomerate development (Figures 5 and 6). Overall, Es3 contains trough cross-bedding, parallel bedding, and massive bedding, indicating stronger hydrodynamic conditions. Ripple cross-lamination and horizontal lamination occur less frequently (Figures 6c–h and 7). Es2 is dominated by massive bedding and ripple lamination, indicating weaker hydrodynamic conditions (Figure 7).

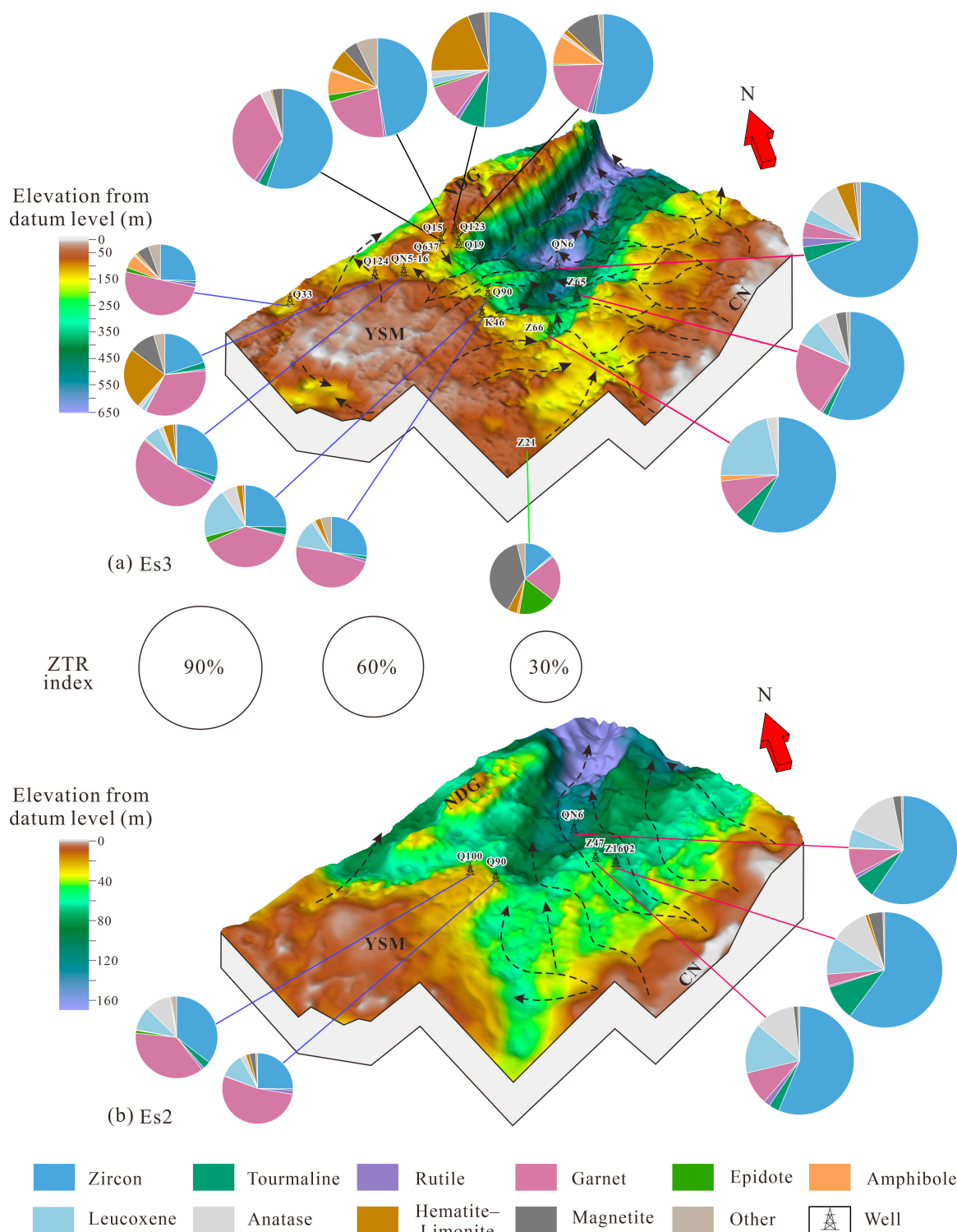


Figure 4. Palaeogeomorphology, main heavy-mineral assemblages, and ZTR index of Es3 and Es2 in the Qinan Sag. (a) Es3 palaeogeomorphology overlay by main heavy-mineral assemblages and ZTR index values. (b) Es2 palaeogeomorphology overlay by main heavy-mineral assemblages and ZTR index values. Pie charts show the relative compositions of ten main heavy minerals from representative well samples. These ten main heavy minerals used for provenance discrimination exclude authigenic heavy minerals. In this study, “main heavy minerals” refer to the ten heavy minerals that together account for more than 90% of the cumulative average abundance across all samples. Black dashed arrows indicate inferred major sediment-dispersal directions based on provenance indicators and palaeogeomorphic relief. Leader lines for pie charts with the same colour indicate similar main heavy-mineral assemblages.

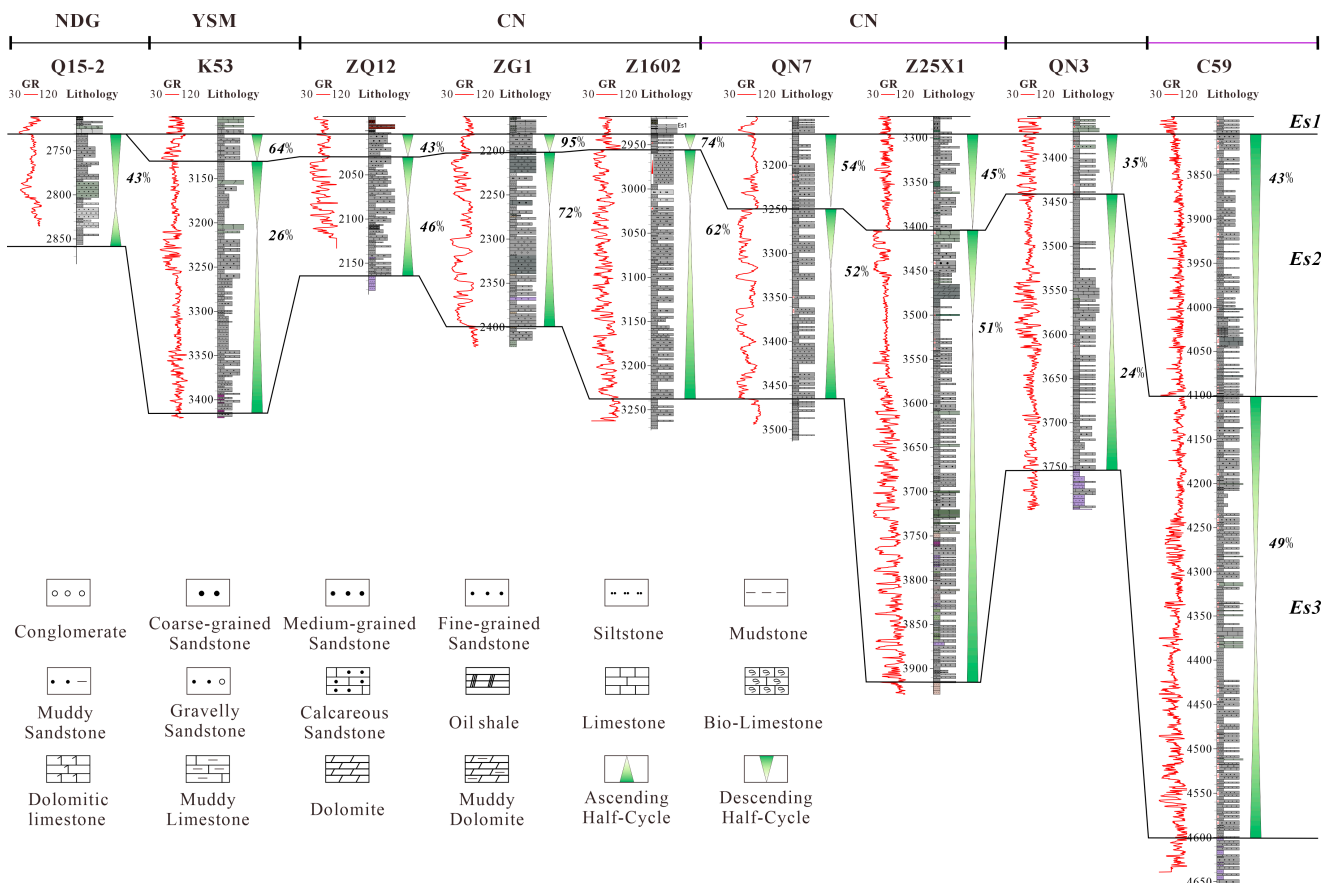


Figure 5. Well correlation panel showing stratigraphic and depositional characteristics of representative wells from different source-related geomorphic belts in Es3 and Es2 of the Qinan Sag. Representative wells include those associated with the CN, YSM, and NDG sides, as well as wells from the slope area and central sag area. Each well column shows, from left to right, GR, depth, lithology, third-order cycle, and sand ratio. Percentage values indicate the sand ratio within the corresponding third-order sequence. Correlation lines indicate second- or third-order sequence boundaries. Different-coloured lines at the top of the panel indicate the structural units in which the wells are located; black denotes the slope area, and purple denotes the sag area.

The study area contains 15 lithofacies: massive clast-supported conglomerate (Gm), massive matrix-supported conglomerate (Gms), massive sandstone (Sm), trough cross-bedded sandstone (St), parallel-bedded sandstone (Sh), ripple cross-laminated sandstone (Sr), deformed sandstone (Sd), massive siltstone (Fsm), horizontally laminated siltstone (Fl), ripple-laminated sandy siltstone (Fr), deformed siltstone (Fd), horizontally laminated mudstone (Mh), massive mudstone (Mm), deformed mudstone (Md), and bioclastic limestone (BioL) (Figure 7; Table 2). Based on their vertical stacking relationships, 15 lithofacies associations (LA-1–LA-15) were identified. These associations record typical lithofacies assemblages formed under different depositional processes in Es3 and Es2.

Es3 contains nine lithofacies associations (LA-1–LA-9), which are more diverse and coarser grained than those in Es2. They include subaqueous distributary-channel associations and related transitional associations represented by LA-1–LA-4, proximal-to-distal gravity-flow associations represented by LA-5 and LA-9, and channel deposits represented by LA-8 (Figure 7; Table 3). This interval commonly shows normal or weak normal grading cycles, traction-current structures, and soft-sediment deformation, indicating a high degree of lithofacies differentiation.

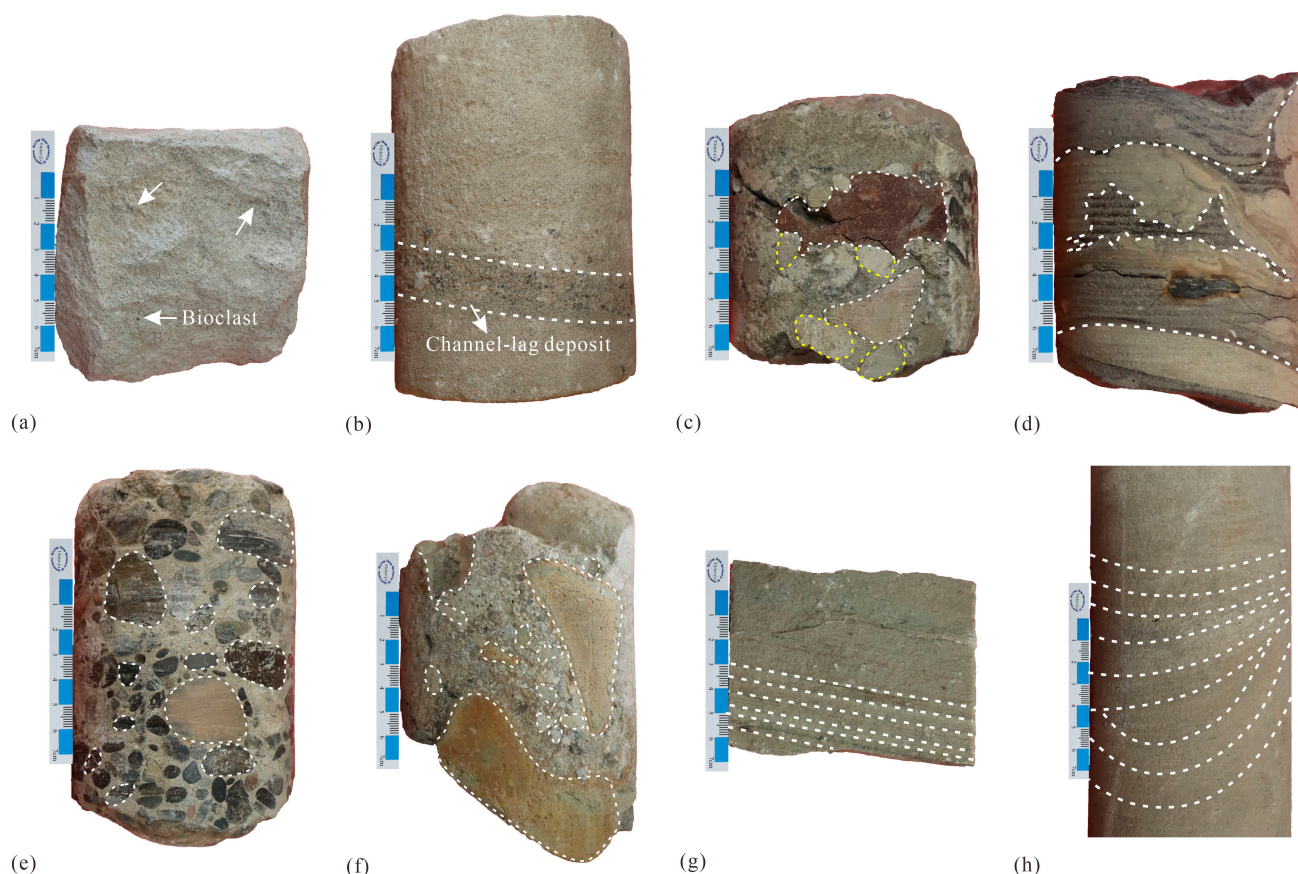


Figure 6. Core photographs from wells in Es3 and Es2 of the Qinan Sag. (a) Greyish-white bioclastic limestone with ooid-like bioclasts, Well K33, Es2, 2389.24 m. (b) Grey pebbly medium- to fine-grained sandstone with a basal erosional surface and channel-lag gravels, Well K47, Es2, 2619.83 m. (c) Grey pebbly medium-grained sandstone with mainly greyish-white clasts and local reddish-brown mudstone clasts, 2–70 mm in diameter, very poor sorting, subangular to subrounded clasts, and clast-to matrix-supported fabric, Well Z1605, Es3, 2974.41 m. (d) Grey to greyish-black sandstone and mudstone with scattered pebbles and deformed bedding, Well QN6, Es3, 3294.46 m. (e) Grey sandy conglomerate with mainly dark grey to black clasts, 2–30 mm in diameter, moderate sorting, rounded clasts, and matrix-supported fabric, Well Z62, Es3, 2900.34 m. (f) Greyish-white conglomerate with yellowish-brown mud clasts, 2–80 mm in diameter, very poor sorting, subangular to subrounded clasts, and clast-supported fabric, Well QN5-16, Es3, 2692.89 m. (g) Grey silty fine-grained sandstone with parallel bedding, Well Z65, Es3, 3001.55 m. (h) Grey fine-grained sandstone with trough cross-bedding, Well Z52, Es3, 3034.40 m.

Es2 contains six lithofacies associations (LA-10–LA-15). These associations are finer grained and simpler. LA-10–LA-12 represent bar-crest, bar-margin, and interbar associations. LA-13–LA-14 represent subaqueous distributary-channel associations, and LA-15 represents sheet-sand to lacustrine associations (Figure 7; Table 3). Overall, the Es2 lithofacies associations are characterized by recurring combinations of shallow-water sandy deposits and fine-grained deposits.

4.3.2. Representative Depositional Successions

Representative depositional successions in Es3 include braided-delta fronts in the southern slope belt, fan-delta fronts in the western slope belt, and proximal-to-distal subaqueous-fan successions developed from the slope-break belt toward the central part of the Qinan Sag. Es2 mainly includes shallow-water delta fronts in the southern slope belt and beach-bar successions in the western gentle-slope belt.

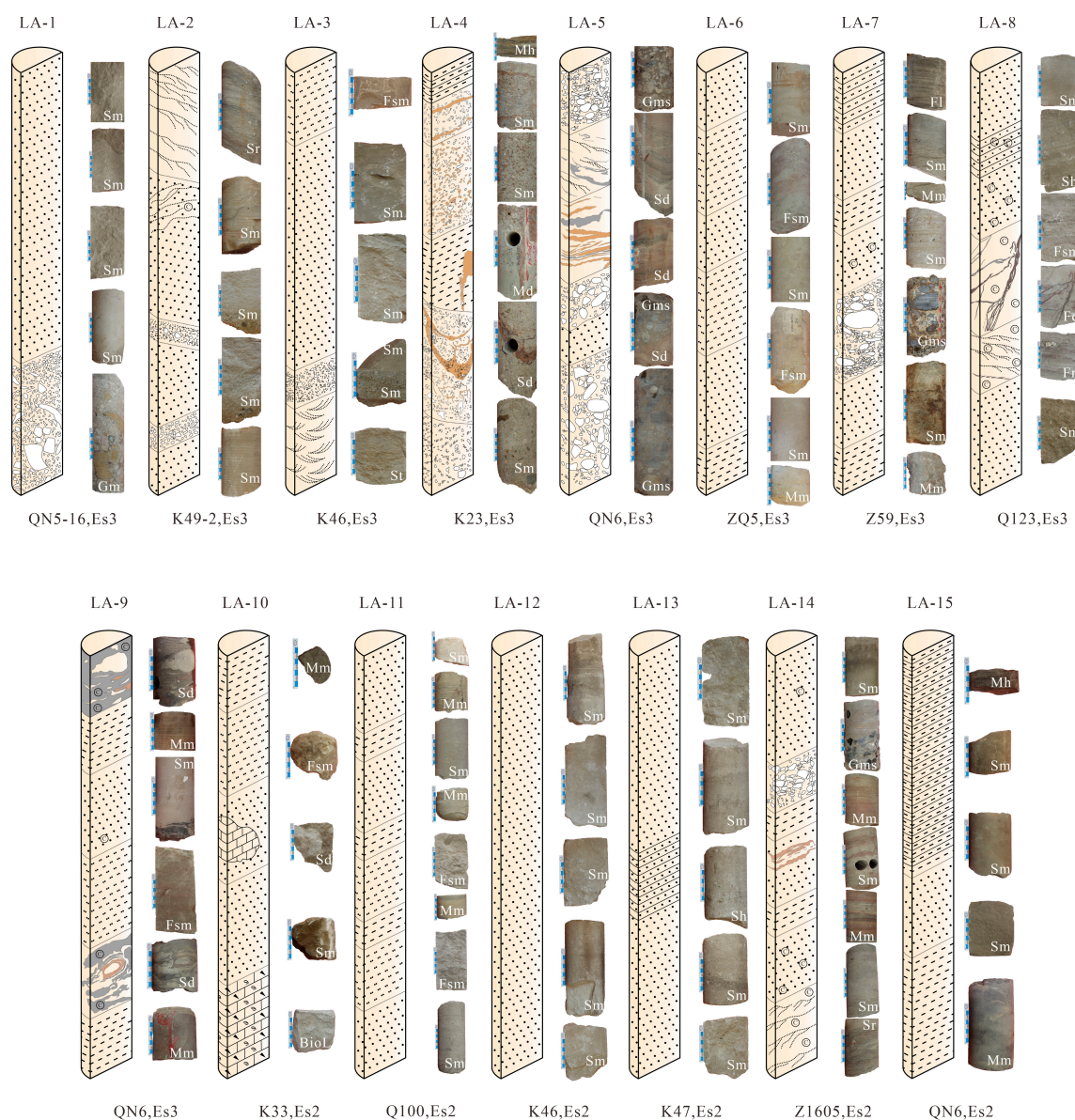


Figure 7. Lithofacies association templates of Es3 and Es2 in the Qinan Sag.

Table 2. Lithofacies and depositional-process interpretations of the Es3–Es2 interval. Lithofacies names are defined in the text.

Lithofacies	Description	Depositional-Process Interpretation	Lithofacies Associations
Gm	Clast-supported conglomerate containing yellowish-brown mud clasts; very poorly sorted fine- to coarse-gravel-sized clasts.	Gravelly bedload and channel-lag deposition by episodic high-energy traction currents; mud clasts indicate erosion and reworking of muddy deposits.	LA-1
Gms	Matrix-supported conglomerate with poorly to moderately sorted, subrounded gravel clasts.	Rapid en masse deposition from high-concentration sediment gravity flows or debris-flow-like processes; locally associated with channelized coarse-grained fills.	LA-5 LA-7 LA-14
Sm	Grey massive fine sandstone, locally containing 2–4 mm lag gravels along erosional surfaces.	Rapid sandy aggradation under relatively strong traction currents; lag gravels along erosional surfaces indicate local scouring and reworking.	LA-1–LA-4 LA-6–LA-15

Table 2. Cont.

Lithofacies	Description	Depositional-Process Interpretation	Lithofacies Associations
St	Grey fine-grained sandstone with trough cross-bedding.	Migration of sinuous-crested subaqueous 3D dunes under unidirectional traction currents.	LA-3
Sh	Grey fine sandstone with parallel bedding and locally aligned carbonaceous clasts.	Upper-flow-regime plane-bed deposition under strong traction currents.	LA-8 LA-13
Sr	Grey silty fine-grained sandstone with ripple cross-lamination, black carbonaceous laminae and carbonaceous clasts; locally showing reddish ferruginous staining.	Ripple migration under weak traction currents during waning-flow stages; carbonaceous laminae and clasts reflect intermittent concentration of carbonaceous material under reduced flow energy.	LA-2 LA-14
Sd	Deformed sandstone with slump deformation, convolute lamination, load structures, and entrained mudstone intraclasts.	Soft-sediment deformation caused by loading and slumping after rapid sand deposition; mudstone intraclasts indicate erosion and entrainment of muddy beds.	LA-4 LA-5 LA-9 LA-10
Fsm	Grey to greyish-brown massive siltstone or muddy siltstone; well sorted.	Suspension-dominated settling of silt-grade sediment from waning flows; its common occurrence above or between sandstone beds records reduced flow competence after sandy deposition.	LA-3 LA-6 LA-8 LA-9 LA-10 LA-11
Fl	Greyish-brown to greyish-black argillaceous siltstone with very thin horizontal silt–mud interlamination; locally cut by microfractures.	Alternation of weak tractional silt transport and suspension fallout of mud during waning-flow stages.	LA-7
Fr	Grey sandy siltstone with ripple lamination, reddish mud laminae, and abundant carbonaceous clasts; locally cut by microfractures.	Ripple migration under weak traction currents, accompanied by intermittent mud draping and concentration of carbonaceous material during waning-flow stages.	LA-8
Fd	Deformed argillaceous siltstone with black mud-filled seams and dark-reddish vein-like mud infillings.	Soft-sediment deformation of muddy silt, with remobilized mud injected along deformation seams during local instability following flow waning.	LA-8
Mh	Yellowish or black mudstone with abundant horizontal laminae.	Continuous suspension fallout of mud under very low-energy conditions, forming well-preserved horizontal laminae.	LA-4 LA-15
Mm	Massive mudstone with variable colours, including light grey, grey, brownish-red, greyish-black, and black.	Suspension fallout of mud under low-energy conditions; the massive texture suggests relatively uniform or comparatively rapid settling, with no clear lamination preserved at core scale.	LA-6 LA-7 LA-9 LA-10 LA-11 LA-14 LA-15
Md	Grey-green deformed mudstone with reddish-brown mud-filled seams and fracture-like deformation features.	Soft-sediment deformation caused by syndimentary slumping and instability; mud-filled seams record remobilization of unconsolidated mud along deformation zones.	LA-4
BioL	Light-grey bioclastic limestone with ooid-like bioclastic particles.	Accumulation and winnowing of bioclastic particles, with local reworking by waves or currents in shallow water.	LA-10

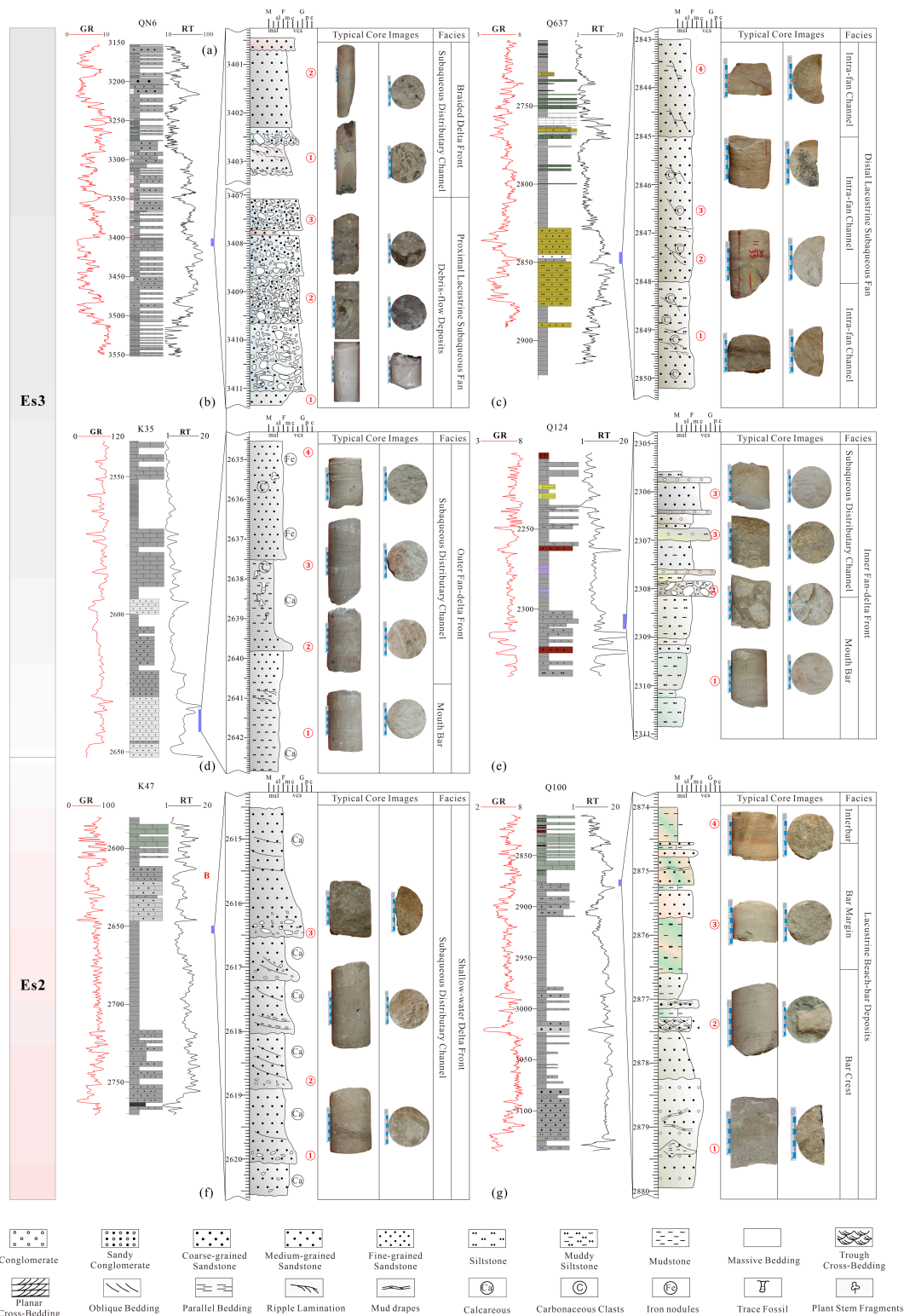


Figure 8. Representative depositional successions of Es3 and Es2 in the Qinan Sag. (a) Braided-delta-front succession with subaqueous distributary-channel deposits, Well QN6. (b) Proximal subaqueous-fan succession with debris-flow deposits, Well QN6. (c) Distal subaqueous-fan succession with intra-fan channel deposits, Well Q637. (d) Outer fan-delta-front succession with subaqueous distributary-channel deposits, Well K35. (e) Inner fan-delta-front succession with subaqueous distributary-channel deposits, Well Q124. (f) Shallow-water-delta-front succession with subaqueous distributary-channel deposits, Well K47. (g) Lacustrine beach-bar succession with bar-crest, bar-margin, and interbar deposits, Well Q100. Vertical labels on the left indicate whether each representative depositional succession belongs to Es3 or Es2.

Table 3. Lithofacies associations and depositional interpretations of Es3 and Es2 in the Qinan Sag. “→” indicates an upward lithofacies succession, from the lower lithofacies on the left to the overlying lithofacies on the right. “↔” indicates repeated vertical alternation between the lithofacies on both sides.

Lithofacies Associations	Component Lithofacies	Brief Description	Depositional Interpretation
Es3			
LA-1	Gm → Sm	Coarse-grained succession from conglomerate to sandstone, recording rapid accumulation of proximal high-energy clastics.	Subaqueous distributary channel
LA-2	Sm → Sr	Weak normal grading with basal channel-lag gravels, recording a transition from strong to moderate–weak hydrodynamic conditions.	Subaqueous distributary channel
LA-3	St → Sm → Fsm	Normal grading cycle from traction-current sandy deposits to fine-grained deposits.	Subaqueous distributary channel
LA-4	Sm → Sd → Md → Mh	Alternating coarse- and fine-grained beds with soft-sediment deformation, including fracture-like deformation, mudstone tearing, and mud-clast incorporation.	Subaqueous distributary channel–subaqueous interdistributary bay
LA-5	Gms ↔ Sd	Multiple episodes of high-concentration gravity-flow input and syndimentary instability.	Proximal gravity flow
LA-6	Mm → (Sm ↔ Fsm)	Alternating fine sandstone, siltstone, and mudstone, with multiple weak normal grading cycles on a low-energy muddy background.	Distributary-channel margin–interdistributary bay
LA-7	(Mm ↔ Sm) → Gms → (Sm ↔ Mm) → Fl	Overall fining-upward succession with local coarse- and fine-grained alternations, poorly sorted subrounded pebbles, and proximal coarse-grained channel characteristics.	Distributary channel–interdistributary bay
LA-8	Sm → Fr → Fd → Fsm → Sh → Sm	Multistage association of sandy deposition, fine-grained deformation, fine-grained deposition, and renewed sandy deposition.	Channel deposits
LA-9	Mm → Sd → Fsm → Sm → Mm → Sd	Repeated fine-grained deposition and soft-sediment deformation, recording distal instability and gravity-flow reworking.	Distal gravity flow
Es2			
LA-10	BioL → Sm → Sd → Fsm → Mm	Normal grading cycle from high- to low-energy shallow-water deposits, with local slump deformation.	Bar crest–bar margin
LA-11	Sm → (Fsm ↔ Mm) → (Mm ↔ Sm)	Alternation of stronger and weaker hydrodynamic conditions during sustained sand-bar development.	Bar margin–interbar
LA-12	Sm	Sustained sandbody development under stable hydrodynamic conditions.	Bar crest
LA-13	Sm → Sh → Sm	Local erosional surfaces and channel-lag gravels, recording rapid channel deposition under strong hydrodynamic conditions.	Subaqueous distributary channel
LA-14	Sr → (Sm ↔ Mm) → Gms → Sm	Lag gravels and carbonaceous laminae, recording channel deposition with enhanced transport capacity.	Subaqueous distributary channel
LA-15	Mm → Sm → Mh	Episodic sandstone input within a muddy background.	Sheet sand–lacustrine deposits

1. Es3: Braided delta

Braided deltas are identified in the southern slope belt and its transition toward the sag area, such as in wells ZQ12, ZG1, and QN6 (Figures 5 and 8a). The main criteria include lithological associations composed of sandy conglomerate, conglomerate, fine sandstone, siltstone, and mudstone. They also include channel-dominated lithofacies associations represented by LA-4, LA-6, and LA-7 in Section 4.3.1 (Figure 7; Table 3), and box-, bell-, funnel-, and finger-shaped log motifs (Figure 5). In Well QN6, the 3401–3403 m interval records a braided-delta-front succession formed by stacked, normally graded subaqueous distributary-channel deposits. Each cycle grades upward from coarser sandy-gravelly deposits at the base to finer sandy deposits at the top (Figure 8a).

2. Es3: Fan delta

Fan deltas are well-developed in the western slope belt, such as in wells QN5-16, K53, K35, and Q124 (Figures 5, 7 and 8d,e). The main criteria include lithological associations dominated by fine sandstone, with pebbly sandstone and conglomerate as subordinate components. They also include high-energy sandy-gravelly channel lithofacies associations represented by LA-1, LA-2, and LA-3 in Section 4.3.1 (Figure 7; Table 3), and funnel-, bell-, and finger-shaped log motifs (Figure 5). Wells K35 and Q124 record depositional successions of the outer fan-delta front and inner fan-delta front, respectively. Well K35 is characterized by vertical stacking of mouth bars and multistage subaqueous distributary channels. It is finer grained overall and is dominated by fine sandstone and siltstone (Figure 8d). Well Q124 shows frequent alternation between gravelly and sandy subaqueous distributary channels, with coarser grain size overall (Figure 8e).

3. Es3: Subaqueous fan

Subaqueous fans are identified along the northern buried-hill slope belt, the slope-break belts where the southern and western slopes pass toward the central sag area, and the central sag area. They are represented by wells such as Q123, QN2, C59, and QN6 (Figures 3, 5 and 8b). The main criteria include lithological associations dominated by conglomerate, fine sandstone, siltstone, and mudstone. They also include the gravity-flow and channel lithofacies associations represented by LA-5, LA-8, and LA-9 in Section 4.3.1 (Figure 7; Table 3), and serrated funnel-, bell-, and finger-shaped log motifs (Figures 3b and 5). In Well QN6, the 3407–3411 m interval records a proximal subaqueous-fan succession formed by stacked debris-flow deposits. It is characterized by conglomerate beds and deformed muddy-sandstone beds (Figure 8b). Well Q637 records a distal subaqueous-fan succession with intra-fan channel deposits, formed by stacked multistage channel deposits. This succession is dominated by silty to fine sandstone and contains repeated fine-grained deposits and deformed beds (Figure 8c). Together, these successions indicate a transition in Es3 subaqueous-fan deposition from proximal coarse-grained debris-flow deposits to distal fine-grained channel and gravity-flow deposits.

4. Es2: Shallow-water delta

Shallow-water deltas are identified in the southern slope belt, such as in wells K47 and ZG1 (Figures 5 and 8f). The main criteria include lithological associations dominated by fine sandstone, silty to fine sandstone, and mudstone. They also include subaqueous distributary-channel lithofacies associations represented by LA-13 and LA-14 in Section 4.3.1 (Figure 7; Table 3), and bell-, funnel-, and finger-shaped log motifs (Figure 5). In Well K47, the Es2 interval records a shallow-water delta-front succession formed by stacked, normally graded subaqueous distributary-channel deposits. Each cycle grades upward from coarser pebbly sandstone at the base to fine sandstone at the top. Local erosional surfaces and channel-lag gravels are observed (Figure 8f).

5. Es2: Lacustrine beach-bar system

Lacustrine beach-bar systems are typical in the western slope belt, such as in wells Q100 and K53 (Figures 5 and 8g). The main criteria include lithological associations dominated by bioclastic limestone, fine sandstone, silty to fine sandstone, and mudstone. They also include bar-crest, bar-margin, and interbar lithofacies associations represented by LA-10, LA-11, and LA-12 in Section 4.3.1 (Figure 7; Table 3), and log motifs dominated by funnel- and finger-shaped patterns, with local bell-shaped patterns (Figure 5). Well Q100 records an overall fining-upward beach-bar succession, showing a vertical transition from higher-energy bar-crest deposits to lower-energy bar-margin and interbar deposits. This succession consists mainly of repeated stacking of fine-sand bar-crest deposits, silty-to-fine-sand bar-margin deposits, and muddy interbar deposits. The mottled mudstone at the top indicates intermittent exposure and oxidation in a shallow-water setting (Figure 8g).

4.4. Depositional-System Distribution and Sediment-Dispersal Domains

4.4.1. Planform Distribution of Depositional Systems and Sandbodies

RMS amplitude attributes can be non-unique. Their sedimentological significance should be interpreted together with sandstone thickness, sand ratio, and planform geometry [63,64]. Comparison of RMS amplitude maps and sandstone-thickness maps shows that high-amplitude areas do not always correspond to the greatest sandstone thicknesses. In some areas, medium-amplitude areas correspond to large sandstone thicknesses (Figure 9a–d). This indicates that amplitude responses in the study area reflect sandstone thickness, lithological associations, and internal architecture.

Three amplitude zones are recognized in Es3. Zone I (ZI) occurs along the western YSM slope belt and is characterized by medium- to high-amplitude values, mainly >80, with continuous fan-shaped and chaotic elongate fan-shaped reflections. This zone is interpreted as fan-delta deposits (Figure 9a). Zone II (ZII) occurs in the central–southern CN slope belt and shows mixed low- and high-amplitude values, mainly <60 and >80, with chaotic to continuous lobate reflections. This zone is interpreted as braided-delta deposits (Figure 9a). Zone III (ZIII) occurs in the central sag area and is characterized by medium-amplitude values, mainly 60–100, with chaotic to continuous elongate fan-shaped reflections. This zone is interpreted as subaqueous-fan deposits (Figure 9a). These three zones correspond to different sandstone thicknesses. The greatest sandstone thickness occurs in the slope-break belt and sag area, followed by the southern slope belt, and the lowest values occur in the western slope belt (Figure 9a,c). Overall, Es3 shows a planform pattern dominated by braided deltas in the central–southern area, fan deltas distributed around the YSM Uplift, and widespread subaqueous fans in the sag area (Figures 4a and 9e).

Several amplitude zones are recognized in Es2. Zone IV (ZIV) occurs along the western YSM slope belt and is characterized by high-amplitude values, mainly >110, with sheet-like reflections of strong continuity. This zone is interpreted as beach-bar deposits (Figure 9b). Zones V–VIII (ZV–ZVIII) occur along the southern CN slope belt and show medium- to high-amplitude values, mainly 70–100 and >100, with lobate and belt-like reflections. These zones are interpreted as shallow-water delta deposits (Figure 9b). Zone IX (ZIX) occurs in the central sag area and is characterized by medium-amplitude values, mainly 50–80, with belt-like reflections of moderate continuity. This zone represents shallow-water delta deposits (Figure 9b). Sandstone thickness in Es2 is markedly smaller than that in Es3, but the relative thickness pattern between the sag area and slope belts remains consistent with that in Es3 (Figure 9d). Overall, Es2 shows a planform pattern characterized by widespread shallow-water deltas and concentrated beach-bar deposits along the western gentle-slope belt (Figures 4b and 9f).

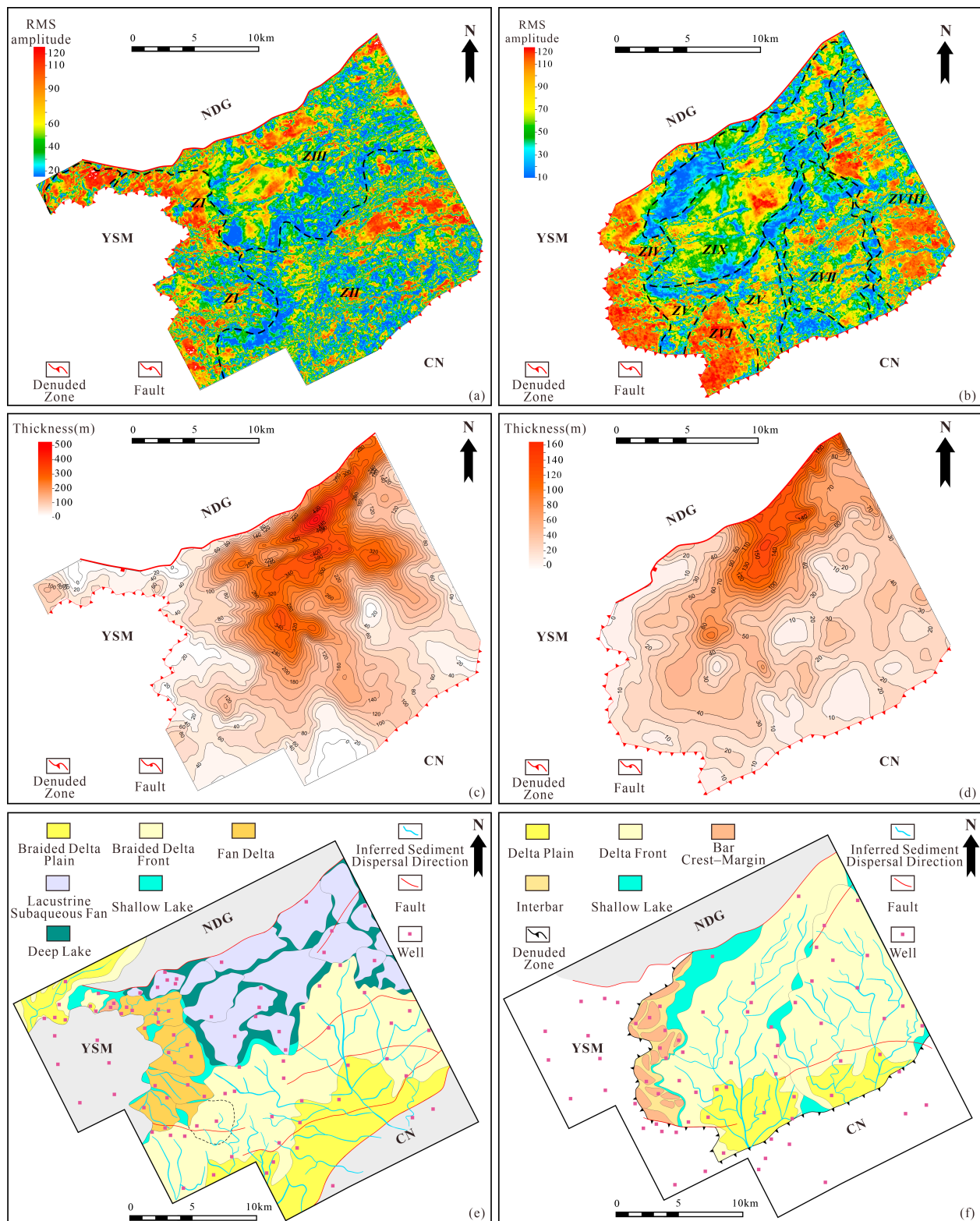


Figure 9. Integrated planform maps of sandstone distribution and depositional systems in Es3 and Es2 of the Qinan Sag. (a) RMS amplitude attribute map of Es3. (b) RMS amplitude attribute map of Es2. ZI–ZIX denote zones with similar amplitude attributes, and black dashed lines mark their boundaries. (c) Sandstone-thickness map of Es3. (d) Sandstone-thickness map of Es2. (e) Planform distribution of depositional systems in Es3. (f) Planform distribution of depositional systems in Es2. Blue lines indicate inferred major sediment-dispersal directions based on provenance indicators, palaeogeomorphological background, and depositional-system distribution. The wells shown are representative wells used for map construction and analysis.

4.4.2. Source-Related Sediment-Dispersal Domains

In this study, a source-related sediment-dispersal domain is used as an operational spatial subdivision of sediment dispersal characterized by a consistent sediment-supply direction, sediment-input pathway, and in-basin dispersal characteristics. Domain identification was based mainly on the integrated interpretation of provenance indicators, including heavy-mineral assemblages and ZTR-index patterns, palaeogeomorphological relief, inferred sediment-input pathways, and depositional-system distribution.

Three source-related sediment-dispersal domains are identified in Es3: CN, YSM, and NDG. In the CN domain, the kernel-density curve shows a broad unimodal distribution, with the main peak at approximately 50% (Figure 10a). The median is 49%, and the interquartile range is 35%–56% (Figure 10b). The YSM domain has the broadest distribution, with the main peak at approximately 35%–40% and a pronounced high-value tail (Figure 10a). The median is 36%, and the interquartile range is 25%–53% (Figure 10b). The NDG domain shows a narrow unimodal distribution, with the main peak at approximately 35% (Figure 10a). The median is 34%, and the interquartile range is 28%–43% (Figure 10b).

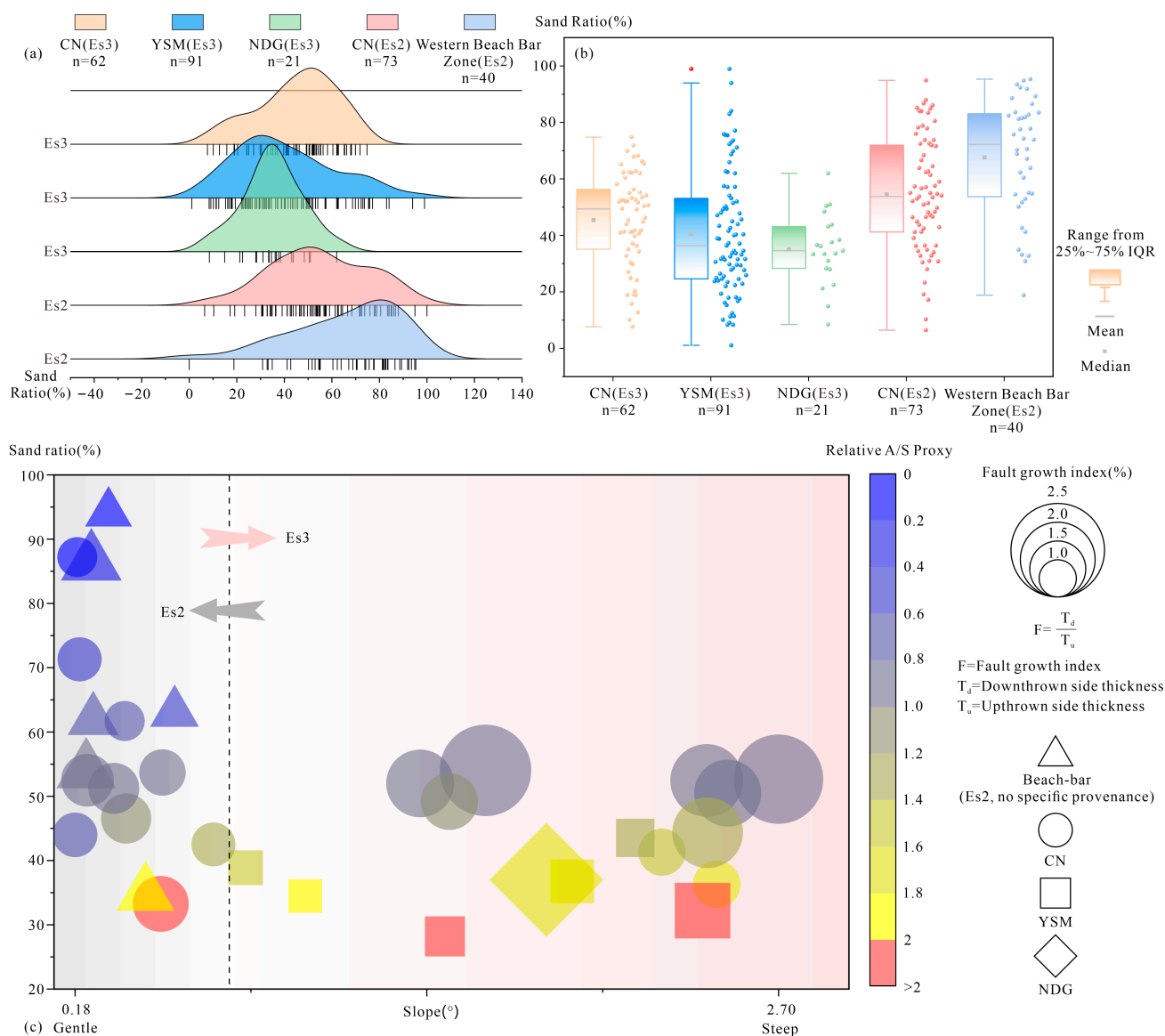


Figure 10. Sand-ratio distributions and controlling-factor framework for Es3 and Es2 source-related sediment-dispersal domains and the Es2 beach-bar zone in the Qinan Sag. (a) Kernel-density ridgeline plot of sand-ratio distributions for the three source-related sediment-dispersal domains in Es3, namely

CN, YSM, and NDG, and for the southern CN-related sediment-dispersal domain and western beach-bar zone in Es2. (b) Corresponding box plots of sand-ratio distributions for the same domains and beach-bar zone. Sand ratio is defined as sandstone thickness/total stratigraphic thickness. (c) Interpretive framework linking slope, relative A/S proxy, fault-growth-index values, and sand-ratio responses. The x-axis represents slope ($^{\circ}$), the left y-axis represents sand ratio (%), and the right y-axis represents the relative A/S proxy. Point colours indicate the relative A/S proxy, with cool colours representing lower values and warm colours representing higher values. Bubble size represents fault-growth-index values. Circles, squares, and diamonds represent depositional-unit samples from the CN, YSM, and NDG sediment-dispersal domains, respectively. Triangles represent samples from the western beach-bar zone, which corresponds to the Es2 sand-prone belt not linked to a specific source area. The dashed line marks an empirical transition boundary, identified from samples in the study area, between gentle and moderate-to-steep slopes and their associated differences in sandy-sediment preservation responses. It does not represent a universal threshold. Samples to the left and right of the dashed line are from Es2 and Es3, respectively.

In Es2, no NDG-related sediment-dispersal domain is identified. The southern CN domain maintains high sand ratios and shows a broad, weakly bimodal distribution (Figure 10a). Its median is 54%, and the interquartile range is 41%–72% (Figure 10b). Relative to the Es3 YSM domain, the western beach-bar zone in Es2 shows the strongest upward shift in sand-ratio distribution. Its kernel-density curve is characterized by a broad high-value distribution related to beach-bar deposits, with the main density peak shifting to approximately 80% (Figure 10a). The median increases to 72%, and the interquartile range is 53%–83% (Figure 10b).

5. Discussion

5.1. Controls on Sediment-Routing Reorganization and Associated Sedimentary Responses

Across the Es3–Es2 syn-rift stage transition in the Qinan Sag, sediment routing after basin entry was reorganized. This reorganization was recorded by coordinated changes in depositional-system assemblages, sediment-dispersal domains, and sandy-sediment preservation patterns. In rift basins, the main controls on such reorganization can be discussed in terms of sediment source, geomorphology, and accommodation–sediment-supply relationships [1,7,59]. Palaeoclimate can also act as a background modulating factor by influencing runoff, weathering intensity, sediment supply, and lake-basin water balance [14,65].

Relative to Es2, the Es3 interval of the Bohai Bay Basin is commonly associated with relatively warm and humid palaeoclimatic conditions [66–68], which tend to enhance runoff, chemical weathering, and siliciclastic sediment supply [65,67,68]. In the Qinan Sag, the higher tectonic subsidence rate during Es3 [21], together with greater hydrological input under humid conditions, would have favoured a high-accommodation, relatively deep-water setting [14,21]. This climatic–tectonic background is consistent with the Es3 depositional responses, including coarser-grained lithofacies and braided-delta, fan-delta, and subaqueous-fan depositional systems (Figures 6–8 and 9e). By contrast, Es2 is generally associated with dry palaeoclimatic conditions [66,69] and a lower tectonic subsidence rate in the Qinan Sag [21]. Reduced subsidence would have limited accommodation creation, and lower hydrological input under dry conditions would have promoted shallow-water conditions [14,21,65]. This background is consistent with the Es2 depositional responses, including shallow-water delta and beach-bar systems (Figures 6–8 and 9f). Against this differential tectono-climatic background across the Es3–Es2 intra-syn-rift transition, sediment routing after basin entry was reorganized, leading to contrasting sandy-sediment preservation responses.

5.1.1. Source-Configuration Changes and Geomorphic Segmentation

During Es3, the palaeogeomorphology was characterized by high relief, well-developed stepped slope breaks, and strong geomorphic segmentation (Figure 4a). The Es3 source configuration was characterized by multidirectional sediment input. Together, these two factors promoted multi-pathway, dispersed sediment routing after basin entry [1,7]. Near the slope-break belts, sediment was prone to local unloading and segmented preservation, and part of the sediment continued to be routed toward the central part of the Qinan Sag (Figures 4a and 9e). During Es2, palaeogeomorphic relief decreased, long gentle slopes developed, and geomorphic segmentation weakened (Figure 4b). The source configuration converged toward the southern CN-related direction. Together, these changes shifted sediment routing after basin entry toward focused dispersal along this dominant CN-related direction. In contrast, lateral redistribution occurred in the shallow-water zone along the western gentle slope near the YSM side (Figures 4b and 9f).

5.1.2. Differential Preservation Responses Under Contrasting Slope–A/S Conditions

Accommodation–sediment-supply relationships are commonly used to explain sediment preservation, stacking patterns, and changes in sand–mud proportions [55,56,59]. Here, we jointly consider the relative A/S proxy and slope conditions to explain differences in sandy-sediment preservation responses among sediment-dispersal domains. This proxy is used in a relative and comparative sense to evaluate muddy versus sandy preservation backgrounds among different sediment-dispersal domains, rather than as a direct quantitative estimate of absolute accommodation, sediment-supply rates, or hydrologic lake-level rise or fall. During Es3, moderate-to-steep slopes and higher relative A/S proxy values enhanced local unloading and segmented preservation near slope-break belts, allowing multi-pathway routing to produce discrete, segmented preservation records of sandy deposits (Figures 9e and 10c). During Es2, gentle slopes and lower relative A/S proxy values reduced the partitioning effect of geomorphic segmentation on sandy-sediment preservation, promoting more continuous preservation along the dominant direction and redistribution-related local shallow-water enrichment (Figures 9f and 10c).

Under these contrasting slope–A/S conditions, the CN domain, NDG domain, and western beach-bar zone represent three preservation-response types: persistent preservation, stage-limited preservation, and shallow-water enrichment. The CN domain maintained high sand ratios in both Es3 and Es2, representing a persistent preservation response of a regional-source-related sediment-dispersal domain across the syn-rift stage transition (Figure 10a,b). The NDG domain shows a narrow low- to middle-value sand-ratio peak only in Es3, and its preservation record is absent in Es2. This represents a stage-limited preservation response and indicates that local-source-related records depended more strongly on the stage-specific background conditions of moderate-to-steep slopes, strong segmentation, and higher relative A/S proxy values (Figure 10a,b). In Es2, the YSM domain was no longer identified, and the western beach-bar zone developed a high-sand-ratio shallow-water enrichment response, further indicating the strong dependence of local-source-related records on stage-specific background conditions (Figure 10a,b).

Fault activity mainly played a modulating role in this process [1,57]. Within the analyzed data points, higher fault-growth-index values in Es3 did not show a clear association with higher sand ratios. Instead, they mainly correspond to medium sand-ratio data points for Es3 and occur across a range of slope gradients. Under comparable slope conditions, higher fault-growth-index values commonly correspond to lower relative A/S proxy values (Figure 10c). Therefore, fault activity in Es3 mainly increased the likelihood of local unloading and segmented preservation of sandy sediments near slope-break belts by enhancing slope-break segmentation and local accommodation differences (Figure 10c). After the transition to Es2, fault activity weakened overall (Figures 9f and 10c), and its modulating effect on sandy-sediment dispersal and preservation also weakened.

It should be noted that the overall higher sand ratios in Es2 may be partly influenced by the statistical effects of unconformity development and reduced stratigraphic thickness. Therefore, their absolute values should not be interpreted solely in terms of depositional processes. However, this effect mainly influences the magnitude of the sand-ratio values. It does not change the relative differences among sediment-dispersal domains, nor does it explain why the high-value area is concentrated in the western gentle-slope beach-bar unit.

5.2. Integrated Model of Sediment-Routing Reorganization and Sedimentary Responses

Es3 represents a multi-source, strongly segmented, and multi-pathway sediment-dispersal end member developed under a warm and humid palaeoclimatic background during the early strong-rifting stage. Its strong segmentation was mainly reflected in sediment partitioning after basin entry and subsequent dispersal along multiple directions, multi-level slope breaks, and different slope units. This configuration corresponded to a strongly differentiated depositional-system assemblage in which braided deltas, fan deltas, and subaqueous fans coexisted (Figure 11a). Es2 represents a dominant-source, weakly segmented, and relatively focused sediment-dispersal end member developed under a dry palaeoclimatic background during the transition from early strong rifting toward relatively stable rifting. Its focused character was mainly reflected in the convergence of sediment dispersal into a dominant basinward pathway along the main slope, with more continuous transport toward the central sag area. This configuration corresponded to a weakly differentiated depositional-system assemblage composed of southern shallow-water deltas and western lacustrine beach-bar systems (Figure 11b).

In terms of sandbody distribution and vertical stacking patterns, Es3 sandbodies were characterized by coarse-grained deposits near source areas and alternating coarse- and fine-grained deposits in distal areas. Overall, they showed multistage, multidirectional, small-scale, and high-frequency stacking patterns (Figure 11a). In contrast, Es2 sandbodies were dominated by relatively fine-grained distal deposits and showed fewer-stage, unidirectional, large-scale, and low-frequency stacking patterns, with local sandbody enrichment (Figure 11b).

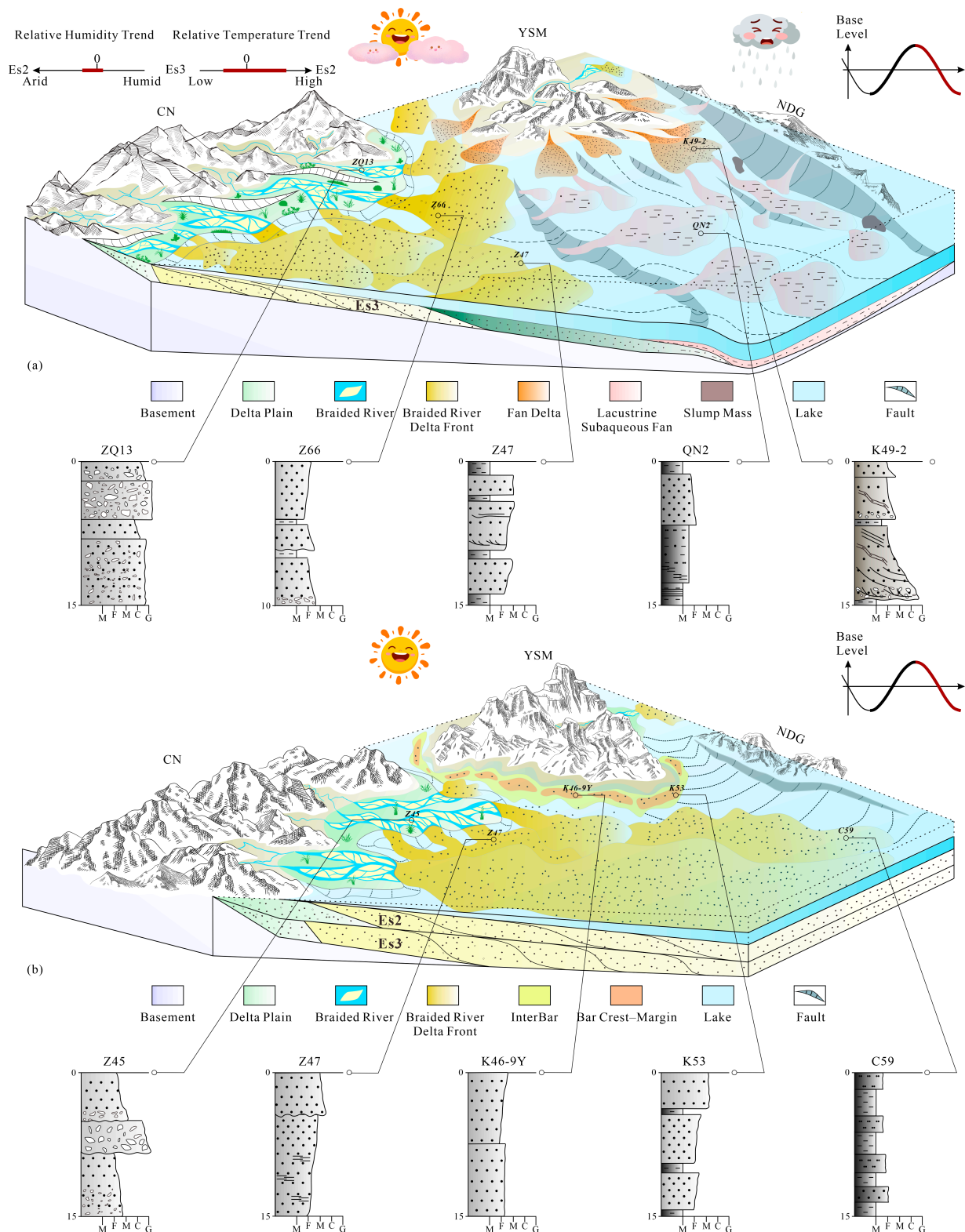


Figure 11. Spatiotemporal evolutionary model of sediment-routing reorganization and associated sedimentary responses across the Es3–Es2 syn-rift stage transition in the Qinan Sag. (a) Dispersed sediment-routing model of Es3 under multi-source supply and strong geomorphic segmentation. (b) Focused sediment-routing model of Es2 under dominant-source supply and weak geomorphic segmentation. Representative well-based depositional successions are shown together with schematic relative base-level curves. The relative humidity and temperature trends for the Dongying Sag, Bohai Bay Basin, are simplified from [66] and used here as regional palaeoclimatic background.

6. Conclusions

- (1) The Es3–Es2 interval in the Qinan Sag records a shift from multi-source supply to dominant-source supply. During Es3, sediments were mainly supplied from the southern Chengning Uplift, western Yangsanmu Uplift, and northern Nandagang Buried Hill. By Es2, the supply pattern had become simplified and was dominated by the southern Chengning Uplift.
- (2) During Es3, the CN, YSM, and NDG source-related sediment-dispersal domains coexisted, forming a strongly differentiated depositional-system assemblage of braided deltas, fan deltas, and subaqueous fans. By Es2, the NDG sediment-dispersal domain was no longer identified, the CN domain persisted, and the western gentle-slope belt evolved into a high-sand-ratio sand-prone belt, corresponding to a weakly differentiated assemblage of southern shallow-water deltas and western lacustrine beach-bar systems.
- (3) Sediment-routing reorganization and sedimentary responses across the Es3–Es2 interval were mainly controlled by source-configuration changes, geomorphic segmentation, and contrasting slope–A/S conditions, and were modulated by stage-dependent fault activity. During Es3, multi-source supply, strongly segmented palaeogeomorphology, moderate-to-steep slopes, and higher relative A/S proxy values favoured multi-pathway, dispersed routing and discrete, segmented preservation of sandy deposits. During Es2, dominant-source supply, weakly segmented long gentle slopes, and lower relative A/S proxy values favoured focused routing and preservation along the dominant direction, as well as local shallow-water enrichment.
- (4) Different types of source-related sediment routing responded differently to changes in stage-specific background conditions. Regional-source-related routing showed stronger persistence across the Es3–Es2 interval, whereas local-source-related routing more commonly weakened or terminated during the transition. Areas associated with weakened or terminated local-source-related routing tended to show shallow-water redistribution and enrichment signals.

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References

- Gawthorpe, R.L.; Leeder, M.R. Tectono-sedimentary evolution of active extensional basins. *Basin Res.* **2000**, *12*, 195–218. [\[CrossRef\]](#)
- Song, Y.; Ren, J.; Liu, K.; Lyu, D.; Feng, X.; Liu, Y.; Stepashko, A. Syn-rift to post-rift tectonic transition and drainage reorganization in continental rifting basins: Detrital zircon analysis from the Songliao Basin, NE China. *Geosci. Front.* **2022**, *13*, 101377. [\[CrossRef\]](#)
- Liu, Q.; Li, Z.; Chen, H.; Zhou, Z.; Tan, M.; Zhu, X. Current Geological Issues and Future Perspectives in Deep-Time Source-to-Sink Systems of Continental Rift Basins. *J. Earth Sci.* **2024**, *35*, 1758–1764. [\[CrossRef\]](#)
- Liu, L.; Liu, Z.; Zhao, R.; Cong, L.; Liu, X.; Xin, S.; Mu, Z. The source-to-sink system in continental rift lacustrine basins of the Nantun Formation in X Sag of the Tamtsag Basin, Mongolia. *Sci. Rep.* **2025**, *15*, 25354. [\[CrossRef\]](#)
- Feng, Y.; Jiang, S.; Hu, S.; Li, S.; Lin, C.; Xie, X. Sequence stratigraphy and importance of syndepositional structural slope-break for architecture of Paleogene syn-rift lacustrine strata, Bohai Bay Basin, E. China. *Mar. Pet. Geol.* **2016**, *69*, 183–204. [\[CrossRef\]](#)
- Muñoz-Barrera, J.M.; Gawthorpe, R.; Cullen, T.; Pechlivanidou, S.; Henstra, G.; Rotevatn, A.; Sharp, I. Tectono-sedimentary evolution of high-displacement crustal-scale normal faults and basement highs on rifted margins: Klakk Fault Complex and Frøya High, Mid-Norwegian Margin. *Basin Res.* **2024**, *36*, e12889. [\[CrossRef\]](#)
- Withjack, M.O.; Schlische, R.W.; Olsen, P.E. Rift-basin structure and its influence on sedimentary systems. In *Sedimentation in Continental Rifts*; Renaut, R.W., Ashley, G.M., Eds.; SEPM Society for Sedimentary Geology: Tulsa, OK, USA, 2002; Volume 73, pp. 57–81. [\[CrossRef\]](#)
- Li, J.; Liu, Z.; Liu, J.; Chen, L.; Liu, H.; Huang, L.; Qian, L.; Lu, K.; Liu, K. Transformation of sediment delivery and dispersal patterns controlled by relay-ramp evolution along the boundary fault of a lacustrine rift: The Eocene Shahejie formation, Dongying Sag, Bohai Bay Basin, NE China. *Mar. Pet. Geol.* **2021**, *128*, 105044. [\[CrossRef\]](#)
- Xia, S.; Lin, C.; Wu, W.; Du, X. Sequence architecture, depositional evolution and responses to tectonic subsidence and lacustrine fluctuation in lacustrine rift basin: A case study from Cenozoic Liaodong Bay, Bohai Bay Basin. *J. Pet. Sci. Eng.* **2022**, *208*, 109494. [\[CrossRef\]](#)
- Zheng, X.; Zhu, H.; Li, S.; Yang, H.; Zeng, Z.; Sun, Z. Seismic characterization of ancient lacustrine source-to-sink systems in a rift basin: The Bozhong Depression, Bohai Bay Basin, China. *Mar. Pet. Geol.* **2025**, *183*, 107648. [\[CrossRef\]](#)
- Romans, B.W.; Castellort, S.; Covault, J.A.; Fildani, A.; Walsh, J.P. Environmental signal propagation in sedimentary systems across timescales. *Earth-Sci. Rev.* **2016**, *153*, 7–29. [\[CrossRef\]](#)
- Allen, P.A. *Sediment Routing Systems: The Fate of Sediment from Source to Sink*; Cambridge University Press: Cambridge, UK, 2017. [\[CrossRef\]](#)
- Caracciolo, L.; Chew, D.; Andò, S. Sediment generation and sediment routing systems. *Earth Sci. Rev.* **2020**, *207*, 103221. [\[CrossRef\]](#)
- Carroll, A.R.; Bohacs, K.M. Stratigraphic classification of ancient lakes: Balancing tectonic and climatic controls. *Geology* **1999**, *27*, 99–102. [\[CrossRef\]](#)
- Bohacs, K.M.; Carroll, A.R.; Neal, J.E.; Mankiewicz, P.J. Lake-basin type, source potential, and hydrocarbon character: An integrated sequence-stratigraphic-geochemical framework. In *Lake Basins Through Space and Time*; Gierlowski-Kordesch, E.H., Kelts, K.R., Eds.; AAPG Studies in Geology; American Association of Petroleum Geologists: Tulsa, OK, USA, 2000; pp. 3–34. [\[CrossRef\]](#)
- Allen, M.B.; Macdonald, D.I.; Xun, Z.; Vincent, S.J.; Brouet-Menzies, C. Early Cenozoic two-phase extension and late Cenozoic thermal subsidence and inversion of the Bohai Basin, northern China. *Mar. Pet. Geol.* **1997**, *14*, 951–972. [\[CrossRef\]](#)
- Hou, G.; Qian, X.; Cai, D. The tectonic evolution of Bohai Basin in Mesozoic and Cenozoic time. *Acta Sci. Nat. Univ. Pekin.* **2001**, *37*, 845–851. (In Chinese) [\[CrossRef\]](#)
- Huang, L.; Liu, C.; Wang, Y.; Zhao, J.; Mountney, N.P. Neogene-Quaternary postrift tectonic reactivation of the Bohai Bay Basin, eastern China. *AAPG Bull.* **2014**, *98*, 1377–1400. [\[CrossRef\]](#)
- Liu, Q.; He, L.; Yi, Z.; Zhang, L. Anomalous post-rift subsidence in the Bohai Bay Basin, Eastern China: Contributions from mantle process and fault activity. *Tectonics* **2022**, *41*, e2021TC006748. [\[CrossRef\]](#)
- Li, Q.; Zhang, Z.; Zhang, J. Characteristics of sedimentary differential response for multi-episode rifting cycles in lacustrine rift basin: A case study of the Palaeogene Baxian sag in the Bohai Bay Basin. *Mar. Pet. Geol.* **2022**, *136*, 105426. [\[CrossRef\]](#)
- Chen, S.; Zhao, R.; Chen, C.; Wang, H.; Ma, J.; Gong, T.; Yu, Z. Tectono-sedimentary evolution of the Paleogene Qikou Sag, Bohai Bay Basin, NE China. *Mar. Pet. Geol.* **2023**, *148*, 106057. [\[CrossRef\]](#)
- Wang, H.; Jiang, S.; Huang, C.; Jiang, H.; Gan, H. Differences in sedimentary filling and its controlling factors in rift lacustrine basins, East China: A case study from Qikou and Nanpu sags. *Front. Earth Sci.* **2011**, *5*, 82–96. [\[CrossRef\]](#)
- Pu, X.; Zhou, L.; Wang, W.; Han, W.; Xiao, D.; Liu, H.; Chen, C.; Zhang, W.; Yuan, X.; Lu, Y.; et al. Medium-deep clastic reservoirs in the slope area of Qikou sag, Huanghua depression, Bohai Bay Basin. *Pet. Explor. Dev.* **2013**, *40*, 38–51. [\[CrossRef\]](#)
- Pu, X.; Zhou, L.; Han, W.; Chen, C.; Yuan, X.; Lin, C.; Liu, S.; Han, G.; Zhang, W.; Jiang, W. Gravity flow sedimentation and tight oil exploration in lower first member of Shahejie Formation in slope area of Qikou Sag, Bohai Bay Basin. *Pet. Explor. Dev.* **2014**, *41*, 153–164. [\[CrossRef\]](#)

25. Zhao, X.; Pu, X.; Zhou, L.; Xiao, D.; Chen, C.; Han, W.; Zhang, W.; Shi, Z.; Lin, C.; Yang, F. Reconstruction of Paleogene sedimentary system and reservoir evaluation in Qikou Sag, Bohai Bay Basin. *J. Chengdu Univ. Technol. (Sci. Technol. Ed.)* **2017**, *44*, 565–578. (In Chinese) [\[CrossRef\]](#)
26. Dong, Y.; Zhu, X.; Xian, B.; Cheng, K.; Wang, P. Mapping sediment-dispersal characteristics using seismic geomorphology: Late Paleogene to Neogene, Qinan sag, Huanghua depression, China. *Mar. Pet. Geol.* **2014**, *54*, 180–197. [\[CrossRef\]](#)
27. Chang, C. Geological characteristics and distribution patterns of hydrocarbon deposits in the Bohai Bay Basin, east China. *Mar. Pet. Geol.* **1991**, *8*, 98–106. [\[CrossRef\]](#)
28. Dong, Y.; Xiao, L.; Zhou, H.; Du, J.; Zhang, N.; Xiang, H.; Wang, C.; Zhao, Z.; Huang, H. Volcanism of the Nanpu Sag in the Bohai Bay Basin, Eastern China: Geochemistry, petrogenesis, and implications for tectonic setting. *J. Asian Earth Sci.* **2010**, *39*, 173–191. [\[CrossRef\]](#)
29. Zhao, X.; Zhou, L.; Pu, X.; Jin, F.; Shi, Z.; Han, W.; Jiang, W.; Han, G.; Zhang, W.; Wang, H.; et al. Formation conditions and enrichment model of retained petroleum in lacustrine shale: A case study of the Paleogene in Huanghua depression, Bohai Bay Basin, China. *Pet. Explor. Dev.* **2020**, *47*, 916–930. [\[CrossRef\]](#)
30. Li, S.; Meng, X.; Fu, L.; Yao, C.; Guo, L.; Chen, Z.; Shi, L. Research on Pre-Cenozoic Residual Basin Structure and Basement Property of the Huanghua Depression. *Chin. J. Geophys.* **2010**, *53*, 838–848. [\[CrossRef\]](#)
31. Qi, J.; Yang, Q. Cenozoic structural deformation and dynamic processes of the Bohai Bay basin province, China. *Mar. Pet. Geol.* **2010**, *27*, 757–771. [\[CrossRef\]](#)
32. Li, S.; Zhao, G.; Dai, L.; Zhou, L.; Liu, X.; Suo, Y.; Santosh, M. Cenozoic faulting of the Bohai Bay Basin and its bearing on the destruction of the eastern North China Craton. *J. Asian Earth Sci.* **2012**, *47*, 80–93. [\[CrossRef\]](#)
33. Yu, F.; Koyi, H. Cenozoic tectonic model of the Bohai Bay Basin in China. *Geol. Mag.* **2016**, *153*, 866–886. [\[CrossRef\]](#)
34. Zhou, L.; Lu, Y.; Xiao, D.; Zhang, Z.; Chen, X.; Wang, H.; Hu, S. Basinal texture structure of Qikou Sag in Bohai Bay Basin and its evolution. *Nat. Gas Geosci.* **2011**, *22*, 373–382. (In Chinese)
35. Zhou, L.; Fu, L.; Da, L.; Lu, Y.; Feng, J.; Zhou, S.; Santosh, M.; Li, S. Structural anatomy and dynamics of evolution of the Qikou Sag, Bohai Bay Basin: Implications for the destruction of North China craton. *J. Asian Earth Sci.* **2012**, *47*, 94–106. [\[CrossRef\]](#)
36. Zhou, L.; Han, G.; Dong, Y.; Shi, Q.; Ma, J.; Hu, J.; Ren, S.; Zhou, K.; Wang, J.; Si, W. Fault-sand combination modes and hydrocarbon accumulation in Binhai fault nose of Qikou Sag, Bohai Bay Basin, East China. *Pet. Explor. Dev.* **2019**, *46*, 919–934. [\[CrossRef\]](#)
37. Qi, P.; Ren, J.; Lu, G.; Shi, S.; Tong, D.; Zhang, J. Cenozoic episodic subsidence in the middle and north part of Huanghua depression, Bohai Bay Basin. *Earth Sci.—J. China Univ. Geosci.* **2010**, *35*, 1041–1052. (In Chinese)
38. Huang, C.; Wang, H.; Wu, Y.; Wang, J.; Chen, S.; Ren, P.; Liao, Y.; Zhao, S.; Xia, C. Genetic types and sequence stratigraphy models of Palaeogene slope break belts in Qikou Sag, Huanghua Depression, Bohai Bay Basin, eastern China. *Sediment. Geol.* **2012**, *261*, 65–75. [\[CrossRef\]](#)
39. Su, Z.; Deng, H.; Tao, Z.; Lin, H.; Qi, L.; Zhou, C.; Qu, J. Correlation of stratigraphic features in regional sequence stratigraphic framework of the Paleogene in Jiyang Depression. *J. Palaeogeogr. (Chin. Ed.)* **2006**, *8*, 89–102. (In Chinese)
40. Huang, C.; Zhang, J.; Wang, H.; Jiang, S. Lacustrine shale deposition and variable tectonic accommodation in the rift basins of the Bohai Bay Basin in Eastern China. *J. Earth Sci.* **2015**, *26*, 700–711. [\[CrossRef\]](#)
41. Wang, J.; Wang, H.; Xiao, D.; Miao, H.; Shang, Y. Determination of second-order stratigraphic sequences in continental extensional basins. *Acta Pet. Sin.* **2009**, *30*, 869–875. (In Chinese) [\[CrossRef\]](#)
42. Li, S. Inconsistency between water-level change in the Bohai Bay Basin and eustasy during the Paleogene. *Geol. Rev.* **1998**, *44*, 31–34. (In Chinese) [\[CrossRef\]](#)
43. Jiang, W.; Liu, S. Distribution and Controlling Factors of High-quality Hydrocarbon Source Rock in Sequential Stratigraphic Framework-Taking Paleogene System in Qikou Depression for Instance. *China Pet. Explor.* **2015**, *20*, 51–58. (In Chinese) [\[CrossRef\]](#)
44. Hubert, J.F. A zircon-tourmaline-rutile maturity index and the interdependence of the composition of heavy mineral assemblages with the gross composition and texture of sandstones. *J. Sediment. Res.* **1962**, *32*, 440–450. [\[CrossRef\]](#)
45. Morton, A.C.; Hallsworth, C. Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. *Sediment. Geol.* **1994**, *90*, 241–256. [\[CrossRef\]](#)
46. Morton, A.C. Value of heavy minerals in sediments and sedimentary rocks for provenance, transport history and stratigraphic correlation. In *Quantitative Mineralogy and Microanalysis of Sediments and Sedimentary Rocks*; Sylvester, P., Ed.; Mineralogical Association of Canada: Quebec City, QC, Canada, 2012; Volume 42, pp. 133–165. [\[CrossRef\]](#)
47. Yuan, H.; Yin, S.; Dong, L.; Tan, C. Restoration of the pre-Jurassic paleogeomorphology and its control on hydrocarbon distribution in western Ordos Basin. *Energy Geosci.* **2022**, *3*, 485–494. [\[CrossRef\]](#)
48. Yu, X.; Liu, Q.; Zhu, H.; Li, Z.; Qin, L.; Xu, D. Paleogeomorphology Restoration of Post-Rift Basin: Volcanic Activity and Differential Subsidence Influence in Xihu Sag, East China Sea. *JMSE* **2024**, *12*, 1542. [\[CrossRef\]](#)
49. Wang, J.; Jiang, C.; Chang, S.; Du, X.; He, S.; Gu, D. Structural trend surface conversion method for micro-amplitude paleotopographic restoration of cratonic basins. *Acta Pet. Sin.* **2017**, *38*, 77–83+104. (In Chinese) [\[CrossRef\]](#)

50. Liu, H.; Xia, Q.; Zhou, X. Geologic-seismic models, prediction of shallow-water lacustrine delta sandbody and hydrocarbon potential in the Late Miocene, Huanghekou Sag, Bohai Bay Basin, northern China. *J. Palaeogeogr.* **2018**, *7*, 66–87. [\[CrossRef\]](#)
51. Torrado, L.; Carvajal-Arenas, L.C.; Mann, P.; Bhattacharya, J. Integrated seismic and well-log analysis for the exploration of stratigraphic traps in the Carbonera Formation, Llanos foreland basin of Colombia. *J. S. Am. Earth Sci.* **2020**, *104*, 102607. [\[CrossRef\]](#)
52. Kowalski, A.; Dąbek-Głowacka, J.; Nowak, G.J.; Górecka-Nowak, A.; Wyrwalska, U.; Furca, M.; Wójcik-Tabol, P. Evolution of a late carboniferous fluvio-lacustrine system in an endorheic basin: Multiproxy insights from the Ludwikowice formation, intra-sudetic basin (SW Poland, NE Bohemian Massif). *Minerals* **2025**, *15*, 1077. [\[CrossRef\]](#)
53. Wei, Z.; Li, S.; Zhang, T.; Liu, Y.; Yao, Z.; Xu, W.; Li, H. The delta-fluvial evolution of a lacustrine basin with gentle slope and low sedimentation rate: A case study of the Fudong Slope, Junggar Basin, Northwest China. *Sediment. Geol.* **2023**, *453*, 106441. [\[CrossRef\]](#)
54. Peng, Z.; Qu, J.; Chen, C.; Wang, H.; Zhu, D.; Mi, Z.; Xie, E.; Zhang, Z.; Yu, X.; Wang, H. Coal accumulation in marine to continental transitional sequence during late carboniferous-early permian in the southeastern ordos basin, China. *Geol. J.* **2026**, *61*, 549–565. [\[CrossRef\]](#)
55. Colomera, L.; Mountney, N.P. Accommodation and sediment-supply controls on clastic parasequences: A meta-analysis. *Sedimentology* **2020**, *67*, 1667–1709. [\[CrossRef\]](#)
56. Li, W.; Yue, D.; Du, Y.; Li, J.; Zhang, C.; Gong, Z.; Zhang, X.; Shu, Q.; Gao, J. Controls of accommodation to sediment-supply ratio on sedimentary architecture of continental fluvial successions. *Pet. Sci.* **2023**, *20*, 1961–1977. [\[CrossRef\]](#)
57. Groshong, R.H., Jr. *3D Structural Geology: A Practical Guide to Quantitative Surface and Subsurface Map Interpretation*, 2nd ed.; Springer: Berlin/Heidelberg, Germany, 2006. [\[CrossRef\]](#)
58. Liu, Q.; Wang, L.; Rao, L.; Wang, G.; Ye, G.; Liu, Y. Provenance analysis of the second member of Shahejie Formation in qikou sag of Huanghua depression. *GEOSCIENCE* **2012**, *26*, 363–369. (In Chinese) [\[CrossRef\]](#)
59. Catuneanu, O. *Principles of Sequence Stratigraphy*; Elsevier: Amsterdam, The Netherlands, 2006. [\[CrossRef\]](#)
60. Shang, W.; Xu, S.; Mao, Z.; Li, X.; Gao, G.; Li, Z.; Qin, L. High-resolution sequence stratigraphy in continental lacustrine basin: A case of Eocene Shahejie formation in the Dongying Depression, Bohai Bay Basin. *Mar. Pet. Geol.* **2022**, *136*, 105438. [\[CrossRef\]](#)
61. Van Wagoner, J.C.; Mitchum, R.M.; Campion, K.M.; Rahmanian, V.D. *Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops: Concepts for High-Resolution Correlation of Time and Facies*; AAPG Methods in Exploration Series, No. 7; AAPG: Tulsa, OK, USA, 1990.
62. Ravnås, R.; Steel, R.J. Architecture of marine rift-basin successions. *AAPG Bull.* **1998**, *82*, 110–146. [\[CrossRef\]](#)
63. Hossain, S. Application of seismic attribute analysis in fluvial seismic geomorphology. *J. Pet. Explor. Prod. Technol.* **2020**, *10*, 1009–1019. [\[CrossRef\]](#)
64. Zeng, H. High-Resolution mapping of subsurface sedimentary facies and reservoirs using seismic sedimentology. *Appl. Sci.* **2025**, *15*, 6387. [\[CrossRef\]](#)
65. Leeder, M.R.; Harris, T.; Kirkby, M.J. Sediment supply and climate change: Implications for basin stratigraphy. *Basin Res.* **1998**, *10*, 7–18. [\[CrossRef\]](#)
66. Zhang, S.; Ji, Y. Control of Paleogene paleoclimate change on sequence development in Dongying Sag. *China Univ. Pet.* **1997**, *22*, 26–30. (In Chinese)
67. Cao, Y.; Diao, F.; Zou, H. Depositional Paleoenvironments and Implications on the Occurrence of the Shahejie Formation Source Rock in the Langgu Sag, Bohai Bay Basin. *Front. Earth Sci.* **2022**, *10*, 922338. [\[CrossRef\]](#)
68. Di, C.; Jiang, F.; Pang, X.; Meng, L.; Wang, Z.; Xu, Z.; Zhang, X.; Huo, L.; Wen, J.; Zhao, R.; et al. Middle Eocene terrestrial paleoweathering and climate evolution in the midlatitude Bohai Bay Basin of eastern China. *Pet. Sci.* **2023**, *20*, 1471–1487. [\[CrossRef\]](#)
69. Zuo, X.; Li, C.; Zhang, J.; Ma, G.; Chen, P. Geochemical characteristics and depositional environment of the Shahejie Formation in the Binnan Oilfield, China. *J. Geophys. Eng.* **2020**, *17*, 539–551. [\[CrossRef\]](#)

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