



Original Paper

Volcanically-induced sedimentary evolution of fine-grained rocks and environmental responses: A case study of the Chang 7₃ submember in Ordos Basin, NW China



Jing-Jing Shen^{a,b}, Wen-Zhi Zhao^{b,*}, Wei Liu^b, Cong-Sheng Bian^b, Yong-Xin Li^b, Jin Dong^b, Zhi-Qian Gao^a

^a College of Energy, China University of Geosciences (Beijing), Beijing, 100083, China

^b Research Institute of Petroleum Exploration and Development, China National Petroleum Corporation, Beijing, 100083, China

ARTICLE INFO

Article history:

Received 15 January 2026

Received in revised form

11 May 2026

Accepted 28 July 2026

Available online 3 August 2026

Edited by Xiu-Fang Hu

Keywords:

Ordos Basin

Volcanism

Sedimentary evolution

Environmental responses

Gravity flows deposits

ABSTRACT

Volcanism is an important controlling factor for organic matter enrichment and sedimentary evolution in proximal continental lakes. Numerous studies have focused on revealing the intrinsic mechanisms of high organic carbon burial regulated by volcanism, while the understanding of the dynamic evolutionary processes of volcanically induced lacustrine depositional systems remains unclear. We integrated core, logging, and geochemical data from more than 20 fully cored wells spanning all sedimentary facies belts of the Chang 7₃, to reconstruct the paleoenvironment and establish sedimentary models during volcanism. By combining sequence stratigraphy, carbon isotope chemostratigraphy, zircon U–Pb dating and astronomical cycle techniques, we established a high-precision isochronous stratigraphic framework, spanning ~241.36 Ma to ~239.7 Ma. This study presented the first detailed record of sedimentary evolution in response to volcanism in the Ordos Basin: Early volcanism led to a transient, relatively dry-cold climate and low weathering intensity; volcanic ash supplied nutrients to the lake, and the accumulation of loose pyroclastics induced overloading and instability of the delta front, triggering slump-type gravity flows. These factors jointly promoted the formation of tuffaceous shale; and sustained volcanism induced a greenhouse effect, resulting in an extremely humid climate and enhanced weathering, thus inducing hyperpycnal flows and appropriate-intensity hyperpycnal flows facilitate felsic shale formation. Furthermore, the climatic background modulated by astronomical cycles amplifies the sedimentary evolutionary responses to volcanism. Multistage siltstone–muddy siltstone assemblages with good reservoir properties, which act as favorable shale oil “sweet intervals”. This study provides new perspectives for understanding the controlling factors of continental lacustrine basin depositional systems and offers guidance for the spatial prediction of shale oil “sweet spots” in the Chang 7₃.

© 2026 Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

During geological history, large-scale black shale deposition has been accompanied by global to regional volcanic events (Liu et al., 2022). Volcanism releases abundant ash and clastics (Xie et al., 2023), serving as a key provenance; however, in sedimentological literature, the clastic material supplied to basins and their

transport mechanisms are generally considered to be a function of tectonics and climate (Mutti et al., 2003). During volcanic activity, sedimentary systems are overwhelmed by volcanic ash and volcanic clastic from redeposition processes (Manville et al., 2009). In drainage systems established in pre-eruption or inter-eruptive stages, massive inputs of unconsolidated clasts force the rapid progradation of clastic rock sequences into the basin, even if the source-to-sink system lacks favorable conditions for such deposition (Szepesi et al., 2019). Furthermore, gravity flows are generally associated with volcanism (Wang et al., 2023), as shown in the Cañadón Asfalto Basin, where terrigenous floods transport volcanics rapidly into sedimentary systems and further move

* Corresponding author.

E-mail address: zwz@petrochina.com.cn (W.-Z. Zhao).

Peer review under the responsibility of China University of Petroleum (Beijing).

them across the entire source-to-sink system for hundreds of kilometres (Di Capua and Scasso, 2020). In addition, volcanism can exert an impact on the ecological environment (Adam, 2022; Zhang et al., 2022). Some studies have revealed the short-term and long-term effects of volcanism on climate (Yang et al., 2021; Men et al., 2022). In the short term, gases such as SO₂ and H₂S released by volcanism into the atmosphere are injected into the stratosphere and react with OH and H₂O to form H₂SO₄-bearing aerosols; together with volcanic ash clouds, they reduce incident solar radiation, thereby resulting in dry and cold surface temperatures (Cooper et al., 2018). However, long-term volcanism continuously releases greenhouse gases such as CO₂ and CH₄ into the atmosphere, which accumulate to a certain concentration and then induce a greenhouse effect, ultimately leading to an increase in surface temperature and precipitation (Huff, 2016; Gong et al., 2017; Cheng et al., 2025). Taken together, volcanism plays an important role in sediment supply and climate regulation, whereas the impact of climate on volcanoclastic supply and the response of gravity flow deposits to volcanism are unclear, and minor consideration has been given to the relationship between volcanism and related processes (Di Capua et al., 2023). The Chang 7 Member in the Ordos Basin is a typical lacustrine deposit affected by volcanism, and provides favorable conditions for investigating the relationship between sedimentary evolution and volcanism. Clarifying how it affects the spatiotemporal distribution of fine-grained rocks will help deepen our understanding of dynamic changes in volcanically induced lacustrine depositional systems, which plays a crucial role in guiding the identification of new potential shale oil enrichment zones.

The Chang 7 Member (Ch7) of the Yanchang Formation in Ordos Basin is one of the few high-yield shale oil intervals. In particular, scale economic development has been realized in the Qingcheng Oilfield, which was proved in the gravity flow interlayer shale oil in the Chang 7₁₊₂ submember (Ch7₁₊₂), with its annual output accounting for 50% of total shale oil production in China, garnering widespread industrial attention (Fu et al., 2023; Jin et al., 2023; Zhao et al., 2025). Compared with the typical “interbedded” sandstones of the Ch7₁₊₂, the Chang 7₃ submember (Ch7₃) features thick organic-rich black shales with volcanic activities. Scholars primarily focus on the hydrocarbon generation potential of source rocks (Zhang et al., 2021; Zheng et al., 2022), the formation mechanisms of shales (Cao et al., 2024), and the relationships between volcanic activities and organic matter enrichment in shales and the evolution of the paleoenvironment (Lu et al., 2021; Xie et al., 2023; Lin et al., 2024; Gao et al., 2025). Recently, Changqing Oilfield deployed two horizontal wells to conduct risk exploration tests for shale oil in the thick shale interlayered with thin siltstone layers of the Ch7₃; the high-yield oil flows of 121.38 t/d and 108.38 t/d were achieved in Wells CY1 and CY2. These interbedded sandstones are mainly of gravity-flow origin (Niu et al., 2023; Wang et al., 2024a), with a single sand body thickness of 1–5 m and a lateral extent of 100–300 m. Distributed in a SW–NE trend and characterized by favorable reservoir physical properties, they serve as “sweet spots” (Fu et al., 2021; Niu et al., 2023; Wang et al., 2024a). The deep-lake areas share similar geological conditions with the Qingcheng Oilfield (Fu et al., 2018; Liu et al., 2018b). Clarifying the spatial distribution of these sand bodies may help identify new potential shale oil zones in the Ordos Basin. It should be noted that the works just mentioned treated the Ch7₃ as a single unit without conducting isochronous stratigraphic subdivision within it, nor did they correlate the southern area with the northern core area, thus leading to an unclear spatial distribution of its sand bodies. However, deep lake shale strata have relatively stable sedimentary processes, and it is difficult to identify obvious unconformities (Schieber and Riciputi, 2004); the

identification of sequence boundaries cannot be achieved based on logging and seismic reflection characteristics (Shi et al., 2023).

Currently, the main methods for shale sequence division are utilizing the trend changes of shale sedimentary records reflected by paleowater depth (Abouelresh and Slatt, 2012), redox changes (Algeo et al., 2004; Turner et al., 2016), biological turnovers (Huang and Gong, 2016), and the occurrence of episodic events, such as volcanism (Huang et al., 2018). Volcanic ash layers are reliable isochronous marker beds (Liu et al., 2025). However, in lacustrine basins with widespread gravity flows, these ash beds are commonly poorly preserved due to intense disturbance and reworking by gravity flows (Liu et al., 2024). On the other hand, massive volcanic eruptions are accompanied by large amounts of CO₂ gas (Zhang et al., 2022; Xie et al., 2023), and volcanic CO₂ is characterized by isotopically light carbon ($-7‰ \leq \delta^{13}C \leq -5‰$) (Jenkyns, 2010). The massive injection of light ¹²C can induce a significant negative carbon isotope excursion (NCIE) of $\delta^{13}C_{org}$ (Korte and Kozur, 2010), thereby causing regional or global carbon-cycle perturbations (Arefifard et al., 2025; Cheng et al., 2025). The NCIE could be synchronously recorded in different sedimentary environments, and such precisely correlatable isochronous signals still provide a core basis for stratigraphic division (Erbacher et al., 2005; Ruhl et al., 2009), even for these formations lacking high-resolution biostratigraphic constraints (Lu et al., 2021; Bian et al., 2025). In addition, previous studies have confirmed that the shale strata of the Ch7 preserve stable astronomical cyclical signals, yet they have merely focused on the stratigraphic chronology and the temporal limits of paleoclimatic events for single wells (Zhang et al., 2019; Li et al., 2023).

In this study, we aim to clarify the spatial distribution characteristics of fine-grained rocks in the Ch7₃ and their controlling factors. The primary work includes: (1) summarizing types of lithofacies associations; (2) establishing a high-precision isochronous stratigraphic framework; (3) clarifying the distribution characteristics of various lithofacies associations within the isochronous framework; and (4) discussing how volcanism controls the sedimentary evolution and establishing a sedimentary model. This research can improve the coupling mechanism of volcanism–climate–sedimentation in lacustrine fine-grained sediments and provide guidance for the spatial prediction of shale oil “sweet spots” in the Ch7₃.

2. Geological background

Ordos Basin is the second largest sedimentary basin in China, located in the western part of the North China Plate. It is bounded by the Qinling Mountains to the south, the Yinshan Mountains to the north, the Lüliang Mountains to the east, and the Helan and Liupan Mountains to the west, covering a total area of 250,000 km² (Fig. 1). The collision of the Yangtze and North China plates resulted in the rapid uplift of the Qinling Orogeny in the Late Triassic, forming the Ordos Basin, a large inland depression lake basin by the basin–mountain coupling, and simultaneously led to extensive volcanism near the Ordos Basin (Liu et al., 2021; Lu et al., 2021), and these volcanoclastic materials then became one of the major provenances for the Yanchang Formation (Cao et al., 2024). The study area is located in the southwestern part of the basin. Regionally, it falls within the western segment of the Tianhuan Depression and the southwestern part of the Yishan Slope, spanning from Jingbian in the north, Yijun in the south, the Western Margin Thrust Belt in the west to Yan'an in the east (Fu et al., 2022) (Fig. 1).

The Yanchang Formation consists of a series of terrigenous clastic rocks primarily of fluvial-lacustrine facies, which are divided into 10 members known as Chang 1–10 (Li et al., 2019). The

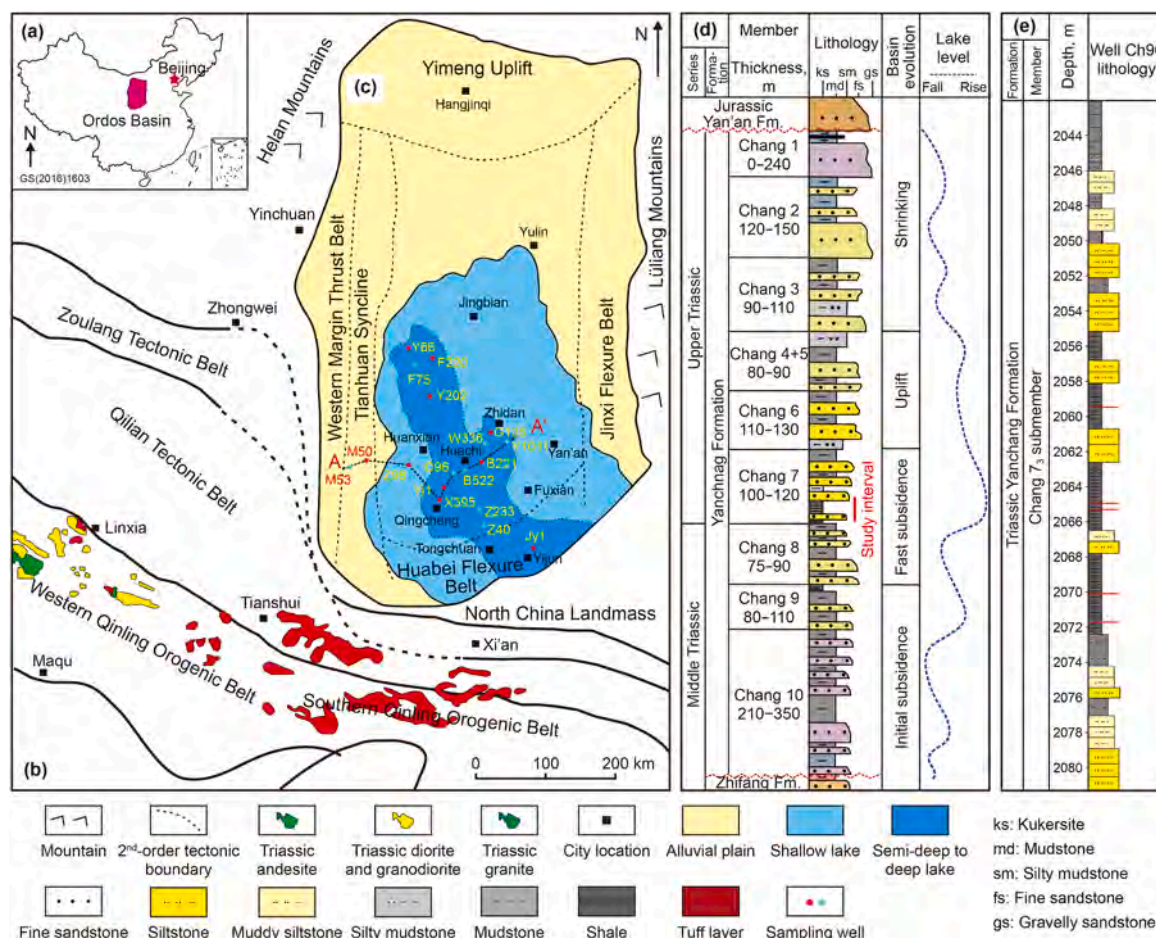


Fig. 1. (a) Location of the present Ordos Basin in China. (b) Tectonic location of the Ordos Basin showing distribution of tectonic uplifts, flexure belts and orogenic belts (revised after Lin et al. (2024)). Based on the zircon U–Pb dating, the ages of granodiorite in the western Qinling Orogenic Belt are from 235 Ma to 240 Ma (Tan et al., 2020), and the ages of granite in the southern Qinling Orogenic Belt are from 228.2 Ma to 240.1 Ma (Liu et al., 2013). (c) Planar distribution characteristics of sedimentary facies and well sites in the Ch7₃. A–A' marks the location of the cross-section shown in Figs. 9 and 10, and the blue dots indicate the locations of the wells in the cross-section of Fig. 8. (d) Integrated stratigraphic column of the Yanchang Formation, showing lithology, basin evolution and lake-level fluctuations (revised after Chen et al. (2023)). (e) Stratigraphic development characteristics in the Ch7₃.

Ch7 was deposited during the maximum transgression period and received abundant sediments from Archean–Paleozoic parent rocks in the northeast and southwest provenances (Wang et al., 2013). During the deposition of the Ch7, the second phase of the Indosinian Orogeny intensified, and the southwestern part of the basin underwent accelerated subsidence. The remarkable difference in lithology between the Ch7 and the Chang 8 Member (Ch8) indicates that the basin expansion was an abrupt process. The Ch7 can be further divided into three submembers: Ch7₁, Ch7₂, and Ch7₃. The climate was extremely warm and humid during the deposition of the Ch7₃ (Fu et al., 2018; Jin et al., 2021), and subsequently, the main thick organic-rich shales of the Mesozoic were formed in the central part of the basin. Lithological observations indicate that gravity-flow sandstones and massive mudstones are predominantly present at the top and bottom of the Ch7₃, whereas thick-bedded shales intercalated with several tuff beds are continuously preserved between these two intervals.

3. Data and methods

The data utilized in this research comprised full core drilling wells, well logging, lithology and geochemical data. These full-core drilling wells were selected because they represent the typical sedimentary types of the Ch7₃, namely M53, M50, Z98, X395 in the

west, YJ1, C96 and B522 in the central region, W336, G135 and Y1011 in the east, JY1, Z40 and Z233 in the south, and F75, F220, Y202 in the north, whose thicknesses range from ~30 m to ~50 m. Among them, M53 and M50 are situated in the western delta front, while other wells are situated in the deep lake, and they are positioned near diverse sedimentary centers. To characterize the sedimentary and geochemical properties of the strata, a series of laboratory analyses were conducted: thin-section observations from 410 samples under a Zeiss microscope; major and trace element geochemical analyses from 171 samples through an ELEMENT XR inductively coupled plasma mass spectrometer; total organic carbon (TOC) content determinations from 325 samples; and grain size analyses from 80 samples using an MS2000 laser particle size analyzer; zircon U–Pb dating from 2 samples using the LA-ICP-MS method (Supplementary Text S1). These analytical works were performed at the Research Institute of Petroleum Exploration & Development (RIPED), China National Petroleum Corporation (CNPC). The well logging data include multiple types of logging curves, such as gamma ray (GR), acoustic (AC), true formation resistivity (RT), and density (DEN). These data provide critical support for interpreting the lacustrine sedimentary environments and accurately dividing the isochronous stratigraphic framework. All wireline log data and core samples were provided by the Changqing Oilfield.

Integrating core descriptions, thin-section analyses, grain-size data, lithology and logging features, we identified lithofacies associations (LAs) and depositional environments. A basin-wide isochronous framework was built by compiling organic carbon isotope data, defining Ch_7_3 boundaries, constraining depositional duration via zircon U–Pb dating, and subdividing strata using astronomical cycles. Volcanism was traced by air-fall tuff thickness and key geochemical ratios, tectonic activity was reflected by stratal thickness, and paleoenvironment was reconstructed via mudstone color and geochemical proxies.

4. Results and interpretations

4.1. Lithofacies association types

4.1.1. LA1: Subaqueous distributary channel deposits

4.1.1.1. Description. LA1 is dominated by gray siltstone with low argillaceous content and massive structure (Fig. 2(a)), occasionally containing dark gray, flat, and well-rounded mud gravel (Fig. 3(a)), and mud stripes (Fig. 3(b)). Wedge cross-bedding (Fig. 2(b) and (c)), and parallel bedding (Fig. 3(c)) are also observed. Its base has small scour surfaces (Fig. 3(a) and (b)), with abrupt contact with underlying strata; single sand bodies are 1–3 m thick (Fig. 2). Based on internal lithology and rhythmicity, LA1 is subdivided into LA1-I and LA1-II. LA1-I, mainly in the Pss1 interval, has multiple internal scour surfaces and no mud interbeds, showing normal grading and smooth box-shaped logging curves. LA1-II of Well M53 developed in the Pss2 interval, consists of medium-thick beds of interbedded siltstone and mudstone, forming multistage positive rhythms, with a single-stage thickness of 1–3 m. Small cross-bedding and wavy bedding are present, with biological backfill structures (Fig. 2(d)), and charcoal fragments are observable (Fig. 3(d)). The logging curves show a toothed bell shape. LA1 is distributed in the delta front, accounting for up to 70% of total lithofacies in Pss1–Pss2.

4.1.1.2. Interpretation. Massive structures, cross-bedding, parallel bedding, and scour surfaces indicate a high sedimentation rate (Miall, 1996; Deng et al., 2025); The laminae within cross-bedding are straight, foreset-like inclined, and obliquely intersecting with set boundaries, reflecting strong hydrodynamic action and shallow-water sedimentary attributes (Zhu et al., 2013). Additionally, abrupt contacts and well-rounded mud gravels in sandstone layers are characteristics of subaqueous distributary channels (Abbas et al., 2018). LA1-I and LA1-II show distinct sedimentary features. LA1-I lacks mudstone interlayers, with continuous thick sandstone and multiple erosion surfaces, indicating strong hydrodynamics that eroded early muddy deposits. (Deng et al., 2019). In contrast, multistage mudstone interlayers within sand bodies indicate that the hydrodynamic force associated with LA1-II is weaker than that of LA1-I (Budai et al., 2021).

4.1.2. LA2: Distributary mouth bar deposits

4.1.2.1. Description. LA2 consists mainly of muddy siltstone, siltstone and silty mudstone with a massive structure. It develops horizontal bedding (Fig. 2(e)), small-scale ripple progradation cross-bedding (Fig. 3(e)), convolute bedding (Fig. 2(f)), and wavy bedding (Fig. 3(f)). Distributed primarily in the delta front, LA2 accounts for 30% of the Pss3 interval, with a thickness of 0.5–3 m. This lithofacies association shows gradational contact with underlying muddy deposits and coarsens upward to form a reverse rhythm, corresponding to funnel-shaped logging curves.

4.1.2.2. Interpretation. The grain size of LA2 is generally finer than that of LA1. Due to the intense interaction between lake water and

fluvial water, sediments from channels are hindered and accumulate rapidly at the river mouth, forming a mouth bar (Edmonds and Slingerland, 2007; Xu et al., 2025). A coarsening-upward grain size trend is also a typical diagnostic feature of mouth bar successions (van Cappelle et al., 2017).

4.1.3. LA3: Sand sheet deposits

4.1.3.1. Description. LA3 primarily comprises silty mudstone and muddy siltstone, with sedimentary structures analogous to LA2, including small-scale cross-bedding (Fig. 2(g)), and wavy bedding (Fig. 3(h)). Plant leaf fossils are also observed (Fig. 3(g)). LA3 has a thickness of 0.5–1 m and accounts for ~25% of the cored succession in the Pss4 interval. It shows gradational contact with underlying muddy sediments, develops both normal and reverse grading, and exhibits finger-shaped logging curves.

4.1.3.2. Interpretation. The grain size, bedding, and thickness of sand sheet deposits are influenced by both waves and mouth bar deposits. The sand bodies of the mouth bar are affected by wave action, leading to lateral migration and sheet-like or band-like distribution in the delta front (Deng et al., 2019; Liu et al., 2025). In estuarine areas under strong lacustrine influence, intense wave action and longshore current reworking processes result in the mixing of muddy sediments with the sand bodies, leading to the formation of wavy and lenticular bedding structures (Hu et al., 2024).

Based on lithofacies associations, logging curves, and organic carbon isotopes, Well M53, located in the delta front, is vertically divided into four parasequence sets (Pss1–Pss4). Pss1–Pss2 corresponds to subaqueous distributary channel microfacies, with $\delta^{13}\text{C}_{\text{org}}$ stable at $\sim -23.5\text{‰}$. The value then drops sharply to $\sim -26\text{‰}$, followed by a 1‰–2‰ positive upward excursion. Lithofacies evolve into mouth bar in Pss3 and further into sand sheet in Pss4, where $\delta^{13}\text{C}_{\text{org}}$ decreases to $\sim -27.2\text{‰}$ at the top.

4.1.4. LA4: Slide-slump deposits

4.1.4.1. Description. LA4 consists of medium-to thick-bedded fine sandstone, siltstone and mudstone, and develops multi-scale soft-sediment deformation structures, including red mud gravels (Fig. 4(a)), irregular mudstone fragments (Fig. 4(b)), and liquefied sand veins (Fig. 4(c) and (d)). LA4 ranges 0.1–6 m in thickness and exhibits an abrupt, inclined contact with underlying mudstone (Fig. 4(c)). The GR logging curves are mainly characterized by medium-to-high amplitude box shapes with local serration. This lithofacies is widely distributed in the Xunyi–Zhengning area, accounting for 60% of the Ch_7_3 in Well JY1.

4.1.4.2. Interpretation. Continuous slump folds reveal sediment remobilization driven by sediment instability in the study area (Shanmugam, 2000; Zou et al., 2012). Slumping is marked by intense syndepositional deformation controlled by bottom friction resistance. Such deformation intertwines sandy and muddy sediments to form mixed sand–mud lithologies. During transport, water-saturated sediments readily develop dewatering and liquefaction structures (Zavala and Arcuri, 2016; Yang et al., 2017a).

4.1.5. LA5: Debris flow deposits

4.1.5.1. Description. LA5 is dominated by low-mud fine sandstone and siltstone with massive bedding. Mud clasts occur in three types: layered clasts concentrate in the upper part of sand bodies, thickening in the middle and thinning at both ends (Fig. 4(e)); isolated clasts float within sand bodies, mostly with torn margins or rotational deformation (Fig. 4(f) and (g)). These two clast types are generally small, with diameters mostly less than 5 cm. The third type is uniformly dispersed in LA5, characterized by

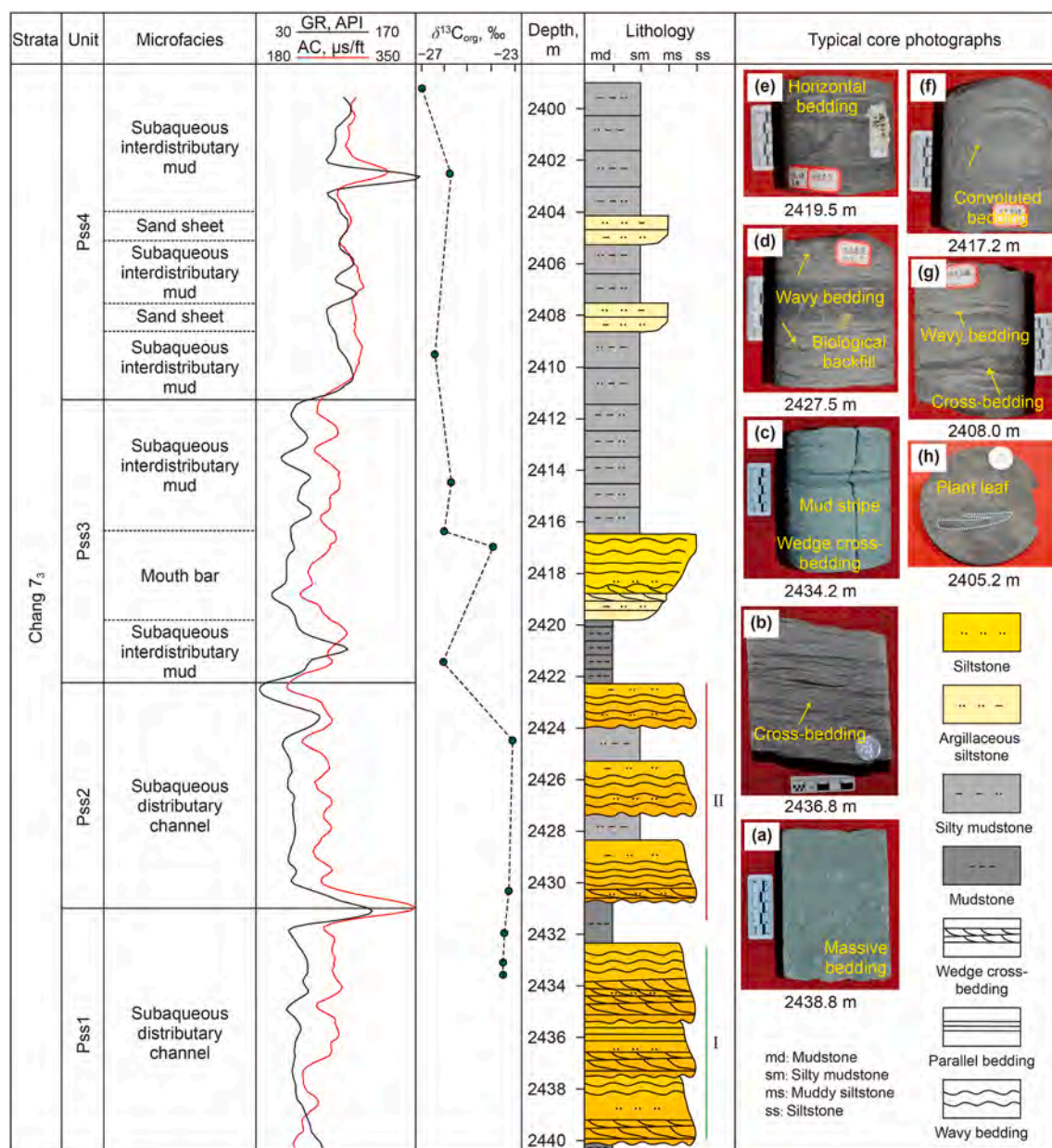


Fig. 2. Cores, well logs and lithological combination characteristics of typical sedimentary facies of Well M53. Subaqueous distributary channel deposits of LA1-I from 2031 m to 2440.5 m and LA1-II from 2022.5 m to 2031 m; mouth bar (LA2) and subaqueous interdistributary mud from 2011.2 m to 2022.5 m; sand sheet (LA3) and subaqueous interdistributary mud from 2397.5 m to 2011.2 m.

outward-stretched and well-developed torn margins and layered distribution, with diameters commonly over 5 cm (Fig. 4(h) and (i)). LA5 displays a unimodal grain-size distribution with a narrow sorting range (Fig. 5(a)). It is 0.5–2 m thick, exhibits sharp contacts with both overlying and underlying mudstones, and corresponds to smooth bell-shaped logging curves. This lithofacies is widely developed in the Zhenyuan–Qingcheng area, accounting for up to 60% of the Pss1–Pss2 intervals.

4.1.5.2. Interpretation. Mud clasts within LA5 show floating and stratified distribution, implying their upward transport by buoyant sorting and reflecting laminar flow features (Talling et al., 2012). The overall massive structure and sharp contacts with overlying and underlying mudstones further indicate plastic rheology and

en-masse depositional consolidation (Talling et al., 2012; Shanmugam, 2013).

4.1.6. LA6: Hyperpycnal flow deposits

4.1.6.1. Description. LA6 is dominated by fine-grained sandstone, siltstone and mudstone, comprising a basal upward-coarsening interval (UCI) and an upper upward-fining interval (UFI). Inter-layer and internal surfaces, usually microerosion surfaces, are obvious between and within the intervals, and mudstone intra-clasts exist near the coarsest level in relatively thick sandstones (Fig. 6(a)). Plant fragments occur at the top of sandstone (Fig. 6(b)). Some UCIs exhibit climbing cross-bedding and wave bedding (Fig. 6(c)). Changes in grain size and clay content can be inferred not only from core color changes from dark gray to gray but also

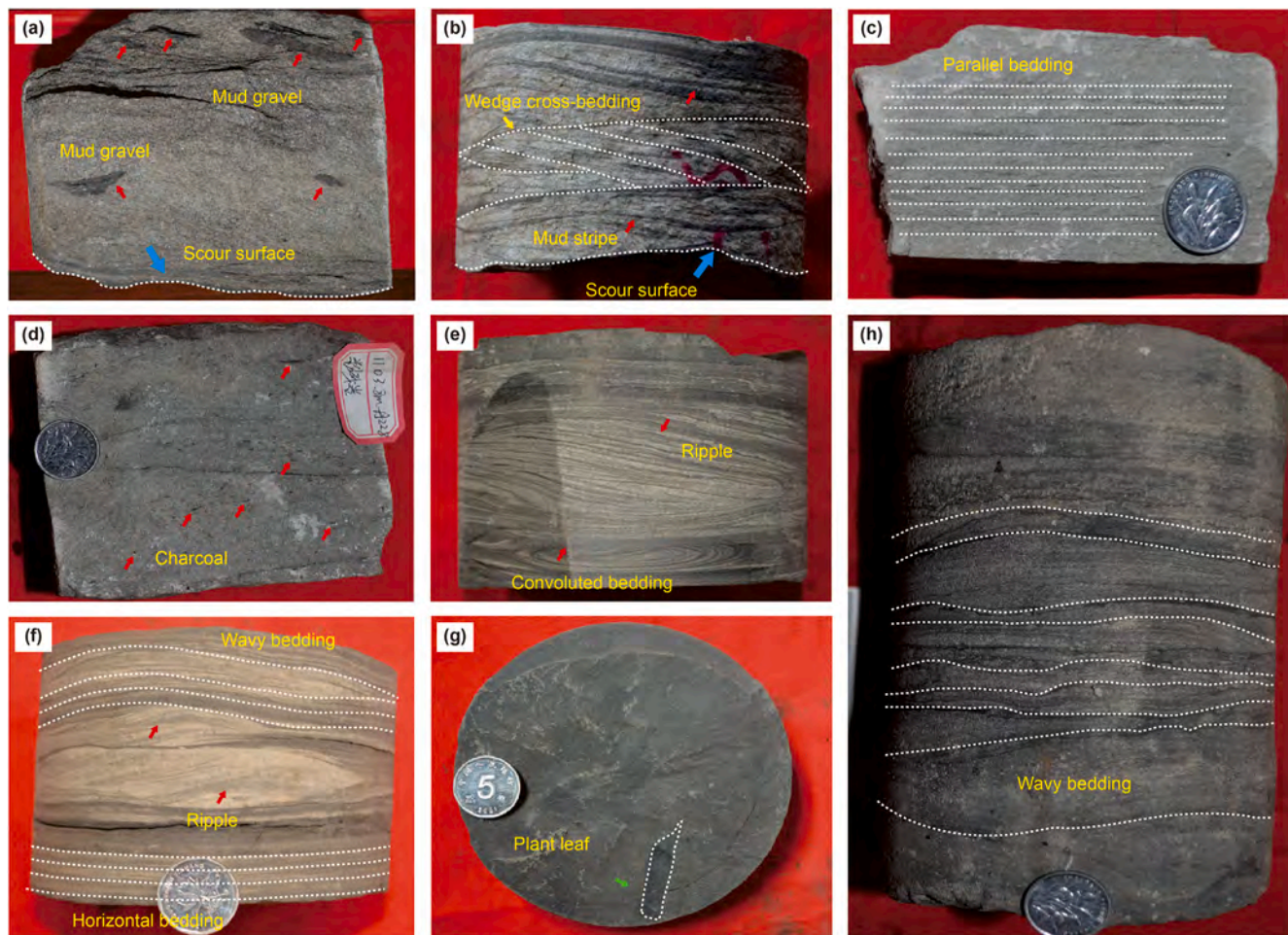


Fig. 3. Core photographs of sedimentary features of the Ch7₃ in Ordos Basin. (a) Siltstones with dark gray mud gravel and basal scour surface, Well Y66, 2359.8 m; (b) siltstones with wedge cross-bedding, basal scour surface, and mud stripe, Well M53, 2439.5 m; (c) siltstones with parallel bedding, Well D228, 1143.25 m; (d) siltstones with mud stripes and charcoals, Well D228, 1150.8 m; (e) muddy siltstone with convoluted bedding, with ripple progradation, Well Y66, 2332.05 m; (f) muddy siltstone with horizontal bedding and wavy bedding, with ripple progradation, Well Y66, 2338.35 m; (g) silty mudstone with plant leaf, Well M53, 2310.5 m; (h) muddy siltstone with mud stripes, Well Y66, 2325.35 m. The diameter of the coin used in all parts is 1.9 cm.

from micrographs (Fig. 6(d)–(f)). In addition, these characteristics are also evident in cumulative frequency–probability curves. The grain size frequency distribution curve exhibits “bimodal” characteristics, with flat peaks and poor sorting (Fig. 5(b)). For Well Y202, the median grain size (ϕ) from 2680.35 m to 2680 m exhibits a sequence of upward coarsening and upward fining (Fig. 5(c)), showing a ‘low–high–low’ pattern, suggesting regularly changing flow energy. This lithofacies is widely distributed in the Zhenyuan–Qingyang area, accounting for up to 64% of the Pss3–Pss4 intervals.

4.1.6.2. Interpretation. The features described above meet the criteria for hyperpynites (Mulder et al., 2001, 2003). These paired UCIs and UFI reflect the full waxing-to-waning cycles of flood-induced hyperpynal flows. Interlayer erosion surfaces form at the sudden onset of hyperpynal flow. Traction structures including cross-bedding and wave bedding are preserved in proximal hyperpynite bedloads, indicating subaqueous fluvial extension (Lamb and Mohrig, 2009; Knight and Evans, 2017). Characterized by turbulent suspension, hyperpynal flows erode soft substrates and levees to suspend abundant sediments. Muddy intraclasts migrate downstream as bedload and eventually transform into debris flows, commonly accumulating in coarsest layers

during flood peaks (Yang et al., 2017b). Variations in core color, grain size and particle composition reflect hydrodynamic fluctuations within individual flood events. Early-stage traction produces high flow energy and mixed-grain sediments, resulting in poorer sorting in LA6 than in LA5 (Chen et al., 2021).

4.1.7. LA7: Turbidity current deposits

4.1.7.1. Description. LA7 is dominated by thin-bedded, clay-rich and well-sorted siltstone with microwave bedding, together with massive mudstone, and develops incomplete Bouma sequences (Fig. 6(g), (h) and (l)). Microerosion surfaces (Fig. 6(h)), and small flute casts (Fig. 6(k)), are mainly developed at the bottom of turbidites. Normal grading characteristics are typically observed under thin sections (Fig. 6(m)), and silt-sized quartz grains exhibit high roundness, minerals have inconsistent long-axis orientations (Fig. 6(j) and (n)). LA7 is widely distributed across the Qingcheng–Huachi area. Turbiditic siltstone with wavy bedding overlies LA5, while turbiditic mudstone laterally occurs in front of LA5 and LA6 sand bodies, accounting for over 50% of the Ch7₃ interval.

4.1.7.2. Interpretation. Turbidity currents represent Newtonian fluids with zero yield strength, where turbulence sustains particle suspension, transport, and deposition (Talling et al., 2012).

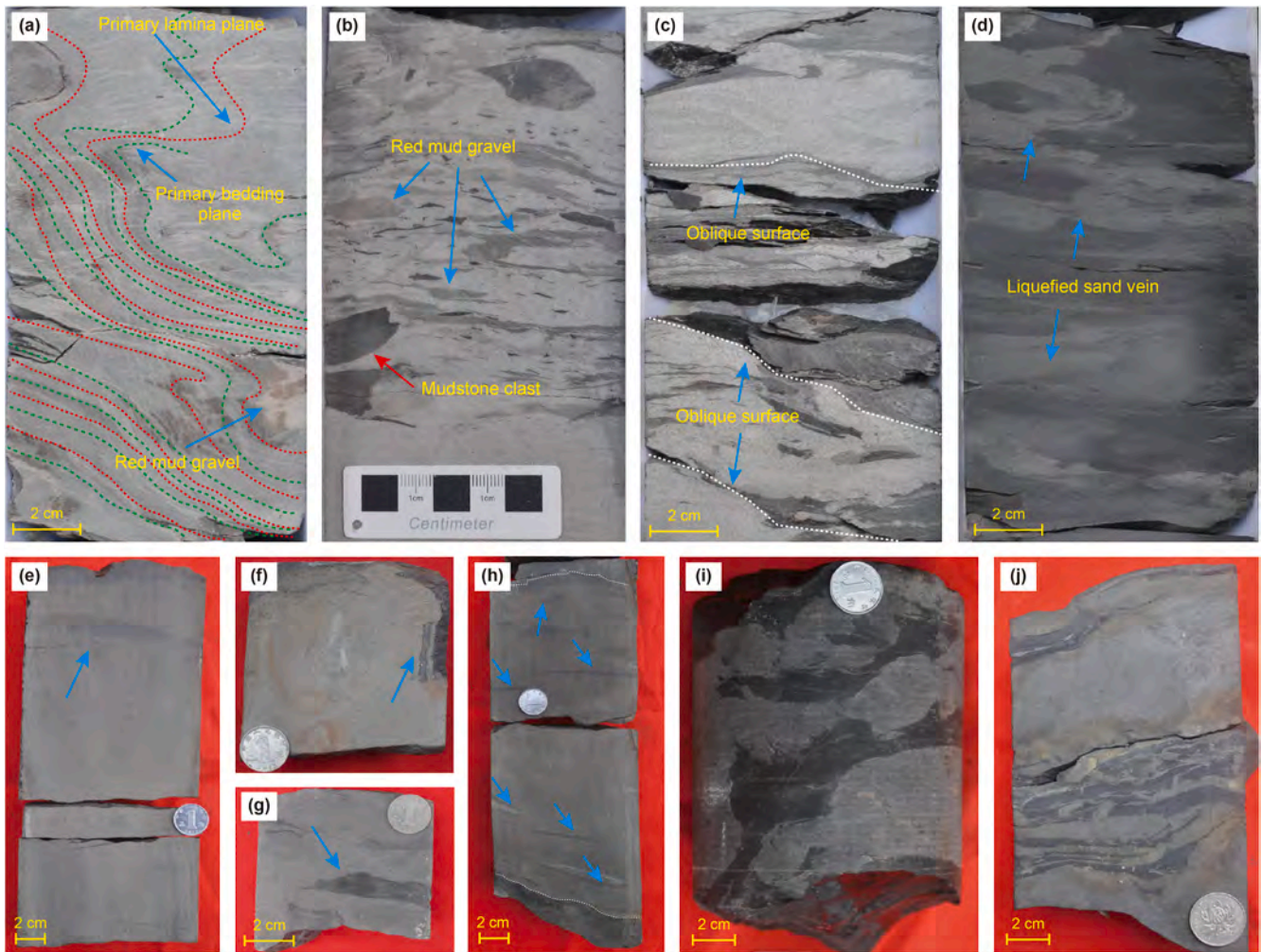


Fig. 4. Core photos of gravity flow deposits of the Ch7₃ in Ordos Basin. (a) Siltstones with deformed bedding, with red mud gravels, Well JY1, 379.5 m; (b) siltstones with red mud gravels and rock clasts, Well JY1, 355.23 m; (c) muddy siltstones with sand–mud mixing and crumpling deformation, Well JY1, 361.18 m; (d) mudstone with liquefied sand vein, Well JY1, 359.25 m; (e) siltstone with upper floating muddy clasts, Well Y202, 2708.6 m; (f) siltstone with floating and rotated muddy clasts in the middle part, Well Ch96, 2079.10 m; (g) siltstone with floating muddy clasts, Well Ch96, 2067.8 m; (h–j) siltstone with floating muddy clasts throughout: (h) Well Y202, 2701.5 m; (i) Well X140, 2002.15 m; (j) Well C96, 2072.2 m.

Generally, turbidity currents can be formed by the transformation of slump-slide and sandy debris flows into turbidity currents (Felix et al., 2009; Shanmugam, 2013), or by the dilution of flood-hyperpycnal flows when entering lakes (Baas et al., 2014; Talling, 2014). They are often distributed in the distal part of event deposits, such as the distal sublacustrine fans in deep lakes (Lyu et al., 2022).

4.1.8. LA8: Deep lake deposits

4.1.8.1. Description. LA8 sediments are dominated by black shales, and cores are mainly black and grayish-black with well-developed bedding. Two shale types are identified: the first is characterized by frequently occurring tuff layers on dark gray cores (Fig. 7(a) and (b)), with thickness ranging from 0.05 cm to 2 cm. Thin sections show multistage felsic laminae with normal grading or dotted felsic grains dispersed within organic-clay matrices (Fig. 7(a) yellow frame and 7(h)). Quartz grains are angular with embayed fractures (Fig. 7(f)), some showing a chicken-skeletal shape (Fig. 7(g)); K-feldspar mostly exhibits a rod-like or baton-shaped morphology (Fig. 7(f), (g) and (i)). The second type displays silt-grade felsic laminae on grayish-white cores (Fig. 7(c) and (d)),

consisting of highly rounded felsic grains in continuous microwavy or lenticular laminae interbedded with organic-rich layers (Fig. 7(j) and (k)). LA8 is stably distributed in deep-lake settings, occupying up to 50% of the Pss2–Pss3 intervals in the Ch7₃.

4.1.8.2. Interpretation. During the deposition of the Ch7₃, the paleolake depth ranged from 50 m to 70 m under a temperate-subtropical humid climate with an annual average temperature above 15 °C, providing favorable conditions for black shale accumulation (Fu et al., 2018). Tuff laminae on cores and typical syn-depositional volcanic clasts—including angular, embayed, and chicken-skeletal quartz as well as rod-like feldspar, indicate that this type of shale is associated with the airfall of volcanic ash into the lake and its good preservation (Niem, 1977; Qiu et al., 2009). The genesis of this type of shale may be related to volcanic ash releasing abundant nutrients, promoting biological bloom and high productivity (Duggen et al., 2010; Olgun et al., 2013). We term it tuff-rich shale. Another shale with felsic laminae being microwavy and grains highly rounded indicates that its provenance may be of terrestrial origin and has undergone long-distance transportation, and we term it felsic-rich shale.

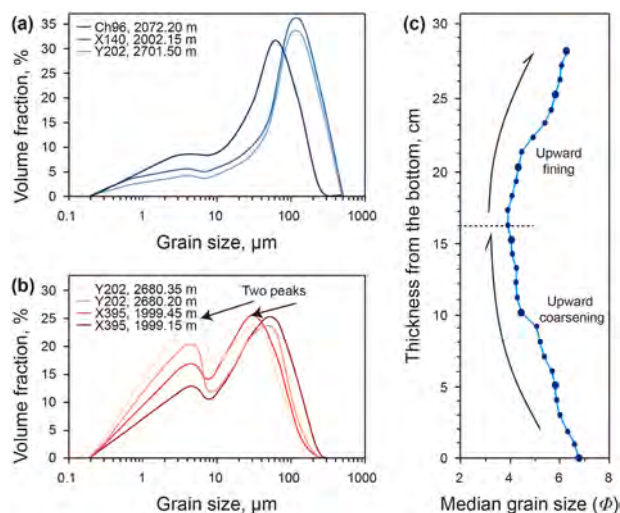


Fig. 5. Grain size analysis of fine-grained rocks of the Ch73 in Ordos Basin. (a) Grain size frequency distribution curves of debris flow sediments in the Ch73; (b) grain size frequency distribution curves of hyperpycnites in the Ch73; (c) variation of median grain size (ϕ) from bottom to top, Well Y202, 2680.35–2680.00 m.

4.2. Isochronous stratigraphic framework

4.2.1. Multiconstraint stratigraphy: Organic carbon isotope integration with astronomical cycles

We used carbon isotopes from core samples of eight wells across different sedimentary facies belts to establish the carbon isotope chemostratigraphic framework. In the Ch8, the $\delta^{13}\text{C}_{\text{org}}$ value remains stable at $\sim -26.5\text{‰}$, then drops sharply to $\sim -31\text{‰}$, accompanied by a rapid rise in GR values from 50 API to 150 API at the base of Ch73 (Fig. 8). Subsequently, the $\delta^{13}\text{C}_{\text{org}}$ rises to -27‰ – -29‰ then decreases to -29‰ – -30.5‰ (Fig. 8). Upward, $\delta^{13}\text{C}_{\text{org}}$ exhibits a 2‰ – 4‰ positive excursion, followed by an abrupt fall to -29‰ – -31‰ at the top of Ch73 (Fig. 8), with GR values decreasing synchronously. In the Ch71+2, $\delta^{13}\text{C}_{\text{org}}$ ranges from -29‰ to -26‰ . Notably, all eight wells record a consistent $\sim 2\text{‰}$ NCIE within the Ch73 (the red dashed line in Fig. 8). The potential factors contributing to the NCIE are as follows: (1) Biotic source difference: algae and plankton contributions to lacustrine sediments generally lower $\delta^{13}\text{C}_{\text{org}}$ values (Meyers, 1994; Andrushevich et al., 1998), whereas increased terrigenous organic matter input leads to positive $\delta^{13}\text{C}_{\text{org}}$, Zhang et al. (2021) reported a NCIE at 2753–2754 m in Well F75, where the Pr/Ph, $\text{C}_{24}\text{TeT}/\text{C}_{26}\text{TT}$, $\text{C}_{19}\text{TT}/\text{C}_{23}\text{TT}$ ratios all increase synchronously, indicating enhanced terrigenous input. Thus, biotic source differences may not be the primary reason. (2) Thermal evolution difference of organic matter: organic matter in the Ch73 are mainly at low-maturity to mature stages, and the buried depth variation of shale is < 15 m (Zhao et al., 2026). This possibility can also be ruled out. (3) Additional ^{12}C injection: Previous studies indicate that intense volcanism prevailed in the lower Ch73 (Gao et al., 2025; Zhao et al., 2026). Massive input of light ^{12}C may trigger the NCIE. (4) Milankovitch cycles: mid-latitude climate change is dominated by eccentricity cycles (Tang et al., 2025; Xu et al., 2026). High eccentricity strengthens Northern Hemisphere insolation, forming a warm humid climate with sufficient precipitation, and intensifying continental weathering and terrigenous input (Martinez-Bracerias et al., 2024). Such processes accelerate the transport and remineralization of terrigenous organic matter, elevate primary productivity, and promote water column stratification and bottom-water anoxia (Zeebe et al., 2017). Ultimately, this causes a greater release of light ^{12}C in the system and induces the NCIE (Ma et al., 2011; Tang et al., 2025).

In recent years, high-precision zircon U–Pb radiometric dating data of tuff layers in the Ch7 published by numerous scholars have provided a basis for stratigraphic division. Liu et al. (2018a) reported an age of 241.5 ± 0.074 Ma by the CA-TIMS method in the upper part of Tongchuan Formation; Zhu et al. (2019) acquired age data of 241.558 ± 0.093 Ma using the ID-TIMS method in the lower part of Yishicun section; Cui et al. (2023) reported an age of 241.36 ± 0.12 Ma using the ID-TIMS method for the tuff layer at the bottom of Well YY1. Their average value of 241.47 Ma was adopted as the bottom age of the Ch7. We acquired age data of 239 ± 1.6 Ma via LA-ICP-MS for the tuff at 1760 m in the Well Y1011 (Supplementary Figs. S1 and S2). Based on the constraints of organic carbon isotopes, this age was comparable to 239.4 ± 2.3 Ma and 239.8 ± 3.0 Ma from the Well F75 (Liu et al., 2023), as well as 240 Ma from the Yishicun section (Zhao et al., 2020). The Ch73 has a depositional duration of ~ 1.77 Ma, consistent with 1.64 Ma reported by Liu et al. (2024) through cyclostratigraphy.

Based on the clearly identified top and bottom boundaries and duration constraints of the Ch73, we conducted high-precision stratigraphic subdivision using astronomical cycles. After detrending and spectral analysis of GR curves, we obtained dominant cyclic frequencies above the 95% confidence curve: 0.09823 cycles/m, 0.2944 cycles/m, 0.4132 cycles/m and 0.8264 cycles/m (Supplementary Text S2 and Fig. S3). Calculation of the stratigraphic thicknesses corresponding to the dominant spectral peaks shows that their thickness ratio of 10.18 m:3.39 m:2.42 m:1.21 m is close to the theoretical astronomical period ratio of 405 ka:125 ka:100 ka:48 ka for the Ch7 (Supplementary Fig. S4). A resolution of 10.18 m per cycle is sufficient for the stratigraphic division in this study. Accordingly, we selected key wells across deep-lake zones, constructed astronomical cycle curves via 405-kyr filtering, and identified 4–4.5 long-eccentricity cycles within the Ch73 (Supplementary Fig. S5). By correlating these astronomical cycle curves with the organic carbon isotope stratigraphic framework, we found that the NCIE within the Ch73 corresponds exactly to the minimum of the second long-eccentricity cycle, and this coupling pattern is present in wells from different provenances (Fig. 8). This basin-wide, traceable NCIE can therefore serve as a marker bed to verify the accuracy of astronomical cycle-based stratigraphic division (Figs. 8 and 9).

4.2.2. Stratigraphic characteristics

The Ch73 was divided into four parasequence sets (Pss1–Pss4). The lithofacies associations, logging responses, sedimentation rates, and organic matter contents exhibited significant differences among the four intervals. In the delta front, the sediments of Pss1 were mainly composed of thick-bedded massive siltstone (LA1-I) and muddy siltstone, with logging curves exhibiting a microtoothed box shape. In deep lake areas, the sediments were characterized by interbedded gray sandstone (LA5) and massive silty mudstone (LA7), with rare tuff layers. The average stratigraphic thickness was 8.5 m, with an average sedimentation rate of 2.4 cm/kyr. There were two sets of sand bodies stably developed vertically, and the sand to formation ratio (S/F) $> 50\%$ occurs in 80% of this interval (Supplementary Fig. S6), and the mudstone color transitions from gray to dark gray from bottom to top (Fig. 10). Pss2 primarily consisted of interbedded massive siltstone and silty mudstone (LA1-II) in the delta front, with logging curves showing a toothed bell shape (Fig. 10). In deep lake areas, the sediments were mainly composed of black tuff-rich shale (LA8-I) and several tuff layers, with the Al/Ti ratio and TOC content increasing (Fig. 11); furthermore, the high organic matter content was mainly distributed in the central area of the deep lake, e.g., Well C96 (Fig. 9). Gray siltstone (LA5) mainly occurred as thin-bedded

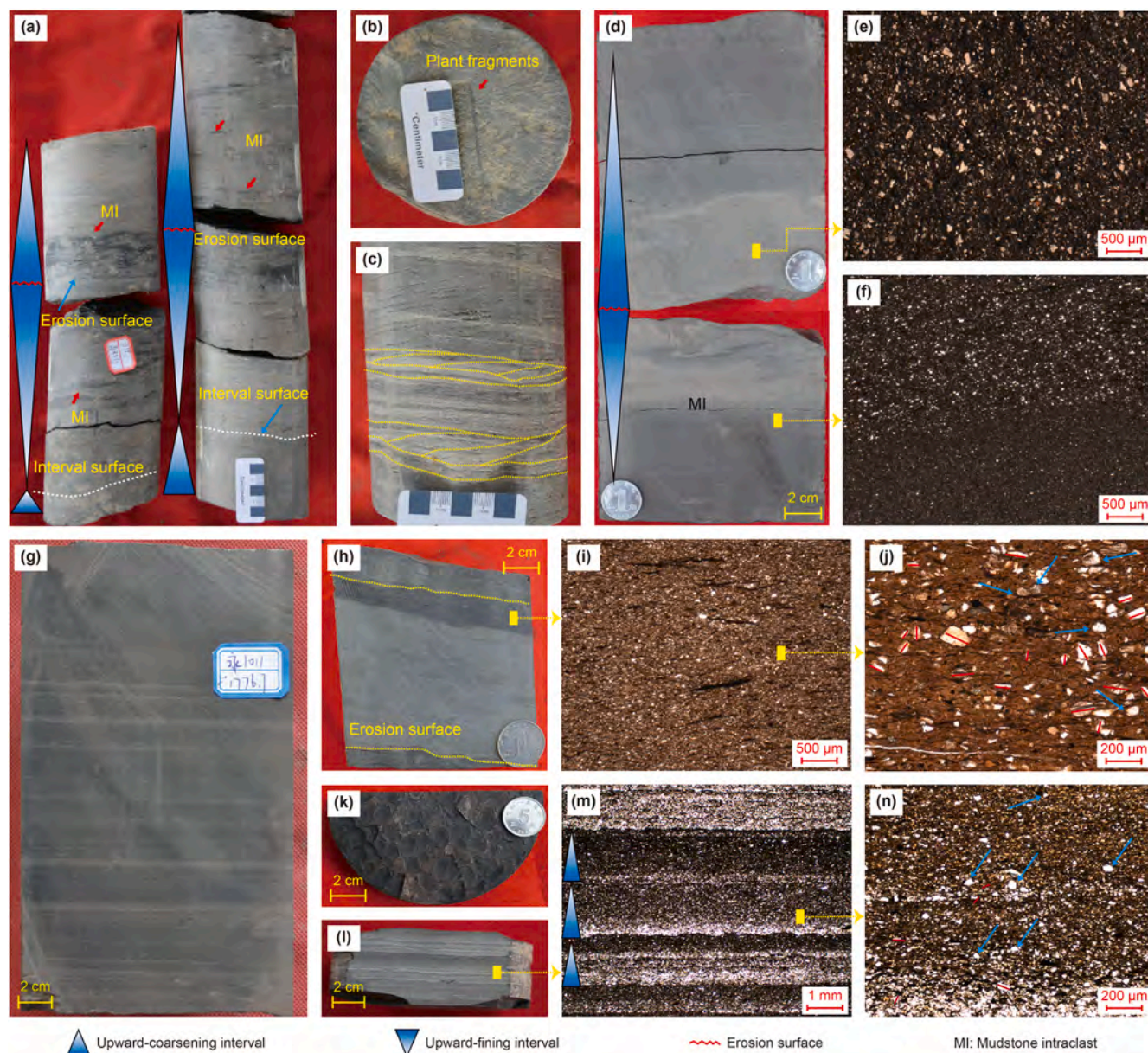
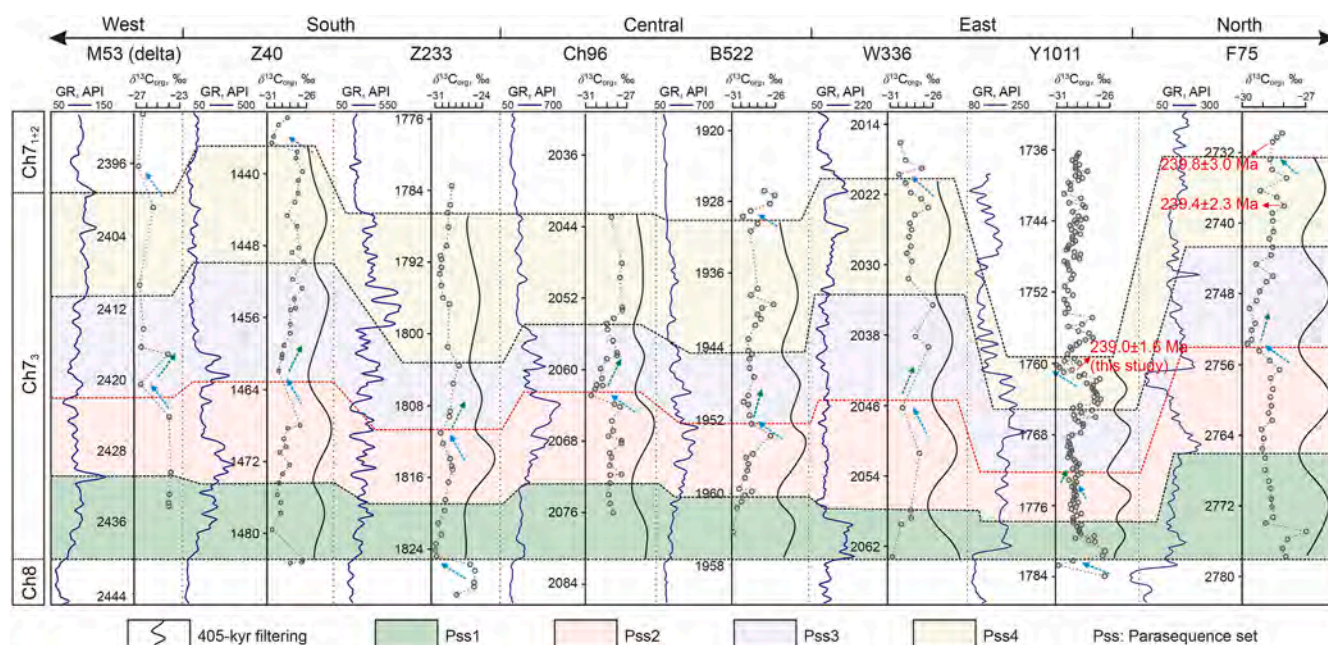
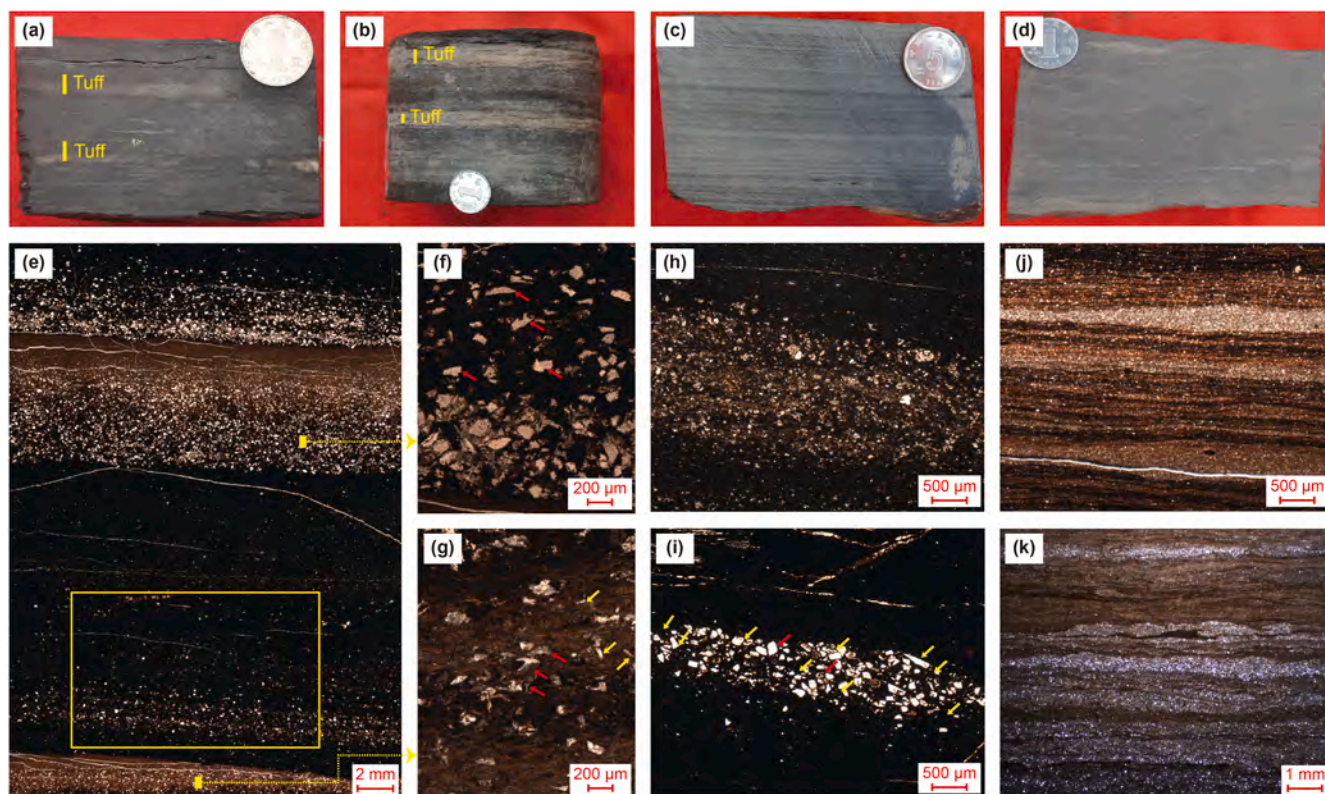


Fig. 6. Core photos of gravity flow deposits of the Ch₇₃ in Ordos Basin. (a) Siltstones with microerosion surfaces, with mudstone intraclasts existing near the coarsest level, Well X395, 1999.7–1999.15 m; (b) siltstone with plant fragments, Well X395, 1997.75 m; (c) muddy siltstone with wave bedding, with cross-bedding, Well X395, 2009.55 m; (d) muddy siltstones with mudstone intraclasts in the coarsest level, Well Y202, 2680.35–2680 m; (e, f) changes in grain size and clay content under plane-polarized light, Well Y202; (g) silty mudstone and mudstone are interbedded, with horizontal bedding, Well Y1011, 1776.7 m; (h) wave bedding siltstone with microerosion surface and massive mudstone, Well F220, 2562.45 m; (i, j) microscopic characteristics of massive mudstone in (h): minerals have inconsistent long-axis orientations (red lines); grains are subrounded (blue arrows); plane-polarized light; (k) silty mudstone flute casts, Well Y202, 2679.4 m; (l) massive mudstone with microwavy silty laminae, Well G135, 1843.6 m; (m, n) microscopic characteristics in (l): multistage-developed silt-grade felsic laminae exhibit normal grading; minerals have inconsistent long-axis orientations (red lines); grains are subrounded (blue arrows); plane-polarized light.

interlayers exhibiting a smooth bell shape on logging curves, accounting for less than 20% of the interval (Supplementary Fig. S6). The average stratigraphic thickness was 6.6 m, with an average sedimentation rate of 1.63 cm/kyr. During the sedimentary transition from Pss1 to Pss2, the Cu/Zn and V/(V + Ni) ratios increased significantly. Pss3 was mainly composed of thick-bedded massive siltstone and muddy siltstone (LA2) in the delta front, with logging curves showing a funnel-to-bell shape combination (Fig. 8). The deep lake area was mainly composed of black felsic shale (LA8-II), and gray siltstone, muddy siltstone and silty mudstone (LA6). The average stratigraphic thickness was 7.3 m, with an average sedimentation rate of 1.8 cm/kyr. Vertically, it exhibited two sets of

stably developed progradational sand bodies, with their distribution scale gradually increasing (Supplementary Fig. S6). Compared with Pss2, the Al/Ti ratio and CIA value increased, while the Rb/Sr ratio decreased (Fig. 11). Additionally, the high organic matter content was mainly distributed in the slope belt, e.g., Well Y1011 (Fig. 9). Pss4 consisted of massive muddy siltstone and mudstone (LA3), with logging curves exhibiting a series of microtoothed bell shapes (Fig. 9). The sediments in the semi-deep and deep lake were primarily composed of interbedded gray sandstone (LA6) and mudstone (LA7), with barely identifiable tuff layers. Vertically, four sets of stable sand bodies were developed; these sand bodies extended further horizontally and continuously, with an average



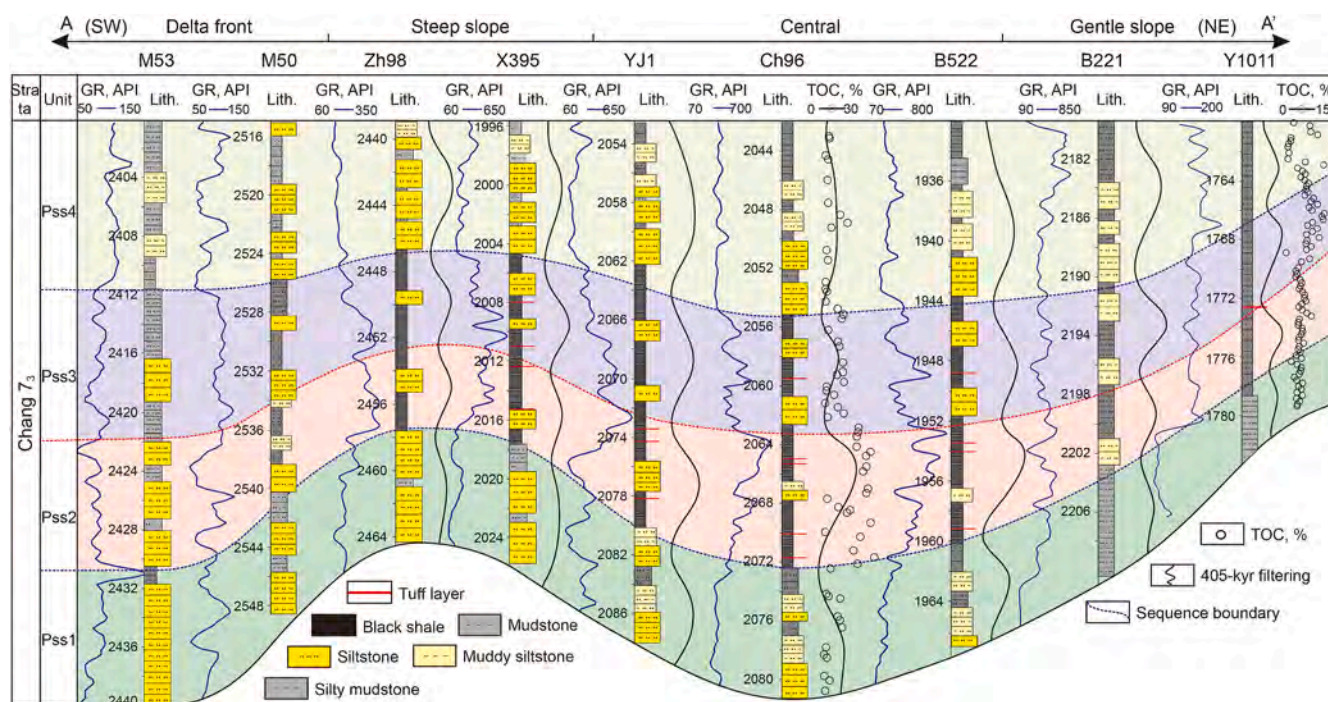


Fig. 9. The isochronous stratigraphic framework across different depositional facies domains in the SW-NE direction of the Ch73, Ordos Basin (see well locations in Fig. 1(b): A-A').

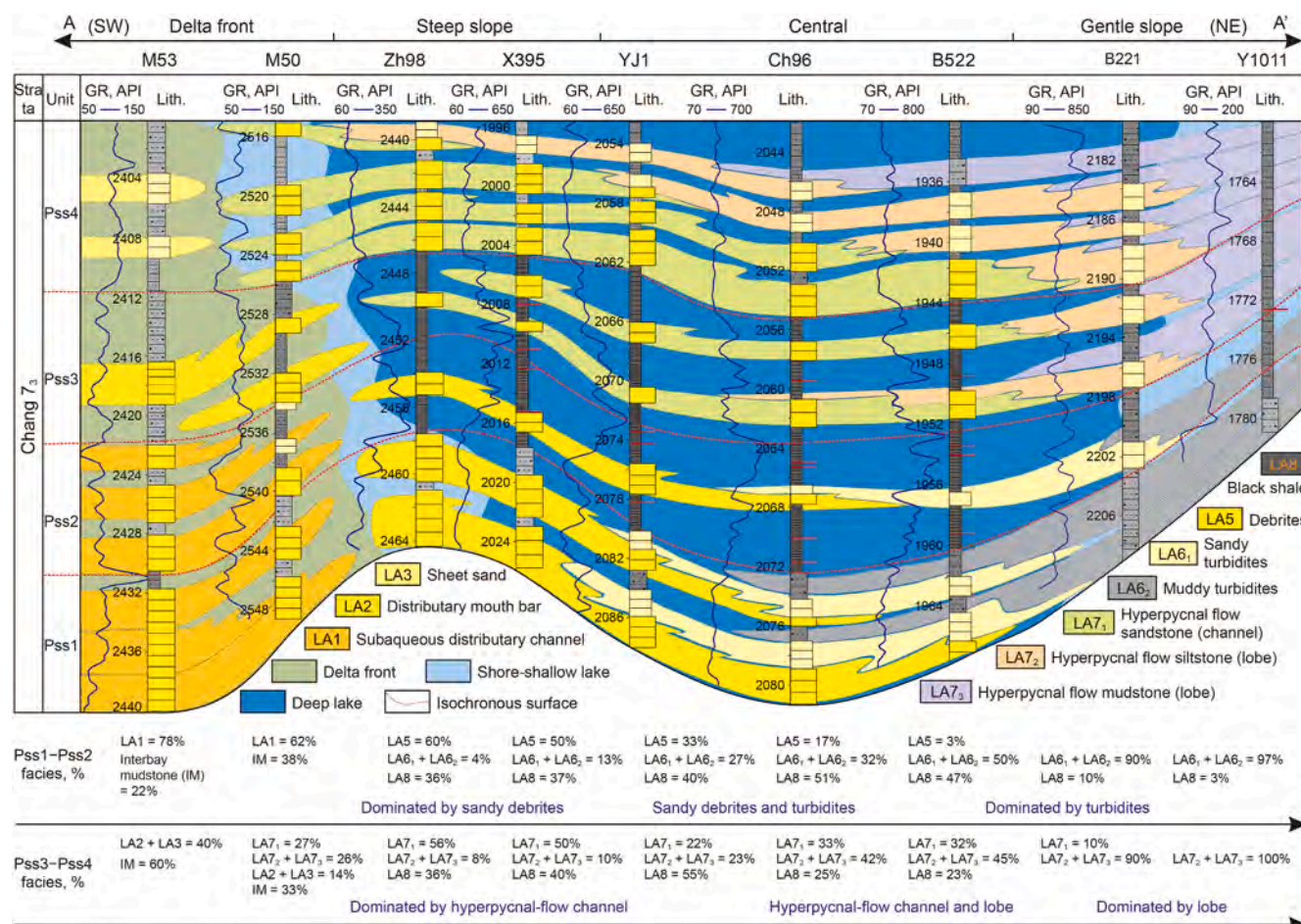


Fig. 10. SW-NE cross section of stratigraphic and sedimentary facies comparison through the wells in the Ch73 in Ordos Basin (see well locations in Fig. 1(b): A-A').

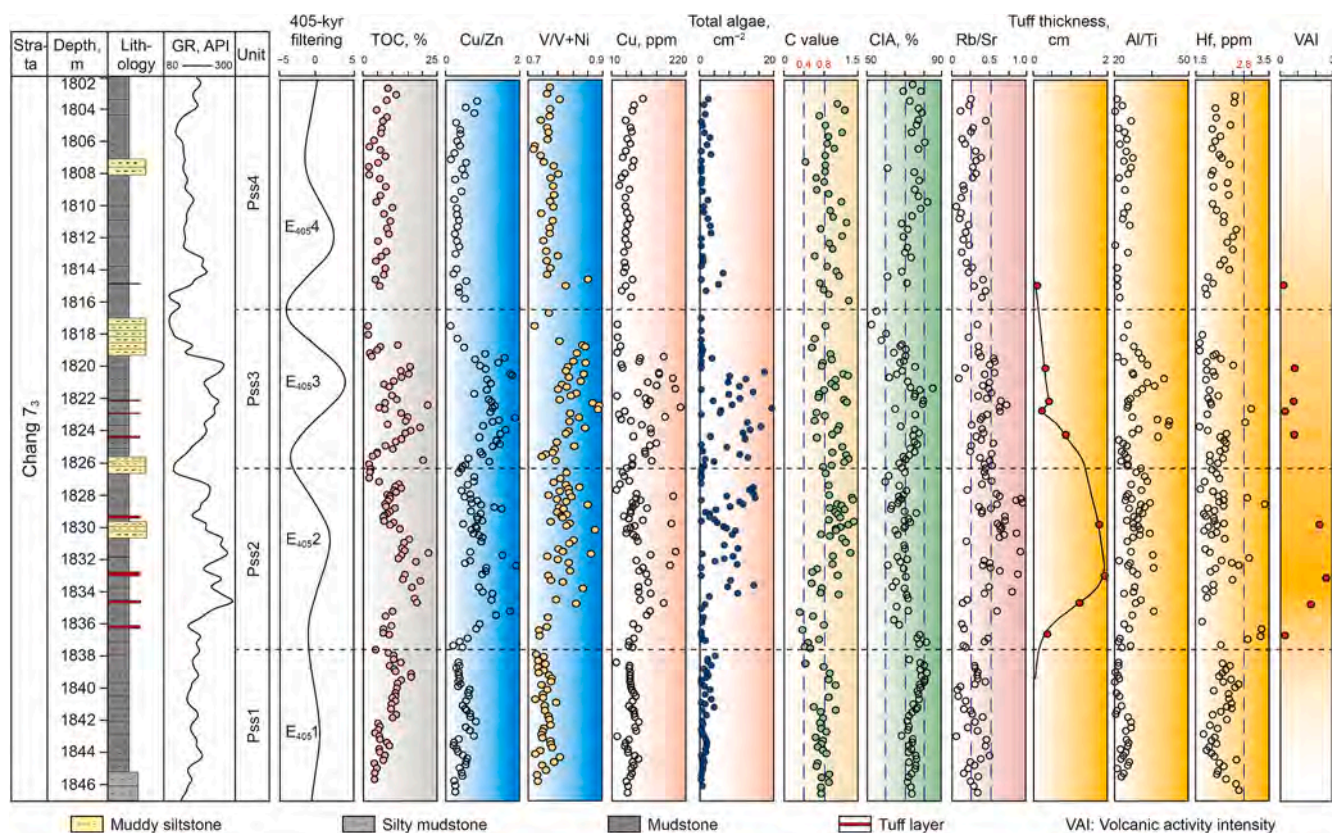


Fig. 11. The variations of geochemical proxies during the depositional period of the Ch 7_3 (Well G135). C value = $\Sigma(\text{Fe} + \text{Mn} + \text{Cr} + \text{Ni} + \text{V} + \text{Co}) / \Sigma(\text{Ca} + \text{Mg} + \text{K} + \text{Na} + \text{Sr} + \text{Ba})$, where each element in the formula represents the content of the corresponding element. CIA = $\text{mol} [\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O})] \times 100$, where all oxides are in molar units, and CaO^* represents only CaO in the silicate fraction and no CaO is present in apatite and carbonate.

stratigraphic thickness of 11 m and a sedimentation rate of 2.71 cm/kyr (Fig. 9). Along with the sedimentary changes, the Mo/Ti and $\text{V}/(\text{V} + \text{Ni})$ ratios dropped suddenly.

4.3. Depositional evolution

By classifying and correlating individual well data, analyzing continuous sedimentary transitions from the delta to the deep lake, and considering sandstone thickness and S/F ratios, the sedimentary evolution model of fine-grained rocks under the constraint of the isochronous stratigraphic framework has been determined. During the deposition of Pss1, the subaqueous distributary channel facies (LA1) was well-developed in the delta front. Sufficient sediment supply tended to trigger the instability, slumping, and retransportation. Under lake water entrainment and dilution, sediments underwent a slide–slump–debris flow–turbidity current evolutionary succession. Basin-margin Well JY1 is dominated by slide-slump deposits (Fig. 4(a)–(d)), whereas thick debris prevail in the Zh98–X395 slope well block. The YJ1–Ch96–B522 well block contains interbedded debris and turbidites, forming two-tiered gravity-flow successions with basal sandy debris flows capped by silty turbidites; these sand bodies extend laterally over 100 km (Supplementary Fig. S6). Distally, muddy turbidites dominate, as recorded by massive mudstones in the B221–Y1011 well block (Fig. 10). During the Pss2 period, delta-front subaqueous distributary channels persisted, while massive mudstones were replaced by tuff-rich black shales with frequent tuff interbeds. Sandy debrites and turbidites decreased to less than 20% in abundance, retaining the lateral evolutionary pattern observed in Pss1 (Fig. 10).

During the Pss3 period, delta-front facies shifted from subaqueous distributary channels to mouth bars, accompanied by expanded deep-lake domains dominated by felsic black shales with sparse thin tuff interbeds. Interbedded thin sandstones within shales originated from hyperpycnal flows. Compared with the gravity flows triggered by sediment instability in the delta front, hyperpycnal flows had higher energy, which could be inferred from the grain size distribution curves of the two. The higher fluid energy enabled the transportation of sediments with a wider grain size range and allowed them to be transported over longer distances; thus, in contrast to the slump-type gravity flow sand bodies during the Pss1–Pss2 periods, the hyperpycnal flow sand bodies exhibited a progradational distribution pattern in Pss3. Furthermore, along the paleocurrent direction, architectural elements resulting from the evolutionary process of hyperpycnal flow channel-lobe transitions could be observed: (1) The preservation of traction structures in the cores and the absence of sandy debris were more likely to record traction currents supplied by channels rather than non-channelized mass transport (Fig. 6(c)); (2) The regular morphological changes in GR logging curves (finger-shaped → box-shaped → dentate funnel-shaped) could explain the transition from channels to lobes (Fig. 10). During the Pss4 depositional period, the delta-front sheet sand gradually retrograded toward Well M53, and the development scale of flood hyperpycnal flows was significantly larger than that in the Pss3 deposition period. Vertically, the four sets of hyperpycnite deposits exhibited a retrogradational distribution pattern. The black shales were once again replaced by massive mudstone deposits (Fig. 10). In the Pss3–Pss4 intervals, hyperpycnites extend laterally for more than 120 km (Fig. 10; Supplementary Fig. S6).

In summary, the Ch₇₃ of the Yanchang Formation is characterized by two distinct gravity flow deposit systems: in the Pss1–Pss2 intervals, deltaic sediments serve as the “reservoir” for deep-lake slump-type gravity flows. From west to east, both the stratal thickness and the thickness of sandy rocks gradually decrease (Fig. 10). In the Pss3–Pss4 intervals, terrigenous floods were directly injected into the basin to provide sediments for gravity flow deposits. Both the stratal thickness and the sandy rock thickness exhibit a “thin–thick–thin” trend. Notably, both of these gravity flow systems were characterized by the development of massive mudstones at their distal ends (Fig. 10), which may be a reason for the extensive development of massive mudstones in the northeastern part of the basin.

5. Discussion

5.1. Factors controlling sedimentary evolution

5.1.1. Tectonics

The intensification of the second phase of the Indosinian Orogeny (233–240 Ma) caused the Yangtze Plate to thrust northward and compress the North China Plate (Zhang et al., 2019), this period of tectonic intensification is highly consistent with the bottom age of the Ch₇₃ (~241 Ma) (Zhu et al., 2019), indicating that tectonics directly participated in shaping the sedimentary paleogeomorphology of the Ordos Basin. Tectonic collision coupled with thrusting jointly triggered the regional downwarping of the Ch₇, resulting in steep slopes on both sides: 3.5°–5.5° in the south and 1.5°–2.5° in the north (Yang et al., 2017a), which laid the foundation for the formation of gravity flows. During the deposition of Pss1–Pss2, the intensive provenance supply, coupled with seismic disturbances associated with tectonic movement and volcanic activity, easily triggered the instability and slumping of sediments in the southern slope belt. The gravitational potential energy of sediments was further converted into kinetic energy (F_1):

$$F_1 = m \cdot g \cdot \sin \theta \quad (1)$$

where θ is slope gradient, °; m is total mass of sediments, kg; g is gravitational acceleration, m/s².

The energy of the slumping flow attenuated rapidly at the slope foot, where sediments accumulated massively and formed thick massive slump rocks and debrites. With the continuous dissipation of energy, thin-bedded turbiditic siltstones and turbiditic mudstones were gradually deposited in the distal part of the lake basin (Figs. 9 and 10).

5.1.2. Volcanic activity

The thickness of air-fall tuff represents the amount of volcanic ash accumulated in the area, and directly reflects the intensity of volcanic activity (Kiipli et al., 2013; Du et al., 2021; Yang et al., 2022; Gao et al., 2025). In this study, we establish a volcanic activity intensity index (VAI) using the thickness and stratigraphic proportion of air-fall tuff beds (Supplementary Text S3; Zhao et al., 2026).

$$VAI = \frac{\text{Air-fall tuff thickness} \times \alpha}{\text{Number of air-fall tuff layers}} \quad (2)$$

where α represents the compaction recovery factor, $\alpha = 1.3$ (Supplementary Text S4). The volcanic ash data comes from Well G135 (Supplementary Fig. S7). Furthermore, geochemical methods exhibit good effectiveness in identifying cryptotephra layers (Xie et al., 2023). Volcanic ash is typically rich in elements such as Al, Zr and Hf, but relatively low in Si and Ti. The thresholds

(Hf > 2.8 ppm, Al/Ti > 30) have been successfully used to reconstruct the volcanism of the Ch₇₃ (Qiu et al., 2014; Lin et al., 2024; Gao et al., 2025). The peaks of these elemental proxies at Ch₇₃ indicate intensive volcanic material inputs, which is consistent with the VAI (Fig. 11). The volcanism in the Ch₇₃ can be divided into four stages: there was no volcanism in the Pss1; intensive volcanism occurred in the Pss2, followed by diminished volcanism during the Pss3; and volcanism was at its weakest in the Pss4 (Fig. 11).

5.1.2.1. Environmental response. Fu et al. (2018) employed the CaO/(MgO-Al₂O₃) ratio to reconstruct the paleotemperature of the Ch₇, revealing a temperate–subtropical climate with a mean annual paleotemperature exceeding 15 °C. Moreover, the average CaO/(MgO-Al₂O₃) rises from 0.061 in the lower Ch₇₃ to 0.10 in the upper, indicating an increasing paleotemperature trend. The C value is often utilized to determine the environmental humidity recorded by lacustrine shales (Qiu et al., 2015; Liu et al., 2024). The C value ranges of 0.4–0.8 and > 0.8 (Fig. 11) reflect humid and strongly humid climatic conditions, respectively (Xiao et al., 2021). The chemical index of alteration (CIA) is an effective proxy to reflect the degree of chemical weathering of in situ materials and transported sediments. The CIA values of 90–80, 80–70, and 70–50 in Ch₇₃ reflect strong, intermediate, and weak weathering conditions in the source area, respectively (Nesbitt and Young, 1982; Gao et al., 2025). The Rb/Sr ratio of riverine sediments is an effective paleoclimatic proxy. Under humid climates, increased precipitation and intense weathering cause Sr enrichment and lower Rb/Sr ratios in lacustrine sediments. By contrast, under relatively dry climate conditions, lake sediments would display high Rb/Sr ratios predominantly due to the low precipitation with decreased weathering intensity (Liu et al., 2001, 2024; Chang et al., 2013). Cu/Zn and V/(V + Ni) ratios are common indices to assess the reducibility of the water column; the increase of both ratios indicates the increase of the reducibility, and vice versa (Hatch and Leventhal, 1992; Fu et al., 2018; Guo et al., 2025). The combined use of multiple indicators enables a more intuitive understanding of the dynamic regulatory process of volcanism on climate. Before explosive volcanism, the climate was in the background state of the Ch₇ interval, the C values ranged from 0.4 to 1, with an average of 0.8, the CIA values ranged from 70 to 80, and the Rb/Sr ratios were <0.5, reflecting relatively humid climate and intense weathering in the Pss1 period (Fig. 11). Notably, in the early stage of intensified volcanism in Pss2, the CIA values ranged from 60 to 70 and the Rb/Sr ratios were >0.5, and the Al/Ti ratio exhibits a significant negative correlation with both the C value and the CIA (Supplementary Fig. S8), reflecting that the “short-term” effects of volcanism result in dry and cold climates as well as weak weathering (Fig. 11). With intensified greenhouse effect, C values in the upper Pss2 interval rose rapidly to ~1.5, entering the strongly humid stage (Fig. 11). In the Pss3 interval, as volcanism diminished, the C values ranged from 0.8 to 1.5, the CIA values varied from 70 to 80, and the Rb/Sr ratios were 0.25–0.5, the Al/Ti ratio exhibits a significant positive correlation with both the C value and CIA (Supplementary Fig. S8), which indicates that the “long-term” effects of volcanism induce an extremely humid climate, with a subsequent increase in weathering intensity (Fig. 11). The C values in the Pss4 interval slightly decreased compared with those in the Pss3 interval, yet this did not affect the weathering intensity; this was coupled with a further decrease in the Rb/Sr ratios (Fig. 11).

5.1.2.2. Sediment supply. The characteristics of sediment sources and supply intensity exert a significant influence on the water environment and the development scale of fine-grained rocks (Abbas et al., 2018; Bayon et al., 2022). The S/F ratio serves as the

most direct indicator of terrigenous input intensity (Deng et al., 2025), which is jointly determined by C value and weathering intensity. Moreover, the Rb/Sr ratio in mudstones is precisely the result of the combined effects of climate and weathering intensity—thus, the Rb/Sr ratio can be used to represent sediment supply intensity. A decrease in the Rb/Sr ratio indicates increased sediment supply intensity, and vice versa. In the Pss1 period (Fig. 12(a)), mudstone sediments were primarily derived from the weathering of parent rocks in southwestern and northeastern provenance areas, while sediments in sandy rocks were dominated by the southwestern provenance (Cao et al., 2024; Lin et al., 2024); the average S/F ratio is 52.5%, indicating relatively high terrigenous supply intensity. The Pss2–Pss3 intervals display higher Al/Ti ratios (>30), suggesting that their provenance shifted to pyroclastic deposits. Quartz grains in the shales of the Pss2 interval show embayed (Fig. 7(f)), chicken-bone-like morphologies with angular edges (Fig. 7(g)), and rod-like feldspar is also identifiable (Fig. 7(i)); all of these are features of air-fall tuff, which is consistent with the elevated $\delta^7\text{Li}$ and low Li contents (Liu et al., 2024); the average S/F ratio is 18.5% and the Rb/Sr ratio reaches its maximum, indicating low terrigenous supply intensity. However, felsic grains in the Pss3 shales are well-rounded with good sorting, and felsic laminae are usually developed in multiple phases with undulatory textures (Fig. 7(j) and (k)). A decrease in the Rb/Sr ratio and an average S/F ratio of 30% corresponds to increased terrigenous input, which demonstrates that pyroclastics entered the lake by flood transportation. During the Pss4 period, the Al/Ti ratio decreases (<25), the Rb/Sr ratio reaches its minimum and the average S/F ratio is 55.3%, which indicates high-intensity sediment supply dominated by the weathering products of parent rocks in the southwestern and northeastern provenance areas.

5.1.3. Eccentricity forcing

Eccentricity forcing is also a key regulator of sub-Myr climate change in the Late Triassic (Xu et al., 2026; Zhang et al., 2026). High eccentricity enhances Northern Hemisphere insolation, creating a warm humid climate with abundant precipitation, intensified weathering, terrigenous input and lower Rb/Sr ratios, and vice versa (Liu et al., 2024; Martinez-Bracerias et al., 2024). In the Pss1 and Pss4 intervals with no or weak volcanism, 405-kyr eccentricity maxima correspond to elevated C values and CIA, as well as

reduced Rb/Sr ratios. Peak TOC and redox indicators are synchronous with or lag behind eccentricity maxima, indicating that sedimentary evolution is regulated by astronomical cycles (Fig. 11). In the Pss2 interval, CIA decreases and Rb/Sr peaks during high 405-kyr eccentricity periods, contradicting the inherent astronomical cycle response. High TOC and reducing conditions precede eccentricity maxima, while all proxies covary with high VAI, indicating volcanism dominates depositional changes. Warm-humid conditions at eccentricity maxima enhanced terrigenous nutrient supply, stimulating primary productivity; biogenic light ^{12}C combined with volcanic ^{12}C drove the internal NCIE in the Ch7₃, i.e., astronomical cycles amplify volcanic sedimentary responses (Fig. 8). In the Pss3 interval, C values and CIA are generally highest, with Rb/Sr ratios of 0.25–0.5 and showing no correlation with 405-kyr eccentricity. However, in the ascending half of astronomical cycles, TOC, nutrients, algal abundance and reducing conditions rise synchronously (Fig. 11), reflecting enhanced solar radiation, a warmer-wetter climate, increased terrigenous nutrients and algal blooms. The astronomically modulated warm-humid background further amplifies the greenhouse effect from prolonged volcanism, triggering extreme humidity and flood-induced density currents.

5.2. Sedimentary model

In the Pss1 interval, a warm and humid climatic background, combined with moderately intense bedrock weathering, jointly contributed to high-intensity sediment supply. Coupled with tectonic activity, these factors triggered shear failure of delta-front sediments, which slumped down the slope and formed multi-stage slump-type gravity flows. These flows transported abundant oxygen into the deep lake, disturbed the reducing environment, and consequently led to low Cu/Zn and V/(V + Ni). Frequent gravity flows disturbed the quiescent lake water, keeping it in a persistent turbulent condition, which inhibited algal growth (<1.07 individuals cm^{-2}) and reduced primary productivity. On the other hand, relatively high terrigenous input intensity diluted organic matter (Supplementary Fig. S9), and thus resulted in generally low TOC contents (Figs. 11 and 12(a)). In the Pss2 interval, intensified volcanism released abundant volcanic ash as air-fall into the lake and liberated substantial bioessential elements (e.g., P, Cu)

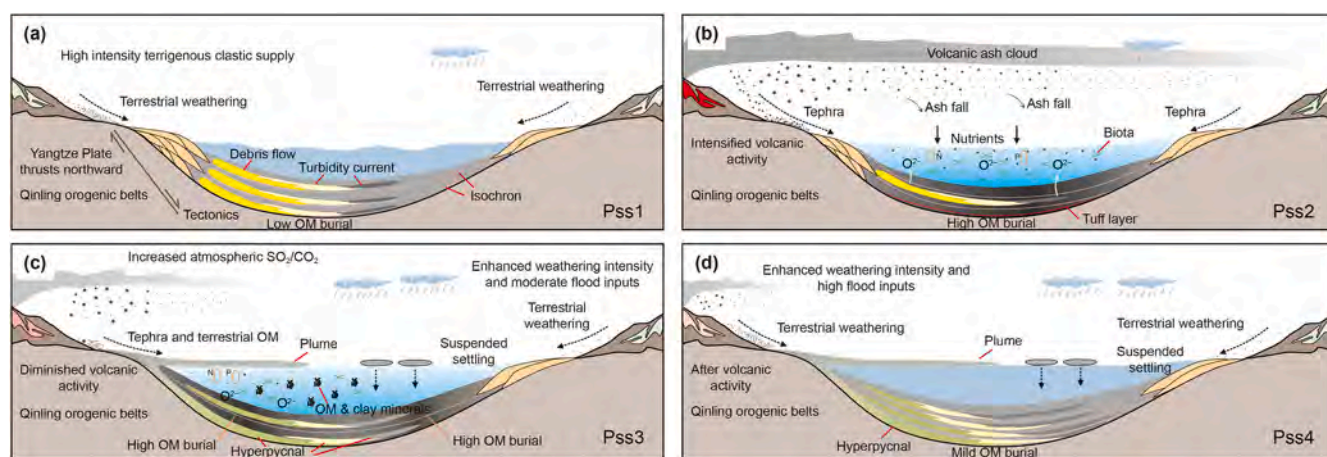


Fig. 12. Evolutionary model of the fine-grained rock sedimentary system in the Ch7₃ induced by volcanic activity. (a) Before volcanic activity, tectonics shape lake basin relief, with high intensity clastic supply from the weathering of parent rocks. (b) The “short-term” effects of volcanism induced a relatively dry-cold climate; ash fall into the lake basin released nutrients, and massive loose pyroclastic accumulations triggered deltaic overloading to generate slump-type gravity flows, together facilitating biological flourishing and the development of organic-rich shales. (c) Diminished volcanism coupled with enhanced weathering and low clastic supply induced moderate hyperpycnal flows, promoting the formation of organic-rich felsic shale. (d) Weakest volcanism, enhanced weathering intensity and high clastic supply triggered high-intensity hyperpycnal flows, forming the interbedding of sandstones and massive mudstones. OM: organic matter.

(Supplementary Fig. S10). Meanwhile, the relatively dry and cold climate coupled with weak weathering resulted in low sediment supply intensity. However massive pyroclastic accumulation at the lake basin margin triggered deltaic overloading, failure and slumping, forming occasional slump-type gravity flows, which suppressed the reducing water environment formation and promoted abundant algal growth (>6.85 individuals cm^{-2}) (Supplementary Fig. S10). Furthermore, the climatic background modulated by the 405-kyr eccentricity maximum further amplified sedimentary responses, elevated primary productivity and water column reducibility. These factors collectively facilitated the deposition and development of organic-rich tuffaceous shales in deep-lake areas (Figs. 11 and 12(a)), consistent with the NCIE associated with elevated $\delta^7\text{Li}$ values (Fig. 8).

In the Pss3 interval, diminished volcanic activity, combined with the climate modulated by the rising half-cycle of the 405-kyr eccentricity, triggered extreme humidity and intensified weathering, and further promoted the development of flood-type hyperpycnal flows, which could transport pyroclastic materials ($\text{Al/Ti} > 30$) and terrigenous organic matter into the basin. Pyroclastic materials release nutrient elements, which are preferentially deposited near the slope as transport distance increases. This greatly promoted the increase in productivity (algal abundance > 8.08 individuals cm^{-2}), transforming the water column into a reducing environment or leading to the formation of metalimnetic oxygen minimum (MOM) areas (Bian et al., 2025). Furthermore, relatively low Rb/Sr ratios indicate a moderate intensity of terrigenous input, which enhanced the preservation efficiency of organic matter (Supplementary Fig. S9). Ultimately, these factors jointly facilitated the deposition of high organic felsic-rich shale (Fig. 12(c)). In the Pss4 interval, volcanism was at its weakest; the Al/Ti ratio decreased, and the supply of pyroclastic nutrients carried by flood hyperpycnal flows was limited. This directly resulted in low primary productivity (algal abundance < 1.01 individuals cm^{-2}). Furthermore, high-intensity terrigenous input produced

strong hydrodynamics that diluted organic matter (Supplementary Fig. S9), ultimately leading to the formation of interbedded sandstones and organic-poor massive mudstones (Fig. 12(d)). Taken together, we suggest that in the Pss2–Pss3 intervals, abundant nutrients released by volcanism triggered algal blooms and elevated paleoproductivity (Supplementary Text S5; Fig. S11). Meanwhile, volcanism modulated paleoclimate and induced moderate-intensity gravity flows to improve organic matter preservation. These processes jointly promoted the formation of organic-rich black shales (Fig. 12).

5.3. Significance for shale oil exploration

The Ch₇₃ is a shale stratum characterized by widely developed fine-grained gravity-flow deposits induced by volcanism, while gravity-flow deposits in continental lacustrine basins hold significant implications for the exploration and development of shale oil and gas (Zhang et al., 2023; Zhao et al., 2025). Gravity flows transport coarser clasts to the deep lake and are proximal to high-quality source rocks, facilitating the accumulation and migration of hydrocarbons. Consequently, gravity-flow sand bodies are more likely to form shale oil “sweet intervals”. The porosity of the gravity-flow sandstones ranged from 2% to 10%, and the permeability is mainly $<10 \times 10^{-3} \mu\text{m}^2$ (Fig. 13(a) and (b)). The sandstone and siltstone reservoirs formed by sandy debris flows have better physical properties, with an average porosity of 4.7% and a permeability of $1.743 \times 10^{-3} \mu\text{m}^2$. They are mainly distributed near the southwestern slope belt, vertically in the Pss1 interval. Siltstone and muddy siltstone reservoirs formed by hyperpycnal flows are of medium quality, with an average porosity of 4.3% and a permeability of $0.832 \times 10^{-3} \mu\text{m}^2$. They are mainly located in the Pss4 interval, with widespread distribution extending from the lacustrine basin margin to the deep lake center. Muddy siltstone and mudstone reservoirs formed by turbidity flows have an average porosity of 1.18% and a permeability of $0.026 \times 10^{-3} \mu\text{m}^2$.

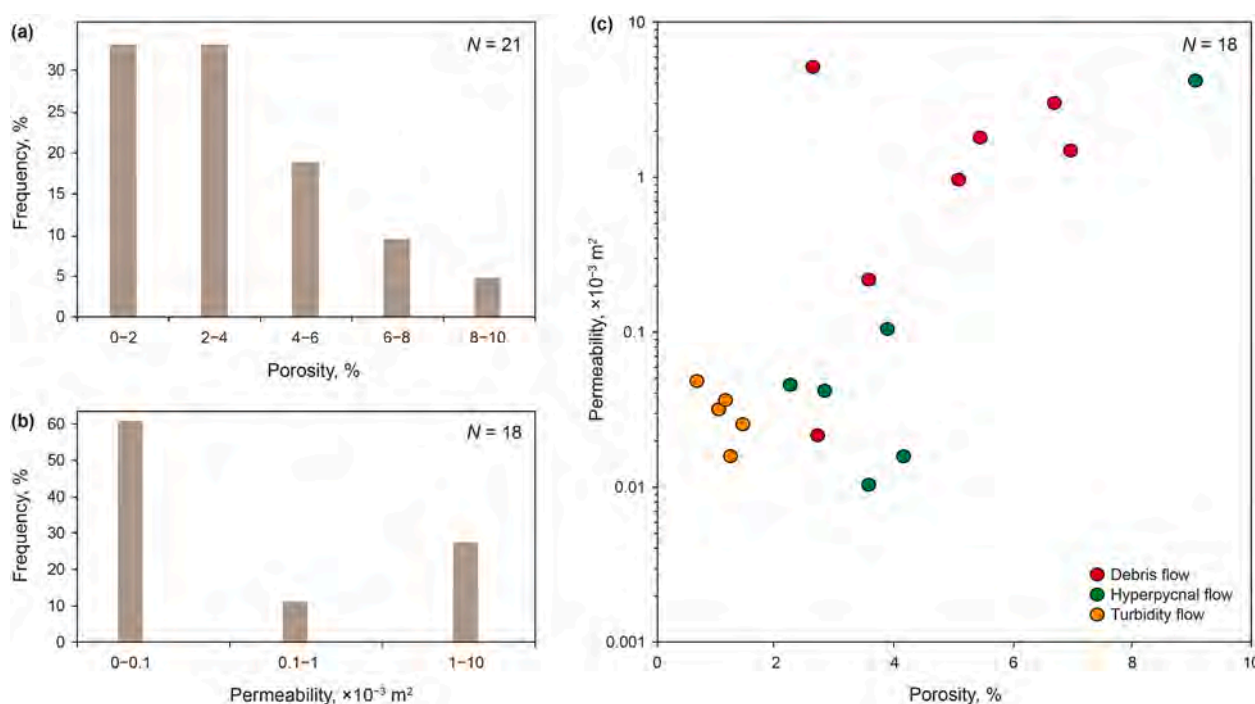


Fig. 13. Petrophysical properties of gravity-flow sand bodies in the Ch₇₃. (a) Histogram of porosity statistics, (b) histogram of permeability statistics, (c) porosity vs. permeability of different types of fine-grained gravity-flow.

(Fig. 13(a)). Overall, the Ch₇₃ exhibits a typical “hamburger”-style vertical structure: the middle part consists of a set of continuously developed high-quality and effective source rocks (Pss2–Pss3), while gravity-flow reservoirs are developed at the top (Pss4) and bottom (Pss1) respectively, forming a favorable “reservoir–source–reservoir” assemblage.

6. Conclusions

- (1) Eight lithofacies associations (LAs) were identified in the Ch₇₃, categorized into three main depositional types: deltaic deposits (subaqueous distributary channels, distributary mouth bars, sheet sands), gravity-flow deposits (slides/slumps, sandy debris flows, hyperpycnal flows, turbidity currents), and deep-lake deposits.
- (2) The Ch₇₃ was subdivided into four isochronous intervals (Pss1–Pss4). The sand bodies in Pss1–Pss2 intervals were composed of deltaic subaqueous distributary channels and slump-type gravity-flow sandy rocks. Pss1 exhibits interbedded thick-bedded massive sandstones and mudstones, with a relatively high sand–mud ratio. Pss2 is characterized by widespread tuff-rich shales coupled with synchronous NCIEs. In the Pss3–Pss4 intervals, the gravity flow depositional systems transition to hyperpycnal flows. Pss3 is featured by the extensive development of felsic shales, intercalated with thin-bedded hyperpycnites, and accompanied by positive excursion of organic carbon isotopes. Pss4 is characterized by the interbedding of multistage superimposed hyperpycnites and mudstones.
- (3) Tectonics, volcanism and astronomical cycles jointly govern the sedimentary evolution of fine-grained deposits in the Ch₇₃. Specifically, tectonics provides a topographic foundation for gravity flow development, volcanism acts as a key driving factor, and astronomical cycles amplify the sedimentary responses of these processes. In the Pss1 and Pss4 intervals, background climate controls gravity-flow sedimentation. In the Pss2–Pss3 intervals, volcanism, coupled with the climatic background modulated by the high-value stage of the 405-kyr eccentricity cycle, promotes the development of high-organic-rich black shales, which is uniquely distinctive among petroliferous basins in China.
- (4) Gravity flows of varying intensities influence the lithologic-lithofacies association patterns of the Ch₇₃. Appropriate intensity gravity flows facilitate the formation of high-organic-rich black shales (Pss2 and Pss3 intervals), which provide the basis for shale oil formation. Relatively high-intensity gravity flows tend to form multistage superimposed combinations of siltstones and muddy siltstones (Pss1 and Pss4 intervals) that exhibit favorable reservoir physical properties and can serve as the main reservoir for shale oil, forming the shale oil “sweet intervals”.

CRediT authorship contribution statement

Jing-Jing Shen: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Wen-Zhi Zhao:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Wei Liu:** Visualization, Formal analysis, Conceptualization. **Cong-Sheng Bian:** Validation, Methodology. **Yong-Xin Li:** Validation, Formal analysis. **Jin Dong:** Visualization, Methodology, Formal analysis. **Zhi-Qian Gao:** Visualization, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (U22B6004 and 42502141), the Core Technology Key Project of China Petroleum Changqing Oilfield Company (KJZX2023-01), and the Project of PetroChina Research Institute of Petroleum Exploration and Development (2022yjccq03).

Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.petsci.2026.07.058>.

References

- Abbas, A., Zhu, H., Zeng, Z., et al., 2018. Sedimentary facies analysis using sequence stratigraphy and seismic sedimentology in the Paleogene Pinghu Formation, Xihu Depression, East China Sea Shelf Basin. *Mar. Petrol. Geol.* 93, 287–297. <https://doi.org/10.1016/j.marpetgeo.2018.03.017>.
- Abouelresh, M.O., Slatt, R.M., 2012. Lithofacies and sequence stratigraphy of the Barnett Shale in east-central Fort Worth Basin, Texas. *AAPG Bull.* 96 (1), 1–22. <https://doi.org/10.1306/0426110116>.
- Adam, D., 2022. Tonga volcano eruption created puzzling ripples in Earth's atmosphere. *Nature* 601 (7894), 497. <https://doi.org/10.1038/d41586-022-00127-1>.
- Algeo, T.J., Schwark, L., Hower, J.C., 2004. High-resolution geochemistry and sequence stratigraphy of the Hushpuckney Shale (Swope Formation, eastern Kansas): Implications for climato-environmental dynamics of the Late Pennsylvanian Midcontinent Seaway. *Chem. Geol.* 206 (3–4), 259–288. <https://doi.org/10.1016/j.chemgeo.2003.12.028>.
- Andrusevich, V.E., Engel, M.H., Zumberge, J.E., et al., 1998. Secular, episodic changes in stable carbon isotope composition of crude oils. *Chem. Geol.* 152 (1–2), 59–72. [https://doi.org/10.1016/S0009-2541\(98\)00096-5](https://doi.org/10.1016/S0009-2541(98)00096-5).
- Arefifard, S., Korte, C., Payne, J.L., 2025. Upper Permian to lowermost Triassic carbon isotope stratigraphy of Iranian open-marine successions. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 679, 113268. <https://doi.org/10.1016/j.palaeo.2025.113268>.
- Baas, J.H., Manica, R., Puhl, E., et al., 2014. Processes and products of turbidity currents entering soft muddy substrates. *Geology* 42 (5), 371–374. <https://doi.org/10.1130/G35296.1>.
- Bayon, G., Bindeman, I.N., Trinquier, A., et al., 2022. Long-term evolution of terrestrial weathering and its link to Earth's oxygenation. *Earth Planet Sci. Lett.* 584, 117490. <https://doi.org/10.1016/j.epsl.2022.117490>.
- Bian, L., Wang, X., Chappaz, A., et al., 2025. Elemental-organic geochemical evidence for the lacustrine metalimnetic oxygen minimum dynamics in the Mid-Late Triassic Chang 7 shales. *Earth Planet Sci. Lett.* 651, 119153. <https://doi.org/10.1016/j.epsl.2024.119153>.
- Budai, S., Colombero, L., Mountney, N.P., 2021. Quantitative characterization of the sedimentary architecture of Gilbert-type deltas. *Sediment. Geol.* 426, 106022. <https://doi.org/10.1016/j.sedgeo.2021.106022>.
- Cao, Y., Lin, M., Xi, K., et al., 2024. Bedload transport and deposition of mud-grade sediments in deep-lacustrine settings: A case study in the Triassic Yanchang Formation, Ordos Basin, China. *Sedimentology* 71 (6), 1984–2008. <https://doi.org/10.1111/sed.13200>.
- Chang, H., An, Z., Wu, F., et al., 2013. A Rb/Sr record of the weathering response to environmental changes in westerly winds across the Tarim Basin in the late Miocene to the early Pliocene. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 386, 364–373. <https://doi.org/10.1016/j.palaeo.2013.06.006>.
- Chen, P., Xian, B., Li, M., et al., 2021. A giant lacustrine flood-related turbidite system in the Triassic Ordos Basin, China: Sedimentary processes and depositional architecture. *Sedimentology* 68 (7), 3279–3306. <https://doi.org/10.1111/sed.12891>.
- Chen, P., Xian, B., Li, M., et al., 2023. Intensified lacustrine turbidite deposition as a response to the Carnian Pluvial Episode: Insights from the Triassic Ordos Basin in North China Plate. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 623, 111599. <https://doi.org/10.1016/j.palaeo.2023.111599>.
- Cheng, C., Zhang, H., Wang, D., et al., 2025. Pulsed volcanism in the Emeishan Large Igneous Province drove deglaciation during the Guadalupian-Lopingian transition. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 679, 113302. <https://doi.org/10.1016/j.palaeo.2025.113302>.

- Cooper, C.L., Swindles, G.T., Savov, I.P., et al., 2018. Evaluating the relationship between climate change and volcanism. *Earth Sci. Rev.* 177, 238–247. <https://doi.org/10.1016/j.earscirev.2017.11.009>.
- Cui, J.W., Zhu, R.K., Xu, W.L., et al., 2023. New cognition and isochronous stratigraphic division scheme of the Yanchang Formation sedimentation in Ordos Basin. *J. Palaeogeogr.* 25 (1), 93–104. <https://doi.org/10.7605/gdxb.2023.01.007> (in Chinese).
- Deng, Q., Hu, M., Hu, Z., 2019. Depositional characteristics and evolution of the shallow water deltaic channel sand bodies in Fuyu oil layer of central down-warp zone of Songliao Basin, NE China. *Arabian J. Geosci.* 12 (19), 607. <https://doi.org/10.1007/s12517-019-4762-9>.
- Deng, Q., Hu, M., Wu, Y., et al., 2025. Lacustrine to deltaic depositional systems: Sedimentary evolution and controlling factors of an Upper Cretaceous continental depression and implications for petroleum exploration. *Mar. Petrol. Geol.* 173, 107234. <https://doi.org/10.1016/j.marpetgeo.2024.107234>.
- Di Capua, A., De Rosa, R., Kereszturi, G., et al., 2023. Volcanically-derived deposits and sequences: A unified terminological scheme for application in modern and ancient environments. *Geol. Soc. Lond. Spec. Publ.* 520, 11–27. <https://doi.org/10.1144/sp520-2021-201>.
- Di Capua, A., Scasso, R.A., 2020. Sedimentological and petrographic evolution of a fluvio-lacustrine environment during the onset of volcanism: Volcanically-induced forcing of sedimentation and environmental responses. *Sedimentology* 67 (4), 1879–1913. <https://doi.org/10.1111/sed.12681>.
- Du, X., Jia, J., Zhao, K., et al., 2021. Was the volcanism during the Ordovician-Silurian transition in South China actually global in extent? Evidence from the distribution of volcanic ash beds in black shales. *Mar. Petrol. Geol.* 123, 104721. <https://doi.org/10.1016/j.marpetgeo.2020.104721>.
- Duggen, S., Olgun, N., Croot, P., et al., 2010. The role of airborne volcanic ash for the surface ocean biogeochemical iron-cycle: A review. *Biogeosciences* 7 (3), 827–844. <https://doi.org/10.5194/bg-7-827-2010>.
- Edmonds, D.A., Slingerland, R.L., 2007. Mechanics of river mouth bar formation: Implications for the morphodynamics of delta distributary networks. *J. Geophys. Res.* 112 (F2), 2006JF000574. <https://doi.org/10.1029/2006JF000574>.
- Erbacher, J., Friedrich, O., Wilson, P.A., et al., 2005. Stable organic carbon isotope stratigraphy across Oceanic Anoxic Event 2 of Demerara Rise, western tropical Atlantic. *G-cubed* 6 (6), Q06010. <https://doi.org/10.1029/2004GC000850>.
- Felix, M., Leszczyński, S., Ślaczka, A., et al., 2009. Field expressions of the transformation of debris flows into turbidity currents, with examples from the Polish Carpathians and the French Maritime Alps. *Mar. Petrol. Geol.* 26 (10), 2011–2020. <https://doi.org/10.1016/j.marpetgeo.2009.02.014>.
- Fu, J., Li, S., Xu, L., et al., 2018. Paleo-sedimentary environmental restoration and its significance of Chang 7 Member of Triassic Yanchang Formation in Ordos Basin, NW China. *Petrol. Explor. Dev.* 45 (6), 998–1008. [https://doi.org/10.1016/S1876-3804\(18\)30104-6](https://doi.org/10.1016/S1876-3804(18)30104-6).
- Fu, J.H., Niu, X.B., Li, M.R., et al., 2022. Breakthrough and significance of risk exploration in the 3rd sub-member, 7th Member of Yanchang Formation in Ordos Basin. *Acta Pet. Sin.* 43 (6), 760–769. <https://doi.org/10.7623/syxb202206002> (in Chinese).
- Fu, J.H., Zhao, H.T., Dong, G.D., et al., 2023. Discovery and prospect of oil and gas exploration in new areas of Ordos Basin. *Nat. Gas Geosci.* 34 (8), 1289–1304. <https://doi.org/10.11764/j.issn.1672-1926.2023.06.004> (in Chinese).
- Fu, S.T., Jin, Z.J., Fu, J.H., et al., 2021. Transformation of understanding from tight oil to shale oil in the Member 7 of Yanchang Formation in Ordos Basin and its significance of exploration and development. *Acta Pet. Sin.* 42 (5), 561–569. <https://doi.org/10.7623/syxb202105001> (in Chinese).
- Gao, J.H., Jin, Z.J., Liang, X.P., 2025. Lacustrine organic carbon sequestration driven by volcanism: A case study of the third submember of the Chang 7 Member of the Yanchang Formation in the Ordos Basin. *Pet. Sci.* 22 (9), 3497–3511. <https://doi.org/10.1016/j.petsci.2025.05.015>.
- Gong, Q., Wang, X., Zhao, L., et al., 2017. Mercury spikes suggest volcanic driver of the Ordovician-Silurian mass extinction. *Sci. Rep.* 7, 5304. <https://doi.org/10.1038/s41598-017-05524-5>.
- Guo, L., Fang, Z., Peng, X., et al., 2025. Major and trace elements in marine black shales from the Lower Cambrian, Yangtze Plate, SW China: Implications for depositional environment. *J. Oceanol. Limnol.* 43 (6), 1769–1791. <https://doi.org/10.1007/s00343-025-4249-3>.
- Hatch, J.R., Leventhal, J.S., 1992. Relationship between inferred redox potential of the depositional environment and geochemistry of the Upper Pennsylvanian (Missourian) Stark Shale Member of the Dennis Limestone, Wabaunsee County, Kansas, U.S.A. *Chem. Geol.* 99 (1–3), 65–82. [https://doi.org/10.1016/0009-2541\(92\)90031-Y](https://doi.org/10.1016/0009-2541(92)90031-Y).
- Hu, X., Zhu, X., Jin, X., et al., 2024. Seismic sedimentology analysis of meter-scale thin sand bodies in the Jurassic Qigu Formation, Yongjin area, Junggar Basin. *Mar. Petrol. Geol.* 169, 107079. <https://doi.org/10.1016/j.marpetgeo.2024.107079>.
- Huang, C., Gong, Y., 2016. Timing and patterns of the Frasnian-Famennian event: Evidences from high-resolution conodont biostratigraphy and event stratigraphy at the Yangdi section, Guangxi, South China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 448, 317–338. <https://doi.org/10.1016/j.palaeo.2015.10.031>.
- Huang, C., Joachimski, M.M., Gong, Y., 2018. Did climate changes trigger the Late Devonian Kellwasser Crisis? Evidence from a high-resolution conodont $\delta^{18}\text{O}_{\text{PO4}}$ record from South China. *Earth Planet Sci. Lett.* 495, 174–184. <https://doi.org/10.1016/j.epsl.2018.05.016>.
- Huff, W.D., 2016. K-bentonites: A review. *Am. Mineral.* 101 (1), 43–70. <https://doi.org/10.2138/am-2016-5339>.
- Jenkyns, H.C., 2010. Geochemistry of oceanic anoxic events. *G-cubed* 11 (3), Q03004. <https://doi.org/10.1029/2009GC002788>.
- Jin, X., Baranyi, V., Caggiati, M., et al., 2021. Middle Triassic lake deepening in the Ordos Basin of North China linked with global sea-level rise. *Global Planet. Change* 207, 103670. <https://doi.org/10.1016/j.gloplacha.2021.103670>.
- Jin, Z.J., Zhang, Q., Zhu, R.K., et al., 2023. Classification of lacustrine shale oil reservoirs in China and its significance. *Oil Gas Geol.* 44 (4), 801–819. <https://doi.org/10.11743/ogg20230401> (in Chinese).
- Kiipli, T., Kallaste, T., Kiipli, E., et al., 2013. Correlation of Silurian bentonites based on the immobile elements in the East Baltic and Scandinavia. *GFF* 135 (2), 152–161. <https://doi.org/10.1080/11035897.2013.783104>.
- Knight, J., Evans, M., 2017. The sediment stratigraphy of a flood event: An example from the Sabie River, South Africa. *Catena* 151, 87–97. <https://doi.org/10.1016/j.catena.2016.12.015>.
- Korte, C., Kozur, H.W., 2010. Carbon-isotope stratigraphy across the Permian–Triassic boundary: A review. *J. Asian Earth Sci.* 39 (4), 215–235. <https://doi.org/10.1016/j.jseas.2010.01.005>.
- Lamb, M.P., Mohrig, D., 2009. Do hyperpycnal-flow deposits record river-flood dynamics? *Geology* 37 (12), 1067–1070. <https://doi.org/10.1306/G30286A.1>.
- Li, W., Liu, X., Zhang, Q., et al., 2019. Deposition evolution of Middle-Late Triassic Yanchang Formation in Ordos Basin. *J. Northwest Univ., Nat. Sci. Ed.* 49, 605–621 (in Chinese).
- Li, Y., Yang, R., van Loon, A.J., et al., 2023. Astronomical cycles and climate change as determined from a continuous core of the Triassic Yanchang Formation (Ordos Basin, China). *Mar. Petrol. Geol.* 151, 106183. <https://doi.org/10.1016/j.marpetgeo.2023.106183>.
- Lin, M., Xi, K., Cao, Y., et al., 2024. Palaeoenvironmental changes in the Late Triassic lacustrine facies of the Ordos Basin of Northwest China were driven by multistage volcanic activity: Implications for the understanding the Carnian Pluvial Event. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 637, 112012. <https://doi.org/10.1016/j.palaeo.2024.112012>.
- Liu, C., Wu, C., Gao, Y., et al., 2013. Zircon LA-ICP-MS U–Pb dating and Lu–Hf isotopic system of Machihhe Country and Shahewan granitoid rock masses, South Qinling Belt, central China. *Earth Sci. Front.* 20 (5), 36–56 (in Chinese).
- Liu, C.Y., Wang, J.Q., Zhang, D.D., et al., 2021. Genesis of rich hydrocarbon resources and their occurrence and accumulation characteristics in the Ordos Basin. *Oil Gas Geol.* 42 (5), 1011–1029. <https://doi.org/10.11743/ogg20210501> (in Chinese).
- Liu, G., Ma, S., Zhang, Z., et al., 2023. U–Pb ages of tuff from the Triassic Yanchang Formation in the Ordos Basin: Constraints on palaeoclimate and tectonics. *Mar. Petrol. Geol.* 150, 106128. <https://doi.org/10.1016/j.marpetgeo.2023.106128>.
- Liu, J., Jahandar, R., Li, L., et al., 2018a. High-precision temporal calibration of Middle Triassic vertebrate biostratigraphy: U–Pb zircon constraints for the Sinokannemeyeria Fauna and Yonghesuchus. *Vert. PalAs.* 56, 16–24. <https://doi.org/10.19615/j.cnki.1000-3118.170808> (in Chinese).
- Liu, Q., Li, P., Jiang, L., et al., 2024. Distinctive volcanic ash-rich lacustrine shale deposition related to chemical weathering intensity during the Late Triassic: Evidence from lithium contents and isotopes. *Sci. Adv.* 10 (11), eadi6594. <https://doi.org/10.1126/sciadv.adi6594>.
- Liu, Q., Yuan, X.J., Lin, S.H., et al., 2018b. Depositional environment and characteristic comparison between lacustrine mudstone and shale: a case study from the Chang 7 Member of the Yanchang Formation, Ordos Basin. *Oil Gas Geol.* 39 (3), 531–540. <https://doi.org/10.11743/ogg20180310> (in Chinese).
- Liu, Q.Y., Li, P., Jin, Z.J., et al., 2022. Effect of volcanic activity on the formation of marine shale and freshwater lacustrine shale. *Geochimica* 51 (5), 556–569. <https://doi.org/10.19700/j.0379-1726.2022.05.005> (in Chinese).
- Liu, X., An, Z., Rolph, T., et al., 2001. Magnetic properties of the Tertiary red clay from Gansu. *Sci. China, Ser. D Earth Sci.* 44 (7), 635–651. <https://doi.org/10.1007/BF02875337>.
- Liu, Y., Li, Y., Zhai, W., et al., 2025. Types and genetic models of sand bodies in shallow water delta front of extremely gentle slope lake basin: A case study of Chang 8₁ sub-member of Triassic in Haotan area, Ordos Basin. *Lit. Res.* 37, 140–152. <https://doi.org/10.11743/ylqyr202503014> (in Chinese).
- Lu, J., Zhang, P., Dal Corso, J., et al., 2021. Volcanically driven lacustrine ecosystem changes during the Carnian Pluvial Episode (Late Triassic). *Proc Natl Acad Sci USA* 118 (40), e2109895118. <https://doi.org/10.1073/pnas.2109895118>.
- Lyu, Q., Fu, J., Luo, S., et al., 2022. Sedimentary characteristics and model of gravity flow channel - lobe complex in a depression lake basin: A case study of Chang 7 Member of Triassic Yanchang Formation in southwestern Ordos Basin, NW China. *Petrol. Explor. Dev.* 49 (6), 1323–1338. [https://doi.org/10.1016/S1876-3804\(23\)60352-0](https://doi.org/10.1016/S1876-3804(23)60352-0).
- Ma, W., Tian, J., Li, Q., et al., 2011. Simulation of long eccentricity (400-kyr) cycle in ocean carbon reservoir during Miocene Climate Optimum: Weathering and nutrient response to orbital change. *Geophys. Res. Lett.* 38 (10), L10701. <https://doi.org/10.1029/2011GL047680>.
- Manville, V., Némethy, K., Kano, K., 2009. Source to sink: A review of three decades of progress in the understanding of volcanoclastic processes, deposits, and hazards. *Sediment. Geol.* 220 (3–4), 136–161. <https://doi.org/10.1016/j.sedgeo.2009.04.022>.
- Martinez-Braceras, N., Payros, A., Dinarès-Turell, J., et al., 2024. Orbitally forced environmental changes during the accumulation of a Pliensbachian (Lower Jurassic) black shale in northern Iberia. *Clim. Past* 20 (7), 1659–1686. <https://doi.org/10.5194/cp-20-1659-2024>.

- Men, X., Mou, C., Ge, X., 2022. Changes in palaeoclimate and palaeoenvironment in the Upper Yangtze area (South China) during the Ordovician–Silurian transition. *Sci. Rep.* 12, 13186. <https://doi.org/10.1038/s41598-022-17105-2>.
- Meyers, P.A., 1994. Preservation of elemental and isotopic source identification of sedimentary organic matter. *Chem. Geol.* 114 (3–4), 289–302. [https://doi.org/10.1016/0009-2541\(94\)90059-0](https://doi.org/10.1016/0009-2541(94)90059-0).
- Miall, A.D., 1996. *The Geology of Fluvial Deposits, Sedimentary Facies, Basin Analysis and Petroleum Geology*. Springer-Verlag, Berlin.
- Mulder, T., Migeon, S., Savoye, B., et al., 2001. Twentieth century floods recorded in the deep Mediterranean sediments. *Geology* 29 (11), 1011–1014. [https://doi.org/10.1130/0091-7613\(2001\)029<1011:TCFRIT>2.0.CO;2](https://doi.org/10.1130/0091-7613(2001)029<1011:TCFRIT>2.0.CO;2).
- Mulder, T., Syvitski, J.P.M., Migeon, S., et al., 2003. Marine hyperpycnal flows: Initiation, behavior and related deposits. A review. *Mar. Petrol. Geol.* 20 (6–8), 861–882. <https://doi.org/10.1016/j.marpetgeo.2003.01.003>.
- Mutti, E., Tinterri, R., Benevelli, G., et al., 2003. Deltaic, mixed and turbidite sedimentation of ancient foreland basins. *Mar. Petrol. Geol.* 20 (6–8), 733–755. <https://doi.org/10.1016/j.marpetgeo.2003.09.001>.
- Nesbitt, H.W., Young, G.M., 1982. Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. *Nature* 299 (5885), 715–717. <https://doi.org/10.1038/299715a0>.
- Niem, A.R., 1977. Mississippian pyroclastic flow and ash-fall deposits in the deep-marine Ouachita flysch basin, Oklahoma and Arkansas. *Geol. Soc. Am. Bull.* 88 (1), 49–61. [https://doi.org/10.1130/0016-7606\(1977\)88<49:MPFAD>2.0.CO;2](https://doi.org/10.1130/0016-7606(1977)88<49:MPFAD>2.0.CO;2).
- Niu, X., Yang, T., Cao, Y., et al., 2023. Characteristics and formation mechanisms of gravity-flow deposits in a lacustrine depression basin: Examples from the Late Triassic Chang 7 oil member of the Yanchang Formation, Ordos Basin, Central China. *Mar. Petrol. Geol.* 148, 106048. <https://doi.org/10.1016/j.marpetgeo.2022.106048>.
- Olgun, N., Duggen, S., Andronico, D., et al., 2013. Possible impacts of volcanic ash emissions of Mount Etna on the primary productivity in the oligotrophic Mediterranean Sea: Results from nutrient-release experiments in seawater. *Mar. Chem.* 152, 32–42. <https://doi.org/10.1016/j.marchem.2013.04.004>.
- Qiu, X.W., Liu, C.Y., Li, Y.H., et al., 2009. Distribution characteristics and geological significances of tuff interlayers in Yanchang Formation of Ordos Basin. *Acta Sedimentol. Sin.* 27 (6), 1138–1146 (in Chinese).
- Qiu, X.W., Liu, C.Y., Mao, G.Z., et al., 2014. Late Triassic tuff intervals in the Ordos Basin, Central China: Their depositional, petrographic, geochemical characteristics and regional implications. *J. Asian Earth Sci.* 80, 148–160. <https://doi.org/10.1016/j.jseaeas.2013.11.004>.
- Qiu, X.W., Liu, C.Y., Mao, G.Z., et al., 2015. Major, trace and platinum-group element geochemistry of the Upper Triassic nonmarine hot shales in the Ordos Basin, Central China. *Appl. Geochem.* 53, 42–52. <https://doi.org/10.1016/j.apgeochem.2014.11.028>.
- Rühl, M., Kürschner, W.M., Krystyn, L., 2009. Triassic–Jurassic organic carbon isotope stratigraphy of key sections in the western Tethys realm (Austria). *Earth Planet. Sci. Lett.* 281 (3–4), 169–187. <https://doi.org/10.1016/j.epsl.2009.02.020>.
- Schieber, J., Riciputi, L., 2004. Pyrite ooids in Devonian black shales record intermittent sea-level drop and shallow-water conditions. *Geology* 32 (4), 305–308. <https://doi.org/10.1130/G20202.1>.
- Shanmugam, G., 2000. 50 years of the turbidite paradigm (1950s–1990s): Deep-water processes and facies models: A critical perspective. *Mar. Petrol. Geol.* 17 (2), 285–342. [https://doi.org/10.1016/S0264-8172\(99\)00011-2](https://doi.org/10.1016/S0264-8172(99)00011-2).
- Shanmugam, G., 2013. New perspectives on deep-water sandstones: Implications for sandstone petroleum reservoirs. In: *Proceedings of the 4th China petroleum Geology Annual Conference*.
- Shi, J.Y., Jin, Z.J., Liu, Q.Y., et al., 2023. Application of astronomical cycles in shale oil exploration and in high-precision stratigraphic isochronous comparison of organic-rich fine-grain sedimentary rocks. *Earth Sci. Front.* 30 (4), 142–151. <https://doi.org/10.13745/j.esf.2022.10.14> (in Chinese).
- Szepesi, J., Lukács, R., Soós, I., et al., 2019. Telkibánya lava domes: Lithofacies architecture of a Miocene rhyolite field (Tokaj Mountains, Carpathian-Pannonian region, Hungary). *J. Volcanol. Geotherm. Res.* 385, 179–197. <https://doi.org/10.1016/j.jvolgeores.2019.07.002>.
- Talling, P.J., 2014. On the triggers, resulting flow types and frequencies of subaqueous sediment density flows in different settings. *Mar. Geol.* 352, 155–182. <https://doi.org/10.1016/j.margeo.2014.02.006>.
- Talling, P.J., Malgesini, G., Sumner, E.J., et al., 2012. Planform geometry, stacking pattern, and extrabasinal origin of low strength and intermediate strength cohesive debris flow deposits in the Marnoso-arenacea Formation, Italy. *Geosphere* 8, 1207–1230. <https://doi.org/10.1130/GES00734.1>.
- Tan, R.W., Wang, Y., Chen, B.L., et al., 2020. U–Pb age and genesis of the Hejiazhuang–Laohuyao intrusion in West Qinling and limitation of plate subduction time. *Geol. China* 47 (4), 1155–1172. <https://doi.org/10.12029/gc20200416> (in Chinese).
- Tang, W., Ma, C., Liu, Y., et al., 2025. Orbital controls and threshold effects on carbon isotope excursions during the Toarcian Oceanic Anoxic Event. *Global Planet. Change* 254, 105050. <https://doi.org/10.1016/j.gloplacha.2025.105050>.
- Turner, B.W., Tréanton, J.A., Slatt, R.M., 2016. The use of chemostratigraphy to refine ambiguous sequence stratigraphic correlations in marine mudrocks. An example from the Woodford Shale, Oklahoma, USA. *J. Geol. Soc.* 173 (5), 854–868. <https://doi.org/10.1144/jgs2015-125>.
- van Cappelle, M., Ravnås, R., Hampson, G.J., et al., 2017. Depositional evolution of a progradational to aggradational, mixed-influenced deltaic succession: Jurassic Tofte and Ile formations, southern Halten Terrace, offshore Norway. *Mar. Petrol. Geol.* 80, 1–22. <https://doi.org/10.1016/j.marpetgeo.2016.11.013>.
- Wang, L., Wang, X., Li, W., et al., 2024a. Analysis of sedimentary types, patterns, and controlling factors of deep-water gravity flows in terrestrial depression lake basins—Taking the Chang 7 member of the Yanchang Formation in the Ordos Basin as an example. *J. Northwest For. Univ.* 54 (6), 1091–1103. <https://doi.org/10.16152/j.cnki.xdxzbzr.2024-06-013> (in Chinese).
- Wang, R.G., Li, W.H., Liao, Y.Y., et al., 2013. Provenance analysis of Chang 7 member of Triassic Yanchang Formation in Ordos Basin. *Geol. Bull. China* 32 (4), 671–684. <https://doi.org/10.3969/j.issn.1671-2552.2013.04.015> (in Chinese).
- Wang, X., Dong, L., Li, T., et al., 2024b. Reconstructing redox landscape with coupled nitrogen–sulfur isotopes: a case study from Middle–Late Triassic Chang 7 Member of the Yanchang Formation in the Ordos Basin (North China). *G-cubed* 25 (8), e2024GC011656. <https://doi.org/10.1029/2024GC011656>.
- Wang, Z., Mao, Z., Yuan, X., et al., 2023. Types, characteristics and geological significance of event deposits of Chang 9 Member of Triassic Yanchang Formation in southwestern Ordos Basin, NW China. *Petrol. Explor. Dev.* 50 (3), 588–602. [https://doi.org/10.1016/S1876-3804\(23\)60412-4](https://doi.org/10.1016/S1876-3804(23)60412-4).
- Xiao, Z.L., Chen, S.J., Zhang, S.M., et al., 2021. Sedimentary environment and model for lacustrine organic matter enrichment: Lacustrine shale of the Early Jurassic Da'anhai Formation, central Sichuan Basin, China. *J. Palaeogeogr.* 10 (4), 584–601. <https://doi.org/10.1016/j.jop.2021.09.002>.
- Xie, H.R., Liang, C., Wu, J., et al., 2023. Impacts of volcanic activity on sedimentary palaeo-environment and organic matter enrichment. *J. Palaeogeogr.* 25 (4), 768–787. <https://doi.org/10.7605/gdxb.2023.04.066> (in Chinese).
- Xu, C., Gao, Y., Liu, J., et al., 2025. Formation mechanisms of composite continental-margin basins and their control of hydrocarbon accumulation: A case study of the Pearl River Mouth Basin, northern South China Sea. *Oil Gas Geol.* 46 (3), 719–739. <https://doi.org/10.11743/ogg20250303> (in Chinese).
- Xu, X.Y., Xu, K., Wu, N., et al., 2026. Cyclostratigraphic study of deep to semi-deep lacustrine facies in Chang 7 Member, Ordos Basin. *Fault-Block Oil Gas Field* 33 (1), 35–42. <https://doi.org/10.6056/dkyqt202601005> (in Chinese).
- Yang, R., Fan, A., Han, Z., et al., 2017a. Lithofacies and origin of the Late Triassic muddy gravity-flow deposits in the Ordos Basin, central China. *Mar. Petrol. Geol.* 85, 194–219. <https://doi.org/10.1016/j.marpetgeo.2017.05.005>.
- Yang, R., Jin, Z., van Loon, A.J.T., et al., 2017b. Climatic and tectonic controls of lacustrine hyperpycnite origination in the Late Triassic Ordos Basin, central China: implications for unconventional petroleum development. *AAPG Bull.* 101 (1), 95–117. <https://doi.org/10.1306/06101615095>.
- Yang, S., Hu, W., Fan, J., et al., 2022. New geochemical identification fingerprints of volcanism during the Ordovician–Silurian transition and its implications for biological and environmental evolution. *Earth Sci. Rev.* 228, 104016. <https://doi.org/10.1016/j.earscirev.2022.104016>.
- Yang, X., Yan, D., Zhang, B., et al., 2021. The impact of volcanic activity on the deposition of organic-rich shales: Evidence from carbon isotope and geochemical compositions. *Mar. Petrol. Geol.* 128, 105010. <https://doi.org/10.1016/j.marpetgeo.2021.105010>.
- Zavala, C., Arcuri, M., 2016. Intrabasinal and extrabasinal turbidites: Origin and distinctive characteristics. *Sediment. Geol.* 337, 36–54. <https://doi.org/10.1016/j.sedgeo.2016.03.008>.
- Zeebe, R.E., Westerhold, T., Littler, K., et al., 2017. Orbital forcing of the Paleocene and Eocene carbon cycle. *Paleoceanography* 32 (5), 440–465. <https://doi.org/10.1002/2016PA003054>.
- Zhang, B., Mao, Z., Zhang, Z., et al., 2021. Black shale formation environment and its control on shale oil enrichment in Triassic Chang 7 Member, Ordos Basin, NW China. *Petrol. Explor. Dev.* 48 (6), 1304–1314. [https://doi.org/10.1016/s1876-3804\(21\)60288-4](https://doi.org/10.1016/s1876-3804(21)60288-4).
- Zhang, H., Wang, F., Li, J., et al., 2022. Potential impact of Tonga volcano eruption on global mean surface air temperature. *J. Meteorol. Res.* 36 (1), 1–5. <https://doi.org/10.1007/s13351-022-2013-6> (in Chinese).
- Zhang, L., Wang, H., Dong, D., et al., 2023. Gravity-flow deposits and implications for unconventional oil and gas in the Ordovician–Silurian Wufeng–Longmaxi Formation, Sichuan Basin, South China. *AAPG Bull.* 107 (6), 957–988. <https://doi.org/10.1306/10112221175>.
- Zhang, Y.P., Chen, X.H., Zhang, J., et al., 2019. Discussion on the initial timing of the Indosinian movement in the Ordos Basin and the Sichuan Basin: Constraints from growth strata evidence. *Geol. China* 46 (5), 1021–1038. <https://doi.org/10.12029/gc20190505> (in Chinese).
- Zhang, Z., Hu, Y., Jiang, D., et al., 2026. Progress and prospects in paleoclimate modeling. *Sci. China Earth Sci.* 69 (5), 1577–1591. <https://doi.org/10.1007/s11430-025-1919-6>.
- Zhao, W., Liu, W., Bian, C., et al., 2026. Enrichment mechanism and optimal *in-situ* conversion recovery method of lacustrine low-to-medium maturity shale oil. *Petrol. Explor. Dev.* 53 (1), 1–15. [https://doi.org/10.1016/s1876-3804\(26\)60671-4](https://doi.org/10.1016/s1876-3804(26)60671-4).
- Zhao, X., Zheng, D., Xie, G., et al., 2020. Recovery of lacustrine ecosystems after the end-permian mass extinction. *Geology* 48 (6), 609–613. <https://doi.org/10.1130/G47502.1>.
- Zhao, Z., Liu, X., Yang, W., et al., 2025. Progress and directional thinking of oil and gas exploration in new areas and new fields of the Ordos Basin. *Acta Geol. Sin.* 99 (12), 4295–4312. <https://doi.org/10.19762/j.cnki.dizhixuebao.2025353> (in Chinese).
- Zheng, R., Wang, Y., Li, Z., et al., 2022. Differences and origins of hydrocarbon generation characteristics between mudstone and shale in the Seventh Member of the Yanchang Formation, Ordos Basin, China. *Int. J. Coal Geol.* 257, 104012. <https://doi.org/10.1016/j.coal.2022.104012>.
- Zhu, R., Cui, J., Deng, S., et al., 2019. High-precision dating and geological significance of Chang 7 tuff zircon of the Triassic Yanchang Formation, Ordos Basin in

- Central China. *Acta Geol. Sin. Engl. Ed.* 93 (6), 1823–1834. <https://doi.org/10.1111/1755-6724.14329>.
- Zhu, X.M., Zhao, D.N., Zeng, H.L., et al., 2013. Sedimentary characteristics and seismic sedimentologic responses of shallow-water delta of Qing-shankou Formation in Qijia area, Songliao Basin. *Acta Sedimentol. Sin.* 31 (5), 889–897. <https://doi.org/10.14027/j.cnki.cjxb.2013.05.009> (in Chinese).
- Zou, C., Wang, L., Li, Y., et al., 2012. Deep-lacustrine transformation of sandy debrites into turbidites, Upper Triassic, Central China. *Sediment. Geol.* 265–266, 143–155. <https://doi.org/10.1016/j.sedgeo.2012.04.004>.