

Original Paper

First high-precision U–Pb age for the Early Jurassic Beipiao Formation (NE China): Implications for source rock deposition and the Toarcian hyperthermal event

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ABSTRACT

The Beipiao Formation in western Liaoning, northeastern China, represents one of the most important Early Jurassic organic-rich successions and is widely regarded as a potential source rock for hydrocarbons. However, the absence of robust radioisotopic age constraints has long hindered accurate stratigraphic correlation, source rock evaluation, and regional paleoenvironmental reconstruction. In this study, zircon U–Pb isotopic dating of a well-preserved volcanic ash layer interbedded within the lower coal-bearing interval of the Beipiao Formation yields a weighted mean age of 187.04 ± 0.98 Ma, providing the first reliable absolute age anchor for this formation. The new age constrains the main depositional interval of the Beipiao Formation to the Pliensbachian–Toarcian, broadly consistent with existing but poorly-constrained biostratigraphic evidence. This refined chronology thus supports the interpretation that the distinctive thick organic-rich mudstones in the upper Beipiao Formation were likely coeval with the well-known early Toarcian hyperthermal event (i.e., the Jenkyns Event). These results establish a temporal framework for future assessments of hydrocarbon generation potential of the Beipiao Formation and the response of continental lacustrine systems to Early Jurassic climatic perturbation.

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1. Introduction

Organic-rich lacustrine successions preserved in continental basins constitute important targets for hydrocarbon exploration and provide valuable archives for understanding the relationship between organic carbon accumulation, basin evolution, and

climatic change (Powell, 1986; Hao et al., 2011; Zou et al., 2019; Liu et al., 2022a, 2026). In northeastern China, the Early Jurassic Beipiao Formation hosts thick coal-bearing and organic-rich mudstone intervals and is widely regarded as one of the most important potential source rock systems in the region (Sun et al., 2017; Wen et al., 2024). Previous studies have reported generally high total organic carbon contents, predominantly type II kerogen, and mature to highly mature thermal evolution, indicating favorable conditions for hydrocarbon generation (Li and Chen, 2014; Li et al., 2015; Sun et al., 2017; Liu et al., 2023). Despite its petroleum significance, the Beipiao Formation lacks robust absolute age constraints, with existing stratigraphic frameworks relying mainly on plant macrofossils and palynological assemblages that only

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broadly assign the formation to Lower Jurassic (Zhang et al., 1985, 2022a; Zhang and Zheng, 1987; Wang et al., 1989; Mi et al., 1996; Liu et al., 2019). This uncertainty hampers accurate stratigraphic correlation and limits evaluation of source rock development and its temporal relationship to regional climatic perturbations, including that during the early Toarcian (Jenkyns, 1988, 2010).

To address this issue, we selected a well-preserved volcanic ash layer interbedded within the lower coal-bearing interval of the Beipiao Formation at the Gajia section in the Beipiao Basin (western Liaoning, NE China) for zircon U–Pb isotopic dating. The resulting age establishes the first robust absolute temporal anchor for the Beipiao Formation and refines its stratigraphic age framework. Improved chronostratigraphic results may further facilitate regional source rock correlation and basin-scale evaluation of lacustrine petroleum systems, particularly where fossil preservation and chronostratigraphic control remain limited in continental successions.

2. Geological setting

2.1. Tectonic setting

Since the late Middle Triassic, the western Liaoning region of modern-day China has undergone recurrent tectonic activity related to the Indosinian and Yanshan orogenies, resulting in a structural framework dominated by NE-trending folds and faults, with Archean–Paleozoic basement uplifts alternating with Mesozoic–Cenozoic basins (Zhen et al., 2016).

The studied Beipiao Basin is elongated northeastward and covers an area of ~1200 km² (Tong, 2012; Zhang et al., 2021; Fig. 1(a)). It is located on the southern slope of the eastern segment of the Inner Mongolia geotectonic axis and is bounded by the Chifeng–Kaiyuan fault to the north, the Jianchang–Chaoyang Depression to the south, the Longtan fault to the west, and the Nantianmen fault and Jinlingsi–Yangshan syncline to the east. During the Early Jurassic, the basin was situated at a relatively high paleolatitude (~50°N) along the western margin of the Panthalassic Ocean (Liu et al., 2020; Fig. 1(b)). The tectonic evolution of the Beipiao Basin can be subdivided into distinct stages. From the Early Triassic to the Late Jurassic, compressional regimes

dominated, forming a structural depression. By the Early Cretaceous, the regional stress regime shifted to extension, transforming the basin into a faulted depression that persists to this day (Xue, 2019). This tectono-sedimentary setting provided favorable accommodation space and depositional conditions for the accumulation and preservation of organic-rich lacustrine sediments during the Early Jurassic (Wen et al., 2024).

2.2. Stratigraphy

The basement of the Beipiao Basin consists of Paleozoic and older strata, overlain by a well-developed Mesozoic sedimentary succession comprising, in ascending order: the Lower Jurassic Xinglonggou and Beipiao formations, the Middle Jurassic Haifanggou and Tiaojishan formations, the Upper Jurassic Tuchengzi Formation, and the Lower Cretaceous Yixian, Jiufotang, and Shalei formations (Fan, 2003; Huang et al., 2003; Fig. 1(a)). Regionally, the Beipiao Formation is ~900 m thick and can be subdivided into lower and upper parts based on lithological characteristics and depositional environments, showing an overall fining-upward trend. The lower part (~250–500 m thick) is characterized by gray polymictic conglomerates, tuffaceous conglomerates, and lithic sandstones, intercalated with multiple coal seams, reflecting a proximal clastic depositional setting associated with delta, braided-fluvial, and littoral-shallow lacustrine environments (Wen et al., 2024). In contrast, the upper part (~500–700 m thick) mainly comprises gray-black and yellow-green mudstones, siltstones, and sandstones, with locally interbedded thin conglomerates, indicating littoral-shallow to semi-deep and deep lacustrine depositional environments (Wen et al., 2024).

The studied Gajia section (41°50'33" N, 120°47'24" E) is situated on the eastern margin of the Beipiao Basin, near Gajia Village, Beipiao City (Figs. 1(a) and 2). The basal part of the section comprises volcanic rocks of the Lower Jurassic Xinglonggou Formation (~130 m thick), which is in paraconformable contact with the overlying Beipiao Formation. The section is capped by conglomerates of the Middle Jurassic Haifanggou Formation (~20 m thick), resting unconformably on the Beipiao Formation. The exposed Beipiao Formation is ~380 m thick, representing a typical stratigraphic succession of the basin (Fig. 2). The lower part consists of

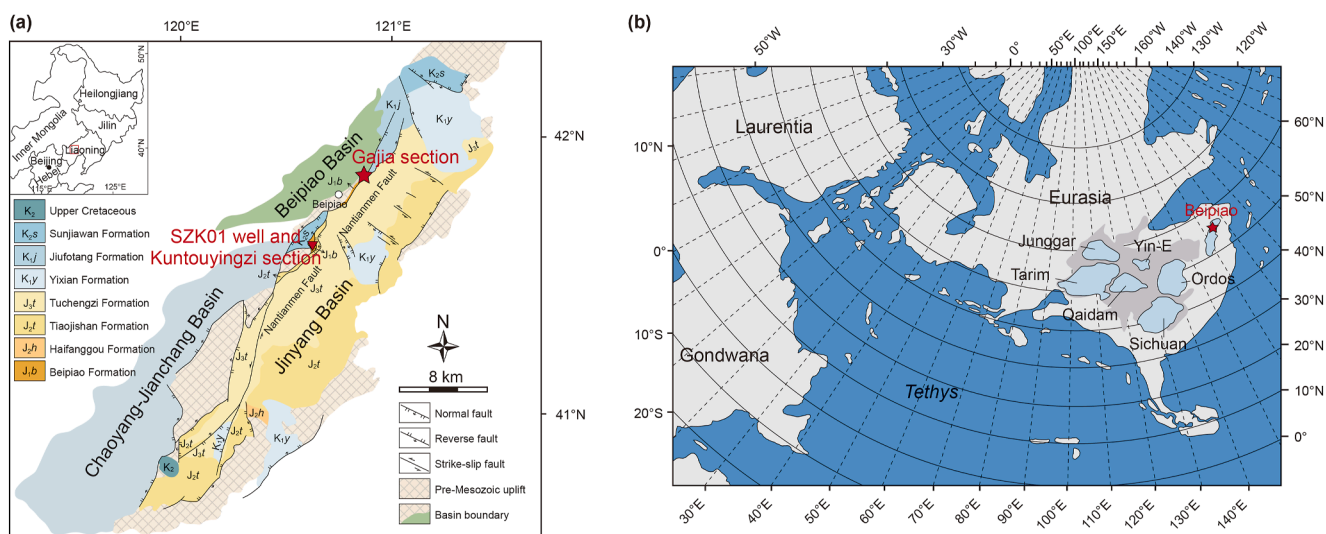


Fig. 1. (a) Simplified geological map of the Beipiao Basin (green area) and its surrounding regions (after Sun et al., 2017). The orange J_{1b} denotes the Beipiao Formation. The red star indicates the location of the studied Gajia section. The red triangle marks the SZK01 well and the Kuntouyingzi section, with the core drilled adjacent to the section. The inset at the top left shows the modern geographic location of western Liaoning, China, highlighted by a red rectangle. (b) Schematic paleogeographic map showing the distribution and extent of major lacustrine basins (light blue) in China at ~179 Ma (after Xu et al., 2017). The red star indicates the paleogeographic location of the studied Beipiao Basin.

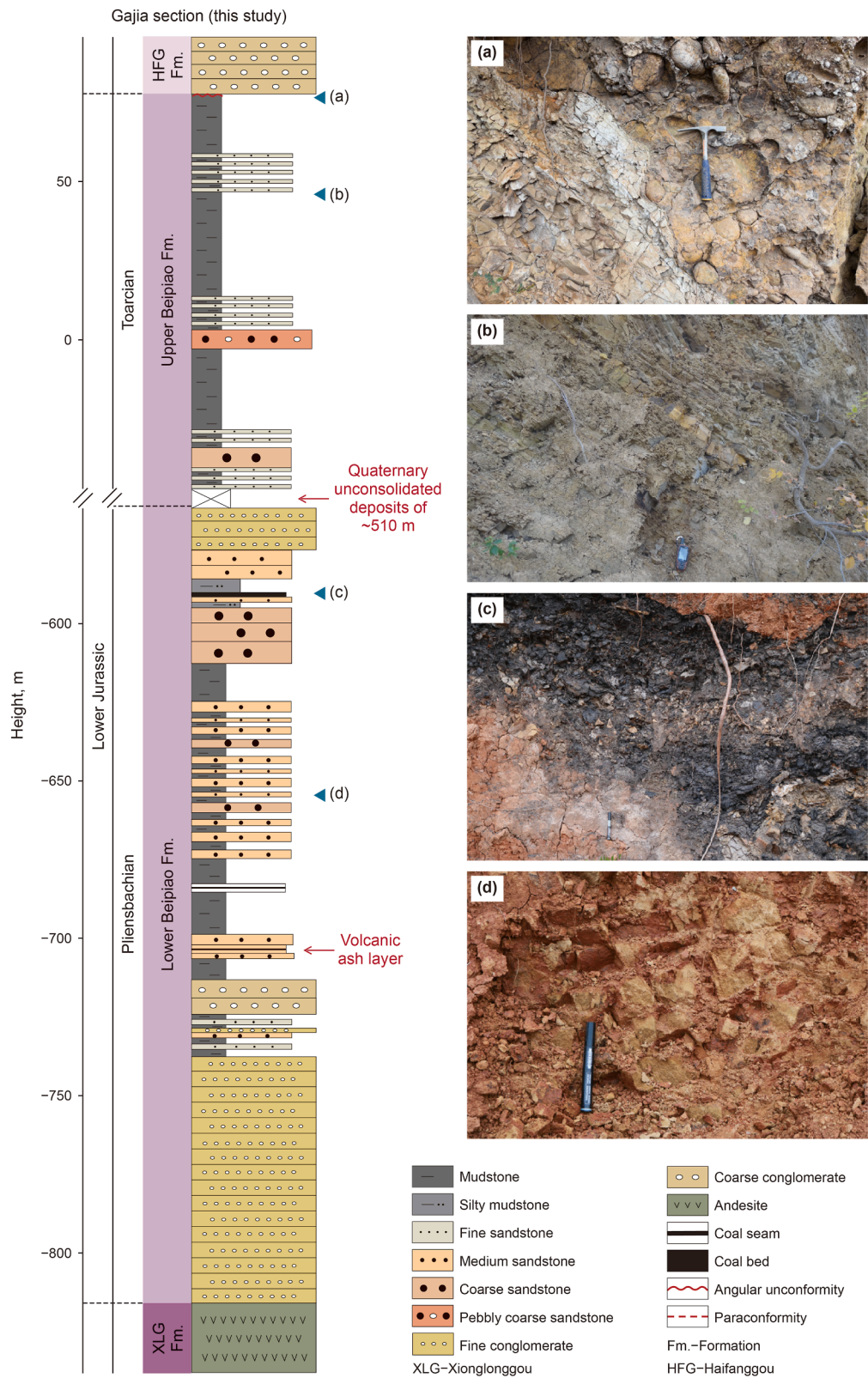


Fig. 2. Lithological profile of the studied Gajia section, Beipiao Basin. Representative outcrop photographs are shown alongside the stratigraphic column, with blue triangles indicating their corresponding stratigraphic horizons. Red arrows mark the Quaternary cover and the volcanic ash layer sampled in this study.

~90 m of conglomerates, overlain by ~60 m of gray to yellow-green mudstones interbedded with conglomerate and sandstone layers, and locally containing several coal seams. This is followed by ~100 m of coarse-grained sandstones intercalated with mudstones and coal beds. The middle portion of the section is covered by ~510 m of Quaternary unconsolidated deposits, resulting in a gap

in surface exposure. Stratigraphically higher strata of the upper Beipiao Formation are re-exposed above this covered interval, comprising ~50 m of alternating sandstones and mudstones, overlain by ~10 m of pebbly coarse-grained sandstones, followed by ~35 m of yellowish-brown mudstones, ~15 m of alternating sandstones and mudstones, and capped by ~20 m of mudstones.

The palynological assemblage of the Beipiao Formation at the Gajia section is dominated by *Osmundacidites*–*Densoisporites*–*Chordasporites*, characterized by the coexistence of fern spores and gymnosperm pollen (Xu et al., 2003). Gymnosperm pollen is overwhelmingly predominant (~88%), mainly composed of weakly differentiated primitive conifers, including *Pseudopicea*, *Piceites*, *Palaeoconiferus*, and *Pseudowalchia*. *Cycadopites* and *Chasmatosporites* are subordinate, while bisaccate pollen (*Chordasporites*) are rare and *Classopollis* (Cheirolepidiaceae) occur sporadically. Fern spores are relatively rare (~12%) and mainly consist of *Osmundacidites*, *Calamospira*, and *Densoisporites* (Xu et al., 2003). This palynological assemblage is typical of the Early Jurassic and, combined with the absence of characteristic Late Triassic taxa (e.g., *Taeniaesporites rhaeticus*, *Lucckisporites triassicus*), supports an Early Jurassic age. Regionally, similar *Chasmatosporites*–*Cyathidites*–*Piceapollenites variabiliformis* assemblages are widespread in western Liaoning and are comparable to Toarcian palynofloras from Siberia, western Caucasus, and Italy (Palliani, 1997; Goryacheva et al., 2018; Nikitenko et al., 2018), suggesting that the Beipiao Formation was mainly deposited during the Pliensbachian–Toarcian interval of the Early Jurassic (Xu et al., 2003).

Plant macrofossils are well preserved in the mudstones of the Beipiao Formation, revealing distinct floral succession patterns (Zhang and Zheng, 1987; Mi et al., 1996; Xu et al., 2003). The flora can be divided into two assemblages: the lower *Dictyophyllum nathorsti*–*Cycadocarpidium tricarpu* assemblage and the upper *Hausmannia ussuriensis*–*Cycadocarpidium erdmanni* assemblage (Xu et al., 2003). The lower assemblage is dominated by ferns, particularly the dipteridaceous species that represent a continuation of Late Triassic lineages. The Coniferopsida comprise some primitive taxa, such as the Late Triassic flourishing genus *Cycadocarpidium*, albeit with markedly reduced diversity. The horse-tails (e.g., *Neocalamites*) are relatively abundant, whereas the Jurassic index element *Coniopteris* is absent (Zhang and Zheng, 1987; Mi et al., 1996; Xu et al., 2003). This assemblage is dominated by ferns and ginkgophytes (Mi et al., 1996). Among the fern group, *Cladophlebis* are extremely abundant with high species diversity. Dipteridaceae are common, including genera *Hausmannia* and *Clathropteris*, but the proportion in the flora has decreased. It is noteworthy that *Coniopteris* appear for the first time in this assemblage (Mi et al., 1996). Overall, no typical Late Triassic taxa (e.g., *Damaeopsis*, *Goeppertella*, *Mironeura*, *Glossophyllum*, *Anthrophyopsis*) have been identified in the Beipiao Formation (Mi et al., 1996). The genus *Cycadocarpidium*, which flourished during the Late Triassic, shows a marked decline in diversity within the formation (Mi et al., 1996). Moreover, the assemblage contains both taxa extending from the Late Triassic into the Early Jurassic (e.g., *Equisetites multidentatus*, *Neocalamites carrerei*, *Dictyophyllum nathorsti*, *Hausmannia ussuriensis*, *Cladophlebis integra*, *Cycadocarpidium* cf. *erdmanni*) and newly evolved Early Jurassic elements (e.g., *Coniopteris hymenophylloides*, *Cladophlebis asiatica*, *Cl. shansiensis*, *Nilssonsonia tenuicaulis*, *Ginkgoites heeri*, *Sphenobaiera huangi*), while typical Middle Jurassic taxa (e.g., *Coniopteris simplex*, *C. bella*, *Raphaelia*) are absent (Mi et al., 1996). The flora from the Beipiao Formation can be readily correlated with late Early Jurassic floras in northern China (Mi et al., 1996; Deng et al., 2010, 2017a, 2024),

and also with Toarcian flora in eastern Europe and central Asia (Deng et al., 2017a, 2024). Collectively, the macrofloral characteristics indicate a late Early Jurassic age for the Beipiao Formation, consistent with the palynological evidence (Xu et al., 2003). These biostratigraphic analyses provide an important relative age framework for the Beipiao Formation, but remain insufficient to resolve its absolute depositional timing, underlining the need for robust radioisotopic age constraints.

3. Materials and methods

A distinct volcanic ash layer was identified in the lower Beipiao Formation at the Gajia section in the eastern Beipiao Basin. This layer occurs within the coal-bearing interval, approximately 120 m above the base of the Beipiao Formation, and 650 m below the main organic-rich intervals developed in the upper Beipiao Formation at the studied section (Figs. 2 and 3). These organic-rich rocks are stratigraphically equivalent to the rocks studied in the SZK01 well near the study area (Sun et al., 2017; Fig. 1), which have been previously correlated with an early Toarcian interval (Liu et al., 2020). We selected this ash layer for zircon U–Pb isotopic dating. Sample preparation and analytical work were carried out at Yuhong Petro-Mineral Technology Co., Ltd., Langfang City, Hebei Province. Weathered surfaces were removed prior to sampling, and thin sections were examined under an optical microscope to identify mineral composition and textures. Zircon grains were separated using heavy-liquid and magnetic techniques, and 50 grains were hand-picked under a binocular microscope, mounted in epoxy resin, and polished to the grain centers. Analytical domains were identified based on transmitted-light, reflected-light, and cathodoluminescence images to avoid inclusions or fractures before coating.

Zircon U–Pb isotopic analyses were performed using a 193 nm ArF excimer laser ablation system (RESOLUTION SE, Applied Spectra Inc.) coupled with a quadrupole inductively coupled plasma mass spectrometer (iCAP RQ, Thermo Fisher Scientific) (LA-ICP-MS). The laser beam was homogenized and focused onto the zircon surface with a fluence of 3.5 J/cm². During each analysis, a 20 s gas background signal was first collected, followed by a 45 s ablation with a 24 µm spot size at a repetition rate of 6 Hz. The ablated aerosol was transported by helium carrier gas, mixed with argon, and introduced into the ICP-MS for ionization and detection. Dwell times for individual isotopes were set as follows: 20 ms for ²⁰⁷Pb, 15 ms for ²⁰⁶Pb and ²⁰⁸Pb, 10 ms for ²³²Th and ²³⁸U, and 8 ms for ²⁰²Hg, ²⁰⁴Pb, and other trace elements. The ²⁰²Hg signal was employed to correct for the isobaric interference of ²⁰⁴Hg on ²⁰⁴Pb.

During the analytical procedure, the zircon standard 91500 (1062 Ma) was employed as an external calibration standard to correct for instrumental mass bias and isotopic fractionation. The Plešovice zircon standard (337 Ma) was analyzed as an independent reference to monitor the accuracy and reproducibility of the U–Pb age data. Trace element concentrations were calibrated using NIST SRM 610 as the external standard and Si as the internal standard. Raw data were processed offline using the ICPMSDataCal software (Liu et al., 2010) for signal drift correction, fractionation correction, and age calculation. Concordia diagrams and weighted-mean age plots (Fig. 4(a)) were generated using Isoplot version 4.15 (Ludwig, 2012). Notably, the analytical precision of LA-ICP-MS zircon U–Pb isotopic dating is sufficient to resolve Early Jurassic chronostratigraphic questions at the Formation to Stage scale, providing a practical temporal framework for constraining the timing of organic-rich source rock development in continental basins.

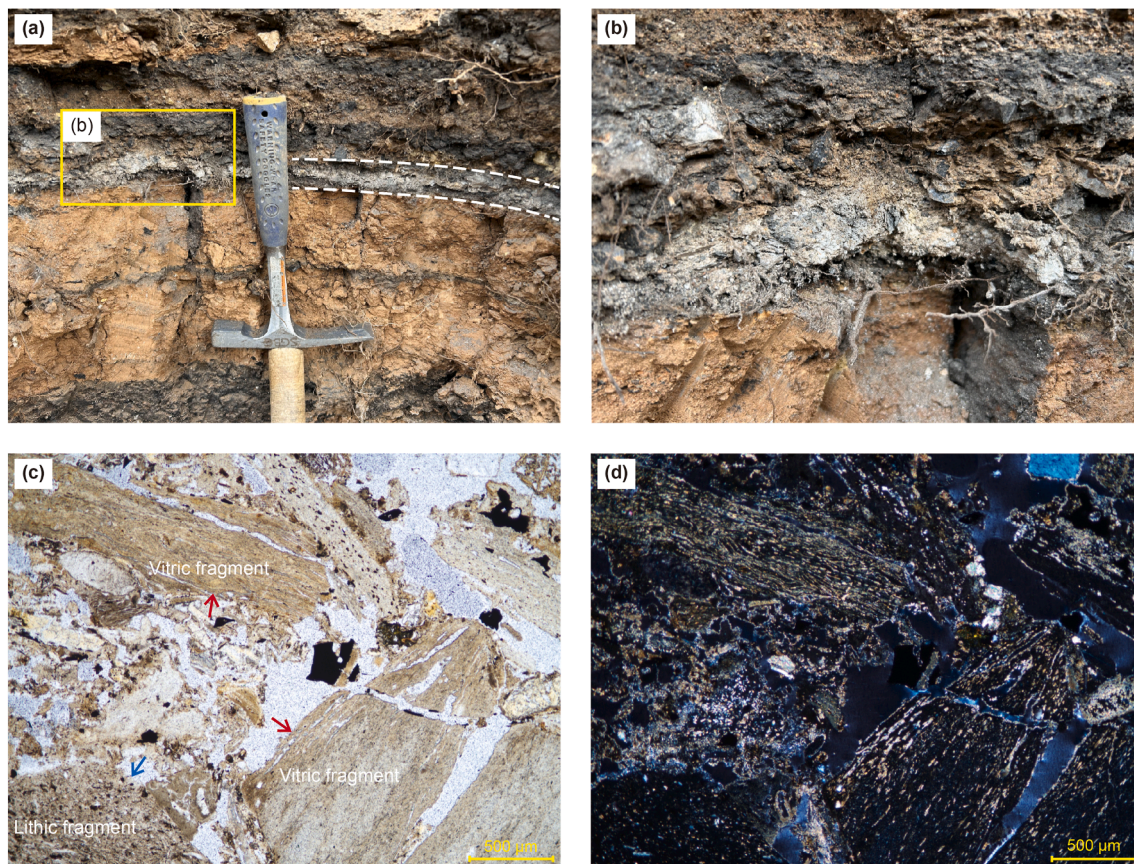


Fig. 3. (a) Volcanic ash layer within the lower Beipiao Formation coal seam at the studied Gajia section (indicated by the white dashed lines). (b) Close-up of the yellow-boxed area in (a). (c and d) Representative photomicrographs of the volcanic ash sample under plane-polarized (c) and cross-polarized light (d). In panel (c), the red and blue arrows indicate vitric and lithic fragments, respectively.

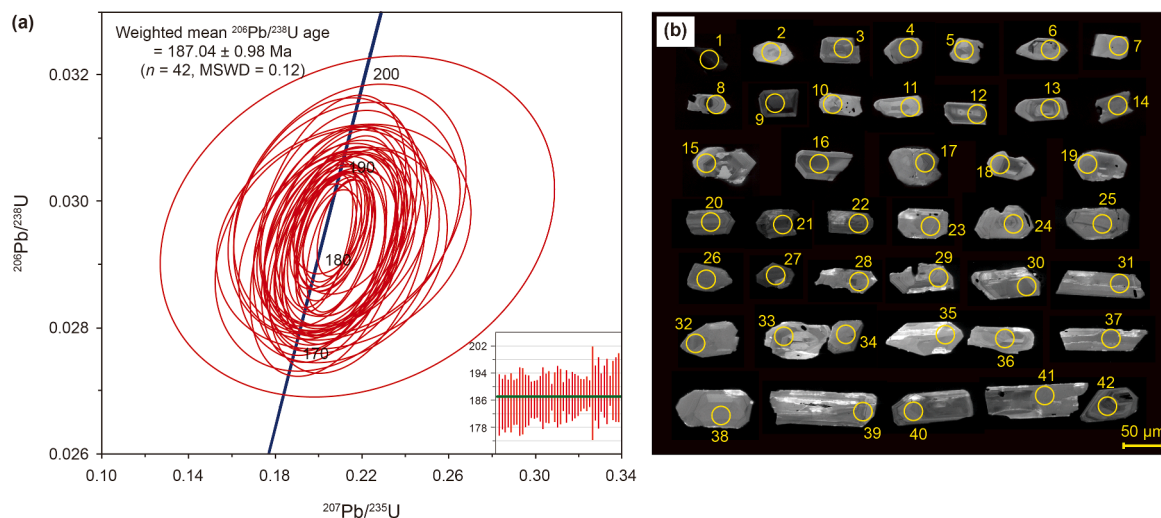


Fig. 4. Concordia diagram (a) and the ranked-age plot (the inset at the bottom right in panel (a)) of the analyzed volcanic ash zircons and their cathodoluminescence images (b). In the ranked-age plot, vertical bars represent 2σ analytical uncertainty of individual zircon analyses.

4. Results

Thin-section observations show that the studied sample consists of welded tuffaceous rock dominated by yellowish-brown plastic vitric fragments, with a small amount of plastic lithic fragments (Fig. 3(c)). The lithic fragments are mainly composed of

crystallized tuff. The vitric fragments are strongly flattened, elongated, and directionally aligned, forming a pseudoflow texture, indicative of intense welding and compaction during deposition. The interstitial materials are primarily volcanic ash, with a minor glassy matrix. These microstructural features collectively suggest high-temperature welding of pyroclastic material, followed by

limited post-depositional alteration and partial devitrification of the glass phase.

Zircon grains separated from the volcanic ash are mostly euhedral to subhedral prismatic crystals with well-defined crystal edges, as observed in the cathodoluminescence images (Fig. 4(b)). They exhibit broad planar zoning or magmatic oscillatory zoning, characteristic of typical magmatic zircons. A total of 50 zircon grains were analyzed by LA-ICP-MS U–Pb isotopic dating. Of these, 42 analyses yield Early Jurassic $^{206}\text{Pb}/^{238}\text{U}$ ages that define a coherent age population. The remaining 8 analyses produce significantly older ages (250–260 Ma), inconsistent with the stratigraphic position of the ash layer and interpreted as inherited zircon components, and were therefore excluded from further consideration. The $^{206}\text{Pb}/^{238}\text{U}$ ages are tightly clustered and display good concordance (Fig. 4(a)). The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of this population is 187.04 ± 0.98 Ma ($n = 42$; mean square of weighted deviates, MSWD = 0.12), which is interpreted as the crystallization age of the magmatic zircons and thus dates the eruption of the welded tuff layer. This age provides a direct temporal constraint on the lower coal-bearing interval of the Beipiao Formation.

5. Discussion

5.1. Early Jurassic geochronology in western Liaoning

Compared with marine strata, continental deposits are more susceptible to weathering and erosion, with poorer fossil preservation and a lack of datable marker horizons such as tuff layers (see Gradstein et al., 2012 for details). These factors complicate the establishment of a high-precision chronological framework, which is essential for evaluating the timing and pace of organic carbon accumulation in continental basins (e.g., Bohacs et al., 2000). In western Liaoning, absolute age constraints for Early Jurassic continental strata have primarily been obtained from radioisotopic dating of volcanic rocks in the Xinglonggou Formation. Various geochronological methods, including K–Ar, Rb–Sr, ^{40}Ar – ^{39}Ar , and U–Pb, consistently yield ages ranging from approximately 192 Ma to 188 Ma for volcanic units in the Chaoyang and Beipiao regions (Wang and Diao, 1983; Chen et al., 1997; Xu et al., 2003; Sun et al., 2014; Liu et al., 2019), indicating that volcanic activity was mainly concentrated in the early–middle Early Jurassic.

The Beipiao Formation, overlying the Xinglonggou Formation, mainly comprises terrigenous clastic deposits (Sun et al., 2019; Wen et al., 2024). A paucity of volcanic materials suitable for high-precision radioisotopic dating resulted in considerable uncertainty in its absolute age. Yan et al. (2006) conducted detrital zircon U–Pb isotopic dating on yellowish-brown sandstones of the Beipiao Formation in the Beipiao Basin, revealing that zircon ages are predominantly concentrated between 194.3 ± 2.9 Ma and 233.8 ± 4.2 Ma. This indicates that the sediments were mainly derived from Early Jurassic and older basement sources (Yan et al., 2006). Liu et al. (2019) performed zircon U–Pb isotopic dating on felsic intrusions in the upper Beipiao Formation at the Kuntouyingzi section in the Jinyang Basin, yielding an age of 172.6 ± 1.3 Ma (Fig. 5). When combined with radioisotopic ages of the underlying Xinglonggou Formation andesites (~189 Ma; Liu et al., 2019), these results provide broad upper and lower bounds for the depositional age of the Beipiao Formation, but do not directly constrain the timing of sedimentation within the formation itself.

Our new age of 187.04 ± 0.98 Ma provides the first high-precision absolute age constraint for the Beipiao Formation. According to the International Commission on Stratigraphy (ICS) Geologic Time Scale (Gradstein et al., 2012), this age corresponds

to the middle Pliensbachian of the Early Jurassic. Consequently, the principal depositional phase of the Beipiao Formation is inferred to have occurred during the Pliensbachian–Toarcian interval. Previously reported plant macrofossil and palynological assemblages are characteristic of the Early Jurassic and collectively indicate a late Early Jurassic age (Pliensbachian–Toarcian) for the Beipiao Formation (Zhang and Zheng, 1987; Mi et al., 1996; Xu et al., 2003; Liu et al., 2019; Zhang et al., 2022a; see Section 2.2 above). Our new zircon U–Pb age obtained in this study is fully consistent with this biostratigraphic interpretation.

Importantly, our established temporal framework places the Beipiao Formation within a time interval marked by severe perturbations of the global carbon cycle and enhanced organic carbon burial in both marine and continental environments (Jenkyns, 1988, 2010; Storm et al., 2020; Reolid et al., 2021; Kemp et al., 2022), and suggests a potential temporal coincidence with the timing of the Jenkyns Event in the early Toarcian—a major hyperthermal event in the Phanerozoic Eon (Jenkyns, 1988; Müller et al., 2017) (see Fig. 5).

5.2. Jenkyns Event in late Early Jurassic terrestrial strata

The Early Jurassic Jenkyns Event (~183 Ma) represents a period of global carbon-cycle perturbation and climatic warming, which exerted profound impacts on continental hydrological systems and sedimentary environments (Jenkyns, 1988, 2010; Müller et al., 2017; Kemp et al., 2024). Enhanced hydrological cycling and continental weathering during this interval could have increased nutrient fluxes to lacustrine basins, promoting eutrophication, water-column stratification, and the development of bottom-water anoxia (e.g., Liu et al., 2022b). Such conditions are widely regarded as favorable for the accumulation and preservation of organic matter in sediments (Pedersen and Calvert, 1990; Bohacs et al., 2000), ultimately contributing to the formation of effective lacustrine source rocks in continental basins.

Despite its significance for understanding the controls of extreme climate on organic-rich sedimentation and hydrocarbon source rock development, accurately assessing whether the Jenkyns Event is preserved or not in Early Jurassic terrestrial successions is challenging. Previous studies have therefore integrated multiple approaches, including paleobotanical and palynological analyses, radioisotopic dating, cyclostratigraphy, and chemostratigraphy, to establish chronostratigraphic frameworks for major lacustrine basins in China (Deng et al., 2017a, 2017b; Xu et al., 2017; Jin et al., 2020; Liu et al., 2020; Fang et al., 2025; Zhang et al., 2025). Plant macrofossils and palynological assemblages are among the most widely used biostratigraphic indicators in continental strata. For example, in Europe and central Asia, Toarcian floras have been calibrated through correlation with marine fossil zones. The genus *Coniopteris* became increasingly abundant during the Toarcian, characterized by larger laminae and more developed rachises, while the occurrence of *Cladophlebis* is also regarded as a diagnostic feature of the late Early Jurassic (Zhang and Zheng, 1987; Xu et al., 2003; Deng et al., 2017a). Palynological assemblage changes likewise provide additional chronological evidence. During the Jenkyns Event, inland regions generally experienced hot and arid climatic conditions (though highly seasonal changes may have occurred; Slater et al., 2019), accompanied by a pronounced increase in the thermophilic pollen *Classopollis* (Wang et al., 2005). Such trends have been reported from Siberia and several Chinese basins, including Sichuan, Qaidam, Junggar, Tarim, Xilinhot, and Yin-E basins (Vakhrameyev, 1982, 1991; Wang et al., 2005; Yang et al., 2006, 2024; Deng et al., 2010, 2017a, 2024; Goryacheva et al., 2018; Nikitenko et al., 2018; Xu et al., 2021). However,

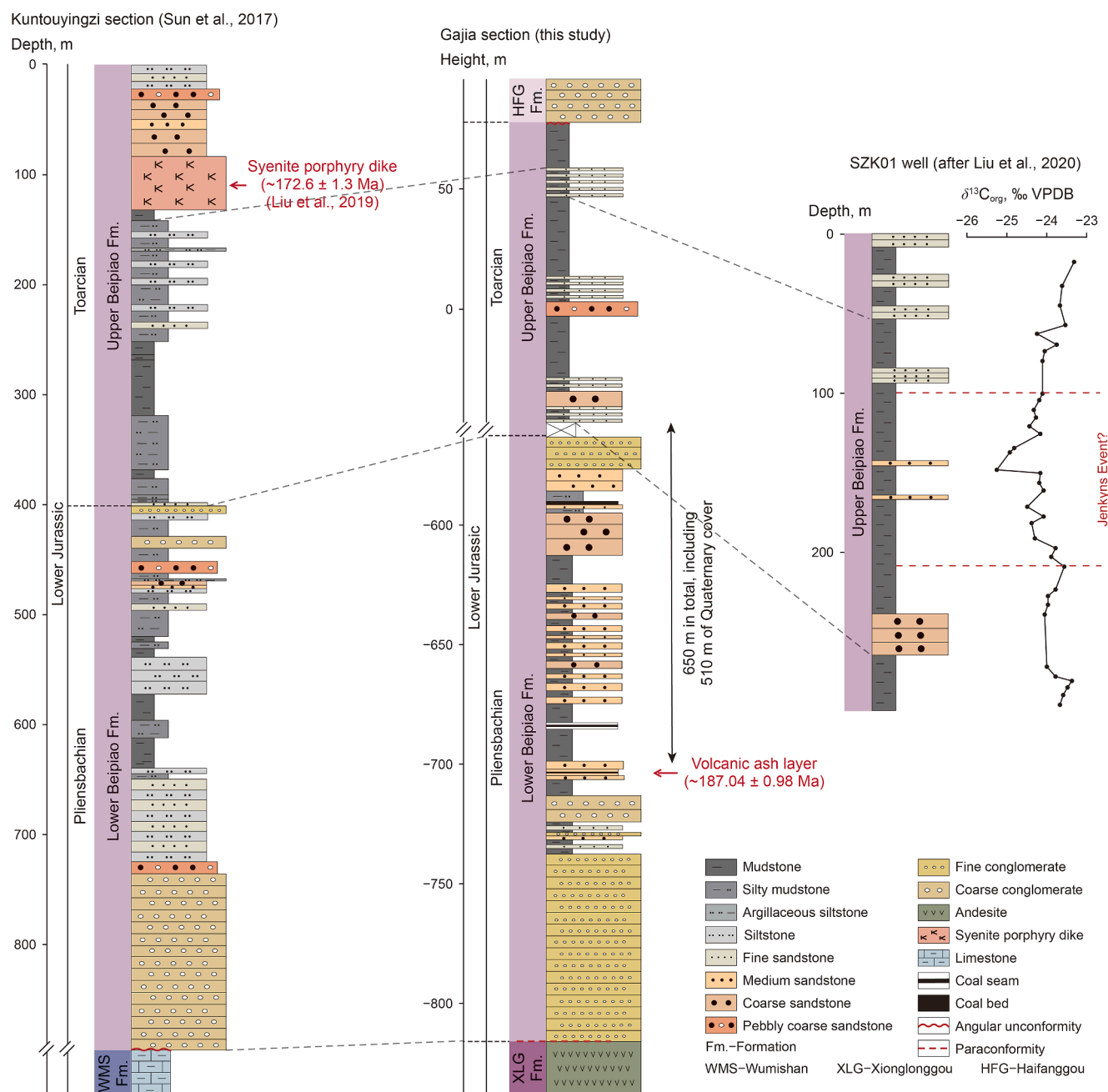


Fig. 5. Lithological correlation of the Beipiao Formation between the studied Gajia section and the nearby SZK01 core (Liu et al., 2020) and Kuntouyingzi section (Sun et al., 2017, 2019), based mainly on the presence of distinctive thick organic-rich mudstones in the upper part of the formation.

because pollen abundance is strongly influenced by paleolatitude and climatic zonation, similar patterns are not observed in certain higher-latitude, more humid regions, such as the Tian-shifu Basin in eastern Liaoning (Zhang et al., 2022b) and the Jinyang Basin in western Liaoning (Liu et al., 2019; Zhang et al., 2022a). Therefore, variations in *Classopollis* abundance alone are insufficient for reliable stratigraphic correlation (Mi et al., 1996; Deng et al., 2017b).

Complementary to the relative age constraints from the biostratigraphic evidence, radioisotopic dating provides critical absolute age anchors for the late Early Jurassic continental successions. The inferred Re–Os isotopic age of black mudstone from

the Da'anzhai Member in the Sichuan Basin is 180.3 ± 3.2 Ma, indicating deposition during the Toarcian (Xu et al., 2017). On the southern margin of the Junggar Basin, zircon U–Pb isotopic dating of a thin volcanic ash layer within the lower Sangonghe Formation at the Haojiagou section yields an age of 185.7 ± 3.6 Ma (Olsen et al., 2024), while detrital zircon U–Pb isotopic dating of sandstones from the Honggou section gives an age of 184.3 ± 2.8 Ma (Zhang et al., 2025). These ages collectively correspond to the late Pliensbachian to early Toarcian. Together, these radioisotopic dating results establish an important chronological framework for correlating the Toarcian continental successions in China with coeval marine strata worldwide, which

is essential for assessing the synchronicity and driving mechanisms of organic-rich source rock development across marine and continental basins.

Cyclostratigraphic analyses have further refined astronomical timescale frameworks for late Early Jurassic terrestrial successions, particularly where biostratigraphic resolution is limited. Orbital-scale cyclicity identified from gamma-ray, geochemical, and sedimentological proxies has allowed the construction of floating astronomical timescales and provided quantitative constraints on sedimentation rates and the duration of the Jenkyns Event (Qiu et al., 2023a, 2023b; Fang et al., 2025; Luan et al., 2025). When integrated with independent radioisotopic age anchors (e.g., Olsen et al., 2024), cyclostratigraphy facilitates the correlation between continental and marine records and improves age control for late Pliensbachian–Toarcian strata in several major Chinese basins. Importantly, these orbitally paced climate oscillations are thought to have influenced hydrological balance, nutrient supply, and redox conditions in continental basins, thereby modulating the rates and preservation efficiency of organic carbon burial during the Jenkyns Event (Fang et al., 2025).

Given that the principal depositional phase of the Beipiao Formation occurred during the late Early Jurassic (Pliensbachian–Toarcian), it has been considered a potential key succession for identifying the Jenkyns Event. Liu et al. (2020) reported a ~2‰ negative carbon-isotope excursion (NCIE, a typical stratigraphic marker of the Jenkyns Event; Hesselbo et al., 2000) from the thick organic-rich mudstones in the upper Beipiao Formation (SZK01 well, Jinyang Basin; Fig. 1(a)), suggesting a possible record of the event (Fig. 5). Notably, the magnitude of this excursion is smaller than that reported from many marine records of the Jenkyns Event, where N-CIE magnitudes typically reach ~4‰–6‰ (e.g., Müller et al., 2017; Reolid et al., 2021). However, continental records of the event often display substantially greater variability in N-CIE magnitude (e.g., Jin et al., 2020; Wang et al., 2025). Such variability may reflect differences in organic matter sources (e.g., mixing between terrestrial higher plants and aquatic algae) and regional hydrological and climatic regimes, which can influence the carbon-isotope composition of sedimentary organic matter (Jin et al., 2020; Liu et al., 2020; Wang et al., 2025). In addition, the relatively small N-CIE magnitude observed in the SZK01 well may partly result from the low sampling resolution (>5 m on average; Liu et al., 2020), which corresponds to a temporal spacing of >25 kyr between samples assuming a sedimentation rate of ~19 cm/kyr—likely an upper bound for coeval continental successions (Luan et al., 2025; see discussion below). As a result, the full magnitude of the N-CIE may not have been captured in the SZK01 well.

Indeed, relatively modest N-CIE magnitudes have also been documented in other Early Jurassic continental basins in China. For example, the lower Sangonghe Formation in the Junggar Basin (NW China) records an excursion of <2‰ despite independent chronostratigraphic constraints indicating an early Toarcian age (Zhang et al., 2025). Comparable N-CIE magnitudes (~3‰) have also been reported from the Da'anzhai Member of the LQ 104X core in the Sichuan Basin (SW China) (Liu et al., 2025). These examples suggest that relatively small N-CIE magnitudes are not uncommon in continental settings and may still reflect the global carbon-cycle perturbation associated with the Jenkyns Event. Nevertheless, the identification of the Jenkyns Event within the Beipiao Formation currently relies primarily on indirect indicators, including carbon-isotope variations, plant macrofossils, and palynological assemblages, and lacks robust constraints from high-precision radioisotopic dating and cyclostratigraphic analyses. Consequently, both the precise stratigraphic position and the

authenticity of the inferred Jenkyns Event record remain uncertain, limiting our ability to fully evaluate the climatic controls on organic carbon enrichment and source rock development in this key continental succession.

In this study, a well-preserved volcanic ash layer within the lower Beipiao Formation at the Gajia section yields a weighted mean zircon U–Pb isotopic age of 187.04 ± 0.98 Ma. Given that the Jenkyns Event occurred at ~183 Ma, this layer predates the event by ~4 Myr. The dated horizon lies ~650 m below the distinctive thick organic-rich mudstone interval in the upper Beipiao Formation, which has been ostensibly linked to the Jenkyns Event in the nearby SZK01 well (Liu et al., 2020, Fig. 5). This would imply an average sedimentation rate of ~16 cm/kyr during this interval, which is reasonable given the rates of 8–19 cm/kyr reported for broadly contemporaneous continental successions in the Sichuan and Junggar basins (Qiu et al., 2023b; Fang et al., 2025; Luan et al., 2025). Nevertheless, it should be emphasized that this estimate (~16 cm/kyr) represents only a first-order approximation, because the calculation integrates stratigraphic thickness across different lithofacies and does not explicitly account for lithology-dependent variations in depositional processes. Consequently, the inferred sedimentation rate inevitably carries some uncertainties. In addition, because fine-grained sediments commonly undergo substantial compaction during burial diagenesis (e.g., Baldwin and Butler, 1985), the rate calculated from present-day stratigraphic thickness may represent a conservative estimate of the original depositional rate.

Although parts of the studied section are locally covered by Quaternary unconsolidated deposits, several lines of evidence suggest that the stratigraphic succession is likely continuous across this interval. Field observations indicate consistent bedding attitudes across the exposed portions of the section, with no evidence of fault zones or erosional unconformities in the surrounding outcrops (Xu et al., 2003; Sun et al., 2019). In addition, a two-dimensional seismic profile (Line JY-12) acquired by the Shenyang Center of China Geological Survey across the Beipiao Formation at the Gajia section shows laterally continuous seismic reflectors near Gajia Village, with no major faults in this region (Li et al., 2018). Furthermore, a close lithological correlation can be made between the Gajia section and the nearby Kuntouyingzi section (Figs. 1(a) and 5), which has been extensively studied in previous sedimentological investigations (Sun et al., 2017, 2019; Wen et al., 2024). The Kuntouyingzi succession represents a relatively complete record of the Beipiao Formation and shows no evidence of significant folding, faulting, or erosional unconformities. These observations suggest that tectonic activity during deposition of the Beipiao Formation was relatively minor at the regional scale.

Despite the uncertainties discussed above, at the regional scale, the thick organic-rich mudstones have been widely recognized as a key stratigraphic marker of the upper Beipiao Formation, allowing reliable stratigraphic correlation between the SZK01 well, the Kuntouyingzi section, and the Gajia section (Sun et al., 2017, 2019, Fig. 5). Within this stratigraphic and temporal framework, the upper organic-rich mudstones of the Beipiao Formation may tentatively record the Jenkyns Event (Liu et al., 2020), though high-resolution carbon-isotope data from both the SZK01 well and the Gajia section are required to more precisely constrain the stratigraphic position of the event. Importantly, this temporal linkage provides a critical basis for interpreting the development of organic-rich mudstones in the Beipiao Formation as a response to Early Jurassic climatic perturbations, potentially involving warming-driven active hydrological cycling, enhanced primary productivity, and improved preservation conditions in lacustrine environments.

More broadly, the establishment of a robust chronostratigraphic framework for the Beipiao Formation provides an important basis for regional correlation of organic-rich intervals within the Beipiao–Jinyang Basin system. In turn, this may facilitate comparison with coeval lacustrine source-rock successions elsewhere in China, where the interaction among climatic perturbation, sedimentation, and organic carbon enrichment remains an active topic of petroleum geological investigation.

6. Conclusions

The Early Jurassic Beipiao Formation in western Liaoning hosts thick coal seams and organic-rich mudstones, and constitutes a key potential lacustrine source rock interval in northeastern China. However, the lack of high-precision chronostratigraphic constraints has long limited reliable reconstructions of its depositional timing, paleoenvironmental evolution, and the climatic controls on organic carbon accumulation.

In this study, LA-ICP-MS zircon U–Pb isotopic dating of a volcanic ash layer interbedded within the lower Beipiao Formation at the Gajia section yields a weighted mean age of 187.04 ± 0.98 Ma ($n = 42$; MSWD = 0.12), corresponding to the middle Pliensbachian of the Early Jurassic. This age provides the first robust, high-precision geochronological anchor for the Beipiao Formation, demonstrating that its principal depositional interval spans the Pliensbachian–Toarcian, in agreement with independent, but poorly-constrained macrofossil and palynological constraints.

Importantly, this refined temporal framework places the development of thick organic-rich mudstones in the upper Beipiao Formation within a critical interval of Early Jurassic climatic perturbation. It supports the interpretation that enhanced organic carbon accumulation in the Beipiao Formation was closely linked to the Jenkyns Event, highlighting the role of extreme climatic warming and associated environmental changes in promoting lacustrine source rock development. More broadly, the robust geochronological framework established here may assist regional source rock correlation and the prediction of favorable organic-rich intervals in lacustrine basins where chronostratigraphic constraints remain limited, thereby contributing to future basin-scale petroleum system evaluation.

CRediT authorship contribution statement

Qi-Tai Xu: Writing – original draft, Visualization, Data curation, Conceptualization. **Wen-Han Chen:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Funding acquisition, Conceptualization. **Chen Zhang:** Writing – review & editing. **Hui-Yuan Xu:** Writing – review & editing. **Shou-Liang Sun:** Writing – review & editing, Visualization, Resources, Methodology. **Xiao-Yong Gao:** Writing – review & editing, Resources. **David B. Kemp:** Writing – review & editing, Funding acquisition. **Sheng-Hui Deng:** Writing – review & editing. **Fu-Hao Xiong:** Writing – review & editing, Visualization, Validation, Methodology. **Chao Li:** Writing – review & editing, Conceptualization, Supervision, Validation.

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.

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