

Late Carboniferous–Early Permian paleoenvironmental evolution of the South Yellow Sea Basin: insights from integrated petrography, mineralogy, and geochemical proxies*

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Abstract The Late Carboniferous–Early Permian was a period of profound paleoenvironmental transformation, yet the depositional response in the South Yellow Sea Basin (SYSB) on the eastern South China Block remains insufficiently understood. This study integrates petrographic, mineralogical (XRD), and geochemical (major and trace element) data from Well CSDP-2 to reconstruct, palaeoweathering, paleoclimate, redox conditions, salinity, terrigenous influx, and paleobathymetry across the Chuanshan, Huanglong, and Gaolishan formations. Geochemical proxies—including CIA, Sr/Cu, V/Cr, U/Th, and Sr/Ba—reveal a stratigraphic transition from a high weathering, warm-humid, brackish, high-energy shelf with predominantly oxic conditions (Gaolishan) to weak weathering, cold-arid, deeper marine carbonate platform characterized by more reducing, intermittently anoxic conditions (Chuanshan). Microfacies analysis identifies seven carbonate facies ranging from restricted platform interiors to high-energy shoals. Principal component and cluster analyses delineate mineralogical differentiation aligned with stratigraphic boundaries and depositional environments. These findings document a long-term transgressive trend accompanied by climatic deterioration and evolving redox conditions. This study provides the first integrated, high-resolution reconstruction of Late Paleozoic paleoenvironmental dynamics in the SYSB, offering critical insights into marginal basin evolution during a pivotal interval of global climate change and contributing to broader paleogeographic reconstructions of the South China Block.

Keyword: South Yellow Sea; Late Carboniferous–Early Permian; paleoenvironmental reconstruction; geochemical-mineralogical analysis; microfacies

1 INTRODUCTION

Reconstructing the paleoenvironmental evolution of marginal marine basins during the Late Paleozoic is essential for understanding the broader geodynamic and climatic changes associated with the assembly of Pangea and the onset of the Late Paleozoic Ice Age (LPIA) (Powell and Veevers, 1987; Eyles et al., 1993; Crowell, 1999). The South Yellow Sea Basin (SYSB), situated on the eastern periphery of the South China Block (Fig.1), represents a geologically strategic but underexplored archive of these environmental transformations (Guo et al., 2019;

Gao et al., 2020). Structurally complex and stratigraphically diverse, the SYSB comprises a thick succession of Paleozoic to Early Mesozoic marine sequences overlain by Mesozoic–Cenozoic continental deposits, preserving a continuum of depositional regimes from carbonate platforms to deep marine environments (Lei et al., 2018; Chen et

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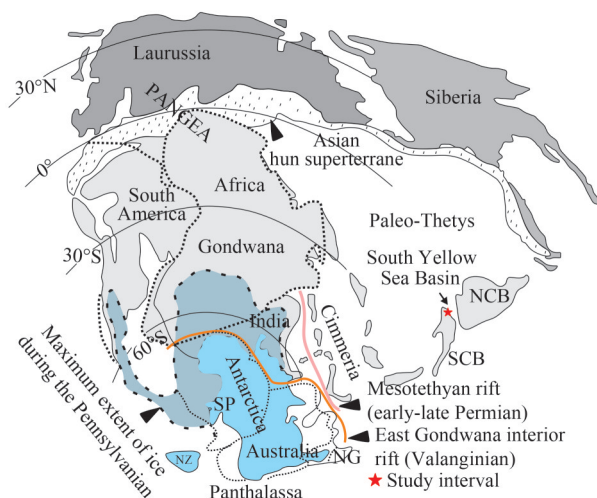


Fig.1 Late Paleozoic paleogeographic reconstruction of Pangea

The figure illustrates the collision of Laurussia and Gondwana along the Asian Hun suture zone during the Late Paleozoic Ice Age. South Pole-centered ice sheets blanket large parts of Gondwana, while the nascent Meso-Tethys opens and Cimmeria begins to detach and drift toward Southeast Asia. Continental outlines and ice-sheet limits are modified from Veevers (2006) and Blakey (2008), and SE Gondwanan rift axes from Haig et al. (2017). South Yellow Sea Basin on the South China Block (SCB), North China Block (NCB), South Pole (SP), New Guinea (NG), and New Zealand (NZ).

al., 2022).

During the Late Carboniferous to Early Permian, the SYSB experienced a series of pronounced facies shifts, transitioning from shallow-marine carbonate systems to deeper-water siliceous and deltaic deposits, reflecting dynamic interactions among sea-level fluctuations, terrigenous influx, and climatic oscillations (Cai et al., 2019; Chen et al., 2022). These transitions were likely modulated by both regional tectonic subsidence and global glacial-interglacial cycles, resulting in stratigraphic heterogeneity and compositional variability across the basin (Powell and Veevers, 1987; Lu et al., 2021). Despite its significance, the paleoenvironmental evolution of this basin remains insufficiently constrained due to the paucity of detailed, integrated mineralogical and geochemical datasets.

Although numerous studies have examined individual portions of the Upper Paleozoic record in the SYSB—such as carbonate-platform development (Cai et al., 2018), geochemical assessments of selected Permian source rocks (Cai et al., 2019, 2021; Pang et al., 2020), and provenance or tectonic analyses of isolated clastic intervals (Gao et al., 2020)—these efforts focus mainly on single/

representative formations or short stratigraphic segments. Consequently, several aspects of the Late Carboniferous–Early Permian paleoenvironment remain unresolved, including: (1) whether facies changes across the Gaolishan-Huanglong-Chuanshan formations reflect coherent basin-wide environmental shifts or localized depositional variations; (2) how palaeoweathering, paleoclimate, redox conditions, salinity, paleowater depth and terrigenous input evolved through the entire interval; and (3) the lack of high-resolution studies integrating major-trace element geochemistry, petrography, and X-ray diffraction (XRD) mineralogy for these key formations. These limitations highlight the need for longer-term, integrative reconstruction that brings together mineralogical, petrographic, and geochemical evidence across these multiple stratigraphic units.

To address this gap, the present study employs a comprehensive multiproxy approach to decode the paleoenvironmental conditions recorded in the Late Carboniferous–Early Permian strata of Well CSDP-2 in the SYSB. By integrating petrographic observations, bulk mineralogical (XRD), and geochemical (major and trace elements) analyses with multivariate statistical tools, we aim to unravel variations in palaeoweathering, paleoclimate, redox conditions, salinity, terrigenous input, and paleowater depth. Geochemical proxies such as the Chemical Index of Alteration (CIA; Nesbitt and Young, 1982), redox-sensitive elemental ratios (e.g., V/Cr, Ni/Co; Hatch and Leventhal, 1992; Jones and Manning, 1994), and isotopic-based parameters (e.g., $\delta^{13}\text{C}$ -values; Keith and Weber, 1964) provide a robust framework for reconstructing these paleoenvironmental factors with high stratigraphic resolution.

Furthermore, microfacies analysis of carbonate intervals based on Dunham (1962) classification and Wilson's standard facies models enables precise interpretation of depositional settings and platform dynamics. The combined mineralogical, geochemical, and petrographic data sets are synthesized through principal component analysis (PCA) and cluster analysis to delineate compositional groupings and stratigraphic boundaries with enhanced clarity.

This integrated analysis offers new insights into the temporal and spatial evolution of environmental conditions in the SYSB and contributes to the broader understanding of Paleozoic marine basin development across the South China Block. The results have significant implications for interpreting sedimentary responses to paleoclimatic shifts and basin-scale tectonics during profound global change.

2 GEOLOGICAL SETTING

The South Yellow Sea Basin (SYSB), part of the South China Block, is a significant marginal marine basin situated between mainland China and the Korean Peninsula (Fig.2a–b) (Guo et al., 2019). It is structurally divided into two sub-basins—the Northern and Southern South Yellow Sea basins—separated by a central uplift zone (Gao et al., 2020). The SYSB evolved atop the Lower Yangtze Platform and contains a thick succession of marine Paleozoic to Middle Triassic strata overlain by Mesozoic–Cenozoic continental deposits (Lei et al., 2018; Gao et al., 2020).

The basin originated as a passive continental margin and later underwent multiple episodes of

tectonic modification during the Indosinian and Yanshanian orogenies (Lei et al., 2018). Its depositional history reflects complex interactions between tectonic subsidence, periodic uplift, and eustatic sea-level changes, producing a diverse stratigraphic record ranging from carbonate platform deposits to lagoonal, deltaic, and deep-marine sediments throughout the Paleozoic–Mesozoic (Cai et al., 2019; Gao et al., 2020; Chen et al., 2022).

During the Late Carboniferous–Early Permian, significant facies transitions occurred across the basin. The Chuanshan Formation (ca. 1 724–1 818 m) forming the uppermost part of the succession (Fig.1c), is dominated by thick-bedded dark gray to flesh-red limestones, occasionally interbedded with

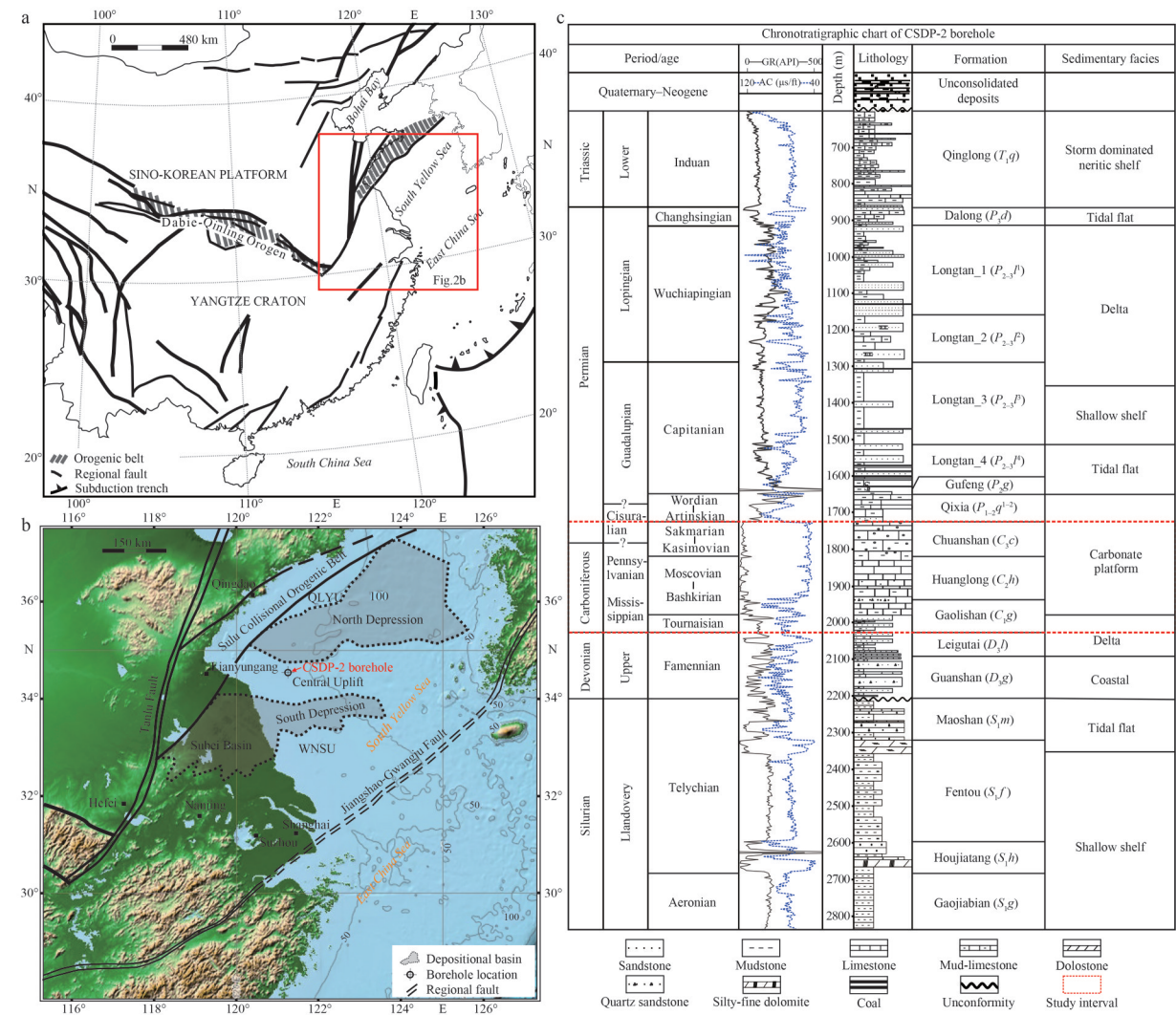


Fig.2 Map illustrates the South Yellow Sea Basin (SYSB), its tectonic units, and the location of the Well CSDP-2 (Pang et al., 2020) (a–b); vertical stratigraphic log of Well CSDP-2 in the SYSB (c), illustrating the succession from the Silurian to the Neogene

The dotted red line marks the stratigraphic interval investigated in this study.

micritic and bioclastic-rich beds (Cai et al., 2019, 2021; Pang et al., 2020). These facies reflect relatively deeper, low-energy carbonate platform conditions with limited siliciclastic input and possible influence from submarine hydrothermal activity. Stratigraphically beneath, the Huanglong Formation (ca. 1 818–1 940 m) consists of alternating gray, dark gray, and flesh-red limestones interbedded with fine-grained quartz sandstones. It represents a shallow-marine carbonate platform influenced by episodic terrigenous influx and sea-level fluctuations. At the base of the studied interval, the Gaolishan Formation (ca. below 1 940 m) comprises dolomite, mudstone, sandy mudstone, and quartz-rich sandstone with alternating oxidized and reduced color bands, reflecting a deltaic plain to marginal marine setting with higher detrital input (Cai et al., 2019, 2021; Pang et al., 2020).

Previous research on Well CSDP-2, drilled in the central uplift zone of the SYSB, has significantly advanced understanding of the region's Paleozoic petroleum systems. The well penetrated over 2 800 m of stratigraphy and revealed multiple hydrocarbon shows, oil staining, gas-logging anomalies, and abundant hydrocarbon-bearing fluid inclusions (Pang et al., 2021). Palynological and paleobotanical analyses correlated Devonian–Carboniferous strata with the Wutong Formation in southern Jiangsu and Nanjing (Guo et al., 2019, 2022). Geochemical and petrological investigations have established the Qixia and Gufeng formations as good to excellent source rocks, with moderate potential in the Longtan and Dalong formations, while the Gaolishan Formation is characterized by fine-grained, organic-rich sediments with fair to good source potential (Pang et al., 2020; Cai et al., 2021). Despite this progress, detailed sedimentological and paleoenvironmental reconstructions of the Late Carboniferous–Early Permian interval remains limited, highlighting the need for comprehensive multiproxy investigations, as conducted in the present study.

3 MATERIAL AND METHOD

The research utilized core samples from Well CSDP-2 situated in the South Yellow Sea near Lianyungang city, China (34°33'19"N, 121°15'41"E) at a distance of 100 km east. Stratigraphic intervals corresponding to the Gaolishan, Huanglong, Chuanshan, formations were systematically sampled for geochemical and petrographic analysis.

3.1 Major and trace element

A total of 43 representative core samples were selected for major and trace-element analysis, spanning a wide range of lithologies. Gaolishan Formation encompasses conglomeratic mudstone, bioclastic grainy mudstone, sandy-muddy micritic dolostone, and fine-grained lithic quartz sandstone (Supplementary Tables S1–S2). In the overlying Huanglong and Chuanshan formations include microcrystalline and fossiliferous micritic limestones, mud-bearing and argillaceous limestones, marlstones, and dolostones.

Samples are ground to <200 mesh using an agate mortar before analysis. Major oxides (SiO_2 , Al_2O_3 , Fe_2O_3 , MgO , CaO , Na_2O , K_2O , MnO , TiO_2 , and P_2O_5) are analyzed by X-ray fluorescence (XRF) with an Axios PW4400 spectrometer, achieving an analytical precision of <5%. Trace elements are determined by inductively coupled plasma mass spectrometry (ICP-MS) using a Thermo X Series 2 spectrometer. For ICP-MS, 50 mg of each powdered sample is digested in 30% HF and 68% HNO_3 at 190 °C for 24 h, then evaporated and redissolved in 2 mL of 6-mol/L HNO_3 . The solution is heated at 150 °C for 48 h, and 1 mL of 6-mol/L HNO_3 is added after further evaporation. ICP-MS precision is <0.1%.

3.2 XRD analysis of bulk minerals

XRD analysis was conducted on whole-rock (bulk) samples to determine their mineralogical composition. A total of 104 core samples were analyzed using bulk-rock XRD. These comprise mainly micritic dolostone together with sandy, bioclastic, fossiliferous micritic limestone and silty marlstone from the Gaolishan Formation and predominantly limestone from the Huanglong and Chuanshan formations (Supplementary Table S3). Samples were finely powdered using an agate mortar and pestle to ensure homogeneity before analysis. XRD measurements were performed using a Bruker D8 ADVANCE diffractometer equipped with a Cu-target X-ray tube and a graphite monochromator, operated at 35 kV and 40 mA. Diffraction patterns were recorded over a 2θ range of 5° to 60° with a step size of 0.02°. Mineral identification and semi-quantitative analysis were done using Bruker Diffra Plus EVA software.

3.3 Petrography

Point counting was performed exclusively on thin sections from sandstone beds to quantify the relative abundance of quartz, feldspar, and lithic

fragments. A total of 19 core samples were examined petrographically. These include fine, medium, and coarse-grained quartz sandstone, as well as mud-bearing lithic quartz sandstone from the Gaolishan and Huanglong formations (Supplementary Table S3). A minimum of 300 points per sample was recorded using a grid-based method. The compositional data were used for petrofacies classification and to infer the provenance and depositional settings of the siliciclastic units.

Microfacies analysis was conducted on standard thin sections (48 mm×28 mm) prepared from representative carbonate samples ($n=30$) of Huanglong and Chuanshan formations. Observations were made under transmitted light using a Leica M80 petrographic microscope to characterize textures, allochems, and matrix/cement relationships. Facies classification followed Dunham (1962) scheme, identifying key carbonate textures such as mudstone, wackestone, packstone, and grainstone. Detailed petrographic examination emphasized the identification of bioclasts—particularly fusulinids—as well as peloids, ooids, intraclasts, and other allochems relevant to depositional interpretation.

3.4 Multivariate statistical analysis

PCA was performed on the quantitative bulk XRD mineralogical data (wt.%) to reduce dimensionality and identify major patterns of mineralogical variation among samples (Supplementary Table S3). The analysis used the correlation matrix to standardize variables, given differing mineral abundance scales. The first few principal components were retained based on eigenvalues (>1.0) and broken-stick criteria, and loading scores were used to interpret mineral associations driving variance.

Cluster analysis was applied using the Neighbor Joining algorithm with Mahalanobis similarity index, which accounts for variance and covariance among variables, making it suitable for multivariate mineralogical data. The resulting dendrogram visualizes sample groupings based on mineralogical dissimilarity, allowing comparison with stratigraphic formation boundaries. All multivariate analyses were conducted using PAST (Paleontological Statistics) software, version 3.

4 RESULT

4.1 Major and trace element

4.1.1 Major element geochemistry

Major element concentrations across the Late

Carboniferous to Early Permian formations in the SYSB exhibit distinct compositional variations. The Gaolishan Formation is characterized by elevated silicate content and relatively low CaO in many samples, along with the highest observed ranges in MgO, TFe_2O_3 , and TiO_2 among the three formations (Supplementary Table S1). This unit displays the widest geochemical spread overall.

In contrast, the Huanglong Formation presents a broader geochemical range, with noticeable variability in carbonate (CaO) and silicate (SiO_2 , Al_2O_3) components. Iron and alkali oxides (TFe_2O_3 , K_2O , Na_2O) also show moderate variability.

The Chuanshan Formation shows generally high CaO and low silicate contents (e.g., SiO_2 and Al_2O_3), reflecting a narrow compositional spectrum with low overall variability for most oxides (Supplementary Table S1). These geochemical characteristics reflect significant lithological and compositional differences between formations.

4.1.2 Trace element geochemistry

Trace element concentrations reveal considerable compositional variability among the Chuanshan, Huanglong, and Gaolishan formations. The Gaolishan Formation shows higher average values for trace elements, including Zr, V, Nb, Cu, Co, and Th (Supplementary Table S2). Elements like Cr and Ni are moderately concentrated, while Sr and Ba show moderate levels compared to the extremes seen in Huanglong. Scandium and thorium exhibit the highest average values in this unit, accompanied by broad ranges.

In the Huanglong Formation, trace element abundances are highly variable, especially for Ba and Cr, which show wide ranges (Supplementary Table S2). This formation also exhibits moderate to high concentrations of Rb, Zr, V, and Nb. Notably, Ba displays an extreme range with a high average. Cu, Hf, Co, Sc, Th, and Mo show higher mean values than the Chuanshan Formation.

The Chuanshan Formation exhibits relatively consistent trace element levels, with moderate enrichment in Sr, Ba, and Rb (Supplementary Table S2). Transition metals such as Cr, Ni, and V are generally low, as are high field strength elements like Nb, Zr, and Hf. Heavy metals including Cu and U remain minor, while Co, Sc, Th, and Mo are all present in trace amounts with limited variability. Overall, the trace element profiles reflect distinct geochemical characteristics across the three formations, with increasing variability and concentration levels from Chuanshan to Gaolishan.

4.2 Mineralogy from XRD, petrographic point-counting, and microfacies

4.2.1 Bulk mineralogy

XRD analysis reveals distinct inter-formational differences in bulk mineralogy across Gaolishan, Huanglong, and Chuanshan formations (Supplementary Table S3; Fig.3a). All three formations are dominated by carbonate minerals, with calcite and

dolomite as the primary phases. Calcite remains consistently abundant in all formations, whereas dolomite shows considerable variability—especially in the Gaolishan and Chuanshan formations. In contrast, the Huanglong Formation is marked by uniformly high dolomite content with moderately varying calcite.

Clay minerals are present in all formations, with relatively higher enrichment in the Huanglong and

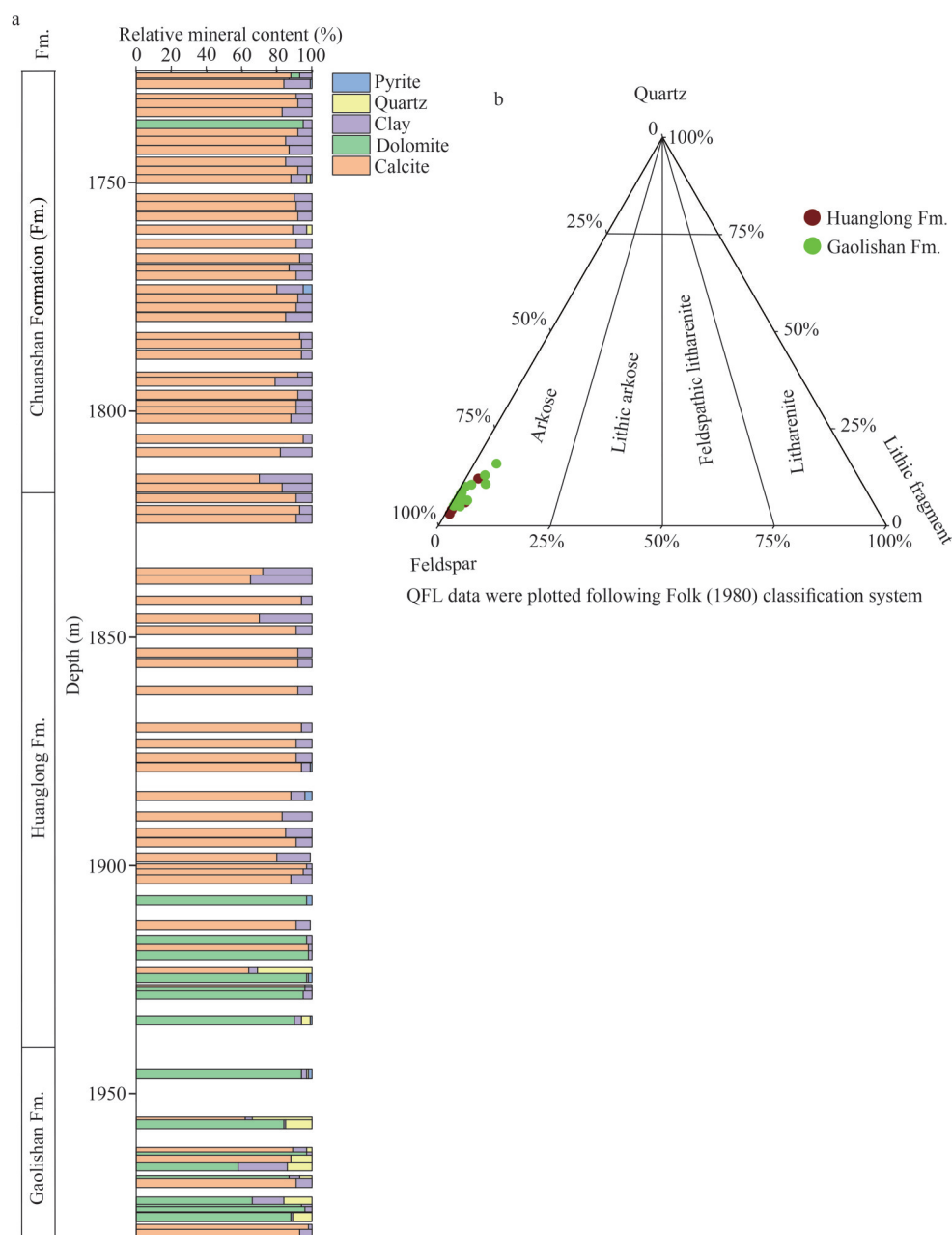


Fig.3 Bulk XRD mineralogy (wt.%) vs. depth (m) for Chuanshan (CSF), Huanglong (HLF), and Gaolishan (GSF) formations (a), calcite dominates CSF/HLF, while GSF is richer in dolomite, quartz, and clay; QFL ternary plot (Folk, 1980) (b) showing HLF and GSF sandstones in arkose/lithic arkose fields

Source data is provided in Supplementary Table S3.

Chuanshan formations. Quartz content is minimal in the Chuanshan Formation but becomes increasingly significant in the Huanglong and Gaolishan formations. Pyrite appears consistently in trace to minor amounts, with limited inter-formational variation. Figure 3a effectively visualizes the relative proportions of these major mineral phases, highlighting both the dominance of carbonates and the mineralogical heterogeneity among the formations.

4.2.2 Petrographic point-counting

Petrographic point-counting of thin sections from sandstone beds in the Gaolishan and Huanglong formations reveals that quartz is the dominant framework grain, indicating high compositional maturity (Supplementary Table S3; Fig.3b). Feldspar occurs in consistently low proportions, while lithic fragments show greater variability and are relatively more abundant in the Gaolishan samples.

Figure 3b depicts the classification of framework grains using QFL (Quartz-Feldspar-Lithic fragment) ternary diagrams based on standard sandstone classification schemes. The plotted samples from both formations predominantly fall within the arkose and arkosic arenite fields, reflecting quartz-rich and feldspathic compositions consistent with mature, recycled sedimentary sources.

4.2.3 Microfacies type

Thick-bedded limestone is extensively developed in the Carboniferous strata of Well CSDP-2 in the South Yellow Sea. Based on core and thin-section observations, grain types, matrix composition, and fossil content, the carbonate rocks from the Huanglong to Chuanshan formations are classified into seven microfacies types according to Dunham (1962) classification. These microfacies reflect environmental changes in the study area.

4.2.3.1 MF-1: micrite/bioclastic micrite

Micrite and bioclastic micrite primarily comprise micritic calcite (Fig.4a–d). Grain structures are almost unobservable, with occasional traces of foraminifera, ostracods, or intraclasts. The grain content is less than 10% and mainly distributed in the middle part of the Huanglong Formation and the upper part of the Chuanshan Formation.

4.2.3.2 MF-2: bioclastic wackestone

Bioclastic wackestone consists mainly of micritic calcite and bioclasts (Fig.4e–f). The bioclasts include fusulinids, non-fusulinid foraminifera, ostracods,

echinoderms, brachiopods, gastropods, and a few bryozoans and calcareous sponge spicules. Bioclasts are often micritized, with content ranging from 10% to 40%. This microfacies is widespread in both the Huanglong and Chuanshan Formations.

4.2.3.3 MF-3: bioclastic sandy wackestone

This microfacies consists of micritic calcite, bioclasts (mainly crinoid stems), and a small number of sand-sized debris (Fig.4g). The sand grains are small and embedded in the micrite, with a total volume fraction under 10%. Fractures are filled with aggregates of sparry calcite crystals. This type is mainly found in the lower Huanglong Formation.

4.2.3.4 MF-4: bioclastic packstone

This microfacies comprises bioclasts and micritic calcite (Fig.4h–i). Bioclasts include fusulinids, non-fusulinid foraminifera, ostracods, echinoderms, gastropods, etc., with a grain content exceeding 50%. This microfacies is widely developed in the Huanglong and Chuanshan Formations

4.2.3.5 MF-5: bioclastic grainstone

Bioclastic grainstone mainly comprises bioclasts and sparry calcite or micritic calcite (Fig.5a–d). The grain content exceeds 50%, consisting mostly of biological fragments, which are cemented by sparry or micritic calcite. Bioclasts include fusulinids and non-fusulinid foraminifera. Most fossil fragments are small, relatively well-preserved, and partially micritized.

4.2.3.6 MF-6: peloidal grainstone

This microfacies is composed of well-sorted, small-sized peloids and sparry calcite (Fig.5e–f). The peloids are sub-rounded to elliptical and cemented by sparry calcite without any micritic matrix. Peloidal grainstone is distributed mainly in the middle to lower parts of the Huanglong Formation.

4.2.3.7 MF-7: oolitic or oncoidal grainstone

This microfacies is primarily composed of oncoids and sparry calcite (Fig.6a–b). The oncoids are mostly elliptical and larger than 5 mm in diameter. They are cemented by sparry calcite without any micritic matrix. This microfacies occurs only in a few intervals in the lower-upper part of the Chuanshan Formation.

4.3 PCA and cluster analysis

PCA of the bulk XRD mineralogical data yielded

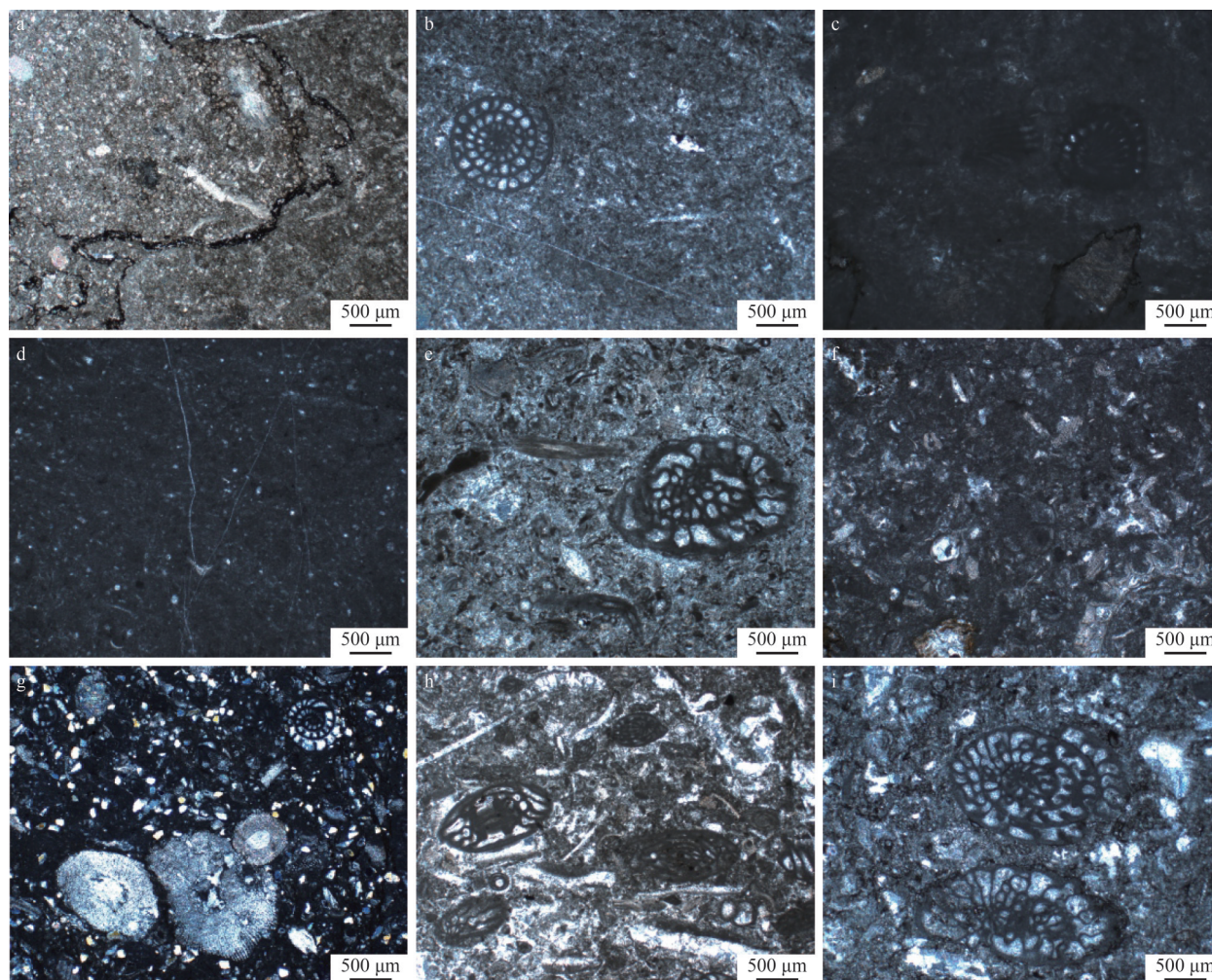


Fig.4 Carboniferous–Early Permian carbonate microfacies types (Part I) in Well CSDP-2, South Yellow Sea

a. 1 737.5 m: mudstone from the Chuanshan Formation; b. 1 753.5 m: bioclastic mudstone from the Chuanshan Formation; c. 1 820.3 m: mudstone from the Huanglong Formation; d. 1 871.6 m: mudstone from the Huanglong Formation; e. 1 758.7 m: bioclastic wackestone from the Chuanshan Formation; f. 1 859.5 m: bioclastic wackestone from the Huanglong Formation; g. 1 933 m: sandy bioclastic wackestone from the Huanglong Formation; h. 1 732.9 m: bioclastic packstone from the Chuanshan Formation; i. 1 853.9 m: bioclastic packstone from the Huanglong Formation.

four significant components with eigenvalues greater than 0.7, collectively explaining 93.82% of the total variance. PC1 accounts for 39.02% of the variance and is characterized by high positive loading for calcite (0.88) and clay (0.59), and a strong negative loading for dolomite (-0.83), reflecting a carbonate-clay compositional gradient (Supplementary Table S4). PC2 (21.11% variance) is primarily defined by high positive loading for pyrite (0.82) and a negative loading for quartz (-0.61), suggesting an association between sulfide content and reduced silicate input. PC3 (19.08%) shows strong contributions from quartz (0.63), clay (0.57), and pyrite (0.43), indicative of a mixed terrigenous signal. PC4 (14.61%) is moderately influenced by clay (0.55) and dolomite (0.39), highlighting further variation within carbonate-clay

relationships.

The dendrogram generated using the Neighbor Joining clustering algorithm based on Mahalanobis similarity indices reveals three distinct mineralogical clusters corresponding to the Gaolishan (GSF), Huanglong (HLF), and Chuanshan (CSF) formations (Fig.7). Depth numbers are color-coded by formation: bisque for GSF, cyan for HLF, and black for CSF. GSF samples (bisque) are separated from the other formations and occupy the leftmost portion of the dendrogram, forming a tightly grouped, compositionally coherent cluster. HLF samples (cyan) appear in discrete clusters that partially overlap with CSF but maintain distinguishable branch paths. Samples from CSF (black) are predominantly clustered toward the right and lower-middle portions of the dendrogram, indicating

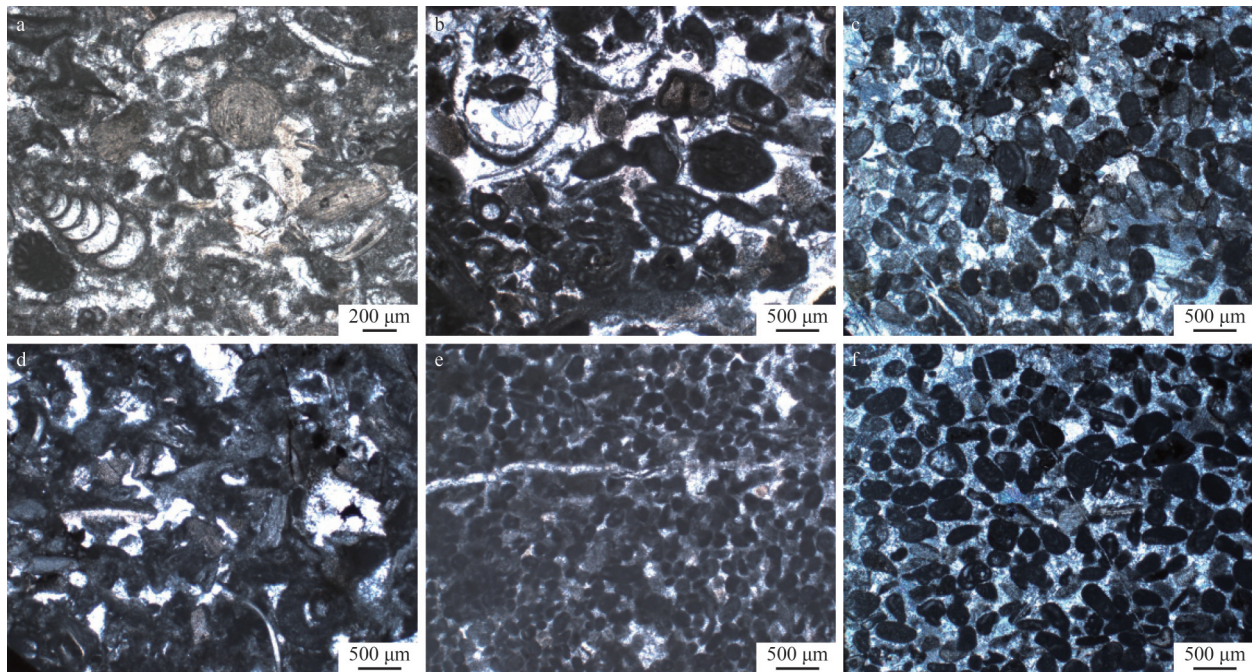


Fig.5 Carboniferous–Early Permian carbonate microfacies types (Part II) in Well CSDP-2, South Yellow Sea

a. 1 725.3 m: bioclastic grainstone from the Chuanshan Formation; b. 1 804.68 m: bioclastic grainstone from the Chuanshan Formation; c. 1 899 m: bioclastic grainstone from the Huanglong Formation; d. 1 901.4 m: bioclastic grainstone from the Huanglong Formation; e. 1 916.7 m: peloidal grainstone from the Huanglong Formation; f. 1 918.1 m: peloidal grainstone from the Huanglong Formation.

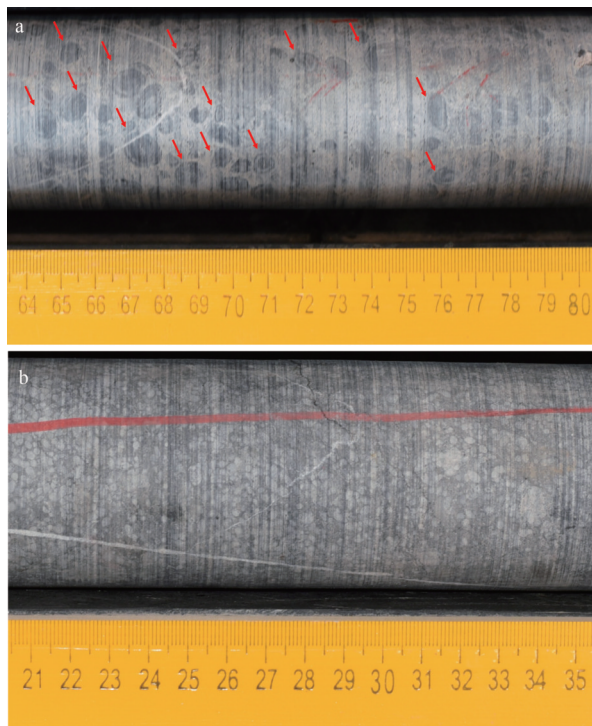


Fig.6 Typical horizons of oncolitic and peloidal limestones in the Carboniferous–Early Permian strata of Well CSDP-2, South Yellow Sea

a. 1 736.04–1 736.2 m: oncolitic limestone from the Chuanshan Formation; b. 1 807.01–1 807.17 m: peloidal limestone from the Chuanshan Formation.

internal mineralogical consistency. The clustering pattern highlights the formation-specific distribution of bulk XRD mineralogical compositions.

5 DISCUSSION

5.1 Geochemical constraint on paleo-depositional environment

5.1.1 Palaeoweathering index and paleoclimate

A suite of palaeoweathering indices (CIA, CIW, PIA, CIX and CPA) were used to characterize source-area chemical alteration and to avoid reliance on a single proxy (Supplementary Table S5). CIA was computed as molar $[Al_2O_3/(Al_2O_3+K_2O+Na_2O+CaO^*)] \times 100$ (Nesbitt and Young, 1982) and widely applied proxy for assessing chemical weathering intensity. Here, CaO^* represents only silicate-bound Ca; phosphate and carbonate-derived Ca were excluded using the procedure of McLennan (1993), where $CaO_{rest} = CaO - (10/3) \times P_2O_5$, and CaO^* is set to CaO_{rest} when $CaO_{rest} < Na_2O$, otherwise to Na_2O . To limit bias from post-depositional K addition, CIA* was obtained through A-CN-K projection (Yang et al., 2018; Lv et al., 2022): samples displaced toward the K apex were shifted back to the A-CN join at constant Al_2O_3 . Only limited adjustment was needed

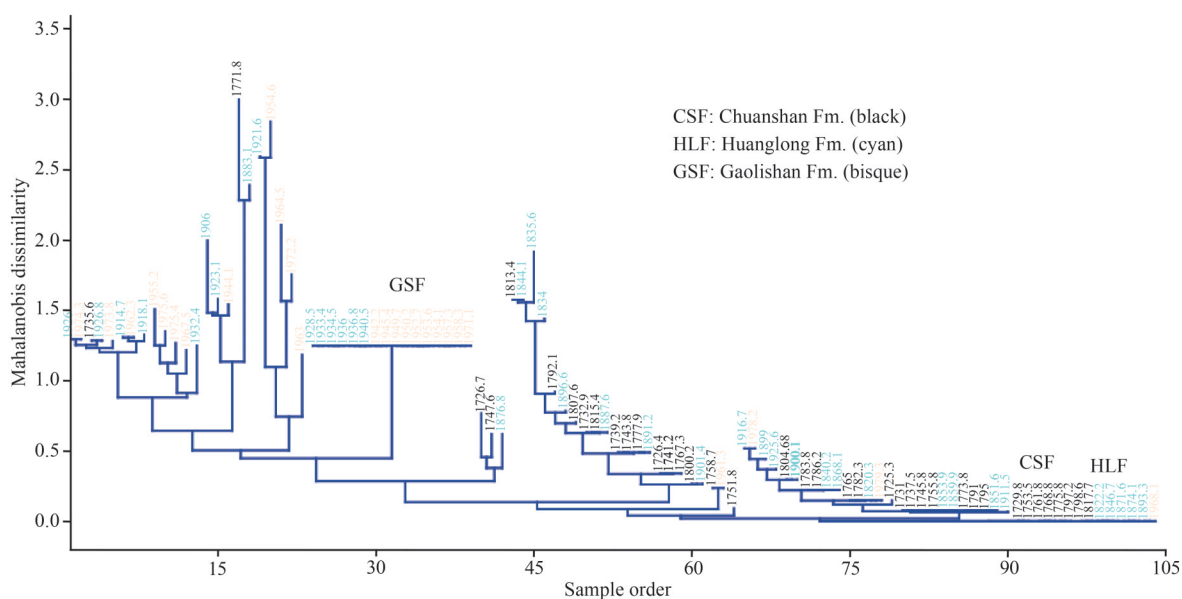


Fig.7 Dendrogram generated using Neighbor Joining clustering based on the Mahalanobis similarity index for bulk XRD mineral data

The y-axis indicates multivariate dissimilarity between clusters, while the x-axis represents the arbitrary sample order determined by the clustering sequence. Depth numbers are color-coded by formation for clarity: black for Chuanshan Formation, cyan for Huanglong Formation, and bisque for Gaolishan Formation.

(Fig.8), implying weak K metasomatism and supporting CIA* as a closer approximation to primary weathering intensity (Lv et al., 2022; Sun et al., 2026).

The statistical summary (Supplementary Table S5) indicates a stepwise enhancement of weathering from the Chuanshan to Huanglong and Gaolishan formations. Mean CIA increases from 59 to 65 and 76, mirrored by CIW (62→69→85) and PIA (60→67→83), while CIX and CPA rise in parallel. Accordingly, the Chuanshan-Huanglong-Gaolishan

formations record a progressive intensification of source-area chemical alteration, culminating in consistently higher palaeoweathering index values in the Gaolishan interval (Supplementary Table S5).

Because bulk indices can be perturbed by non-climatic processes, provenance, recycling and sorting effects were screened using standard cross-plots (Sun et al., 2026). Provenance was tested with $\text{Al}_2\text{O}_3/\text{TiO}_2$, which tracks felsic-mafic source composition because Al_2O_3 is preferentially hosted by felsic phases whereas TiO_2 is associated with

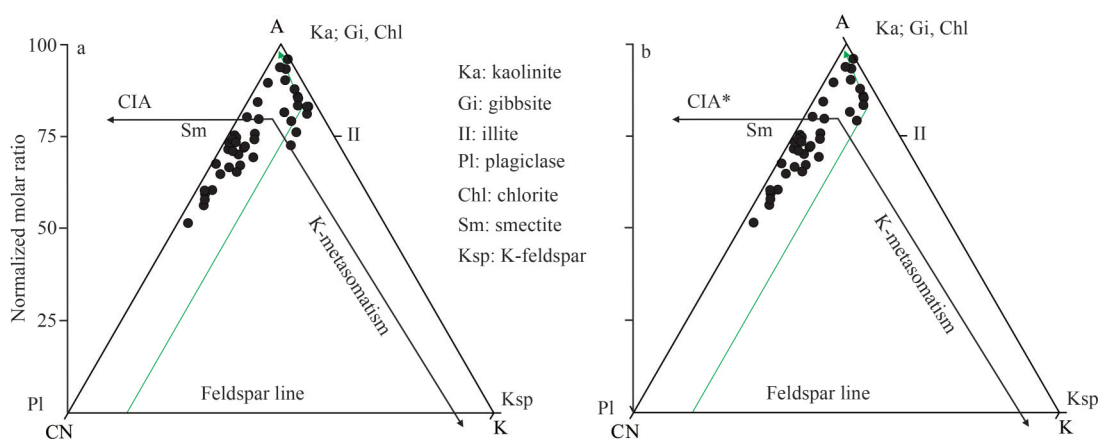


Fig.8 A-CN-K ternary diagram for the siliciclastic-carbonate succession of Well CSDP-2, with most samples plotting in the low-weathering field along the inferred silicate trend (a); recalculated CIA* after excluding a few K-enriched points to minimize diagenetic bias (b)

A. Al_2O_3 , CN: $\text{CaO}^* + \text{Na}_2\text{O}$, K: K_2O , CIA: chemical index of alteration, CIA*: corrected CIA. Source data are provided in Supplementary Table S1.

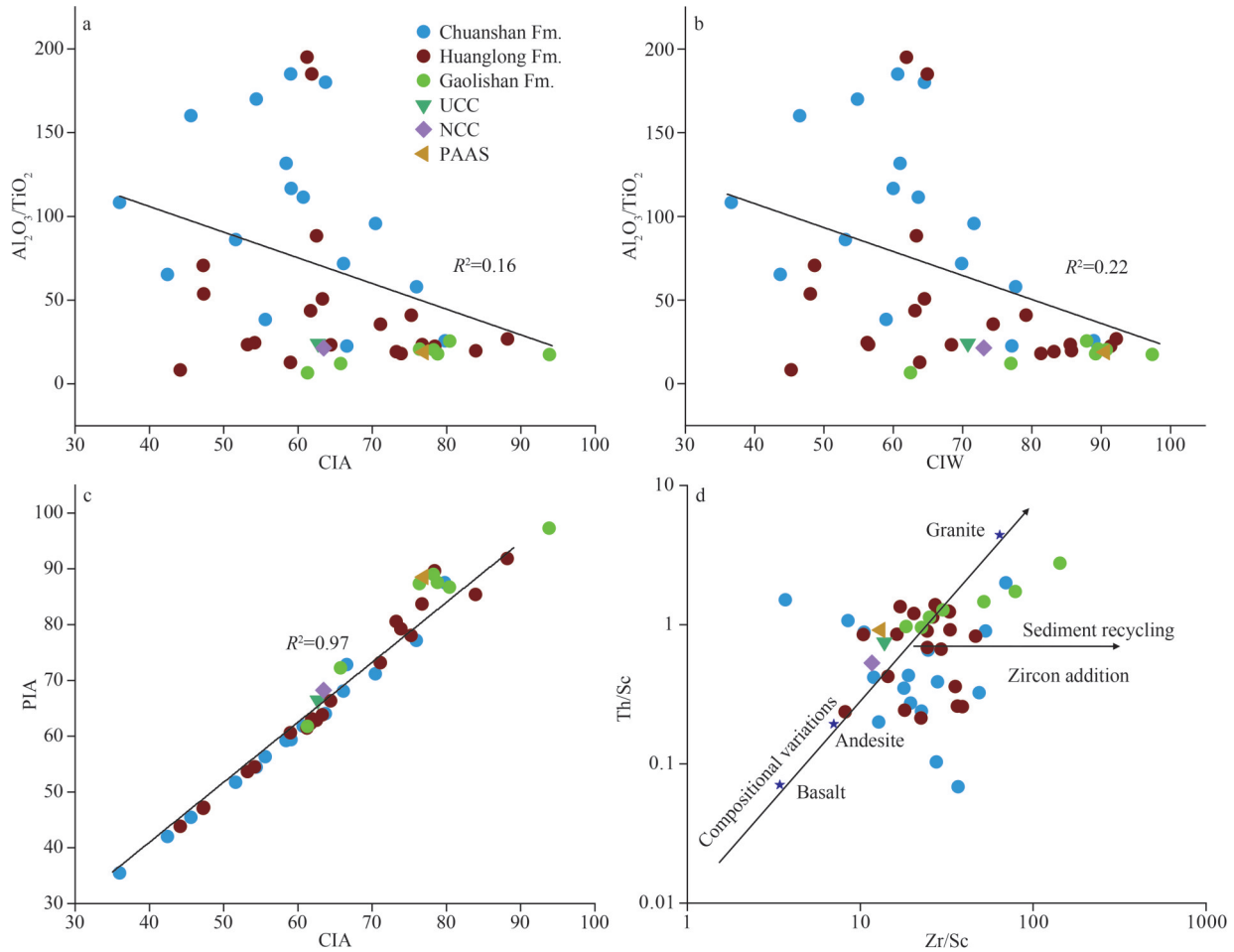


Fig.9 Cross-plots of $\text{Al}_2\text{O}_3/\text{TiO}_2$ versus CIA and CIW showing weak relationships, indicating minimal provenance control on weathering indices of study formations (a–b); bivariate plots of PIA versus CIA and Th/Sc versus Zr/Sc plot illustrating compositional variation and clustering around upper-crustal reference fields, including the Upper Continental Crust (UCC: Rudnick and Gao, 2014), North China Craton (NCC: Gao et al., 1998), and Post-Archean Australian Shale (PAAS: Taylor and McLennan, 1985), with no pronounced zircon enrichment, suggesting negligible influence of sediment recycling (c–d)

Source data are provided in Supplementary Tables S1–S2.

mafic components, and both are largely immobile during transport (Moosavirad et al., 2011; Yang et al., 2018; Sun et al., 2026). The weak $\text{Al}_2\text{O}_3/\text{TiO}_2$ relationships with CIA and CIW ($R^2=0.16\text{--}0.22$) indicate that the weathering-index rise is not primarily a provenance-mixing effect (Fig.9a–b). The near-perfect PIA–CIA linear trend ($R^2\approx 0.97$) supports a primary weathering control (Fig.9c), with no indication of recycling-related decoupling of alteration indices (Lv et al., 2022; Sun et al., 2026). Recycling was also evaluated using Th/Sc–Zr/Sc, where zircon enrichment elevates Zr/Sc with little change in Th/Sc (Cox et al., 1995; Roddaz et al., 2005), the absence of a strong drift toward high Zr/Sc suggests minimal recycling influence (Fig.9d). Sorting was assessed with $\text{Al}_2\text{O}_3/\text{SiO}_2$ against CIA

and CIW because quartz-clay fractionation modifies bulk chemistry (Roddaz et al., 2006; Lv et al., 2022; Sun et al., 2026). The low explanatory power of these plots ($R^2=0.27\text{--}0.34$) supports weak sorting control (Fig.10). Collectively, these checks indicate that the down-section increase in CIA–CIW–PIA–CIX–CPA mainly reflects a real intensification of source-area chemical weathering rather than secondary overprints from provenance variability, sediment recycling or sorting.

Paleoclimate conditions during the deposition of the Chuanshan, Huanglong and Gaolishan formations were evaluated using multiple geochemical proxies, including CIA, Sr/Cu, Rb/Sr, and the C-value. The CIA values for the Chuanshan and Huanglong formations average 59 and 65, respectively,

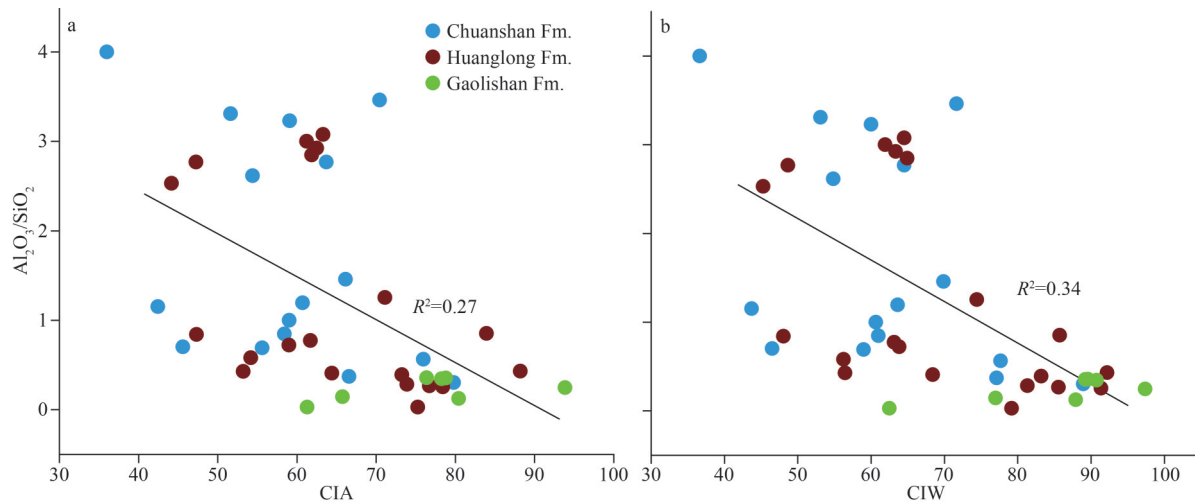


Fig.10 Cross-plots of $\text{Al}_2\text{O}_3/\text{SiO}_2$ versus CIA and CIW showing weak associations, indicating limited sorting control on weathering indices

indicating dominantly arid to arid-cold climates with relatively weak chemical weathering (Table 1 and references therein). This is supported by high Sr/Cu ratios (Chuanshan: avg. 114; Huanglong: avg. 71), exceeding the arid-cold threshold of >10 . Similarly, low Rb/Sr ratios (avg. 0.03 and 0.09) further suggest dry paleoclimatic conditions.

The use of Sr/Cu and Rb/Sr as paleoclimate indicators assumes that most Sr is hosted by silicate and clay minerals rather than by carbonate phases, because Sr enriched in carbonates can raise Sr/Cu and lower Rb/Sr, mimicking an arid signal that is not driven by continental weathering (Wei and Algeo, 2020; Sun et al., 2024, 2026). To check this assumption for our section, we compared Sr with CaO, taking CaO as a proxy for carbonate content. It shows a weak positive correlation ($R^2=0.34$), which points to some carbonate control on Sr but also indicates that a substantial share of Sr resides in non-carbonate (silicate/clay) hosts (Fig.11a). On this

basis, we regard Sr/Cu and Rb/Sr as applicable paleoclimate proxies in this dataset. The generally coherent evolution of all these indices suggests that, despite partial carbonate influence, Sr/Cu and Rb/Sr still reflect the first-order climatic changes recorded by the studied siliciclastic carbonate succession.

The C -value, calculated as $C = \Sigma(\text{Fe} + \text{Mn} + \text{Cr} + \text{Ni} + \text{V} + \text{Co}) / \Sigma(\text{Ca} + \text{Mg} + \text{Sr} + \text{Ba} + \text{K} + \text{Na})$ (Chen et al., 2024), reflects the contrast between immobile and mobile elements. The Chuanshan and Huanglong formations exhibit a low C -value average of 0.02 and 0.1, consistent with cold-dry conditions (Table 1). Overall, these proxies point to a predominantly arid to arid-cold climatic regime during the deposition of both formations.

The C -value index is sensitive to the mobility of major cations during chemical weathering, but its climatic interpretation can be biased where Ca is supplied by carbonate minerals rather than silicates. To minimise this effect, followed the approach of

Table 1 Paleoclimate proxies for the Chuanshan, Huanglong, and Gaolishan formations, with interpretative thresholds indicating weathering intensity and paleoclimatic conditions (thresholds from published literature)

Proxy	Common threshold (paleoclimate)	Chuanshan (range/avg.)	Interpretation (Chuanshan)	Huanglong (range/avg.)	Interpretation (Huanglong)	Gaolishan (range/avg.)	Interpretation (Gaolishan)
CIA	<70 (arid-cold), 70–80 (warm-humid), >80 (hot-humid) (Nesbitt and Young, 1982; Ma et al., 2015)	36–80/59	Arid-cold	44–88/65	Arid-cold	61–94/76	Warm-humid
Sr/Cu	>10 (arid-cold), 1–10 (humid) (Lerman, 1978; Liu and Zhou, 2007)	11–194/114	Arid-cold	4–184/71	Arid-cold	1–297/78	Arid-cold
Rb/Sr	Low (dry), high (humid) (Chen et al., 2000; Fu et al., 2018)	0.002–0.30/0.03	Dry	0.002–0.76/0.09	Dry	0.003–0.77/0.21	Dry
C -value	>0.2 (warm-humid) (Chen et al., 2024)	0.003–0.21/0.02	Dry-cold	0.004–0.6/0.1	Dry-Cold	0.03–2.92/0.88	Warm-humid

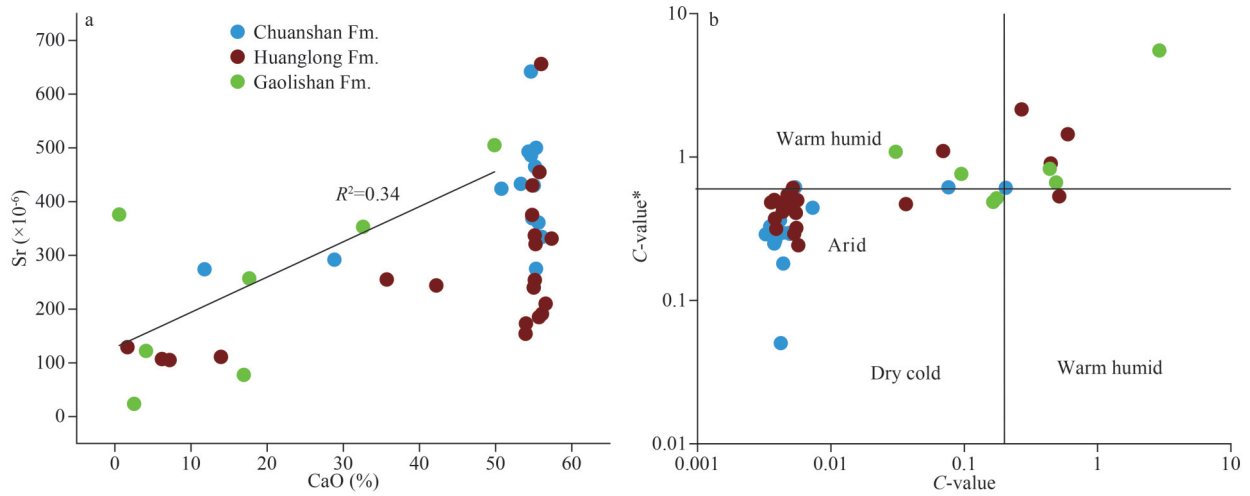


Fig.11 Bivariate diagrams of Sr vs. CaO and C-value* vs. C-value illustrating the influence of carbonate-derived components on climate-sensitive proxies

Sun et al. (2026) and recalculated the index using CaO^* , representing the silicate-derived component of Ca obtained after removing carbonate Ca through mass-balance correction. This adjustment reduces the influence of lithology on the numerator of the index and yields a corrected parameter (C-value*) that more faithfully reflects primary weathering intensity and climate (Fig.11b). K-metasomatism is minor in the study samples. The resulting C-value* exhibits more internally coherent behavior and aligns closely with independent paleoclimate proxies, supporting its application to this siliciclastic carbonate succession.

To further assess paleoclimatic conditions, cross-plots of key geochemical proxies were employed (Fig.12). In the CIA vs. Sr/Cu plot (Fig.12a), the majority of samples from both the Chuanshan and Huanglong formations fall within the arid-cold climatic regime ($\text{CIA} < 70$ and $\text{Sr/Cu} > 10$), consistent with limited chemical weathering. However, a subset of Huanglong samples trends toward the warm-humid and hot-humid fields ($\text{CIA} > 70$), suggesting episodic intensification of chemical weathering, possibly due to climatic fluctuations or stratigraphic variations. The Chuanshan Formation remains more tightly constrained within the arid-

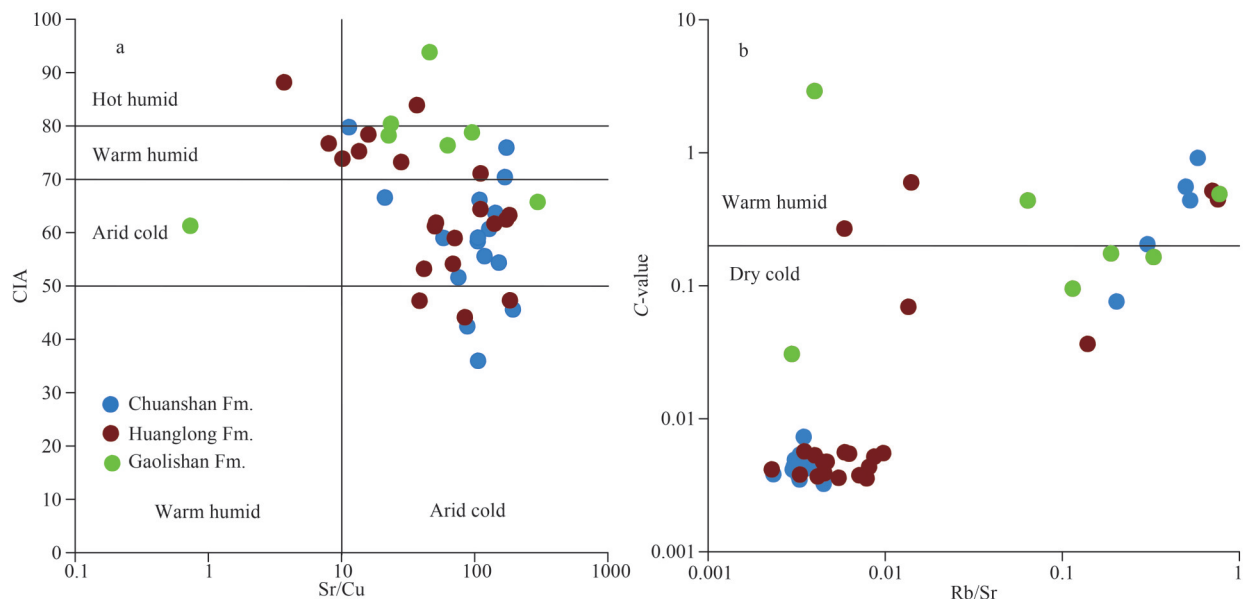


Fig.12 Paleoclimate proxies (CIA vs. Sr/Cu and C-value vs. Rb/Sr) for the Chuanshan, Huanglong, and Gaolishan formations, illustrating variations in weathering intensity and climatic conditions

cold field, supporting persistent cold and dry conditions during deposition, except for a few warm-humid samples indicating episodic warmer intervals.

In Fig.12b, low *C*-values and Rb/Sr ratios for most Chuanshan samples reinforce this interpretation, although a few exceed 0.2. Conversely, the Huanglong Formation displays a broader spread, with several samples—also above 0.2—indicative of a more chemically active setting (Table 1; Fig.12b). These results collectively imply a shift from predominantly arid and cold climates in the Chuanshan and Huanglong formations.

The Gaolishan Formation, in contrast, displays geochemical characteristics indicative of significantly warmer and more humid paleoclimatic conditions. As summarized in Table 1, the formation exhibits a higher average CIA value (76), with several samples exceeding 80, placing them in the hot-humid regime. Although the Sr/Cu ratio (avg. 78) is generally aligned with arid-cold thresholds. The Rb/Sr ratio (avg. 0.21) is substantially higher than in the Chuanshan and Huanglong formations, indicating higher chemical weathering intensity and increased humidity. Most notably, the *C*-value average of 0.88 is well above the warm-humid threshold (>0.2), reflecting enhanced geochemical activity and mobilization of redox-sensitive elements.

In Fig.12a, Gaolishan samples extend into the warm-humid and hot-humid fields, while in Fig.12b, they are separated by higher Rb/Sr and *C*-values, clustering in the warm-humid zone. These data collectively suggest that the Gaolishan Formation was deposited under significantly more humid and chemically dynamic conditions, distinguishing it from the arid-cold regimes of the overlying units.

Vertically, the stratigraphic succession from the Gaolishan Formation (below 1 940 m) through the Huanglong Formation (1 940–1 818 m) to the Chuanshan Formation (1 818–1 724 m) exhibits a clear trend of climatic deterioration, marked by a progressive decline in CIA values and increase in Sr/Cu ratios (Fig.13). This shift reflects a long-term transition from warm-humid conditions with intense chemical weathering in the Gaolishan Formation to transitional cold-arid phases and weakly weathered conditions in the Huanglong and Chuanshan formations, based on vertical stratigraphic trend of paleoclimate proxies (i.e., CIA and Sr/Cu).

5.1.2 Paleoredox condition

The paleoredox conditions of the Chuanshan, Huanglong, and Gaolishan formations were

evaluated using commonly applied geochemical proxies, including V/Cr, V/(V+Ni), Ni/Co, Th/U, and U/Th (Table 2 and references therein). These proxies provide valuable insights into bottom-water oxygenation, trace metal enrichment, and redox-controlled sedimentary processes. In the Chuanshan Formation, the average values of V/Cr (0.50) and V/(V+Ni) (0.37) are indicative of dominantly oxic depositional conditions, supported by their narrow ranges (0.17–1.53 and 0.16–0.73, respectively), which lie below dysoxic and anoxic thresholds (Table 2). Conversely, the Ni/Co (11.47), Th/U (0.56), and U/Th (24.14) values suggest an anoxic environment, with the wide U/Th range (0.27–129.23) highlighting possible fluctuations in redox conditions. This apparent contradiction among proxies implies that the formation was deposited under largely oxic background conditions, intermittently disrupted by localized anoxic microenvironments, possibly driven by organic matter hotspots or variable bottom-water oxygenation.

In contrast, the Huanglong Formation shows a V/Cr average of 0.72 and V/(V+Ni) average of 0.40, both of which point toward a transition between oxic and dysoxic conditions (Table 2). The Ni/Co (8.54) and U/Th (8.36) averages fall within the anoxic range, while the Th/U ratio (1.62) indicates dominantly dysoxic conditions. The broader ranges of several proxies (e.g., Th/U=0.02–9.38; U/Th=0.11–52.04) demonstrate considerable redox variability within the formation.

The Gaolishan Formation, in contrast to the two overlying units, generally reflects more oxic redox conditions. The average V/Cr (1.46) and Ni/Co (2.38) values are below the dysoxic threshold, indicating deposition under oxygenated conditions (Table 2). However, the V/(V+Ni) ratio (avg. 0.68) lies in the anoxic range, suggesting the presence of localized reducing environments. This mixed signal is further illustrated by Th/U (avg. 4.68)—falling within the dysoxic range—and U/Th (avg. 0.33), supporting an oxic interpretation. Collectively, these proxies suggest that the Gaolishan Formation was deposited under predominantly oxic conditions, but with potential episodic development of dysoxic to anoxic microenvironments influenced by redox stratification or variable organic input.

In the V/(V+Ni) vs. V/Cr plot (Fig.14a), most Chuanshan and Huanglong samples fall within the oxic field, whereas several Huanglong samples shift into the dysoxic and anoxic zones. Similarly, the

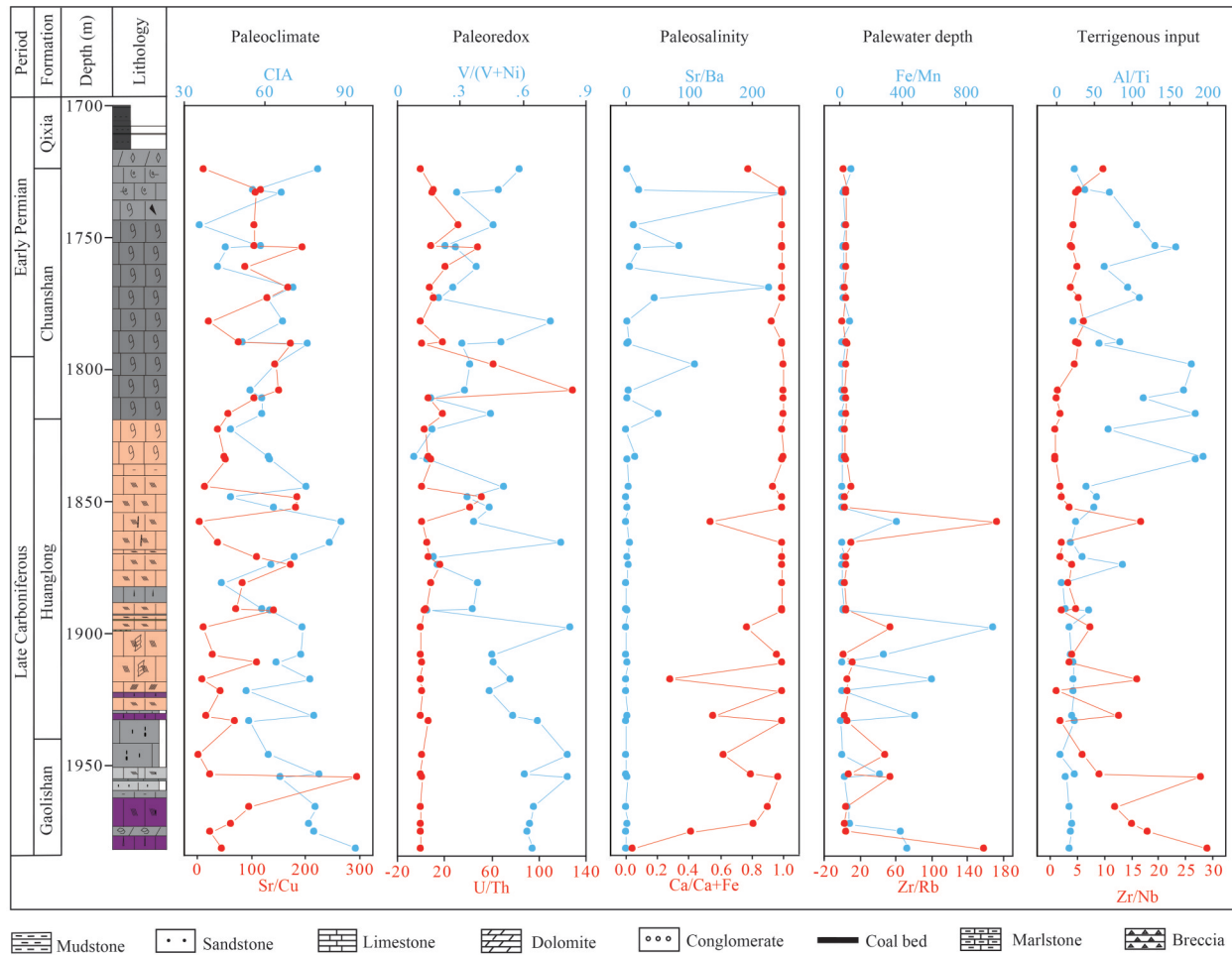


Fig.13 Vertical stratigraphic profile illustrating variations in paleoenvironmental proxies (e.g., Paleoclimate, Paleoredox etc.) across the Chuanshan, Huanglong, and Gaolishan formations

Table 2 Paleoredox proxies for the Chuanshan, Huanglong and Gaolishan formations, with threshold ranges and redox interpretations based on average and range values

Proxy	Common thresholds (redox conditions)	Chuanshan (range/avg.)	Interpretation (Chuanshan)	Huanglong (range/avg.)	Interpretation (Huanglong)	Gaolishan (range/avg.)	Interpretation (Gaolishan)
V/Cr	<2 (oxic), 2–4 (dysoxic), >4 (anoxic) (Jones and Manning, 1994)	0.17–1.53/ 0.50	Oxic	0.17–3.43/ 0.72	Oxic	0.77–2.87/ 1.46	Oxic
V/(V+Ni)	<0.46 (oxic), 0.46–0.60 (dysoxic), >0.60 (anoxic) (Hatch and Leventhal, 1992)	0.16–0.73/ 0.37	Oxic	0.08–0.83/ 0.40	Oxic-dysoxic	0.61–0.82/ 0.68	Anoxic
Ni/Co	<5 (oxic), 5–7 (dysoxic), >7 (anoxic) (Jones and Manning, 1994)	2.96–23.52/ 11.47	Anoxic	2.36–15.88/ 8.54	Anoxic	1.93–3.11/ 2.38	Oxic
Th/U	>7 (oxic), 2–7 (dysoxic), <2 (anoxic) (Adams and Weaver, 1958)	0.01–3.65/ 0.56	Anoxic	0.02–9.38/ 1.62	Dysoxic	1.23–7/ 4.68	Dysoxic
U/Th	<0.75 (oxic), 0.75–1.25 (dysoxic), >1.25 (anoxic) (Jones and Manning, 1994)	0.27–129.23/ 24.14	Anoxic	0.11–52.04/ 8.36	Anoxic	0.14–0.81/ 0.33	Oxic

U/Th vs. Ni/Co plot (Fig.14b) reveals persistently higher values for Chuanshan samples, confirming reducing depositional conditions, while Huanglong samples exhibit a wider spread that reflects redox

fluctuations. Gaolishan samples plot mainly within the oxic field, consistent with proxy averages, but with isolated points reaching dysoxic boundaries (Fig.14a–b). These trends collectively indicate

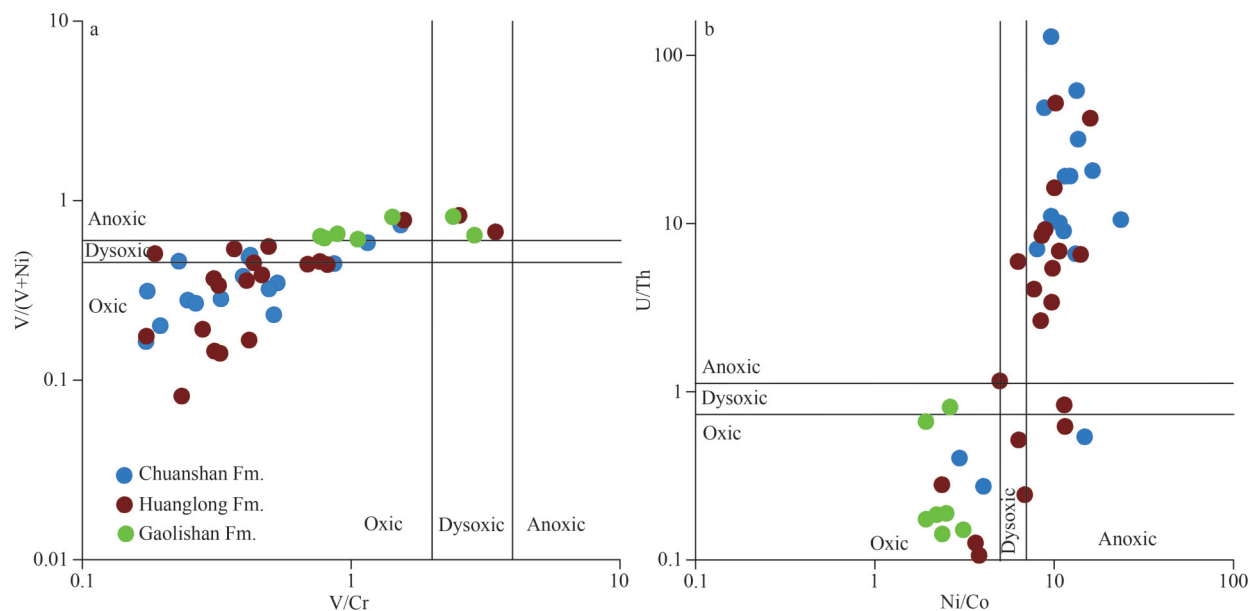


Fig.14 Paleoredox proxies ($V/(V+Ni)$) vs. V/Cr and U/Th vs. Ni/Co in the Chuanshan, Huanglong and Gaolishan formations, showing variations from oxic to anoxic depositional conditions

progressive redox variability through time, modulated by bottom-water oxygenation and organic productivity.

Vertically, the stratigraphic succession from the Gaolishan Formation through the Huanglong Formation to the Chuanshan Formation reflects a shift from stable oxic conditions to more reducing depositional environments (Fig.13). The Gaolishan Formation represents predominantly oxic-anoxic conditions by vertical stratigraphic trend of U/Th and $V/(V+Ni)$ (Fig.13). Similarly, the Huanglong Formation shows sustained dysoxic to anoxic conditions, and the Chuanshan Formation reflects a return to variable oxic settings punctuated by intermittent anoxia. This vertical redox trend suggests a dynamic interplay between sedimentary redox processes, organic matter input, and water column oxygenation during basin evolution.

By the reassessment of elemental redox proxies by Algeo and Liu (2020), we adopt a formation-specific, multiproxy strategy rather than relying on single parameters or universal thresholds. For each formation, paleoredox conditions are constrained by the combined behavior of V/Cr , $V/(V+Ni)$, Ni/Co , Th/U , and U/Th together with carbonate microfacies, lithofacies, and mineralogical data. In the Gaolishan Formation, the coherent signal from these proxies, coupled with siliciclastic-dominated lithofacies, higher weathering and quartz contents, and elevated average SiO_2 (Supplementary Tables S1 & S3), supports predominantly oxic, shallow-shelf conditions under a warm-humid climate. By contrast, in the

Huanglong and Chuanshan formations, most proxies indicate more reducing conditions, and the integrated response of U/Th , $V/(V+Ni)$, other trace-metal ratios, and facies characteristics points to overall dysoxic-anoxic bottom waters.

As highlighted by Algeo and Liu (2020), trace element enrichment factors serve as robust proxies for reconstructing paleoredox conditions. Enrichment factor profiles of key metals (Cr_{EF} , Co_{EF} , Cu_{EF} , Ni_{EF} , U_{EF} , V_{EF}) from the Gaolishan, Huanglong, and Chuanshan Formations reveal temporal shifts in redox states (Supplementary Fig.S1). The Gaolishan Formation exhibits low enrichment, consistent with oxidizing conditions, while the Huanglong Formation shows higher enrichment, indicative of reducing conditions (Supplementary Fig.S1). The Chuanshan Formation reflects moderate enrichment, suggesting dysoxic-anoxic conditions. These patterns emphasize the necessity of a multiproxy approach to refine the understanding of paleoredox dynamics.

5.1.3 Paleosalinity

The paleosalinity conditions of the Chuanshan, Huanglong and Gaolishan formations were assessed using multiple geochemical proxies, including Sr/Ba , Mg/Ca , $Ca/(Ca+Fe)$, and the isotopic-derived Z value (Table 3 and references therein). The weak $Sr-CaO$ correlation ($R^2=0.34$) indicates that Sr is not overwhelmingly carbonate-bound (Fig.11a), supporting the use of Sr/Ba as a robust paleosalinity proxy in this succession (Wei and Algeo, 2020). In the

Chuanshan Formation, Sr/Ba ratios range from 1 to 250 with an average of 56, clearly indicating a marine depositional setting (Table 3). The Mg/Ca ratio remains low (0.005–0.14; avg. 0.02), consistent with cold and saline conditions that favor calcite precipitation, as described by Morse et al. (1997). The Ca/(Ca+Fe) ratio exceeds 0.8 across all samples, reinforcing the interpretation of a saline environment. The Z value, calculated using the empirical equation $Z = 2.048 \times (\delta^{13}\text{C} + 50) + 0.498 \times (\delta^{18}\text{O} + 50)$ (Keith and Weber, 1964), ranges from 121 to 136 with an average of 132, further supporting a fully marine setting ($Z \geq 120$).

In contrast, the Huanglong Formation exhibits a broader range in salinity indicators. Sr/Ba ratios span from 0.1 to 14 with an average of 2, suggesting a transition from brackish to marine conditions. The Mg/Ca ratio shows wider variability (0.002–1.80; avg. 0.12), indicative of cold and slightly hypersaline environments. The Ca/(Ca+Fe) ratio ranges from 0.28 to 1.0 (avg. 0.9), straddling the brackish-saline boundary. The Z values range from 116 to 130 with an average of 122, supporting a generally marine depositional setting, though with some influence from freshwater or restricted circulation.

The Gaolishan Formation shows additional variability. Sr/Ba values range from 0.1 to 1.0, with an average of 1, indicating brackish conditions, right at the threshold. In contrast, Mg/Ca values range from 0.007 to 2.80 with an average of 0.64, suggesting cold and hypersaline conditions. The Ca/(Ca+Fe) ratio ranges from 0.04 to 1.0 (avg. 0.7), placing the formation in the brackish-saline regime. Although Z values are unavailable for Gaolishan, the combined Sr/Ba and Mg/Ca signals suggest a variable salinity environment, potentially controlled by restricted marine inflow or episodic evaporation.

In the Sr/Ba vs. Mg/Ca plot (Fig.15a),

Chuanshan samples cluster in the marine to cold-saline field, marked by high Sr/Ba (>3) and low Mg/Ca (<0.1). Huanglong samples display a wider spread across the brackish-freshwater and slightly hypersaline zones, reflecting salinity variability. Gaolishan samples show lower Sr/Ba values (~ 1) but significantly higher Mg/Ca, clustering in the cold-hypersaline region. In the Z vs. Ca/(Ca+Fe) plot (Fig.15b), nearly all Chuanshan samples fall above the marine thresholds ($Z \geq 120$; Ca/(Ca+Fe) > 0.8), confirming deposition in stable marine waters. Huanglong samples show more scatter, with some trending toward brackish-freshwater conditions (Ca/(Ca+Fe) < 0.8 ; $Z \approx 116$ –123).

Vertically, the stratigraphic succession from the Gaolishan Formation through the Huanglong Formation to the Chuanshan Formation reveals a transition from fluctuating brackish-hypersaline conditions in Gaolishan Formation to intermittent brackish-marine conditions in Huanglong Formation and finally to stable marine saline environments in Chuanshan Formation, based on the vertical stratigraphic trend of Paleosalinity proxies (Fig.13). This upward trend suggests progressive marine transgression and salinity stabilization, likely reflecting improved marine connectivity and reduced continental influence.

5.1.4 Paleowater depth

To evaluate the paleowater depth of the Chuanshan, Huanglong and Gaolishan formations within a marine depositional context, a suite of geochemical proxies was applied. These proxies include elemental ratios such as Fe/Mn, (Fe+Al)/(Ca+Mg), Zr/Rb, (Zr+Rb)/Sr, and Rb/K, each of which reflects variations in hydrodynamic conditions, clastic input, and sediment grain size (Table 4 and references therein). To ensure that these ratios record paleowater depth rather than

Table 3 Paleosalinity proxies for the Chuanshan and Huanglong formations, with threshold ranges and interpretations based on average and range values

Proxy	Thresholds & interpretation	Chuanshan (range/avg.)	Interpretation (Chuanshan)	Huanglong (range/avg.)	Interpretation (Huanglong)	Gaolishan (range/avg.)	Interpretation (Gaolishan)
Sr/Ba	<1 (freshwater), 1–3 (brackish), >3 (marine) (Wang et al., 2021; Xiao et al., 2021)	1–250/56	Marine	0.1–14/2	Brackish-marine	0.1–1/1	Brackish
Mg/Ca	Low=cold and saline, high=warm/hypersaline (Morse et al., 1997)	0.005–0.14/0.02	Cold and saline	0.002–1.80/0.12	Cold and slightly hypersaline	0.007–2.80/0.64	Cold and hypersaline
Ca/(Ca+Fe)	<0.4 (freshwater), 0.4–0.8 (brackish), >0.8 (saline) (Nelson, 1967; Kumar et al., 2024)	0.8–1.0/0.98	Saline	0.28–1.0/0.9	Brackish-saline	0.04–1.0/0.7	Brackish-saline
Z	<120 (freshwater), ≥ 120 (marine) (Keith and Weber, 1964; Wang et al., 2024)	121–136/132	Marine	116–130/122	Marine		

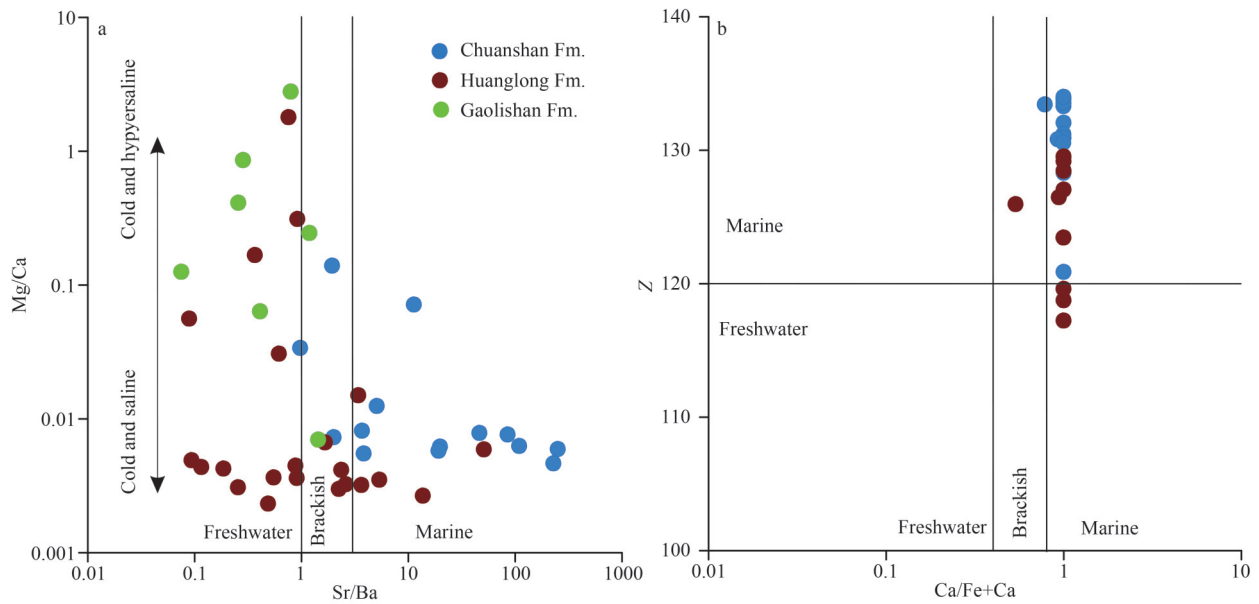


Fig.15 Paleosalinity proxies (Mg/Ca vs. Sr/Ba and Z vs. Ca/Fe+Ca) in the Chuanshan, Huanglong, and Gaolishan formations, demonstrating variations from stable marine to fluctuating brackish conditions

Table 4 Paleowater depth proxies for the Chuanshan, Huanglong and Gaolishan formations

Proxy	Common interpretation (with references)	Chuanshan (range/avg.)	Interpretation (Chuanshan)	Huanglong (range/avg.)	Interpretation (Huanglong)	Gaolishan (range/avg.)	Interpretation (Gaolishan)
Fe/Mn	<100=deeper marine; 100–150=semi-deep; >150=shallow marine (Chen et al., 2008; Wang et al., 2025)	13–77/30	Deeper marine shelf environment	8–973/146	Shallow marine shelf with high variability	18.6–428/178	Shallow marine shelf with high variability
(Fe+Al)/(Ca+Mg)	↓ ratio=deeper marine (carbonate-rich); ↑ ratio=shallower (terrigenous-dominated) (Chen et al., 2008; Wang et al., 2025)	0.01–1.37/0.11	Carbonate-rich deeper shelf	0.01–4.60/0.57	Terrigenous influence, shallower setting	0.07–13.47/2.84	Terrigenous influence, shallower setting
Zr/Rb	↑ ratio=coarser detrital input (shallower); ↓ ratio=finer sediments (deeper) (Dypvik and Harris, 2001; Cao et al., 2020; Zhang et al., 2023)	1.0–6.4/4.17	Moderately shallow marine shelf	1.63–173/16	Shallow shelf, episodic high-energy input	3.2–157/40	Shallow shelf, episodic high-energy input
Zr+Rb/Sr	↑ ratio=more clastics, less carbonate (shallower); ↓ ratio=carbonate-rich (deeper) (Dypvik and Harris, 2001)	0.02–0.82/0.10	Carbonate-dominated setting	0.01–4/1.00	Siliciclastic-rich marine setting	0.0.2–4/2	Siliciclastic-rich marine setting
Rb/K	↓ ratio=more feldspar (deeper); ↑ ratio=more clays (shallower), sensitive to clay input and weathering (Zhang et al., 2023)	0.003–0.04/0.01	Limited clay input, deeper marine	0.000 2–0.03/0.01	Limited clay input, shallow marine	0.000 3–0.003/0.002	Limited clay input, shallow marine

changes in sediment provenance, the covariance of key terrigenous indicators. Al_2O_3 and TiO_2 show a strong positive correlation ($R^2=0.86$), indicating a stable siliciclastic source throughout the succession (Supplementary Fig.S2). Mn is effectively decoupled from Al ($R^2=0.05$), consistent with dominantly authigenic enrichment controlled by redox structure and water-column stratification. In contrast, Fe exhibits a moderate correlation with Al ($R^2=0.57$), reflecting a largely detrital component (Supplementary Fig.S2). This partitioning implies that variations in Fe/Mn and related ratios are governed chiefly by

redox conditions, hydrodynamic regime, and carbonate-siliciclastic balance rather than by shifts in provenance, supporting their use as paleowater-depth proxies.

The Fe/Mn ratio, a redox-sensitive proxy, indicates relative water depth due to its association with bottom-water oxygenation and detrital input. In marine settings, lower Fe/Mn ratios (<100) typically reflect deeper, more stable depositional environments, while higher values (>150) are indicative of shallower, oxygenated, high-energy marine shelf settings (Chen et al., 2008; Wang et al., 2025). The

Chuanshan Formation displays Fe/Mn values ranging from 13 to 77 (avg. 30), consistent with a relatively deeper marine shelf setting (Table 4). In contrast, the Huanglong Formation exhibits a much wider Fe/Mn range (8–973, avg. 146), indicating greater variability and deposition in more transitional to shallow shelf environments.

The ratio of $(\text{Fe}+\text{Al})/(\text{Ca}+\text{Mg})$ distinguishes terrigenous (Fe, Al) versus carbonate (Ca, Mg) input. Lower values reflect carbonate-rich, deeper marine environments, whereas higher values suggest terrigenous-dominated, shallower water conditions (Chen et al., 2008; Wang et al., 2025). In the Chuanshan Formation, values remain low (0.01–1.37; avg. 0.11), indicating a carbonate-dominated deeper shelf. Conversely, the Huanglong Formation exhibits a higher average (0.01–4.60; avg. 0.57), suggesting increased terrigenous input and shallower conditions.

The Gaolishan Formation exhibits further variability, with Fe/Mn ratios ranging from 18.6 to 428 (avg. 178), exceeding the shallow marine threshold (Table 4). Similarly, the $(\text{Fe}+\text{Al})/(\text{Ca}+\text{Mg})$ ratio ranges widely from 0.07 to 13.47 (avg. 2.84), indicating a strong terrigenous influence and shallower marine setting. These proxy values suggest that the Gaolishan Formation was deposited in a high-energy, shallow shelf environment, influenced by strong clastic input and possible proximity to terrestrial sources.

This differentiation is illustrated in Fig.16a,

where Chuanshan samples cluster in the deep marine carbonate zone (low Fe/Mn and $(\text{Fe}+\text{Al})/(\text{Ca}+\text{Mg})$), while Huanglong and Gaolishan samples plot across broader areas, with many extending into the shallow, terrigenous-dominated zone, indicating progressively shallower and more dynamic environments.

Additional support comes from Zr/Rb and $(\text{Zr}+\text{Rb})/\text{Sr}$ ratios. Zirconium is associated with coarse-grained detritus, while Rb and Al are enriched in fine-grained clays. Higher Zr/Rb and $(\text{Zr}+\text{Rb})/\text{Sr}$ values correspond to coarse detrital input typical of shallow, high-energy settings, whereas lower values suggest deeper, low-energy conditions (Dypvik and Harris, 2001; Yin et al., 2017; Cao et al., 2020; Zhang et al., 2023). The Chuanshan Formation shows moderate Zr/Rb values (1.0–6.4; avg. 4.17), suggesting limited detrital influx in a deeper setting. In contrast, the Huanglong Formation exhibits much higher values (1.63–173; avg. 16), and the Gaolishan Formation even higher (3.2–157; avg. 40), reflecting coarse sediment input and episodic high-energy depositional events.

The $(\text{Zr}+\text{Rb})/\text{Sr}$ ratio, which reflects siliciclastic versus carbonate input, follows a similar pattern. Chuanshan samples maintain low values (0.02–0.82; avg. 0.10), supporting a carbonate-dominated shelf. In contrast, Huanglong (0.01–4; avg. 1.00) and Gaolishan (0.02–4; avg. 2.00) samples exhibit higher ratios, consistent with increased siliciclastic

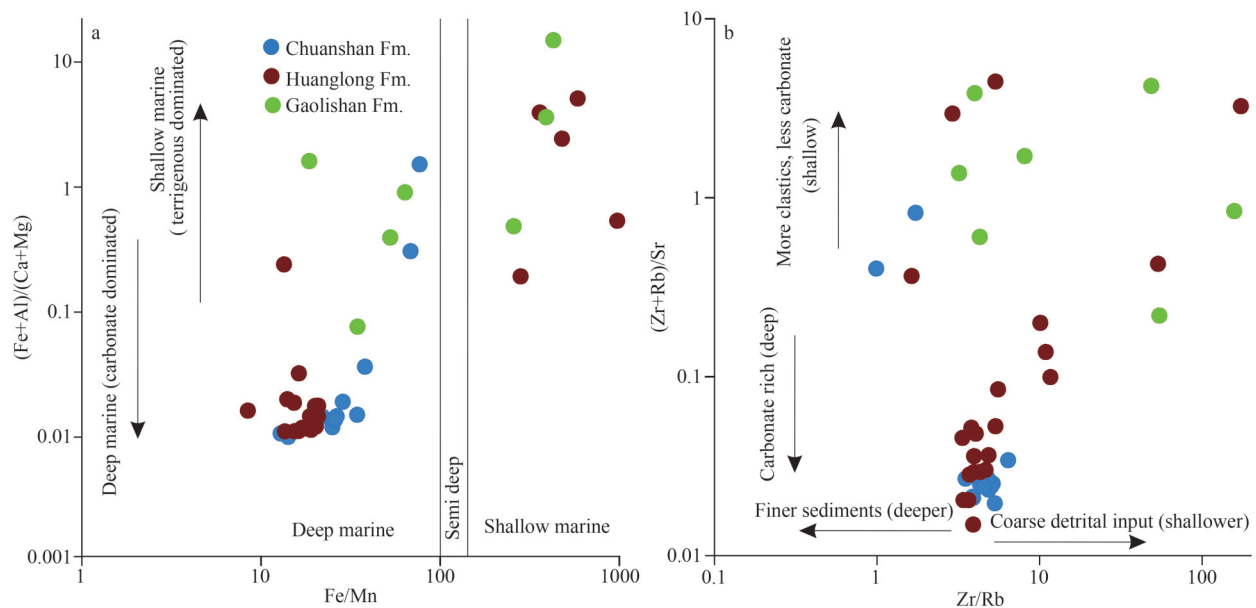


Fig.16 Paleowater depth proxies (Fe/Mn vs. $(\text{Fe}+\text{Al})/(\text{Ca}+\text{Mg})$ and Zr/Rb vs. $(\text{Zr}+\text{Rb})/\text{Sr}$) in the Chuanshan, Huanglong and Gaolishan formations, demonstrating variations from deeper carbonate shelf to shallower, siliciclastic-influenced environments

contributions under shallower marine conditions.

In the Zr/Rb vs. (Zr+Rb)/Sr plot (Fig.16b), Chuanshan samples cluster in the lower-left field, associated with finer sediments and carbonate-rich deep-water settings. Huanglong and Gaolishan samples plot more widely, with many occupying the upper and right portions of the diagram, suggesting increased detrital influx and shallower water deposition.

Importantly, the Rb/K ratio was evaluated in light of XRD-determined average clay mineral contents—11% in the Chuanshan Formation and 9% in the Huanglong Formation and 7% in Gaolishan Formation. These levels are sufficiently high to support the application of Rb/K as a clay-related proxy. The Rb/K ratio, a proxy for clay input and weathering, also supports these trends. All three formation samples display low Rb/K values, indicative of lower clay content and deeper to shallower carbonate settings, respectively (Table 4).

Vertically, the stratigraphic succession from the Gaolishan Formation through the Huanglong Formation to the Chuanshan Formation reflects a clear deepening trend, based on the vertical stratigraphic trend of paleowater depth proxies (Fig.13). The Gaolishan Formation records deposition under shallow, terrigenous-rich, high-energy shelf conditions, followed by the Huanglong Formation, which represents a transitional setting with greater variability and episodic high-energy input. The Chuanshan Formation marks the deepest, most stable carbonate-rich marine shelf environment, with limited siliciclastic influx and fine-grained, low-energy sedimentation. This vertical evolution suggests a progressive shift from nearshore, high-energy environments to a deeper, quiescent marine setting during basin development.

5.1.5 Terrigenous input

Terrigenous input refers to the influx of land-derived detrital material into sedimentary environments and plays a significant role in determining the bulk geochemical composition and depositional facies of sedimentary rocks. Such input is primarily influenced by surface processes such as river runoff, storm activity, and aeolian transport, all of which affect the grain size and mineralogy of sediments (Mansour et al., 2024). Terrigenous components are typically characterized by a suite of major and trace elements, particularly Al, titanium (Ti), silicon (Si), and zirconium (Zr), which are associated with silicate minerals, clays, and heavy minerals. As such, elemental ratios involving these elements—such as Al/Ti, Si/Al, Zr/Nb, and Zr/Al—have become widely accepted as proxies for tracking detrital input, grain size variability, and sediment source proximity (Table 5 and references therein).

The Al/Ti ratio reflects the balance between clay-rich inputs (high Al) and coarse-grained, heavy mineral components (Ti), and is therefore useful for distinguishing fine versus coarse terrigenous fractions (Murphy et al., 2000; Tian et al., 2011). The Si/Al ratio is commonly applied as a proxy for the relative abundance of quartz and feldspar (Si-bearing minerals) to clay minerals (Al-rich), where higher values indicate greater siliciclastic influx and coarser material, and lower values correspond to more clay-rich or carbonate-influenced settings (Ratcliffe et al., 2012; Zeng et al., 2015). Zr/Nb is another key ratio; Zr is typically enriched in detrital zircon (coarse grains), while Nb is associated with finer clay minerals like illite. Hence, Zr/Nb effectively captures changes in grain size and terrigenous flux, largely unaffected by biogenic

Table 5 Terrigenous input proxies for the Chuanshan, Huanglong and Gaolishan formations

Proxy	Common threshold (literature-based)	Chuanshan (range/avg.)	Interpretation (Chuanshan)	Huanglong (range/avg.)	Interpretation (Huanglong)	Gaolishan (range/avg.)	Interpretation (Gaolishan)
Al/Ti	Al in clays (illite/kaolinite), Ti in heavy minerals (rutile, ilmenite) high ratio=clay-rich input (Murphy et al., 2000; Tian et al., 2011)	23–185/ 102	Moderate clay-dominated input	8–195/49	Mixed input, some coarse detritus	7–26/17	Low clay- dominated input
Si/Al	High=quartz-rich siliciclastic input; low=clay or carbonate dominated (Ratcliffe et al., 2012; Zeng et al., 2015)	0.3–3.3/1.1	Low siliciclastic input	0.3–34.6/ 3.4	Moderate siliciclastic influx	2.8–34.6/ 8.9	High siliciclastic influx
Zr/Nb	Zr in coarse zircon grains; Nb in illite (clay); high ratio=coarse detritus, low=clay-rich (Ratcliffe et al., 2012; Mansour et al., 2024)	1.2–9.8/4.4	Moderate detrital grain size	0.9–17/4.6	Moderate detrital grain size	5.9–29/ 16.7	High detrital grain size
Zr/Al (×10 ³)	Zr in heavy minerals (zircon); Al in clays; high ratio=coarse, proximal input (Zeng et al., 2015; Mansour et al., 2024)	0.9–2.5/1.8	Intermediate detrital input	0.9–3.6/ 1.8	Intermediate detrital input	1.9–5.6/ 2.7	Coarse, proximal detritus

silica interference (Ratcliffe et al., 2012; Mansour et al., 2024). Likewise, Zr/Al ratios are used to assess the proportion of coarse, heavy-mineral input relative to clay-bound aluminum, serving as a proxy for both grain size and proximity to the source area (Zeng et al., 2015; Mansour et al., 2024).

The Chuanshan Formation is characterized by relatively high Al/Ti values (23–185; avg. 102), indicative of a moderate clay-dominated terrigenous input (Table 5; Fig.13). Its Si/Al ratio (0.3–3.3; avg. 1.1) suggests a low siliciclastic content, while the Zr/Nb (1.2–9.8; avg. 4.4) and Zr/Al $((0.9–2.5) \times 10^{-3}$; avg. 1.8) ratios indicate moderate grain size and an intermediate distance from the sediment source. Collectively, these proxies suggest that the Chuanshan Formation was deposited in a relatively low-energy marine environment with fine-grained detrital supply, consistent with a more distal depositional setting.

In contrast, the Huanglong Formation displays significantly different geochemical characteristics. The Al/Ti ratio is lower (8–195; avg. 49), while Si/Al values are markedly higher (0.3–34.6; avg. 3.4), indicating a greater influx of siliciclastic material (Table 5; Fig.3b). Similarly, the Zr/Nb (0.9–17; avg. 4.6) and Zr/Al $((0.9–3.6) \times 10^{-3}$; avg. 1.8) values reflect moderate detrital grain sizes and slightly more energetic depositional conditions relative to the Chuanshan Formation. These trends imply that the Huanglong Formation experienced mixed input conditions, with pulses of higher-energy sediment delivery and greater proximity to terrestrial sources.

The Gaolishan Formation, in comparison, exhibits a distinct geochemical fingerprint. Al/Ti values are the lowest (7–26; avg. 17), implying minimal clay input and a dominance of coarser sediments. Its Si/Al ratio (2.8–34.6; avg. 8.9) is the highest among the three formations, suggesting a strong siliciclastic influx. Furthermore, both Zr/Nb (5.9–29; avg. 16.7) and Zr/Al $((1.9–5.6) \times 10^{-3}$; avg. 2.7) values are elevated, reflecting coarse-grained detritus from proximal sources (Fig.13). These signatures support interpretation of the Gaolishan Formation as having been deposited under high-energy conditions with strong terrigenous input, likely close to the sediment source.

These observations are consistent with stratigraphic trends in detrital enrichment. High Si/Al and Zr/Nb values have previously been linked to regressive systems tracts and maximum regressive surfaces (MRS), while decreasing trends are associated with transgressive phases and maximum flooding

surfaces (MFS) (Ratcliffe et al., 2012). In the current dataset, the transition from coarse, proximal detritus in the Gaolishan Formation to moderate siliciclastic input in the Huanglong Formation, followed by clay-dominated fine sediments in the Chuanshan Formation, marks a clear upward fining trend, likely reflecting a transgressive depositional sequence driven by rising sea level and shoreline retreat.

5.2 Multivariate mineralogical differentiation and stratigraphic clustering of carbonate-siliciclastic succession

The integration of bulk XRD, petrographic, and statistical analyses reveal coherent mineralogical and compositional trends across the Chuanshan (CSF), Huanglong (HLF), and Gaolishan (GSF) formations. As illustrated in the bulk mineralogical bar graph (Fig.3a), CSF and HLF are dominated by calcite, while GSF exhibits elevated dolomite, quartz, and clay contents, indicative of increased siliciclastic input and greater compositional heterogeneity. These trends are further supported by QFL ternary diagrams (Fig.3b), where sandstone samples from HLF and GSF plot mainly in the arkose and arkosic arenite fields, reflecting mature, quartz-rich sources with low feldspar content. The higher lithic fragment proportions and compositional variability in GSF suggest a more tectonically active or heterogeneous sediment source than the more compositionally stable CSF and HLF.

PCA results (Fig.17a) reinforce these distinctions, with PC1 separating calcite-dominated samples from those enriched in dolomite, quartz, and clay—effectively distinguishing GSF from CSF and HLF. PC2 captures additional variance driven by pyrite content, likely associated with redox fluctuations during deposition, particularly within HLF. The scree plot (Fig.17b) confirms the significance of the first two components using the broken-stick model, validating their role in explaining most mineralogical variance. Together, these multivariate findings align with petrographic and XRD data, demonstrating that each formation exhibits a distinct mineralogical fingerprint shaped by depositional processes, sediment provenance, and diagenetic overprint.

These interpretations are further supported by the cluster analysis (Fig.7), where samples are grouped based on Mahalanobis similarity using the Neighbor Joining algorithm. The resulting dendrogram reveals well-defined clusters that correspond closely to formation boundaries, with CSF (black depth numbers) and HLF (cyan) forming moderately

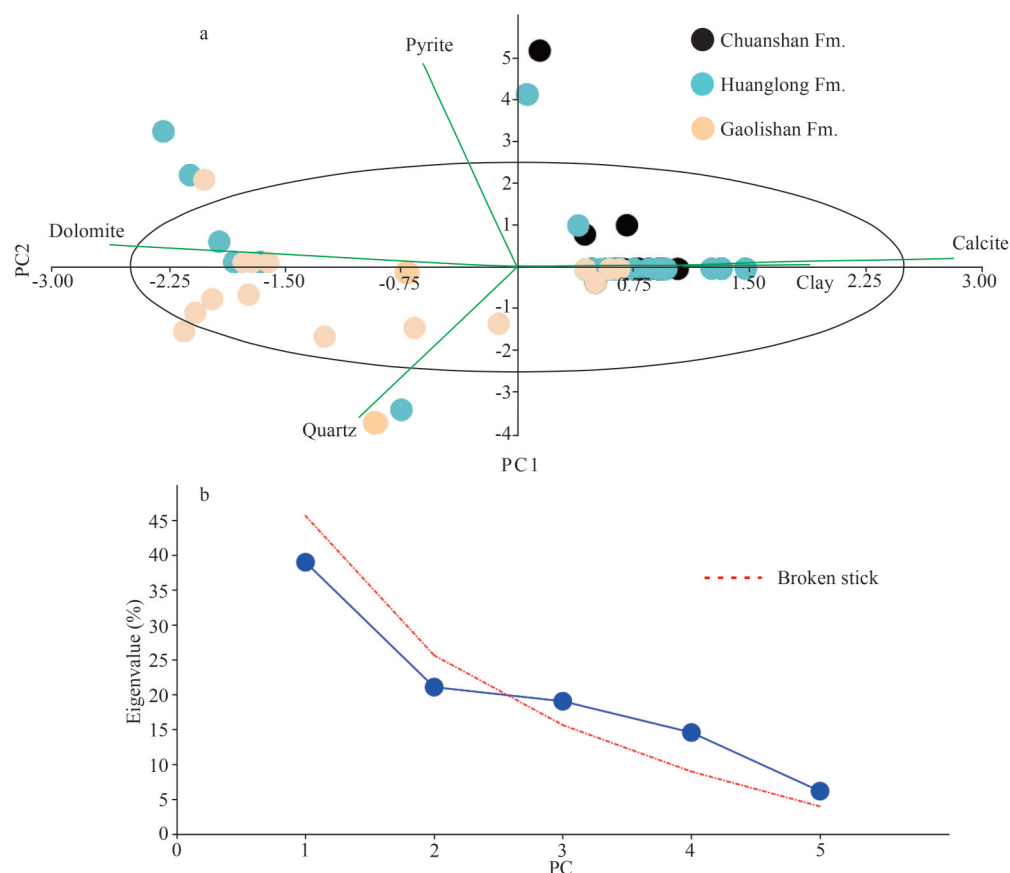


Fig.17 PCA biplot of PC1 vs. PC2 based on correlation matrix of bulk XRD mineralogical data (a); scree plot showing eigenvalue percentage for each principal component (b)

In (a), vectors represent mineral loadings, while symbols indicate formation-specific sample scores (black=CSF, cyan=HLF, orange=GSF). PC1 differentiates calcite vs. quartz-dolomite-rich compositions; PC2 reflects redox-related variation via pyrite. In (b), the red dashed line represents the broken-stick threshold used to determine significant components. The blue line connects the observed eigenvalue percentages for PC1–PC5, as indicated by the x-axis (PC) and y-axis (eigenvalue percentage).

distinct but partially overlapping groups, while GSF (bisque) samples appear as a separate cluster. The low Y-join distances within each formation highlight internal compositional consistency, whereas larger branch lengths between formations reflect significant multivariate dissimilarity. This clustering pattern not only corroborates the PCA separation but also underscores the stratigraphic coherence and lithofacies uniqueness of each formation. Combining clustering with PCA and mineralogical data provides a robust multivariate framework for distinguishing formation-scale heterogeneity in mixed carbonate-siliciclastic successions.

5.3 Microfacies characteristics and depositional environment of carbonate rock

MF-1 indicates a very low-energy depositional environment unsuitable for most marine organisms (Fig.4a–d). It corresponds to Wilson’s standard microfacies SMF-23: homogeneous fossil-poor micritic

limestone, typically formed in low-energy, quiet-water environments such as restricted or deeper open platform interiors (Wilson 1975).

Some samples in MF-2 show well-preserved fossils but with low diversity and abundance, indicating high mud content, weak bioturbation, and low hydrodynamic energy—corresponding to Wilson’s SMF-18: mud-dominated wackestones, typically formed in restricted platform environments (Fig.4e–f). Other samples contain a relatively higher abundance of broken and diverse bioclasts, suggesting normal seawater circulation and a favorable environment for marine life. The microfacies correspond to Wilson’s SMF-8: fossiliferous wackestones, formed in low-lying areas of an open platform.

MF-3 is characterized by well-rounded sand grains and low diversity and abundance of bioclasts (Fig.4g). It corresponds to Wilson’s SMF-18 and suggests deposition in a quiet-water, restricted platform setting.

Many fossils in MF-4 show varying degrees of fragmentation and micritization, though some fusulinids and foraminifera remain intact (Fig.4h–i). In addition to bioclasts, a few peloids and aggregates may be present. The high fossil diversity and abundance indicate that this marine setting was not restricted and was suitable for biological activity. MF-4 corresponds to Wilson's SMF-8: fossiliferous packstones, suggesting good water circulation and moderate hydrodynamic conditions typical of open platform environments.

The biological diversity (species richness) is relatively low in MF-5, but fossil abundance is high, indicating a setting with strong water energy and well-circulated seawater (Fig.5a–d). This microfacies is mainly found in the middle part of the Huanglong Formation and corresponds to Wilson's SMF-11: coated bioclastic grainstone, typically formed in high-energy open platform or platform-margin shoal environments.

The fine grain size, good sorting, and rounding indicate moderate and stable hydrodynamic energy in MF-6 and corresponding to Wilson's SMF-16: structureless (non-laminated) peloidal grainstone, typical of stable grain shoals in platform interiors (Fig.5e–f).

In MF-7, the high content and large size of oncoids, along with the absence of micritic matrix, suggest deposition in a high-energy environment strongly influenced by wave and tidal action (Fig.6a–b). It corresponds to Wilson's SMF-13: oncoidal rudstone/grainstone facies, indicative of high-energy shoals on the platform margin.

6 CONCLUSION

1) Geochemical, mineralogical, and petrographic data from the Chuanshan, Huanglong, and Gaolishan formations in Well CSDP-2 reveal a stratigraphic trend from a shallow, brackish, high weathering, warm-humid shelf (Gaolishan) to a deeper, saline, weak weathering, arid-carbonate platform (Chuanshan). This vertical succession reflects a long-term marine transgression with concurrent climatic deterioration during the Late Carboniferous–Early Permian.

2) Paleoredox proxies (e.g., V/Cr, V/(V+Ni), U/Th) and carbonate microfacies indicate fluctuating bottom-water oxygenation, transitioning from dysoxic-anoxic conditions in the Huanglong and Chuanshan formations. These redox shifts are closely linked with changes in organic input and basin circulation,

as confirmed by microfacies types ranging from restricted platform mudstones to high-energy shoal grainstones.

3) Multivariate analyses of bulk XRD data (PCA and cluster analysis) confirm distinct mineralogical groupings corresponding with lithostratigraphic boundaries. These patterns demonstrate the value of integrated mineralogical and geochemical approaches in resolving depositional processes and paleoenvironmental shifts, offering a refined framework for basin-scale correlation and paleogeographic reconstruction in the eastern South China Block.

7 DATA AVAILABILITY STATEMENT

All data supporting the findings of this study are available within the article and its Supplementary Information files. Additional raw analytical data are available from the corresponding authors on request.

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Electronic supplementary material

Supplementary material (Supplementary Tables S1–S5 and Figs.S1–S2) is available in the online version of this article at <https://doi.org/10.1007/s00343-026-5333-z>.