

Original Paper

Depositional environmental evolution and reservoir controlling effects of the P_2x formation in the Mahu Sag: Insights from the PCA-HCA coupled analysis

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ABSTRACT

The conglomerates of the Xiaizijie (P_2x) Formation in the Mahu Sag are dominated by dissolution pores of zeolite cement as the primary hydrocarbon reservoir spaces. Consequently, the storage characteristics of conglomerates determine that the depositional environment is one of the key factors controlling reservoir quality. To address the lack of clarity regarding the types of paleo-depositional environments of the P_2x Formation and their controlling effects on reservoir characteristics, this study integrated elemental geochemical analysis with machine learning and other analytical approaches. A dynamic mapping relationship was established among elemental assemblages, depositional environments, and reservoir characteristics to elucidate the evolutionary features of the paleo-depositional environments of the P_2x Formation and their controlling effects on reservoir physical properties. The results indicate that the paleo-depositional environment of the P_2x Formation is subject to the coupled control of provenance supply and paleoclimatic conditions, exhibiting significant spatial heterogeneity. Spatially, the depositional water depth increased gradually from north to south, accompanied by a synchronous decrease in oxidizing condition of the environment. Meanwhile, the region featured a dual provenance supply system consisting of terrigenous debris and intermediate-mafic magmatic materials. The input intensity of terrigenous debris showed clear regional heterogeneity, accompanied by the differential supply of intermediate-mafic magmatic components. Influenced by peripheral tectonic uplift induced by plate collision, moisture transport to the basin center was obstructed. This factor resulted in the formation of an anomalous paleoclimatic distribution pattern characterized by increasing aridity trend from north to south. These regional variations in the depositional environment further control the spatial differentiation of zeolite cement types. In the Mabei area, Na- and Al-rich volcanic glass derived from terrigenous debris and intermediate magmatic materials, under the synergistic influence of a semi-humid climate and phasic salinization events, promoted the development of cements dominated by analcime and heulandite. The Manan area developed a dysoxic, open, and low-salinity water environment, where zeolite cement is dominated by laumontite. In contrast, the Maxi area developed a two-stage depositional environment evolution, resulting in the balanced development of the three types of zeolite cement. The spatial differentiation of zeolite cement and their coupling with the depositional environment further determined the variations in dissolution intensity. Ultimately, this characteristic resulted in a distribution pattern of reservoir physical properties in the P_2x Formation conglomerates that follows the distribution pattern of “Maxi > Mabei > Manan”.

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1. Introduction

In recent years, substantial progress in oil and gas exploration of deep reservoirs has been achieved in such as Ordos Basin, Tarim Basin, and Junggar Basin, rendering deep reservoirs a focal point of hydrocarbon research in China (He et al., 2023; Li et al., 2021; Shi et al., 2024; Si et al., 2024). In particular, the discovery of several giant oilfields with reserves on the order of hundreds of millions of tons in Permian-Triassic conglomerate reservoirs within the Mahu Sag underscores the considerable exploration potential of conglomerate hydrocarbon reservoirs in this region (Sun et al., 2023; Tang et al., 2024; Yuan et al., 2024). Previous studies demonstrate that the conglomerate reservoirs in the Mahu Sag developed in fan-delta depositional systems (Yuan et al., 2024; Zhang et al., 2025), characterized by the development of abundant volcanic components and zeolite and carbonate cements (Sun et al., 2023; Yu et al., 2022a, 2022b). Secondary porosity systems serve as the primary spaces for hydrocarbon accumulation, particularly zeolite cement dissolution pores and micro-fractures (Sun et al., 2023; Lu et al., 2019; Xiao et al., 2020; Yu et al., 2022b). As the primary formation for conglomerate hydrocarbon reservoirs developing in the Mahu Sag, the unique reservoir characteristics of the Xiazijie (P_{2x}) Formation conglomerates render hydrocarbon accumulation intrinsically linked to the evolution of depositional environments. Current research on the influence of depositional environments on hydrocarbon accumulation elements in the Mahu Sag predominantly focuses on the coupling relationship between depositional environments and hydrocarbon generation potential of Fengcheng Formation (P_{1f}) source rocks (Dang et al., 2024; Gong et al., 2024; Tang et al., 2021; Zhang et al., 2025). However, comparatively limited attention has been devoted to the intrinsic control exerted by the dynamic evolution of the depositional environment on reservoir heterogeneity. For instance, the cementation and dissolution of zeolitic cement are key factors altering the physical properties of conglomerate reservoirs (Zhu et al., 2012). Yet, the relationship of zeolitic cement with changes in the depositional environment remains insufficiently explored systematically.

As the crucial archive of depositional environments evolution, mudstones preserve abundant geochemical signatures that reflect paleoclimate, paleohydrology, and tectonic settings, etc., thereby serving as the critical tool for reconstructing paleo-depositional environments (Chaudhuri et al., 2020; Sun et al., 2024; Unomah et al., 2025). The major and trace elements in mudstones exhibit distinct differentiation behaviors under the combined influences of climate variability, provenance input, redox conditions, and water salinity (Chen et al., 2022; Peng and Guo, 2023; Wei and Algeo, 2020; Zhang et al., 2020; Zou et al., 2021). For instance, the Chemical Index of Alteration (CIA) and Sr/Ba quantitatively reflect provenance area weathering intensity and water salinity, respectively (Lv et al., 2022; Nesbitt and Young, 1984; Tao et al., 2017; Wei et al., 2018; Zhang et al., 2023a). Similarly, the enrichment of redox-sensitive elements (e.g., Mo, U, V, Cr) is correlated with redox conditions of the depositional water body (Algeo and Tribouillard, 2009; Jones and Manning, 1994; Sun et al., 2024; Tribouillard et al., 2012), while rare earth element (REE) distributions and elemental ratios (e.g., La/Sc) enable quantitative discrimination of provenance characteristics and tectonic settings (Murray et al., 1990; Shen et al., 2023; Yan et al., 2021). However, regional geological heterogeneity coupled with the overprinting alterations of diagenetic processes and late-stage fluid often leads to elemental redistribution, which exists in ambiguities in paleo-environmental reconstructions based solely on elemental

proxies (Jana et al., 2021; Lan et al., 2024; Wang et al., 2012; Yan et al., 2021). To address the above limitations, the integrated inversion of multiple geochemical indicators and the cross-disciplinary comprehensive application of methodologies such as elemental geochemistry and machine learning are emerging as pivotal trends for future research.

In recent years, with the development of artificial intelligence algorithms, Principal Component Analysis (PCA) has been widely adopted in geochemical analysis to extract key environmental factors and reduce data dimensionality, thereby revealing the primary drivers of paleoenvironmental changes (Han et al., 2024; Park et al., 2024; Srivastava et al., 2024; Wang et al., 2024a). For example, Park et al. applied PCA to reconstruct the depositional dynamics evolutionary process of the Agardhfjellet Formation during the shelf dysoxic-anoxic event (Park et al., 2024). However, the PCA results reflect only mathematical correlations among elements and fail to capture complex post-stage disturbance elements in the depositional environment. Consequently, PCA limits resolving the temporal sequencing of elemental variations and spatial distribution of depositional environments (Hajihosseini et al., 2021; Sadeghi et al., 2024; Shahrestani et al., 2024). Hierarchical Cluster Analysis (HCA) is a machine learning algorithm widely used for sample classification, partitions samples by computing Euclidean distances or similarity coefficients, thereby enabling precise revealing of sample categories and evolutionary trends (Abdi and Williams, 2010; Li et al., 2014). Previous studies have combined PCA with HCA to achieve notable results in areas such as groundwater classification and pollution source apportionment, petroleum source typing and quality monitoring, as well as depositional types of delineation and paleoenvironmental reconstruction (Gómez-Hernández et al., 2025; Shahrestani et al., 2024; Wang et al., 2020a). For example, Garcia et al. employed PCA-HCA analyses to delineate depositional environment types for different source rocks in the Parnaíba Basin (Garcia et al., 2020). Nevertheless, in most studies of paleo-environment reconstruction, PCA and HCA are used separately or only as parallel cross-checks, which tend to be subjective and usually lack iterative optimization between dimensionality reduction and clustering.

The study establishes an iteratively optimized PCA-HCA coupled analytical model to address the limited understanding of paleoenvironmental characteristics and the insufficient analysis of dynamic coupling mechanisms between paleoenvironments and reservoir characteristics in the P_{2x} Formation. The model follows a cyclic process of “principal component clustering—cluster validity assessment—re-screening of variable loadings”, which strengthens the interaction between dimensionality reduction and clustering while enhancing the resistance of the model to geochemical data noise. Ultimately, by integrating the coupled analytical model with elemental geochemical indicators, the study quantitatively classified the paleoenvironment types of the P_{2x} Formation. It further reconstructs the spatiotemporal evolution of depositional environments, thereby revealing the synergistic control mechanisms of depositional environments on the mineralogical assemblages and reservoir physical properties of the conglomeratic reservoirs. This approach enables a multi-scale linkage between elemental assemblages, principal components, depositional environments, and reservoir-controlling effects. The findings establish a dynamic mapping framework linking elements, depositional environments, and reservoirs physical properties, providing a robust basis for elucidating the interaction mechanisms between geochemical signatures and depositional environmental constraints under complex geological conditions. Moreover, the framework also provides a

theoretical foundation for deep hydrocarbon exploration in the Mahu Sag.

2. Geologic settings

The Mahu Sag is located on the northwestern margin of the Junggar Basin (Fig. 1(a)), bound to the west by the Wuxia and Kebai fault zones, adjacent to the Shiyintan, Sangequan, and Xiayan uplifts to the east, and connects southward with the Dabasong and Zhongguai uplifts. It exhibits overall asymmetric dustpan-shaped fault-depression features (Dang et al., 2023, 2024; Du et al., 2023; Gong et al., 2024; Fig. 1(b)). Influenced by orogenic activity to the west, the northwestern basin margin

develops thrust and strike-slip faults, which together form a tectonic framework characterized by “faulted in the north, denuded in the west, and overlapped in the southeast” (Gong et al., 2024; Lu et al., 2019; Zhang et al., 2022; Fig. 1(b)). The strata from the Carboniferous to the Quaternary are well developed in the Mahu Sag, with conglomerate hydrocarbon reservoirs mainly found in the Permian Urho Formation (P_{2-3w}) and P_{2x} Formation, as well as the Triassic Baikouquan Formation (T_1b) (Guo et al., 2021; Sun et al., 2023; Xi et al., 2021; Yu et al., 2024). During the sedimentary period of the P_{2x} Formation influenced by the thrust nappe tectonism of Hala’alate Mountain, a fan delta-lacustrine sedimentary system developed in the basin (Yang et al., 2022; Zhang et al., 2023a; Fig. 1(b)). The lithology is dominated by

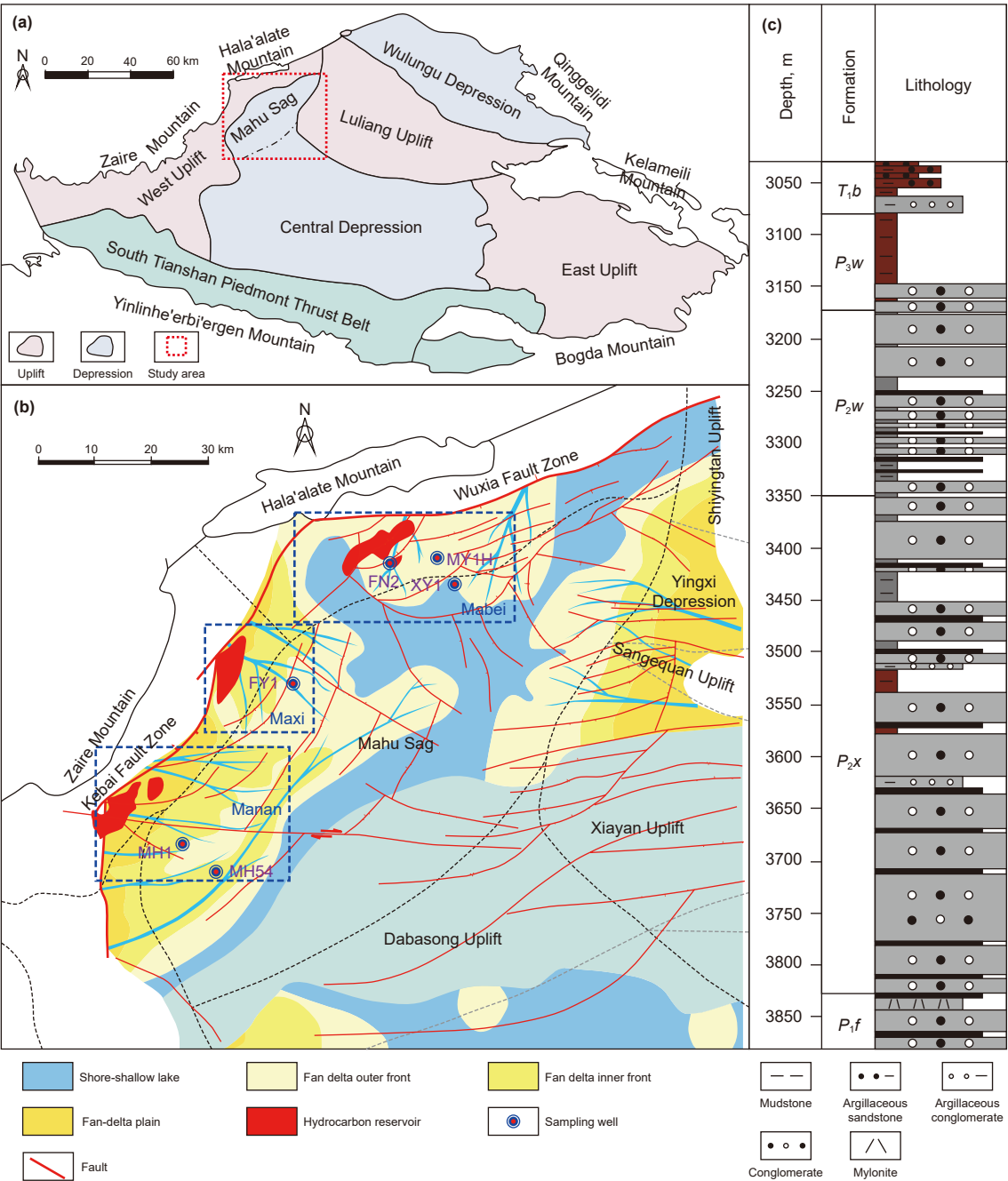


Fig. 1. (a) Geographic location overview map of the Mahu Sag, (b) sedimentary and structural overview map of the P_{2x} in the Mahu Sag, showing the locations of the sampling wells (modified from Yang et al. (2022)), (c) synthetical stratigraphic histogram of the strata in the Mahu Sag (modified from Yang et al. (2022)).

gray and brown conglomerate, glutenite intercalated with dark gray mudstone and sandstone, with a thickness ranging from 30 to 100 m. This formation generally exhibits positive cycle characteristics, and the rocks have low textural maturity and compositional maturity (Yang et al., 2022; Zhu et al., 2025; Fig. 1(c)). The fan delta type in the study area is dominated by traction current fan deltas, with only debris flow fan deltas developed locally in the Maxi area (Yang et al., 2022). Overall, the fan delta can be generally divided into two depositional subfacies: the fan delta plain subfacies and the fan delta front subfacies. Specifically, the fan delta plain subfacies are mainly composed of glutenite and conglomerate, with developed scour structures and tabular cross-bedding, while the fan delta front subfacies are dominated by sandstone, characterized by wedge-shaped cross-bedding (Wang et al., 2025; Zhang et al., 2023a). The study area received dual provenance supply from the Hala'ate Mountain and the Zaire Mountain, forming three sedimentary centers distributed along mountain passes or fault zones, which are arranged from north to south as Mabei, Maxi, and Manan (Yang et al., 2022; Zhang et al., 2022; Fig. 1(b)). The parent rocks of the Hala'ate Mountain are mainly intermediate-acidic magmatic rocks, containing heavy minerals such as zircon, magnetite, and ilmenite. In contrast, the parent rocks of the Zaire Mountain are a mixed deposition of intermediate-basic magmatic rocks and sedimentary rocks, with lithology dominated by conglomerate and abundant volcanoclastic components (Wang, 2018; Zhang et al., 2014).

3. Methods

3.1. Major and trace element analysis

39 fresh mudstone samples from the P_2x Formation were collected from the Mahu Sag, including 17 samples from the Mabei area, 12 from the Maxi area, and 10 from the Manan area. Before geochemical analysis, the air-dried samples were ground to below 200 mesh, treated with 30% H_2O_2 for 48 h, and then rinsed with 5% HNO_3 to remove organic matter and secondary carbonate contamination. Major element concentrations were measured using the wavelength-dispersive X-ray fluorescence spectrometer (ZSX Primus II), with a relative standard deviation of 0.5%. Trace element concentrations were determined by inductively coupled plasma mass spectrometry (Agilent 7700e) using the ammonium bifluoride fusion method, with detection limits ranging from 0.01 to 2 ppm. Both major and trace element analyses were conducted strictly according to international standards to ensure the accuracy of the experimental results.

3.2. Principal component analysis method

PCA is a multivariate statistical method based on linear algebra that aims to project original high-dimensional data into a lower-dimensional space through orthogonal transformation while retaining the maximum variance information within the data (Jolliffe and Cadima, 2016; Lu et al., 2019; Moreira et al., 2022). The method extracts mutually independent principal components through eigenvalue decomposition of the covariance matrix, with components ranked according to explained variance. This study retained principal components with cumulative variance contribution rates $\geq 85\%$ to reduce data dimensionality while effectively capturing latent relationships among variables and dominant influence factors (Abdi and Williams, 2010; Lu et al., 2019).

Before analysis, the original major and trace element data are standardized using a Z-score to eliminate dimensional effects on the analytical results in the study. Subsequently, the covariance

matrix between variables is constructed based on standardized data to characterize elemental covariation patterns. Eigenvalue decomposition is then performed on the covariance matrix, with principal components ranked by descending eigenvalues to determine their explained variance rates and cumulative variance contribution rates. The first k principal components with cumulative variance contribution $\geq 85\%$ are selected as core variables to analyze the primary controlling factors of paleo-depositional environments. The depositional environments can be revealed by examining the elemental assemblage characteristics of the principal component loadings. Meanwhile, a two-dimensional scatter plot of principal components is constructed to visualize environmental differentiation among samples, providing foundational data for subsequent HCA.

3.3. Hierarchical cluster analysis method

HCA is a multivariate statistical method that gradually merges or divides samples based on their similarities (Han et al., 2023; Li et al., 2014). The fundamental principle of this method involves grouping samples with high similarity into the same cluster, thereby revealing inherent classification structures or latent grouping characteristics among samples (Cohen-addad et al., 2019; Yang et al., 2023). The principal component score matrix derived from PCA is combined with the Ward method using Euclidean distance as the similarity metric, together with the Silhouette Coefficient, to determine the optimal cluster number (K) and generate the dendrogram in this study, and cross-validation is applied to evaluate the rationality and stability of clustering results. Finally, this study combines the intra-cluster elemental assemblage characteristics with principal component loadings interpretations to distinguish the paleo-depositional environment type of each cluster.

This study employs a coupled PCA-HCA analysis model, aiming to iteratively optimize the interaction between dimensionality reduction and clustering to mitigate noise interference inherent in geochemical datasets and improve the accuracy of paleoenvironmental classification. PCA is applied to extract principal component scores, thereby eliminating multicollinearity among elements. While HCA is used to partition in the principal component score space to identify paleo-depositional environment types through maximization of intra-cluster homogeneity and inter-cluster heterogeneity, thereby establishing multi-scale correlations spanning "element assemblages-principal components-environmental types-reservoir-controlling effects". To overcome limitations of the conventional PCA-HCA model, the study dynamically determines the retained k through inflection points in the scree plot and abrupt changes in cumulative variance contribution rates (85% threshold), thereby avoiding excessive compression of meaningful environmental signals. The loading matrix of the retained components is further interpreted in terms of geochemical associations and environmental implications, with priority given to components most relevant to depositional settings. Iterative refinement of this procedure yields clustering outcomes that are not only statistically stable but also geologically meaningful. Furthermore, the model integrates the Ward method, the Silhouette Coefficient, and the geological differentiation index (GDI) to determine K , ensuring classification results exhibit both statistical significance and geological interpretability.

3.4. Geochemical data correction

Elements in sediments are affected not only by the depositional environment but also by the superimposed influences of post-depositional diagenesis, bioturbation, and other factors (Taylor

et al., 2003; Tarhan, 2018). These factors result in deviations in the spatial distribution of elements and geochemical signals, thereby restricting the accuracy of paleoenvironmental reconstruction (Morad et al., 2010; Stockdale et al., 2009). Therefore, when conducting paleo-depositional environment reconstruction, it is necessary to perform standardization correction on major and trace element data to minimize the interference from non-environmental factors and extract chemical information directly related to the depositional environment (Morad et al., 2010; Soetaert et al., 1996; Ye et al., 2021). Based on the results of PCA, this study first identifies low-loading elements (loading values <0.3) closely associated with the provenance principal components, which are prioritized as environmental indicators to reduce the impact of differences in provenance input on the interpretation of indicators (Huang et al., 2019; Zeng et al., 2022). For elements still significantly controlled by provenance, the AI correction method is adopted for data standardization to weaken the interference of different provenance types on the reliability of geochemical indicators (Birch, 2020; Eq. (1)). Furthermore, the effectiveness of the correction and the reliability of the post-correction data are evaluated by comparing the correlations between target elements and provenance indicators after correction (Chen et al., 2025). This validation ensures that the corrected data effectively reflects depositional environmental information.

$$C_1 = C_{\text{meas}} - \left(\frac{X_{\text{meas}}}{X_{\text{paas}}} \right) \times C_{\text{paas}} \quad (1)$$

C_1 : corrected data; C_{meas} : measured data of element; C_{paas} : element data in PAAS; X_{meas} : measured data of inert elements; X_{paas} : reference element content in PAAS.

4. Results

4.1. Reservoir characteristics

Observations of cast thin sections reveal that the pore types within the conglomerate reservoirs of P_2x Formation in the Mahu

Sag are mainly composed of secondary pores and fractures (Fig. 2). Secondary pores are dominated by the dissolution of zeolite and calcite cements (Fig. 2(a) and (b)), followed by the dissolution of lithic and mineral grains (Fig. 2(c)–(e)). Fractures are only observed in local samples developed near fault zones (Fig. 2(f)). The pore types of reservoirs in the basin exhibit obvious spatial heterogeneity. In the Mabei area, dissolution pores are dominated by calcite, laumontite and heulandite (Fig. 2(b)). In the Maxi area, the dissolution intensity of zeolite cement is higher than that in the Mabei area. In contrast, the Manan area is dominated by analcime dissolution, while laumontite and heulandite dissolution only occur locally (Fig. 2(a)). The differences in pore types determine the variations in reservoir physical properties among various regions. The average porosity and permeability of conglomerates reservoirs in the Mabei area are 9.17% and 4.77 mD, respectively. In comparison, the reservoir physical properties in the Maxi area (porosity: 11.25%; permeability: 6.03 mD) are significantly better than those in the Mabei area, whereas the reservoir physical properties in the Manan area are the poorest, with average porosity and permeability of 8.95% and 4.35 mD, respectively.

4.2. Principal component analysis

The first seven principal components derived from major and trace elements in the P_2x Formation mudstones account for the cumulative variance contribution of 85.9%. Among these, PC1 (36.7%) and PC2 (16.0%) explain 53.03% of the total variance, reflecting primary elemental differentiation trends among samples. In comparison, PC3 (10.2%) and PC4 (9.0%) contribute an additional 19.2% variance, aiding in the more comprehensive characterization of the depositional environments (Table 1). PC1 is characterized by negative loadings for clay mineral components such as SiO_2 (−0.142), Al_2O_3 (−0.160), and REE (e.g., La, Ce; loadings amount < −0.13), contrasting with positive loadings for carbonate and mafic components, including CaO (0.128), MgO (0.108), etc. This phenomenon indicates a differentiation between terrigenous debris input and carbonate or mafic minerals contributions.

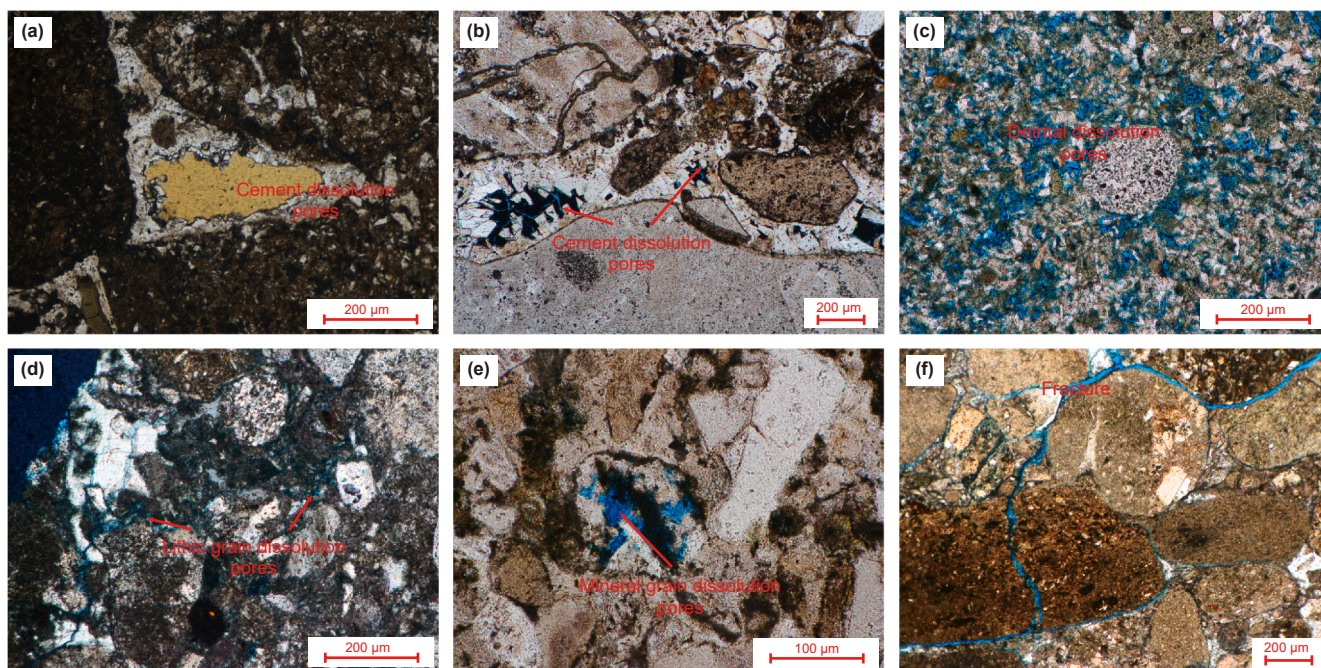


Fig. 2. Pore types of conglomerates of the P_2x Formation in Mahu Sag. (a) Cement dissolution pore, well MH1, 4106.2 m, (b) cement dissolution pore, well FN2, 3852 m, (c) lithic dissolution pore, well MH1, 4108.9 m, (d) lithic grain dissolution pore, well BQ2, 3374.5 m, (e) mineral grain dissolution pore, well FN2, 3852 m, (f) fracture, well MH15, 3799.7 m.

Therefore, negative PC1 scores may reflect enrichment in clay mineral or enhanced weathering, whereas positive PC1 scores likely correlate with carbonate deposition or mafic material inputs.

PC2 is predominantly characterized by strong negative loadings of transition metal elements including MgO (−0.24), Fe₂O₃ (−0.241), MnO (−0.241), Cr (−0.29), V (−0.20), Ni (−0.36), and Co (−0.33) etc., along with positive loadings of K₂O (0.15), La (0.18), U (0.23), and Th (0.19) (Table 1). This loading pattern reflects variations in redox conditions and terrigenous debris inputs. Negative PC2 scores may correspond to reducing conditions or Fe–Mn oxide enrichment, whereas positive PC2 scores likely reflect K-feldspar weathering and intensified terrigenous debris input.

4.3. Hierarchical cluster analysis

The hierarchical clustering dendrogram shows that when the number of clusters merges from 3 to 2, the merge distance increases significantly (from 13 to 8) (Fig. 3(a)). At this point, the elbow method exhibits the most pronounced inflection point on the within-cluster sum of squares curve, indicating the optimal clustering effect when divided into 3 clusters. Therefore, the samples in this study are classified into 3 clusters (Cluster 1, Cluster 2, Cluster 3). Samples of Cluster 1 are concentrated in the medium PC1 and high PC2 region, with PC1 ranging from −2.77 to

15.86 and PC2 ranging from −0.18 to 4.88 (Fig. 3(b)). These samples have moderate contents of carbonates and transition metal elements, with an average CaO content of 2.60%, an average MgO content of 1.54%, an average V content of 92 ppm, and an average Ni content of 8.52 ppm (Tables 2 and 3). Notably, sample XY1-30 (PC1 = 15.86) deviates significantly from the main population distribution in this cluster, suggesting that its composition may represent a special provenance or sedimentary event and being therefore regarded as an outlier. It should be noted that subsequent analyses focus on the overall characteristics of the samples. Whether this outlier is included or excluded has no substantial impact on the main conclusions of this study.

Samples of Cluster 2 are distributed in the region of moderately negative PC1 and medium PC2 in the PCA space, with PC1 ranging from −7.20 to −3.35 and PC2 ranging from −1.99 to 2.05 (Fig. 3(b)). The samples of this Cluster are rich in terrigenous debris mineral indicator elements such as SiO₂ (avg. 61.36%), Al₂O₃ (avg. 13.94%), and TiO₂ (avg. 0.61%), and trace elements including Th (avg. 5.59 ppm), Sc (avg. 13.0 ppm), and Zr (avg. 168 ppm) also show significant enrichment (Tables 2 and 3). Samples of Cluster 3 are mainly distributed in the medium PC1 and low PC2 region in the PCA space, with PC1 ranging from −2.06 to 5.44 and PC2 ranging from −4.46 to −0.80 (Fig. 3(b)). The samples of Cluster 3 are rich in carbonate components such as CaO (avg. 3.06%) and MgO (avg.

Table 1

Principal component scores and elemental loadings of major and trace elements in the collected samples.

PCA	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Explained variance rate	0.37	0.16	0.10	0.09	0.06	0.04	0.03
Cumulative	0.37	0.53	0.63	0.73	0.79	0.83	0.86
SiO ₂	−0.14	0.03	−0.33	−0.02	0.02	0.01	−0.09
TiO ₂	−0.09	−0.21	−0.04	−0.26	−0.15	−0.11	0.07
Al ₂ O ₃	−0.16	0.03	−0.19	−0.24	−0.06	0.00	0.04
Fe ₂ O ₃	−0.09	−0.24	0.12	−0.23	−0.03	−0.03	0.03
MnO	−0.03	−0.24	0.14	0.06	0.21	0.09	0.17
MgO	0.11	−0.25	0.17	0.04	0.01	−0.11	0.01
CaO	0.13	0.00	0.25	0.07	0.29	0.12	0.00
Na ₂ O	0.05	−0.06	−0.01	0.24	−0.21	0.14	0.49
K ₂ O	−0.06	0.15	0.11	−0.15	−0.26	−0.20	−0.20
P ₂ O ₅	−0.05	−0.20	0.05	−0.12	0.19	0.24	0.08
Li	0.11	−0.11	0.16	0.21	−0.19	−0.15	−0.05
Sc	−0.05	−0.28	0.12	−0.20	0.01	0.01	0.08
V	0.07	−0.02	0.32	−0.13	−0.14	−0.11	−0.14
Cr	−0.03	−0.30	−0.08	−0.11	−0.06	−0.10	−0.06
Co	−0.01	−0.26	0.15	−0.17	−0.04	0.03	0.33
Ni	−0.01	−0.33	0.03	−0.11	−0.03	−0.10	−0.03
Cu	−0.02	−0.10	−0.04	−0.04	−0.17	0.43	−0.43
Zn	−0.03	−0.14	−0.03	−0.05	−0.19	0.52	−0.08
Ga	−0.20	0.00	−0.08	−0.18	0.01	0.01	0.09
Rb	−0.09	0.08	0.14	−0.29	0.12	−0.13	−0.10
Sr	0.13	0.15	0.09	0.06	0.20	0.07	0.10
Y	−0.19	−0.03	0.14	0.19	−0.03	−0.05	−0.10
Zr	−0.19	0.01	−0.17	−0.03	−0.03	−0.16	0.00
Nb	−0.17	0.05	0.00	−0.03	0.00	−0.19	0.19
Sn	−0.18	−0.01	−0.13	0.17	0.05	0.14	−0.05
Cs	−0.05	0.04	0.14	−0.23	0.35	0.06	−0.22
La	−0.14	0.18	0.19	−0.12	−0.17	0.08	0.08
Ce	−0.17	0.12	0.22	−0.11	−0.06	0.08	0.08
Pr	−0.21	0.09	0.14	−0.06	−0.05	0.09	0.02
Nd	−0.21	0.07	0.15	−0.02	−0.02	0.07	0.01
Sm	−0.21	0.02	0.16	0.06	−0.02	0.02	−0.02
Eu	0.06	0.17	0.12	−0.01	−0.32	−0.06	0.03
Gd	−0.21	−0.05	0.15	0.11	−0.01	−0.02	−0.09
Tb	−0.20	−0.03	0.16	0.15	−0.02	−0.05	−0.09
Er	−0.20	−0.09	0.05	0.18	0.02	−0.03	−0.09
Tm	−0.21	−0.09	−0.01	0.15	0.06	0.02	−0.05
Yb	−0.21	−0.08	−0.04	0.16	0.10	0.06	0.02
Lu	−0.21	−0.09	−0.06	0.12	0.12	0.08	0.03
Hf	−0.20	0.01	−0.21	−0.02	0.04	−0.08	0.06
Th	−0.14	0.19	0.16	0.03	−0.09	−0.01	0.04
U	0.01	0.23	0.20	−0.02	0.05	0.13	0.10

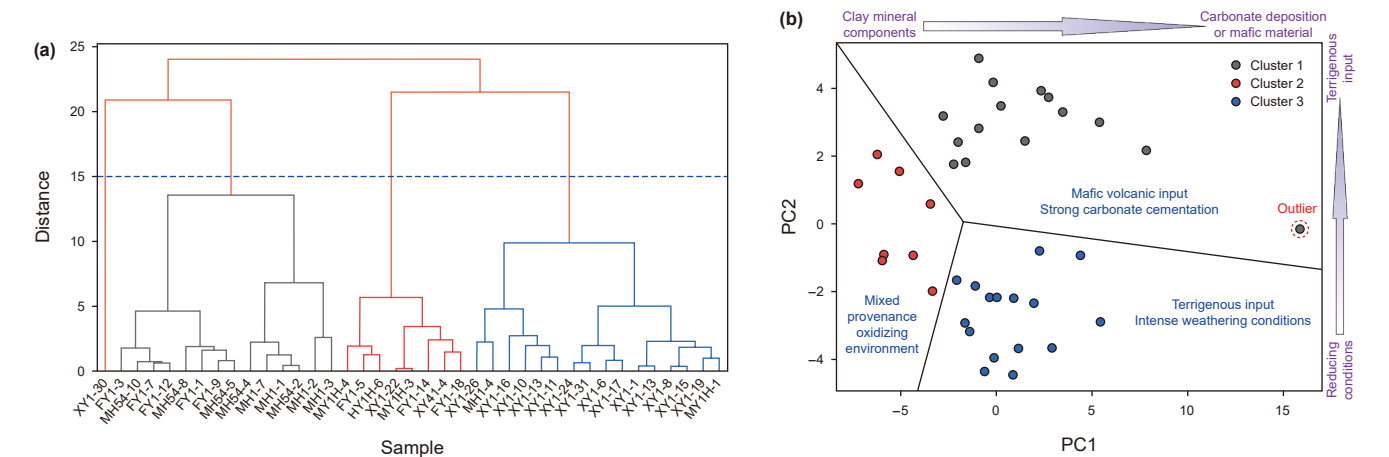


Fig. 3. Results of PCA-HCA coupled analysis. (a) Hierarchical clustering dendrogram, (b) principal component clustering scree plot.

Table 2
Major elements and cluster classification results of the P₂x Formation mudstone samples in the Mahu Sag.

SiO ₂ , %	TiO ₂ , %	Al ₂ O ₃ , %	Fe ₂ O ₃ , %	MnO, %	MgO, %	CaO, %	Na ₂ O, %	K ₂ O, %	P ₂ O ₅ , %	LOI, %	Cluster
63.02	0.66	13.87	5.30	0.09	2.99	1.93	2.78	2.93	0.15	5.41	3
61.21	0.65	13.43	5.14	0.07	3.29	2.56	2.82	3.15	0.15	6.28	3
59.59	0.69	14.26	5.82	0.10	3.37	2.86	3.03	2.69	0.13	6.36	3
60.16	0.83	14.10	5.30	0.08	3.85	2.33	2.77	3.21	0.14	6.32	3
64.35	0.63	13.74	4.55	0.07	2.35	2.12	3.65	2.50	0.15	5.11	3
59.71	0.67	13.63	5.54	0.07	3.00	3.57	3.15	2.93	0.13	6.93	3
64.14	0.61	13.27	4.33	0.06	2.16	2.03	3.41	2.99	0.15	5.30	3
56.86	0.71	13.66	5.98	0.08	3.21	3.21	2.73	4.03	0.15	7.69	3
57.75	0.71	13.89	5.29	0.08	3.12	2.95	3.84	3.33	0.13	7.40	3
57.87	0.76	14.19	5.79	0.10	3.02	1.95	4.27	3.41	0.14	6.53	3
63.10	0.62	13.74	4.89	0.08	2.15	1.76	3.95	3.36	0.12	5.90	3
53.16	0.67	12.84	5.97	0.11	4.34	6.34	2.74	3.19	0.17	9.64	3
52.79	0.64	11.48	5.37	0.09	5.27	4.52	4.45	3.72	0.11	10.32	3
58.13	0.76	13.89	6.19	0.10	3.63	2.37	3.33	3.62	0.11	6.64	3
52.67	0.60	12.52	4.91	0.10	2.99	5.74	7.34	2.28	0.17	8.35	3
60.95	0.68	14.44	5.48	0.11	2.72	2.70	3.00	2.51	0.17	6.74	3
59.88	0.68	14.52	5.69	0.07	2.68	3.06	2.70	3.19	0.18	6.50	2
66.19	0.53	13.34	3.71	0.10	2.06	1.48	5.35	1.88	0.12	4.65	2
63.48	0.67	15.21	5.99	0.06	1.56	1.45	2.36	5.14	0.14	4.17	2
58.36	0.59	13.80	5.29	0.11	2.25	4.73	3.02	3.41	0.12	7.79	2
58.61	0.63	13.19	5.54	0.10	3.01	5.53	2.38	3.67	0.14	6.82	2
60.02	0.69	14.49	5.48	0.08	2.39	1.59	2.77	3.17	0.16	6.62	2
64.83	0.53	13.34	3.79	0.08	1.85	2.17	3.62	2.40	0.11	6.47	2
59.49	0.55	13.61	4.35	0.06	1.80	4.50	3.08	2.82	0.12	9.05	2
43.45	0.35	7.80	3.32	0.06	6.94	9.26	3.84	2.16	0.07	18.27	1
62.36	0.60	14.68	4.13	0.03	1.59	1.84	2.85	4.61	0.11	5.70	1
62.13	0.58	14.71	4.71	0.03	1.39	1.84	3.18	4.26	0.09	5.43	1
60.85	0.60	15.05	5.36	0.07	1.37	2.17	2.49	4.80	0.11	6.06	1
66.25	0.48	13.75	4.35	0.05	1.23	1.95	3.14	4.06	0.09	4.16	1
62.62	0.57	14.09	5.32	0.12	1.81	3.28	2.39	3.76	0.13	5.97	1
65.56	0.57	14.05	2.82	0.03	0.97	2.88	2.76	3.59	0.11	5.39	1
57.00	0.58	13.28	3.39	0.04	1.15	2.89	3.88	2.90	0.12	7.17	1
47.21	0.48	10.85	3.84	0.10	2.45	14.95	2.49	2.14	0.16	13.71	1
61.69	0.55	13.19	3.39	0.05	1.16	2.54	2.59	4.06	0.12	6.74	1
57.45	0.62	14.24	4.22	0.03	1.42	2.69	3.13	3.90	0.08	7.48	1
60.44	0.61	13.93	4.11	0.06	1.29	2.67	3.46	3.73	0.11	6.50	1
58.65	0.59	14.16	4.32	0.05	1.43	2.33	3.07	4.28	0.11	6.73	1
57.74	0.61	14.40	4.41	0.02	1.62	1.84	2.73	4.30	0.12	6.47	1
47.81	0.60	11.10	4.56	0.06	2.64	4.94	4.54	5.95	0.11	8.89	1

3.22%), and transition metals including Ni (89.6 ppm), Sr (290 ppm), Cr (128 ppm), Cu (56.9 ppm), and Fe₂O₃ (avg. 5.37%) also show significant enrichment (Tables 2 and 3).

4.4. Rare earth elements (REE)

The REEs exhibit extremely low mobility during weathering, transportation, and metamorphism processes, thereby playing a

critical role in inferring provenance characteristics and redox conditions. The total REE contents of the mudstones from the P₂x Formation range from 235.37 to 472.07 ppm (Tables 2 and 3), generally showing significant enrichment of light rare earth elements (LREEs) and relatively flat heavy rare earth elements (HREEs) distribution, with chondrite-normalized REE patterns presenting a right-dipping trend (Fig. 4). Meanwhile, the Ce/Ce* of the P₂x Formation samples range from 0.94 to 1.10, while Eu/Eu*

Table 3Trace elements and cluster classification results of the P_2x Formation mudstone samples in the Mahu Sag.

Li	Be	Sc	V	Cr	Co	Ni	Cu	Zn	Ga	Rb	Sr	Zr	Nb	Cs	B	Ba	La	Ce	Nd	Sm	Eu	Tb	Er	Tm	Pb	Th	U	Cluster
37.2	1.39	13.4	87.6	112	12.4	95.2	42.2	74.9	16.8	63.5	217	158	6.34	2.61	1104.79	2975	19.0	39.4	19.2	4.71	1.40	0.72	2.70	0.42	9.43	4.59	1.42	3
48.6	1.31	12.8	86.0	144	12.4	93.7	44.9	85.1	16.7	66.7	304	152	6.11	2.78	28.69	7529	18.6	38.4	18.3	4.46	1.88	0.69	2.69	0.40	10.1	4.42	1.42	3
35.3	1.31	15.4	100	163	15.2	126	44.8	80.4	17.1	61.1	221	152	6.00	2.98	28.34	3789	18.0	38.8	18.0	4.35	1.78	0.68	2.60	0.40	10.5	4.19	1.40	3
30.8	1.34	13.8	87.8	244	14.8	104	43.4	73.9	17.1	81.8	218	206	9.37	2.92	47.76	5756	18.6	38.4	18.5	4.52	1.57	0.67	2.56	0.39	9.86	4.60	1.39	3
40.3	1.29	11.6	87.3	127	7.83	45.1	37.0	63.5	16.1	47.7	268	148	5.67	1.17	40.11	4662	16.9	35.0	17.8	4.39	1.72	0.66	2.54	0.38	8.69	4.17	1.72	3
56.0	1.25	14.0	83.1	145	12.0	89.9	52.4	85.5	15.7	56.9	235	146	5.64	2.88	76.34	6734	17.7	37.0	17.9	4.44	1.64	0.68	2.61	0.39	21.5	3.96	1.23	3
68.7	1.27	11.4	75.9	129	8.54	56.0	189	163	15.6	52.2	253	160	6.17	1.96	30.60	5401	17.6	36.3	18.7	4.49	1.68	0.68	2.70	0.41	14.3	4.50	1.41	3
161	1.45	15.4	86.6	106	14.1	99.4	59.5	84.1	16.8	70.3	189	160	6.27	3.55	24.45	6365	18.6	41.5	19.7	4.91	2.17	0.75	2.83	0.44	10.1	4.32	1.29	3
194	1.19	14.7	93.7	139	13.5	99.3	47.6	75.6	16.0	52.5	295	149	5.64	2.54	136.92	9496	15.4	34.0	17.1	4.27	1.96	0.66	2.56	0.38	8.46	3.61	1.31	3
222	1.39	14.6	96.0	178	14.7	107	54.5	85.4	17.0	57.9	304	159	6.28	2.51	27.20	8663	16.6	36.6	18.2	4.54	2.23	0.68	2.66	0.40	8.61	3.72	1.12	3
205	1.53	12.1	80.5	130	10.5	63.8	48.7	75.7	16.5	59.1	214	168	6.57	2.54	22.55	9817	18.9	39.9	19.8	4.93	1.79	0.77	3.01	0.45	9.15	4.51	1.28	3
83.0	1.52	16.7	91.5	90.0	16.5	124	56.6	83.7	17.0	65.8	244	144	6.85	3.22	24.39	7716	19.1	41.3	19.5	4.83	1.51	0.72	2.93	0.42	11.8	4.43	1.12	3
407	1.33	12.5	116	88.9	15.9	107	59.8	80.3	15.2	50.2	410	127	6.12	1.73	35.22	6567	16.8	36.7	17.2	4.30	1.69	0.63	2.32	0.34	7.56	3.27	1.72	3
126	1.47	15.9	90.7	109	16.6	114	54.4	88.2	17.6	62.8	269	162	6.71	3.16	42.33	4545	18.1	39.9	18.9	4.75	1.83	0.72	2.68	0.39	9.01	3.89	1.19	3
76.8	1.64	12.9	70.8	52.6	19.8	31.2	25.3	115	15.4	56.5	679	128	6.78	1.08	129.05	6551	18.6	39.3	17.5	4.07	1.76	0.55	2.13	0.34	15.8	4.89	1.84	3
51.9	1.55	14.5	90.4	98.8	12.5	78.6	50.1	77.1	17.5	64.3	313	160	6.60	3.51	36.55	15705	20.2	42.8	19.9	4.91	1.76	0.73	2.69	0.41	9.74	5.11	1.93	3
26.5	1.59	15.3	97.0	121	13.9	88.6	54.6	80.8	17.8	74.5	201	158	7.00	3.72	47.43	6489	21.9	46.9	21.8	5.29	1.54	0.78	2.86	0.44	11.6	5.21	1.40	2
175	1.70	10.4	71.0	65.7	6.92	34.4	43.5	69.2	16.9	35.2	191	178	7.17	1.33	35.22	8493	20.0	41.3	21.9	5.66	1.67	0.88	3.67	0.56	7.88	4.95	1.49	2
31.9	1.73	13.1	89.2	40.4	10.1	21.0	62.6	80.2	19.3	92.8	220	165	7.89	5.35	101.36	8265	26.1	53.7	24.2	5.61	1.21	0.79	2.94	0.45	14.6	5.98	1.72	2
137	1.66	13.5	106	50.6	12.8	34.0	55.7	77.0	17.6	62.4	358	160	6.93	3.14	107.45	1382	23.9	52.5	23.3	5.51	1.23	0.83	2.91	0.43	13.5	6.05	2.06	2
51.6	1.82	15.1	82.0	100.0	12.7	60.3	46.2	77.4	17.9	78.2	230	160	7.03	5.04	30.63	2737	21.1	48.3	22.1	5.35	1.05	0.84	3.02	0.45	11.6	5.59	1.69	2
48.6	1.78	15.2	99.0	101	13.3	73.5	61.3	84.6	18.6	72.2	319	169	7.56	4.20	55.04	2243	22.6	50.9	24.2	5.90	2.92	0.84	3.10	0.47	11.8	5.83	1.77	2
32.8	1.88	10.6	63.5	68.0	7.96	37.1	27.0	73.4	18.2	58.1	280	183	8.03	2.35	72.20	1828	21.5	46.4	23.2	5.73	1.56	0.92	3.41	0.50	11.3	5.65	1.53	2
28.4	1.92	11.3	69.2	49.3	8.21	31.2	27.6	70.0	18.6	71.6	265	173	7.34	3.54	28.68	1593	21.8	44.5	21.9	5.39	1.64	0.86	3.19	0.48	13.1	5.43	1.47	2
536	1.07	10.7	110	45.6	8.58	29.7	43.9	59.8	9.88	54.1	582	71.2	5.15	2.17	34.78	553	12.2	26.3	11.6	2.93	2.72	0.45	1.72	0.25	9.18	1.97	1.76	1
45.3	1.56	10.2	84.3	51.7	7.76	16.7	47.8	77.1	18.0	67.9	295	165	6.93	2.78	32.84	8620	20.8	41.8	20.3	4.85	1.88	0.69	2.62	0.39	11.5	5.04	1.70	1
60.0	1.77	10.2	74.4	35.4	8.46	17.5	46.3	71.2	18.3	72.0	227	168	7.53	3.98	30.89	36715	21.9	45.7	21.1	4.94	1.81	0.71	2.77	0.42	12.6	5.55	1.85	1
49.8	1.67	11.0	93.1	63.9	10.9	16.9	58.9	78.9	18.5	69.2	336	168	6.97	3.66	25.50	8981	20.9	44.4	20.6	4.83	1.27	0.70	2.62	0.40	11.9	5.27	1.75	1
38.4	1.60	8.51	89.4	40.4	7.22	12.8	35.2	63.8	16.0	70.8	422	185	7.07	2.59	51.93	8127	19.0	38.7	17.9	4.14	0.98	0.61	2.50	0.39	10.6	5.54	1.88	1
34.6	1.64	11.7	84.6	42.0	10.4	20.7	52.7	69.1	17.5	69.2	493	168	7.19	3.55	31.82	21203	21.8	46.5	21.4	4.96	1.11	0.74	2.67	0.41	13.3	6.09	1.68	1
21.0	1.48	9.93	65.2	21.2	5.57	9.44	28.1	58.7	15.5	56.6	685	160	6.81	2.03	153.21	6101	15.5	32.9	16.4	4.06	1.89	0.61	2.29	0.35	11.6	5.36	1.65	1
32.2	1.41	10.3	79.9	24.6	6.62	12.1	37.7	66.3	15.1	54.3	358	148	6.27	2.01	45.76	15088	16.4	33.3	15.9	4.07	5.32	0.54	2.02	0.31	11.0	4.83	1.23	1
28.5	1.19	10.4	109	27.2	8.85	21.4	35.3	62.2	12.9	61.9	976	113	5.00	6.65	66.59	5374	17.5	38.3	17.5	4.29	2.10	0.62	2.17	0.32	10.9	4.68	2.23	1
23.9	1.38	10.3	73.4	21.0	6.22	12.1	34.3	64.4	14.9	65.4	787	156	6.00	2.71	70.69	5782	16.6	34.8	17.6	4.28	3.38	0.61	2.30	0.35	9.36	5.06	1.43	1
67.4	1.56	11.4	93.2	43.4	9.84	22.2	39.4	69.7	17.0	54.6	369	150	6.29	2.40	301.78	31017	26.7	49.0	19.8	4.42	4.65	0.60	2.17	0.33	20.1	5.11	1.73	1
65.5	1.62	10.8	86.2	30.4	7.87	16.5	47.6	69.3	16.7	50.0	228	153	6.21	2.21	148.14	20638	21.7	40.1	19.1	4.58	3.31	0.64	2.36	0.36	15.0	4.98	1.70	1
53.7	1.68	11.6	93.3	32.4	9.26	18.5	41.2	71.6	17.6	65.9	333	151	6.45	3.25	70.93	24480	27.5	51.3	21.9	5.00	4.04	0.67	2.32	0.36	17.6	5.69	2.10	1
32.2	1.68	12.4	120	47.9	9.60	24.0	51.6	79.6	17.8	89.6	373	149	6.94	3.90	164.39	30355	29.4	52.2	21.8	4.98	4.69	0.68	2.39	0.36	22.1	5.83	2.23	1
254	1.26	10.8	118	42.6	10.6	30.8	36.3	76.3	13.4	66.9	513	157	7.32	0.57	26.93	35714	26.5	50.8	22.7	5.86	5.81	1.01	3.18	0.41	10.5	9.44	1.94	1

Note: Units: ppm.

(0.61 to 4.35) show the coexistence of positive and negative Eu anomalies (Table 3). Specifically, samples of Cluster 1 mainly exhibit positive Eu anomalies with only a few showing negative anomalies (Fig. 4(a)), samples of Cluster 2 generally display negative Eu anomalies (Fig. 4(b)), whereas samples of Cluster 3 are characterized by positive Eu anomalies (Fig. 4(c)).

5. Discussion

To further identify the depositional environments represented by each cluster, this study employed diagram-based geochemical proxies to characterize the paleoclimate, provenance, paleoredox conditions, palaeowater depth, and paleosalinity, thereby revealing the evolutionary patterns of the paleo-depositional environments during the sedimentary period of the P_2x Formation.

5.1. Provenance

Zr and Ti exhibit exceptional chemical stability and resistance to weathering and transport (Fralick and Kronberg, 1997; Roser and Korsch, 1988; Yamamoto et al., 1986), thereby effectively preserving the geochemical signatures of their parent rocks. Therefore, the contents and ratios of Zr and TiO_2 are used to analyze the provenance and tectonic setting (He et al., 2010; Li

et al., 2025; Sun et al., 2024; Tao et al., 2017). Additionally, due to the differential migration of mobile elements (Na, K, Ca) and immobile elements (Al, Ti) during chemical weathering, the CIA are commonly used to evaluate weathering intensity (Nesbitt and Young, 1984; Passchier and Kriese, 2008). Research shows that $CIA \leq 50$ indicates unweathered parent rocks, $50 < CIA \leq 65$ reflects weak weathering, $65 < CIA \leq 85$ suggests moderate weathering, and $CIA > 85$ signifies intense weathering (Bomou et al., 2013; Lan et al., 2024; Pipe et al., 2025). To avoid the interference of diagenesis, this study adopts the CIA correction formula proposed by Panahi et al. (2000) and Panahi and Young (1997) and the K_2O correction formula proposed by Fedo et al. (1996) to correct the CIA values by calculating the primary K_2O content. The specific calculation formula is as follows:

$$CaO^* = CaO - P_2O_5 \times 10/3 \quad (2)$$

$$m = K_2O / (Al_2O_3 + CaO^* + Na_2O + K_2O) \quad (3)$$

$$K_2O_{corr} = K_2O - 0.35 \times (Na_2O - 2) \quad (4)$$

$$CIA_{corr} = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O_{corr})] \times 100 \quad (5)$$

The mudstones of the P_2x Formation exhibit SiO_2 contents ranging from 43.45% to 66.25%, with Al_2O_3/TiO_2 of 17.00–28.47 and

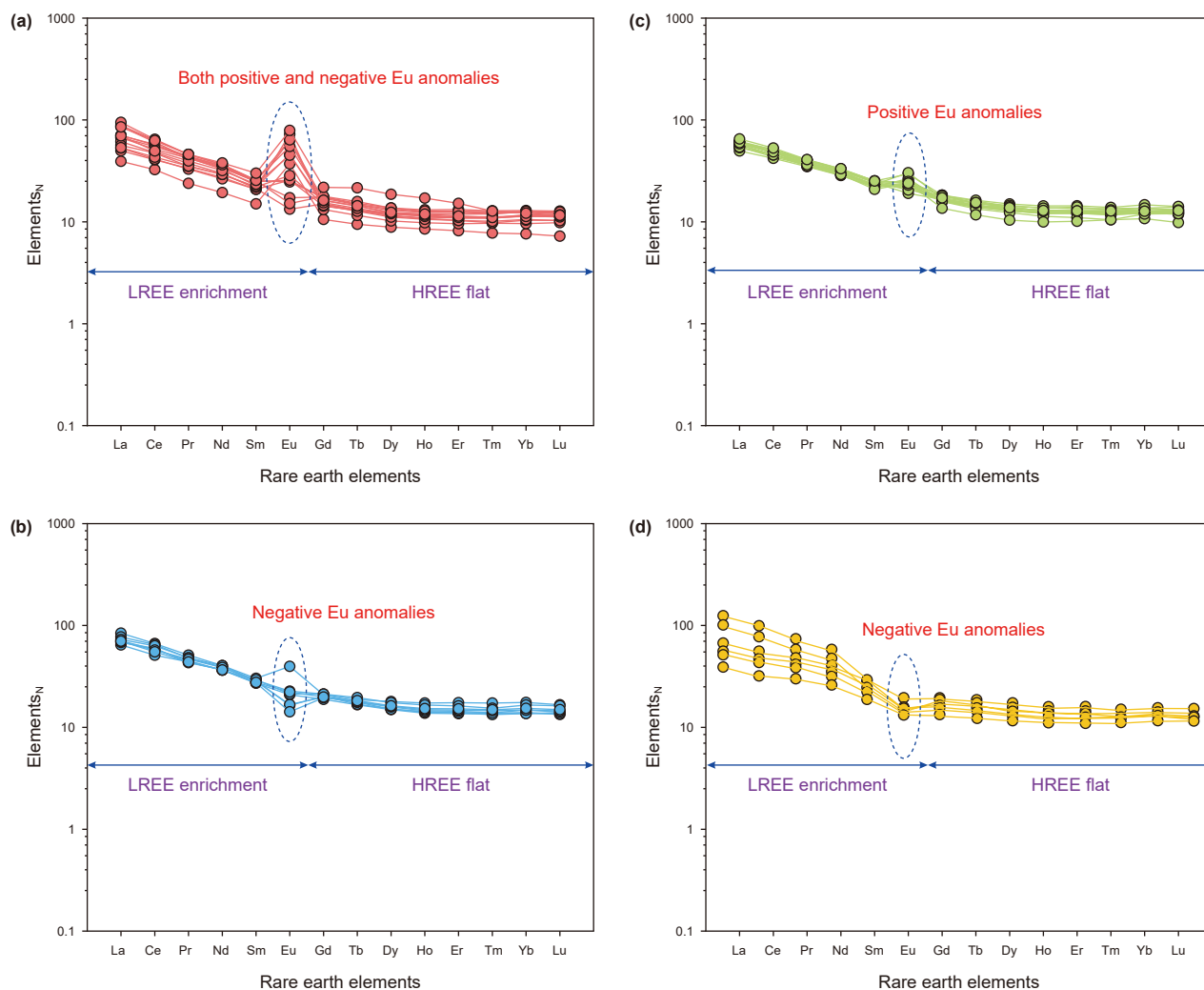


Fig. 4. Distribution patterns of REE in the P_2x Formation mudstone samples. (a) Cluster 1 samples, (b) Cluster 2 samples, (c) Cluster 3 samples, (d) Hala'ate and Zaire Mountains (Xu et al., 2021).

Zr contents of 71.22–205.73 ppm (Tables 2 and 3), generally falling within the typical compositional range of continental crust debris sediments (Fig. 5(a)). The mean Th/Sc and La/Sc are 0.41 and 1.65, respectively, which are significantly lower than those of the typical Upper Continental Crust (UCC) endmember but higher than the characteristic values of mafic rocks (Augustsson et al., 2023; Cullers, 1994; Taylor and McLennan, 1995). This feature indicates that the provenance is dominated by felsic rocks, accompanied by a certain degree of intermediate-mafic material input (Abu et al., 2023). Simultaneously, the CIA of the P_2x Formation mudstones range from 35.17 to 68.31, reflecting weak to moderate chemical weathering intensity (Fig. 5(a)). In the A-CN-K ternary diagram, the samples generally migrate toward the Al end along the theoretical weathering trend line of felsic parent rocks and are mainly distributed on the CN-A side (Fig. 5(a)). This distribution indicates that the weathering process is dominated by the decomposition of plagioclase and the selective leaching of Ca and Na, while K-metasomatism or intense illitization is not prevalent, reflecting relatively mild weathering environmental conditions (Algeo et al., 2025; Fu et al., 2023; Wang et al., 2020b). Specifically, Cluster 1 samples are characterized by relatively high K_2O contents (mean 3.90%), with moderate contents of Al_2O_3 (mean 13.68%) and SiO_2 (mean 58.08%), with CIA ranging from 35.17 to 63.70 (Table 2), indicating weak to moderate chemical weathering conditions (Algeo et al., 2025; Tao et al., 2016). The cluster samples predominantly exhibit positive Eu anomalies (Eu/Eu^*), with only a few displaying negative anomalies (0.61–0.96) (Fig. 4(a); Table 3), suggesting a distinct enrichment of plagioclase in the source area (Sawant et al., 2017). Consequently, the provenance of Cluster 1 is dominated by terrigenous felsic debris (such as granitoids), with inputs from intermediate-mafic provenance during localized depositional stages (Fig. 5(b)). In contrast, Cluster 2 samples display higher contents of SiO_2 (mean 61.36%) and Al_2O_3 (mean 13.94%), relatively stable K_2O (mean 3.21%), and moderate $CaO + Na_2O$ (mean 5.66%) (Table 2). The CIA of samples (54.53–68.31) are generally higher than those of Cluster 1 (Fig. 5(a)), indicating more intense chemical weathering (Algeo et al., 2025; Tao et al., 2013). In the A-CN-K diagram, Cluster 2 samples migrate further towards the Al end along the felsic weathering trend line, suggesting enhanced plagioclase weathering and clayization compared to Cluster 1 (Fig. 5(a)).

Furthermore, the prevalent negative Eu anomalies indicate a relative depletion of plagioclase in the provenance (Fig. 4(b)), suggesting that the sediments are mainly derived from a relatively stable felsic terrigenous debris system (Armstrong-Altrin et al., 2017; Sawant et al., 2017; Fig. 5(b)). Compared with the previous two clusters, Cluster 3 samples exhibit relatively higher contents of $CaO + Na_2O$ (mean 5.98%) and MgO (mean 3.22%) (Table 2), along with enrichment of mafic elements such as Cr and Ni (Table 3), displaying intermediate provenance characteristics. Combined with distinct positive Eu anomalies and CIA ranging from 49.20 to 66.87 (Figs. 4(c) and 5(a)), this reflects weak to moderate weathering conditions. Therefore, the provenance of Cluster 3 is dominated by a mixture of terrigenous felsic debris and intermediate magmatic materials (Fig. 5(b)).

The above characteristics indicate that the mudstones of the P_2x Formation are not derived from a single felsic provenance. Instead, rather reflect the mixed contributions of multiple types of provenances at different time periods or spatial scales. The Hala'alate and Zaire Mountains, surrounding the Mahu Sag, are extensively developed with felsic and intermediate-mafic parent rocks (Ablimiti et al., 2019; Huang et al., 2017; Xu et al., 2021), which exhibit LREE enrichment, overall right-inclined REE distribution, and negative Eu anomalies (Xu et al., 2021; Fig. 4(d)). The REE content of the P_2x Formation mudstones is comparable to that of the Hala'alate and Zaire parent rocks, also exhibiting similar right-inclined distribution (Fig. 4). Furthermore, both the mudstones and the parent rocks fall within the similar field on the K_2O - Al_2O_3 -($CaO + Na_2O$) diagram (Fig. 5(a)). Consequently, provenance of the P_2x Formation mudstones is predominantly derived from the Hala'alate and Zaire Mountains, with spatially systematic distribution of provenance inputs by controlling factors such as transport distance.

5.2. Paleoclimate

Elements such as Ca, Rb, Al, K, Sr, and Cu are hosted in carbonate minerals and clay minerals. Their concentrations vary with the intensity of evaporative processes, chemical weathering, and hydrolysis driven by shifts in arid and humid climatic conditions, thereby leading to the differential enrichment of distinct elements (Cao et al., 2012; Jia et al., 2013; Nesbitt and Young, 1984).

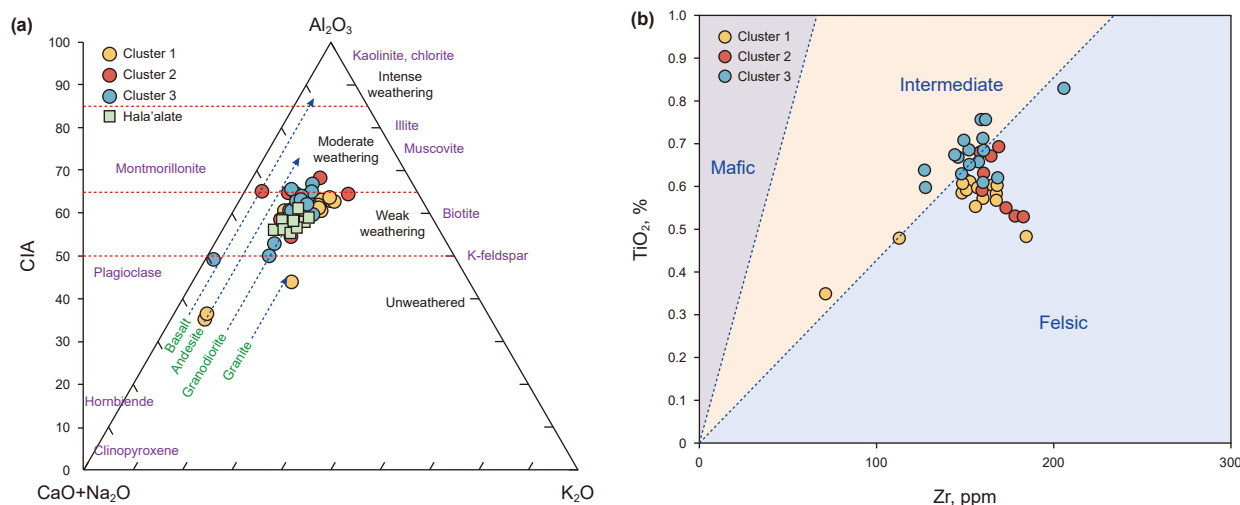


Fig. 5. Discrimination diagrams of provenance of P_2x Formation mudstone samples. (a) Zr-TiO₂ diagram (Hayashi et al., 1997), (b) K_2O - Al_2O_3 -($CaO + Na_2O$) diagram (Nesbitt and Young, 1984; Sun et al., 2024).

Consequently, ratios including Ca/Rb, Rb/Sr, and Sr/Cu are commonly employed as proxies to reconstruct paleoclimatic characteristics (Bai et al., 2015; Shaltami and Ben Hkoma, 2024; Tao et al., 2017; Wei and Algeo, 2020; Wu et al., 2024). However, due to the complex background of the provenance of the felsic and mafic mixture in the study area, the variations in Ca, K, and Al content reflect not only climatic signals but are also significantly influenced by shifts in provenance composition. This dual influence compromises the reliability of these elements as paleoclimatic discriminant indicators. To achieve more accurate paleoclimate reconstruction, this study selects the Rb/Sr and Sr/Cu as primary indicators, which are relatively insensitive to provenance shifts (An et al., 2018; Fu et al., 2019). The effectiveness of these indicators is validated through correlation analysis with provenance indicators, including La/Th (parent rock type), Zr/Sc (sorting degree and parent rock type), and Th/Sc (sediment input intensity) (Paul et al., 2023). Furthermore, the relative dominance of physical weathering versus chemical weathering under different climatic regimes is typically manifested in variations of CIA. It is generally accepted that high CIA values (>80) correspond to warm and humid climates, whereas low CIA values indicate cold and arid conditions (Li et al., 2022; Wang et al., 2020b; Wu et al., 2021).

The mudstones of the P_2x Formation exhibit overall low Rb/Sr (0.42 to 0.9) and significant fluctuations in Sr/Cu (1.34 to 27.68), reflecting distinct phased variations and differentiation in paleoclimatic conditions during this period (Fig. 6). Samples of Cluster 2 are distributed in humid zone and semi-arid to semi-humid zone, with Sr/Cu ranging from 3.52 to 10.37, Rb/Sr from 0.17 to 0.42 (Fig. 6(a)), and a mean CIA value of 62.13 (Fig. 5(a)), indicating an overall relatively humid climate. In contrast, Cluster 3 samples have higher Sr/Cu (1.34 to 26.84) but lower CIA values (mean 61.09) than those of Cluster 2 (Figs. 5(a) and 6(a)), with ratios spanning 0.08 to 0.38. This cluster of samples are primarily distributed in the semi-arid to semi-humid climatic zone, reflecting a tendency toward aridification. Cluster 1 samples are characterized by Sr/Cu of 4.8 to 27.68, Rb/Sr of 0.06 to 0.32 (Fig. 6(a)), and the lowest CIA values (mean 57.19) (Fig. 5(a)). These samples are partly located in the semi-arid to semi-humid zone, with some samples falling into the arid zone, indicating climate dominated by aridity with seasonal precipitation.

Correlation analysis of the indicators reveals that Sr/Cu and Rb/Sr exhibit a strong negative correlation (Pearson correlation

coefficient (P) = -0.71) (Fig. 6(b)), which is consistent with the geochemical mechanism whereby Sr becomes relatively enriched via evaporative concentration under arid conditions, while Cu and Rb are mobilized and leached along with clay minerals. Meanwhile, Sr/Cu and Rb/Sr exhibit weak or no correlation with provenance indicators such as Zr/Sc, Th/Sc, and La/Th (Fig. 6(b)). These results demonstrate that variations in Sr/Cu and Rb/Sr are primarily controlled by climatic factors rather than changes in provenance composition, thereby confirming their reliability as paleoclimate proxies.

5.3. Paleoredox condition

Elements such as V, U, and Ni tend to undergo complexation with organic matter or be adsorbed on the surface of clay minerals under reducing conditions, resulting in significant enrichment. In contrast, elements including Cr, Th, and Co are more prone to enrichment under oxidizing conditions, forming a distinct contrast in their geochemical behaviors (Arthur and Sageman, 1994; Cullers, 2002; Jones and Manning, 1994; Tiwari et al., 2023). Based on this differential characteristic, the aforementioned elements and their ratios are widely recognized as effective geochemical indicators for reconstructing paleoredox conditions (Algeo and Maynard, 2004; Sun et al., 2024; Yan et al., 2021; Zou et al., 2021). Previous studies have demonstrated that $V/Cr > 4.25$, $2-4.25$, and <2 indicate oxic, dysoxic, and anoxic conditions, respectively (Jones and Manning, 1994). Similarly, the $V/(V + Ni)$ uses thresholds of 0.6 and 0.46 to distinguish oxic (<0.46), dysoxic (0.46–0.6), and anoxic environments (>0.6), while $Ni/Co < 5$, $5-7$, and >7 correspond to oxic, dysoxic, and anoxic conditions (Zhang et al., 2019). However, PCA results show that Cr, Ni, and Sc exhibit highly clustering on PC2 (with loading factor all greater than 0.3), indicating that the abundance variations of these elements are largely controlled by provenance input rather than only the paleoredox conditions. This feature thus undermines the reliability of their use as indicators for paleoredox environments. In this study, Cr and Ni contents are normalized using the Al normalization method to reduce provenance effects. Combined with elements less affected by provenance (e.g., V, Co), multiple indicators including V/Cr , $V/(V + Ni)$, and Ni/Co are comprehensively applied to reconstruct the paleoredox environment of the study area (Fig. 7(a)), thereby enhancing the robustness and credibility of the interpretation results. Notably, the corrected Ni/

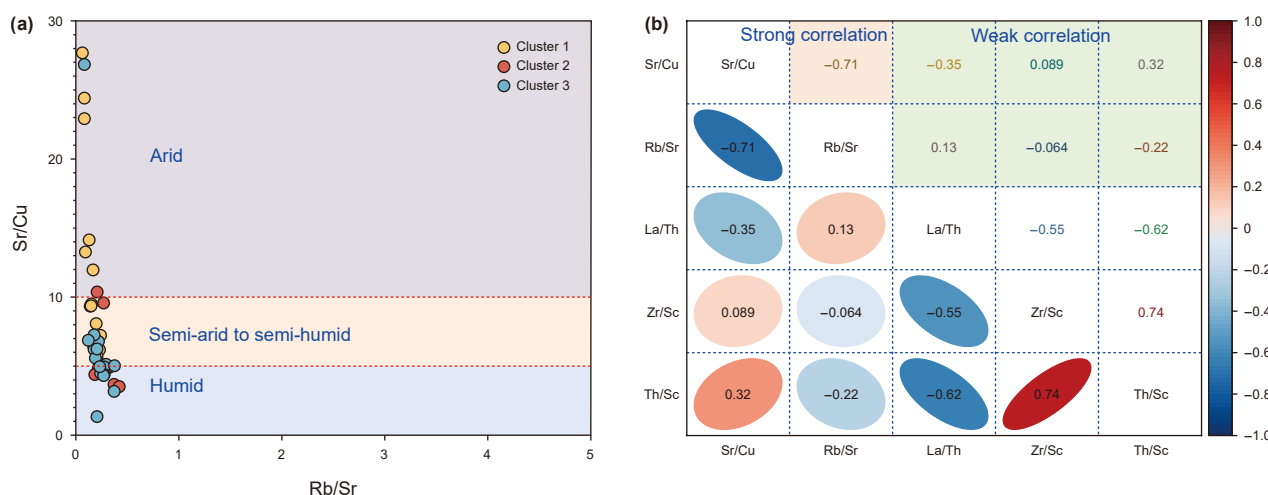


Fig. 6. Discrimination diagrams of paleoclimate of the P_2x Formation mudstone samples in the Mahu Sag. (a) Rb/Sr-Sr/Cu diagram (Shaltami and Ben Hkoma, 2024), (b) correlation heatmap of paleoclimate indicators and provenance indicators.

Co still shows a moderate correlation with provenance indicators ($P = 0.41$) (Fig. 7(a)), suggesting that this indicator is affected by terrigenous debris input, resulting in relatively low ratio values. Nevertheless, the trend of its ratio variation can still reflect changes in the paleoredox conditions of the depositional environment.

The V/Cr of mudstones in the P_2x Formation range from 0.36 to 4.00, V/(V + Ni) from 0.42 to 0.87, and Ni/Co from 1.55 to 8.27 (Fig. 7(b) and (c)). These values exhibit the characteristics of an oxic-dysoxic-anoxic transitional environment with significant differentiation. For Cluster 1 samples, the Ni/Co range from 1.55 to 3.46, V/Cr from 1.46 to 4.00, and V/(V + Ni) from 0.79 to 0.87, indicating a predominantly dysoxic-anoxic environment (Fig. 7(b) and (c)). For Cluster 2 samples, the mean V/Cr (1.29) and mean V/(V + Ni) (0.65) are lower than those of Cluster 1 (Fig. 7(c)), while the mean Ni/Co (4.35) is higher than that of Cluster 1 (2.18) (Fig. 7(b)). In addition, all indicators exhibit greater dispersion, indicating that the depositional water column for Cluster 2 is generally more oxidizing than that of Cluster 1, punctuated by intermittent dysoxic events (Ocupalidet et al., 2018). Combined with Sr/Rb ranging from 2.37 to 5.73 (Table 3), these dysoxic events may reflect periodic changes in water column ventilation and organic matter supply within a shallow-water background. For Cluster 3 samples, the V/Cr (mean 0.77) and V/(V + Ni) (mean 0.51) further decrease, generally falling within the oxic zone (Fig. 7(b) and (c)). These features indicate that the bottom water during deposition was predominantly oxic, with localized samples shifting towards dysoxic, reflecting short-term in aeration or increased organic matter load (Ocupalidet et al., 2018; Yuan et al., 2020).

5.4. Paleosalinity

Elements such as B, Ga, Sr, and Ba exhibit differential adsorption and dissolution behaviors in environments with different salinities. Consequently, ratios such as Sr/Ba, K/Na, and B/Ga are widely regarded as critical indicators for reconstructing paleosalinity of depositional environments (Qiao et al., 2023; Wei et al., 2018; Wei and Algeo, 2020; Wu et al., 2023). Under high-salinity conditions, the solubility of Sr increases, leading to its enrichment, whereas Ba are more prone to precipitation in low-salinity environments. Furthermore, B exists stably as boric acid or borate in high-salinity water and is easily adsorbed by clay minerals. In contrast, the geochemical behavior of Ga is mainly controlled by terrigenous debris input, maintaining relatively stable content across different salinity environments (Elton, 1971; Ring et al., 2025). Thus, Sr/Ba and B/Ga can effectively reflect changes in the salinity of the depositional water body while remaining insensitive to shifts in terrigenous input (Qiao et al., 2025; Wei and Algeo, 2020; Zheng et al., 2019). However, the Ba contents in mudstones of the P_2x Formation are significantly abnormal, generally exceeding 2000 ppm and a maximum of 35713.79 ppm (Table 3). Correlation analysis reveals that Ba exhibits weak correlations with indicators such as Fe/Mn (0.41) and K_2O (0.29) (Fig. 8(a)), suggesting that its enrichment process was controlled by multiple factors. Specifically, the weak correlation between Ba and K_2O contents indicates that terrigenous debris provide the fundamental material source for Ba enrichment. In contrast, the strong correlation between Ba and Eu anomalies suggests that Ba abundances are highly coupled with hydrothermal fluid activity (Fig. 8(b)). In summary, the anomalously high Ba contents in the study area are a product of the synergistic superposition of terrigenous input and hydrothermal processes. In contrast, the loadings of B and Ga on PC2 are both less than 0.1 (Table 1), and their ratio shows weak correlations with provenance indicators (Fig. 9(a)). Therefore, the B/Ga was selected as the

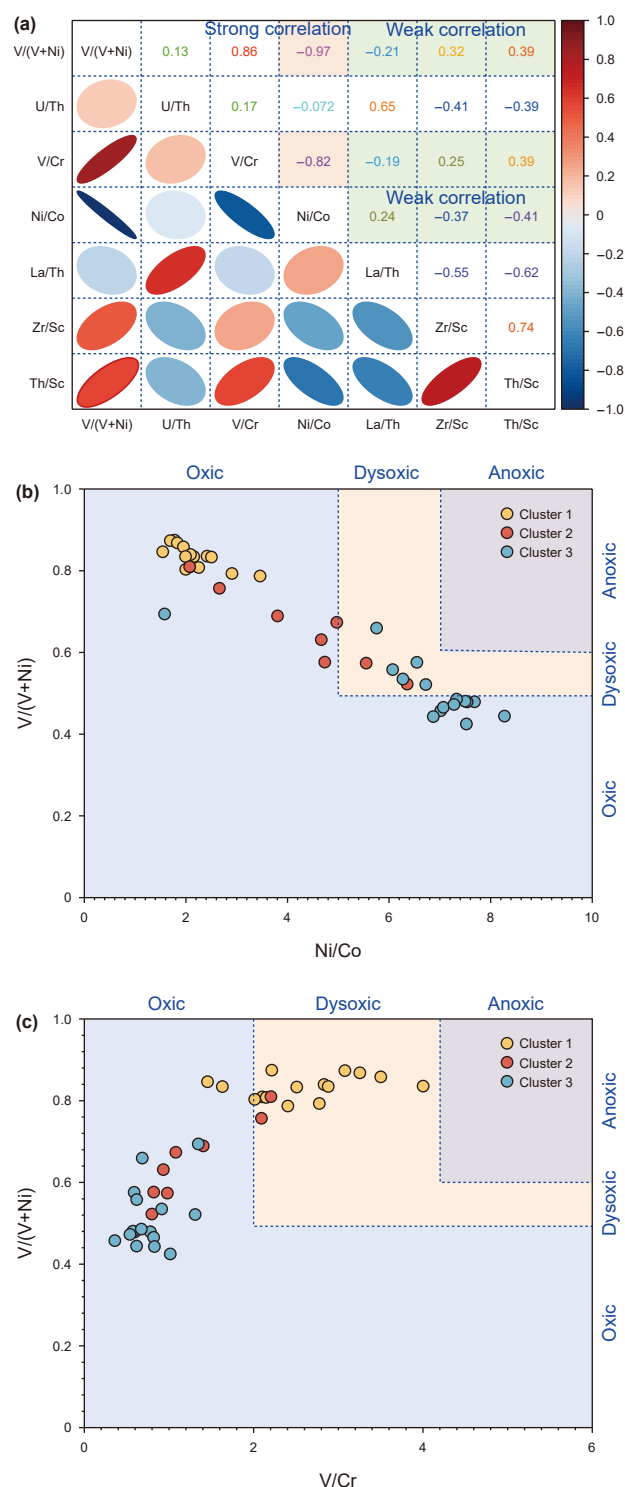


Fig. 7. Discrimination diagrams of paleoredox conditions of the P_2x Formation mudstone samples in the Mahu Sag. (a) Correlation heatmap of paleoredox indicators and provenance indicators, (b) Ni/Co-V/(V + Ni) diagram (Zhao et al., 2016), (c) V/Cr-V/(V + Ni) diagram (Zhao et al., 2016).

primary paleosalinity indicator for this study which is less affected by terrestrial debris interference. Previous studies have suggested that B/Ga < 3, 3–6, and > 6 indicate freshwater, brackish water, and saline water conditions, respectively (Elton, 1971; Ring et al., 2025). Cluster 1 samples from the P_2x Formation have relatively

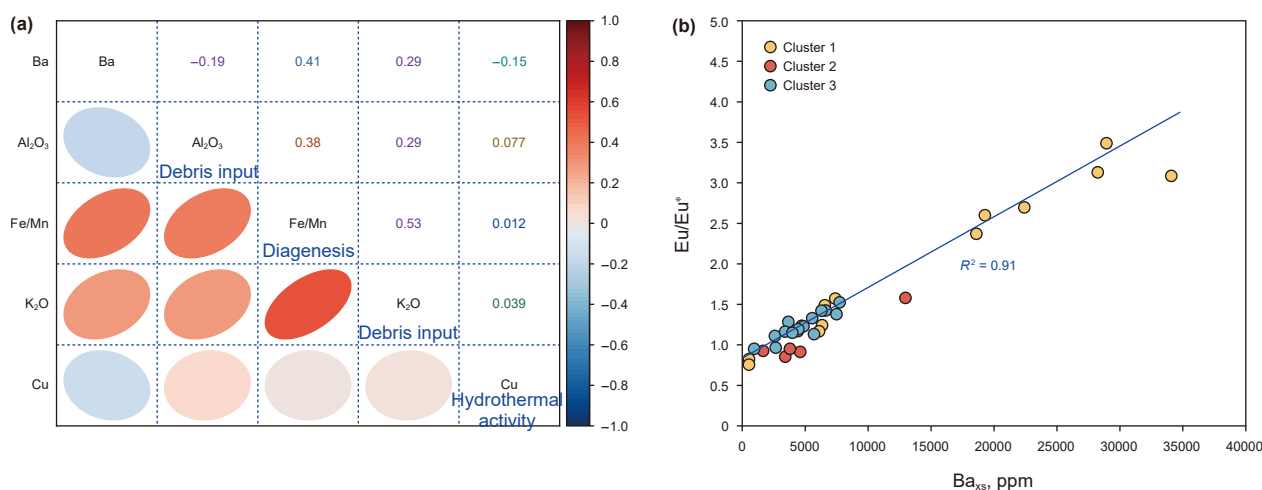


Fig. 8. (a) Correlation heatmap between Ba element and other indicators, (b) Ba-Eu anomalies scatter plot.

low B/Ga (1.33–2.58), with some exceeding 3 (4.37 to 10.63) (Table 3). This feature indicates a predominantly freshwater environment (78% of samples), while a minority of samples fall into the 3–6 range or even exceed 6 (Fig. 9(b)), suggesting episodic brackish-salinization events or local salinity enhancement during the deposition period (Sun et al., 2024). In contrast, Cluster 2 samples have higher B/Ga (1.64–5.99) than Cluster 1 (Fig. 9(b)), indicating a freshwater environment characterized by seasonal evaporation or water column stratification (Wei and Algeo, 2020). Cluster 3 samples exhibit a broad range of B/Ga (1.54–17.73) (Table 3), with most falling within the freshwater range and being accompanied by distinct high-value points (>6) (Fig. 9(b)), indicating episodic salinity fluctuations within a mixed sedimentary background (Wei and Algeo, 2020).

5.5. Palaeowater depth

Al₂O₃ is mainly hosted in clay minerals and felsic debris, representing a stable background of terrigenous debris input, whereas CaO is predominantly derived from carbonate minerals (He et al., 2021). In nearshore shallow-water environments, sedimentary systems are strongly influenced by terrigenous debris input, and carbonate sedimentation is relatively suppressed, thereby typically exhibiting low CaO/Al₂O₃. Conversely, with increasing water depth, the supply of terrigenous debris gradually diminishes while carbonate sedimentation intensifies, resulting in a corresponding increase in the CaO/Al₂O₃ (Amosova et al., 2024; He et al., 2021). Thus, variations in the CaO/Al₂O₃ can effectively indicate the evolutionary process of depositional water body from shallow to deep. Similarly, Sr exhibits a strong affinity for carbonates and readily incorporates into the crystal lattice of carbonate minerals, while Rb is typically associated with K and enriched in clay minerals such as illite, representing terrigenous debris input (Gussone et al., 2020; Higgins et al., 2018). Therefore, low Sr/Rb generally indicate nearshore shallow-water environments, while high Sr/Rb reflect deep-water environments characterized by weakened terrigenous debris input and enhanced carbonate sedimentation. Furthermore, PCA results show that the factor loadings of Ca, Al, Sr, and Rb on the principal components representing provenance differences are all below 0.3 (Table 1). This characteristic suggests that the variations in the abundance of these elements are not significantly controlled by the mixing of different provenances, but rather primarily reflect changes in depositional environmental conditions. Although diagenesis may influence the contents of Ca

and Sr to a certain extent, its systematic impact on element is limited (Fig. 9(a)). Therefore, this study combines CaO/Al₂O₃ and Sr/Rb as comprehensive discriminant indicators for paleowater depth changes, aiming to reduce the potential impacts of provenance variations and diagenetic alteration on the reliability of the indicators.

The samples from Cluster 1 of the P₂x Formation exhibit a wide range of CaO/Al₂O₃ (0.13–1.38) and Sr/Rb (3.15–15.7) (Tables 2 and 3), spanning the indicative intervals for shallow water, semi-deep water, and deep water environments. Although these indicators show large variation, most samples fall within the semi-deep water zone (Fig. 9(c)), indicating that this cluster generally represents a depositional environment characterized by semi-deep water, accompanied by intermittent water-level fluctuations likely related to changes in lacustrine basin water volume. In contrast, the CaO/Al₂O₃ (0.1–0.42) and Sr/Rb (2.37–5.73) of Cluster 2 samples are distributed in the shallow water indicator zone (Fig. 9(c)), with some samples in the semi-deep water zone, indicating that the water conditions during the deposition of Cluster 2 are relatively stable and weakly influenced by water-level fluctuations, primarily reflecting a nearshore shallow water environment. For Cluster 3 samples, the CaO/Al₂O₃ range from 0.13 to 0.49 and Sr/Rb from 2.66 to 12.02, indicating a shallow water environment (Fig. 9(c)). However, some samples exhibit significantly elevated Sr/Rb (5.62–12.02) and CaO/Al₂O₃ (0.39–0.49) (Table 3), indicating localized, episodic deepening of the water body against the general shallow background. This variation corresponds well with the discrimination results for paleosalinity and paleoredox conditions (Figs. 7 and 9(b)). Consequently, Cluster 3 indicates a transitional depositional environment ranging from shallow water, potentially reflecting episodic water-level rises or changes in water body structure during the depositional period (Remírez et al., 2025; Wang et al., 2021).

5.6. Hydrothermal activity

Hydrothermal fluids are typically generated in relatively reducing environments. In such settings, Eu exists in a reduced valence state, rendering it more mobile than other REEs and thus prone to enrichment in reservoir spaces (Allen and Seyfried, 2005; Han et al., 2017; McLennan et al., 1993). Eu anomalies are commonly utilized as indicators of hydrothermal fluid activity, with the magnitude of anomaly exhibiting a positive correlation with the intensity of hydrothermal alteration. In contrast, Ce

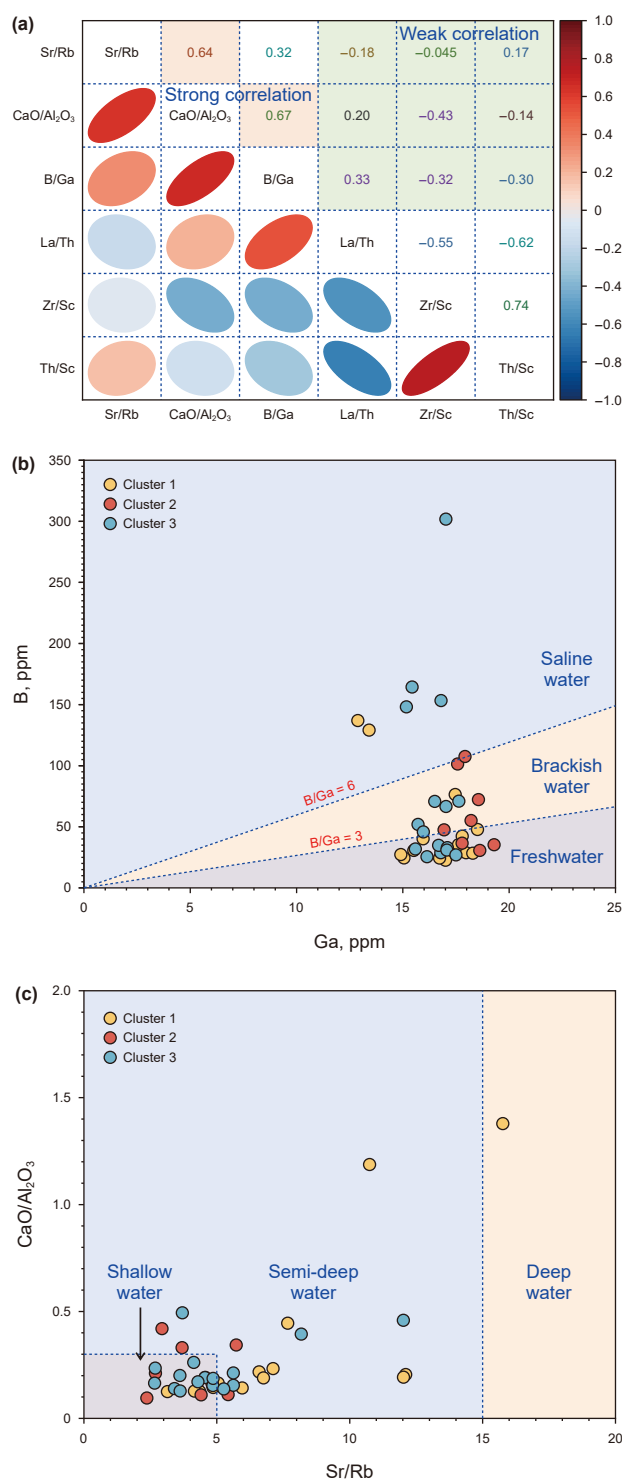


Fig. 9. Discrimination diagrams of paleosalinity and palaeowater depth of the P_{2x} Formation mudstone samples in the Mahu Sag. (a) Correlation heatmap of paleosalinity and provenance indicators, (b) B-Ga diagram (Wei and Algeo, 2020), (c) Sr/Rb-CaO/Al₂O₃ diagram.

anomalies are primarily governed by the redox conditions of depositional waterbodies. The influx of hydrothermal fluids disrupts the oxidative equilibrium of depositional waterbodies, inhibiting the oxidative removal of Ce and thereby resulting in negligible or positive Ce anomalies (Astakhov et al., 2019;

Pitchaimani et al., 2025; Wei et al., 2020). Furthermore, Pb, Zn, Cu, and Mn are recognized as typical indicator elements for hydrothermal activity. These elements can form soluble complexes with Cl^- , S^{2-} , and other ligands in hydrothermal fluids, which subsequently precipitate and accumulate rapidly in sediments (Liao et al., 2019; Yang et al., 2025). Their concentrations generally show a positive correlation with the intensity of hydrothermal activity.

Eu anomalies in the mudstones of the P_{2x} Formation range from 0.61 to 4.36, with 70% of the samples showing Eu anomalies greater than 1 (ranging from 1.11 to 4.36), whereas Ce anomalies vary between 0.94 and 1.10 (Table 3). These data indicate the presence of varying degrees of hydrothermal fluid activity in the study area. Additionally, the enrichment factors (EFs) of Zn, Cu, and Mn primarily range between 1 and 3 (Fig. 10), suggesting that hydrothermal activity in the study area was characterized by the input and redistribution of metallic elements rather than by exhalative hydrothermal sedimentation (Qiu et al., 2023; Wang et al., 2024b). Spatially, the Eu anomalies in the Mabei area range from 0.95 to 1.52 (mean = 1.22) and Ce anomalies vary between 0.94 and 1.07 (mean = 1.01) (Fig. 10), with average EFs for Zn, Cu, and Mn of 1.4, 2.4, and 1.4, respectively (Fig. 10), indicating the development of moderate-intensity hydrothermal fluid activity (Schmidt et al., 2010; Wang et al., 2024b). In contrast, Eu anomalies in the Maxi area range from 0.61 to 1.17 (mean = 0.78), reflecting relatively weak hydrothermal signals. However, the Ce anomalies in this area (1.0–1.10, mean = 1.04) are higher than those in the Mabei area (Fig. 10), implying that the increased oxidizing conditions of the sedimentary environment and enhanced input of terrigenous debris may have exerted a dilution effect on Eu anomalies (Long and Luo, 2017; Zhang et al., 2023b). Therefore, based on a comprehensive analysis of various geochemical indicators, the Maxi area is characterized by weak to moderate hydrothermal activity. The Manan area exhibits the highest Eu anomalies (1.49–4.36), yet its Ce anomalies (0.94–1.07) and average EFs for Zn (1.16), Cu (1.69), and Mn (0.97) are the lowest among the regions (Fig. 10). This phenomenon indicates that the weak input of terrigenous debris and relatively reducing sedimentary environment in this area have amplified the Eu anomalies (Long and Luo, 2017; Zhang et al., 2023b). Consequently, a comprehensive evaluation suggests that the intensity of hydrothermal fluid activity in the Manan area is lower than that in the Mabei area but higher than that in the Maxi area.

5.7. Depositional model

The depositional environment of the P_{2x} Formation in the Mahu Sag was developed a lacustrine basin depositional system under a semi-arid to semi-humid climatic background (Fig. 6). The depositional water body was characterized by freshwater to brackish environments (Fig. 9(b)), with local areas exhibiting periodic salinity increases influenced by enhanced evaporation or water column stratification. During the deposition period, the environment was generally characterized by oxic to dysoxic conditions with distinct spatial heterogeneity (Fig. 7), reflecting spatial variations in hydrodynamic conditions and sediment supply within lacustrine basin. Meanwhile, the Mahu Sag received terrigenous felsic debris and intermediate-mafic magmatic materials from the surrounding orogenic belts during the deposition of the P_{2x} Formation (Fig. 6). Notably, felsic debris was widely distributed in the basin due to its strong resistance to weathering and potential for long-distance transport, while intermediate-mafic magmatic components were mainly enriched in proximal areas.

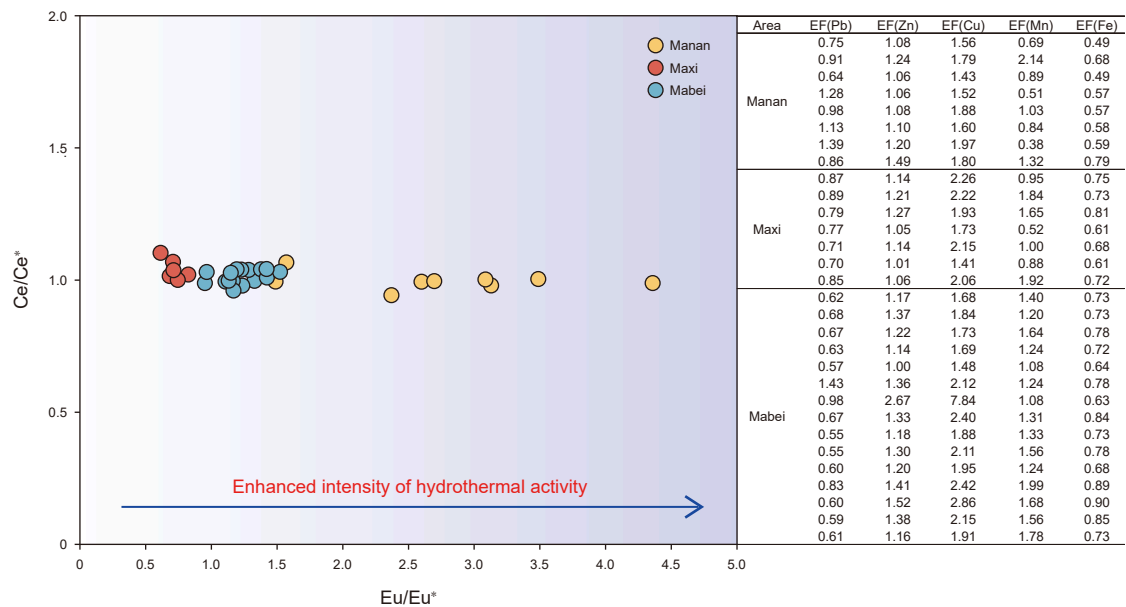


Fig. 10. Eu/Eu*-Ce/Ce* scatter plot and enrichment factors of Pb, Zn, Cu, Mn, Fe in different areas.

Spatially, the P_2x Formation in the Mabei area is dominated by a Cluster 3-type depositional environment (Fig. 11), characterized by dual provenance inputs of felsic debris and intermediate magmatic materials (Fig. 5(b)). The climatic conditions in this region were in a transitional state between semi-arid and semi-humid (Fig. 6(a)), with the depositional water body maintaining freshwater environment (Fig. 9(b)). However, under the influence of climatic fluctuations and changes in water body structure, localized episodic increases in salinity occurred. During the deposition of the P_2x Formation, the Mabei area exhibited good aeration conditions, with the water environment primarily being oxic, and only transient dysoxic characteristics appeared locally during certain periods affected by water level changes or increased organic matter input (Fig. 7(b) and (c)). Therefore, the Mabei area generally

represents a shallow water depositional environment with proximal supply.

In contrast, the P_2x Formation in the Manan area exhibits a Cluster 1-type depositional environment (Fig. 12), with provenance characteristics dominated by terrigenous felsic debris input and local intermediate-mafic provenance supply (Fig. 5(b)). During this period, the Manan area experienced increased aridity, dominated by an arid climate with seasonal precipitation (Fig. 6). The depositional water body of this region was generally freshwater, with local periodic salinity increases (Fig. 9(b)). Paleoredox indicators show that the water body in this area was mainly in dysoxic-anoxic state (Fig. 7), representing an overall semi-deep water environment with a certain degree of water level fluctuation (Fig. 9(c)).

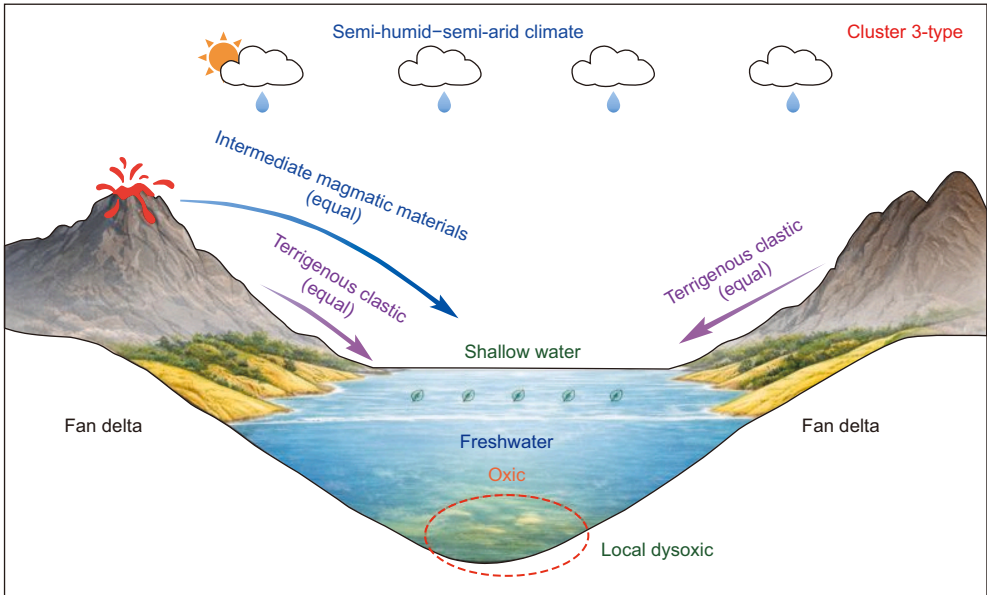


Fig. 11. Depositional model of the Mabei area.

The depositional environment of the P_2x Formation in the Maxi area shows distinct vertical evolutionary characteristics (Fig. 13). The early stage was dominated by a Cluster 2-type environment, featuring stable felsic provenance supply and relatively humid climatic conditions (Fig. 13(a)). During this stage, the Maxi area was dominated by freshwater-to-brackish water environments with limited influence from water-level changes (Fig. 9(b)), representing an overall nearshore shallow water depositional environment (Fig. 9(c)). With depositional evolution, the climate gradually became arid, evaporation intensified, and the depositional environment transformed into a Cluster 1-type (Fig. 13(b)). At this stage, the contribution of terrigenous felsic detritus relatively weakened, while the input of intermediate-mafic magmatic components increased, and hydrodynamic instability in the depositional water body intensified.

In summary, from north to south, the paleoclimate of the P_2x Formation tends to be arid, the depositional water depth slightly increases, accompanied by weakened oxic conditions and fluctuating water salinity. Controlled by the distance from the provenance area, the intensity of terrigenous debris input to the P_2x Formation displays a spatial pattern of “Maxi > Mabei > Manan”. Furthermore, due to differences in the lithology of parent rock between the Hala’alate Mountains (intermediate-acidic) and the Zhai’er Mountains (intermediate-mafic) (Ablimiti et al., 2019; Huang et al., 2017; Xu et al., 2021), the Mabei area receives intermediate magmatic material supply, while the Manan area is enriched in intermediate-mafic magmatic materials.

5.8. Controlling factors of depositional environment

The spatial differentiation and evolutionary characteristics of the depositional environment in the P_2x Formation record the synergistic evolution among tectonic activity, provenance supply, climate change, and lacustrine hydrological conditions in the Mahu Sag and its periphery during the Late Paleozoic. During the deposition of the P_2x Formation, the provenance was dominated by felsic debris (mean $\text{SiO}_2 = 59.17\%$), accompanied by certain proportion of intermediate-mafic magmatic materials input (mean $\text{TiO}_2 = 0.62\%$; mean $\text{MgO} = 2.50\%$; mean $\text{Zr} = 141.85$ ppm; mean $\text{Th} = 5.23$ ppm) (Fig. 5), constituting a mixed-lithology provenance system. The intensity of terrigenous debris supplies

generally exhibited clear regional heterogeneity (mean Zr content: Mabei = 154.97 ppm; Maxi = 167.22 ppm; Manan = 148.48 ppm). Meanwhile, the distribution of intermediate-mafic components also showed distinct spatial variability (Fig. 5(b)), indicating spatiotemporal differences in the uplift magnitude and lithological denudation processes of the peripheral orogenic belts. The synergistic variation between climatic conditions and basin hydrology provides key constraints for understanding the intensification of basin restriction in the background of tectonic uplift. During the deposition of the P_2x Formation, the study area was characterized by weak-moderate weathering conditions (CIA: 35.17–68.31), with the weathering process characterized by plagioclase decomposition and selective leaching of Ca (mean: 3.37%) and Na (mean: 3.31%) (Fig. 5(a)). This characteristic indicates that the weathering in the provenance area was controlled by the combined effects of tectonic uplift and climate change (Taylor and McLennan, 1995). Concurrently, the climate exhibited a trend of increasing aridification from north to south (mean Sr/Cu: Mabei = 6.47; Maxi = 6.63; Manan = 14.24) (Figs. 11–13), suggesting that climate aridification and intensified evaporation collectively led to increased basin closure, specifically reflected by episodic water salinization events (Luan et al., 2024; Merdith et al., 2019). Notably, the sedimentary evolution of the P_2x Formation, intense plate collisions triggered the rapid uplift of the orogenic belts surrounding the Mahu Sag, which not only altered provenance supply through mechanical erosion (Zr: 158.29 ppm) but also blocked the transport of water vapor to the interior of the basin (Broussolle, 2022; Stampfli et al., 2013; Zhao et al., 2018), thereby forming the abnormal climatic zone distribution pattern of “humid in the north and arid in the south” in the P_2x Formation (Fig. 6).

The principal component loadings of PC1 and PC2 are mainly contributed by provenance indicators (e.g., Mn, Fe, Th, Sc) and redox indicators (e.g., Cr, U) (Table 1), indicating that provenance input intensity and depositional water column redox conditions are the two dominant controlling factors for the spatial differentiation of the depositional environment of the P_2x Formation, together explaining 63.03% of the depositional environment variation in the study area. The Hala’alate Mountain is characterized by intermediate-acidic parent rocks, while the Zaire Mountain is mainly composed of intermediate-mafic parent rocks. Due to the strong weathering resistance of felsic parent rocks, the rocks can

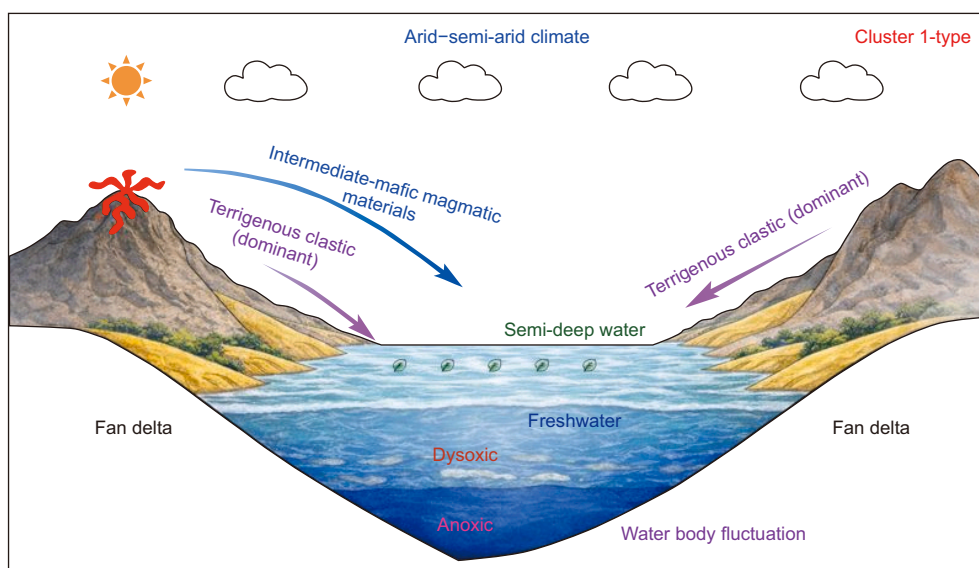


Fig. 12. Depositional model of the Manan area.

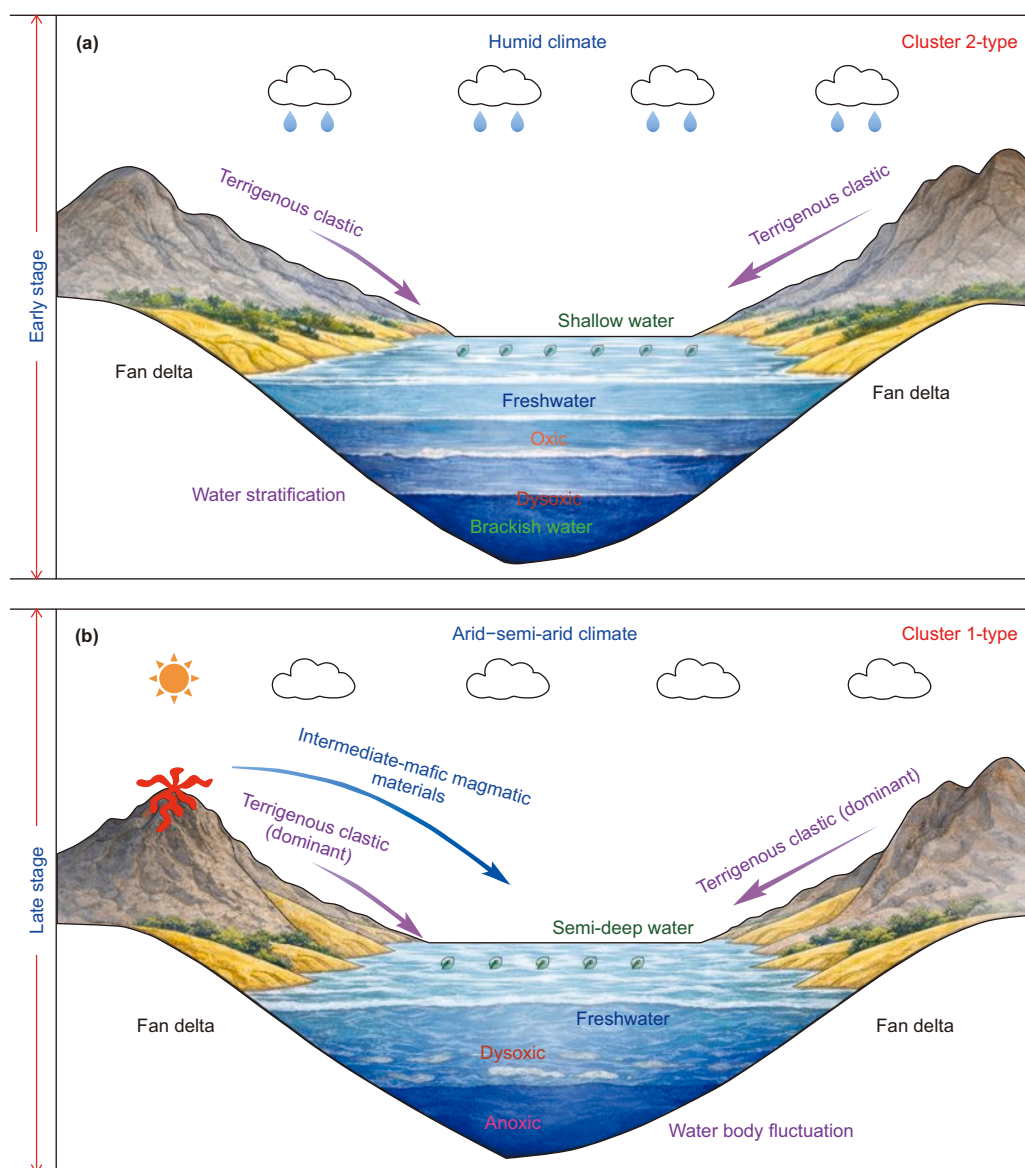


Fig. 13. Depositional model of the Maxi area.

be transported over long distances for deposition, whereas magmatic components are only deposited in proximal areas (Agangi et al., 2022; He et al., 2010; Qi et al., 2024). Consequently, the sediments in the Mabei area are mainly supplied with terrigenous debris from the Hala'alate Mountain, accompanied by some intermediate magmatic material (Fig. 5(b)). The provenance of the Manan area is dominated by terrigenous debris and intermediate-mafic magmatic components from the Zaire Mountain. Affected by the distance from the source area, the Maxi area is mainly supplied with terrigenous felsic debris.

In conclusion, the sedimentary evolutionary sequence of the P_2x Formation reveals the characteristics of "tectonic control on the basin and source-to-sink coupling" in the Mahu Sag. These findings not only provide critical geological constraints for deep to ultra-deep hydrocarbon exploration in the region but also offer new regional evidence for understanding the evolution of late intracontinental tectonic activities in the Central Asian Orogenic Belt.

5.9. Reservoir control effect of sedimentary environment

Previous studies have confirmed that the conglomerate reservoirs of the P_2x Formation in the Mahu Sag are rich in zeolite cement, which is one of the critical factors affecting reservoir quality (Chen et al., 2022; Sun et al., 2023; Yu et al., 2022a; Yu et al., 2023; Zhou et al., 2023; Zhu et al., 2012; Fig. 14(a)–(c)). Constrained by the combined effects of alternating arid and humid climatic conditions, evolution of water body properties, and a dual provenance supply system, the depositional environmental conditions regulate the pore water recharge mechanisms, fluid salinity, and ion composition, thereby affecting the fluid chemical properties and zeolite formation pathways during the diagenetic stage (Caliro et al., 2025; Lothenbach et al., 2017; Rabelo et al., 2019). This mechanism results in significant spatial differentiation in the types of zeolite cement in the study area. Specifically, terrigenous felsic debris and magmatic materials together provide the material basis for zeolite formation (Su et al., 2016). During

diagenesis, felsic debris provide a Si-Al-rich reaction matrix for zeolite precipitation (Table 2), while magmatic components regulate the crystal structure and type stability of zeolites by releasing cations such as Na^+ and Ca^{2+} (Lothenbach et al., 2017; Rabelo et al., 2019). On the regional scale, climatic conditions, water salinity, and percolation conditions influence the relative abundance of different zeolite cement types by affecting freshwater recharge intensity, evaporative concentration effects, and pore fluid circulation patterns. For instance, under humid climatic conditions, continuous freshwater recharge favors the formation of a diagenetic environment with low salinity, relative Na^+ enrichment, and frequent fluid renewal, thereby promoting the formation of analcime and inhibiting the development of laumontite and heulandite, which are more sensitive to high-salinity environments and high Ca^{2+} activity (Renaut, 1993; Zhu et al., 2012, 2020).

In the Mabei area, the P_2x Formation received a mixed provenance of felsic debris and intermediate magmatic materials (Fig. 5(b)), providing volcanic glass and feldspar debris relatively rich in Na and Al with moderate Si/Al ratios. The combined effect of semi-humid climate and episodic salinization events enhanced the Na^+ activity in pore water and system closure, leading to the preferential alteration of precursors (e.g., volcanic glass) to form analcime and heulandite (Renaut, 1993; Zhu et al., 2012; Table 4). The development of laumontite was restricted due to the low Ca^{2+} concentration in fluids and increased water salinity (Kousehlar et al., 2012; Rabelo et al., 2019). In contrast, the reduced input intensity of intermediate-mafic magmatic materials and lower water salinity in the Manan area resulted in decreased contents of Ca-Al-Si-rich materials and lower fluid $\text{Na}^+/\text{Ca}^{2+}$. The pore water

environment presented an open low-salinity system, which inhibited the formation of heulandite and promoted the formation of Ca-rich laumontite. Therefore, laumontite dominates the zeolite cement in this area, with subordinate heulandite (Table 4). The Maxi area exhibits a two-stage sedimentary evolution pattern. During the early stage, a stable supply of felsic debris provided balanced inputs of Si^{4+} , Al^{3+} , and minor Na^+ (Barreyre et al., 2025; Tan et al., 2024). Under humid climatic conditions and good aeration conditions, a solid material foundation and stable diagenetic fluid environment for zeolite cement formation is established. In the late stage, the Maxi area received supplementary intermediate-mafic provenance inputs. Regulated by intermittent fluid circulation caused by seasonal precipitation, the ionic composition of pore water remained relatively balanced, resulting in a relatively equal content of laumontite, heulandite, and analcime cements in the region (Table 4).

The coordinated coupling between the spatial differential distribution of zeolite cements and the depositional environment determines the distribution pattern of reservoir quality in the P_2x

Table 4
Statistical table of zeolite cement content in different exploratory areas.

Cement	Mabei	Maxi	Manan
Laumontite, %	9.2	43.2	53.6
Heulandite, %	40.8	27.9	21.5
Analcime, %	31.2	28.9	21.6
Calcite, %	18.8	0	3.3
Porosity, %	9.17	11.25	8.95
Permeability, mD	4.77	6.03	4.35

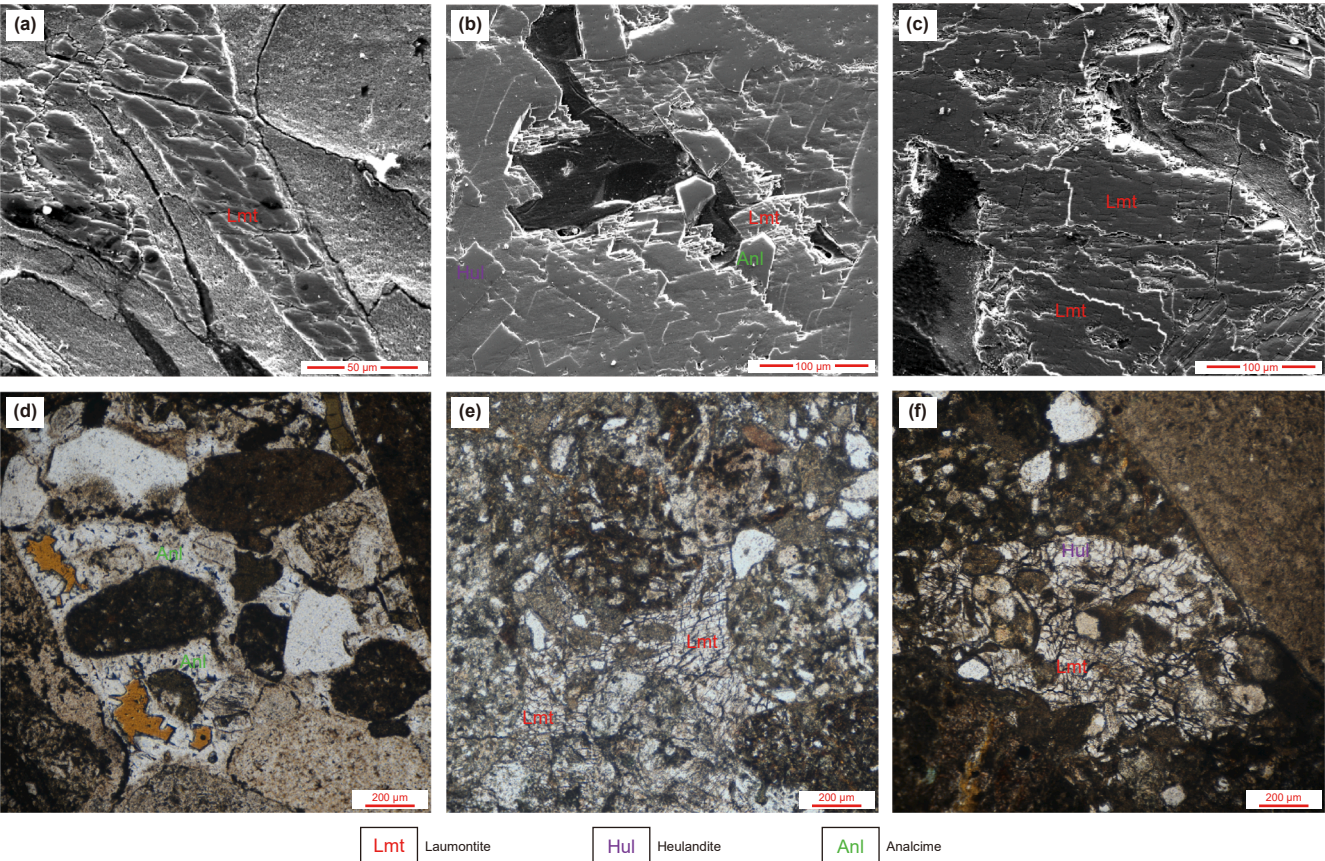


Fig. 14. (a)–(c) Scanning electron microscope images of zeolite cement. (a) MH15, 3661.65 m, (b) FY1, 3852 m, (c) MH15, 3803.15 m; (d)–(f) microscopic images of zeolite cement, (d) MH1, 4108.9 m, (e) MH15, 3810.9 m, (f) MH15, 3806.05 m.

Formation as "Maxi > Mabei > Manan" (Table 4). Under humid climatic conditions, continuous freshwater recharge not only provides a stable supply source for pore fluids but also enhances fluid circulation capacity, forming favorable percolation conditions. Meanwhile, volatile components carried by the intermediate magmatic provenance dissolve in pore water to generate H^+ , which fully mixes with freshwater driven by good percolation conditions, gradually transforming the original alkaline pore fluids into a weakly acidic environment (Heard et al., 2020; Zhu et al., 2012). In the acidic environment, Ca-rich laumontite and part of heulandite undergo dissolution to form secondary pores (Fig. 14(a)–(c)), thereby improving reservoir physical properties (Grifoni et al., 2021; Lavoie et al., 2025; Zhou et al., 2023). Due to the dominance of heulandite and analcime among zeolite cements with limited laumontite content in the Mabei area (Table 4), thereby the conglomerate reservoir quality in this region is moderate. In the Maxi area, the total content of laumontite and heulandite is higher than that in the Mabei area. Under the action of acidic fluids, the intensity of cement dissolution is greater than in the Mabei area, resulting in better conglomerate reservoir quality compared to the Mabei area. In contrast, the Manan area is characterized by greater depositional water depth, poor water column aeration, and weak pore fluid circulation capacity. Meanwhile, alkaline cations such as Ca^{2+} and Mg^{2+} carried by mafic provenance input reduce fluid acidity under limited fluid circulation conditions, forming local alkaline fluid environments. Under the combined effect of above factors, analcime in the conglomerate of the Manan area undergoes dissolution due to the destruction of Al–O–Si bonds by OH^- ions (Lin et al., 2024; Novembre and Gimeno, 2021; Fig. 14(d)), but the dissolution of laumontite and heulandite is limited (Fig. 14(e) and (f)). Therefore, the reservoir quality of the conglomerate reservoirs in this area is lower than those in the Maxi and Mabei areas.

6. Conclusion

- (1) The depositional environments of the P_2x Formation in the Mahu Sag consist of a freshwater environment under a semi-humid to semi-arid climate (Cluster 3), a freshwater environment under an arid climate (Cluster 1), and a freshwater-brackish water environment under a humid climate (Cluster 2). The water body exhibits anoxic to oxic conditions, and the provenance is characterized by terrigenous felsic debris and intermediate-mafic magmatic components.
- (2) Spatially, from north to south, the paleoclimate of the P_2x Formation exhibits a distinct trend toward aridification, concurrent with a gradual decrease in both oxidizability and salinity of the water body. Furthermore, controlled by the distance of provenance input, the terrigenous debris input intensity in the study area exhibits a distribution pattern of "Maxi > Mabei > Manan", accompanied by the differential input of intermediate-basic magmatic components.
- (3) The spatial heterogeneity of depositional environments in the P_2x Formation is primarily controlled by variations in provenances and redox conditions. The coexistence of dual detrital-magmatic provenance inputs and anomalous climatic distribution patterns may be genetically linked to the global assembly event of Pangea supercontinent.
- (4) The spatial heterogeneity of depositional environments controls the differential enrichment of zeolite cement. Moreover, the coupling between the regional enrichment of zeolite cement and depositional environments dictates the variations in the intensity of zeolite cement dissolution

across different areas, thereby forming the distribution pattern of reservoir quality in the P_2x Formation characterized by "Maxi > Mabei > Manan".

CRediT authorship contribution statement

Yi-Jie Wen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Shu Tao:** Writing – review & editing, Methodology, Conceptualization. **Fan Yang:** Writing – review & editing. **Yi Cui:** Software, Data curation. **Ding Song:** Software, Data curation. **Bin Zhang:** Software, Data curation. **Zhuo-Yuan Ma:** Software, Data curation. **Xin-Yu Fu:** Software, Data curation.

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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