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# Palaeoclimatic characteristics of the Late Jurassic-Cretaceous in Emei area, Sichuan Basin, China

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The Late Mesozoic is a typical period for studying the greenhouse climate and the interaction of the Eearth's systems. To expound the interaction between the evolution process of the terrestrial surface system and the environment in the Late Jurassic -Cretaceous, a typical profile with relatively complete exposure of the Mesozoic strata in the Emei area of the Sichuan Basin, the Chuanzu Profile, was selected for this study. The sedimentary environment of the study area was qualitatively analysed based on the macroscopic characteristics of the lithostratigraphy of outcrop profiles in the field and the statistical data of detrital composition under a microscope. Factor analysis and the chemical alteration index after correction (CIAcorr) were used to quantitatively analyse the characteristics of major and trace elements. Finally, the palaeoclimatic evolutionary characteristics of the Late Jurassic-Cretaceous in the Emei area are systematically discussed. The results show that the formation of Cretaceous sediments in the Emei area of the Sichuan Basin is mainly controlled by climatic factors, but is little affected by tectonic activities, and the maturity of the rock clastic composition is relatively low; therefore, it should be a near-provenance deposit. The range of CIAcorr values was 55–79, indicating that the degree of chemical weathering of the provenance was weak to moderate. The palaeoclimate in the Late Jurassic gradually became humid from Early to Late; in the Early Cretaceous, it was semiarid to semihumid, with an extremely dry event occurring; and in the Late Cretaceous, it was semiarid and drier than that of the Early Cretaceous.

KEYWORDS

**Emei area, Late Jurassic-Cretaceous, paleoclimate, factor analysis, chemical alteration index after correction (CIAcorr)**

## 1 Introduction

One of the most effective methods for exploring the relationship between greenhouse gases, such as carbon dioxide produced by human activities, and the Earth's surface system is to find typical examples from geological history for comparative research (Wang et al., 2009). The Mesozoic was an important period in the history of Earth and the evolution of life and had a typical warm climate that is closest to the present day (Parrish, 1993; Ogg et al., 2016). The global climate variability, high atmospheric carbon dioxide concentration and large-scale climate fluctuation events of the Mesozoic are similar to those of the present-day changeable Earth system (Wang et al., 2014). Evidence of the Mesozoic climate and environmental change mainly comes from the environmental records of marine sediments, whereas records from terrestrial sediments are scanty (Wilf et al., 2003; Bodin et al., 2015).

The Sichuan Basin, located in southwest China, is a representative Mesozoic continental sedimentary basin (Li et al., 2022). Relatively continuous Triassic, Jurassic, and Cretaceous profiles are exposed in the Emei area of the southwestern Sichuan Basin, providing a natural laboratory set-up withideal materials for studying Mesozoic continental climate change (Wang et al., 2010a). Previous studies have been conducted on the palaeoclimate of the Emei area. For example, Hu et al. (1991) concluded that the Early Cretaceous Jiaguan Formation in the Emei area was an arid fluvial environment, based on the distribution characteristics of trace fossil communities in fluvial depositional environments. Deng et al. (2013) inferred that the Jiaguan Formation in the Emei area is in a arid environment based on lithologic associations and sedimentary structure characteristics. Based on dinosaur footprints in the vertical profile of the Jiaguan Formation in the Emei area, Lu et al. (2013) inferred that dinosaurs lived in an arid environment. By studying lithological markers and continental ichnofabric, Chen (2014) concluded that the Jiaguan Formation in the Emei area was formed in an alternating dry and wet climate. Previous studies on the palaeoclimate of the Emei area in the Sichuan Basin have mainly focused on the Early Cretaceous Jiaguan Formation, with little attention paid to the entire evolutionary process and changes in palaeoclimate from the Late Jurassic to the Late Cretaceous. Elemental geochemistry is an important tool for studying the composition of sedimentary materials; the distribution of the sedimentary materials in geological layers is closely related to climate change (Chakrapani, 2005; Mahanipour, et al., 2019), which can effectively reflect changes in the ancient climate (Chen et al., 2024). Therefore, it is necessary to conduct an elemental geochemical analysis of sediments in the Emei area of the Sichuan Basin.

In this study, a typical profile with relatively complete exposure of Mesozoic strata in the Emei area of the Sichuan Basin, the Chuanzu Profile, was used to study the sedimentary petrological characteristics, geochemical records, and palaeoclimatic changes. The main factors controlling the chemical composition of the sediments were identified through factor analysis and the corrected chemical index of alteration (CIAcorr) was used to analyse the palaeoclimate of this sedimentary basin. This study provides important references and basic data for further research on the evolutionary process of the Jurassic-Cretaceous palaeoclimate in the Sichuan Basin, and current and future possible climate change.

## 2 Geological setting

The Sichuan Basin is a diamond-shaped tectonic basin located in southwestern China that comprises Mesozoic continental foreland basin sediments dominated by thick terrestrial clastic rocks (Hao et al., 2008). According to the differences in the sedimentary environment, sedimentary facies, biofacies, strata development, and ore bearing-strata, the distribution area of Cretaceous strata in the Sichuan Basin was divided into four districts: Jiange District, Zitong-Bazhong District, Ya'an-Chengdu District, and Yibin District (Geology and Mineral Resources Bureau of Sichuan Province, 1991). Emei area is located in the southwest of Sichuan Basin, belonging to Chengdu-Ya' District, with a total area of 1,183 $km^2$ enclosed within the latitudes 103°10′to 103°37′E and longitudes 29°16'to 29°43′N (Figure 1).

The Mesozoic strata in the Emei area, from old to new, are the Penglaizhen Formation of the Late Jurassic, Jiaguan Formation of the Early Cretaceous, and Guankou Formation of the Late Cretaceous. The Penglaizhen Formation is composed mainly of purple mudstone, shale, and siltstone. The Jiaguan Formation is mainly composed of red brick sandstone and mudstone, and contains parallel bedding, large cross-bedding, wedge cross-bedding, wavy bedding, mud cracks, and trace insect structures. The Guankou Formation is mainly composed of purple–red and brick–red mudstone interbedded with thin layers of siltstone with visible horizontal bedding, cross bedding, wavy bedding, and insect trace structures. This basin during the Late Jurassic experienced a lacustrine sedimentary environment (Wang and Xu, 2001), whereas during the Cretaceous it experienced a delta sedimentary environment, further divided into delta front, delta plain, and pre-delta sedimentary environments (Cao et al., 2008) (Figure 2).

## 3 Samples and experimental method

### 3.1 Samples

In the Emei Area, this study selected a relatively complete Mesozoic stratum, Chuanzu Province, with a total length of 958.93 m. Samples were taken with an average of 50–100 m spacing, and with obvious colour or lithological differencesto maintain homogeneity and freshness of the samples, respectively. A total of 17 samples were collected, including 11 mudstones and 6 sandstones (Figure 2).

### 3.2 Experimental method

#### 3.2.1 Identification of rock and minerals

Rocks and minerals were identified at the State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, China. Micro-section identification and analysis of detrital components in the sandstone samples were carried out in accordance with the SY/T5368.2–1995 and GB/T 17,412.2–1998 standards, respectively. The microscope model used was OLYMPUS-BX51. Scanning electron microscope (SEM) analysis of the mudstone was carried out in accordance with the SY/T 5162–1997 standard, using backscattered electrons and a Qunta 250 PEG instrument. The observation magnification limit of the instrument is 500,000–30000000 times, and the magnification for this test was 2,600–48000 times.

#### 3.2.2 Geochemical analysis

Major and trace element analyses of the mudstone samples were completed at the Ausilicon Analytical Testing (Guangzhou) Co.,

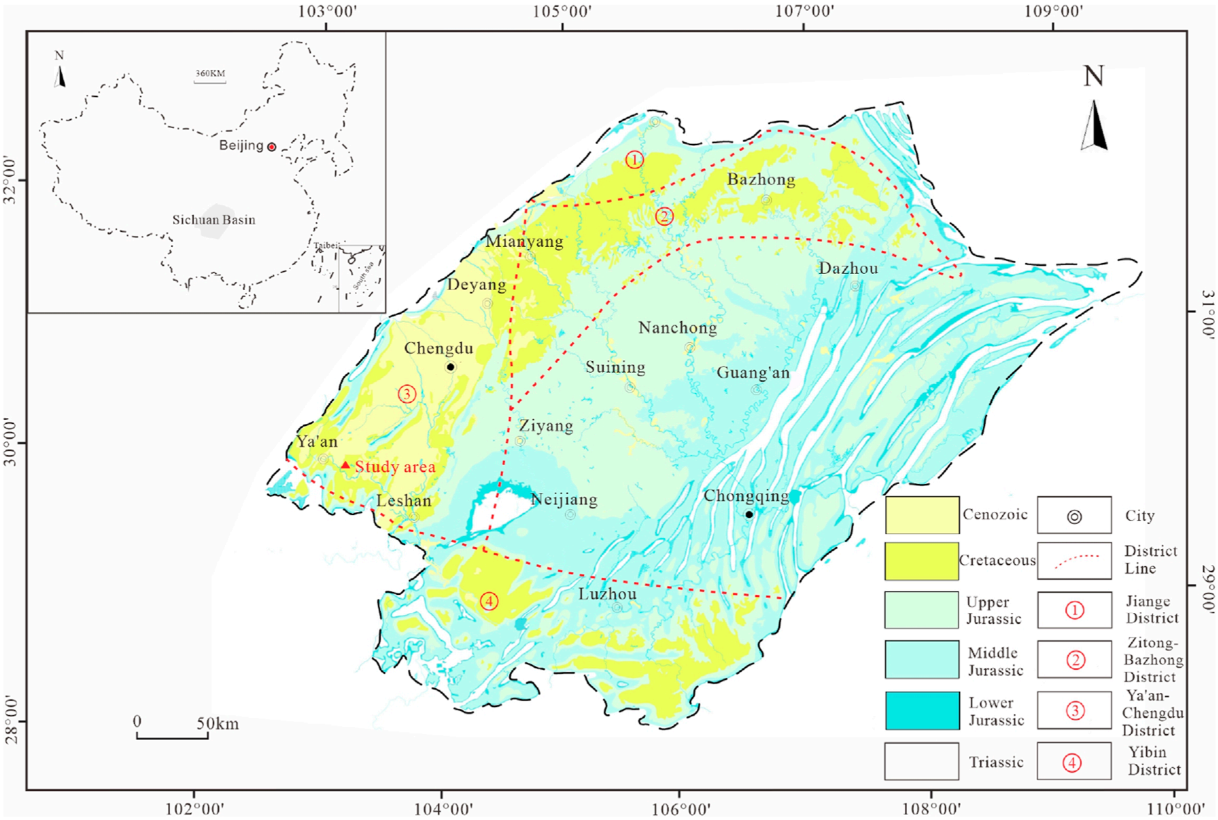


FIGURE 1
Map showing regional geological feature and profile location (revised from Chen and Lu, 2009; Li, 2016).

Ltd. Analysis of the major elements were performed according to GB/T14506.28–2010. The mudstone sample (0.7 g) was placed in a platinum crucible, and 5.2 g of anhydrous lithium tetraborate ($Li_2B_4O_7$), 0.4 g of lithium fluoride, 0.3 g, ammonium nitrate, and 1 mL of lithium bromide were poured into the crucible; the mixture was stirred evenly, dried on an electric heating plate, and then melted using a melting machine at 1,150 °C. The melt was allowed to cool and crystallize, and finally, glass samples were prepared and tested using an X-ray fluorescence spectrometer (Panalytical DY3595; Panaco, Sweden) with a testing error of less than 5%.

The trace elements were prepared according to the GB/T14506.30–2010. First, a mudstone sample (50 mg) was placed in tetrafluoroethylene (PTFE) test tube. Nitric acid (HNO3) and hydrofluoric acid (HF) were then added and dissolved in a sealed melt vessel. The sample was removed and placed on an automatic temperature-controlled electric heating plate for evaporation. Finally, $HNO_3$ was added and the sample was dissolved in a sealed melting vessel before cooling to room temperature (~26°C). Finally, the samples was diluted to volume by adding $H_2O$, shaken well, and transferred to a test tube for testing. Trace elements were determined using an ICP-MS instrument (Agilent 7900, US) with a testing error of less than 10%.

## 4 Results

### 4.1 Detrital component characteristics

Macroscopically, the Late Jurassic in the study area was represented by a set of purple-red silty mudstones with thin layers of limestone (Figures 3a), being sedimentation of the delta front (Li et al., 2020). The Early Cretaceous Jiaguan Formation is mainly composed of a set of thick brown–red massive fine-grained sandstone with thin layers of mudstone (Figures 3b) and a mud-cracked structure (Figures 3c), being sedimentation of the delta plain. In the Late Cretaceous Guankou Formation, the lithology is mainly purple and brick red mudstone and siltstone (Figures 3b), with a large amount of gypsum development (Figures 3d), forming anhydrite-moldic pores (Figures 3e), gypsum grains, and crystal holes (Figures 3f), being sedimentation of the delta front and predelta - shallow lacustrine.

Microscopically, for the quartz sandstone of the Jiaguan Formation, the sorting was medium, and the grains were subrounded to subangular. The content of quartz (Q), feldspar (F), and rock debris (R) ranged from 38% to 43%, 18%–20%, and 16%–17%, respectively; the content of calcareous cement was in the range of 6%–11% (Table 1). For the Guankou argillaceous

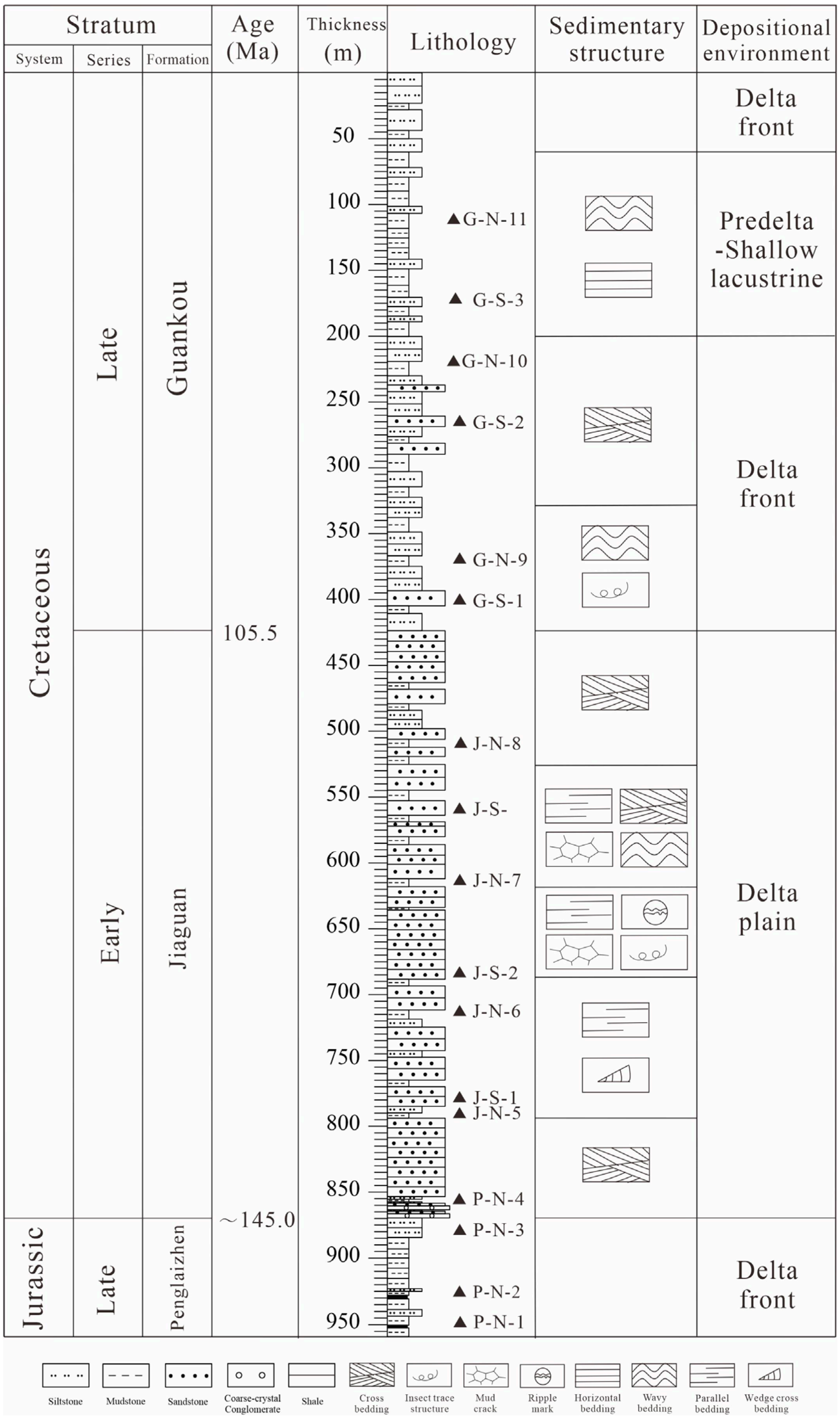


FIGURE 2
Columnar section showing the stratigraphy, sedimentary structures, and environment of the Mesozoic in the Emei area of Sichuan Basin.

siltstone, the sorting was poor, and the grains were subrounded to subangular. The content of Q, F, and R ranged from 24% to 32%, 13%–15%, and 11%–13%, respectively. Additonally this rock contained some (15%–17%) calcareous cemen. In both formations, the iron was oxidised under the microscope, showing a brownish-red colour (Figures 3g,h), and dolomite in the Jiaguan Formation can be seen under a scanning electron microscope (Figures 3i).

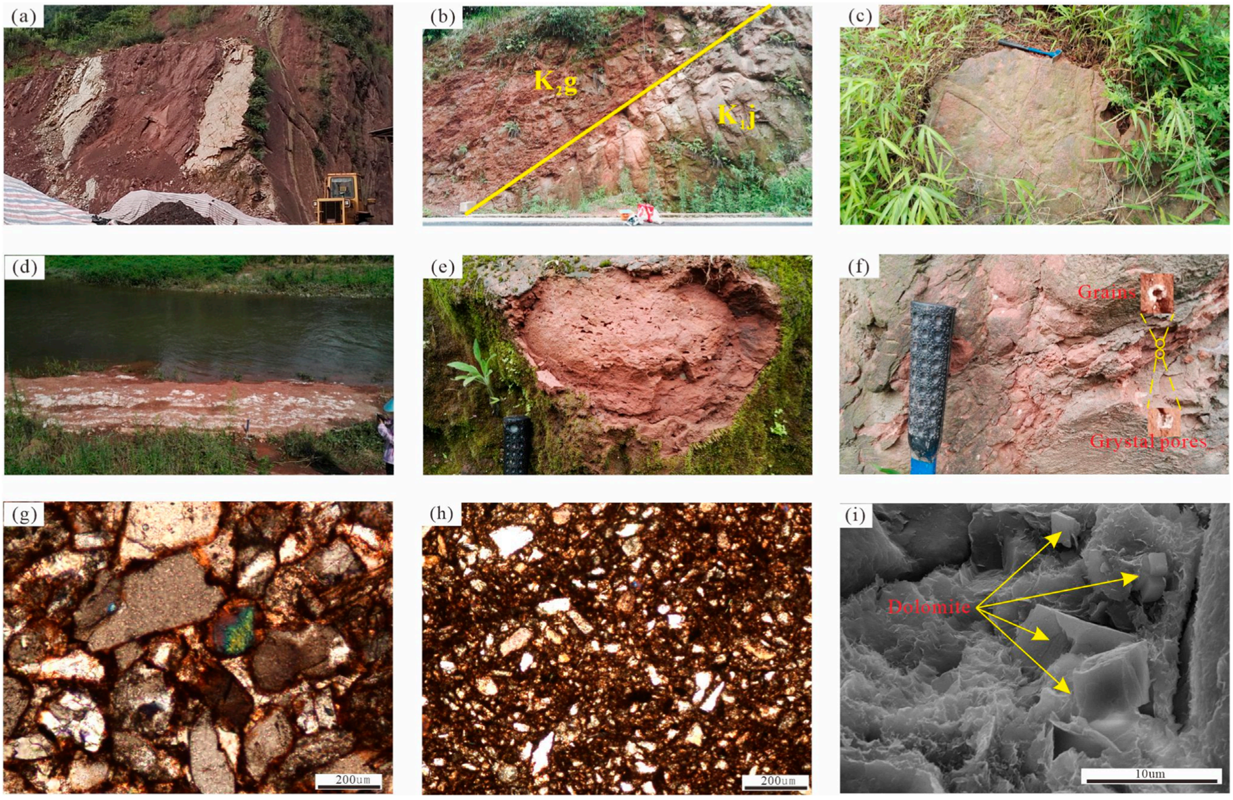


FIGURE 3
Photographs showing the lithological and detrital characteristics of the Jiaguan and Guankou Formations in the Emei Area (modified from Li, 2018). **(a)** Purple-red mudstone within thin-bedded limestone, Penglaizhen Formation; **(b)** The boundary between Jiaguan and Guankou Formations; **(c)** Mud cracks, Jiaguan Formation; **(d)** Gypsum, Guankou Formation; **(e)** Anhydrite-moldic pores, Guankou Formation; **(f)** Gypsum grains and crystal hole, Guankou Formation; **(g)** Calcareous quartz Sandstone, Jiaguan Formation; **(h)** Calcareous claystone siltstone, Guankou Formation; **(i)** Dolomite, Guankou Formation.

## 4.2 Major and trace elemental data

The major and trace element concentrations are listed in Table 2. Among the major elements (Figure 4a), the concentration of $SiO_2$ (47.93%–76.70%, average 55.35%) is the highest, while the concentration of $P_2O_5$ is the lowest, ranging from 0.13% to 0.18%, with an average of 0.15%. For the other major elements, the average concentrations, in descending order, is $Fe_2O_3$ (3.05%–8.46%, average 6.31%) > CaO (0.59%–9.31%, average 5.04%) > MgO (0.93%–5.87%, average 3.9%) > $K_2O$ (1.48%–4.17%, average 3.31%) > $Na_2O$ (0.73%–3.43%, average 1.54%) > $TiO_2$ (0.55%–0.85%, average 0.74%). The trends of changes in $SiO_2$ and $Na_2O$ were essentially the same, and their concentrations changed slightly in the Penglai Formation, with a large change amplitude in the Jiaguan Formation, first increasing and then decreasing, and then slightly increasing in the Guankou Formation. The changes in the concentrations of $A1_2O_3$, $Fe_2O_3$, $K_2O$, MgO, $TiO_2$, CaO and $P_2O_5$ are relatively similar, with their concentrations showing a gradual increase in the Penglai Formation, first increasing and then decreasing in the Jiaguan Formation, and a slight decrease in the Guankou Formation.

For the trace elements (Figure 4b), such as Cu, Cr, Ni, Zn, V, Pb, Co, and Ba the same trend in concentration change was observed, with their concentrations gradually increasing in the Penglai Formation, first increasing and then decreasing in the Jiaguang Formation, and slightly decreasing in the Guankou Formation. However, the trend of Sr change is exactly opposite; it gradually decreases from 153.00 to 78.20 μg/g during the Late Jurassic period, fluctuates greatly during the Early Cretaceous period, first increasing from 78.40 to 107.00 μg/g, then decreasing from 107.00 to 78.40 μg/g, and then increasing again from 78.40 to 87.40 μg/g. By the Late Cretaceous period, the Sr concentration in the sediments again rose from 121.50 to 141.00 μg/g. For Mn, the trend of change was even more distinct; several fluctuations were noted in the sedimentary record from the Late Jurassic to the Early Cretaceous, but the range of variation was not significant, reaching its maximum value (1,130.00 μg/g) in the Late Cretaceous.

## 4.3 Factor analysis

There was a correlation between the different elements, as shown in Table 3, where the correlation coefficients between Ni and V, Zn, Co, Cr, and Mn were all greater than 0.9. The greater the correlation, the more similar the geochemical behaviour of the different elements (Han et al., 2006). Analysing the complex sedimentary process and reconstructing the sequence of environmental changes

TABLE 1 Statistical data of clastic components of the Jiaguan and Guankou Formations in the Emei Area.

| Formation | Sample No. | Q/% | F/% | R/% | Matrix/% | Calcareous cement/% | F/Q | R/Q | Q/F + R | Sorting | Roundness |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Guangkou | G-S-6 | 24 | 15 | 12 | 32 | 17 | 0.63 | 0.50 | 0.89 | Medium | Subangular-angular |
| | G-S-5 | 32 | 16 | 13 | 24 | 15 | 0.50 | 0.41 | 1.10 | Medium | Subangular-angular |
| | G-S-4 | 26 | 13 | 11 | 35 | 15 | 0.50 | 0.42 | 1.08 | Medium | Subangular-Subcircular |
| Jiaguang | J-S-3 | 43 | 18 | 17 | 14 | 8 | 0.41 | 0.40 | 1.25 | Medium | Subcircular-Subangular |
| | J-S-2 | 42 | 20 | 16 | 16 | 6 | 0.48 | 0.38 | 1.17 | Medium-good | Subcircular-Subangular |
| | J-S-1 | 38 | 19 | 17 | 15 | 11 | 0.50 | 0.45 | 1.06 | Medium | Subcircular-Subangular |

through the changing trend of each elementis tedious, and may also lead to contradictory conclusions (Chen et al., 1999). Factor analysis is a commonly used mathematical statistical method that groups original variables according to their degree of correlation and reorganises them into a new set of uncorrelated composite indicators, known as common factors (principal components), which can represent the main information in the original data for analysis (Jolliffe, 2002). This method not only scientifically and accurately describes the changing features of the original variables but also achieves dimensionality reduction, simplifies complex problems, and overcomes the one-sidedness of changes in individual variables (Kang et al., 2017; Li et al., 2020). The factors extracted from the research data should account for more than 71% of the total variance to effectively illustrate the potential correlation between the variables (Muller et al., 2008). SPSS software (version 25.0) was used to conduct a factor analysis of the major and trace elements of the sediments in the study profile. The minimum variance contribution value (i.e., the minimum eigenvalue) of the common factor was set to 1. After maximum variance orthogonal rotation, variables with a common factor load absolute value greater than 0.71 were selected (Table 4).

Two factors were extracted as major elements, representing 83.568% of the total variance. Factor 1 (F1) accounts for a large proportion of the variance (62.837%) and is dominated by high positive loadings (0.749–0.970 for $K_2O$, $Fe_2O_3$, $TiO_2$, $A1_2O_3$, $P_2O_5$, MgO) and negative loadings for $SiO_2$ (−0.742) and $Na_2O$ (−0.726). F2 accounted for 19.366% of the total variance, with one significant factor loading (−0.982) on CaO.

For trace elements, the same two factors were extracted, representing 89.200% of the total variance. Factor 1 (F1) accounted for 74.449% of the total variance, with positive loadings (0.766–0.938) for Cu, Cr, Ni, Zn, V, Pb, and Co. Factor 2 (F2) explained 14.751% of the total variance and was associated with a high positive loading (0.951) for Sr and negative loading (−0.861) for Ba.

## 4.4 Chemical index of alteration(CIA)

The Chemical index of alteration (CIA) is closely related to temperature and humidity and is an important indicator of the degree of weathering and palaeoclimate analysis in the source area of clastic rocks (Nesbitt and Young, 1989; Young, 2002; Xu and Shao, 2018; Chen et al., 2024; Li et al., 2023). The Formula 1 is as follows:

$$CIA = \left[Al_2O_3/\left(Al_2O_3 + CaO * + Na_2O + K_2O\right)\right] \times 100 \quad (1)$$

where $CaO^*$ refers to the CaO in silicate minerals. However, the CaO data measured in this study were the sum of silicate, carbonate, and phosphate minerals. Therefore, the value of $CaO^*$ is calculated indirectly using the method proposed by McLennan (1993): $CaO_{rest} = CaO-(10/3) \times P_2O_5$, If $CaO_{rest} < Na_2O$, then $CaO^* = CaO_{rest}$, otherwise $CaO_{rest} > Na_2O$, $CaO^* = Na_2O$.

The parent rock becomes more complex during weathering, transportation, and sedimentation. When CIA values are used to determine the palaeoclimate of the source area, rock sorting, sedimentary recycling, pedogenesis, and potassium metasomatism should be excluded. For rock sorting, all samples in this study

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TABLE 2 Major and trace element compositions of mudstones from the Penglaizhen, Jiaguan, and Guankou Formations in the Emei Area.

| Sample No. | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | CaO (%) | MgO (%) | $K_2O$ (%) | $Na_2O$ (%) | $TiO_2$ (%) | $P_2O_5$ (%) | Mn (μg/g) | Ba (μg/g) | Co (μg/g) | Cr (μg/g) | Cu (μg/g) | Zn (μg/g) | Sr (μg/g) | V (μg/g) | Ni (μg/g) | Pb (μg/g) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| G-N-11 | 55.75 | 12.60 | 5.48 | 8.39 | 3.01 | 2.80 | 1.46 | 0.85 | 0.16 | 633.00 | 409.00 | 15.90 | 103.00 | 21.10 | 82.00 | 141.00 | 114.00 | 45.70 | 18.40 |
| G-N-10 | 53.97 | 12.29 | 5.15 | 9.31 | 3.42 | 2.67 | 1.22 | 0.75 | 0.15 | 540.00 | 405.00 | 14.30 | 96.00 | 21.20 | 86.00 | 121.00 | 111.00 | 44.40 | 19.20 |
| G-N-9 | 47.61 | 15.57 | 6.69 | 8.69 | 4.97 | 3.96 | 0.73 | 0.82 | 0.17 | 577.00 | 484.00 | 17.50 | 124.00 | 22.30 | 106.00 | 121.50 | 144.00 | 57.00 | 22.30 |
| J-N-8 | 54.02 | 16.46 | 6.44 | 4.88 | 4.36 | 3.97 | 1.22 | 0.67 | 0.15 | 519.00 | 492.00 | 18.50 | 97.00 | 23.30 | 106.00 | 87.40 | 120.00 | 52.10 | 19.60 |
| J-N-7 | 51.99 | 18.80 | 8.46 | 2.24 | 5.54 | 4.15 | 1.48 | 0.84 | 0.17 | 604.00 | 723.00 | 26.00 | 137.00 | 26.00 | 139.00 | 78.60 | 163.00 | 75.30 | 27.10 |
| J-N-6 | 55.47 | 18.04 | 7.36 | 1.71 | 5.00 | 3.77 | 1.70 | 0.80 | 0.18 | 546.00 | 631.00 | 25.90 | 127.00 | 21.30 | 126.00 | 78.40 | 129.00 | 61.70 | 21.70 |
| J-N-5 | 76.70 | 11.57 | 3.05 | 0.65 | 0.93 | 1.48 | 3.43 | 0.55 | 0.13 | 626.00 | 439.00 | 5.00 | 57.00 | 7.90 | 29.00 | 107.00 | 59.00 | 19.00 | 15.10 |
| J-N-4 | 47.93 | 15.93 | 6.84 | 5.38 | 5.87 | 3.35 | 2.01 | 0.74 | 0.13 | 721.00 | 653.00 | 18.50 | 102.00 | 19.80 | 89.00 | 95.80 | 137.00 | 63.70 | 23.40 |
| P-N-3 | 56.21 | 19.62 | 7.28 | 0.59 | 4.37 | 4.17 | 0.82 | 0.77 | 0.16 | 1,130.00 | 573.00 | 21.10 | 130.00 | 28.70 | 158.00 | 78.20 | 137.00 | 72.80 | 25.20 |
| P-N-2 | 54.55 | 17.05 | 7.29 | 4.50 | 3.02 | 3.52 | 1.31 | 0.74 | 0.16 | 669.00 | 524.00 | 17.40 | 114.00 | 24.70 | 109.00 | 131.00 | 143.00 | 58.40 | 29.80 |
| P-N-1 | 54.63 | 13.38 | 5.39 | 9.05 | 2.44 | 2.62 | 1.54 | 0.62 | 0.14 | 675.00 | 382.00 | 13.50 | 89.00 | 26.30 | 86.00 | 153.00 | 95.00 | 45.10 | 20.40 |
| Average | 55.35 | 15.57 | 6.31 | 5.04 | 3.90 | 3.31 | 1.54 | 0.74 | 0.15 | 633.00 | 519.55 | 17.60 | 106.91 | 22.05 | 101.45 | 108.45 | 122.91 | 54.11 | 22.02 |

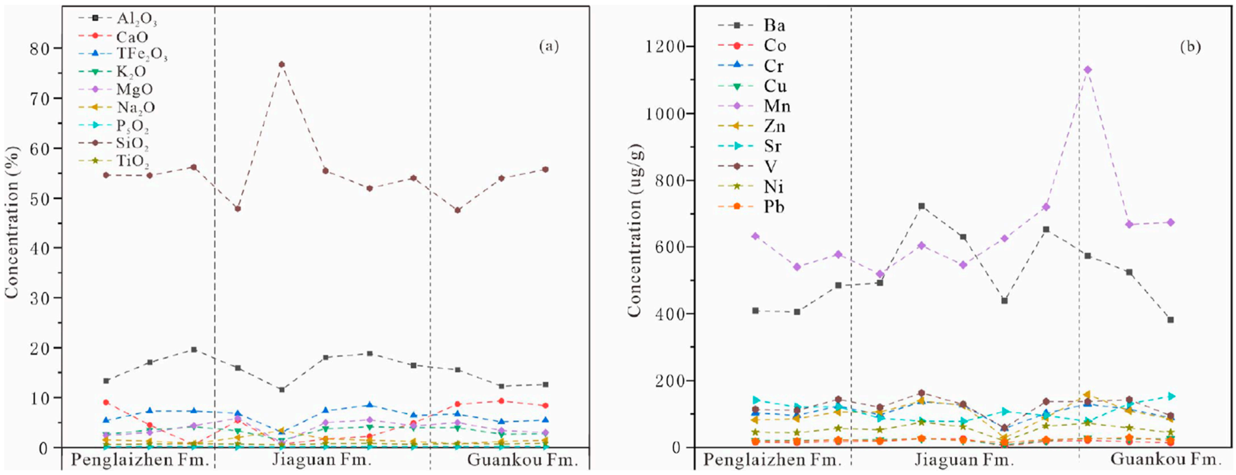


FIGURE 4
Distribution of major **(a)** and trace elements **(b)** in mudstones from the Penglaizhen, Jiaguan, and Guankou Formations in the Emei Area.

were mudstones, which effectively excluded the influence of sedimentary differentiation (Xu et al., 2020). Cox et al. (1995) proposed the index of compositional variability (ICV) to determine whether sedimentary recycling occurred in the source area. The specific Formula 2 is as follows:

$$ICV = (Fe_2O_3 + K_2O + Na_2O + CaO + MgO + MnO + TiO_2)/A1_2O_3 \quad (2)$$

When ICV>1, it is the first sedimentation (Kamp and Leake, 1985); and when ICV<1, it may have undergone re-cycling and could not be determined as the first sedimentation (Barshad, 1966).

Nesbitt and Young (1982), Nesbitt and Young (1989) proposed that potassium metasomatism in the diagenetic period can be determined by whether the weathering curve of the sample in the A-CN-K diagram (Figure 5) is parallel to the ideal weathering curve of the A-CN line. For a parallel curve, the inference was the absence of potassium metasomatism; a non-parallel curve, indicated potassium metasomatism. In addition, Panahi et al. (2000) proposed a correction formula (Formula 3) for $K_2O$ in mudstones undergoing potassium metasomatism.

$$K_2O_{corr} = [m \times Al_2O_3 + m \times (CaO * + Na_2O)]/(1 - m) \quad (3)$$

where m is the proportion of $K_2O$ in the parent rock, which is approximately determined by the intersection of the ideal weathering curve parallel to the A-CN line and the CN-K coordinate axis. The corrected $CIA_{corr}$ formula (Formula 4) is as follows.

$$CIA_{corr} = [Al_2O_3/(Al_2O_3 + CaO * + Na_2O + K_2O_{corr})] \times 100 \quad (4)$$

According to Formula 1, the CIA values of the Late Jurassic Penglaizhen Formation range from 62.85 to 74.93, with a mean of 68.50. The CIA values of the Early Cretaceous Jiaguan Formation range from 58.76 to 66.73, with a mean of 63.62. The CIA values of the Late Cretaceous Guankou Formation range from 61.64 to 69.92, with a mean of 65.19. The Late Jurassic Penglaizhen Formation has the highest average CIA value, followed by Late Cretaceous Guankou Formation, and the Early Cretaceous Jiaguan Formation. According to formula 2, the ICV values of the mudstone from the Late Jurassic to the Late Cretaceous range from 1.11 to 1.87, all of which are greater than 1 (Table 5). Therefore, it is concluded that all the mudstone samples taken were the first-cycle sediments without a history of recycling. From the A-CN-K diagram (Figure 5), it can be seen that the weathering curve of the selected samples is not parallel to the ideal weathering curve thereby indicating that potassium metasomatism occurred in these rocks, possibly during the diagenetic stage; the determined m value was 0.1281 approximately. After correcting the $K_2O$ concentration, CIAcorr was further obtained, and in the Penglaizhen Formation it ranged from 64.55 to 80.62, with an average value of 72.07; in the Jiaguan Formation it ranged from 56.94 to 71.55, with an average value of 66.07; and in the Guankou Formation it ranged from 64.43 to 77.11, with an average value of 69.54. Compared with the uncorrected CIA value, the difference ranges from 0.98 to 6.32, which is not very large, indicating that the potassium metasomatism in these three formations of samples is relatively weak.

# 5 Discussion

## 5.1 Detrital components for indicating paleoclimate

The clastic components of sediments are composed of Q, F, and R and contain information about the climate and structure of the sedimentary period (Liu, 1980). The F/Q ratio represents the climate index, with a larger ratio indicating a drier and colder climate (Chen, 2018). The R/Q ratio represents the structural index, with a larger ratio reflecting stronger changes in tectonic activity in the parent rock area (Chen, 2018). In general, F/Q was greater than R/Q, indicating that climatic factors had a greater influence on sedimentation at that time. The ratio of the relative contents of

TABLE 3 Correlation analysis of major and trace elements of mudstones from the Penglaizhen, Jiaguan, and Guankou Formations in Emei Area.

| Elements | $Al_2O_3$ | CaO | $Fe_2O_3$ | $K_2O$ | MgO | $Na_2O$ | $P_2O_5$ | $SiO_2$ | $TiO_2$ | Ba | Co | Cr | Cu | Ni | Pb | Sr | V | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $Al_2O_3$ | 1.00 | | | | | | | | | | | | | | | | | |
| CaO | −0.54 | 1.00 | | | | | | | | | | | | | | | | |
| $Fe_2O_3$ | 0.90 | −0.20 | 1.00 | | | | | | | | | | | | | | | |
| $K_2O$ | 0.89 | −0.16 | 0.93 | 1.00 | | | | | | | | | | | | | | |
| MgO | 0.71 | −0.06 | 0.83 | 0.83 | 1.00 | | | | | | | | | | | | | |
| $Na_2O$ | −0.47 | −0.39 | −0.63 | −0.75 | −0.51 | 1.00 | | | | | | | | | | | | |
| $P_2O_5$ | 0.57 | −0.10 | 0.65 | 0.67 | 0.45 | −0.59 | 1.00 | | | | | | | | | | | |
| $SiO_2$ | −0.44 | −0.48 | −0.73 | −0.72 | −0.79 | 0.79 | −0.39 | 1.00 | | | | | | | | | | |
| $TiO_2$ | 0.46 | 0.14 | 0.69 | 0.65 | 0.67 | −0.63 | 0.76 | −0.66 | 1.00 | | | | | | | | | |
| Ba | −0.12 | −0.40 | −0.38 | −0.19 | −0.11 | 0.45 | −0.13 | 0.50 | −0.45 | 1.00 | | | | | | | | |
| Co | −0.26 | −0.18 | −0.49 | −0.34 | −0.25 | 0.39 | −0.18 | 0.42 | −0.43 | 0.77 | 1.00 | | | | | | | |
| Cr | −0.23 | −0.12 | −0.49 | −0.29 | −0.32 | 0.18 | −0.11 | 0.41 | −0.38 | 0.65 | 0.92 | 1.00 | | | | | | |
| Cu | −0.56 | 0.38 | −0.60 | −0.43 | −0.37 | 0.07 | −0.26 | 0.18 | −0.18 | 0.25 | 0.67 | 0.74 | 1.00 | | | | | |
| Ni | −0.33 | −0.01 | −0.55 | −0.29 | −0.27 | 0.21 | −0.22 | 0.36 | −0.41 | 0.76 | 0.91 | 0.93 | 0.78 | 1.00 | | | | |
| Pb | −0.51 | 0.15 | −0.63 | −0.41 | −0.35 | 0.13 | −0.21 | 0.36 | −0.30 | 0.62 | 0.64 | 0.75 | 0.67 | 0.81 | 1.00 | | | |
| Sr | −0.25 | 0.47 | −0.08 | −0.16 | −0.32 | −0.34 | −0.03 | −0.13 | 0.15 | −0.78 | −0.58 | −0.41 | −0.04 | −0.50 | −0.21 | 1.00 | | |
| V | −0.30 | −0.10 | −0.58 | −0.35 | −0.36 | 0.23 | −0.36 | 0.44 | −0.55 | 0.70 | 0.86 | 0.92 | 0.70 | 0.93 | 0.83 | −0.37 | 1.00 | |
| Zn | −0.29 | 0.05 | −0.44 | −0.25 | −0.17 | 0.16 | −0.09 | 0.23 | −0.21 | 0.61 | 0.89 | 0.93 | 0.84 | 0.93 | 0.73 | −0.51 | 0.83 | 1.00 |

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TABLE 4 Factor analysis of major and trace elements from mudstones in the Penglaizhen, Jiaguan, and Guankou Formations of the Emei Area.

| Major element | F1 loadings | F2 loadings | Trace element | F1 loadings | F2 loadings |
|---|---|---|---|---|---|
| $K_2O$ | 0.970 | | Cu | 0.938 | |
| $TFe_2O_3$ | 0.965 | | Cr | 0.88 | |
| $Al_2O_3$ | 0.880 | | Ni | 0.873 | |
| MgO | 0.862 | | Zn | 0.87 | |
| $TiO_2$ | 0.777 | | V | 0.87 | |
| $P_2O_5$ | 0.749 | | Pb | 0.828 | |
| $SiO_2$ | −0.742 | | Co | 0.766 | |
| $Na_2O$ | −0.726 | | Sr | | 0.951 |
| CaO | | −0.982 | Ba | | −0.861 |
| % of the total variance | 62.837 | 20.730 | % of the total variance | 74.449 | 14.751 |
| Cumulative variance/% | 62.837 | 83.568 | Cumulative variance/% | 74.449 | 89.2 |

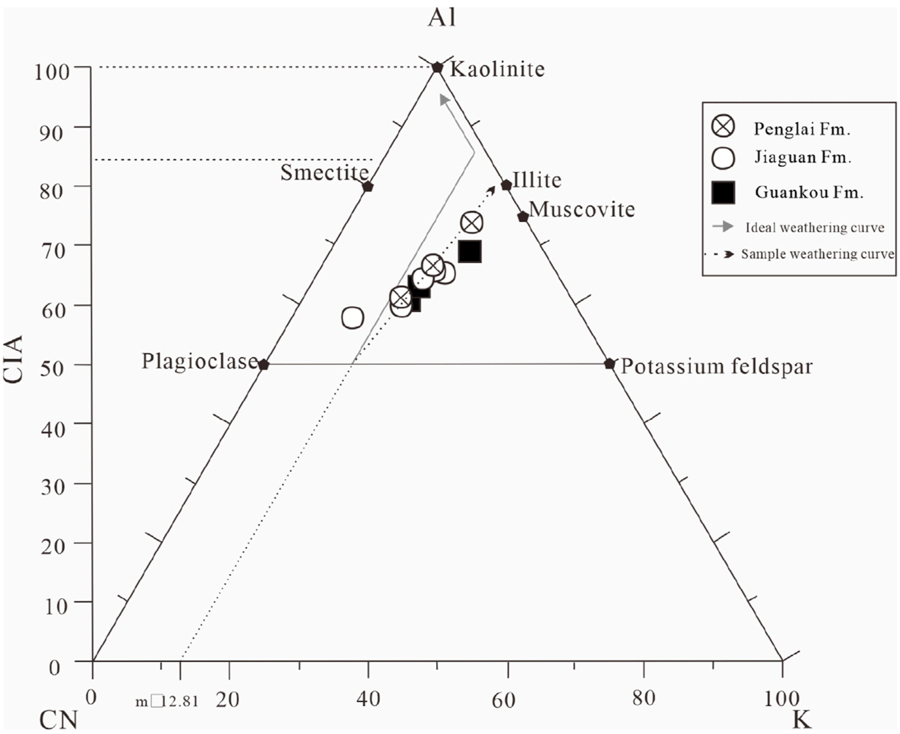


FIGURE 5
A-CN-K ternary diagrams (Fedo et al., 1995) for mudstones from the Penglaizhen, Jiaguan, and Guankou Formations in Emei Area (A: $Al_2O_3$; CN: $CaO^*+Na_2O$; K: $K_2O$).

stable and unstable components is called mineral maturity (Q/F + R), which represents the maturity of detrital components; a larger ratio indicates a higher maturity of detrital components, indicating a longer transport distance (Shi et al., 1995).

The F/Q values of the samples from Jiaguang Formation vary from 0.41 to 0.50 (average: 0.46) (Table 1). The F/Q values of the samples from Guankou Formation are higher, varying in ranges of 0.50–0.63 (average: 0.54), suggesting that

TABLE 5 Variable data associated with CIA values.

| Strata | Sample No. | CaO* | $K_2O_{corr}$ | CIA | CIA average | ICV | $CIA_{corr}$ | $CIA_{corr}$ average |
|---|---|---|---|---|---|---|---|---|
| Guangkou Fm | G-N-11 | 0.02 | 0.03 | 61.64 | 65.19 | 1.53 | 64.43 | 69.54 |
| | G-N-10 | 0.02 | 0.02 | 64.01 | | 1.55 | 67.09 | |
| | G-N-9 | 0.01 | 0.02 | 69.92 | | 1.46 | 77.11 | |
| Jiaguang Fm | J-N-8 | 0.02 | 0.02 | 66.42 | 63.62 | 1.38 | 71.55 | 66.07 |
| | J-N-7 | 0.02 | 0.02 | 66.73 | | 1.52 | 70.69 | |
| | J-N-6 | 0.03 | 0.02 | 65.34 | | 1.49 | 68.26 | |
| | J-N-5 | 0.01 | 0.03 | 58.76 | | 1.20 | 56.94 | |
| | J-N-4 | 0.03 | 0.03 | 60.85 | | 1.87 | 62.89 | |
| Penglaizhen Fm | P-N-3 | 0.01 | 0.02 | 74.93 | 68.50 | 1.11 | 80.62 | 72.07 |
| | P-N-2 | 0.02 | 0.03 | 67.71 | | 1.19 | 71.04 | |
| | P-N-1 | 0.02 | 0.03 | 62.85 | | 1.34 | 64.55 | |

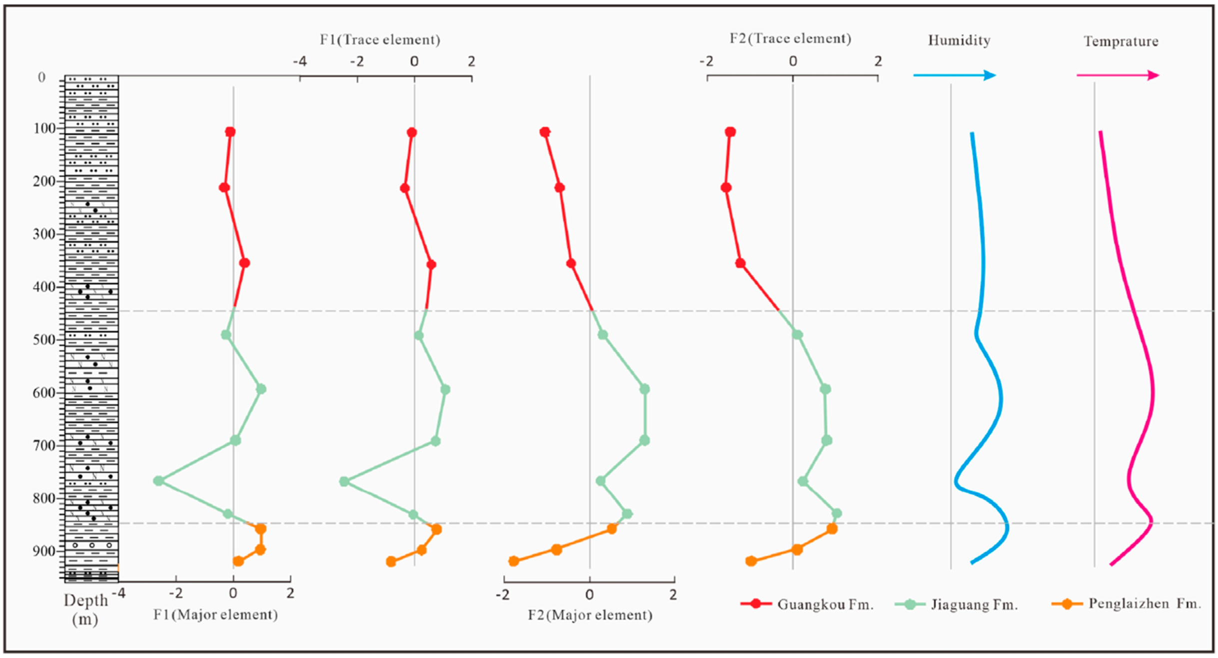


FIGURE 6
Change curves of F1 and F2 scores for the extraction of major and trace elements of mudstones from the Penglaizhen, Jiaguan, and Guankou Formations in the Emei Area.

the Late Cretaceous palaeoclimate was lower in humidity and temperature than that of the Early Cretaceous. The R/Qvalues of the samples from the Jiaguang and Guankou formations vary from 0.38 to 0.50, which were all less than the F/Q values, indicating that the formation process of Cretaceous sediments was mainly controlled by climatic factors.

The Q/(F + R) values of the samples from the Jiaguang and Guankou Formations vary from 0.89 to 1.25, with an average value of 1.09. It can be concluded that most values are close to 1, with low component maturity (Ge et al., 2015), further suggesting near-provenance deposits, which are consistent with the characteristics of the sandstones observed under the microscope, whose sorting

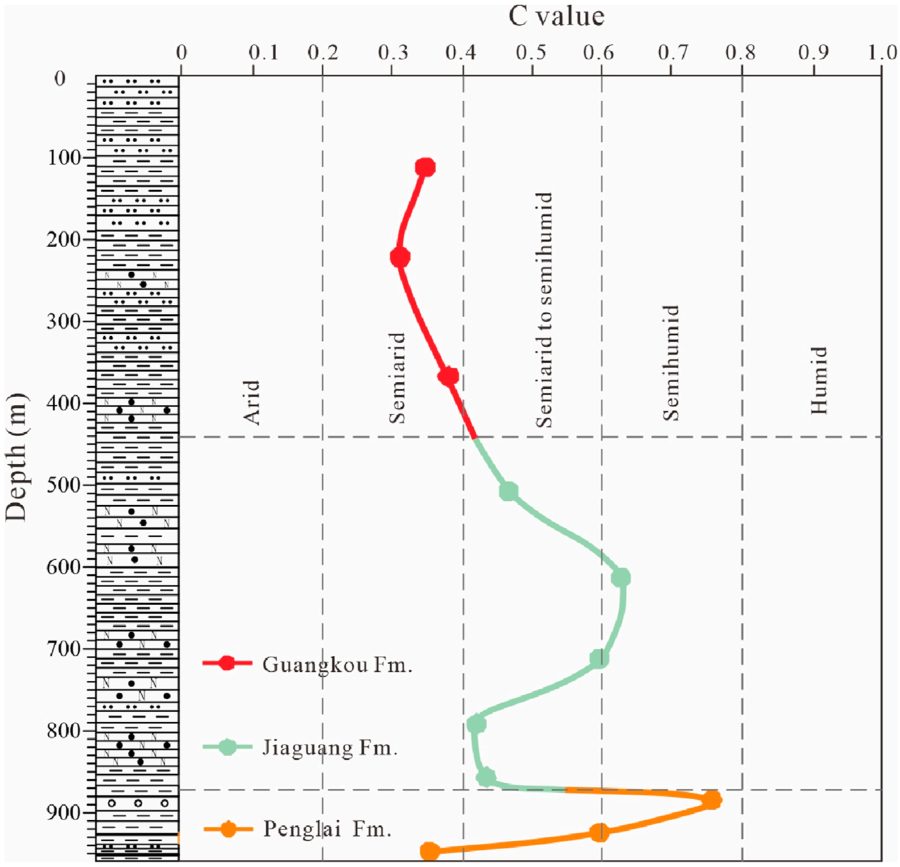


FIGURE 7
Characteristics of C value changes for mudstones from the Penglaizhen, Jiaguan, and Guankou Formations in the Emei Area.

degree is poor and medium, and the grains are subrounded and subangular.

## 5.2 Factor analysis for indicating paleoclimate

Factor 1 of major and trace elements include Si, Ti, A1, Fe, Cu, Cr, Ni, Zn, V, Pb, Co, P, Mg and Na (Table 4). Si, Ti, A1, Fe, Cu, Cr, Ni, Zn, V, Pb, and Co are elements that are stable in superbiotic environments, occur in terrigenous clastic minerals, and indirectly reflect the amount of terrigenous material input (Shotyk, 1988; Muller et al., 2008; Yang et al., 2014). The variation of these elements is mainly controlled by basin erosion whose intensity is closely related to the degree of basin surface runoff, which in-turn depends on the amount of rainfall in the local climate area, that is, the dry and wet conditions of regional climate (Chen et al., 1999; Yao et al., 2010; Fan, 2010; Yuan and li, 2014). In addition, the higher the concentration of the above elements in the sediments, the more humid is the palaeoclimate inferred to be (Tian and Zhang, 2016). K, P, Mg, and Na are migratory elements that are often used to judge the degree of dryness and weathering of the climate (Zhang et al., 2011). Therefore, F1 represents the intensity of erosion in the basin and reflects changes in dry and wet climates.

Factor 2 for the major and trace elements included Ca, Sr, and Ba (Table 4). Ca, Sr and Ba are migratory elements and alkaline earth metals, which form bicarbonates, chlorides and sulfates into aqueous solutions during the process of epigenesis, and also become major elements in bioclastic sediments under biogenetic processes (Yao et al., 2010). Sr and Ba are chemically and structurally similar to Ca and have similar environmental effects (Cheng et al., 2011). However, the Sr and Ba concentrations have an inverse relationship due to their competition for carbonate ions (Chen et al., 1999). The precipitation factors of calcium carbonate include temperature, pressure (water depth), salinity, and light, among which temperature not only determines the saturation degree of calcium carbonate but also has important significance for biological reproduction (Luo et al., 2008). These elements (Sr, Ba, and Ca) therefore indirectly reflect the temperature changes of climate (Wang et al., 2010b; Tian et al., 2005). The F2 factor, therefore, represents surface deposition under biological action, reflecting temperature changes in the climate.

From the bottom to the top of the Penglaizhen Formation, the F1 and F2 scores from major and trace elements gradually increased from 0.17 to 0.95, −0.83 to 0.76, −1.76 to 0.53, and −0.85 to 1.04, respectively (Figure 6), indicating that the basin erosion and calcium carbonate precipitation increased during this period, further indicating that the Late Jurassic palaeoclimate gradually

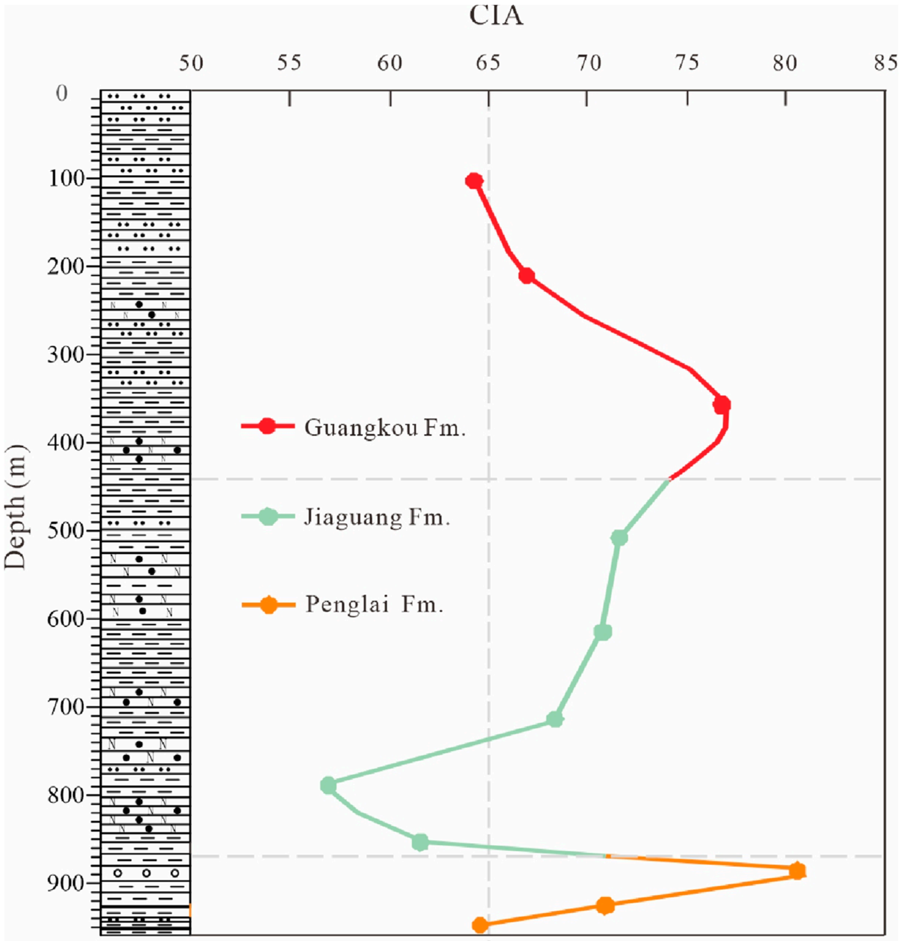


FIGURE 8
Characteristics of $CIA_{cor}$ value changes for mudstones from the Penglaizhen, Jiaguan, and Guankou Formations in the Emei Area.

witnessed an increase in temperature and humidity from the Early to the Late stages. For the Early-Cretaceous-age Jiaguan Formation, the F1 and F2 of major and trace elements has low peak scores of −2.62, −2.47, 0.27 and 0.34, respectively, indicating that an extremely cold and arid climate event occurred during the Early Cretaceous. Except for the peak, the F1 and F2 scores from major and trace elements values range from −0.26 to 0.95, −0.06 to 1.07, 0.33 to 1.30, and 0.22 to 1.14, respectively. For the Late Cretaceous Guankou Formation, the F1 and F2 scores for the major and trace elements range from −0.32 to 0.46, −0.35 to 0.88, −0.42 to −1.02, and −1.11 to −1.44, respectively. The palaeoclimate of the Late Cretaceous was clearly less humid and warm than that of the Early Cretaceous, which is consistent with the results of the aforementioned palaeoclimate indicated by the clastic components.

## 5.3 The ratio of elements for indicating paleoclimate

Climatic conditions have a strong control over the transport and sedimentation processes of sediments, thus affecting the degree of sediment enrichment. Therefore, palaeoclimatic conditions can be restored using geochemical element composition characteristics. According to this correspondence between elements and climate, Guan (1992) proposed the value of the climate index (C-value) to represent the degree of dryness and wetness in the palaeoclimate using the Formula 5:

$$C = (Fe + Mn + Cr + V + Co + Ni) / (Ca + Mg + Sr + Ba + K + Na) \ldots\ldots\ldots\ldots\ldots \quad (5)$$

Since then, it has become a widely used palaeoclimatic indicator (Moradi et al., 2016; Shi et al., 2023; Zhang et al., 2022). Qiu et al. (2015) further divided the C-value into five stages indiating different degrees of humidity: C-value >0.8, palaeoclilmate are humid; C-value = 0.6–0.8, semi-humid; C-value = 0.4–0.6, semiarid-semihumid; C-value = 0.2–0.4, semiarid; and C-value <0.2, arid condition.

As shown in Figure 7, the C values from the Late Jurassic age Penglaizhen Formation range from 0.36 to 0.76, being in the semiarid to semihumid stage. In addition, from top to bottom of the Formation, the C value gradually increased, indicating that the palaeoclimate of the Late Jurassic gradually became humid from the Early to Late stages. For the Early-Cretaceous-age Jiaguan

Formation, the C values vary from 0.42 to 0.63, indicating semiarid to semihumid conditions. Similar to the factor analysis, there was a minimum C-value (0.42) at the same stratigraphic location, indicating the occurrence of an extremely arid climate event during the Early Cretaceous. Previous studies have also shown that an extreme drought climate occurred during the Early Cretaceous in the Sichuan Basin (Chen, 2009), which may correspond to a global extreme drought event from the Aptian to the Albian during the Cretaceous period (Jenkyos et al., 1994; Stoll and Schrag, 2000). For the Late-Cretaceous-age Gangkou Formation, the C values vary 0.31 to 0.38, being in a semiarid environment. It can be seen that the paleoclimate of the Late Cretaceous was drier than that of the Early Cretaceous, which is consistent with the results obtained from the detrital component characteristics and the factor analysis of major and trace elements. This result is consistent with the conclusions of previous studies on palaeoclimate in Ya 'an area, Sichuan Basin (Cao et al., 2008; Chen, 2009) and the trend of palaeoclimate change in China (Song, 2011; Xu, et al., 2021).

Since the Cretaceous, there has been no latitudinal movement in the landmasses of South and North China (Chen et al., 1993; Enkin et al., 1992). Palaeomagnetic studies have shown that the palaeo-latitude of the Sichuan Basin has not changed significantly and should be in the middle to low latitudes of the Northern Hemisphere (Jiang et al., 1999). In the Cretaceous, the Sichuan Basin was bordered by the Old Tethys Ocean to the south and the Palaeo-Pacific Ocean to the east, which should have influenced a humid climate; however, the Cretaceous climate was mainly characterised by drought. This is mainly because the Sichuan Basin straddles the then-Northern Hemisphere subtropical high-pressure belt (Jiang, 1996; Cooke et al., 1993), which is mainly controlled by the planetary wind system, resulting in a dry climate in the southwestern Sichuan Basin with a large number of gypsum–salt and desert deposits (Jiang et al., 1999; Jiang, 2003). The paleoclimate of the Late Cretaceous was more arid than that of the Early Cretaceous, which may be related to the rapid uplift of the southeastern coastal mountain range in the eastern regions of Zhejiang, Fujian, and Guangdong caused by the northward and westward subduction of the Indian and Pacific plates and the activation of the Lishui Haifeng Fault in the early Late Cretaceous (Chen, 1997; Qu et al., 2024). In addition, Chen (2008) used the mass balance method to calculate that the height of the southeastern coastal mountains in the early Late Cretaceous reached at least 2,500 m, which likely hindered warm and humid airflow from the east.

### 5.4 Determination of weathering degree

Chemical weathering is strongly sensitive to climate, with temperature and humidity proposed as the driving factors (Nesbitt and Young, 1982). The chemical index of alteration can be effectively used to assess the degree of chemical weathering in a provenance (Nesbittand Young, 1982). High CIA values reflect a relatively intense degree of chemical weathering, whereas low CIA values reflect a relatively weak degree of chemical weathering (Fedo et al., 1995). Nesbitt and Young (1982) divided it into three stages according to the size of the CIA value: a CIA value of 50–65, low chemical weathering degree; a CIA value of 65–85, moderate chemical weathering degree; and a CIA value of 85–100, strong chemical weathering degree.

The $CIA_{corr}$ values of the Penglaizhen, Jiaguan, and Guangkou Formations ranged from 55 to 79, with a mean of 67.24 (Table 4), all higher than the average value of the upper crust (UCC: 47.92) (Rudnick and Gao, 2003). In addition, some CIA values are similar to those of glacial clay (60–65), whereas others are similar to the average value of Precambrian Australian shale (PAAS: 70.36) (Taylor and McLennan, 1985) (Figure 8). This indicates that most of the mudstones in the Emei area from the Late Jurassic to Late Cretaceous have a weak-to-moderate weathering degree, and no strong weathering occurred, which is consistent with the view that the sedimentary area observed under the microscope contains more than 10% feldspar clastic particles, medium sorting, and a low grinding degree, reflecting the low maturity of the rock composition.

## 6 Conclusion

1) The formation of Cretaceous sediments in the Emei area of the Sichuan Basin was mainly controlled by climatic factors and was only slightly affected by tectonic activities. Moreover, the maturity of the rock clastic compositions is relatively high, indicating distant provenance sources.
2) In the Emei area of the Sichuan Basin, the Late Jurassic palaeoclimate gradually became semiarid to semihumid, the Early Cretaceous palaeoclimate became semiarid to semihumid followed by an extremely dry event, and the Late Cretaceous palaeoclimate was semiarid and more arid than the Early Cretaceous palaeoclimate which is related to the southeastern coastal mountain.
3) From the Late Jurassic to the Late Cretaceous, the degree of chemical weathering of the provenance in the Emei area of the Sichuan Basin was mainly weak to moderate.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

## Author contributions

SL: Data curation, Formal Analysis, Methodology, Resources, Writing – original draft. FX: Methodology, Resources, Supervision, Validation, Visualization, Writing – review and editing. LS: Formal Analysis, Investigation, Supervision, Validation, Visualization, Writing – review and editing. FZ: Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review and editing. HM: Formal Analysis, Resources, Validation, Visualization, Writing – review and editing. BX: Formal Analysis, Funding acquisition, Methodology, Resources, Supervision, Writing – review and editing. SS: Formal Analysis, Software, Writing – review and editing.

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## Conflict of interest

Author HM was employed by CCTEG Xi'an Research Institute (Group) Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

## Publisher's note



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