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Geochemical characteristics of the upper triassic Bagong formation mudstones in the eastern North Qiangtang depression and their constraints on the provenance, palaeoclimate and palaeoenvironment

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The black mudstones of the Upper Triassic Bagong Formation, Qiangtang Basin, are important hydrocarbon source rocks, but significant differences are found in their quality across the region; thus, the genetic mechanism of these mudstones needs to be revealed to determine the spatial distribution of the high-quality hydrocarbon source rocks in the Bagong Formation of the North Qiangtang Depression. To elucidate the genetic mechanism of the Bagong Formation mudstones, 31 samples of the Bagong Formation mudstones from the Tielong Section in the eastern North Qiangtang Depression were collected and analysed to determine their total organic carbon (TOC) and major and trace element contents. The results revealed that the Bagong Formation mudstones in the study area had a low to moderate TOC contents; these results indicated that they were poor to moderate hydrocarbon source rocks. The elemental geochemical characteristics indicate that the provenance of the Bagong Formation mudstones in the study area was mainly felsic rocks that formed in collisional tectonic settings; these results are consistent with the tectonic regime of early Late Triassic intracontinental compression in the North Qiangtang Depression. During the deposition of the Bagong Formation mudstones, the climate was warm and humid, and the environment was a shallow oxidizing saltwater column, with a large input of rapidly deposited fine-grained argillaceous detritus. The warm and humid climate conditions and rapid sedimentation rate during the deposition of the Bagong Formation mudstones in the study area promoted the preservation of partly organic matter; however, the overall abundance of

organic matter remained low because of the influence of the oxidizing water column.

KEYWORDS

provenance and tectonic setting, palaeoenvironment, organic matter enrichment, Bagong formation, north Qiangtang depression

1 Introduction

The Qiangtang Basin is located in the eastern section of the Tethys tectonic domain and features the most abundant oil and gas resources in that domain. Its adjacent western section is the Middle East oil and gas region, and the southeastern section is the Southeast Asian oil and gas region. This unique tectonic setting has drawn significant attention from petroleum geologists, and the Qiangtang Basin in China's Qinghai-Tibet Plateau is an optimal area, with the greatest potential for strategic breakthroughs in oil and gas resources (Tan et al., 2002; Wang et al., 2004; 2009; 2020; Wu et al., 2014). With the continuous advancement of oil and gas exploration in the Qiangtang Basin in recent years, widely distributed and high-quality argillaceous hydrocarbon source rocks and oil and gas shows have been discovered in the Upper Triassic strata using surface outcrop investigations and exploratory wells for geological survey; these discoveries have established Upper Triassic strata as the primary target layer for oil and gas exploration in the Qiangtang Basin. In addition, the recently completed Qiangke one well in the hinterland of the North Qiangtang Depression features a significant gas logging anomaly, where the total hydrocarbon content has increased from 0.044% to 3.544%; this depression is located in the pyroclastic rocks of the Upper Triassic Nadigangri Formation within the well interval of 4,246.0–4,253.7 m, and the underlying Upper Triassic strata are the possible gas sources (Wang J. et al., 2022).

Global oil and gas exploration practices have confirmed that the quality of hydrocarbon source rocks fundamentally controls the distribution of oil and gas resources and the formation of large oil and gas fields; this research topic has attracted extensive attention from scholars worldwide. In particular, the study of the genetic mechanism of black mudstone has become a cutting-edge research topic in the field of earth sciences (Pedersen and Calvert, 1990; Gallego-Torres et al., 2007; Wei et al., 2012; Lash and Blood, 2014; Qiu et al., 2019). The black mudstones of the Upper Triassic Bagong Formation in the eastern North Qiangtang Depression are widely distributed and commonly found in delta-shallow marine shelf environments. However, their qualities and hydrocarbon generation potentials are significantly different (Zeng et al., 2013; Song et al., 2018; Wang et al., 2021; 2022b; Sui et al., 2025). Therefore, determining the spatial distribution of high-quality hydrocarbon source rocks in the Upper Triassic Bagong Formation is a crucial prerequisite for the next phase of oil and gas exploration. In particular, the process of organic matter enrichment in hydrocarbon source rocks and its controlling factors are key to predicting high-quality hydrocarbon source rocks. Since the factors controlling organic matter enrichment are unclear and the depositional environment is poorly understood, the range of distribution of hydrocarbon source rocks is difficult to delineate and predict. However, the genetic mechanism of black mudstones is controversial, and the primary debate is centred on whether

organic matter enrichment is controlled by initial productivity (Pedersen and Calvert, 1990; Sageman et al., 2003; Wei et al., 2012), preservation conditions (Demaision and Moore, 1980; Canfield, 1994; Yan et al., 2009; Zeng et al., 2015), or a combination of both factors (Algeo and Tribovillard, 2009; Ross and Bustin, 2009; Wang et al., 2017; Li et al., 2025).

Previous studies on the genetic mechanism of the Upper Triassic Bagong Formation black mudstones have focused mostly on the 1:250,000 scale Chibuzhangcuo area (Yu et al., 2019; Wang et al., 2022c); however, studies on its eastern Wenquanbingzhan area are limited, creating an unfavourable situation for delineating and predicting the spatial distribution of hydrocarbon source rocks in this area. Therefore, in this study, the black mudstone of the Bagong Formation in the Tielong Section of the Wenquanbingzhan area in the eastern North Qiangtang Depression is used as the research object to carry out total organic carbon (TOC) and element geochemical analyses to determine the sedimentary provenance and tectonic attributes of the Bagong Formation black mudstone. On this basis, we reconstruct the paleoenvironmental conditions, such as palaeoclimate, palaeo-redox conditions, palaeowater depth and palaeosalinity, of the shale depositional period to reveal the genetic mechanism of this set of mudstones and provide a basis for predicting the distribution of high-quality hydrocarbon source rocks in the Bagong Formation.

2 Regional geological setting

The Qiangtang Basin is located in the north-central Qinghai-Tibet Plateau and is tectonically adjacent to the Tarim Block, Kunlun Block, Hoh Xil Block, Songpan-Ganzi Block and Lhasa Block. Previous geological and geophysical data indicate that the southern and northern boundaries of the basin are the Bangong Lake–Nujiang Suture Zone and the Hoh Xil–Jinsha River Suture Zone, respectively (Figure 1A; Wang et al., 2004); from south to north, the basin can be further divided into the following three secondary structural units: the South Qiangtang Depression, the Central Uplift Zone and the North Qiangtang Depression; these units form a structural pattern of two depressions flanking one uplift (Figure 1A; Wang et al., 2004; Xiong et al., 2020). However, the latest aeromagnetic data show that the South and North Qiangtang regions have completely different gravity and magnetic field characteristics; these results indicate that they are two entirely different structural units, whereas the Central Uplift Zone is a suture zone formed by the closure of the Longmucuo–Shuanghu Palaeo-Tethys Ocean during the Late Triassic (Xiong et al., 2020). During the early to middle Late Triassic (Carnian–Norian), influenced by the closure and collisional orogeny of the Hoh Xil–Jinsha River and Longmucuo–Shuanghu Palaeo-Tethys Oceans, the North Qiangtang Depression was under a strong compressional environment, and

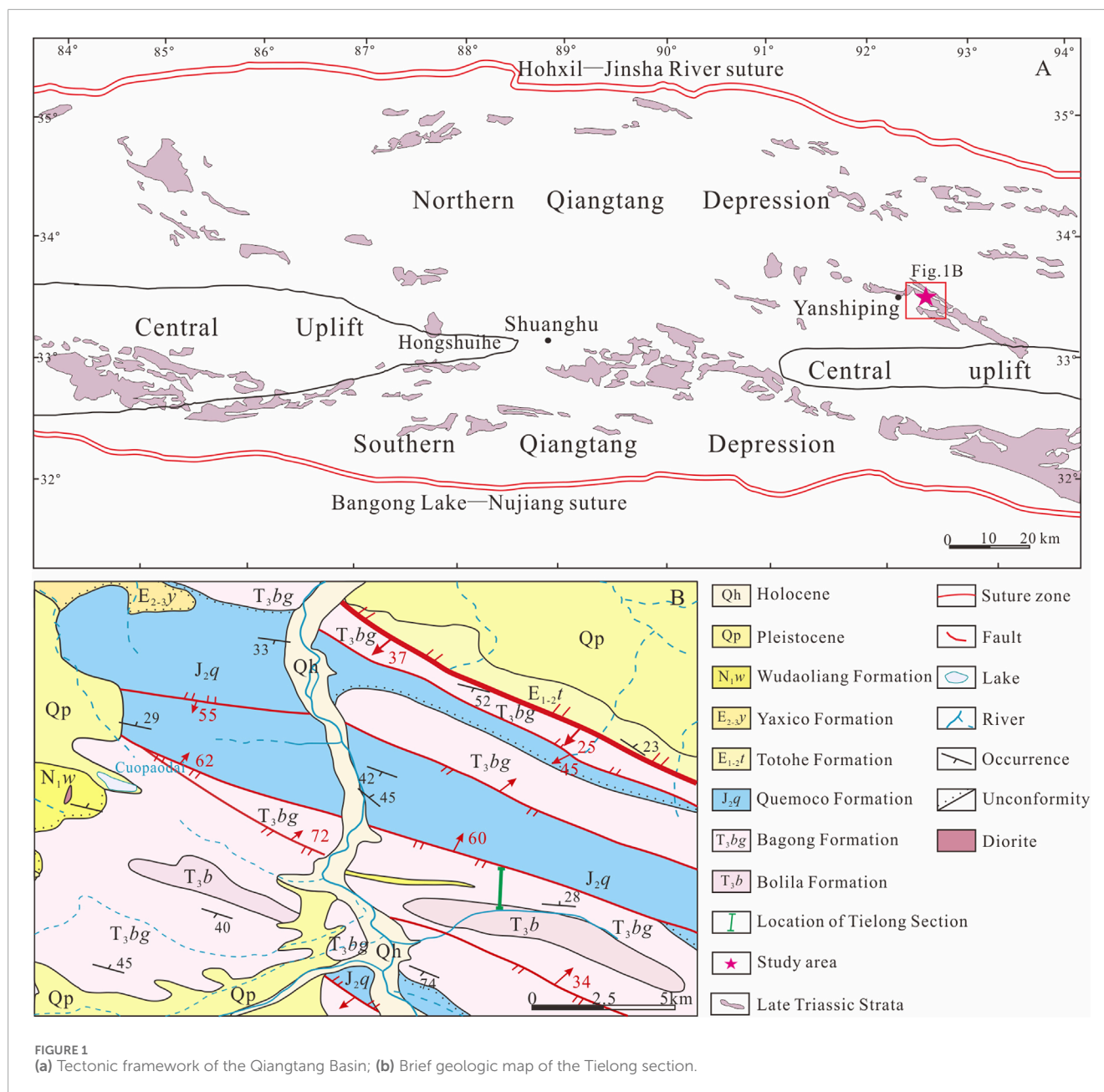


FIGURE 1
(a) Tectonic framework of the Qiangtang Basin; (b) Brief geologic map of the Tielong section.

a composite foreland basin subsequently formed (Shen et al., 2024). With the large-scale regression caused by the closure of the Palaeo-Tethys Ocean, the North Qiangtang foreland basin gradually shrank and was filled sequentially from bottom to top with the Upper Triassic Jiapila Formation, Bolila Formation, and Bagong Formation (Wang et al., 2009).

The Tielong Section in the study area is located east of the Yanshiping subsag in the eastern North Qiangtang Depression, with the section starting at E92°32'29.99", N33°36'19.78" (Figure 1B); additionally, the exposed Upper Triassic Bagong Formation exceeds a thickness of 326.45 m and is in conformable contact with the underlying Bolila Formation, and its top is not exposed (Figure 2). In terms of lithological assemblage, the Tielong Section consists of interbedded grey-greyish-green-light grey medium-bedded

siltstone, greyish-black-dark grey-grey thin-bedded mudstones with varying thicknesses, and grey medium-bedded lithic sandstone (Figure 2). Vertically, the grain size of clastic rocks gradually coarsens upwards and forms an overall progradational inverse grading sequence. Normally graded bedding, parallel bedding, and groove and gutter casts are present in the sandstone, thin-layer conglomerate is present in the siltstone, and the mudstone features horizontal bedding and horizontal trace fossils (Figure 2). On the basis of the sedimentary characteristics of the Bagong Formation in the adjacent Dongqu area, this sequence likely represents slump-turbidite facies in the proximal delta front (Zhan et al., 2019). Regionally, the lower part of the Bagong Formation contains Carnian bivalve species (*Halobia convexa* and *H. yunnanensis*), early and middle Norian species

(*Halobia superbescens*, *H. disperseinsecta*, *Amonotis togtonheensis*, and *Cardium (Tulongocardium) xizhangensis*) and ammonite species (*Nodotibetites cf. Nodosus*, and *Paratibetites cf. Wheeleri*) (Niu et al., 2003; Tang et al., 2007), whereas the upper part of the Bagong Formation contains Carnian–Norian bivalve species (*A. rothpletzi yushuensis*, *Bakevella pannonica* and *Costatoria goldfussi*). Recently, researchers have constrained the stratigraphic age of the Bagong Formation from different perspectives. For example, the detrital zircon dating of sandstones at the top of the Bagong Formation obtained from the Quemocuo area yields the youngest zircon ages ranging from 217 to 227 Ma, with a weighted mean age of 222.0 ± 1.5 Ma ($n = 9$), whereas the detrital zircons from the upper sandstones of the Bagong Formation in Well QZ-16 yield ages between 223 Ma and 229 Ma, with a weighted mean age of 227.2 ± 1.2 Ma ($n = 19$; Zeng, 2021). On the basis of the biostratigraphic characteristics of the Bagong Formation and the maximum depositional ages of detrital zircons, its age is estimated to be Carnian–Norian of the Late Triassic.

3 Samples and methods

In this study, 31 dark mudstone samples were collected from the bottom to the top of the Bagong Formation in the Tielong Section, and the specific sampling locations are shown in Figure 1C. Systematic TOC and element geochemical analyses were carried out on 31 mudstone samples to reconstruct the sedimentary palaeoenvironment and identify its origin.

The TOC and sulfur contents were measured with a LECO CS-200 carbon–sulfur analyser at the Organic Geochemistry Laboratory of Yangtze University, with an error of less than 10%. Detailed processes were presented in Peters and Cassa (1994). Major elements were analysed using the fusion method. A total of 0.5 g of whole-rock powder (200 mesh) and 5 g of flux ($\text{Li}_2\text{B}_4\text{O}_7\text{:LiBO}_2 = 12\text{:}22$) were weighed and evenly mixed in a crucible made of 95% platinum–5% gold, and the sample was heated in a high-frequency melting furnace at 1,050 °C for 11 min. The molten liquid was poured into a mould (diameter = 34 mm) to form a fused disc for testing. The samples were tested using a Philips PW2404 X-ray fluorescence spectrometer according to the GB/T 14,506.28–2010 standard. The loss-on-ignition was determined by weighing 1 g of dry powder sample into a corundum crucible, heating it in a muffle furnace at 1,000 °C for 90 min, cooling it in the furnace, weighing it, and recording the loss-on-ignition during heating. Trace elements were analysed using mainly the acid dissolution method. A total of 0.5 g of dried whole-rock powder was weighed and placed in a Teflon crucible. The sample was wetted with one to two drops of high-purity water; 1.5 mL of high-purity nitric acid and 1.5 mL of high-purity hydrofluoric acid were then sequentially added, and the sample was sealed in a steel jacket and heated in an oven at $190^\circ\text{C} \pm 5^\circ\text{C}$ for 48 h. After cooling, the crucible was uncovered and placed on an electric hot plate to evaporate any remaining liquid in the sample at a constant temperature of 140 °C. Then, 1 mL of HNO_3 was added to the sample and then evaporated; next, 3 mL of 30% HNO_3 was added to the sample, and the sample was resealed in a Teflon crucible in a steel jacket and heated in an oven at $190^\circ\text{C} \pm 5^\circ\text{C}$ for 12 h. The solution was then transferred to a polyethylene bottle, diluted with 2% HNO_3 to 100 g (dilution factor of 2,000), and sealed for testing.

The trace element contents were determined according to GB/T 14,506.30–2010 using a Finnigan MAT high-resolution inductively coupled plasma–mass spectrometer (HR-ICP–MS). Major and trace element analyses were conducted at the Beijing Research Institute of Uranium Geology, and the relative standard deviations were less than 5%. More analytical processes of major and trace elements were following the methods described by Ma et al. (2015).

4 Results

4.1 TOC contents of the upper triassic Bagong Formation mudstones

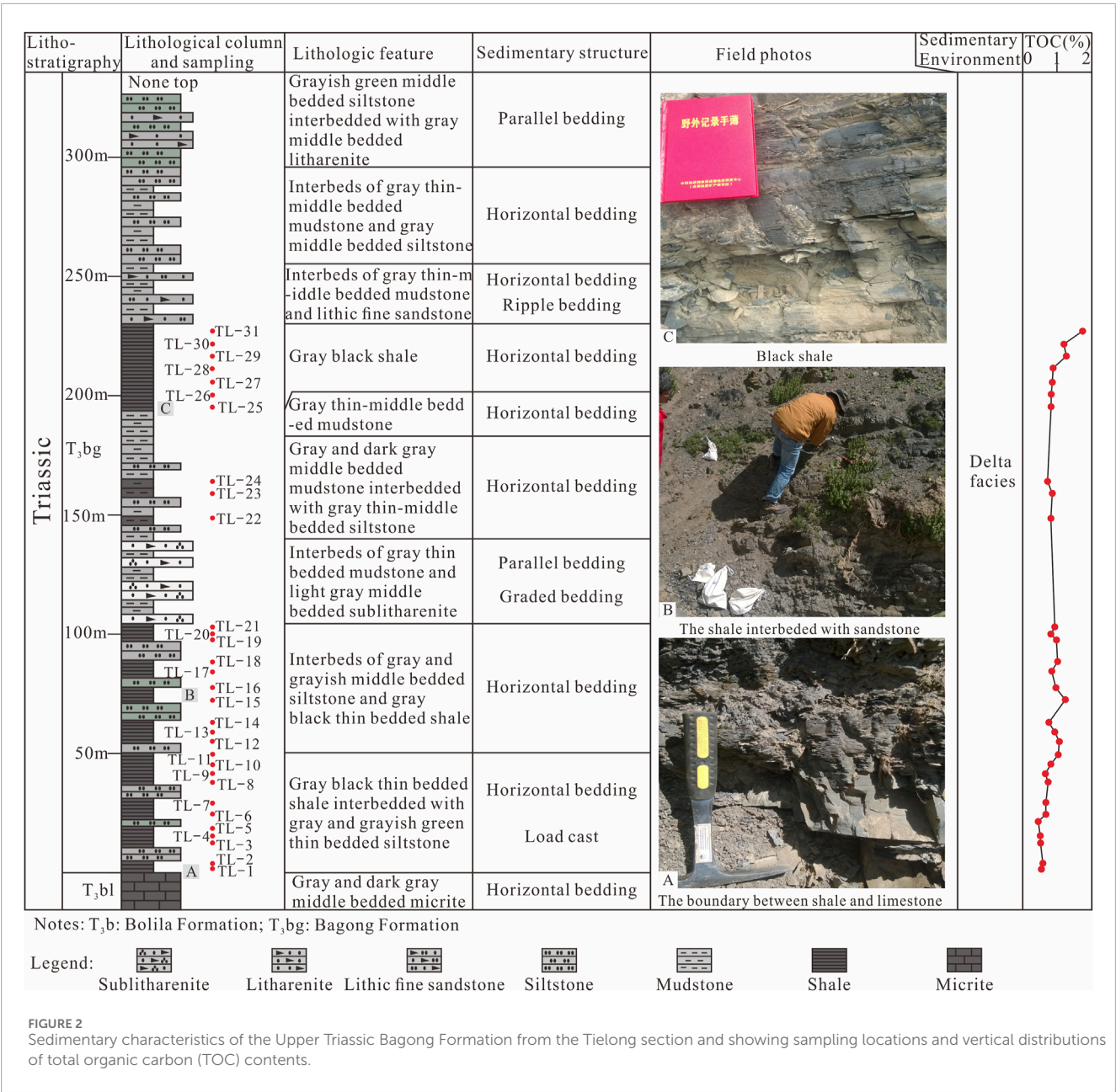
The TOC contents of 31 mudstone samples from the Tielong Section of the Bagong Formation significantly fluctuate and range from 0.47% to 1.73% (Supplementary Table S1), with an average of 0.87%. Among the samples, the TOC contents are less than 0.5% for one sample, greater than 1.0% for seven samples, and between 0.5% and 1.0% for the remaining 23 samples. Vertically, the overall TOC content initially increases, then decreases, and finally increases again, and the highest TOC content occurs at the top (Figure 2).

4.2 Element geochemical characteristics of the upper triassic Bagong Formation mudstones

4.2.1 Major elements

The major element contents of the Bagong Formation mudstones in the Tielong Section are listed in Supplementary Table S1. In the studied samples, the most abundant oxides are SiO_2 and Al_2O_3 , with contents of 53.77%–61.31% and 14.45%–19.75%, respectively, followed by Fe_2O_3 , MgO , K_2O , and CaO , with contents of 5.81%–7.09%, 2.35%–2.74%, 2.85%–4.64%, and 1.33%–3.05%, respectively; the contents of the other oxides are generally less than 1%. Ross and Bustin (2009) proposed that SiO_2 , Al_2O_3 , and CaO can be used to represent siliceous, argillaceous and calcareous materials, respectively, to distinguish different shale/mudstone types. In the SiO_2 – Al_2O_3 – CaO ternary diagram (Figure 3), the samples from the study area have significantly higher SiO_2 contents than CaO and Al_2O_3 contents, and all the samples are located in the SiO_2 end-members; these results indicate that the Bagong Formation mudstones from the Tielong Section are characterized by high silica contents.

For the oxides in the Bagong Formation in the study area, K_2O has a significant positive correlation with Al_2O_3 ($R = 0.99$, $n = 31$; Supplementary Table S2) but a significant negative correlation with Na_2O ($R = -0.95$, $n = 31$; Supplementary Table S2); these results indicate that K_2O primarily originates from clay minerals, which from the alteration of feldspar, rather than directly from feldspar minerals (Ross and Bustin, 2009). Fe_2O_3^T and MgO are significantly correlated with Al_2O_3 ($R = 0.67$ and 0.84 , respectively; $n = 31$; Supplementary Table S2), whereas no correlation is observed between MgO and CaO ($R = -0.23$, $n = 31$; Supplementary Table S2); these results indicate that Fe_2O_3^T and MgO have similar properties and are derived mostly from terrigenous detritus rather than carbonate minerals. A significant

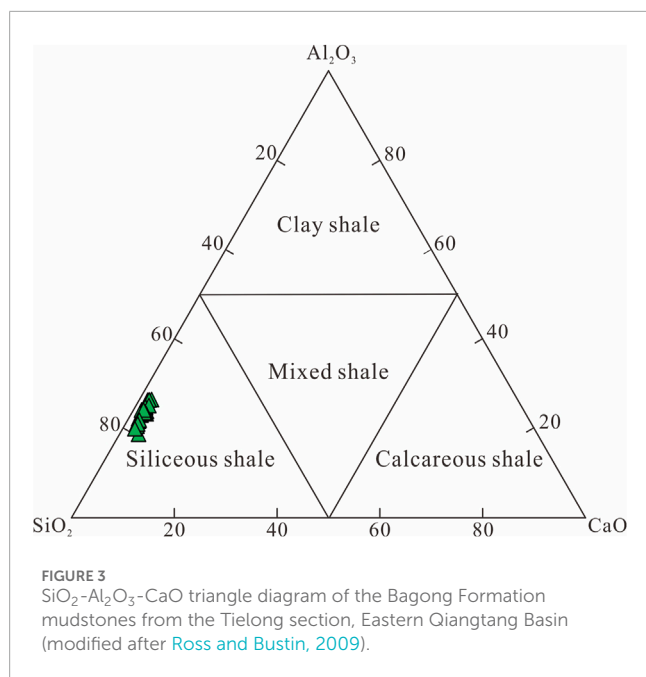


positive correlation is observed between the TiO_2 and Al_2O_3 contents ($R = 0.89$, $n = 31$; [Supplementary Table S2](#)); these results show that Ti is derived from mainly terrigenous detritus and occurs in clay minerals in the form of heavy minerals. A significant negative correlation is observed between SiO_2 and Al_2O_3 contents ($R = -0.94$, $n = 31$; [Supplementary Table S2](#)); thus, Si originates from nonclay minerals and may occur mainly in detrital quartz.

4.2.2 Trace and rare earth elements

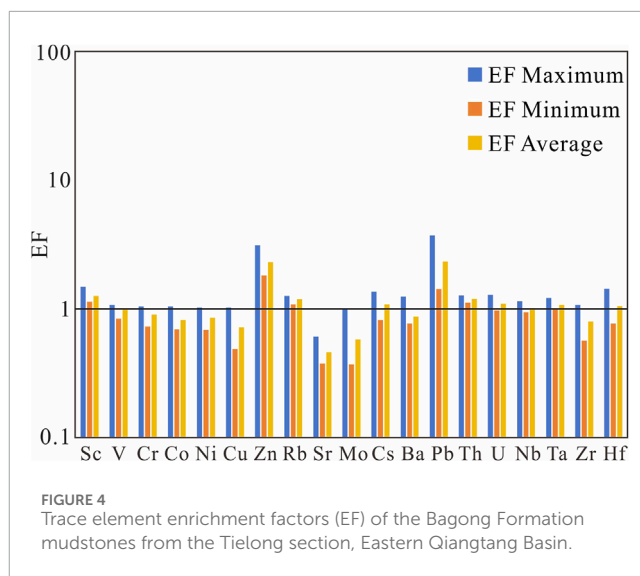
The trace element results for the Bagong Formation mudstones in the study area are provided in [Supplementary Table S3](#). The contents of the large-ion lithophile elements Rb, Sr, Cs, Ba, Pb, Th and U in the mudstone are 142–210 ppm, 73.1–97.5 ppm, 10.2–19.7 ppm, 427–648 ppm, 24.4–74.4 ppm, 13.5–18.6 ppm, and 2.76–3.80 ppm, respectively ([Supplementary Table S3](#)). In the

samples, the Al_2O_3 contents are significantly positively correlated ([Supplementary Table S2](#)) with the Rb ($R = 0.96$, $n = 31$), Cs ($R = 0.86$, $n = 31$), Ba ($R = 0.88$, $n = 30$), Th ($R = 0.91$, $n = 31$), and U contents ($R = 0.73$, $n = 30$); these results indicate that these elements are sourced mainly from terrigenous detritus and occur mostly in clay minerals. However, the Al_2O_3 content is not significantly correlated with the Sr or Pb contents ($R = -0.2$ and 0.16 , respectively, $n = 31$; [Supplementary Table S2](#)), indicating that Sr and Pb are not derived from detritus. The contents of high-field strength elements Nb, Ta, Zr, and Hf in the Bagong Formation mudstones of the study area are 16.3–19.4 ppm, 1.16–1.40 ppm, 124–196 ppm, and 3.71–6.52 ppm, respectively ([Supplementary Table S3](#)). Significant positive correlations are observed between Nb and Ta ($R = 0.88$, $n = 31$), and between Zr and Hf ($R = 0.67$, $n = 31$) ([Supplementary Table S3](#)); these results indicate that these elements



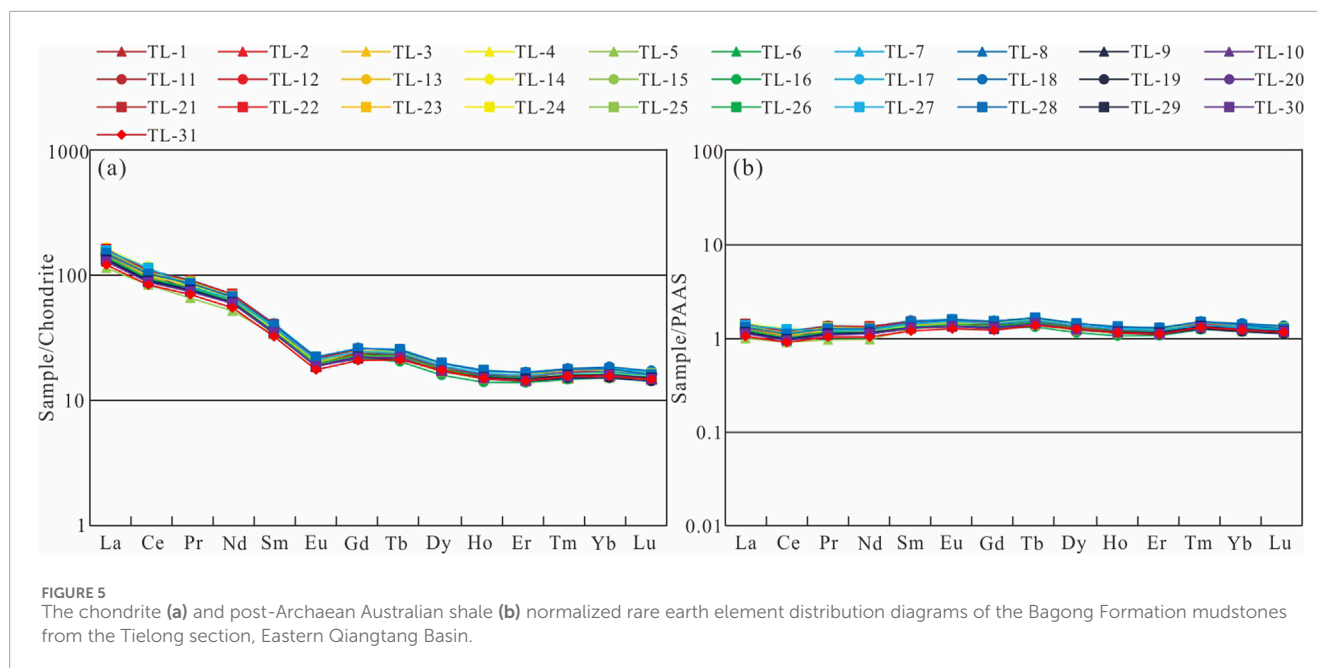
have similar geochemical properties and sources. The contents of the transition elements of Sc, V, Cr, Co, Ni, Cu, Zn and, Mo are 15.5–21.7 ppm, 104–163 ppm, 79.1–111 ppm, 14.7–25.1 ppm, 36.5–50.2 ppm, 24.4–42 ppm, 144–211 ppm, and 0.36–0.94 ppm, respectively (Supplementary Table S3). The Al₂O₃ content has no significant correlation with the contents of Cu ($R = 0.15$, $n = 31$), Zn ($R = 0.04$, $n = 31$), Cr ($R = 0.46$, $n = 31$) or Mo ($R = -0.22$; $n = 31$) in the samples (Supplementary Table S2); thus, these elements are not derived from detritus. The contents of Sc, Ni, Co, and V are significantly positively correlated with the Al₂O₃ content ($R = 0.63$, 0.65 , 0.52 , and 0.94 , respectively; $n = 31$; Supplementary Table S2); therefore, most of these elements are derived from terrigenous detritus.

The element enrichment factor (EF) is commonly used to evaluate the degree of element enrichment and is calculated as follows: $EF_X = (X/Al)_{\text{sample}} / (X/Al)_{\text{PAAS}}$, where X represents the element content and PAAS represents the Post-Archean Australian Shale. For rocks or sediments, an EF value greater than one usually represents element enrichment, whereas an EF value less than one indicates depletion (Tribouillard et al., 2006). The EFs of trace elements in the Bagong Formation mudstones in the Tielong Section are shown in Figure 4. Compared with those in PAAS, Zn and Pb are significantly enriched, with EF values generally greater than 2.0 (Figure 4), whereas Sc, Rb, Th, U, and Ta are weakly enriched, with EF values generally between one and 1.5 (Figure 4). Cr, Co, Ni, Cu, Sr, Mo, Ba, and Zr are significantly depleted, whereas V, Cs, Nb, and Hf are both weakly depleted and weakly enriched in the samples (Figure 4). A sample with Mn/Sr < 10 indicates that the sample has not been affected by diagenetic alteration (Kaufman and Knoll, 1995). The Mn/Sr ratios of the Bagong Formation mudstone samples in the study area range from 4.85 to 9.55 (Supplementary Table S3); since these values are lower than 10, the samples have not been affected by diagenetic alteration and the element contents



can be used for palaeoclimate and palaeoenvironmental reconstruction.

The results and related parameters for the rare earth elements (REEs) in the Bagong Formation mudstones in the Tielong Section are listed in Supplementary Table S4. The results show that the total REE contents in the Bagong Formation mudstone samples in the study area greatly fluctuate and range from 177.3 to 234.7 ppm (average of 212.0 ppm), with the majority of samples having Σ REE contents higher than the PAAS content (185 ppm; Taylor and McLennan, 1991). A significant positive correlation is observed between the Σ REE content and the Al₂O₃ content of the samples in the study area ($R = 0.85$; $n = 31$; Supplementary Table S2); these results indicate that the enrichment of REEs is associated mainly with the input of terrigenous detritus. In addition, the contents of light REEs (LREEs) (156.3–212.4 ppm) in the Bagong Formation mudstone samples from the study area are significantly greater than those of heavy REEs (HREEs) (20.3–24.8 ppm), and the LREE/HREE ratios range from 7.48 to 9.58 (Supplementary Table S4); these results clearly distinguish LREEs and HREEs. The chondrite- and PAAS-normalized REE distribution curves of the Bagong Formation mudstone samples in the study area are shown in Figure 5. All the samples exhibit similar REE distribution curves. After PAAS normalization, the (La/Yb)_N ratios of almost all the samples are close to 1.0 and range from 0.88 to 1.15, with an average of 0.98 (Supplementary Table S4); these results indicate weak differentiation between the LREEs and HREEs in the Bagong Formation mudstones. In addition, almost all mudstone samples show slight positive Eu anomalies, with Eu anomaly (δ Eu) values ranging from 0.99 to 1.10 (avg. of 1.04), and weak negative Ce anomalies, with Ce anomaly (δ Ce) values ranging from 0.84 to 0.96 (avg. of 0.87) (Supplementary Table S4). However, the Bagong Formation mudstone samples after chondrite normalization all exhibit significant negative Eu anomalies (δ Eu = 0.63–0.70; avg. of 0.66; Supplementary Table S4) and weak negative Ce anomalies (δ Ce = 0.85–0.95; avg. of 0.87; Supplementary Table S4).



5 Discussion

5.1 Provenance and tectonic setting of the Bagong Formation mudstones

5.1.1 Provenance

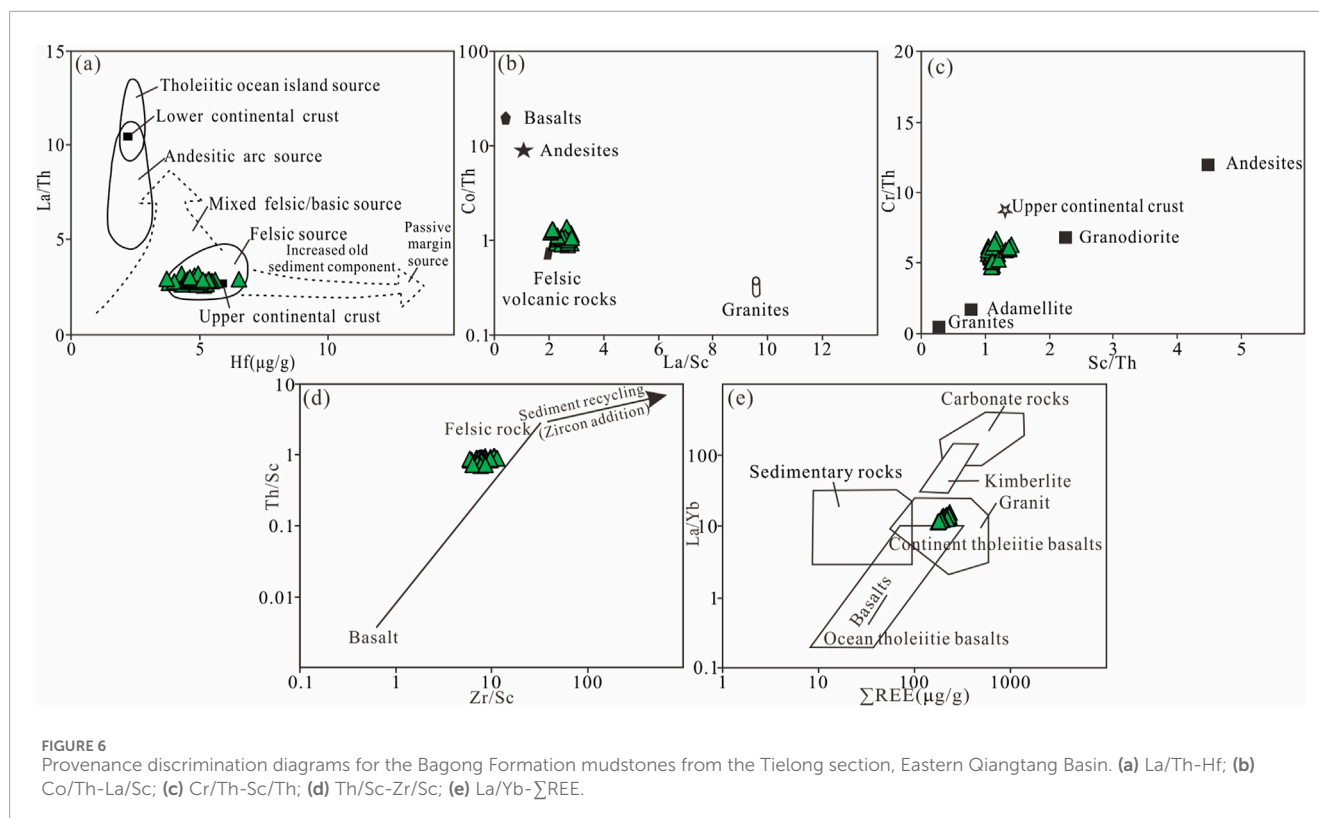
Owing to the stability of certain trace elements (such as Cr, Th, Co, Zr, Sc, and Hf) in clastic rocks, their contents in clastic rocks are similar to those in their parent rocks and are thus often used for provenance tracing (Armstrong-Altrin et al., 2004; Tao et al., 2014; Moradi et al., 2016). In general, La, Th, and Hf tend to occur in felsic rocks and their weathering products, whereas Co, Sc, and Cr are more likely to occur in mafic rocks and their weathering products (Armstrong-Altrin et al., 2004; Cheng et al., 2024). The La/Th–Hf (Floyd and Leveridge, 1987), Cr/Th–Sc/Th (Condie and Wronkiewicz, 1990) and Co/Th–La/Sc (Condie, 1993) diagrams are widely used in the identification of clastic provenances. In the La/Th–Hf diagram, the mudstones of the Bagong Formation in the Tielong Section present low and clustered La/Th ratios and high Hf contents, ranging from 2.61 to 3.22 and 3.73–6.53 ppm, respectively (Supplementary Table S3), and most samples plot within the felsic provenance field, except two samples that plot into the mixed mafic and acidic provenance field (Figure 6a). In the Co/Th–La/Sc diagram, the mudstone samples from the Bagong Formation in the Tielong Section have low Co/Th and La/Sc ratios overall, ranging from 0.90 to 1.39 (avg. of 1.08) and 2.05–2.81 (avg. of 2.49) (Supplementary Table S3), respectively, and all plot between monzogranite and granodiorite, indicating a primarily felsic provenance (Figure 6b). In the Cr/Th–Sc/Th diagram, the Bagong Formation mudstones in the study area also have low Cr/Th and Sc/Th ratios, ranging from 4.75 to 6.73 and 1.05–1.41, respectively, and all plot between those of monzogranite and granodiorite and indicate a primarily felsic provenance (Figure 6c). In addition, in the Th/Sc–Zr/Sc cross-plot (Figure 6d), the Bagong Formation mudstone samples in the study area are all located

along the trend line indicating compositional variation (near the granite end-members) and are far from the trend line indicating sedimentary cycling; these results indicate that the sediments did not undergo significant sedimentary recycling during deposition and are characterized by a felsic provenance.

Considering their stable geochemical properties, REEs are also widely used in sediment source tracing (Moradi et al., 2016; Wang et al., 2018; Casas-Peña et al., 2021). In general, felsic source rocks tend to have high LREE/HREE ratios and significant negative Eu anomalies, whereas mafic source rocks often have low LREE/HREE ratios and no evident negative Eu anomalies (Roddaz et al., 2006; Wang et al., 2017). However, the δEu values of clastic sedimentary rocks can also be affected by diagenesis and are thus significantly positively correlated with δCe and ΣREE (Shields and Stille, 2001). As mentioned earlier, the δEu values of the Xiali Formation clastic rock samples in the study area are not significantly correlated with the δCe and ΣREE values (Supplementary Table S2); these results indicate that the δEu values of the clastic rock samples are basically unaffected by diagenesis but are inherited from the source rocks. In this study, after chondrite normalization, the REEs of the Bagong Formation mudstones exhibit a significant negative Eu anomaly (Figure 5a), with δEu values ranging from 0.67 to 0.75 (avg. of 0.70; Supplementary Table S4); thus, they originate mainly from a felsic source. In addition, the La/Yb– ΣREE diagram proposed by Allègre and Minster, (1978) can be used to effectively distinguish the properties of four types of source rocks: sedimentary rocks, granite, alkaline basalt and tholeiite. In this diagram, all the samples plot within the granite region, indicating that their parent rocks are mainly acidic rocks, such as granite (Figure 6e).

5.1.2 Tectonic setting

The tectonic setting of sediments largely depends on the chemical composition of clastic rocks because clastic rocks that form in different tectonic environments have different chemical compositions (Roser and Korsch, 1988; Bhatia and Crook, 1986;



Armstrong-Altrin and Verma, 2005). To define the tectonic setting of sediments, many traditional discriminant diagrams, such as K_2O/Na_2O-SiO_2 , $Th-Co-Zr/10$, and $La-Th-Sc$ diagrams, have been proposed to distinguish tectonic settings and include passive continental margins, active continental margins, continental island arcs and oceanic island arcs (Roser and Korsch, 1988; Bhatia and Crook, 1986). However, these traditional discriminant diagrams have a low success rate in determining tectonic settings and have been used with caution in recent years (Armstrong-Altrin and Verma, 2005; Verma and Armstrong-Altrin, 2013).

Recently, Verma and Armstrong-Altrin (2013) applied statistical principles to propose two multidimensional discriminant diagrams based on the main oxides of Cenozoic sediments, and these oxides can effectively be used to differentiate three different tectonic settings (collision, rift and island arc) during the period of clastic rock deposition; thus, these diagrams are widely used (Moradi et al., 2016; Deng et al., 2019). In the discriminant diagrams, these sediments are further classified into high-silica $(SiO_2)_{adj} = 63-95\%$ and low-silica $(SiO_2)_{adj} = 35-63\%$ types, where the subscript “adj” indicates the value that corresponds to oxides being comprehensively adjusted to 100% (ignoring the loss-on-ignition value). For more details, refer to Verma and Armstrong-Altrin (2013). To define the tectonic setting of the Bagong Formation mudstones in the study area more precisely, the two multidimensional discriminant diagrams described above are used instead of the traditional discriminant diagram. Among the 31 mudstone samples from the Bagong Formation in the Tielong Section, the $(SiO_2)_{adj}$ contents range from 58.8% to 66.1% (Supplementary Table S1), with 11 samples classified as high-silica type and 20 samples classified as low-silica type. In the discriminant

diagrams of the tectonic setting for high-silica and low-silica types (Figures 6b, 7b), all the Bagong Formation samples in the study area plot within or near the collision zone; these results indicate that the Bagong Formation mudstones in the Tielong Section formed in a collisional tectonic setting and are consistent with the tectonic regime of intracontinental compression in the North Qiangtang Depression in the early Late Triassic (Li et al., 2001; Wang et al., 2017; Shen et al., 2024).

5.2 Palaeoclimate reconstruction and terrigenous clastic input of the Bagong formation mudstones during the depositional period

Palaeoclimate conditions can, on the one hand, control the process of clastic input from the provenance into the sedimentary basin and, on the other hand, influence the growth and reproduction of organisms, thus affecting the preservation and enrichment of organic matter in the sediments. The Sr/Cu ratios of trace elements in mudstone are usually used to identify palaeoclimate conditions during deposition; a Sr/Cu ratio less than 10 indicates a warm and humid climate, whereas a Sr/Cu ratio greater than 10 reflects a hot and arid climate (Lerman, 1978). In the study area, the Sr and Cu contents of the Bagong Formation mudstones in the Tielong Section are not significantly correlated with the Al_2O_3 content ($R = -0.2$ and 0.15 , respectively; $n = 31$); these results indicate that the Sr and Cu in the samples are derived from nonclastic origins and can effectively reflect the palaeoclimate characteristics. The Sr/Cu ratios of the mudstone samples in the study area range from 2.05 to 3.50 (avg. of

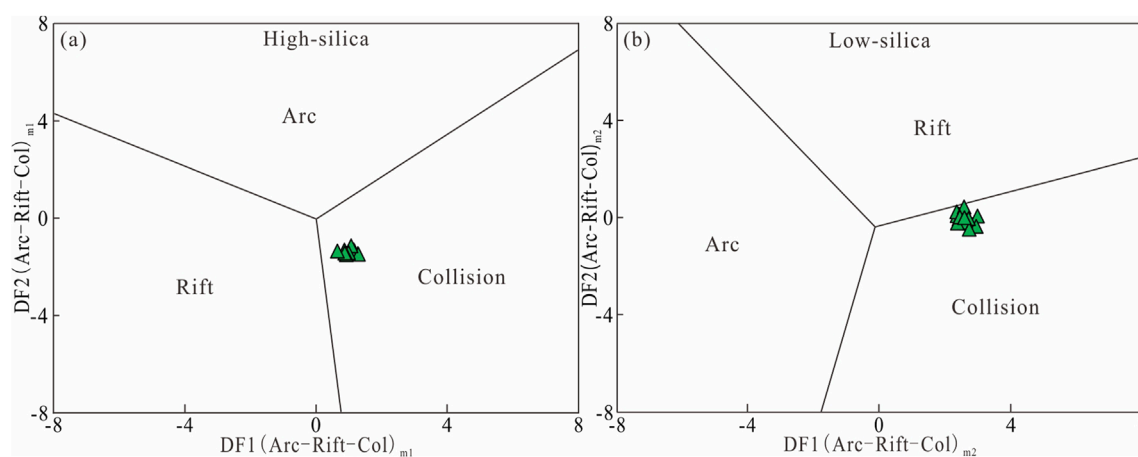


FIGURE 7
Multidimensional tectonic setting discrimination diagrams for the Bagong Formation clastic rocks from the Tielong section, Eastern Qiangtang Basin (Verma and Armstrong-Altrin, 2013). (a) High-silica clastic rocks; (b) Low-silica clastic rocks.

2.59), and all the ratios are significantly lower than 10.0 (Figure 8); these results indicate warm and humid climate conditions during the deposition of the Bagong Formation. In addition, under a humid climate, the contents of Fe, Mn, Cr, V, Ni, and Co are high in sediments, whereas under arid conditions, evaporation leads to the relative enrichment of Ca, Mg, K, Na, Sr, and Ba. The C value, which is calculated from the ratios of these two types of elements ($\Sigma(\text{Fe} + \text{Mn} + \text{Cr} + \text{Ni} + \text{V} + \text{Co}) / \Sigma(\text{Ca} + \text{Mg} + \text{Sr} + \text{Ba} + \text{K} + \text{Na})$), is widely used to reconstruct the palaeoclimate conditions during the deposition of fine-grained sedimentary rocks. Studies have shown that C values <0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, and >0.8 indicate arid, semiarid, semiarid to semihumid, semihumid and humid climate conditions, respectively (Zhao et al., 2007; Cao et al., 2012). The C values of the Bagong Formation mudstone samples in the study area range from 0.65 to 0.77 (avg. of 0.71; Supplementary Table S1; Figure 8); these values range between 0.6 and 0.8 and indicate overall semihumid climate conditions in the study area. The variations in the Rb/Sr ratios of the sediments are caused by the differences in the material compositions of rock weathering products due to climate change (Li et al., 2019). High Rb/Sr values generally indicate a humid climate, and low values indicate an arid climate (Lei et al., 2024). The Rb/Sr ratios of the Bagong Formation mudstone samples in the study area are relatively high and range from 1.46 to 2.55 (avg. of 2.09; Figure 8); these results indicate warm and humid climate conditions. On the basis of the Sr/Cu–C values (Figure 9a) and the Rb/Sr–Sr/Cu diagram (Figure 9b), the climate during the deposition of the Bagong Formation mudstones was likely warm and humid overall.

In addition, the chemical weathering intensity of the clastic rock source area is closely related to the palaeoclimate (Nesbitt and Young, 1982; Fedo et al., 1997). The chemical index of alteration (CIA), proposed by Nesbitt and Young (1982) as an important chemical weathering indicator, has been widely used in evaluating the chemical weathering intensity and reconstructing the palaeoclimate in geographical periods (Nesbitt and Young, 1982; Fedo et al., 1997; Yan et al., 2010; Hessler et al., 2017; Xu and Shao, 2018; Liu et al., 2019). Through systematic assessment

of the factors influencing the chemical weathering index, Xu and Shao (2018) proposed that when the CIA is used to determine the degree of weathering of the source area, the following recommended process should be used: argillaceous rock samples need to be initially selected; the index of compositional variability (ICV) value (molar $(\text{Fe}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO}^* + \text{MgO} + \text{MnO} + \text{TiO}_2) / \text{M}(\text{Al}_2\text{O}_3)$) should then be calculated on the basis of the major elements of the argillaceous rock; afterwards, the CIA (molar $[\text{Al}_2\text{O}_3 / (\text{CaO}^* + \text{Na}_2\text{O} + \text{Al}_2\text{O}_3 + \text{K}_2\text{O})] \times 100$) for samples with $\text{ICV} > 1$ can be calculated; the CIA value needs to be corrected for potassium metasomatism using the A–CN–K ternary diagram; finally, the potassium-corrected CIA_{corr} value should be used to reflect the degree of chemical weathering in the source area. In the formulas for calculating the ICV and CIA, CaO^* represents the CaO content in silicate minerals (Nesbitt and Young, 1982). In the present study, the method proposed by Taylor and McLennan, (1991) is used to correct for the CaO^* , i.e., molar $\text{CaO}^* = \min(\text{molar}(\text{CaO} - 10/3 \text{ P}_2\text{O}_5), \text{Na}_2\text{O})$. For the mudstones in the Bagong Formation in the Tielong Section in the study area, the ICV values range from 1.75 to 2.22 (avg. of 1.92; all values greater than 1), and the CIA values are between 69.9 and 75.4 (avg. of 73.2) (Supplementary Table S1). In the A–CN–K ternary diagram, the mudstone samples from the Bagong Formation in the Tielong Section greatly deviate from the ideal weathering trend line and are close to the AK line (Figure 10); these results indicate a strong influence of potassium metasomatism. Therefore, potassium correction of the CIA values of the Bagong Formation mudstone samples in the study area needs to be performed. When potassium correction is performed using the A–CN–K ternary diagram, the first step involves observing the interval in which the sample points are located. On the basis of the distribution of these points, the ideal weathering trend line of the samples without potassium metasomatism is determined (Figure 10). A reverse extension line is then drawn from the K end-member through the sample points, and its intersection with the ideal weathering trend line of the sample represents the CIA value of the sample before potassium metasomatism (Fedo et al., 1995). The potassium-corrected CIA (CIA_{corr}) values of the Bagong Formation mudstone

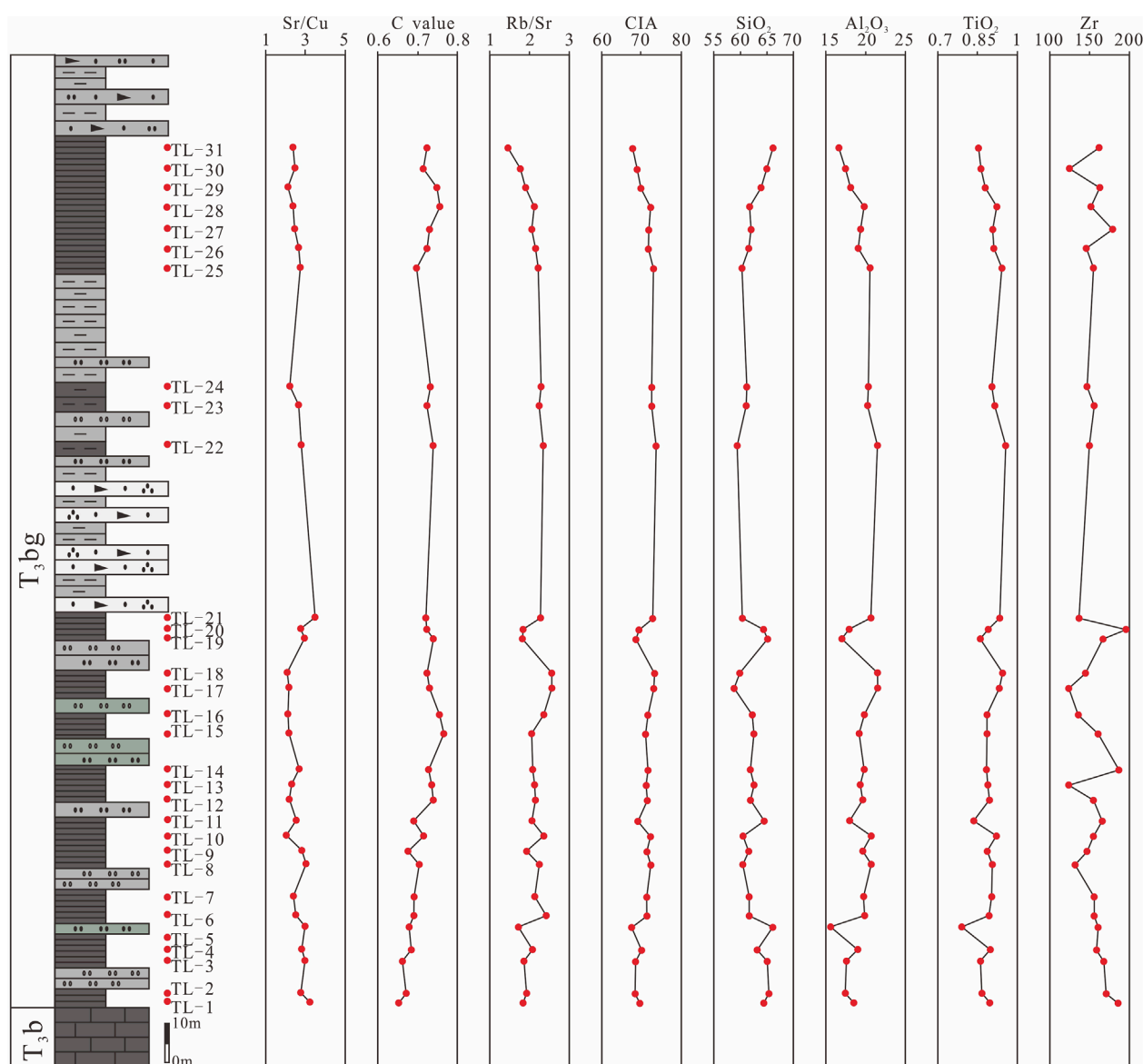


FIGURE 8

Vertical variation of paleoclimate and terrigenous influx of the Bagong Formation mudstones from the Tielong section, Eastern Qiangtang Basin.

samples in the study area range from 73.3 to 83.2. Since most CIA_{corr} values are between 70 and 80 (Supplementary Table S1; Figure 10), the provenance area of the Tielong Section experienced moderate chemical weathering and warm and humid climate conditions; these results are generally consistent with previous results determined using Sr/Cu, Rb/Sr ratios, and C values.

In summary, the Bagong Formation mudstones experienced warm and humid climate conditions during deposition, and their provenance was mainly felsic rocks. The warm and humid climate promoted chemical weathering in the provenance area, which may have allowed more felsic detritus to enter the depositional area. Si, Al, Ti, and Zr usually originate from terrigenous clastic grains and are considered important indicators for evaluating

clastic material input (Tribouillard et al., 2006; Lézin et al., 2013; Liu et al., 2018; Wang et al., 2022c). Among these elements, Si, Ti, and Zr in sediments are usually used as indicators of coarse-grained sedimentary input, whereas Al is generally an indicator of fine-grained sedimentary input (Canfield, 1994). The SiO_2 , Al_2O_3 , TiO_2 , and Zr contents of the Bagong Formation mudstones in the study area are 53.8–61.3% (avg. of 57.6%), 14.5–19.8% (avg. of 17.7%), 0.73–0.88% (avg. of 0.82%), and 124–196 ppm (avg. of 156 ppm), respectively; these values are generally lower than those of PAAS (62.8%, 18.9%, 0.99%, and 210 ppm, respectively) (Figure 8). These results indicate that during the deposition of the Bagong Formation mudstones in the Tielong Section, the input of fine-grained terrigenous detritus was greater than that of coarse-grained detritus.

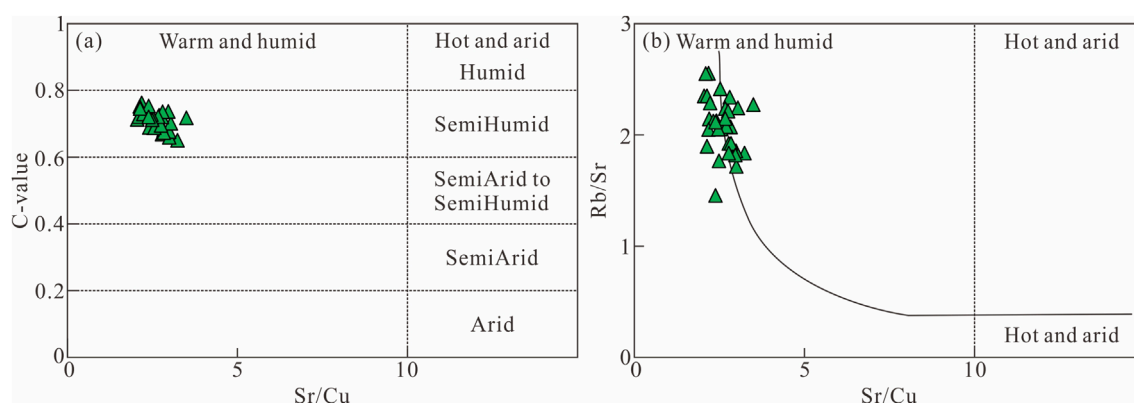


FIGURE 9 Discrimination diagram of paleoclimate and paleosalinity of the Bagong Formation mudstones from the Tielong section, Eastern Qiangtang Basin. **(a)** C-Sr/Cu, **(b)** Rb/Sr-Sr/Cu.

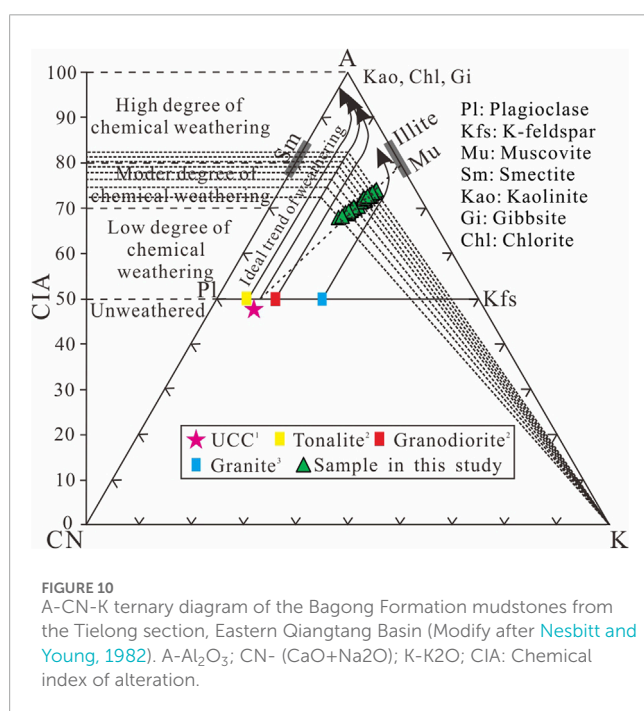


FIGURE 10 A-CN-K ternary diagram of the Bagong Formation mudstones from the Tielong section, Eastern Qiangtang Basin (Modify after Nesbitt and Young, 1982). A-Al₂O₃; CN- (CaO+Na₂O); K-K₂O; CIA: Chemical index of alteration.

5.3 Reconstruction of the palaeoenvironment of the Bagong formation mudstones during the depositional period

5.3.1 Palaeo-redox conditions

The redox conditions of the water column can affect the decomposition and preservation of organic matter (Demaison and Moore, 1980; Tyson and Pearson, 1991). Trace elements, such as V, U, Mo, and Cr, are sensitive to the redox conditions of the water column, and their EFs and element ratios, such as V_{EF} , U_{EF} , Mo_{EF} , V/Cr , Ni/Co , and U/Th , are often used to reconstruct the redox level of the water column (Algeo and Maynard, 2004; Tribouillard et al., 2006; Li et al., 2015; Wang et al., 2022c).

Tribouillard et al. (2006) proposed that in marine systems, V, U, and Mo are usually enriched under anoxic conditions and have high EF values. This understanding has since been widely applied in lacustrine, transitional and carbonate depositional environments (Kara-Gülbay and Korkmaz, 2008; Cao et al., 2018). The EF values of U in the Bagong Formation mudstones in the Tielong Section range from 0.97 to 1.28 (Supplementary Table S3; Figure 11), and only one sample has an EF value slightly greater than 1; thus, these results indicate weak depletion. The EF values of Mo are in the range of 0.37–0.99 (Supplementary Table S3; Figure 11); these results generally correlate with significant depletion. Under anoxic-sulfidic conditions, in the chemocline of the marine water column, Mo can be deposited in large quantities on the sediment surface, whereas when U is deposited on the sediment surface near the chemocline, U partially dissipates, resulting in $U_{EF} < Mo_{EF}$. Under suboxic conditions, owing to the absence of H₂S in the water column, the redox interface of Fe appears near the sediment interface, whereas the chemocline is below the sediment-seawater interface; this process results in minimal Mo deposition and substantial U deposition on the sediment surface, leading to $U_{EF} > Mo_{EF}$. Under oxidizing conditions, the contents of U and Mo in the sediments are both low (Zhang et al., 2017). In the U_{EF} - Mo_{EF} cross-plot (Figure 12a), the Bagong Formation mudstone samples in the study area all plot within 0.3 to one times the value of seawater (SW); thus, the sedimentary water column was in an oxidizing environment.

In terms of trace element ratios, U/Th , V/Cr and Ni/Co all decrease with increasing degrees of oxidation in the benthic water column. $U/Th < 0.75$, $V/Cr < 2$, and $Ni/Co < 5$ indicate an oxidizing environment; U/Th values in the ranges of 0.75–1.25, 2.0–4.25, and five to seven indicate a hypoxic environment; and $U/Th > 1.25$, $V/Cr > 4.25$, and $Ni/Co > 7$ reflect an anoxic environment (Jones and Manning, 1994). Significant positive correlations are observed between the V and Cr contents, between the Ni and Co contents, and between the U and Th contents ($R = 0.50$, 0.72 , and 0.86 , respectively; $n = 31$; Supplementary Table S2) in the Bagong Formation mudstone samples in the study area; these results indicate that these elements have the same properties and sources

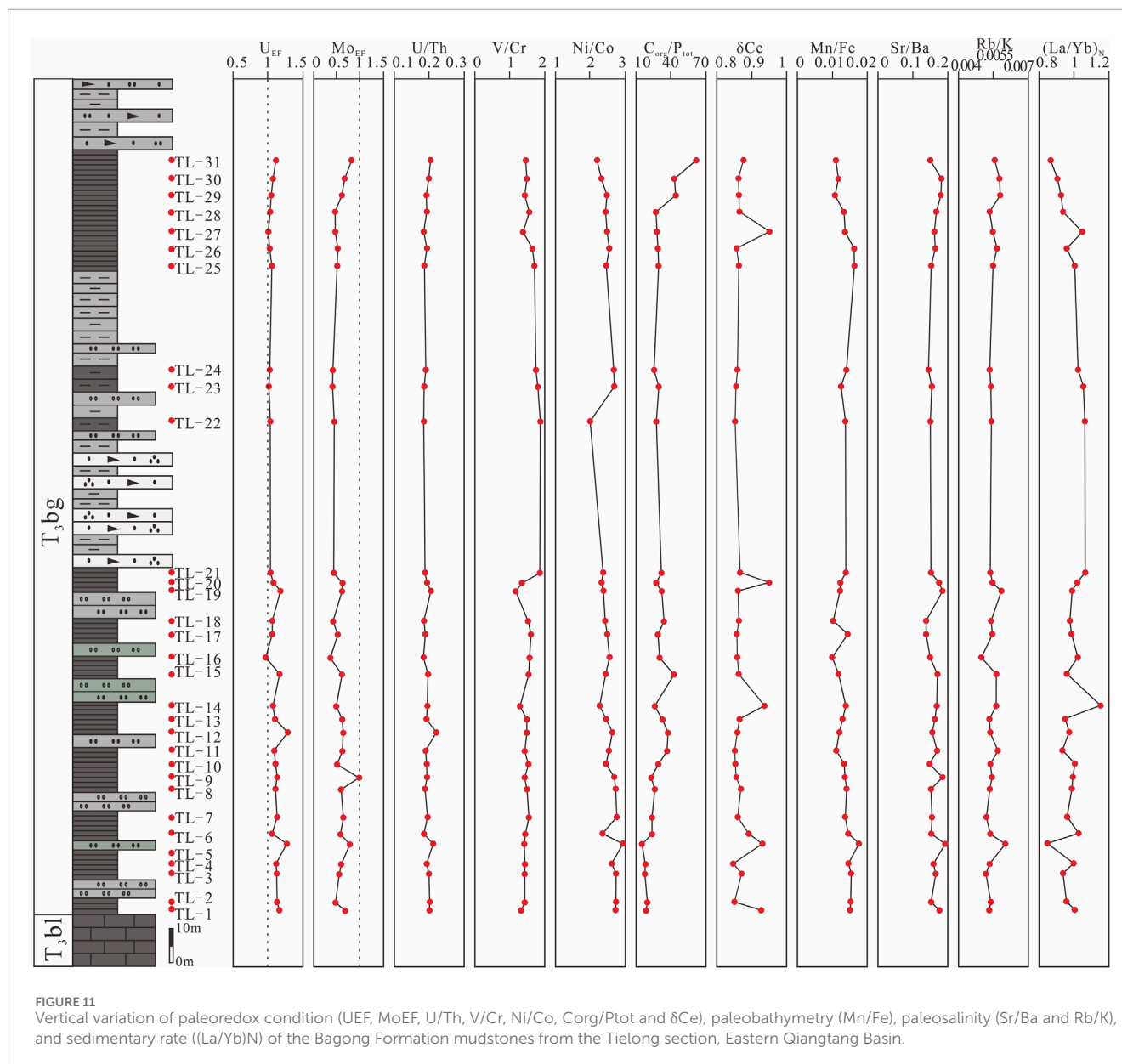


FIGURE 11
Vertical variation of paleoredox condition (U_{EF} , Mo_{EF} , U/Th , V/Cr , Ni/Co , C_{org}/P_{tot} and δCe), paleobathymetry (Mn/Fe), paleosalinity (Sr/Ba and Rb/K), and sedimentary rate ($(La/Yb)_N$) of the Bagong Formation mudstones from the Tielong section, Eastern Qiangtang Basin.

and that their ratios can effectively reflect the redox conditions of the water column. The U/Th , V/Cr , and Ni/Co ratios of the Bagong Formation mudstones in the Tielong Section range from 0.18–0.22 (avg. of 0.19), 1.18–1.89 (avg. of 1.53), and 2.00–2.94 (avg. of 2.52) (Supplementary Table S3), respectively; the three parameters are all less than the threshold values under oxidizing conditions and indicate an oxidizing environment (Figure 11). In addition, Algeo and Ingall (2007) proposed that the organic carbon (C_{org})/total phosphorous (P_{tot}) ratio is closely related to the redox conditions in marine sediments; this ratio has been widely used in recent years (Algeo and Ingall, 2007; Shen et al., 2015; Wang et al., 2017; 2022c). In general, low C_{org}/P_{tot} values (<50) reflect oxidizing conditions, moderate C_{org}/P_{tot} values (50–200) indicate suboxic conditions, and high C_{org}/P_{tot} values (>200) reflects anoxic reducing conditions (Algeo and Ingall, 2007; Shen et al., 2015). The C_{org}/P_{tot} values of the mudstones in the study area

range from 15 to 62 (avg. of 30; Supplementary Table S1), with one value slightly higher than 50 and the remaining values all lower than 50; these results indicate overall oxidizing conditions. On the basis of the V/Cr – U/Th (Figure 12b), Ni/Co – U/Th (Figure 12c), and C_{org}/P_{tot} – U/Th (Figure 12d) discriminant diagrams, the Bagong Formation mudstones in the Tielong Section experienced an oxidizing water column during the depositional period.

In addition, Ce anomalies in sediments are usually considered important indicators for reconstructing palaeoredox conditions (Alibo and Nozaki, 1999; Yan et al., 2009; Hu et al., 2019). Under oxidizing conditions, Ce^{3+} is usually oxidized to Ce^{4+} ; this reaction occurs in sediments in the form of CeO_2 (Alibo and Nozaki, 1999). In contrast, Ce^{4+} is often reduced to soluble Ce^{3+} in anoxic water columns (Alibo and Nozaki, 1999). Therefore, negative Ce abnormalities usually indicate an oxidizing environment, whereas positive Ce abnormalities reflect a hypoxic–anoxic environment.

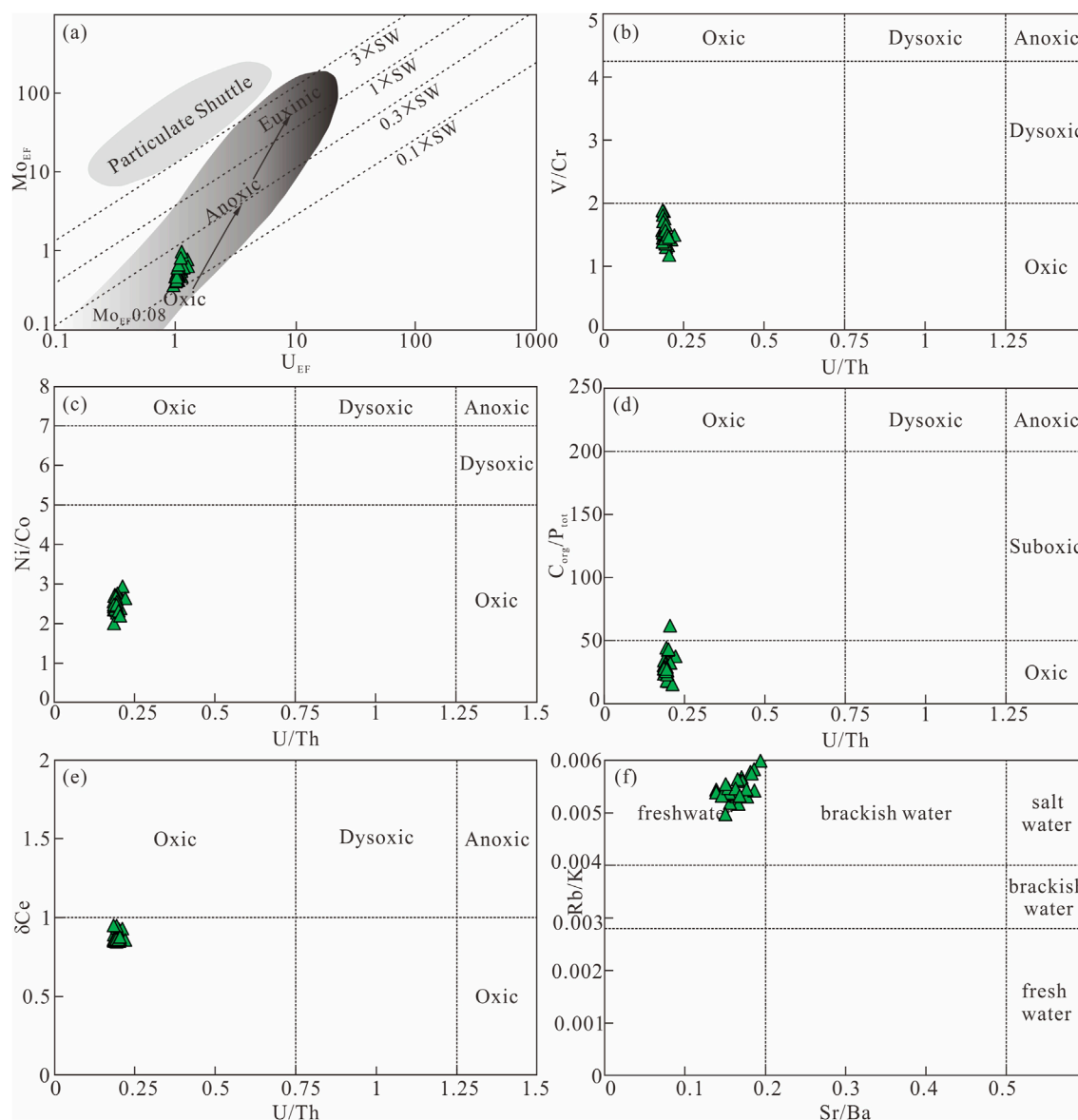


FIGURE 12
Discrimination diagram for redox conditions and paleosalinity of the Bagong Formation mudstones from the Tielong section, Eastern Qiangtang Basin. (a) U_{EF}-Mo_{EF}; (b) V/Cr-U/Th; (c) Ni/Co-U/Th; (d) C_{org}/P_{tot}-U/Th; (e) δCe-U/Th; (f) Sr/Ba-Rb/K.

The Ce anomaly values ($\delta\text{Ce} = 2 \cdot \text{Ce}_N / (\text{La}_N + \text{Pr}_N)$) of the Bagong Formation mudstones in the study area range from 0.84 to 0.96 (avg. of 0.87; [Supplementary Table S4](#); [Figure 11](#)) and show a weak negative Ce anomaly; these results indicate an oxidizing environment during the depositional period of the Bagong Formation in the Tielong Section ([Figure 12e](#)).

5.3.2 Palaeo-water depth and palaeosalinity

In large palaeolakes and oceans, the enrichment of Mn and Fe is significantly correlated with water depth and distance from the shore. Owing to its unstable geochemical properties, Fe is enriched mainly in shallow-water areas near the shore, whereas Mn can be transported over long distances and enriched in deep water far from the shore because of its stable geochemical

properties ([Li et al., 2017](#); [Lei et al., 2024](#)). Therefore, the Mn and Fe contents and the Mn/Fe ratio can be used as proxy indicators for determining the palaeowater depth. The Mn and Fe contents of the Bagong Formation mudstones in the Tielong Section range from 465–790 ppm (avg. of 613 ppm) and 40,670–49,630 ppm (avg. of 45,866 ppm) ([Supplementary Table S1](#)), respectively; these values are lower than those of the PAAS (852 and 50,260 ppm, respectively). The Mn/Fe ratios of the Bagong Formation mudstones in the study area range from 0.01 to 0.018 (avg. of 0.013; [Supplementary Table S1](#)); these values are generally lower than those of the PAAS (0.016). These results indicate that the water column of the Bagong Formation mudstones in the study area was shallow during the depositional period and was consistent with the oxidizing environment discussed above.

Palaeosalinity is an important aspect of the study of sedimentary palaeoenvironments and a key factor in the preservation of organic matter. The Ba and Sr contents exhibit different geochemical behaviours in nature. In marine systems, Sr can stably exist in dissolved form in the water column for a long time (approximately 2.4 Ma; Krabbenhoft et al., 2010), whereas Ba^{2+} readily combines with SO_4^{2-} to form BaSO_4 precipitates (Tribouillard et al., 2006). In general, the Sr content in seawater is significantly greater than the Ba content, whereas the Ba content in fresh water is greater than the Sr content. Therefore, the Sr/Ba ratio in fine-grained sedimentary rocks is widely used to reconstruct the palaeosalinity of the water column (Meng et al., 2012; Wei and Algeo, 2020; Wang et al., 2022c). In the study area, the Bagong Formation mudstone samples from the Tielong Section have low CaO contents, and no correlation is observed between the CaO and Sr contents ($R = 0.16$; $n = 31$); these results indicate that the Sr content is not affected by carbonate minerals. Recently, Wei and Algeo (2020) conducted a statistical analysis and proposed that the optimal thresholds of Sr/Ba in freshwater and saltwater are 0.2 and 0.5 (Remírez and Algeo, 2020), respectively. Specifically, Sr/Ba ratios < 0.2 indicate a freshwater environment, values of 0.2–0.5 represent a brackish environment, and values > 0.5 reflect a saline environment. The Sr/Ba ratios of 31 mudstone samples from the Bagong Formation in the study area range from 0.14 to 0.19 (avg. of 0.16; Supplementary Table S3), indicating a freshwater environment during their deposition. However, a significant positive correlation is observed between the Ba content (excluding sample TL-31) and the Al_2O_3 content of the Bagong Formation mudstone samples ($R = 0.88$, $n = 30$; Supplementary Table S2); these results indicate that the Ba content in the samples is derived mainly from terrigenous detrital input, resulting in a low Sr/Ba ratio in the samples. Therefore, the mudstones in this study may have formed in a brackish to saline environment.

Rb/K is another important indicator for reconstructing palaeosalinity. Generally, $\text{Rb/K} < 0.0028$ indicates a freshwater environment, $0.0028 < \text{Rb/K} < 0.004$ indicates a brackish environment, and $\text{Rb/K} > 0.004$ indicates a saline environment (Zhang et al., 2024). In the study area, a significant positive correlation is observed between the Rb and K contents of the Bagong Formation mudstone samples from the Tielong Section ($R = 0.96$, $n = 31$; Supplementary Table S2); thus, they have the same properties and sources, and their ratios can effectively reflect the salinity of the water column. The Rb/K values of the 31 mudstone samples from the Bagong Formation in the study area range from 0.005 to 0.006 (avg. 0.0055; Supplementary Table S3); these results indicate that the Bagong Formation mudstones formed in a saline environment (Figure 11). On the basis of the Sr/Ba–Rb/K discriminant diagram, the Bagong Formation mudstones in the Tielong Section were deposited in a saline environment (Figure 12f).

5.4 Genetic mechanism of the black mudstones in the Bagong formation

The mudstones of the Upper Triassic Bagong Formation in the Tielong Section in the eastern North Qiangtang Depression exhibit large fluctuations in TOC contents (0.47%–1.73%, avg. of

0.87%), with vertically differentiated organic matter enrichment. Research has shown that organic matter enrichment in mudstones is a complex process involving the interaction of multiple factors, including the palaeoproductivity of the surface water column, redox degree of the bottom water column, salinity stratification, sedimentation rate, and detrital input (Canfield, 1994; Sageman et al., 2003; Katz, 2005; Wei et al., 2012; Wang et al., 2017). However, the factors controlling organic matter enrichment vary under different depositional settings; thus, the organic matter enrichment process is a subject of ongoing debate.

The palaeoclimate largely affects the chemical weathering of rocks and the growth and reproduction of organic matter in the provenance area (Carroll and Bohacs, 1999; Meng et al., 2012; Ma et al., 2015) and thus controls the organic matter content in the mudstone sedimentation process. Palaeoclimate indicators (C value, Sr/Cu and Rb/Sr ratios, and CIA) reveal that the palaeoclimate during the deposition of the Bagong Formation mudstones in the Tielong Section was generally warm and humid. The TOC contents of almost all the Bagong Formation mudstone samples in the study area are significantly negatively correlated with the palaeoclimate indicator of Sr/Cu ($R = -0.63$, $n = 29$; Figure 13a) and significantly positively correlated with Rb/Sr ($R = 0.66$, $n = 24$; Figure 13b), the C value ($R = 0.71$, $n = 30$; Figure 13c), and the CIA ($R = 0.75$, $n = 24$; Figure 13d); these results indicate that organic matter enrichment was mainly controlled by warm and humid climate condition and that these conditions were conducive to the growth and reproduction of organisms and thus promoted the enrichment of organic matter. Additionally, in a warm and humid climate, owing to the input of a large amount of fine-grained argillaceous detritus (the Al content is high) and a small amount of coarse-grained felsic terrigenous detritus (the contents of Si, Ti, and Zr are low), overall, the depositional period of the Bagong Formation mudstones occurred because the adsorption rate of the organic matter by argillaceous detritus exceeded the dilution rate of organic matter by felsic detritus, and the large specific surface area of clay minerals enhanced their ability to protect organic matter (Li et al., 2025); this reasoning is supported by the significant positive correlation between the TOC content and the Al_2O_3 content ($R = 0.67$, $n = 24$; Figure 13e) and the significant negative correlation between the TOC content and the SiO_2 content ($R = -0.68$, $n = 24$; Figure 13f) in most mudstone samples.

In addition, redox conditions and sedimentation rates are important factors controlling the preservation of organic matter. A comprehensive analysis of multiple redox indicators ($U_{\text{EF}}\text{--Mo}_{\text{EF}}$, U/Th , V/Cr , Ni/Co , $C_{\text{org}}/P_{\text{tot}}$, and δCe) reveals that the Bagong Formation mudstones in the study area were deposited in an oxidizing environment. However, a fast sedimentation rate in an oxidizing environment is usually beneficial for the preservation of partly organic matter since it effectively shortens the contact time between the organic matter and oxygen, accelerates the accumulation of organic matter, and consequently enables the rapid burial and preservation of partly organic matter (Tyson, 2001; Ding et al., 2015; Wang et al., 2017; Li et al., 2025). The sedimentation rate can be characterized by the $(\text{La/Yb})_{\text{N}}$ (the subscript N indicates PAAS-normalized) value of the REEs; here, a value significantly greater than or less than one indicates a slow sedimentation rate, and a value close to 1.0 indicates a fast sedimentation rate (Tenger et al., 2006). The $(\text{La/Yb})_{\text{N}}$ values of the 31 mudstone samples from the

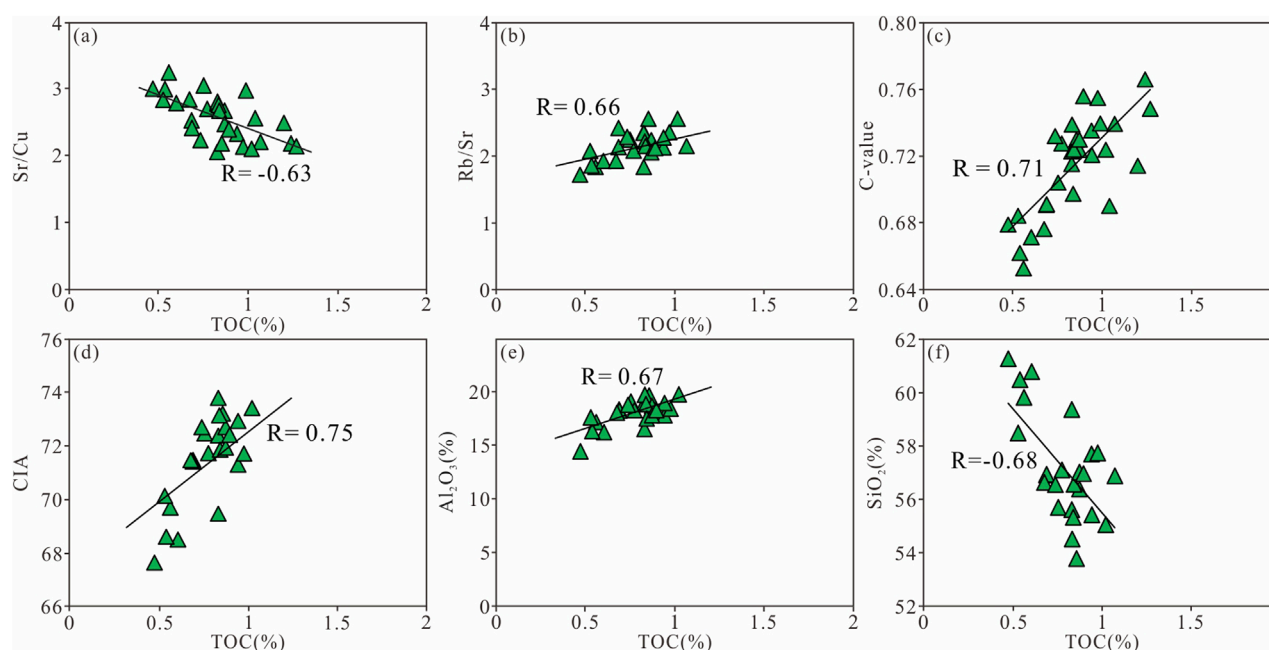


FIGURE 13
Relationship between TOC content and paleoclimate (C value, Sr/Cu, Rb/Sr ratios and CIA value) and terrigenous influx (Al_2O_3) of the Bagong Formation mudstones from the Tielong section, Eastern Qiangtang Basin.

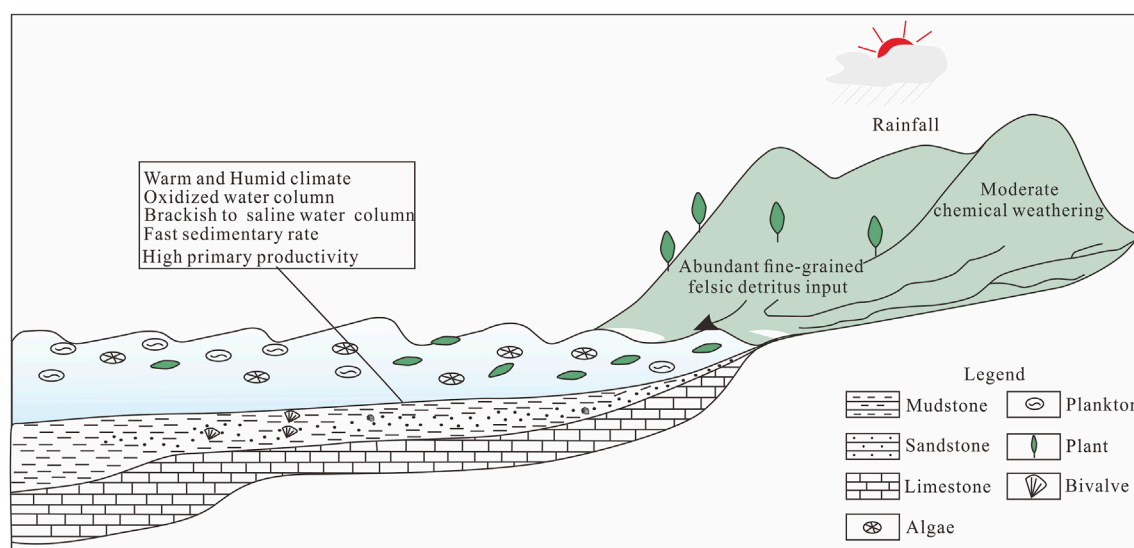


FIGURE 14
Sketch of a sedimentary model for the Bagong Formation mudstones from the Tielong section, Eastern Qiangtang Basin (modified after Yu et al., 2019).

Bagong Formation in the study area range from 0.85 to 1.15 (avg. of 0.98; [Supplementary Table S4](#)) and are predominantly concentrated at approximately 1.0 for most samples ([Figure 11](#)); these results indicate an overall high sedimentation rate of the Bagong Formation mudstones in the Tielong Section during the depositional period. The high sedimentation rate in an oxidizing water column caused the burial rate of the organic matter to exceed its degradation rate. Several organic matter was degraded by aerobic bacteria during the

burial process, and consequently only a portion of the organic matter was preserved.

In summary, the warm and humid palaeoclimate and rapid sedimentation rate were the main factors controlling the enrichment of organic matter in the Upper Triassic Bagong Formation mudstones in the Tielong Section. On the one hand, warm and humid palaeoclimate conditions promoted the proliferation of organisms, enhancing the palaeoproductivity of the water

column; on the other hand, compared with the diluting effect of coarse-grained felsic terrigenous detritus, the input of fine-grained clayey terrigenous detritus resulted in a stronger adsorption effect on organic matter and led to the preservation of partly organic matter. In addition, although the oxidizing environment led to the degradation of most organic matter, a small amount of organic matter was buried due to rapid sedimentation. As a result, overall, the Bagong Formation mudstones in the Tielong Section had relatively low organic carbon contents during their depositional period (Figure 14).

6 Conclusion

- (1) The comprehensive analysis of the La/Th-Hf, Co/Th-La/Sc, Cr/Th-Sc/Th, Th/Sc-Zr/Sc, A-CN-K and La/Yb-ΣREE discriminant diagrams and the presence of significant negative Eu anomalies indicate that the provenance of the Bagong Formation in the Tielong Section in the eastern North Qiangtang Depression was mainly felsic rocks. The multidimensional discriminant diagram of the tectonic setting established using the major elements revealed that the Bagong Formation mudstones in the Tielong Section were all deposited in a collisional tectonic setting; this result was consistent with the tectonic regime of the early Late Triassic intracontinental compression in the North Qiangtang Depression.
- (2) On the basis of multiple palaeoclimate indicators (C value, Sr/Cu and Rb/Sr ratios, and CIA), the depositional period of the Bagong Formation mudstones in the Tielong Section was generally characterized by a warm and humid climate, with a large amount of fine-grained detritus (with a high Al content) and a small amount of coarse-grained felsic terrigenous detritus (with low Si, Ti, and Zr contents).
- (3) On the basis of the comprehensive analysis of the U_{EF} - Mo_{EF} cross-plots, the U/Th, V/Cr, Ni/Co, and C_{org}/P_{tot} ratios and negative Ce anomalies indicate that the Bagong Formation mudstones in the Tielong Section were deposited in an oxidizing environment; additionally, the low Mn/Fe ratio and relatively high Rb/K ratio indicate that the Bagong Formation mudstones in the study area were deposited in a shallow saline environment.
- (4) A warm and humid palaeoclimate and a rapid sedimentation rate were the main factors controlling organic matter enrichment in the Upper Triassic Bagong Formation mudstones in the Tielong Section. The warm and humid palaeoclimatic conditions promoted the massive proliferation of organisms and the input of fine-grained clayey terrigenous detritus, which led to the adsorption and preservation of partly organic matter. Moreover, a small amount of organic matter was buried in the oxidizing environment because of rapid sedimentation. Since most of the organic matter was degraded during the above processes, the Bagong Formation mudstones in the study area generally have low organic carbon contents.

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 author.

Author contributions

QP: Writing – review and editing, Writing – original draft, Investigation, Resources, Data curation. BD: Data curation, Investigation, Writing – review and editing, Resources. JP: Writing – review and editing, Writing – original draft. ZL: Investigation, Software, Resources, Writing – review and editing. PD: Investigation, Resources, Writing – review and editing.

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Conflict of interest

The 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.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feart.2025.1596376/full#supplementary-material>

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