Application of GEM Elemental Capture Logging in the Identification of Paleodepositional Environments in Shale Reservoirs

Authors: Li Bin, Dong Zhenguo, Luo Qun, Li Bin

Date: 2024-04-09T00:00:00+00:00

Abstract

Element capture logging can obtain the elemental content of rocks in formations. To investigate the development and distribution patterns of shale gas reservoirs, taking the first shale gas parameter well BY2 in the Cambrian Niutitang Formation of the Baojing block in the Middle Yangtze region as the research object, through interpretation and processing of element capture logging data, the precise elemental composition and content of the shale reservoir were obtained, a geochemical indicator profile for the Niutitang Formation was established, and element geochemical indicators were utilized to conduct identification and inversion of the paleo-sedimentary environment. The research results indicate that: elements in the Niutitang Formation shale are dominated by Si, Al, and Fe, with minor amounts of K, Ca, Mg, S, etc.; the shale has relatively high contents of Si, Fe, S and other elements, indicating good fracability; the Niutitang Formation shale belongs to active continental margin deposition, the original material of the sedimentary source rocks should have come from the Kangdian paleo-land in the northwest, basically being normal deposition in an active continental tectonic belt with hydrothermal participation; during the deposition period of the upper Niutitang Formation, the climate was dry, representing anoxic stagnant basin margin gentle slope deposition with high water salinity, sufficient terrestrial supply, and low paleo-productivity; during the deposition period of the lower Niutitang Formation, the climate was humid, representing deep-water stagnant basin deposition with insufficient terrestrial supply, relatively high water salinity, and high paleo-productivity, which was conducive to organic matter formation, the water environment was dominated by oxygen-poor facies, which was favorable for organic matter preservation, representing a favorable sedimentary environment for shale gas formation and enrichment.

Full Text

Preamble

Funding: Supported by the National "973" Project "Genetic Mechanism and Fine Characterization of Continental Tight Oil Sweet Spots" (No. 2015CB250901) and the Doctoral Startup Project of Hanshan Normal University in 2021 "Fine Description of Silurian Longmaxi Formation Shale Gas Reservoirs and Mechanism of Shale Gas Enrichment in Baojing Area" (No. QD202106).

First Author: LI Bin, male, born in 1970, received his Ph.D. from China University of Geosciences (Beijing) in 2009. His research focuses on sedimentology, wireline logging, and geological-geographic information systems. E-mail: 20200034@hstc.edu.cn.

Received: July 20, 2023; Revised: September 7, 2023

Application of GEM Elemental Capture Logging in Paleosedimentary Environment Identification of Shale Reservoirs

LI Bin[1], **DONG Zhenguo**[2], **LUO Qun**[3]
[1]Hanshan Normal University, Chaozhou 521014, China
[2]Shenhua Geological Exploration Ltd., Beijing 102211, China
[3]China University of Petroleum (Beijing), Beijing 102249, China

Abstract

Background: Elemental capture logging can determine the elemental composition of rocks in formations. **Purpose**: This study focuses on the BY2 well, the inaugural parameter well for shale gas in the Cambrian Niutitang Formation of the Baojing Block in the Middle Yangtze region, aiming to investigate the developmental and distributional characteristics of shale gas reservoirs. **Methods**: By interpreting and processing elemental capture logging data, precise elemental compositions of the shale reservoirs were determined, leading to the creation of a comprehensive geochemical index profile for the Niutitang Formation. Elemental geochemical indicators were then employed to identify and reconstruct the paleosedimentary environments. **Results**: The analysis revealed that the predominant elements in the Niutitang Formation shale are Si, Al, and Fe, with lesser amounts of K, Ca, Mg, and S. The shale features relatively high concentrations of Si, Fe, and S, contributing to enhanced fracturing potential. The sedimentation is categorized as active continental margin deposition, with source materials originating from the Kangdian ancient landmass to the northwest. The deposition was primarily normal but influenced by hydrothermal fluids in the region' s active tectonic zone. **Conclusions**: The upper section of the Niutitang Formation experienced a dry climate during deposition, charac-

terized by gentle slope sedimentation at the periphery of a stagnant basin under anoxic conditions, with high water salinity, ample terrestrial supply, and low paleoproductivity. In contrast, the lower section experienced a humid climate and represented a deep-water retention basin with limited terrestrial supply but high water salinity and paleoproductivity, favorable for organic matter formation. The aquatic setting was primarily anaerobic, creating conditions conducive to organic matter preservation and providing an optimal sedimentary environment for shale gas generation and enrichment.

Keywords: Shale reservoir; Elemental logging; Interpretation and processing; Geochemistry; Depositional environment

Introduction

Shale gas represents a promising clean energy source with vast application potential. Currently, China' s proven shale gas reserves account for only 4.79% of total resources, indicating enormous development potential. After more than a decade of technological 攻关 and exploration, China has achieved major breakthroughs in shale gas production, reaching 25 billion cubic meters in 2023, making it the world' s second-largest shale gas producer. The main domestic shale gas fields are located in the Sichuan Basin, while the Xiangxi (western Hunan) region outside the Sichuan Basin has become a key exploration area in recent years. This region features favorable geological conditions for shale development and organic-rich formations, but also faces challenges including complex surface and subsurface geological conditions, high thermal evolution, poor reservoir physical properties, and difficult exploration and development.

Unlike conventional hydrocarbon resource evaluation, assessing shale gas potential requires studying both mineral composition and depositional environment. Mineral composition forms the basis for high-quality reservoir development, while depositional environment controls the spatial distribution of reservoirs. Therefore, using elemental geochemical characteristics to reconstruct paleosedimentary environments is essential for understanding reservoir quality, fracability, and spatial development features. Characteristic parameters of shale reservoirs obtained through elemental logging interpretation and processing can support geological research and paleosedimentary environment reconstruction.

Since the 1970s, geochemical methods have been used to analyze tectonic settings, geotectonic backgrounds, and metallogenic environments. Rock geochemical analysis has been widely promoted and applied in mineral exploration, scientifically guiding mineral prospecting and development. In recent years, with the exploration and development of complex hydrocarbon reservoirs and unconventional reservoirs, their evaluation and analysis have become increasingly important. Li Zhoubo et al. [?] demonstrated that formation elemental capture logging plays a special role in establishing lithological profiles, understanding elemental abundance and mineral composition variations, and reconstructing geochemical profiles. Yuan Zugui [?] utilized elemental capture logging to detect formation element contents and analyze elemental content and assemblage relationships, providing a basis for depositional environment studies. Halliburton developed the Gamma Elemental Mineralogical Analysis Logging Tool (GEM). Yang Xingqin et al. [?] showed that formation elemental analysis logging can solve problems in mineral composition measurement and lithology identification for reservoirs. Through oxide closure model processing and interpretation, formation mineral contents can be obtained, enabling identification of minerals in complex reservoirs. Liao Dongliang [?] established elemental capture logging response equations, using inversion methods to determine mineral types, calculate mineral content, matrix density, and brittleness index, enabling evaluation of mineral composition and content in shale formations to guide fracturing design and operations. Zhang Xin et al. [?] used rigid mineral content obtained from GEM logging interpretation to evaluate "brittle" mineral content in formations, providing a basis for selecting test and fracturing intervals. Fan Yunfeng et al. [?] established mineral content calculation models to obtain fine lithological characteristics of shale oil reservoirs for comprehensive evaluation.

Since 1998, although elemental capture logging has made progress and achieved many results in petroleum exploration, its applications have primarily focused on lithology identification and stratigraphic correlation in conventional sand-shale profiles. Application data and literature on unconventional shale reservoir depositional environment identification and formation evaluation remain scarce, particularly regarding systematic studies of paleoclimate, paleosalinity, and paleosedimentary environments using elemental logging.

Elemental capture logging can obtain rock element contents in formations, offering advantages of continuous data, high efficiency, and low cost compared to core testing and analysis. Therefore, shale gas evaluation and analysis methods centered on elemental capture logging can provide substantial useful information for shale gas exploration and development. In recent years, elemental capture logging has experienced rapid development and wide application in North American shale reservoir evaluation. GEM can directly measure major formation elements such as Mg, Al, Si, S, K, Ca, Ti, Mn, Fe, and Gd, which primarily originate from upper crustal sources through terrigenous, chemical, and biological deposition. These elements can indicate depositional conditions and possess clear facies significance, aiding shale depositional environment research and favorable area selection for shale reservoirs.

Based on GEM logging results from the Baojing shale gas block and calibrated with core analysis data, this study obtained shale mineral composition and elemental assemblage characteristics. Using these as a foundation, we analyzed and evaluated the tectonic background and depositional environment of the study area' s shale gas to provide a scientific basis for fine exploration and large-scale development of shale gas in this region.

1 Geological Overview

The Baojing shale gas block is located tectonically on the western margin of the Middle Yangtze paraplatform within the Xiang-Exi (western Hunan-western Hubei) trough-like thrust-fold belt, spanning the Yidu-Hefeng composite anticline and Sangzhi-Shimen composite syncline. The primary shale gas exploration target in the area is the Majizhai-Yezhuping syncline, with drilling targets mainly focusing on the Longmaxi and Niutitang formations. In recent years, eight wells have been drilled in this block, four of which underwent elemental capture logging. The primary purpose of elemental capture logging is to determine mineral content in formations to provide a basis for lithology identification, reservoir evaluation, and depositional environment reconstruction. This study uses the BY2 vertical exploration well in the Baojing block as an example.

The BY2 well is located 200 m north of Xinqiao Village, Angdong Township, Baojing County, Xiangxi Prefecture, Hunan Province. Structurally, it lies on the eastern flank of the Majizhai-Yezhuping syncline in the Hunan Baojing shale gas area. As the first deep shale gas exploration well in the Baojing block, it was designed to a depth of 3,217 m but was drilled to 3,275 m. The elemental logging interval covered 2,522.32–3,275 m, with the geological target being the Lower Cambrian Niutitang Formation.

2.1 Principle of Elemental Capture Logging

Halliburton' s GEM elemental capture spectroscopy logging tool employs an americium-beryllium neutron source to emit 4 MeV fast neutrons into the formation. These fast neutrons primarily undergo inelastic scattering with formation nuclear elements, releasing gamma rays. After multiple scattering events, they slow down to thermal neutrons, which are captured by formation elements and emit capture gamma rays [?] (Fig. 1 [Figure 1: see original paper]). The energy and quantity of gamma rays depend on specific nuclear elements, with each element possessing a unique capture gamma ray characteristic spectrum. GEM records these inelastic and capture gamma rays using a bismuth germanate ($Bi_4Ge_3O_{12}$, BGO) crystal detector, obtains measurement spectra for various elements, and through spectral analysis and processing, determines the mass percentages of formation elements and corresponding mineral volume percentages [?].

2.2 Measurement of Formation Elements

Geochemical analysis indicates that more than 90 chemical elements exist naturally in the Earth' s crust. Major elements include oxygen (O) at 46.6%, silicon (Si) at 26.75%, aluminum (Al) at 8.13%, iron (Fe) at 5%, calcium (Ca) at 3.65%, sodium (Na) at 2.83%, potassium (K) at 2.59%, and magnesium (Mg) at 2.09%. These eight major elements account for 98.59% of the mass of crustal elements.

Additionally, certain elements serve as indicators of typical minerals (Table 1

). For example, quartz is rich in silicon, dolomite and calcite contain calcium, gypsum and pyrite contain sulfur, and clay components such as kaolinite are rich in aluminum. Therefore, by measuring major element contents and establishing relationships between elemental mass percentages and mineral composition percentages through processing and interpretation methods, qualitative and quantitative analysis of reservoir mineral composition can be performed [?].

2.3 Instrument Structure of the GEM Elemental Capture Logging Tool

The GEM instrument consists of two parts: an upper electronic section and a lower measurement probe (Fig. 2 [Figure 2: see original paper]). The tool emits fast neutrons into the formation using a 15Ci americium-beryllium isotopic neutron source housed in a source chamber. It employs BGO for acquisition of inelastic and capture gamma rays, with a thermal neutron shield covering the BGO crystal to prevent direct neutron interaction with the BGO [?]. BGO converts gamma rays into fluorescence, enabling indirect gamma ray detection. Due to GEM' s enlarged BGO crystal probe with sensitive photopeak identification, it can directly measure elements with small capture cross-sections such as magnesium and aluminum.

GEM represents a new generation of geochemical elemental logging tools with wide applicability, capable of operating in various well conditions and high-temperature, high-pressure environments (Table 2).

3 GEM Logging Interpretation

3.1 Logging Information

To accurately evaluate shale reservoir quality characteristics and obtain mineral composition content, GEM elemental capture logging was conducted in the Ø215.9 mm third-opening section (2,510–3,270 m) of the BY2 well. The wellbore contained water-based drilling fluid (mud density 1.19 $g \cdot cm^{-3}$, mud resistivity 0.56 $\Omega \cdot m$ at 18 °C). Through logging processing and interpretation, GEM elemental spectral curves were obtained. Combined with regional stratigraphic data and outcrop lithological characteristics, quantitative analysis of formation mineral composition was performed, providing mineral and fluid volume percentage data.

GEM interpretation results were calibrated using core X-ray diffraction (XRD) analysis data to improve the precision and accuracy of logging interpretation. Based on regional geological data and core testing, the main minerals in the BY2 well formation are quartz, feldspar, illite, chlorite, pyrite, kerogen, calcite, and dolomite.

3.2.1 Selection of Minerals and Fluids

The GEM logging interval in the BY2 well covers the Lower Cambrian Shipai Formation ($_1$s) to the Doushantuo Formation (Z_2d). The Niutitang Formation features well-developed black mudstone/shale, is rich in organic matter, and contains high quartz mineral content, making it a favorable hydrocarbon source rock with certain shale gas exploration potential (Table 3).

To obtain accurate elemental logging interpretation results and elemental abundance characteristics, the GEM logging interpretation model and mineral selection referenced BY2 well core XRD analysis data. Mineral volume percentages obtained from core analysis were used to calibrate elemental logging interpretation, ensuring GEM logging results essentially matched core-analyzed mineral volume percentages (Fig. 3 [Figure 3: see original paper]).

Core XRD analysis shows Niutitang Formation mineral content is dominated by quartz and clay minerals, with locally developed carbonate minerals. Quartz content ranges from 7.9% to 81.3%, potassium feldspar 0–9.6%, plagioclase 0–14.1%, calcite 0–70.8%, dolomite 14.8%, pyrite 3.8%–14.8%, and clay minerals 4.6%–44.1%. Overall, quartz content increases while carbonate minerals decrease from top to bottom (Fig. 4 [Figure 4: see original paper]).

Clay mineral analysis indicates that clay minerals are primarily illite and illite-smectite mixed layers, with illite content of 64%–97%, illite-smectite mixed layers 2%–39%, and chlorite 0–14% (Fig. 4 [Figure 4: see original paper]).

Based on the above information, selected mineral components include kerogen, quartz, feldspar, calcite, dolomite, pyrite, and illite (or illite-smectite mixed layers). Other minerals such as montmorillonite were excluded due to trace amounts and relative instability. Silicon primarily occurs in quartz and illite, aluminum in illite, calcium in plagioclase, calcite, and dolomite, magnesium in dolomite, and iron in chlorite and pyrite. As this is a shale gas well, fluid types selected were gas and water.

3.2.2 GEM Logging Interpretation

1) Upper Niutitang Formation (3,071–3,114 m): Lithology consists of argillaceous limestone interbedded with calcareous mudstone. GEM interpretation results show low clay mineral content, reduced quartz and feldspar content, and increased carbonate mineral content, consistent with core analysis. Rock chemical composition is characterized by low Si (18.97%) and high Ca (15.85%), with Fe (2.69%), Mg (2.11%), Al (2.01%), and S (1.63%) elements, plus trace Ti and Mn. High Ca and Mg contents reflect developed calcareous shale, while high S content indicates an anoxic environment.

2) Lower Niutitang Formation (3,114–3,171.5 m): Lithology consists of mudstone and carbonaceous mudstone. GEM interpretation results show high kerogen content, consistent with core analysis, representing the primary shale gas target interval. Rock chemical composition is characterized by high

Si (34.41%) and low Ca (2.72%), with Al (4.15%), Fe (3.21%), Mg (0.27%), and S (1.78%) elements, plus trace Ti and Mn. High Al indicates developed argillaceous shale and significantly increased terrestrial clastic material sources with abundant organic matter.

Rock chemical composition changes substantially from top to bottom in the Niutitang Formation, with increasing Si, Al, Fe, and S contents and decreasing Ca and Mg contents, indicating a transition from calcareous shale to argillaceous shale with deepening depositional water. Quartz, pyrite, and other brittle minerals increase in the shale, improving reservoir fracability (Table 4 , Fig. 5 [Figure 5: see original paper]).

Black shale, being pure and brittle, rich in organic matter, sulfides, and graptolite fossils, typically forms in anoxic stagnant water environments, preserving paleoecological and original paleoclimatic information from geological history. Different elements respond differently to depositional environments and redox conditions, making elemental contents and ratios in sediments useful parameters for reconstructing paleoclimate, paleosalinity, and paleo-oxygenation environments. Elemental ratios and diagrams can effectively reflect source area characteristics and tectonic backgrounds, providing evidence for paleogeographic environment reconstruction [**?**].

4.1 Source Area Tectonic Background

Tectonic background is the primary factor controlling sediment weathering, transport, and deposition in basins, significantly influencing sedimentary rock grain size, mineral composition, and elemental composition. Si, Al, and Ti are generally stable in seawater and can indicate terrigenous clastic input, while Fe and Mn are sensitive to water quality changes and serve as indicators of hydrothermal participation. The ω(Al/Si) ratio is commonly used to determine quartz enrichment and source type in sedimentary rocks, while the ω(Al)/ω(Al+Fe+Mn) ratio can identify hydrothermal sources [**?**].

Sediments from active continental margins show significantly higher Fe, Mg, and Al/Si contents than those from passive continental margins. The Fe+Mg–Ti and Fe+Mg–Al/Si diagrams can be used to discriminate the tectonic background of sediment source areas [**?**]. Niutitang Formation samples plot within the active continental margin region on both Fe+Mg–Ti and Fe+Mg–Al/Si diagrams (Fig. 6 [Figure 6: see original paper]), indicating that the provenance tectonic background is primarily related to active continental margins. According to regional data, during the Early Cambrian Longwangmiao period to Middle Ordovician, the Kangdian uplift at the northwestern end of the study area experienced small-scale uplift, presenting a paleogeographic pattern of high northwest and low southeast. The Kangdian ancient land in the northwest contained a provenance area composed of intermediate volcanic rocks, suggesting that the source material likely originated from the Kangdian ancient land to the northwest.

4.2.1 Silica-Alumina Coefficient ω(Si/Al) and Alumina-Titania Coefficient ω(Al/Ti)

The Niutitang Formation lithology is primarily mudstone, shale, marl, and limestone with mixed sedimentation characteristics. The ω(Si/Al) and ω(Al/Ti) coefficients can be used to determine source rock types. Previous studies suggest that Si/Al in the continental crust is approximately 3.6. When $\omega(\text{Si/Al}) \leq 3.6$ in sedimentary rocks, it indicates primarily terrigenous provenance, whereas values exceeding 3.6 suggest biological or hydrothermal supplementation. When ω(Al/Ti) ranges from 8 to 21, it indicates provenance from intermediate (mafic) rocks, while $\omega(\text{Al/Ti}) > 21$ indicates provenance from basic (felsic) rocks [?]. The Niutitang Formation shows $\omega(\text{Si/Al}) = 8.29$–$9.44$ (average 8.87), indicating biological or hydrothermal sediment participation, and $\omega(\text{Al/Ti}) = 5.43$-$17.29$ (average 11.36) with relatively stable distribution, indicating that the parent rock primarily originated from intermediate sedimentary rocks with influence from deep magnesium-rich granite provenance (Fig. 7 [Figure 7: see original paper]).

4.2.2 ω(Al)/ω(Al+Fe+Mn) Ratio

Continental margin sediments account for over half of total marine sediments, with ω(Al)/ω(Al+Fe+Mn) ratios greater than those of oceanic basin and mid-ocean ridge sediments [?]. The upper Niutitang Formation shows $\omega(\text{Al})/\omega(\text{Al+Fe+Mn}) = 0.43$, falling within the range of deep-water oceanic basin sediments, while the lower section shows $\omega(\text{Al})/\omega(\text{Al+Fe+Mn}) = 0.56$, within the continental margin sediment range. This indicator suggests that Niutitang Formation sediments primarily exhibit characteristics of continental margin and deep-water oceanic basin depositional environments (Table 5 , Fig. 8 [Figure 8: see original paper]). Th and U data in Fig. 8 are derived from natural gamma spectroscopy logging.

4.2.3 Depositional Conditions

Hydrothermally influenced sediments are typically enriched in Si, Fe, and Mn but depleted in Al, Ti, K, and Na. Rona [?] utilized the ω(Fe/Ti) ratio to distinguish between hydrothermal and normal marine sediments, with ω(Fe/Ti) > 20 generally indicating hydrothermal origin. The upper Niutitang Formation shows average $\omega(\text{Fe/Ti}) = 7.27$, while the lower section shows average ω(Fe/Ti) $= 13.38$, significantly higher than the upper section. Specifically, the interval 3,133–3,153 m shows $\omega(\text{Fe/Ti}) > 20$, suggesting normal deposition in the upper section and hydrothermally influenced deposition in the lower section. Proximity to the Baojing-Cili fault zone likely facilitated deep crustal fluid mixing through deep fractures, with hydrothermal activity bringing nutrient-rich fluids to surface waters, promoting biological development and prosperity. The ω(Th/U) ratio is an effective indicator of hydrothermal activity [?], with hydrothermal activity typically showing $\omega(\text{Th/U}) < 1$. The lower Niutitang Formation predominantly shows $\omega(\text{Th/U}) < 0.5$, further confirming hydrothermal sediment influence in the lower section.

4.2.4 Index of Compositional Variability

Cox et al. noted that potassium metasomatism during diagenesis and recycled sedimentation of clastic rocks can alter composition, necessitating discrimination of recycled deposition. The Index of Compositional Variability (ICV) can determine whether fine-grained clastic rocks are recycled sediments, defined by Equation (1):

$$ICV = \frac{\omega(Fe + K + Na + Ca + Mg + Mn + Ti)}{\omega(Al)}$$

When ICV > 1, the sample contains few clay minerals, indicating first-cycle deposition in an active tectonic belt. When ICV < 1, the sample contains abundant clay minerals, suggesting possible recycled deposition. ICV values from this study show the upper Niutitang Formation with ICV $= 11.32$ (average) and the lower section with ICV $= 2$ (average), with the upper section showing significantly higher values. Higher ICV values represent first-cycle deposition in active tectonic belts without sediment recycling, effectively indicating source rock composition.

4.3.1 Chemical Weathering Intensity

The upper crust is primarily composed of quartz, feldspar, and other minerals. During chemical weathering, feldspar minerals weather gradually, with alkali metals such as K, Na, and Ca being leached while clay minerals form. Aluminum content in weathering products increases with weathering intensity. Based on this, Nesbitt and Young [**?**] proposed the Chemical Index of Alteration (CIA) to characterize weathering degree in source areas, expressed by Equation (2):

$$CIA = \left[\frac{\omega(Al)}{\omega(Al + Ca^* + Na + K)}\right] \times 100$$

where Ca* represents Ca content in silicate rocks after removing excess Ca.

Chemical weathering intensity varies under different climatic conditions. CIA can reflect chemical weathering conditions in source areas and serves as a good indicator of rock weathering degree, being directly proportional to weathering intensity. When CIA < 65, it indicates low chemical weathering under cold and dry climatic conditions. The upper Niutitang Formation shows CIA $= 10.38$ (average) and the lower section CIA $= 47.7$ (average), with CIA increasing from top to bottom, indicating that the source area experienced initial weathering with increasing intensity.

4.3.2 Paleoclimate Discrimination

Paleoclimate influences elemental abundance and distribution in sediments. Elements such as Si, Al, Ti, and Mn are stable and typically enriched in seawater of warm-humid regions, while Ca, Mg, Na, and K are related to biogenic carbonates formed under dry climates, with abundances significantly increased in nearshore shallow sea areas.

1) C Value: During deposition, elemental abundances can reflect climatic characteristics. In humid climates, elements such as Fe, Mn, Cr, V, Co, and Ni tend to enrich, while in arid climates, evaporation increases water salinity, causing enrichment of Ca, Mg, Sr, Ba, K, and Na. Zhao Zengyi et al. [**?**] proposed using the paleoclimate index C value to determine climate characteristics, expressed by Equation (3):

$$C = \frac{\omega(Fe + Mn + Cr + V + Co + Ni)}{\omega(Ca + Mg + Sr + Ba + K + Na)}$$

When C $<$ 0.4, it indicates semi-arid to arid climate; C $>$ 0.4 indicates semi-humid to humid climate. The upper Niutitang Formation shows C = 0.14 (average) and the lower section C = 0.67 (average), with C values increasing from top to bottom. This indicates that the upper section was deposited under cold, dry paleoclimate conditions, while the lower section experienced warm, humid paleoclimate conditions.

2) ω(Al/Mg) Ratio: The ω(Al/Mg) ratio in sediments reflects paleoclimate during deposition, with high values typically corresponding to warm-humid climates and low values to dry-hot climates. The upper Niutitang Formation shows ω(Al/Mg) = 0.95 (average), reflecting dry-hot climate characteristics, while the lower section shows ω(Al/Mg) = 15.37 (average), reflecting humid climate characteristics.

4.3.3 Paleosalinity

1) m Value and n Value: Elements such as K, Na, Ca, P, Fe, Mn, Mg, Al, and Cl in rocks can be used for paleosalinity discrimination. Typically, K, Na, Ca, and Mg contents increase with water salinity, while Fe^{2+} decreases with increasing salinity.

Magnesium in rocks primarily represents products of strong evaporation in saline environments, while aluminum precipitates as Al_2O_3 only when certain salinity exists in water. Therefore, the m value ω(Mg/Al) serves as a sensitive indicator for paleosalinity discrimination [**?**]:

$$m = 10^2 \times \frac{\omega(Mg)}{\omega(Al)}$$

Iron is a common rock-forming element with distinct variable valence characteristics. Fe exists as dissolved Fe^{2+} in reducing and acidic environments and precipitates as Fe^{3+} in oxidizing and alkaline environments. The ω(Ca)/ω(Ca+Fe) ratio in rocks is sensitive to paleosalinity changes, with high values indicating high-salinity environments and low values reflecting freshwater environments. Therefore, the n value (Ca/Fe^{2+}) serves as a sensitive indicator for paleosalinity:

$$n = \frac{\omega(Ca)}{\omega(Ca + Fe^{2+})}$$

The upper Niutitang Formation shows m = 104.98 and n = 0.85, reflecting high-salinity water media, while the lower section shows m = 6.51 and n = 0.46, reflecting moderate-salinity water media.

2) ω(Ca/Mg) Ratio: Due to magnesium salts being more difficult to precipitate than calcium salts, Ca is more enriched than Mg during chemical sedimentary differentiation. During mechanical sedimentary differentiation, as grain size decreases, water depth increases, salinity rises, and alkalinity strengthens, the ω(Ca/Mg) ratio shows an increasing trend. Therefore, the ω(Ca/Mg) ratio positively correlates with salinity and alkalinity and can be used to determine paleosalinity and pH conditions. The Niutitang Formation shows ω(Ca/Mg) = 8.79 (average), reflecting saline and alkaline water media.

4.4 Paleo-oxygenation Facies

Shale elements are primarily composed of Si, Al, Fe, and other elements, with elemental assemblages capable of reconstructing depositional environments and redox conditions. High contents of acidic elements ω(Si, Al, Ti) in shale reflect weakly reducing depositional environments with good mechanical brittleness, while high contents of alkaline elements ω(Fe, Ca, Mg, Mn) reflect strongly reducing depositional environments. Therefore, the acid-base ratio (K) can reflect reduction intensity, calculated using Equation (6), where lower K values indicate stronger reduction [**?**]:

$$K = \frac{\omega(Si + Al + Ti)}{\omega(Fe + Ca + Mg + Mn)}$$

K value calculations indicate that the Niutitang Formation was deposited in a deep-water anoxic environment overall, favorable for organic matter preservation. K values increase from top to bottom, indicating increased quartz content in the lower section and improved shale fracability.

Sulfur is a common element in black shale closely related to depositional environment, typically occurring as pyrite and serving as an excellent indicator of shale formation environment. The Niutitang Formation shale shows S content of 0.017, indicating a reducing environment.

Under reducing conditions, clay and organic matter easily adsorb large amounts of uranium ions during deposition, causing anomalously high uranium content in high-quality shale. Generally, $\omega(\text{Th/U}) < 2$ indicates anoxic environments and marine shale formation. The upper Niutitang Formation shows $\omega(\text{Th/U})$ = 1-4, while the lower section shows $\omega(\text{Th/U}) < 2$, further confirming a marine reducing environment for Niutitang Formation deposition.

4.5 Paleowater Depth

Certain elements show regular dispersion and concentration patterns with water depth changes during deposition. For example, Mn and Al contents increase with water depth, while Fe, Ca, and Mg contents decrease with increasing water depth, providing good indicators of paleowater depth.

Geochemical studies of sedimentary rocks reveal that $\omega(\text{Mn/Fe}) \times 100$ values increase with water depth, while Ca/Fe values decrease with water depth. Therefore, $\omega(\text{Mn/Fe}) \times 100$ and Ca/Fe values can be used to characterize water depth changes. The upper Niutitang Formation shows $\omega(\text{Mn/Fe}) \times 100 = 0.65$ and $\omega(\text{Ca/Fe}) = 6.51$, while the lower section shows $\omega(\text{Mn/Fe}) \times 100 = 0.79$ and $\omega(\text{Ca/Fe}) = 0.92$, indicating shallower water during upper section deposition and deeper water during lower section deposition. Paleowater depth shows a gradual increasing trend from top to bottom, consistent with regional data indicating large-scale marine transgression during this period.

4.6 Paleoproductivity

In high-productivity water bodies, Al is easily adsorbed onto organic matter surfaces and precipitates through complexation. Therefore, high Al content in shale indicates abundant organic matter and high primary productivity. Variations in $\omega(\text{Al/Ti})$ in sediments represent changes in particle settling flux and primary productivity, and the $\omega(\text{Al/Ti})$ ratio can be used to reconstruct primary productivity in different geological periods [**?**].

The upper Niutitang Formation shows lower $\omega(\text{Al/Ti})$, indicating limited organic matter sources and low paleoproductivity during deposition. The lower section shows higher $\omega(\text{Al/Ti})$, comparable to modern river sediment $\omega(\text{Al/Ti})$ ratios, indicating abundant organic matter sources and high paleoproductivity during deposition, creating favorable conditions for high-quality source rock formation (Table 6).

4.7 Discussion of Sedimentary Environment

The Middle Yangtze region formed during the terminal Proterozoic Jinning Movement, with a basement of shallow metamorphosed thick turbidites. During the Sinian to Middle Triassic, the region remained relatively stable, dominated by vertical uplift and subsidence, depositing stable shallow marine-littoral facies clastic and carbonate rocks with several major marine transgressions and regional mineralization events.

During the Early Cambrian, large-scale marine transgression caused seawater to deepen from northwest to southeast, depositing a set of black mudstone formations in the Middle Yangtze region—the Niutitang Formation shale. The depositional environment gradually shallowed laterally, evolving from early deep-water shelf to shallow shelf and tidal flat, though the Hunan Baojing block remained essentially deep-water shelf facies.

During the early Niutitang period, the Baojing block represented an anoxic stagnant basin deposition, primarily consisting of gray-black thin-bedded radiolarian siliceous rock interbedded with black carbonaceous sericite slate (Fig. 9 [Figure 9: see original paper]a–c). The formation contains abundant pyrite nodules and disseminated pyrite grains, relatively high organic carbon, and well-developed horizontal lamination. Occasional agnostid and trilobite fossils occur, with radiolarians concentrated in laminae reaching 20%–40% content. These characteristics indicate a quiet, stagnant, reducing deep-water environment far from terrigenous supply, with high paleoproductivity but limited thickness, suggesting a starved basin nature.

During the late Niutitang period, the Baojing block represented a stagnant basin margin slope clastic-carbonate mixed shelf facies. Lithology includes gray-black nodular argillaceous limestone, bioclastic limestone, intraclastic limestone interbedded with gray-black mudstone, siltstone, and fine-grained calcareous quartz sandstone (Fig. 9 [Figure 9: see original paper]d). This facies had limited organic matter sources and low paleoproductivity but flourishing benthic organisms with abundant trace fossils. Due to unobstructed seawater and sufficient material supply, pyrite essentially disappeared, with carbonates dominated by micritic and intraclastic limestone. Local pressure solution stylolite structures occur, and clastic rocks appear as interbeds within carbonates, developing lenticular, flaser, wedge-shaped, and trough cross-bedding, representing carbonate ramp turbidite sand deposition.

Conclusions

1) The GEM elemental capture logging tool solves the problem of conventional logging data being unable to identify reservoir mineral composition. It can directly measure ten elements in formations including Mg, Al, Si, S, K, Ca, Ti, Mn, Fe, and Gd, which primarily originate from the upper crust through terrigenous, chemical, and biological deposition. These elements can indicate depositional conditions, possess clear facies significance, and aid shale depositional environment research and favorable area selection for shale reservoirs.

2) BY2 well GEM logging interpretation results are essentially consistent with core testing, reflecting the rationality of mineral model selection. According to GEM logging interpretation, shale mineral composition is clearly controlled by depositional facies. The upper Niutitang Formation

shale mineral composition shows "low silica, high calcium" characteristics, while the lower section shows "high silica, low calcium" characteristics. With increasing depositional water depth, shale lithofacies types transition from calcareous shale and mixed shale to siliceous shale. Shale elements are dominated by Si, Al, and Fe, with minor K, Ca, Mg, and S. From top to bottom, Si, Al, Fe, and S contents increase, correspondingly increasing reservoir brittleness index and improving rock fracability.

3) GEM elemental logging provides new methods and ideas for lithofacies paleogeographic research and paleosedimentary environment reconstruction. Using the continuity of GEM elemental logging, a complete Niutitang Formation geochemical index profile was established. Based on shale ω(Al)/ω(Al+Fe) and ω(Fe/Ti) indicators, Niutitang Formation shale source material originated from the Kangdian ancient landmass to the northwest, representing deposition in an active continental margin with hydrothermal participation that can effectively indicate source rock composition. Based on C, m, n, K, ω(Ca/Mg), and ω(Al/Ti) indicators, the upper Niutitang Formation was deposited under dry paleoclimate conditions in an anoxic stagnant basin margin slope environment with high water salinity, sufficient terrestrial supply, and low paleoproductivity. The lower section was deposited under warm-humid paleoclimate conditions in a saline water environment with abundant organic matter sources, high paleoproductivity favorable for organic matter generation, and an anoxic stagnant basin deep-water depositional environment favorable for organic matter preservation, providing the material basis for shale gas enrichment.

4) Currently, GEM elemental capture logging does not provide interpretation and processing of trace elements (such as Cu, V, Ni, Mo, etc.). Applications of elemental capture logging in shale reservoir evaluation have primarily focused on shale element measurement and mineral volume calculation, with insufficient involvement in shale reservoir brittleness and fracability analysis. Shale gas reservoir fracability parameters are mostly estimated using electrical imaging and dipole acoustic logging. With the development and innovation of elemental capture logging methods, it is hoped that these aspects will receive attention and in-depth research in future work.

Author Contributions

LI Bin was responsible for research conception and design, sedimentary environment analysis, and manuscript drafting and final revision. DONG Zhenguo was responsible for data collection and organization, and instrument working principle. LUO Qun was responsible for logging data processing and interpretation, and manuscript modification and polishing.

References

1. LI Zhoubo, WANG Zhuwen. Technique of elemental logging in scientific drilling project[J]. Earth Science Frontiers, 1998, 5(1): 119–130.

2. YUAN Zugui. Using elemental capture spectroscopy (ECS) data to study depositional environment[J]. Nuclear Electronics & Detection Technology, 2005, 25(4): 347–352, 357. DOI: 10.3969/j.issn.0258-0934.2005.04.003.

3. YANG Xingqin, WANG Huan. Formation element logging technology: solving the problem of lithology identification of complex reservoirs[J]. Well Logging Technology, 2011, 35(3): 296. DOI: 10.16489/j.issn.1004-1338.2011.03.021.

4. LIAO Dongliang. Interpretation and application of ECS logging data in shale formations[J]. Petroleum Drilling Techniques, 2015, 43(4): 102–107. DOI: 10.11911/syztjs.201504018.

5. ZHANG Xin, ZHENG Jiakui, WU Du, et al. Application of gamma elemental mineralogical analysis logging in shale oil evaluation of santanghu basin[J]. Xinjiang Oil & Gas, 2019, 15(3): 22–27.

6. FAN Yunfeng, AN Jixing, YUE Aizhong, et al. Shale oil reservoir evaluation based on formation element logging[J]. Well Logging Technology, 2022, 46(5): 563–571. DOI: 10.16489/j.issn.1004-1338.2022.05.010.

7. ZHANG Haoyu, WU Wensheng, XIONG Shitao. Optimal design of neutron gamma logging tool for rock-forming elements[J]. Nuclear Techniques, 2022, 45(9): 090402. DOI: 10.11889/j.0253-3219.2022.hjs.45.090402.

8. ZHANG Li, HAN Xiao, YU Huawei, et al. Lithology affects and correction of neutron porosity logging using D-D source[J]. Nuclear Techniques, 2022, 45(5): 050501. DOI: 10.11889/j.0253-3219.2022.hjs.45.050501.

9. GUO Cong, ZHANG Chong, ZHU Linqi, et al. Method and application of shale brittleness evaluation based on elemental capture spectroscopy logging[J]. Bulletin of Mineralogy, Petrology and Geochemistry, 2017, 36(6): 1040–1047. DOI: 10.3969/j.issn.1007-2802.2017.06.020.

10. ZHAO Jun, XU Shuo, PENG Hao, et al. Improving interpretation accuracy of ECS mineral content with core analysis data[J]. Well Logging Technology, 2018, 42(1): 49–53. DOI: 10.16489/j.issn.1004-1338.2018.01.009.

11. LIU An, LI Xubing, WANG Chuanshang, et al. Analysis of geochemical feature and sediment environment for hydrocarbon source rocks of Cambrian in west hunan-hubei area[J]. Acta Sedimentologica Sinica, 2013, 31(6): 1122–1132. DOI: 10.14027/j.cnki.cjxb.2013.06.014.

12. MAO Ruiyong, ZHANG Jie, LENG Jigao, et al. Geochemical characteristics of rare earth elements and depositional environments of the niutitang

formation black shale in Cen’ gong shale gas block[J]. Journal of Mineralogy and Petrology, 2016, 36(4): 66-73. DOI: 10.19719/j.cnki.1001-6872.2016.04.009.

13. Bhatia M R. Plate tectonics and geochemical composition of sandstones: a reply[J]. The Journal of Geology, 1985, 93(1): 85-87.
14. WU Yuping, LIU Chenglin, GONG Hongwei, et al. Geochemical characteristics and sedimentary tectonic setting of the lower Cambrian niutitang formation in western Hunan Province[J]. Geology and Exploration, 2021, 57(5): 1065-1076. DOI: 10.12134/j.dzykt.2021.05.011.
15. PAN Bo, ZHAO Weibo, LIU Die, et al. Geochemical characteristics of bauxite deposits of Benxi Formation in Shenmu-Mizhi area, Ordos Basin[J]. Natural Gas Geoscience, 2023, 34(6): 1072-1089. DOI: 10.11764/j.issn.1672-1926.2023.01.009.
16. Rona P. Hydrothermal mineralization at oceanic ridges[J]. Canadian Mineralogist, 1988, 26: 431-465.
17. BI Mingliang, LIAO Shen, LI Xiaoyan. Optimization of thorium content determination method in typical associated ore waste residue[J]. Journal of Radiation Research and Radiation Processing, 2023, 41(4): 040701. DOI: 10.11889/j.1000-3436.2023-0024.
18. Nesbitt H W, Young G M. Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations[J]. Geochimica et Cosmochimica Acta, 1984, 48(7): 1523-1534.
19. ZHAO Zengyi, ZHAO Jianhua, WANG Haijing, et al. Distribution characteristics and applications of trace elements in Junggar Basin[J]. Natural Gas Exploration and Development, 2007, 30(2): 30-32, 40, 77. DOI: 10.3969/j.issn.1673-3177.2007.02.007.
20. LI Guoli, CUI Chunlan, DONG Zhenguo, et al. Study on geochemical characteristics and sedimentary paleoenvironment of Yan’ an Formation Coal Seam in Huojitu Mine Field[J]. China Energy and Environmental Protection, 2023, 45(5): 55-63. DOI: 10.19389/j.cnki.1003-0506.2023.05.010.
21. SHE Gang, CHEN Bao, ZHU Hanbin, et al. Reliability and application evaluation of FEM formation element logging tool[J]. Logging Technology, 2020, 44(3): 233-240. DOI: 10.16489/j.issn.1004-1338.2020.03.004.
22. REN Jingling, ZHANG Jing, LIU Sumei. A review on aluminum to titanium ratio as a geochemical proxy to reconstruct paleoproductivity[J]. Advance in Earth Sciences, 2005, 20(12): 1314-1320. DOI: 10.3321/j.issn:1001-8166.2005.12.006.

Note: Figure translations are in progress. See original paper for figures.