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Comprehensive characterization of geological features and reservoir potential of high-quality shale of Wufeng-Longmaxi Formation in the north Guizhou dipping zone, South China

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Abstract

Amid global energy innovation, shale gas exploration is of great significance to China, and stratigraphic information research is paramount for its exploration and development. This study advances theoretical understanding of shale gas accumulation in northern Guizhou, thereby providing solid theoretical support for gas accumulation in the target area. We analyzed the mineralogical, geochemical, and petrological properties of a large number of organic-rich shale samples from the Wufeng-Longmaxi Formation in northern Guizhou. Analyses of the rocks' redox environment reveal that this formation was mainly deposited under anoxic conditions, with most shales being silica-rich and dominated by Type Ⅰ organic matter-confirming their marine origin. Integrating field investigations, experimental analyses, and well logging interpretation, we systematically evaluated the organic geochemical characteristics, reservoir performance, and gas content of shales in the study area. The results show that the Wufeng-Longmaxi shales have high total organic carbon (TOC, average 3.5%), high thermal maturity (vitrinite reflectance, Ro: 2.1%~3.4%), and favorable brittle mineral content (40%~65%), qualifying them as high-quality shale gas reservoirs with viable development potential, while substantial reserves and recoverable volumes of shale gas are predicted around the northern Guizhou syncline swarm. This study shows a high correlation with existing shale wells in the syncline-controlled area, and provides theoretical support for the exploration and accumulation assessment of undeveloped organic-rich shales of the Wufeng-Longmaxi Formation.

Introduction

As the global energy landscape shifts, shale gas has become a significant player in unconventional hydrocarbon development. With abundant resources, shale gas holds considerable potential for exploitation worldwide, as evidenced by current exploration activities. China and the United States, as leading energy powers, are also major producers of shale gas. The Ministry of Natural Resources of China, in its 2016 China Mineral Resources Report, projected optimistic estimates for China's shale gas reserves and highlighted promising prospects for exploitation(Ministry of Natural Resources of the People's Republic of China (MNR) (2022)). In 2023, the United States achieved an average daily shale gas production rate of 2.4×10^{10} m^3, whereas China's rate was 6.8×10^{7} m^3, indicating a notable disparity in daily output between the two nations (Bao. U.S. production is primarily concentrated in Devonian-Mississippian strata. In contrast, China's shale development has been smaller in scale, hindered by less favorable preservation conditions. Additionally, shales in the southern Sichuan-northern Guizhou region are prevalent. The Ordovician Wufeng Formation-Silurian Longmaxi Formation, a typical marine shale succession on the Yangtze Plate, is noted for its stable depositional settings and organic-rich intervals. Consequently, early exploration in China targeted Cambrian-Silurian shales, particularly around the Sichuan Basin (Guo, X.S.,2022).

Guizhou Province, situated in southwestern China (a), is divided into 13 geological units based on its tectonic and geological evolution (Fig1b). The northern region of Guizhou is characterized by intricate tectonic structures and stratigraphic layers that extend to tens of thousands of meters(Xu, S.,2022). These sedimentary sequences include shale intervals rich in organic matter, indicating significant exploration potential. According to the Ministry of Natural Resources of the People's Republic of China, the area holds high prospective value for shale exploration. However, the conditions for organic matter deposition in northern Guizhou differ significantly from those in the Sichuan Basin(Wu, J.,2025). Thus, it is crucial to analyze the thickness and spatial distribution of organic-rich shales, as well as the reservoir and storage characteristics of the strata, to assess the exploration prospects in northern Guizhou comprehensively.

Geological Background

The South Sichuan-North Guizhou region lies on the southeastern edge of the Upper Yangtze block, characterized by deep-water shelf deposits from the Late Ordovician to Early Silurian periods(Guo, X.S.,2025). The Wufeng Formation (O_3w) is composed of dark siliceous shale, while the lower section 1 of the Longmaxi Formation (S_1l) features organic-rich black shale, which gradually transitions into interbedded sandstones and mudstones(Wu, L.,2023). This Wufeng-Longmaxi sequence conformably overlays the Baota Formation (O_3b). In the North Guizhou area, the effective thickness of the Wufeng-Longmaxi shales reaches up to 80 meters.

Significant tectonic activity in northern Guizhou has resulted in numerous folds, creating potential storage spaces for shale gas(Yerger, D.,2025). Both domestically and internationally, the exploitation of shale gas encounters challenges such as damage to reservoir layers. Effectively utilizing limited technical exploration to assess storage conditions is essential for reducing costs and improving efficiency(Liang, C.,2012). Compared to most regions worldwide, southern Guizhou presents more complex tectonics, while northern Guizhou possesses relatively abundant shale gas resources(Yang, W.Q., 2025). Field investigations in the synclines of the northern Guizhou-southern Sichuan area involved wing profile field analyses and sample analyses of key synclines(Wang, D.D., 2024). By examining regional formation porosity, total organic carbon (TOC), formation thickness, and other parameters, the storage characteristics of the shale reservoirs were ultimately clarified.

3 Major Synclines in northern Guizhou

The distribution of organic-rich shale thickness in northern Guizhou is mainly influenced by fault zones and fold belts. Using data from various field-survey profiles and existing literature, we have compiled statistics on the major synclines in this region. The Guizhou Provincial Geological Survey has designated names for these synclines(Fig2)(Xu, S.,2020). The thickness of the Wufeng-Longmaxi Formation shale is greatly affected (Table 1).

The extraction and classification of synclinal features reveal that residual synclines in northern Guizhou predominantly exhibit oblique-deformed morphologies(Qiu, Y.,2024;Zhou, J,G.,2016;He, X., 2015;Chen, H.,2011;Wei, X.F., 2017). In the Wulong-Zheng'an composite structural belt synclines are primarily gentle, oblique-gentle, and oblique-open short-axis types(Guo, Y.C., 2022). Conversely, in the Yanhe-Meitan composite structural belt, linear oblique-tight and oblique-open synclines predominate. The northern Yunnan-Guizhou fold belt is characterized mainly by oblique-tight, oblique-open synclines, and

synclinal basins, with closed-type synclines occurring along major fault margins. In northern Guizhou, the syncline-controlled shale thickness is predominantly marine, with the Chishui extending deeper toward Sichuan than in central Guizhou(Yu, X.Q.,2020;Guo, Y.C.,2022;Kong, X.X., 2021). The synclinal zones significantly influence the thickness of the Wufeng-Longmaxi Formation. Tectonic superposition and modification during the Yanshanian period have notably affected thickness distribution. In synclinal areas like the Daozhen and Fuyan synclines, shale preservation is relatively intact, resulting in greater thickness. In contrast, anticlinal areas have experienced compressional uplift, leading to shale erosion and reduced thickness or local absence(Wang, T., 2022). Overall, the pattern, controlled by paleo-uplift and structural superposition, shows "thicker in the north and thinner in the south, thicker in the east and thinner in the west". High-thickness zones of organic-rich shale correspond to northern deep-water shelf depressions and synclinal structural domains(Naylor, M.A., 1981).

Table 1: Synclinal Characteristics of northern Guizhou region

	Anticline name	area	Aspectration	ShaleThickness (m)	well	Ro (%)	resource availability (10^8m^3)	Comprehensive Evaluation	Type	Gas contentof shale($10^8m^3/t$)	DailyGasprc
1	WL Syncline	1180	3:1	30~40	Long 1	2.4~2.8	6079	0.9	□	11.28	4.6
					Long 2						9.22
					Long 3						7.2
2	LL Syncline	293	2:7	30		2.4~2.8	1364	0.9	□	6.3	
3	DZ Syncline	2	4:2	30	Zhen 3	2.4~2.8	3751	0.89	□	13.36	3.1
					Zhen 2						
					Zhen 1						6.02
					Dao 1						
4	PS Syncline	616		25~30	Peng 1	2.4~2.8	3081	0.83	□	5.41	2.3
					Peng 3	2.4~2.8	923	0.81	□	1.14~3.95	2
5	FX Syncline	210		5~15	Fudi 1						
6	AC Syncline	139		15~25	An 1	2.0~2.5	546	0.79	□	20.01	4.08
					An 2						2.68
					An 3						1.21
					An 4						4.43
					An 5						
					An1-6HF						2.33
7	SX Syncline	165		30~35	Shixi 1	2.4~2.8	684	0.79	□	1.878	
					Shixi 2						
8	DZ East Syncline	664	6:3	20~25		2.4~2.8	3336	0.59	□	2.12	
9	TB Syncline	226		5~15	Sui 1	2.4~2.8	1008	0.54	□	3.14	
10	BZ Syncline	483		5~10	Banzhu 1	2.4~2.8	1786	0.49	□	1.77	
11	JX Syncline	218	5:4	15~25		2.6~3.0	436	0.73	□	1.3	
12	TZ Syncline	372		5~25	Tong 1	2.0~2.8	744	0.69	□	0.6	
13	SB Syncline	244	4:6	3~15	Shidi 1	2.8~3.4	488	0.46	□	2.43	

Qianbei Organic-Rich Shale

4.1 Control of Organic-Rich Lithofacies

The Ordovician-Silurian Wufeng-Longmaxi Formation is the primary shale gas target within the organic-rich shales of northern Guizhou. This formation, situated above the Baota Formation, serves as a crucial field marker for identifying and locating the Wufeng-Longmaxi strata. The stratigraphic thickness of this formation is primarily influenced Guizhou Geological Survey, 2017 by the northern Guizhou and Wuling depressions(Fig3a)(Xu, S.,2020).

The Wufeng-Longmaxi and Niutitang formations, rich in organic material, represent the primary marine shale gas reservoirs in southwestern China(Wang, S.Y., 2022). The Wufeng-Longmaxi shales extend through Sichuan and northern Guizhou, showing a trend of thinning toward the south. This stratigraphic unit is strategically crucial for China's shale gas development. Despite this, production in northern Guizhou has been suboptimal, with most development occurring along the southeastern edge of the Sichuan Basin. The significant difference in shale gas yields between the Sichuan Basin and northern Guizhou likely results from the effects of the Qianzhong and western Sichuan uplifts (Fig3b).

4.2 Interconnected-Well Analysis of Organic-Rich Shale

We compiled and analyzed publicly available shale gas well data from northern Guizhou (Table 1). By comparing regional outcrop sections and borehole profiles, we found that the vertical depositional facies of the Wufeng-Longmaxi formations in northern Guizhou show a continuous transition from a deep-water shelf to a shallow-water shelf(Chen, L.,2015). This transition corresponds to a complete sea-level cycle characterized by a rapid rise, a stable interval, and a gradual fall, with no depositional hiatus observed. During the Wufeng deposition, northern Guizhou experienced a deep-water shelf environment with a total organic carbon (TOC) content exceeding 3.5%, leading to the development of carbonaceous mud-shelf microfacies. The Henan Te (Baota) interval marks a transition from carbonaceous mud-shelf to silty carbonaceous mud-shelf(Leng, Y.J.,2025, featuring abundant fossils. In the early Longmaxi deposition, marine transgression continued, albeit at a reduced rate. During this period, carbonaceous mud-shelf and silty carbonaceous mud-shelf facies alternated, and the siliceous content slightly decreased, with TOC ranging from 2.5 to 3.5%, In the late Longmaxi, as the sea level fell, calcareous and sandy contents increased, and TOC dropped below 2.5%(Meng, Z., 2016).

The thickness of the Wufeng-Longmaxi Formation in northern Guizhou displays a zonal distribution due to the influence of the Qianzhong Uplift and the Sichuan Basin. This distribution is marked by a trend where the formation becomes shallower, coarser, and poorer in the south, while it deepens, becomes finer, and richer in the north (Fig.4).

The deep-water shelf area located north of the Zheng'an-Wuchuan-Daozhen line, known for its excellent preservation conditions, serves as the primary target zone for shale gas exploration in the Wufeng-Longmaxi Formation of northern Guizhou.

By calculating the thicknesses of the Wufeng-Longmaxi Formation from over twenty cross-sections in northern Guizhou and southern Sichuan, and statistically analyzing these thicknesses, we have determined that the Qianbei syncline significantly influences shale thickness. Within the synclinal domain, shale thickness exhibits frequent variations (Fig.5)(Meng, Z., 2016;Zhao, L.,2023).

4.3 Ordovician-Silurian Depositional Facies

Marine organic-rich shales primarily consist of black siliceous and carbonaceous shales, characterized by their brittleness and the presence of millimeter-scale spherulitic tuff fragments. Analyzes of samples reveal TOC values ranging from 3.5% to 5.0%. The stratigraphy is predominantly composed of the Wufeng Formation (O_3w) and the lower section21 of the Longmaxi Formation (S_1l), both featuring Type I kerogen. This interval also displays significant bioturbation and a high concentration of belemnite remains, which are crucial indicators of a marine depositional environment(Qian. P., 2022). The Wufeng-Early Longmaxi interval exemplifies a dual favorable regime of "high primary productivity + strong reducing preservation," with TOC levels generally exceeding 3.0%, marking the main phase of premium source-rock development(Wang, S.X., 2021). However, during the Middle-Late Longmaxi period, a sea-level decline resulted in shallower waters, increased hydrodynamics, and more oxic conditions. These changes hindered the preservation of organic matter, causing TOC levels to rapidly drop below 2.0%.

The V/Cr ratio shows a positive correlation with Ni/Co ; as Ni/Co rises, V/Cr also increases, both reflecting redox conditions (Fig.6a). Total Organic Carbon (TOC) is strongly positively correlated with Ni/Co; as Ni/Co increases, TOC rises significantly, suggesting that reducing conditions primarily control TOC enrichment (Fig.6b). The V/(V+Ni) ratio is also strongly positively correlated with Ni/Co; as Ni/Co increases, V/(V+Ni) rises, and using these two indices together provides the highest accuracy for redox interpretation (Fig.6c). Conversely, V/Cr is weakly negatively correlated with U/Th; as U/Th increases, indicating more oxic conditions, V/Cr generally decreases, also suggesting increased oxidation. However, the data are scattered, showing significant influences from terrigenous input and mineralogical interference (Fig.6d). Ni/Co is strongly negatively correlated with U/Th; as U/Th increases, Ni/Co decreases markedly, with the data clustered, indicating high interpretative stability (Fig.6e). Similarly, V/(V+Ni) is strongly negatively correlated with U/Th; as U/Th rises, V/(V+Ni) decreases significantly, making it a highly precise index for redox determination (Fig.6f).When U/Th is less than 0.8, V/Cr exceeds 6, Ni/Co is greater than 10, V/(V+Ni) surpasses 0.85, and TOC exceeds 4%, the preservation of organic matter is excellent, and the potential for hydrocarbon generation is very high, indicating superior shale quality. Under these conditions, the interval corresponds to class I "sweet spot" layers, which are the main gas-producing horizons, such as the lower section of the Longmaxi Formation at Jiaoshidam, characterized by strongly reducing conditions (AX).

The U/Th ratio ranges from 0.8 to 1.5, the V/Cr ratio from 3 to 6, and the Ni/Co ratio from 5 to 10. Additionally, the V/(V+Ni) ratio is between 0.75 and 0.85, while the total organic carbon (TOC) content is between 2% and 4%. The organic matter is well-preserved, indicating moderate hydrocarbon generation potential. The shale quality is moderate, classifying these layers as Type II sweet spot intervals, which are suboptimal for gas production. These conditions are characterized as suboxic to weakly reducing (OD).

When the ratios U/Th exceed 1.5, V/Cr fall below 3, Ni/Co are under 5, and V/(V+Ni) is less than 0.75, combined with a total organic carbon (TOC) content of less than 2%, the preservation of organic matter is poor, and the potential for hydrocarbon generation is weak. Consequently, the quality of the shale is suboptimal, and the potential for exploitation in non-sweet spots is extremely limited.

The redox conditions in the Wufeng-Longmaxi Formation shales play a crucial role in organic matter enrichment and determining shale quality. Strongly reducing environments (AX) are essential for forming high-quality shale gas reservoirs. Utilizing the combined indicators of U/Th, V/(V+Ni), and Ni/Co enables precise delineation of redox facies, offering a reliable foundation for predicting shale gas sweet spots(Guo, X.S.,2020).

At the Ordovician-Silurian boundary, northern Guizhou was located in the restricted shallow-marine environment of the "Sanlongwei Basin". Anoxic conditions on the deep inner shelf primarily facilitated the enrichment of organic matter. High-quality, organic-rich shales, with total organic carbon (TOC) exceeding 3.0%, were concentrated in the Wufeng Formation and the lower part of the Longmaxi Formation(Li. Y.S., 2022;Zhong, C.,2019).

Organic matter pores have a preference for adsorbing methane. Transitional marine-terrestrial shales typically develop organic micropores with sizes ranging from 0.4 to 0.7 nm(Han, M.,2018). In contrast, marine shales primarily develop larger organic pores in pyrobitumen, generally measuring 50 to 300 nm and often elliptical in shape(Wang, Y.M.,2017). Methane adsorption in these large organic pores of marine facies occurs through micropore filling and surface adsorption (Fig.7). As these shales produce significant free gas, once the adsorption sites on organic pore surfaces are saturated, a substantial amount of free gas emerges. Conversely, in transitional facies shales, organic matter develops micropores associated with the stacking of aromatic structures, which methane cannot directly enter. However, variations in aromatic stacking increase the specific surface area of the organic matter, thereby enhancing methane adsorption capacity. Consequently, in transitional marine-terrestrial shale reservoirs, methane is commonly found in a strongly adsorbed state on organic surfaces (Fig.7), resulting in a relatively high proportion of adsorbed gas in transitional facies shale gas(Han, M.,2018).

The central part of the Upper Yangtze Platform in northern Guizhou comprises three major tectonic units (Fig.8). From the Late Ordovician to the Early Silurian, this region was bounded by the Qianzhong Uplift, the central Sichuan Uplift, and the Xuefeng Uplift, creating a semi-enclosed, shallow-marine basin. This "three uplifts enclosing a basin" paleogeographic pattern established critical "retention-anoxia" depositional conditions(Liu, Z.C., 2023). These conditions were conducive to the formation of organic-rich shales by minimizing hydrodynamic activity that could otherwise destroy or oxidize organic matter. During the early Caledonian movement, following the Hernantian, a regional transgression occurred, placing the entire study area within a transgressive system tract. Water depth varied significantly, with a south-shallow, north-deep differentiation. South of the Zunyi-Shiqian line, near the Qianzhong Uplift, water depths were generally less than 50 meters. In contrast, moving north toward the Zheng'an-Wuchuan-Daozhen axis, depths increased to 80-150 meters, forming a deep-water shelf depression. This area became the core zone for organic matter enrichment. In northern Guizhou, marine shelf facies dominate, characterized by a vertical transition from deep-water to shallow-water shelves and a lateral zonation from south-shallow to north-deep(Li. W.Z., 2025). Notably, no shoreface or continental facies developed. The deep-water shelf subfacies serves as the primary development zone for high-quality source rocks (Fig. 3).

4.4 Depositional Environment of Organic-Rich Shales in Wufeng-Longmaxi

The TOC content of organic-rich shale determines the shale color, with such shale being predominantly black(Ma, X.Y., 2023;Karami, M.,2023). Wufeng-Longmaxi organic-rich shales are marine shales (Fig.3). In the marine sedimentary environment, the Baota Formation (O_3b) and other marl rocks are found at the bottom of the Wufeng-Longmaxi Formation. Stratigraphic records indicate that the Wufeng Formation shales are rich in graptolite fossils (Fig.9a, f) and characterized by black shales containing pyrite crystals (Fig.9g). Within this sequence, the Guanyinqiao Formation (O_3g) is notable for its numerous paleontological fossils (Fig.9b). The Longmaxi succession is divided into Long Section, which includes subunits 1-3 (S_1l^{1-1}, S_1l^{1-2},S_1l^{1-3}), and Long Section 2(S_1l^2). Calcite veins in the Longmaxi succession provide samples of inclusions (Fig.9c). Furthermore, the top of Long Section1(S_1l) features abundant nodules, which contain numerous crystals (Fig.9d).

Quality Assessment Indicators

5.1 Organic Matter Abundance

According to the proportion of feldspar carbonate and clay minerals, the TOC enriched shale in the oilfield profile is classified(Han. Y.Y.,2021). In the northern Guizhou profiles, where Total Organic Carbon (TOC) exceeds 2%, the predominant lithologies include siliceous shale, calcareous siliceous shale, argillaceous siliceous shale, and argillaceous calcareous shale. Conversely, in regions where TOC is less than 2%, the main lithologies are chert, siliceous shale, argillaceous siliceous shale, calcareous shale, and argillaceous calcareous shale. Within the Wufeng-Longmaxi Formation, the organic-rich shale facies primarily consist of calcareous siliceous shale, argillaceous siliceous shale, and argillaceous calcareous shale (Fig.10). We performed thin-section petrographic analysis on 210 samples, revealing significant mineralogical differences between the northern Guizhou and Southern Sichuan regions (Fig.11).

5.2 Chloroform-Asphaltene "A" Content in the Wufeng-Longmaxi Middle Chloroform

Chloroform-Asphaltene of the northern Guizhou-Southern Sichuan Region. This section examines the content of Chloroform-Asphaltene "A" within the Wufeng-Longmaxi Formation, specifically focusing on the middle chloroform-asphaltene layer in the northern Guizhou-Southern Sichuan region. The analysis aims to provide insights into the geochemical characteristics and potential implications for hydrocarbon exploration in this area. The Wufeng-Longmaxi Formation is known for its rich organic content and has been a subject of extensive research due to its potential for unconventional hydrocarbon resources(Shi, S.Y.,2022;Wattana, P., 2005). Recent studies have highlighted the significance of asphaltene content as an indicator of the maturity and quality

of organic matter within these formations(Zahra, S., 2022;Mansour, M.,2025;Ren. X.J.,2024). In our study, we employed standard geochemical methods to quantify the Chloroform-Asphaltene "A" content. The results revealed a notable variation in asphaltene concentration across different samples, suggesting a heterogeneous distribution of organic material. This variability may influence the hydrocarbon generation potential and requires further investigation to understand its impact on resource exploitation strategies. The findings contribute to the broader understanding of the Wufeng-Longmaxi Formation's geochemical profile and underscore the importance of detailed asphaltene analysis in assessing the viability of hydrocarbon resources in the northern Guizhou-Southern Sichuan region. Future research should focus on correlating asphaltene content with other geochemical markers to enhance predictive models for hydrocarbon exploration.

We performed parameter analyses of TOC and Ro for the Wufeng-Longmaxi Formation shales using statistical analysis of the dataset and our measured values. The following relationships were derived from linear analysis based on the table below.

Table 2: Chloroform Bitumen "A" of Qianbei Wufeng-Longmaxi Shale

Region	Horizon	Chloroform-Asphaltene "A" (μg/g)	TOC (%)	Ro	Lithofacies Features
Jiaoshiba	Wufeng Fm	65	4.2	2.2	Siliceous Shale Facies
	Lower Longmaxi Fm	59	3.8	2.1	Siliceous-Mixed Shale Facies
Changnin	Wufeng Fm	57	4	2.3	Siliceous Shale Facies
	Lower Longmaxi Fm	51	3.5	2.2	Mixed Shale Facies
Weiyuan	Wufeng Fm	49	3.6	2.4	Siliceous Shale Facies
	Lower Longmaxi Fm	43	3	2.3	Argillaceous Mixed Facies
Hongxian	Wufeng Fm	53	3.9	2.1	Siliceous Shale Facies
	Lower Longmaxi Fm	47	3.3	2	Mixed Shale Facies
Xuyong	Wufeng Fm	38	2.5	1.9	Argillaceous Shale Facies
	Lower Longmaxi Fm	32	2.1	1.8	Argillaceous Shale Facies
Xishui	Wufeng Fm	52	3.7	2	Siliceous Shale Facies
	Lower Longmaxi Fm	46	3.2	1.9	Mixed Shale Facies
Zunyi	Wufeng Fm	44	3.1	1.9	Siliceous Mixed Shale Facies
	Lower Longmaxi Fm	37	2.7	1.8	Argillaceous Mixed Facies
Renhuai	Wufeng Fm	35	2.4	1.8	Mixed Shale Facies
	Lower Longmaxi Fm	29	2.0	1.7	Argillaceous Shale Facies
Suiyang	Wufeng Fm	41	2.8	1.9	Mixed Shale Facies
	Lower Longmaxi Fm	34	2.3	1.8	Argillaceous Shale Facies
Tongzhi	Wufeng Fm	39	2.6	1.8	Mixed Shale Facies
	Lower Longmaxi Fm	31	2.2	1.7	Argillaceous Shale Facies

The equation (y=15.23x+2.15) represents the relationship between chloroform bitumen "A" content (μg/g) and TOC content (%). The correlation coefficient (R^2=0.89) signifies a strong positive correlation, indicating that TOC significantly influences the concentration of soluble organic matter. As the TOC in shale increases, so does the amount of thermally generated soluble organic matter "A." The Wufeng Formation, with a mean TOC of 3.2%, exhibits a higher average "A" content of 47.8 (mu g/g) compared to the lower Longmaxi Formation, which has a mean TOC of 2.6% and an average "A" content of 39.1 (mu g/g). This difference underscores the impact of depositional environments on organic matter enrichment.

In siliceous shale facies, total organic carbon (TOC) typically exceeds 3.0%, and "A" is greater than 45 (μg/g). Conversely, in clay-rich shale facies, TOC is less than 2.5%, and "A" is below 35 (μg/g). This difference indicates the dilutive effect of clay minerals on the relative abundance of organic matter. The relationship between "A" and Ro is influenced by the thermal maturation stage. During the early overmature stage, Ro ranges from 1.7 to 2.2, whereas in the late overmature stage, Ro ranges from 2.2 to 2.4.

Total Organic Carbon (TOC) serves as the foundational component of chloroform asphalt "A." Organic-rich shale with TOC exceeding 3.0% is a key indicator of high-quality source rocks, aligning with an "A" content greater than 45 (μg/g). This makes it a direct metric for selecting exploration targets. The vitrinite reflectance (Ro) dictates the evolutionary path of "A." For the Wufeng-Longmaxi Formation shales, an Ro range of 2.0-2.2% represents the ideal hydrocarbon generation window. During this phase, the "A" content peaks, optimizing shale gas generation and retention potential(Hao. F., 2013;Hao. F.,2013) .

Composition of Different Shales

6.1 Geochemical Characteristics of Organic-Rich Shales

6.1.1 Organic Abundance

The organic richness of shale is crucial for its classification, characterized by organic abundance, type, and maturity(Xia. P., 2018). The Total Organic Carbon (TOC) content serves as the most effective measure of organic abundance. Generally, shale gas resources are identified as a regional "sweet spot" when TOC levels exceed 3%(Wu, L.Y.,2016). However, in some cases, it is essential to analyze TOC in conjunction with shale porosity or thickness to accurately determine if an area qualifies as a shale gas "sweet spot".

The TOC abundance in the Wufeng-Longmaxi Formation of northern Guizhou ranges from 0.5% to 7.0%, with an average of 3.5% (Fig 10). The TOC in this formation varies from 0.5% to 7.0%, with an average of 3.5%. Research suggests that the organic matter abundance here is similar to that in the Sichuan region(Wang, Y.C.,2022;Du, W., 2022). The organic-rich Wufeng-Longmaxi shales exhibit a decreasing TOC trend from north to south. Analysis of 210 outcrop-section samples and 108 core samples reveals that 16.67% of section samples have TOC below 0.5%, while 45.24% exceed 3.0%. In contrast, only 0.93% of core samples have TOC below 0.5%, and 71.30% exceed 3.0%. Both datasets consistently demonstrate a north-to-south decline in TOC within the Wufeng-Longmaxi Formation. This trend indicates that the optimal areas for shale gas, or "sweet spots" in Guizhou are primarily located in the Zheng'an, Daozhen, and Tongzi regions(Mou, Y.L.,2024).

6.1.2 Types of Organic Matter

In the Qianbei region, the Wufeng-Longmaxi Formation's organic matter primarily consists of Type I kerogen, with some Type Ⅱ, as determined by organic geochemical analyses and microscopic kerogen component characterization of core samples(Mou, Y.L.,2024;Feng, X.B.,2009;Lu, S.F.,2019)_. Geochemically, the high hydrogen indices (HI), low oxygen indices (OI), elevated H/C atomic ratios, and reduced O/C atomic ratios suggest a strong potential for hydrocarbon generation. Microscopically, the composition is mainly amorphous sapropelic material and algal groups, with minor siliceous components. Solid bitumen fills pores and fractures, while vitrinite is scarce, aligning with a low-level planktonic source typical of anoxic deep-water shelf depositional environments(Tang, Q.S.,2021). This kerogen type is found in the Wufeng Formation and the lower interval of the Longmaxi Formation's high-quality shales, offering an excellent material basis for shale gas enrichment.

6.1.3 Organic Matter Maturity

Vitrinite reflectance (Ro) is a crucial metric for determining the maturity of organic matter, serving as the standard for evaluating thermal maturity(Wang, S.Y., 2022). In the Wufeng-Longmaxi Formation in northern Guizhou, measurements and comparisons of outcrop sections and core samples revealed that core Ro values ranged from 1.8 to 4.0, whereas section values varied from 1.45 to 4.56.

The Wufeng-Longmaxi Formation in the organic-rich shales of northern Guizhou is categorized as overmature shale. As these shales transition from late mature to overmature stages, kerogen and other hydrocarbons undergo thermal cracking, producing methane that escapes at high temperatures(Zhu.Y.Q., 2016). As a result, the Wufeng-Longmaxi strata in northern Guizhou exhibit a significant deficiency in oil, highlighting their potential as promising unconventional gas reservoirs.

Deep-water anoxic conditions have facilitated the preservation of organic matter. Moving from the Sichuan Basin to northern Guizhou, the effective shale thickness decreases. This reduction, coupled with multiple tectonic events and variations in reservoir thickness, has led to comparatively lower shale gas retention.(Dong. T., 2019) In northern Guizhou, the overall shale Ro value exceeds 2%, indicating favorable conditions for shale preservation and exploitation. Gas content is notably high in the Wulong and Anchang syncline blocks, where shale gas content ranges from 11.28 to 20.01 m/t. This exceeds the regional average, suggesting these areas as prime candidates for shale gas development in structurally complex settings. The Fig illustrates the Ro values of core and outcrop shale samples within the region.

6.2 Quality Grading Criteria

Shales were categorized using a ternary classification system based on three primary components: felsic minerals, carbonate minerals, and clay minerals(Hu, H.Y.,2017). This approach identified four main shale groups and twelve distinct shale types. The groups include the Siliceous shale group (Ⅰ), Argillaceous shale group (Ⅱ), Calcareous shale group (Ⅲ), and Mixed shale group (Ⅳ). The twelve shale types are as follows: siliceous shale (Ⅰ-1), carbonate-rich siliceous shale (Ⅰ-2), argillaceous-rich siliceous shale (Ⅰ-3), argillaceous shale (Ⅱ-1), silica-rich argillaceous shale (Ⅱ-2), carbonate-rich argillaceous shale (Ⅱ-3), calcareous shale (Ⅲ-1), silica-rich calcareous shale (Ⅲ-2), argillaceous-rich calcareous shale (Ⅲ-3), argillaceous/siliceous mixed shale (Ⅳ-1), calcareous/argillaceous mixed shale (Ⅳ-2), and siliceous/calcareous mixed shale (Ⅳ-3) (Table 3).

The mineralogical analysis of samples from northern Guizhou reveals that the Wufeng-Longmaxi organic-rich shales consist mainly of several lithofacies. These include carbonate-rich siliceous shale, siliceous shale, silica-rich argillaceous shale, and argillaceous-rich calcareous shale. The primary organic-rich shale lithotypes are argillaceous shale, carbonate-rich argillaceous shale, argillaceous-siliceous mixed shale, calcareous-argillaceous mixed shale, and siliceous/calcareous mixed shale(Fig13), In the Wufeng-Longmaxi Formation throughout northern Guizhou, there is a noticeable trend where calcareous content progressively decreases from west to east, while siliceous content diminishes from east to west.

The mineral composition of the Qianbei region, as detailed below, and the calculations of mineralogical and mechanical parameters based on the China Petroleum and Natural Gas Industry Standard (NB/T 10248-2019), reveal that the Wufeng-Longmaxi organic-rich shales have a brittleness index (BI) ranging from 38 to 77, with an average of 58. This suggests promising prospects for exploitation.

Table 3: Shale Types

Shale groups	Shale types	Code	Minerals composition (%)		
			Felsic minerals	Carbonate minerals	Clay minerals
Siliceous shale group (I)	Siliceous shale	I-1	> 50	< 25	< 25
	Carbonate-rich siliceous shale	I-2	> 50	25~50	< 25
	Argillaceous-rich siliceous shale	I-3	> 50	< 25	25~50
Argillaceous shale group (II)	Argillaceous shale	II-1	< 25	< 25	> 50
	Silica-rich argillaceous shale	II-2	25~50	< 25	> 50
	Carbonate-rich argillaceous shale	II-3	< 25	25~50	> 50
Calcareous shale group (III)	Calcareous shale	III-1	< 25	> 50	< 25
	Silica-rich calcareous shale lithofacies	III-2	25~50	> 50	< 25
	Argillaceous-rich calcareous shale	III-3	< 25	> 50	25~50
Mixed shale group (IV)	Argillaceous/siliceous mixed shale	IV-1	25~50	< 30	25~50
	Calcareous/argillaceous mixed shale	IV-2	< 30	25~50	25~50
	Siliceous/calcareous mixed shale	IV-3	25~50	25~50	< 30

SEM image analysis reveals that the carbonaceous shale samples from the Wufeng-Longmaxi formations in northern Guizhou and southern Sichuan exhibit a variety of pore types. These include interlayer pores within clay minerals, intercrystalline pores, intracrystalline dissolution pores, fractures, and organic-matter pores[63-65] (Fig.14). Both pores and fractures are well developed, with mineral crystal dissolution pores and microfractures providing effective flow pathways. Despite the relatively low thermal maturity of the Wufeng-Longmaxi organic-rich shales (TOC 2.4%~3.4%, as shown in Table 1), there is significant research potential regarding their organic-hosted porosity. The results show that the porosity is well developed, (porosity > 50 nm) accounts for less than 5%, (porosity between 2 and 50 nm) accounts for 30~40%, and the micropore is the main pore of the Wufeng Formation-Longmaxi Formation carbonaceous shale (Fig14.a).

Bedding fractures form between shale's clayey material and rigid bodies (Fig.14c). Platy minerals, such as micas within the shale, readily develop intercrystalline fractures, while interparticle voids emerge between clay minerals. Additionally, pyrite crystals are present in the Wufeng-Longmaxi Formation carbonaceous shales (Fig.9e). These characteristics significantly enhance the potential for shale gas storage and migration.

6.3 Calcite Vein Inclusions Enriched in Organic Matter

Previous studies have found that the calcite-filled veins are abundant in the Wufeng-Longmaxi strata sequence in several sites in northern Guizhou(Li, X.Y., 2023). We performed microthermometric and petrographic analyses on fluid inclusions within these calcite veins. The table classifies the inclusion types and their relative abundances. Under microscopic observation, the inclusions appear unevenly and dispersed at room temperature. Based on petrographic characteristics, the inclusions are categorized as follows: Type I two-phase (liquid + vapor) saline inclusions (Fig15d, i). These Type I inclusions are primarily gray-white or colorless, transparent, and typically elongated (Fig 15d, j), measuring 3-8 μm, and serve as the primary targets for temperature measurement (Fig 15). Type II consists of liquid-only inclusions; they are mostly colorless and transparent, appearing in rounded to elliptical shapes and often clustered. Their volumes are minimal, and they frequently coexist with Type I inclusions (Fig.15h).

By analyzing the data of the inclusions, revealing that the gas-liquid ratio is less than 5%. Most inclusion volumes are between 3 and 6 μm. The freezing temperatures vary from -3.8 to -5.0 °C, while homogenization temperatures range from 172.2 to 215.1 °C. Typically, each sample group contained an average of five visible liquid-phase inclusions. In certain cases, inclusions exhibited a linear distribution (Table 4).

This study investigates the types of calcite vein inclusions, gas-liquid ratios, freezing point temperatures, and homogeneity temperatures within the Longmaxi Formation in the northern Guizhou region. The research aims to verify the sedimentary equivalence of organic-rich shale in this area.

Table 4: Calcite Inclusions.

Number	Type	Gas-Liquid Ratio	Size	Freezing Point Temperature (°C)	Homogenization Temperature (°C)	Shape
A1-1	liquid phase	≤5%	4~6	-3.9~ -4.8	181.2~216.2	irregular
A1-2			3~5	-3.4~ -4.3	195.0~219.1	
A2-1			4~5	-3.7~ -4.6	173.5~192.3	
A3-1			3~5	-3.8~ -5.0	174.4~215.1	
Bijie Langyan 1-15			3~5	-4.0~ -5.0	174.4~215.1	
Bijie Linkou3-18			3~6	-3.8~-5.0	172.2~210.2	
Xuyong Maolin 4-4			3~8	-3.8~ -5.2	178.9~215.2	
Xuyong Dapo 5-9			3~6	-3.8~ -5.0	178.2~215.0	
Bijie Mula 6-15			3~5	-3.8~ -5.0	174.4~215.1	
PM7-5			3~5	-3.8~ -5.0	174.4~215.1	
Xishui Xianyuan-15			3~5	-3.8~ -5.0	178.2~215.1	
PM10-6			3~5	-3.8~ -5.0	174.4~215.1	
PM11-10			3~6	-4.0~ -5.0	178.2~210.2	
Daozhen 05			3~5	-4.0~ -5.0	202.6~215.1	
SD3-2			3~5	-3.8~ -5.0	172.2~210.4	

6.4 Prospects for Exploitation and Exploration of 'Sweet Spots' in Shale Gas

This study examines the geochemistry of shale gas, emphasizing that synclinal structural factors significantly influence organic-rich shales. The Wufeng-Longmaxi Formation, with shale gas burial depths typically exceeding 4000 meters, presents a promising "sweet spot" for deep to ultra-deep shale gas exploration and development. According to estimates, the geological resources of this formation in Guizhou are approximately 1.48×10^{12} m^3(Zhang, J.C.,2023).

A comprehensive evaluation of the synclinal area in northern Guizhou was conducted by integrating various factors, including the size and type of synclines, sedimentary facies types, thickness of organic-rich shale, regional shale TOC and Ro, pore structures of the Wufeng-Longmaxi Formation shales, and measurements of calcite vein-hosted inclusions within interbeds. The synclinal belt in northern Guizhou is categorized into four preservation levels: well-preserved, fairly well-preserved, moderately-preserved, and poorly-preserved synclinal zones(Fig.16).

Conclusion

The macroscopic distribution and preservation of organic-rich shales are controlled by tectono-sedimentary coupling. On the southeastern margin of the Upper Yangtze Block in northern Guizhou, a paleogeographic framework characterized by "three uplifts surrounding a basin" favored continuous deposition of marine deep-water shelf sequences in the Wufeng-Longmaxi Formation, which recorded a complete sea-level cycle. Yanshanian tectonism and subsequent synclinal structures-predominantly asymmetric synclines-constitute the dominant controlling factors. Shales within synclinal zones such as Daozhen, Fuyan, Wulong, and Anchang are well preserved, with maximum thickness reaching 80 m, exhibiting a regional trend of "thicker in the north than in the south, and thicker in the east than in the west". In contrast, anticlinal areas experienced extensive denudation due to compressive uplift, leading to markedly reduced shale thickness or local absence. The deep-water shelf north of the Zheng'an-Wuchuan-Daozhen corridor represents the core zone for both organic matter enrichment and shale preservation.

Shale gas reservoir quality is defined by multiple synergistic geological factors, for which a reliable geochemical discrimination system has been established. Organic matter enrichment in the Wufeng-early Longmaxi formations was jointly driven by high paleoproductivity and strongly reducing stagnant conditions, resulting in high-quality shales dominated by type I kerogen (average TOC 3.5%; 71.30% of core samples with TOC >3%). These shales are concentrated in siliceous shale facies, though locally diluted by clay minerals. The shales are over-mature (Ro: 2.1%~3.4%) and primarily generate methane. The combination of U/Th, V/(V+Ni), and Ni/Co proxies enables high-accuracy discrimination of redox conditions, classifying sweet spots into Class I (TOC >4%, strongly reducing) and Class II (TOC 2%~4%, oxygen-poor/weakly reducing). Reservoir pore spaces are dominated by micropores (2~50 nm), with pyrite crystals and bedding fractures enhancing gas migration. An average brittleness index of 58 (range 38~77), together with an east-west differentiation in mineral composition (siliceous-rich in the east, calcareous-rich in the west), provides favorable conditions for fracturing stimulation. Calcite vein inclusions (3~8 μm; homogenization temperature 172.2~215.1 °C) effectively record post-depositional fluid activity and tectono-thermal evolution.

Northern Guizhou possesses substantial shale gas resource potential, with clear exploration directions yet notable development challenges. The study area hosts an estimated geological resource of 1.48×10^{12} m^3 of deep to ultra-deep normal-pressure shale gas (burial depth > 4000 m). Synclinal zones such as Wulong and Anchang exhibit superior gas content (11.28~20.01 m^3/t) and stable gas logging anomalies. Drawing an analogy with the Mugan Syncline in northeastern Yunnan, the core and limb areas of synclines are identified as prime enrichment zones. The northern deep-water shelf of the Zheng'an-Wuchuan-Daozhen corridor is a key target for exploration beyond the Sichuan Basin. Nevertheless, challenges persist, including the identification of sweet spots in normal-pressure shale gas reservoirs, stringent technical requirements for drilling, flowback, and production, and the economic viability of large-

scale development in low-quality reservoirs. Integrated geological-engineering research and stimulation technologies such as CO_2 injection are essential to advance the scaled development of low-grade resources in this structurally complex region.

Declarations

CRediT authorship contribution statement

Peilong Li: Investigation, Software, Methodology, Validation, Visualization, Writing original draft.

Gan lu Wang: Funding acquisition, Supervision, Writing review editing. Resources.

Yuliang Mou: Supervision, Writing review & editing.

Peng Xia: Supervision, Resources.

Sheng Shi: Investigation.

Peng Chen:Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Competing interests

The authors declare no competing interests.

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Figures

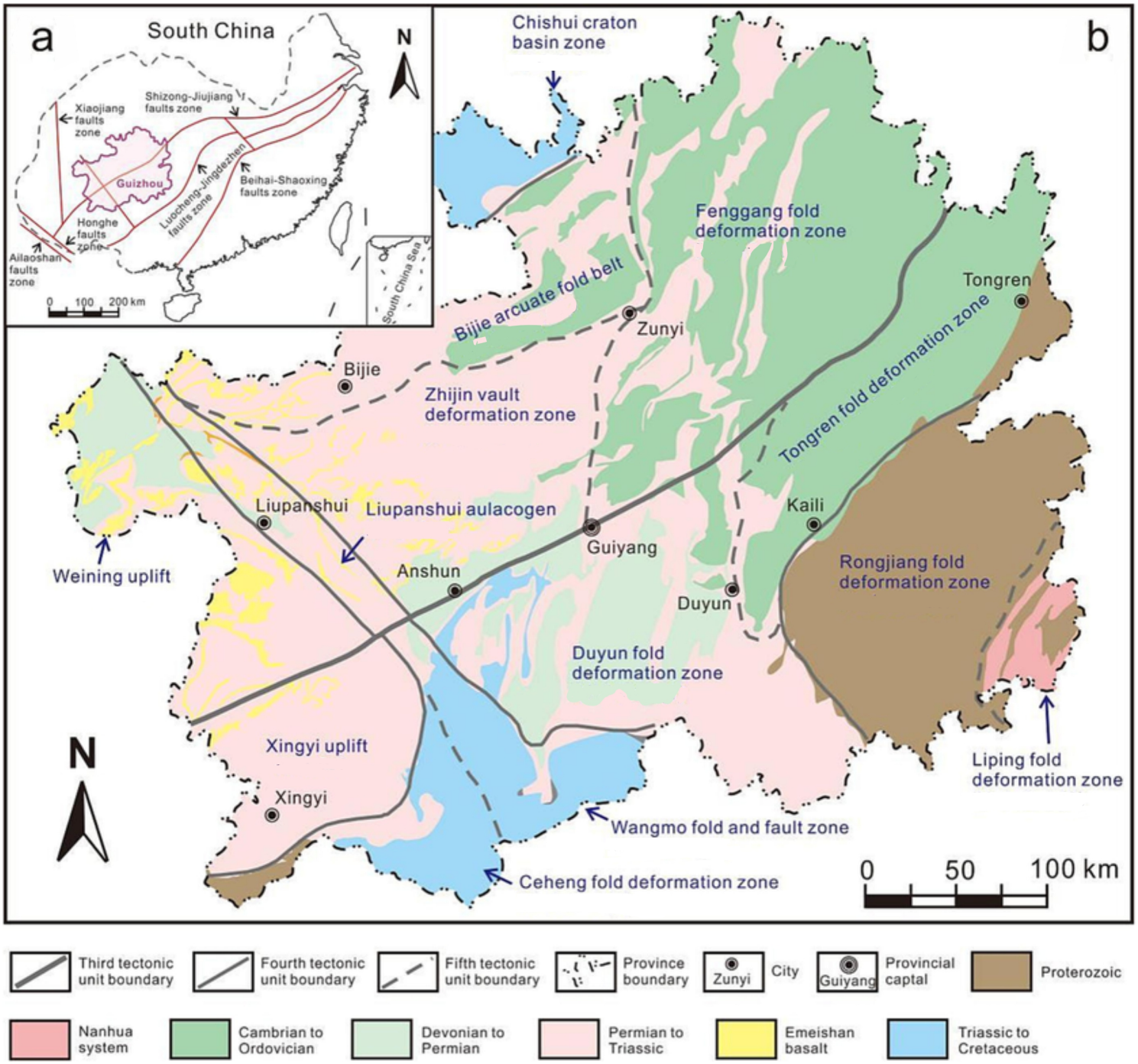


Figure 1

Geological map of structural belts in Guizhou Province

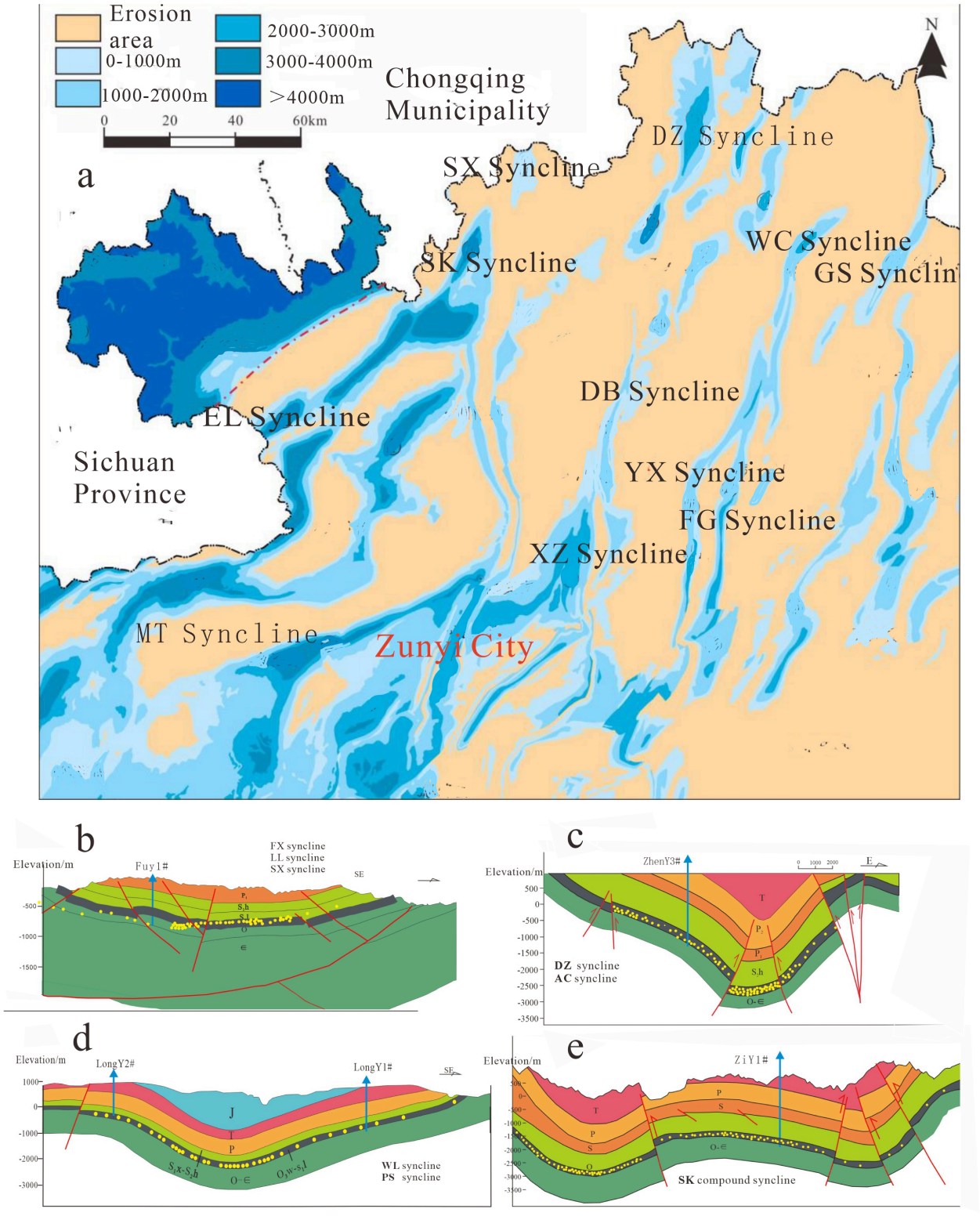


Figure 2

Position and Types of the Qianbei Syncline.

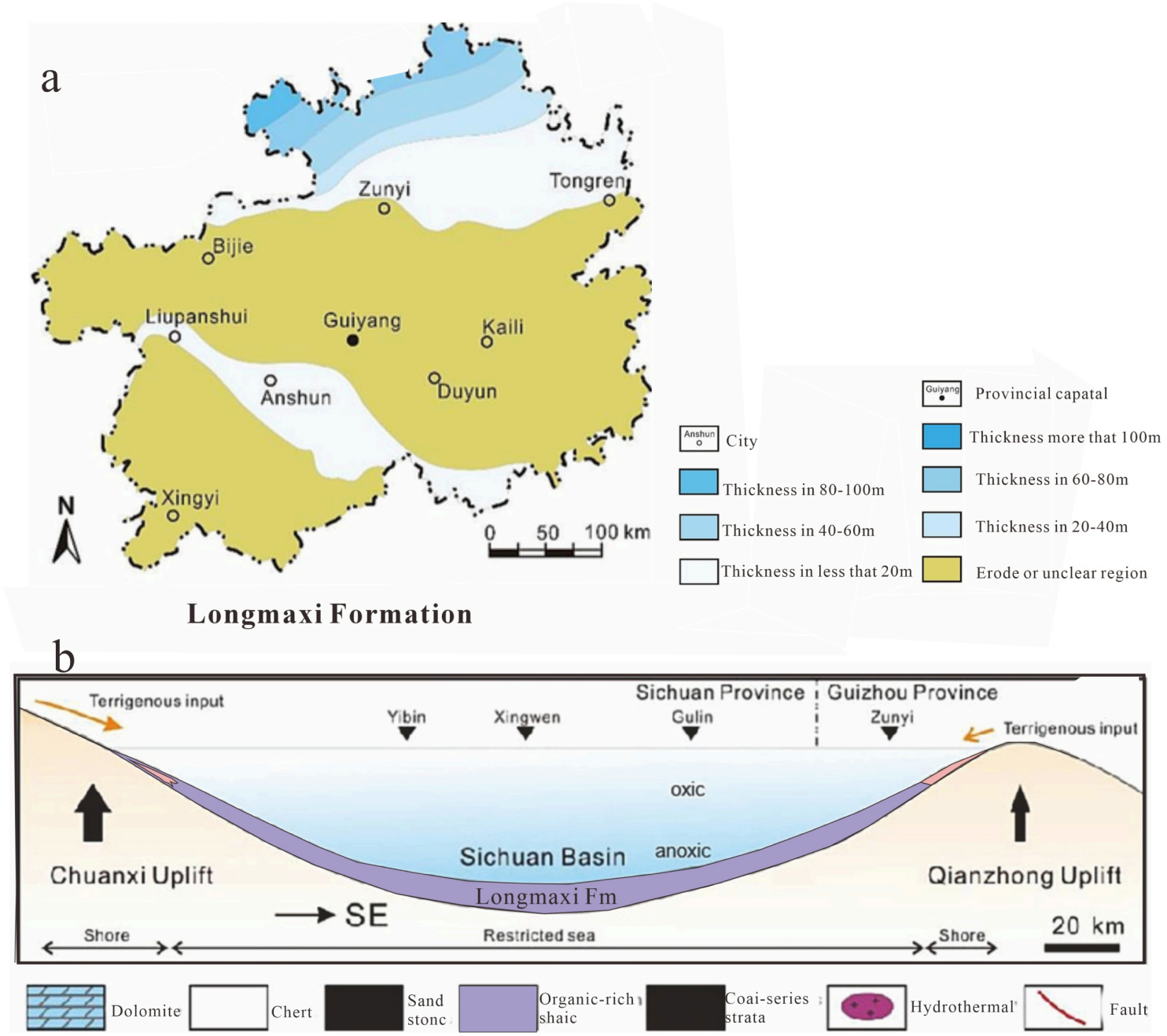


Figure 3

Isopach map of organic-rich shale thickness of the Wufeng-Longmaxi Formation, Guizhou.

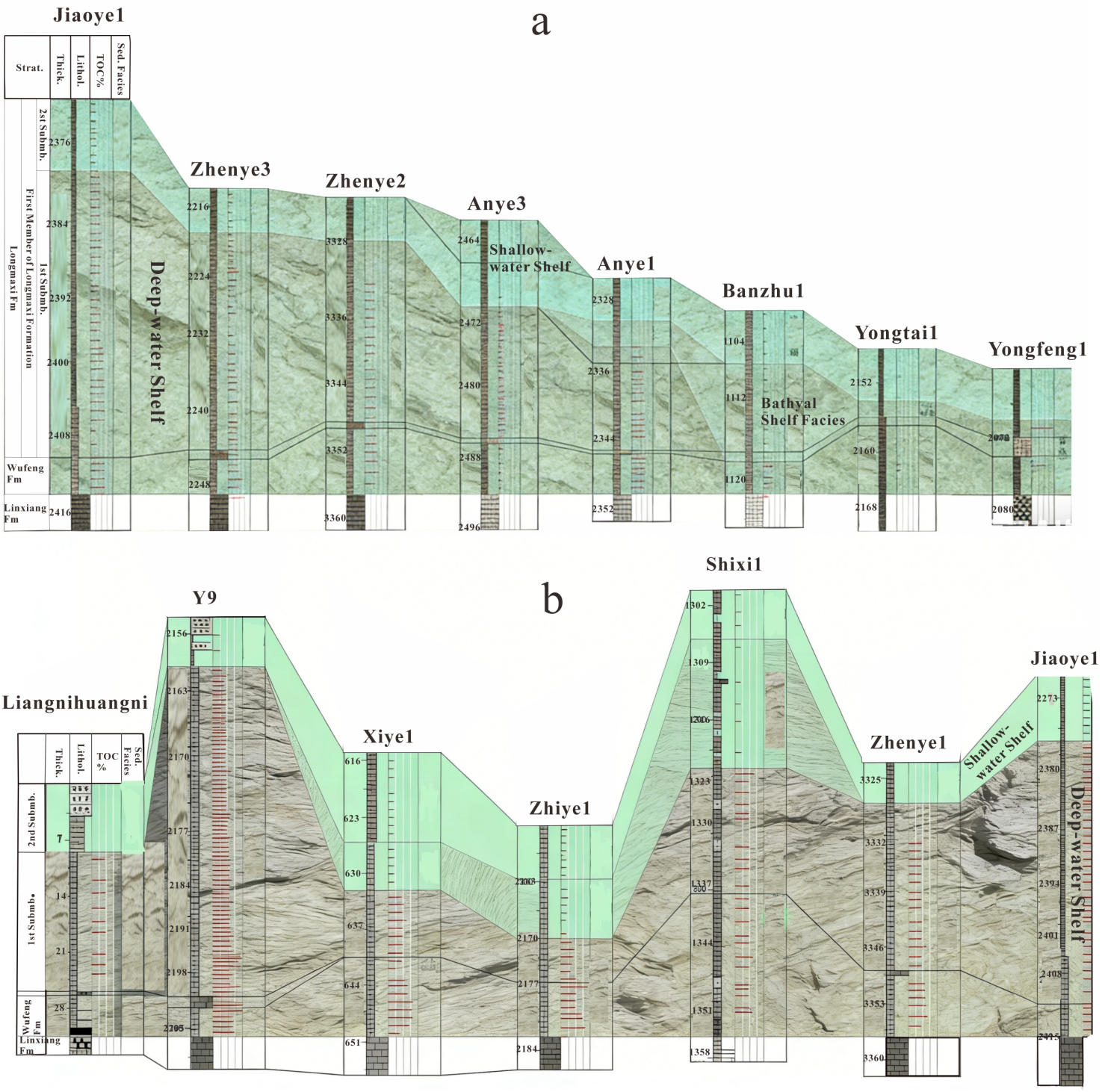


Figure 4

Interwell Correlation of Shale Wells in the Wufeng-Longmaxi Formation, Qianbei Mine.

Note: a represents the well tie section in the central part of northern Guizhou , and brepresents the well tie section in the northern part of northern Guizhou represents the well tie section in the central part of northern Guizhou.

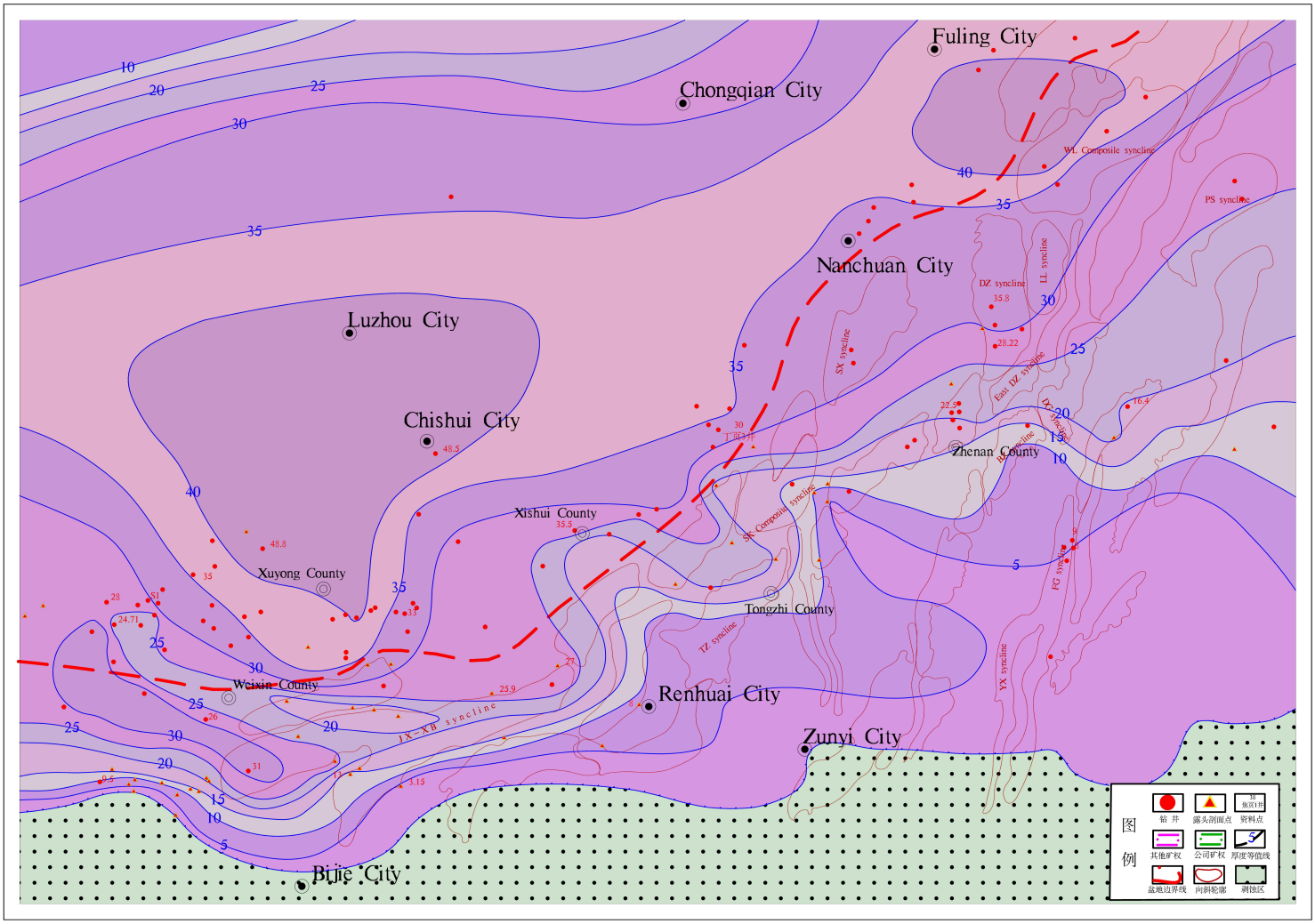


Figure 5

illustrates the thickness of high-quality, organic-matter-rich shale within the Wufeng-Longmaxi Formation, located in the northern Guizhou synclinal area.

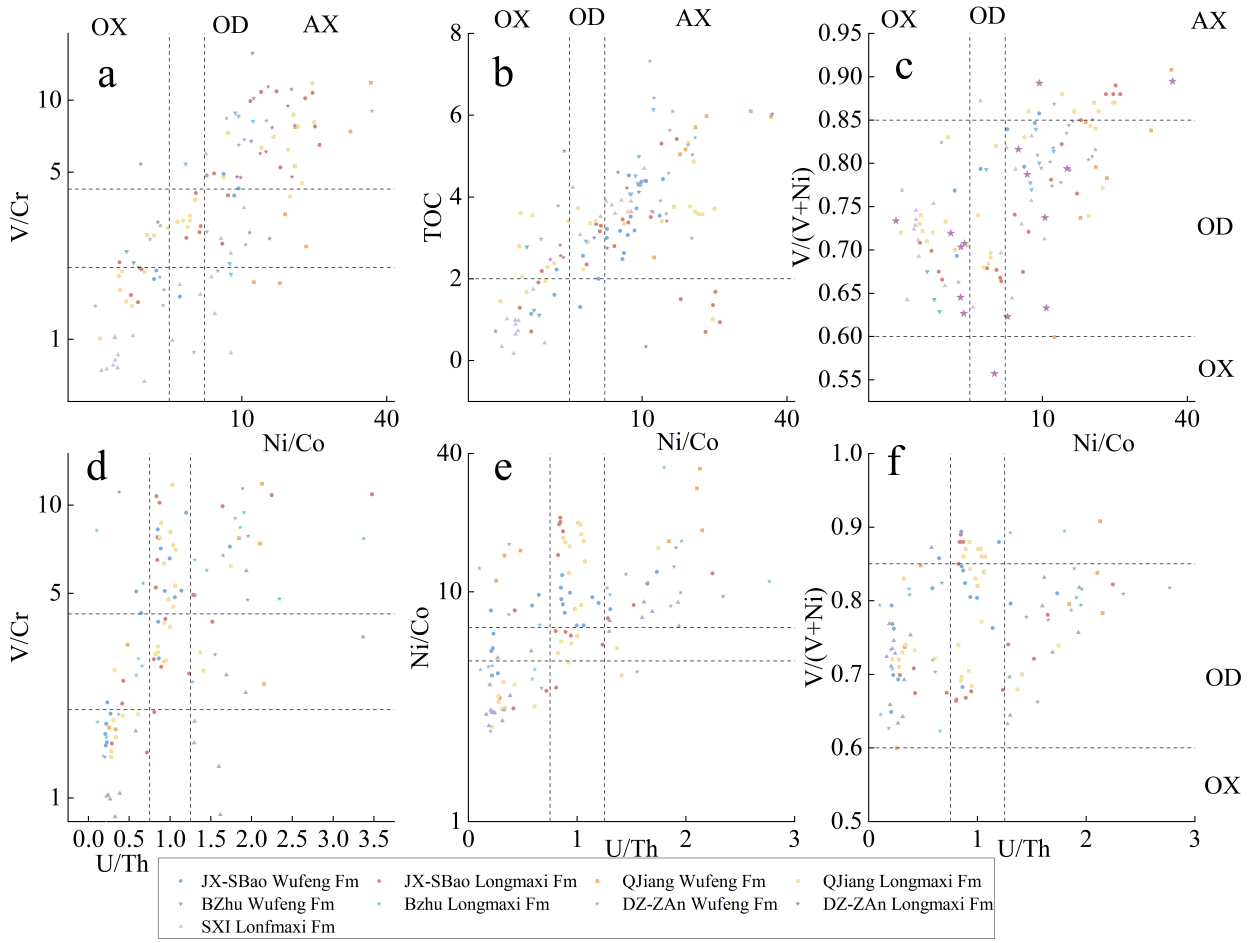


Figure 6

Oxidation Condition of Organic-Rich Shales in the Wufeng-Longmaxi Formations

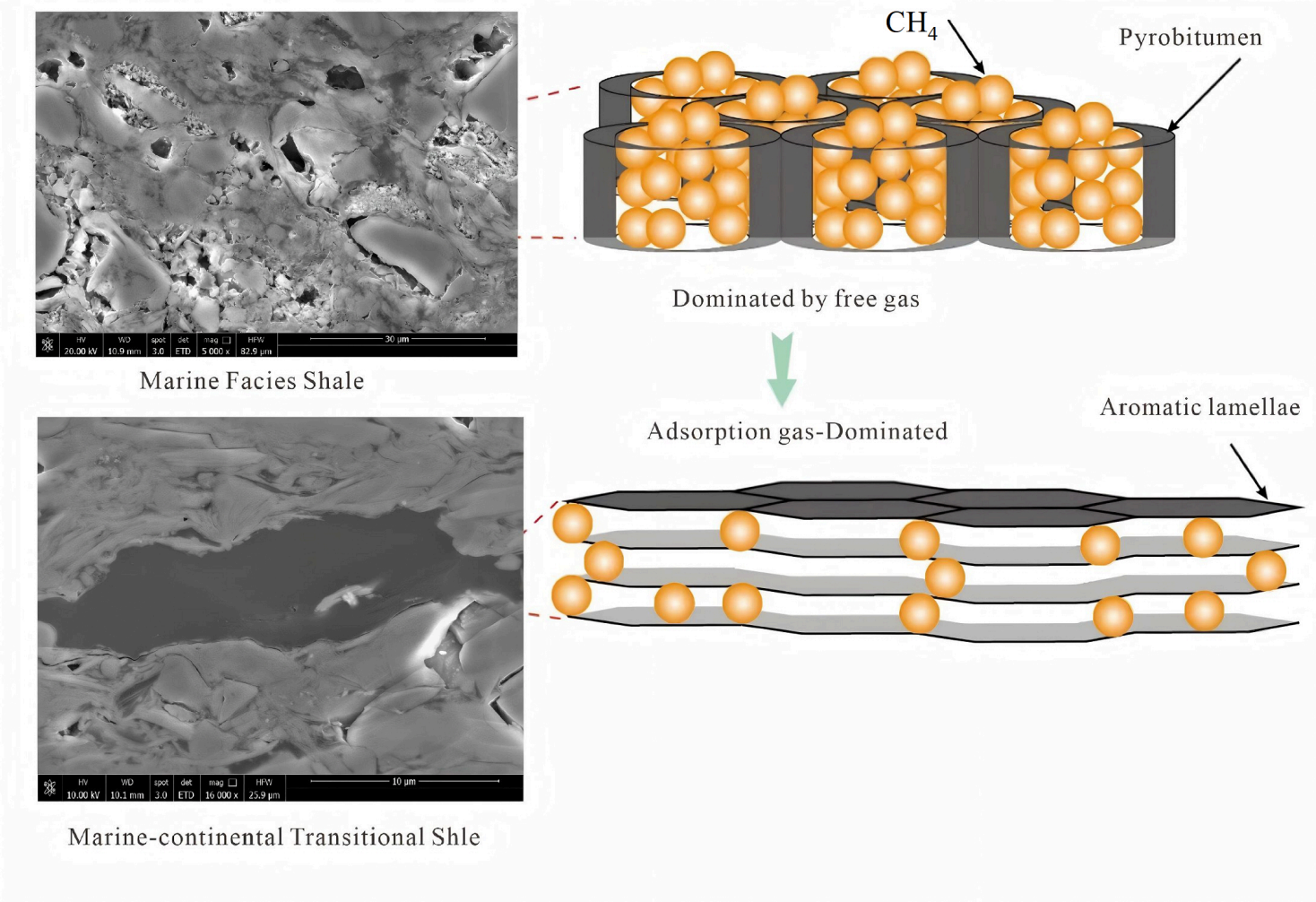


Figure 7

Pore and Gas Characteristics of the Wufeng-Longmaxi Formations Shale

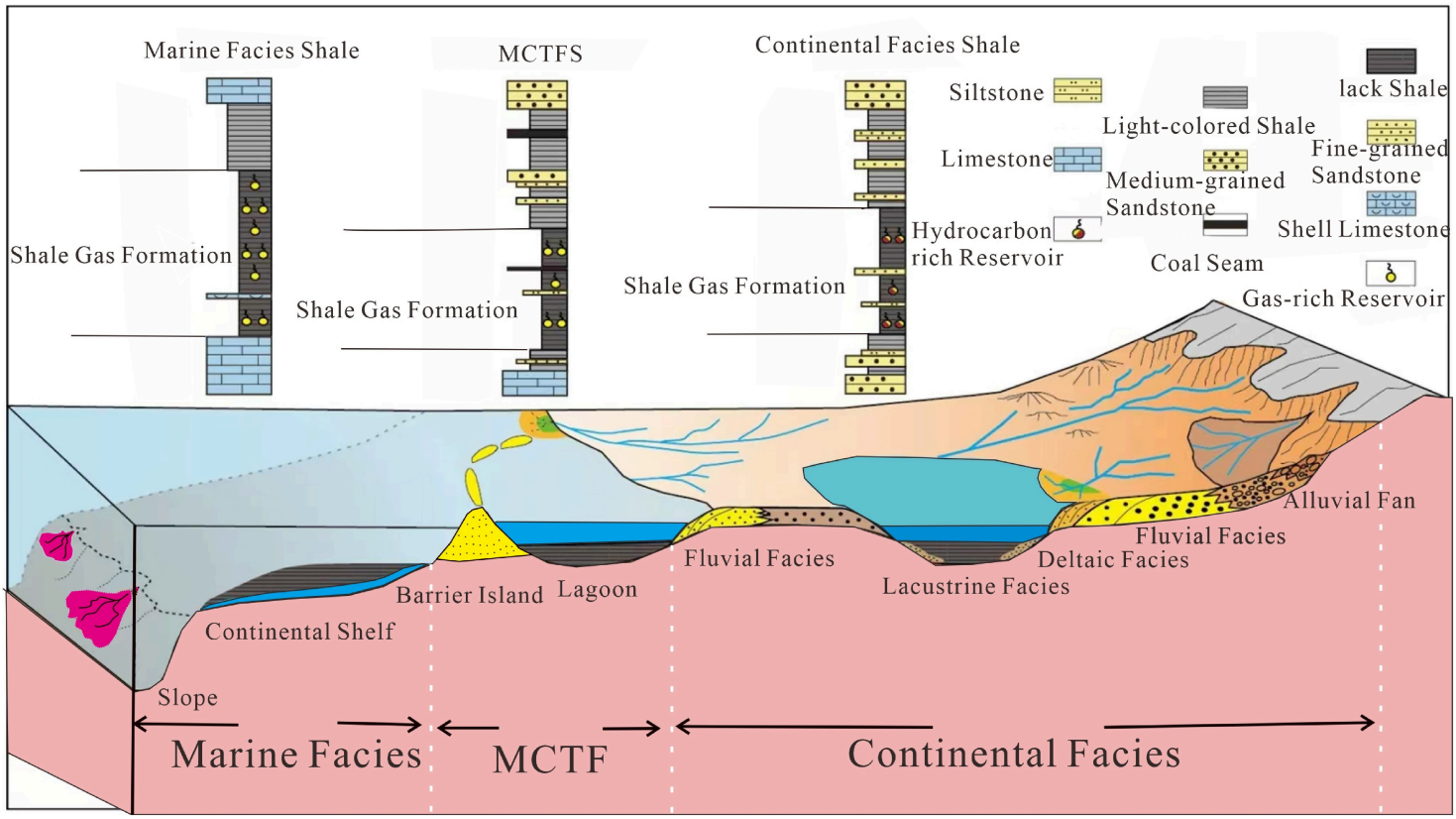


Figure 8

Sedimentary Characteristics of Three Major Types of Shale Gas Reservoirs (Continental, Marine, and Marine-Continental Transitional Facies)

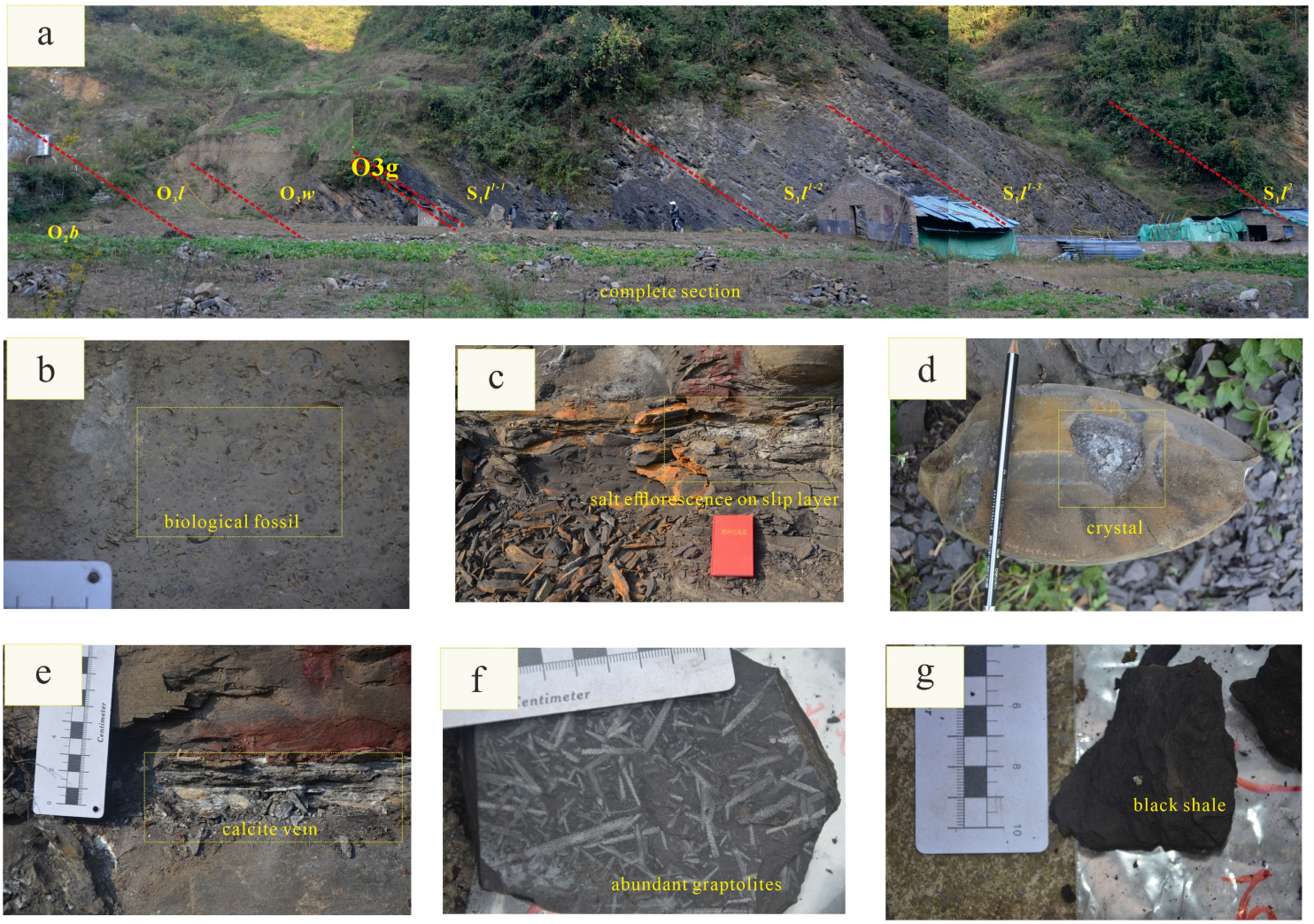


Figure 9

Stratigraphic information of the Wufeng-Longmaxi Formation

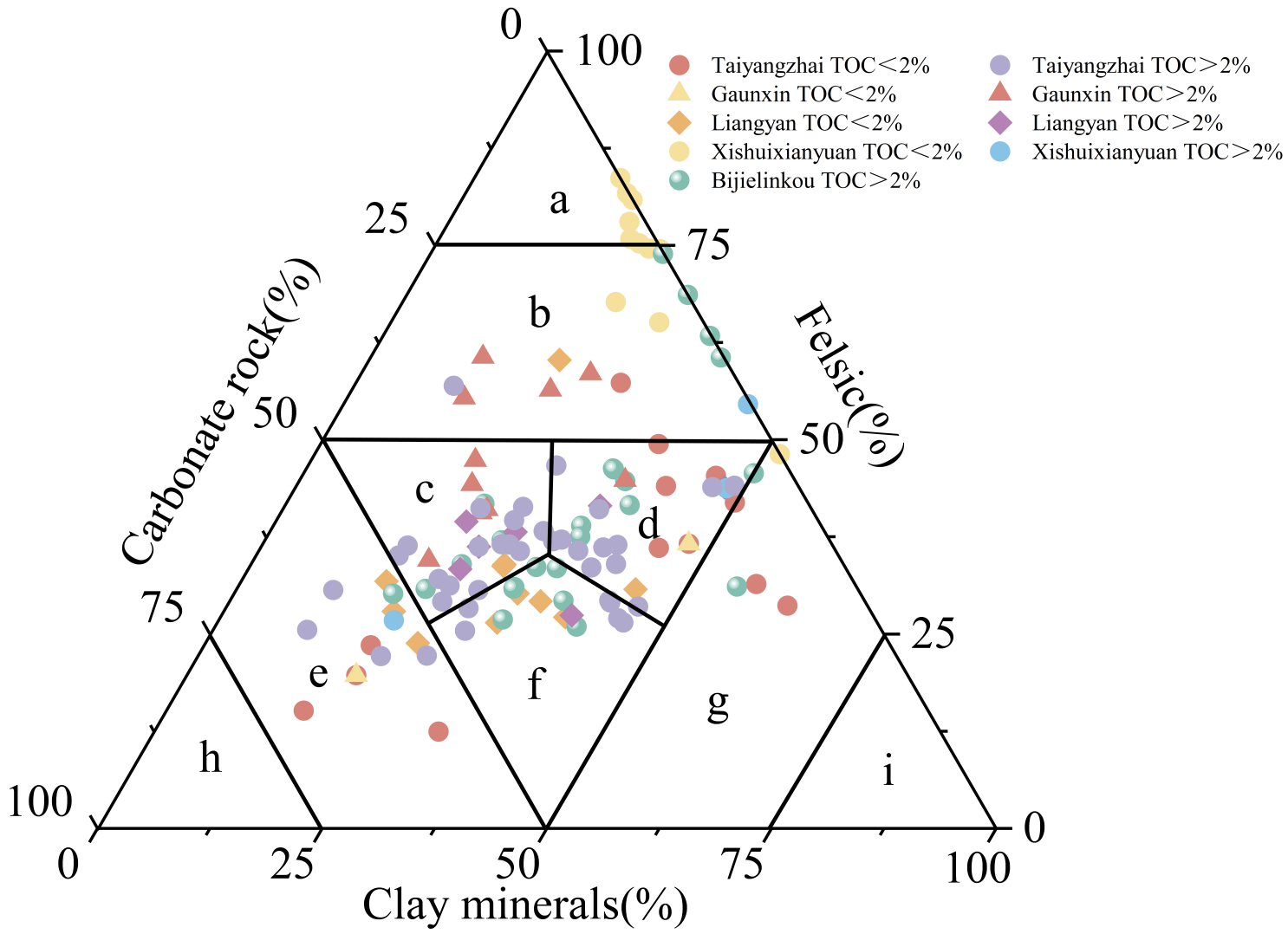


Figure 10

Mineralogical composition corresponding to TOC in northern Guizhou.

Note: (a) Chert; (b) Siliceous shale; (c) Calcareous siliceous shale; (d) Argillaceous siliceous shale; (e) Calcareous shale; (f) Argillaceous calcareous shale; (g) Argillaceous shale; (i) Argillite.

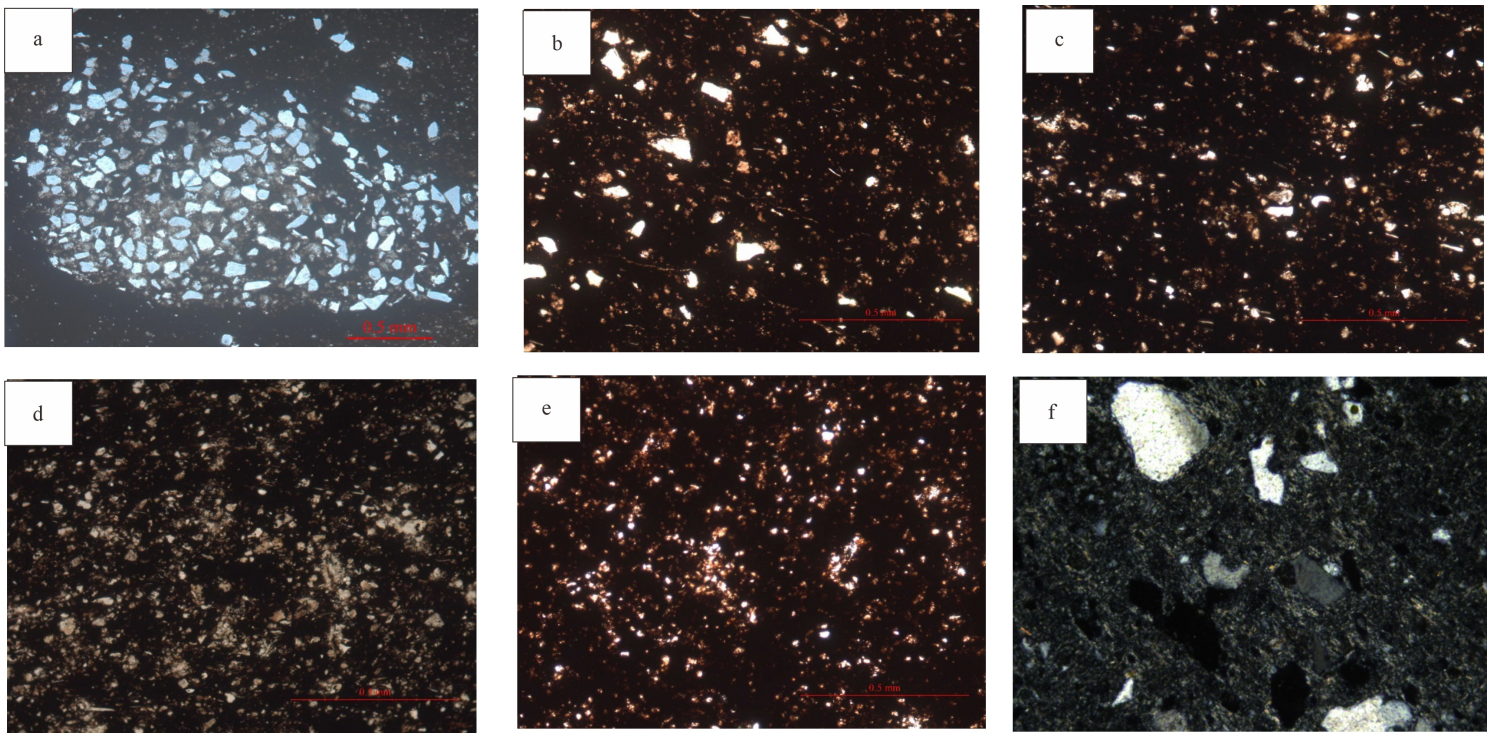


Figure 11

Mineral composition of shale thin sections from the Wufeng-Longmaxi Formation.

Note: a represents the Longmaxi Formation of Liangyan, Bijie. b represents the Longmaxi Formation of Lingkou, Bijie. c represents the Longmaxi Formation of Mula, Xuyong. d represents the Wufeng Formation of Liangyan, Bijie. e represents the Wufeng Formation of Lingkou, Bijie. f represents the Wufeng Formation of Mula, Xuyong.

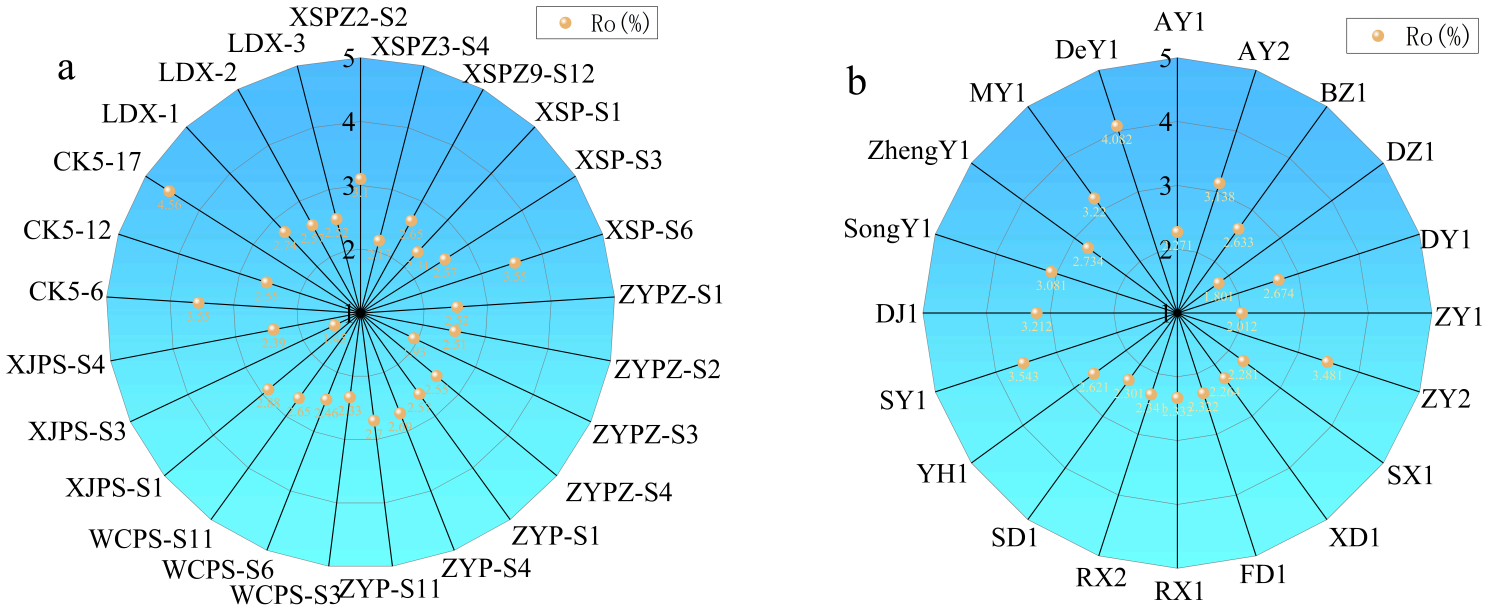


Figure 12

Rock cores and profile samples Ro from northern Guizhou

Note: a represents the vitrinite reflectance (Ro%) of the outcrop samples.b represents the vitrinite reflectance (R%) of the core samples.

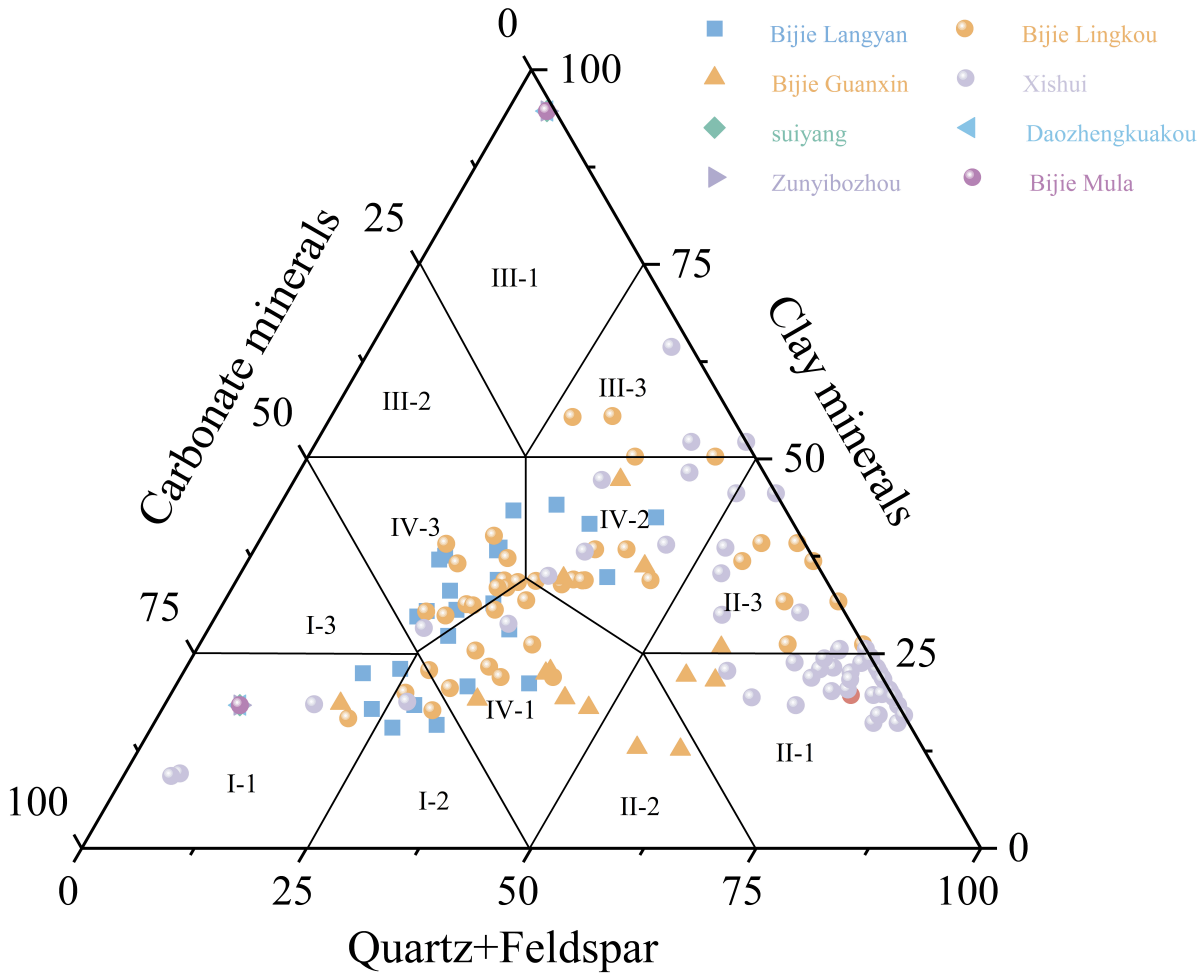


Figure 13

Trace Elements of Minerals in Northern Guizhou

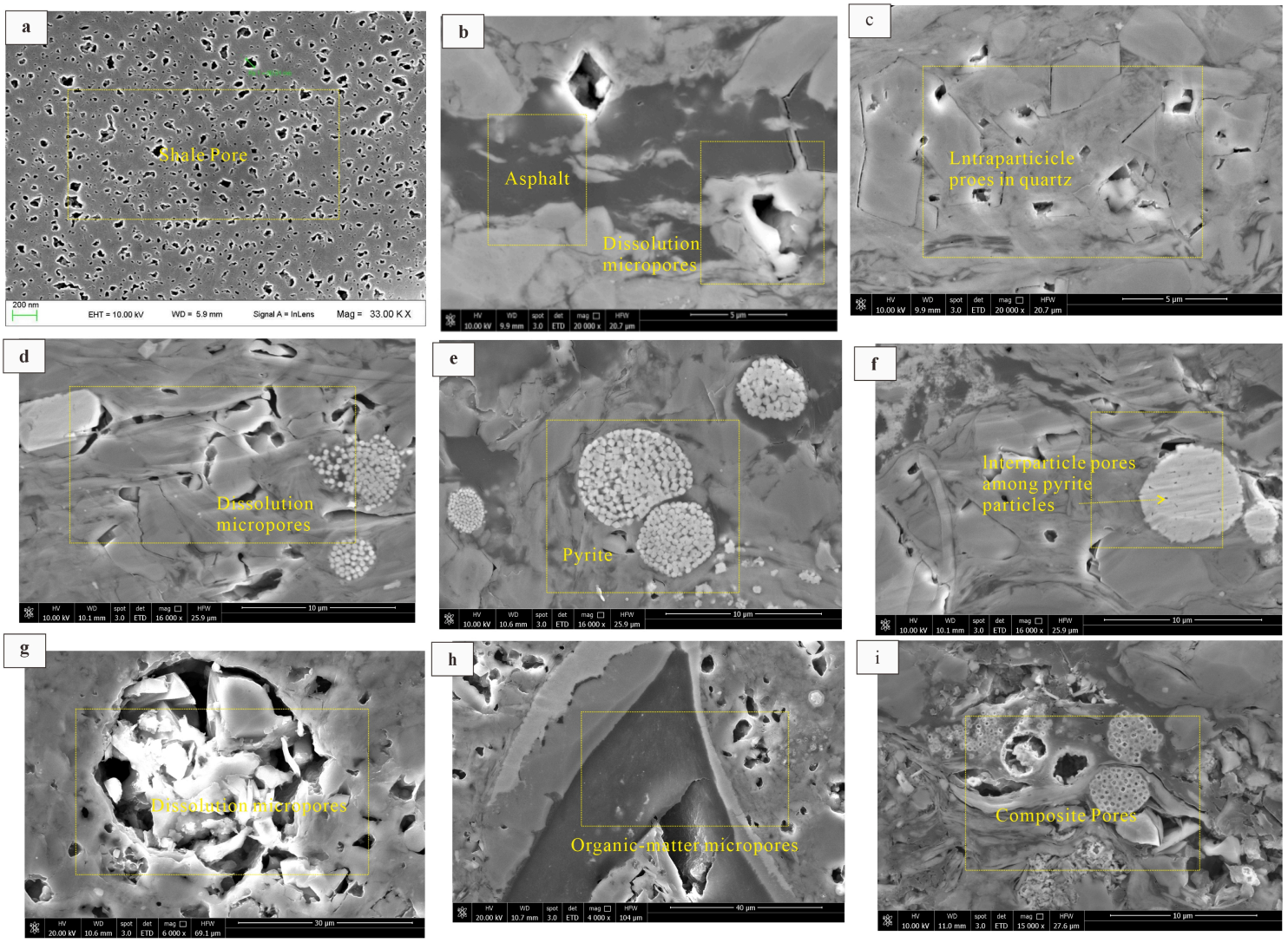


Figure 14

Pore structures of the Wufeng-Longmaxi Formation shales

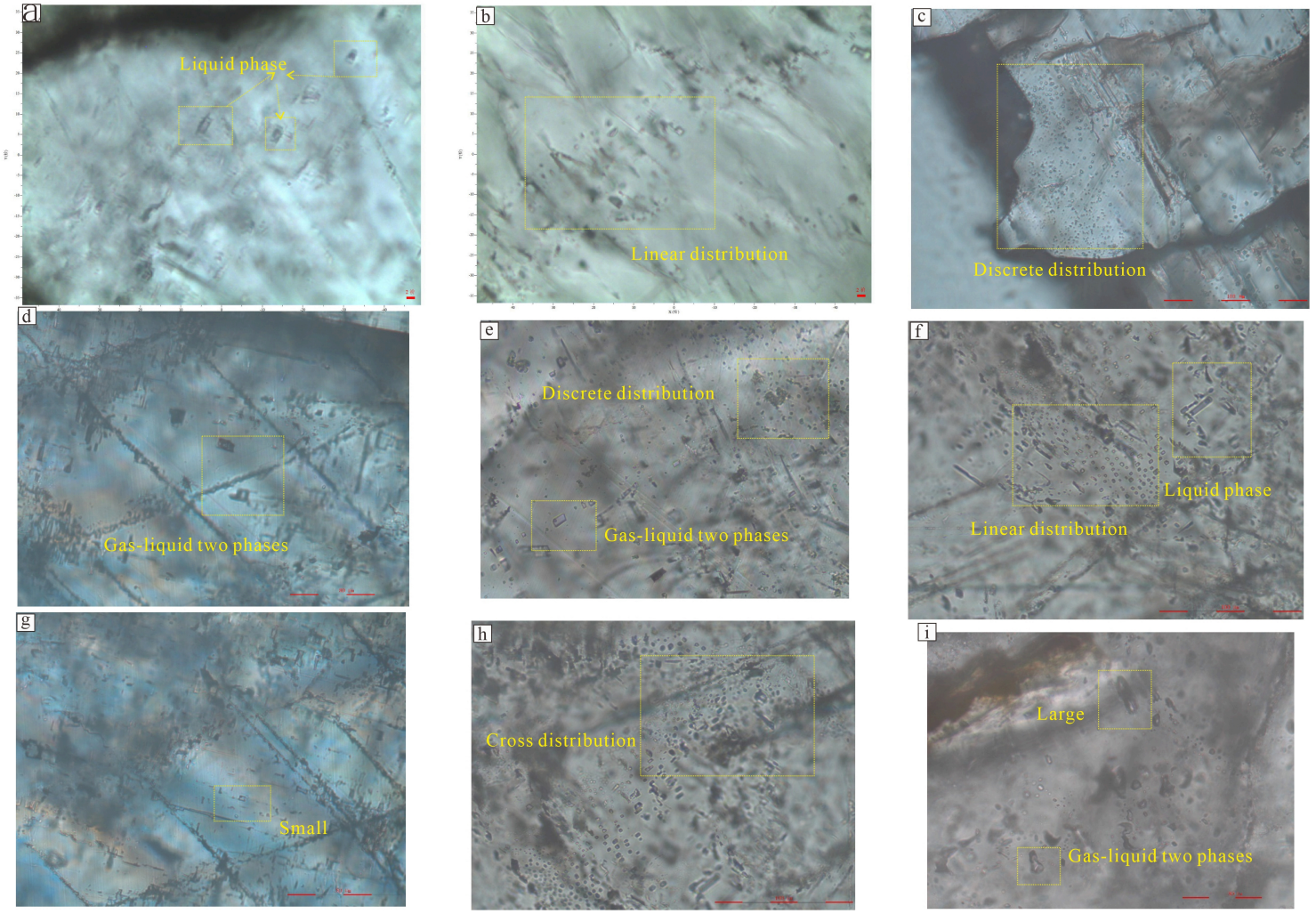


Figure 15

Calcite vein inclusions within the Wufeng-Longmaxi Formation

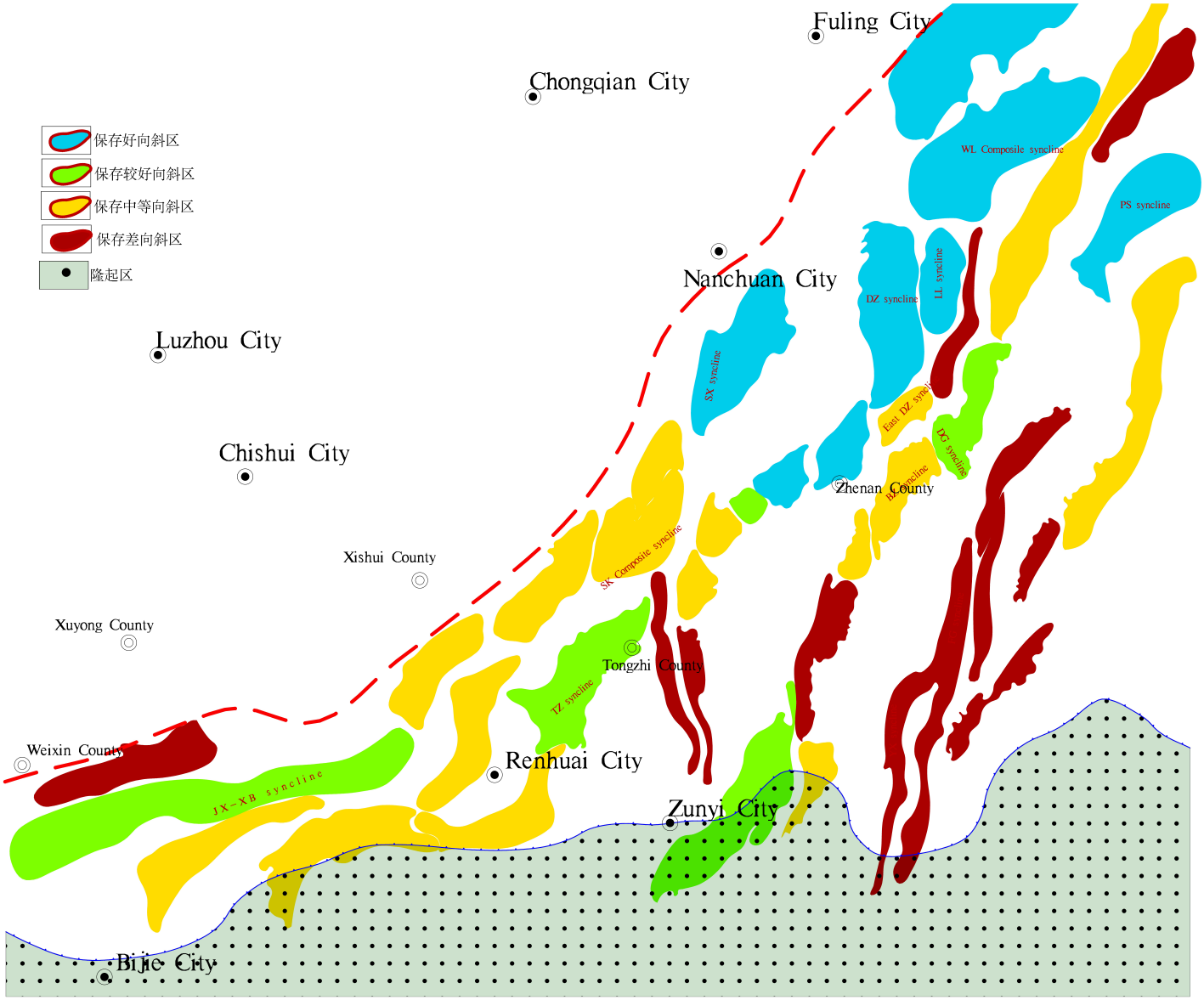


Figure 16

Evaluation of the Wufeng-Longmaxi Shale in Synclinal Areas of Northern Guizhou.

Supplementary Files

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