

Article

Geological Control Factors and Accumulation Patterns of Harmful Gas in Tunnels in Northwest Hunan, China, and the Sustainable Development of Tunnel Engineering

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Abstract

This research addresses the critical safety issue of harmful gas influx during tunnel excavation through unconventional gas-bearing structures. It focuses on six tunnels affected by shale gas influx along the Zhangnan Expressway of northwestern Hunan, China. The research reveals the geochemical characteristics, distribution patterns, and accumulation mechanisms of harmful gas in the shale formations of northwestern Hunan. The research adopts an integrated approach of “geological background analysis—multi-parameter testing—comprehensive evaluation”. It is based on geological and borehole data, field geological surveys, as well as laboratory and field tests. The research systematically analyzes the gas-bearing structural characteristics, geochemical parameters, and reservoir physical properties of the shale gas area in the Zhangnan Expressway. The geological regularities are summarized. The results show that the Longmaxi Formation of the Silurian system and the Qixia Formation of the Permian system serve as source rocks in the tunnel sites. The reservoirs are characterized by ultra-low porosity and permeability, with limited late-stage hydrocarbon generation potential. The gas-related hazard during tunnel construction and operation is primarily associated with the release of existing free and adsorbed gas. According to the calculation standards for absolute gas emission rates during construction, three tunnels are classified as micro-gas tunnels and three as non-gas tunnels. Two accumulation patterns are proposed: the self-sourcing composite accumulation pattern with micro-scale migration, and the accumulation pattern of self-generated and self-storage type of water pressure confinement. Enhanced monitoring, ventilation, and grouting sealing are recommended. This study develops an integrated “geology—testing—evaluation” assessment method for shale-gas-bearing tunnels. It provides important guidance for controlling harmful gas hazards in such tunnels and guaranteeing the sustainable development of tunnel construction.

Keywords: tunnel engineering; shale gas; source rock; geological characteristics; accumulation pattern

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1. Introduction

Highway tunnel engineering constitutes a vital component of modern transportation infrastructure. Its development plays a significant role in enhancing urban transportation efficiency and promoting economic growth. Tunnel engineering is growing larger and more complex, both domestically and internationally. Meanwhile, harmful gas leaks in complex geology are becoming more common. For example, the Sylmar Tunnel in the United States exploded when it exposed gas while traversing a fault zone, resulting in the deaths of 17 people; Italy's Great Apennine Tunnel was passing through carbon-rich shale, which triggered a fire and multiple explosions, causing 97 fatalities; the Dongjiashan Tunnel in China experienced multiple fires and one explosion while traversing coal-bearing strata, resulting in the deaths of 44 people. These cases show that gas tunnels face risks in conventional oil and gas structures. They are also at risk when passing through unconventional formations, like coal seams and shale layers.

Geological structures and strata distribution are key to assessing gas hazards. To understand gas distribution in complex tectonic settings, previous studies have established three primary controlling mechanisms: (i) fault-controlled gas migration, where fracture zones and fault systems act as efficient vertical and lateral conduits for gas movement [1–6]; (ii) source-rock characteristics, particularly total organic carbon content, kerogen type, and thermal maturity, which determine the hydrocarbon generation potential [7–11]; and (iii) cap rock sealing efficiency, where overlying tight formations and hydrodynamic confinement govern gas preservation and accumulation [12–16]. These mechanisms have been widely documented in both Chinese and international contexts, providing a robust framework for evaluating gas hazards in tunnel engineering. Su Peidong and his team, through a series of case studies in structurally complex areas [17–32], systematically demonstrated that harmful gases primarily migrate through fault zones and accumulate in fracture zones, forming localized high-pressure gas pockets with sac-like migration patterns. Zhang Xiaolin and his team studied the Longquanshan structure in Sichuan Basin. They used noble gas isotopes and biomarker experiments. Results show that shallow gas comes from the underlying Triassic Xujiahe Formation sandstone. This is a quality source rock. Together with the overlying Suining and Shaximiao Formations, it creates a complete source–reservoir–cap system. Faults provide effective migration pathways. This combination allows harmful gases to accumulate and persistently threaten tunnels [33]. Wang Hailin's team, based on extensive monitoring data from coal-bearing strata tunnels [34–46], proposed comprehensive control measures, including ventilation optimization and grouting sealing. Zhang Xuying's group, through multiple field investigations [47–55], documented two typical migration patterns: vertical flow through steep fractures and lateral movement through high-porosity sandstones.

Hunan Province has widespread natural gas resources. The central-southeastern region is rich in coalbed methane; the northwestern region holds primarily shale gas. In Central and Southeastern Hunan, coalbed methane centers on the Baisha–Matian Mining Area. There are three high-concentration areas: the Longtan Formation in Southeastern Hunan, and the Longtan and Ceshui Formations in Central Hunan. Northwestern Hunan has substantial shale gas potential. The estimated resource range is $5.5 \times 10^{12} \text{ m}^3 \sim 8.5 \times 10^{12} \text{ m}^3$. The region's marine mud-shale strata, distributed along the Shimen–Cili–Zhangjiajie–Yongshun–Huayuan belt, hold significant exploration promise. The main shale gas layers are found in three formations: the Lower Cambrian Niutitang, Lower Silurian Longmaxi, and Lower Carboniferous Ceshui. These layers are primarily composed of organic-rich black carbonaceous and siliceous shale. Structurally, Hunan Province can be divided into two distinct regions. Northwestern Hunan features broad, gentle folds with moderately developed faults. In contrast, central-southern Hunan is characterized by tight, box-shaped folds and extensively developed fault systems. The Zhangnan Expressway is lo-

cated in northwestern Hunan, with numerous tunnels along its route. These tunnels primarily pass through the Permian Maokou and Qixia formations, and the Silurian Luoreping Formation. Among these, the Luoreping Formation, along with the underlying Cambrian Niutitang and Silurian Longmaxi formations, are all major source rocks. Existing research confirms that harmful gas can migrate upward through joint fractures. This poses significant accident risks to tunnels along the route. Current literature shows gas hazards in this area mainly occur in shallow zones with low concentrations. These typically involve single-source gases, like coalbed methane, in conventional reservoirs. Research relies heavily on traditional methods: core analysis, petrophysics, and well logging. However, studies are lacking on tight, deep mudstone reservoirs with dual-porosity systems. This gap hinders risk assessment for tunnels crossing unconventional strata. This research provides safety guidelines for similar zones by studying six tunnels along the Zhangnan Expressway and guaranteeing the sustainable development of tunnel construction.

2. Research Background

The Zhangnan Expressway is a vital component of national and Hunan provincial highway networks. Its Sangzhi section begins in Hongjiaguan Township, passing through Chenjiahe Town and Shanghexi Township. It then enters Longshan County, connecting with the existing Zhangjiajie–Sangzhi and Longshan–Yongshun expressways. The total length of this section is approximately 61.45 km. All six tunnels are located in a dissected mid-mountain landscape with prominent relief. The terrain exhibits steep slopes, deep valleys, and fragmented rock formations. The tunnel axes cross the topographic contours at a large oblique angle. A thin layer of overburden covers the slopes, leaving bedrock extensively exposed.

Tectonically situated in the Yangtze Platform's Hubei–Guizhou Belt (Figure 1), the region experienced multi-phase deformation. This created the characteristic NNE–NE structural grain of mountains and basins, with well-developed fold and fault systems. Bounded by the Hefeng and Sangzhi anticlinoria, the study area features folds with a NE–SW orientation. Neotectonic effects are manifested in multi-level planation surfaces and fluvial terraces. This geomorphology evidences a tectonic regime dominated by intermittent uplift.

The local stratigraphy and lithology are complex. The main outcrops include the Upper Silurian Shamao Group, the Upper-Middle Devonian, and the Lower Permian Maokou, Qixia, and Maon formations. The main lithologies are sandy shale, shale, quartz sandstone, and limestone. Among these, the Qixia Formation serves as a source rock. It contains a 3-m interlayer of carbonaceous mudstone. This formation is dense, making it a good natural gas cap rock. The strata have gentle dip angles, and the source rock is directly connected to the surface, allowing strong lateral migration. Local faults and well-developed fractures are also present.

On 18 February 2025, a welding spark ignited a fire at the bench face of Leijiashan Tunnel (Figure 1). The fire burned for two days before extinguishing. Gas concentration in advance boreholes repeatedly exceeded 20%, reaching a maximum of 84.4%. This posed an extremely high risk to construction safety. Intensive gas monitoring was conducted in all six tunnels along the Sangzhi section. Results confirmed gas presence in every tunnel. The highest harmful gas concentrations were recorded in Leijiashan and Chenjiapo Tunnels. In this area, harmful gases are primarily located in Silurian to Triassic strata (Figure 1), influenced by lithology and faults. The rocks are mainly source rocks like grey-black carbonaceous and sandy shale. Gas migrates upward through open fault fractures and is trapped by overlying unconformities and dense quartz sandstone cap rocks. Remeasure-

ment in an investigation borehole at Leijiashan Tunnel, 24 h after sealing, showed a maximum gas concentration of 103 ppm.

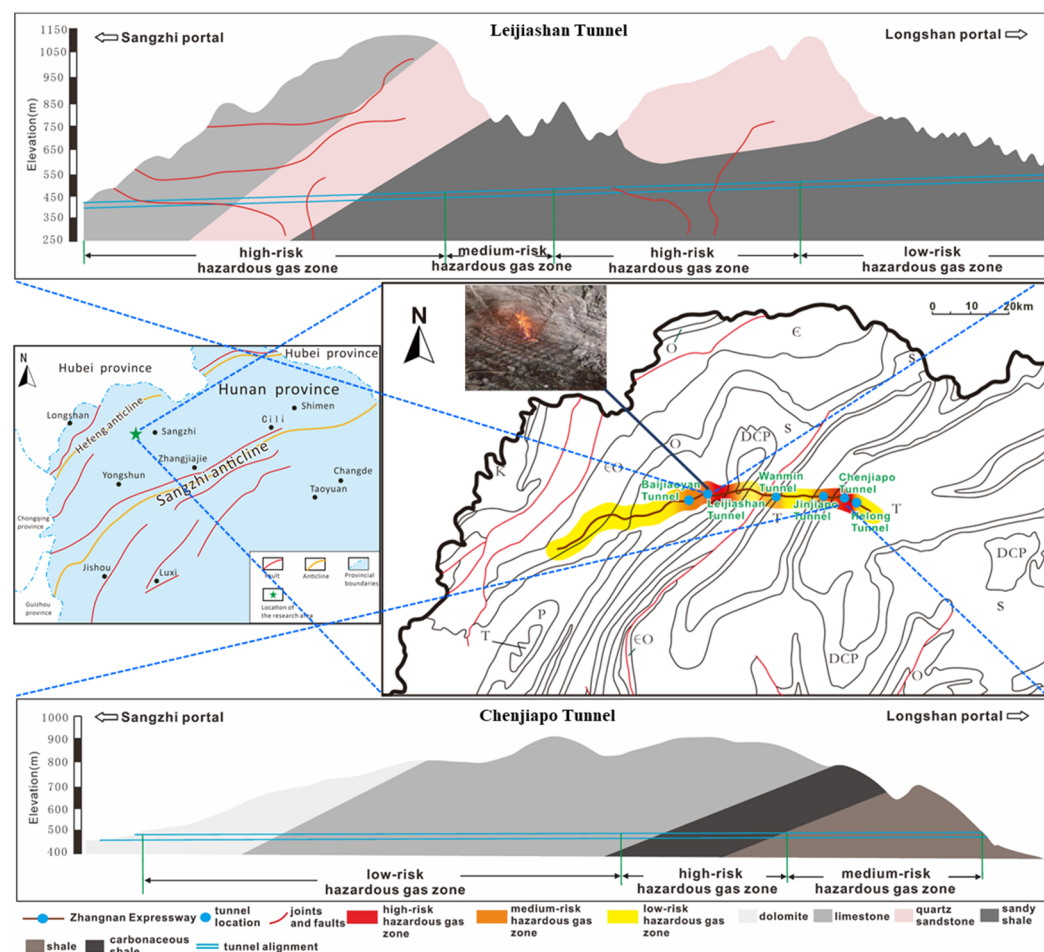


Figure 1. Harmful gas volume fraction distribution and regional tectonic outline of the Zhangnan Expressway.

3. Materials and Methods

3.1. Study Area and Sample Collection

The study area is the Sangzhi section of the Zhangnan Expressway in northwestern Hunan, China. Six tunnels affected by shale gas influx were investigated. Fourteen boreholes were drilled, and 14 core samples were collected from these tunnels. The cores were used for laboratory analysis of geochemical parameters and reservoir properties. From these 14 core samples, 16 representative plug samples were selected for porosity and permeability tests, of which 13 were successfully measured (three samples failed during preparation due to limited core volume or sample integrity issues). In addition, 26 samples were selected for desorption tests (with 1–3 samples per borehole). A comprehensive sample inventory listing tunnel name, borehole number, depth interval, lithology, and types of analyses performed for each sample is provided in Appendix A Table A1.

3.2. Laboratory Tests

3.2.1. Geochemical Analysis

Three geochemical parameters were measured: total organic carbon (TOC), kerogen type, and Rock-Eval pyrolysis maximum temperature (Tmax).

TOC content was determined using a LECO CS230 carbon–sulfur analyzer (LECO Corporation, St. Joseph, MI, USA). Rock samples were ground to 200 mesh (<75 µm). The

pulverized samples were treated with dilute hydrochloric acid (HCl, 1:4) to remove inorganic carbonates. After acid treatment, the samples were rinsed with deionized water to neutral pH and dried at 60 °C. The dried samples were combusted in an oxygen furnace at 1350 °C, and the evolved CO₂ was measured by infrared detection. Calibration was performed using LECO certified reference materials. Routine inclusion of blanks and replicate analyses was conducted for quality control. Analytical precision for TOC determination is typically within ± 0.5 wt% for samples with TOC > 1% and relative standard deviation <5% for lower concentrations. This uncertainty is relative, and all reported values in Table 1 have been rounded to reflect the appropriate significant figures for the analytical methods used. The TOC determination procedure follows the standard method for sedimentary rocks [56].

Table 1. Statistics of geochemical parameters of tunnel strata along the Sangzhi section of the Zhangnan Expressway.

Sampling Point	Sample Number	Lithology	Geochemical Parameters								
			TOC (wt%)	Tmax/(°C)	S ₁ (mg/g. Rock)	S ₂ (mg/g. Rock)	S ₃ (mg/g. Rock)	PI	OI (mg/g. TOC)	HI/(mg /g.TOC D/(%))	
Leijiashan Tunnel	LJS-05-1	Sandstone	0.08	465.3	0.04	0.10	0.18	0.29	217.4	125.0	175.0
	LJS-05-2	Sandstone	0.12	331.6	0.03	0.08	0.22	0.27	177.8	66.7	91.7
Chenjiapo Tunnel	CJP-04-1	Limestone	0.74	475.3	0.05	0.12	0.28	0.29	37.9	16.2	23.0
	CJP-04-2	Carbonaceous shale	5.92	441.2	0.15	0.85	0.32	0.15	5.4	14.4	16.9
	CJP-04-3	Carbonaceous shale	5.65	464.5	0.12	0.70	0.30	0.15	5.3	12.4	14.5
	CJP-04-4	Dolomite	0.49	373.7	0.06	0.15	0.20	0.29	40.9	30.6	42.9
Jinjiapo Tunnel	JJP-03-1	Limestone	0.13	442.4	0.04	0.12	0.24	0.25	179.5	92.3	123.1
	JJP-03-2	Limestone	0.22	395.8	0.06	0.15	0.28	0.29	127.6	68.2	95.5
	JJP-03-3	Limestone	0.10	487	0.07	0.14	0.25	0.33	241.5	140.0	210.0
Baiyanjia Tunnel	BJY-03-1	Limestone	0.19	388.7	0.07	0.13	0.28	0.35	145.7	68.4	105.3
	BJY-03-2	Grey-green shale	0.11	494.9	0.08	0.11	0.30	0.42	276.8	100.0	172.7
Helong Tunnel	HE-05-1	Carbonaceous limestone	1.06	422.8	0.08	0.14	0.35	0.36	33.0	13.2	20.8
	HE-05-2	Carbonaceous limestone	1.31	468.3	0.14	0.45	0.32	0.24	24.5	34.4	45.0
	HE-05-3	Carbonaceous limestone	0.80	464.5	0.08	0.20	0.28	0.29	34.9	25.0	35.0
Wanmin Tunnel	WM-04-1	Limestone	0.85	479.5	0.09	0.22	0.25	0.29	29.4	25.9	36.5
	WM-04-2	Limestone	0.44	490.8	0.06	0.18	0.24	0.25	54.4	40.9	54.6

Note: Measurement uncertainties are based on instrument specifications: TOC $\pm 0.5\%$, HI $\pm 3\%$, D (%) $\pm 3\%$, and Tmax ± 2 °C. All values are rounded to reflect reasonable significant digits for the analytical methods used.

Kerogen types were identified by maceral analysis using transmitted-light microscopy. Kerogen was separated from rock samples by standard acid digestion (HCl and HF) followed by heavy liquid separation. The relative contents of four maceral groups—sapropelinite (A), exinite (B), vitrinite (C), and inertinite (D)—were determined by point-counting under a polarizing microscope (DM4 P, Leica Microsystems, Germany, Wetzlar). The kerogen type index (T) was calculated using the following formula:

$$T = \frac{100A + 50B - 75C - 100D}{100} \quad (1)$$

Kerogen types were classified according to the T index: Type I ($T > 80$), Type IIA ($40 < T \leq 80$), Type IIB ($0 < T \leq 40$), and Type III ($T \leq 0$).

Rock-Eval pyrolysis was performed using a Rock-Eval 6 pyrolyzer (Vinci Technologies, Rueil-Malmaison, France). Approximately 50–100 mg of whole-rock powder was heated in an inert atmosphere (helium) following a standard temperature program: initially at 300 °C for 3 min, then pyrolyzed from 300 °C to 650 °C at 25 °C/min. The hydrocarbon products released during pyrolysis (S_1 and S_2 peaks) were detected by a flame ionization detector (FID). CO and CO₂ released during oxidation (S_3 peak) were measured by infrared detectors. Tmax was recorded as the temperature at which the S_2 peak reached its maximum. The following primary Rock-Eval parameters were obtained: S_1 (free hydrocarbons, mg HC/g rock), S_2 (remaining hydrocarbon potential, mg HC/g rock), and S_3 (organic CO₂, mg CO₂/g rock). TOC was determined separately as described above. The hydrogen index ($HI = S_2/TOC \times 100$, mg HC/g TOC), oxygen index ($OI = S_3/TOC \times 100$, mg CO₂/g TOC), production index ($PI = S_1/(S_1 + S_2)$), and degradation potential ($D = (S_1 + S_2)/TOC \times 100$, %) were calculated from the primary Rock-Eval data and TOC.

3.2.2. Petrological Property Tests

Porosity and permeability were tested on 16 core plug samples prepared from the 14 borehole cores, of which 13 yielded valid measurements (Table 2). Porosity was measured using a helium porosimeter (PoroPDP-200, Core Laboratories, Houston, TX, USA). Permeability was determined by the steady-state method using a gas permeameter (PDP-200, Core Laboratories, Houston, TX, USA). The lithology of each sample was identified by visual inspection and confirmed by thin-section analysis under a polarizing microscope (DM4 P, Leica Microsystems, Germany, Wetzlar).

Table 2. Statistics of lithologic parameters of tunnel strata along the Sangzhi section of the Zhangnan Expressway.

Sampling Point	Sample Number	Sampling Depth/(m)	Lithology	Porosity/(%)	Permeability/(mD)
Leijiashan Tunnel	LJS-05-1	118.31–118.47	Sandstone	1.58	0.0019
	LJS-05-2	157.42–157.68	Sandstone	0.51	0.0016
Chenjiapo Tunnel	CJP-04-1	91.33–91.47	Limestone	1.46	0.0044
	CJP-04-2	146.37–146.50	Carbonaceous shale	/	/
	CJP-04-3	154.70–155.00	Carbonaceous shale	/	/
	CJP-04-4	175.10–175.21	Dolomite	1.36	0.0055
Jinjiapo Tunnel	JJP-03-1	140.73–141.00	Limestone	2.06	0.0049
	JJP-03-2	169.04–169.22	Limestone	0.40	0.0039
	JJP-03-3	193.92–194.13	Limestone	2.49	0.0018
Baiyanjiao Tunnel	BJY-03-1	123.79–124.00	Limestone	0.29	0.0089
	BJY-03-2	195.35–195.51	Grey-green shale	0.33	0.0102
Helong Tunnel	HE-05-1	106.83–107.02	Carbonaceous limestone	0.15	0.0032
	HE-05-2	156.40–156.60	Carbonaceous limestone	1.63	0.0028
	HE-05-3	162.90–163.20	Carbonaceous limestone	/	/
Wanmin Tunnel	WM-04-1	89.40–89.66	Limestone	0.19	0.0059
	WM-04-2	207.35–207.56	Limestone	0.25	0.0047

Note: Measurement uncertainties are based on instrument specifications: porosity $\pm 0.1\%$, permeability $\pm 5\%$ of the reading. ☉ indicates that the sample was not tested due to limited core volume or sample failure during preparation.

3.3. Field Tests

3.3.1. Gas Logging While Drilling

Gas logging was performed continuously during drilling. A gas chromatograph (Agilent 7890B, Agilent Technologies, Santa Clara, CA, USA) was used to analyze C₁–C₅ hydrocarbon components. Gas samples were collected in Mylar gas sampling bags and analyzed within 24 h of collection. The chromatograph was calibrated using standard C₁–C₅ gas mixtures prior to each measurement cycle. Total gas (TG) was recorded in real time. The analytical uncertainty for the gas chromatographic measurements is characterized by a relative standard deviation of less than 5% for replicate analyses.

3.3.2. Gas Content Desorption Test

The United States Bureau of Mines (USBM) direct method was adopted for gas content measurement (Table A1) [57]. This method is widely used for determining the gas content of coal and shale core samples. The test procedure involves sealing a freshly recovered core sample (approximately 500–1000 g) in a desorption canister (volume ~1000 mL) immediately after retrieval from the borehole, with the time from core retrieval to sealing kept within 5 min to minimize gas loss. The sealed canister is then heated to the original formation temperature (~40–60 °C). The volume of desorbed gas released over time is recorded by a gas-flow meter (GMC-100, Ritter GmbH, Bochum, Germany). Desorption is continued for 7–14 days or until no gas release is observed for three consecutive days. All gas volumes are corrected to standard conditions (0 °C, 101.325 kPa). Lost gas (the gas volume lost during core retrieval before sealing) is estimated by plotting the measured desorption rates against the square root of elapsed time and extrapolating to time zero, following standard USBM protocols. Residual gas is measured by crushing the sample in a sealed ball mill (MM 400, Retsch GmbH, Haan, Germany) for 40 min to release any remaining gas trapped within closed pores. The total gas content is the sum of lost gas, desorbed gas, and residual gas.

3.3.3. Harmful Gas Detection in Boreholes

A portable multi-gas detector (Model SL-808A, Jiangsu Shengli Detection Instrument Co., Ltd., Haian, Jiangsu, China) was used to measure CH₄ concentrations in tunnel boreholes. The detector has a detection range of 0 to 10,000 ppm for CH₄ and a response time of less than 30 s. Field calibration was performed using standard CH₄ gases before each set of measurements. The detection limit of this instrument for CH₄ was 1 ppm; all readings below this threshold were recorded as “Not Detected (ND)” to distinguish them from a true zero baseline. The boreholes were sealed with rubber stoppers combined with sealant after each measurement cycle. Measurements were taken at three stages: immediately after drilling, 24 h after hole sealing, and after ventilation. All measurements were conducted under ambient tunnel ventilation conditions.

4. Results

4.1. Geological Characteristics of Harmful Gas in Tunnel Site Areas

4.1.1. Types of Harmful Gas and Characteristics of Hydrocarbon Source Rocks in Tunnel Site Areas

Investigations involving drilling, field surveys, and construction verification have confirmed a clear result. The tunnel site develops harmful gas that are predominantly shale gas [58]. This is supported by the lithology of the tunnel site (the Longmaxi Formation black shale) and the gas chromatographic data, which show that the gas is composed almost entirely of methane, with other hydrocarbon components (C₂+) present only in trace amounts or below detection limits. Such methane-dominated composition is char-

acteristic of a dry gas [59] and is consistent with the typical composition of over-mature shale gas. Northwestern Hunan contains multiple Paleozoic marine mud-shale strata. These formations have moderate depth, great thickness, high organic content, and strong gas generation potential. The Lower Cambrian Niutitang and Lower Silurian Longmaxi Formations hold the highest resources. Both are sets of organic-rich black carbonaceous and siliceous shale. Meanwhile, shale gas from the Silurian Luoreping and Lower Permian formations seeps to the surface along joints and fractures in the Shimen–Cili–Yongshun area. These formations are the main source rocks for shale gas in the tunnel site.

The Longmaxi Formation is subdivided into upper and lower members. The total thickness typically exceeds 300 m. The lower member constitutes a significant source rock, characterized by grey-black carbonaceous/siliceous shale. This unit measures 5.3–57.6 m thick, averaging 24.0 m. Field studies confirm a shale coal seam at the formation base where carbon content significantly increases (Figure 2a,b). The upper member consists mainly of blue-grey and yellow-green shale, mudstone, silty shale, and siltstone. It sometimes contains thin sandstone layers or lenticular, nodular argillaceous limestone and dolomite. The black carbonaceous shale is the source rock. The mudstone serves as the reservoir. The overlying Luoreping Formation's siltstone and quartz sandstone form the cap rock. This is a self-sourcing gas system with an excellent source rock.

The Luoreping Formation has distinct layers. Its lower part contains yellow-green and dark grey, thick-bedded fine- to medium-grained quartz sandstone with shale and argillaceous quartz siltstone. The middle-upper part features grey-green, medium- to thick-bedded fine-grained quartz sandstone interbedded with grey-green silty shale (Figure 2c,d). The Luoreping Formation formed in a shallow-water shelf environment. Its thickness reaches 563 m. The source rock is the underlying black carbonaceous shale of the Longmaxi Formation. The reservoir includes sandy shale and siltstone, while the cap rock is the overlying Shamao Formation's siltstone and quartz sandstone. This constitutes a lower-source gas system with good reservoir properties, which also acts as an effective seal for the underlying Longmaxi Formation.

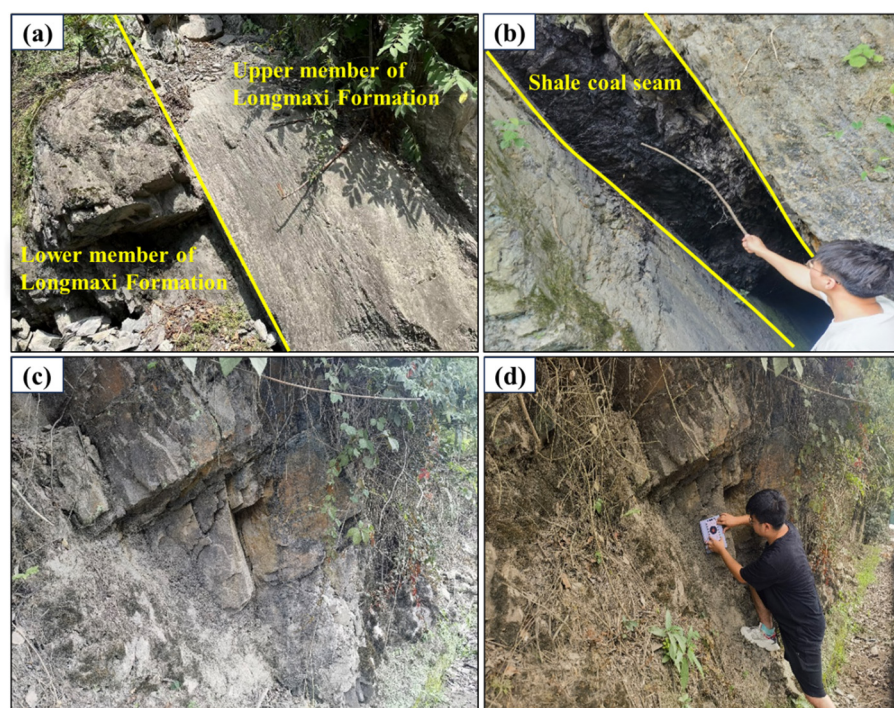


Figure 2. Mapping of field outcrops along Sangzhi section of Zhangnan Expressway. (a) The upper and lower members of the Longmashi Formation (b) The shale coal seam at the bottom of the Longmashi Formation (c) Fine-grained quartz sandstone (d) Grey-green silty shale.

The Upper Permian source rocks are swamp coal-bearing strata. These deposits developed in nearshore barrier lake basins and deep-water muddy shelves. The tunnel site is located on the southeastern flank of the Qianzhong Uplift. It contains multiple isolated, NW-SE trending depositional centers for source rocks. This pattern reflects the paleotectonic and marine depositional setting (Figure 3). The source rocks are predominantly composed of type IIB-III kerogen. Their thermal evolution has progressed to high-over mature stage, with R_o values of 0.70–3.27%. The quality classification follows this scheme: $R_o > 1.6\%$ = good source rock; $1.0\% < R_o \leq 1.6\%$ = moderate source rock; $R_o \leq 1.0\%$ = poor source rock.

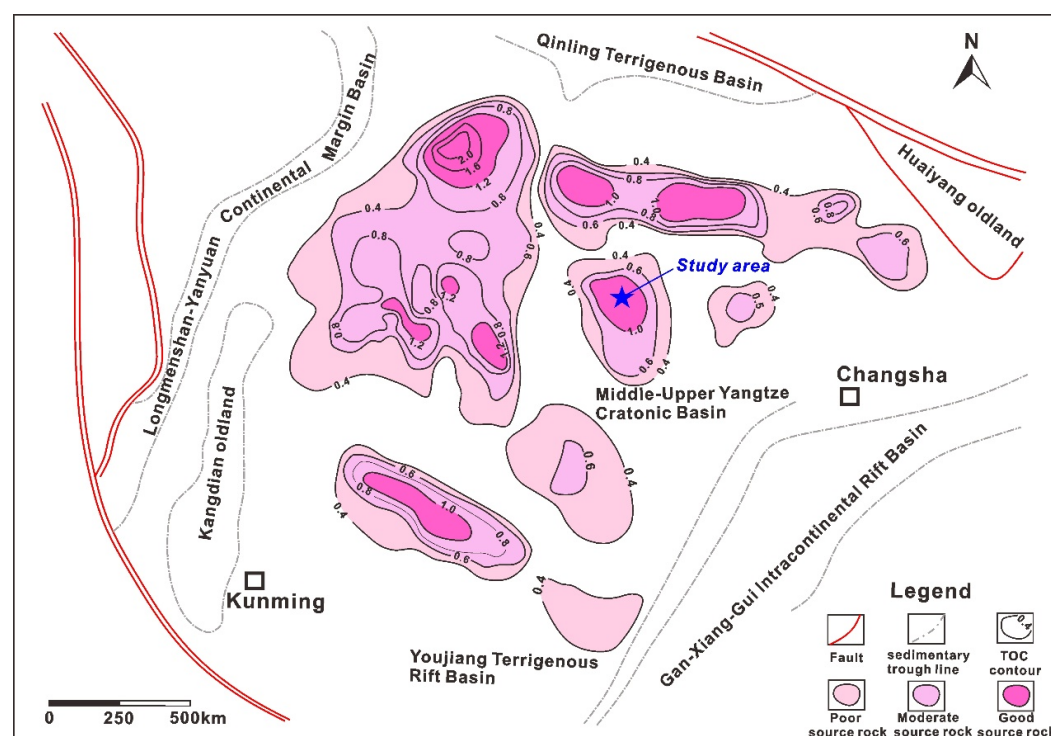


Figure 3. Evaluation of Lower Permian hydrocarbon source rocks in the Southern Yangzi region.

4.1.2. Gas-Bearing Structural Features

The Paleozoic marine mud-shale strata in northwestern Hunan are extensively developed throughout southern China. These sequences are characterized by moderate burial depth, large thickness, high organic matter content, intense gas generation, and high thermal evolution. The rocks are predominantly composed of organic-rich black carbonaceous and siliceous shale. Black and grey-black carbonaceous mud-shale is predominantly distributed in the upper interval. Black siliceous shale mainly occurs in the lower interval. The complete sedimentary package reaches 150–400 m in thickness. This provides the essential material foundation for shale gas generation, developing as a significant regional source rock. Isothermal adsorption tests show a clear result. The Lower Cambrian Niutitang Formation mud-shale has strong gas adsorption capacity [60]. This makes it a good shale gas reservoir. Structurally, the area is dominated by broad, gentle folds with less fault development. The Sangzhi anticlinorium serves as a favorable shale gas accumulator. The Cili–Zhangjiajie fault system provides effective migration pathways. These elements combine with regional source rocks to form multiple gas-bearing structural assemblages.

- Folded structure;

Due to prolonged uplift and erosion in northwestern Hunan, the tunnel area experienced significant fold uplift. The overall structural relief is substantial. The Sangzhi anticlinorium maintains good stratigraphic continuity. Its secondary synclines and anticlines mostly trend E-W, creating repeated outcrops. The main folds along the route are distrib-

uted from north to south. They are: Taipingpu Anticline, Taiqingshan Syncline, Datongshan Anticline, Yangongdu Syncline, Huangchang Anticline, and Dongyueguan Syncline. The anticlines are characterized by an approximate E-W trend and tight, banded folding. The core is formed by the Middle-Upper Cambrian Loushanguan Group. The limbs comprise strata ranging from Ordovician to Triassic in age. These synclines are oriented E-W to NE. The core is composed of Middle Triassic rocks. The limbs comprise Lower Triassic, Permian, and Devonian strata. The Neocathaysian tectonic framework creates favorable conditions for shale gas accumulation. Regional fold uplift and erosion particularly enhanced gas enrichment in the Paleozoic marine mud-shale layers.

- Fault structure;

Fault systems significantly impact shale gas accumulation. They create migration pathways for hydrocarbons while also enhancing fractures and porosity. These changes provide effective reservoir spaces for gas storage. The area contains three principal regional faults: Xiannüshan, Cili-Zhangjiajie, and Lixian-Shishou. These E-W trending faults dip with the bedding, controlled by Yanshanian NEE structures and displaying terminal splays. The fault zone traverses the Banxi Group, Sinian, Paleozoic, and Triassic formations. Its position between the Jiangnan Depression and Huarong Uplift controlled Neogene tectonic evolution. Fault movements generated significant subsidence in the Chentuokou Depression, accumulating 500 m of sediments. This process formed a shale-bearing structural depression that provides critical accumulation spaces for shale gas.

4.2. Test and Trial Results Analysis

A quantitative assessment of harmful gas distribution was performed using shale gas resource methodology. The systematic evaluation examined geochemical properties, reservoir characteristics, and mechanical parameters from 14 tunnel boreholes. This integrated approach, incorporating gas concentration measurements, provides complete formation gas content assessment.

4.2.1. Geochemical Parameter Analysis

This research analyzed three key geochemical parameters. These include TOC, kerogen type, and Tmax. Organic matter provides fundamental control on shale gas accumulation in these carbonaceous shales. Gas storage capacity directly correlates with organic content, governing the potential impact on tunnel construction. Based on elemental composition, kerogen has four types: I (sapropelic), IIA (humic-sapropelic), IIB (sapropelic-humic), and III (humic). Marine settings typically contain Type I; transitional settings contain Type II; terrestrial settings contain Type III. The Tmax parameter defines five maturity stages: immature, oil, condensate, wet gas, and dry gas. Gas generation capacity becomes progressively higher with increasing maturity. Kerogen type and maturity jointly control hydrocarbon output, enabling genetic characterization of harmful gases encountered in tunneling.

Geochemical results show TOC values ranging from 0.08 to 5.92 wt%, averaging 1.14 wt% (Table 1). This exceeds China's 0.5 wt% lower limit for marine/transitional shale exploration [61]. Samples from Chenjiapo and Helong Tunnels reached 5.92 wt% and 1.31 wt%, surpassing the 1.2 wt% USA commercial shale benchmark [61]. The primary Rock-Eval parameters are summarized as follows. S₁ values range from 0.02 to 0.18 mg HC/g rock, averaging 0.08 mg HC/g rock. S₂ values range from 0.05 to 1.30 mg HC/g rock, averaging 0.42 mg HC/g rock. S₃ values range from 0.10 to 0.35 mg CO₂/g rock, averaging 0.21 mg CO₂/g rock. The production index (PI) ranges from 0.06 to 0.32, with an average of 0.15, indicating that the organic matter is at an early stage of thermal maturation. The oxygen index (OI) ranges from 18.5 to 125.6 mg CO₂/g TOC, with an average of 55.3 mg CO₂/g

TOC. These values are consistent with the interpretation of Type III kerogen at low to moderate thermal maturity. This indicates that the shale sequences in the study area possess considerable gas-generation potential, which poses a significant impact on tunnel construction.

The hydrogen index (HI) ranges from 12.4 to 140.0 mg/g·TOC, averaging 56.9 mg/g·TOC. The degradation potential (D) ranges from 14.5% to 210.0%, with a mean of 80.9%. The Tmax values are between 331.6 °C and 494.9 °C, averaging 442.89 °C (Table 1). Based on the combined HI–Tmax cross-plot classification and the PI values (mean 0.15) [62], the organic matter is interpreted as predominantly Type III kerogen at low to moderate thermal maturity (early oil window). Current total gas production is low. However, as kerogen pyrolysis slowly advances over geological timescales, gas volume from crude oil cracking may gradually increase. On the engineering timescale of tunnel construction and operation, the main risk is associated with release of existing free and adsorbed gas, rather than new hydrocarbon generation.

4.2.2. Petrological Characteristic Test Analysis

Shale reservoirs contain significant adsorbed gas alongside free gas, producing in comparable quantities. Free-phase gas resides in microscopic pores and natural fracture networks. These systems can form localized gas accumulations that migrate into tunnels through the same conduits when exposed by excavation. Reservoir properties tests were performed on 16 core plug samples prepared from the 14 borehole cores, of which 13 provided valid porosity and permeability data (Table 2). Effective porosity variation and directional permeability served as core parameters. These provided the basis for integrated reservoir and cap rock assessment.

Analysis reveals three primary lithologies: carbonaceous shale, carbonaceous limestone, and dark grey limestone (Table 2). The carbonaceous shale exhibits a dual function as both hydrocarbon source rock and gas adsorption medium. The formations exhibit porosity values of 0.15–2.49% (mean 0.98%) and permeability values of 0.0016–0.0102 mD (mean 0.005 mD). Based on CNPC's unconventional reservoir criteria, these intervals are designated as ultra-low porosity, ultra-low permeability zones. Shale gas exists mainly in adsorbed form within shales. This characteristic provides high resistance to structural damage, allowing accumulation in tight reservoirs. The shale and overlying tight formations collectively create the sealing system for gas preservation.

4.2.3. Analysis of Field Test Results

Field measurements employed three direct techniques: gas logging, gas content desorption, and harmful gas detection in tunnel boreholes. The gas logging method facilitates continuous monitoring of C1–C5 hydrocarbons. This allows comprehensive quantitative and qualitative analysis of total hydrocarbon content. Gas content analysis employs the USBM buoyancy method, maintaining the industry standard for shale and coalbed gas. The procedure requires sealed core samples heated to the original formation temperature. Total gas content consists of three components: lost gas (unmeasured escape during retrieval), desorbed gas, and residual gas. Lost gas is determined by graphical analysis (Figure 4) of the desorption rate versus square root time, while other components are physically measured.

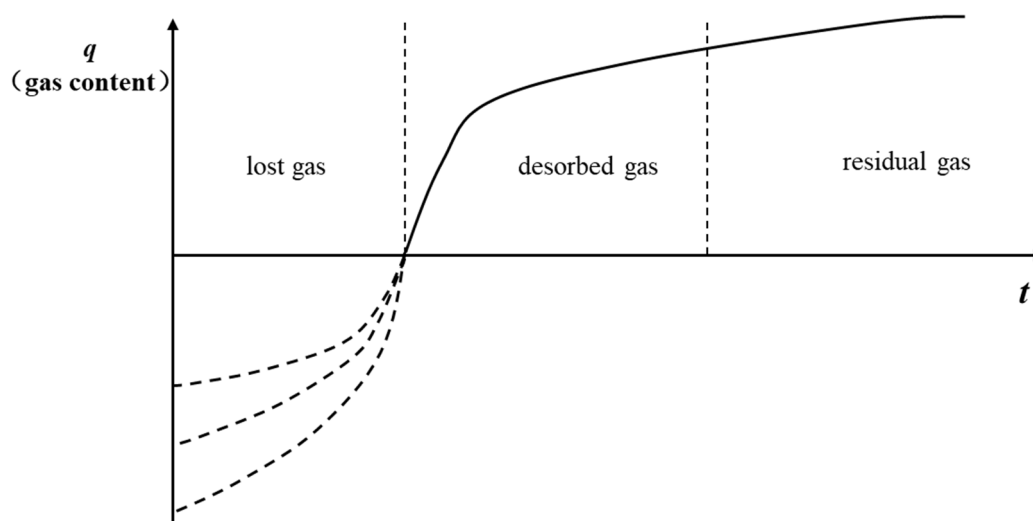


Figure 4. Model diagram of gas content of samples determined by desorption method.

- Gas-Phase Total Hydrocarbon Analysis;

Gas logging while drilling was conducted on 10 tunnel borehole samples. Total hydrocarbon values range from 0 to 0.026%, averaging 0.0098% (Figure 5). Leijiashan, Jinjiapo, Baiyanjiao, and Wanmin Tunnels show no significant gas. Chenjiapo and Helong Tunnels display weak gas indications, confirming limited gas-bearing potential in the shale formations.

- Desorption Analysis of Gas Content;

Field desorption tests were conducted on 26 tunnel samples (Table A1). The desorbed gas content ranges from 0–0.1620 m³/t (avg. 0.0711 m³/t), lost gas 0–0.0056 m³/t (avg. 0.0024 m³/t), and total gas content 0–0.1676 m³/t (avg. 0.0722 m³/t) (Figure 6). These values are far below the 0.5–1.0 m³/t minimum thresholds for shale gas enrichment zones. This confirms low gas content and limited distribution in the mud-shale formations.

- Harmful Gas Detection and Absolute Gas Outburst Volume Calculation;

Harmful gas detection was conducted in tunnel boreholes along the Sangzhi section (Figure 7). CH₄ was identified as the primary gas component. In Leijiashan Tunnel, the CH₄ volume fraction was 87 ppm in the return airway under full ventilation after drilling, rising to 103 ppm 24 h after sealing. This differs from the 84.4% value measured in the sealed advance borehole during the 18 February incident (pre-ventilation, closed-system measurement). This indicates continuous shale gas recharge. The concentration dropped to below the detection limit (ND, <1 ppm) after 100 min of ventilation, showing the escape rate exceeds recharge, and ventilation effectively dilutes harmful gas. Gas chromatographic analysis of advance borehole samples shows CH₄ concentrations of 8.36–11.25%, with C₂H₆ and C₃H₈ below detection or present only in trace amounts. The gas is therefore composed almost entirely of methane, with essentially no measurable heavier hydrocarbons. Such methane-dominated composition is characteristic of a dry gas and is consistent with the typical composition of over-mature shale gas [59,63].

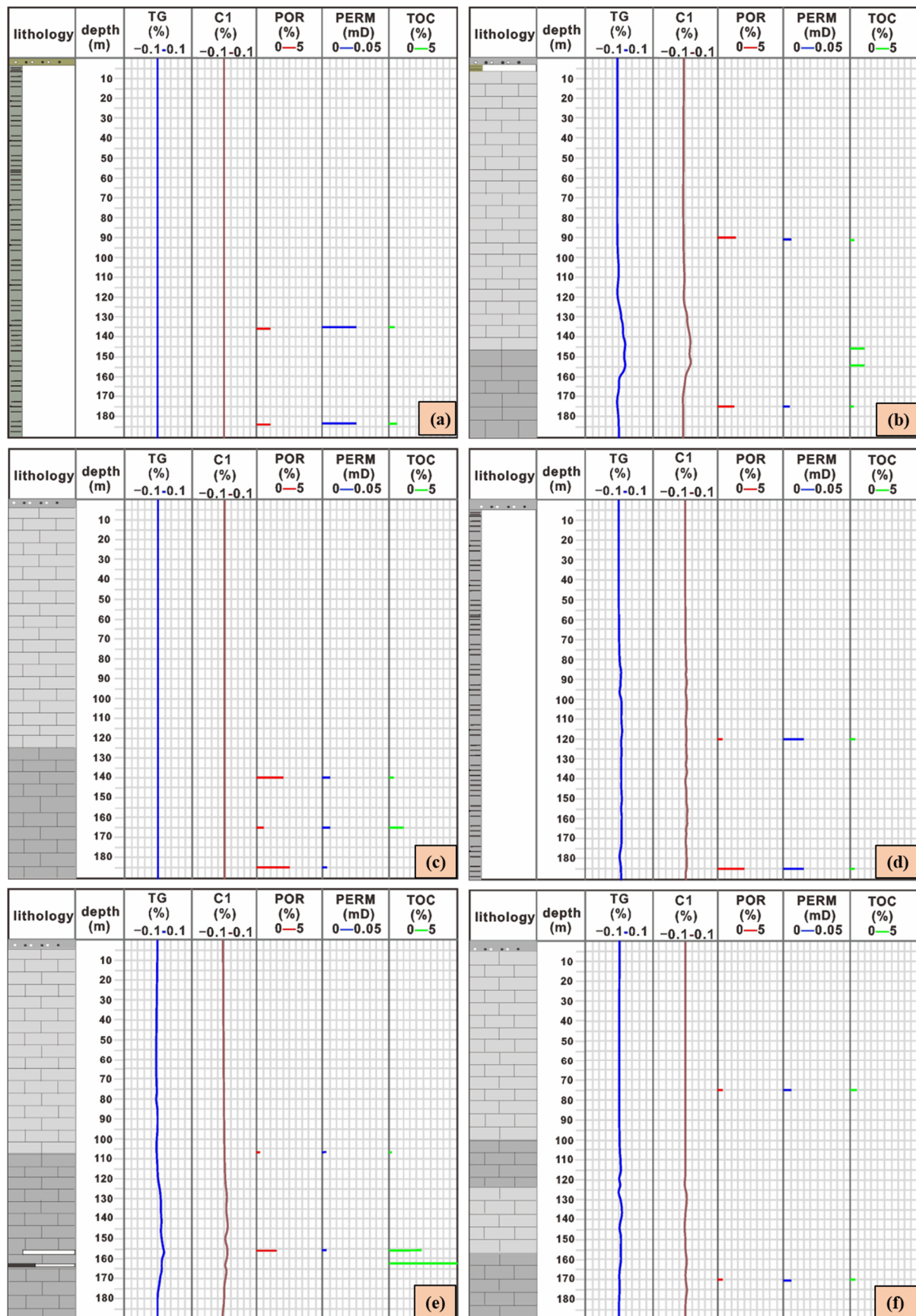
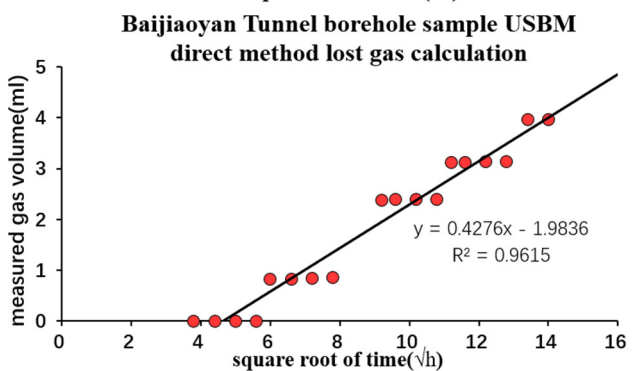
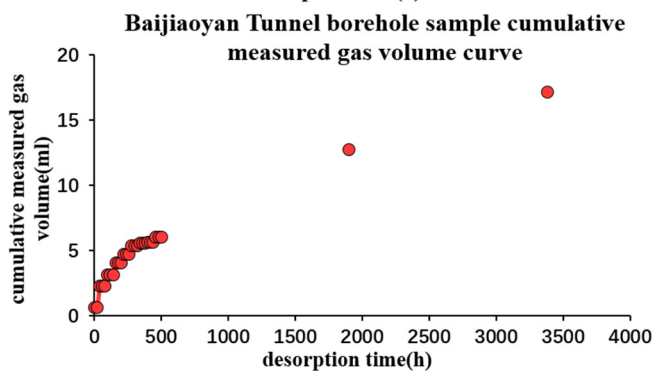
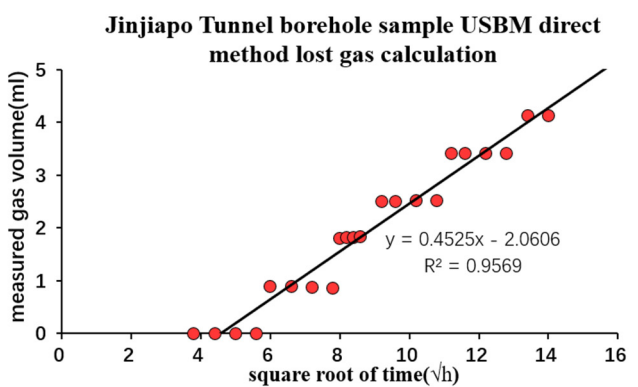
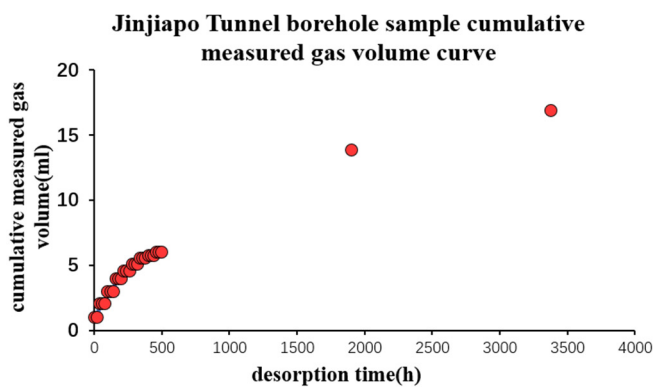
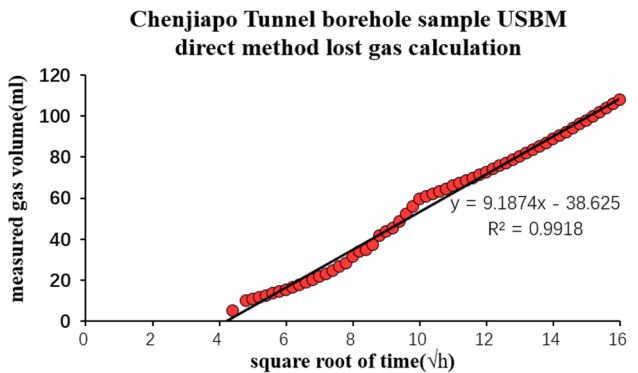
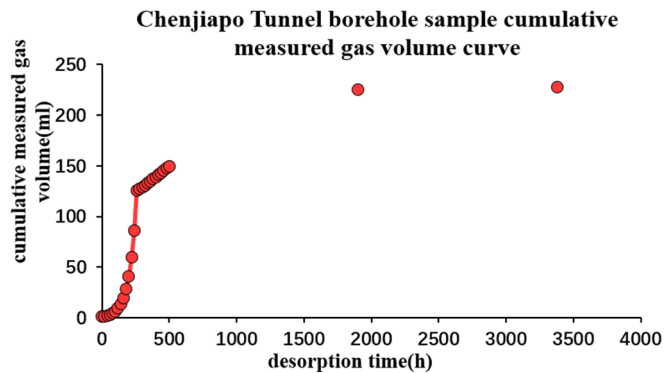
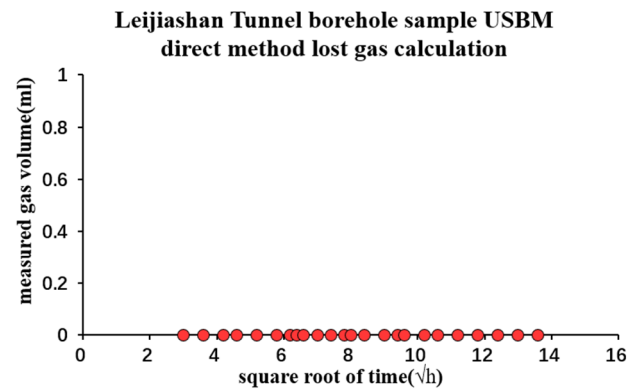
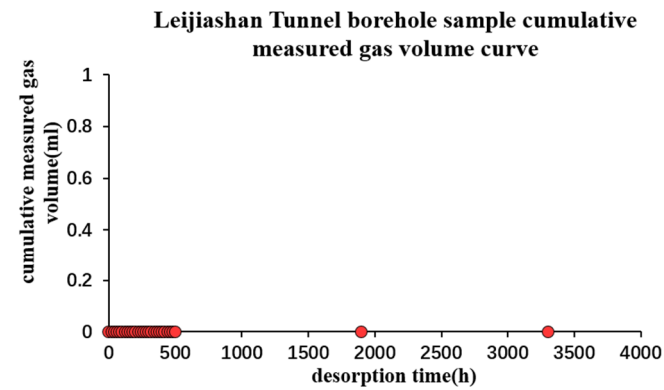


Figure 5. Borehole gas measurement curves of six tunnels along Sangzhi section of Zhangnan Expressway (a) Leijiashan Tunnel (b) Chenjiapo Tunnel (c) Jinjiapo Tunnel (d) Baijiaoyan Tunnel (e) Helong Tunnel (f) Wanmin Tunnel.



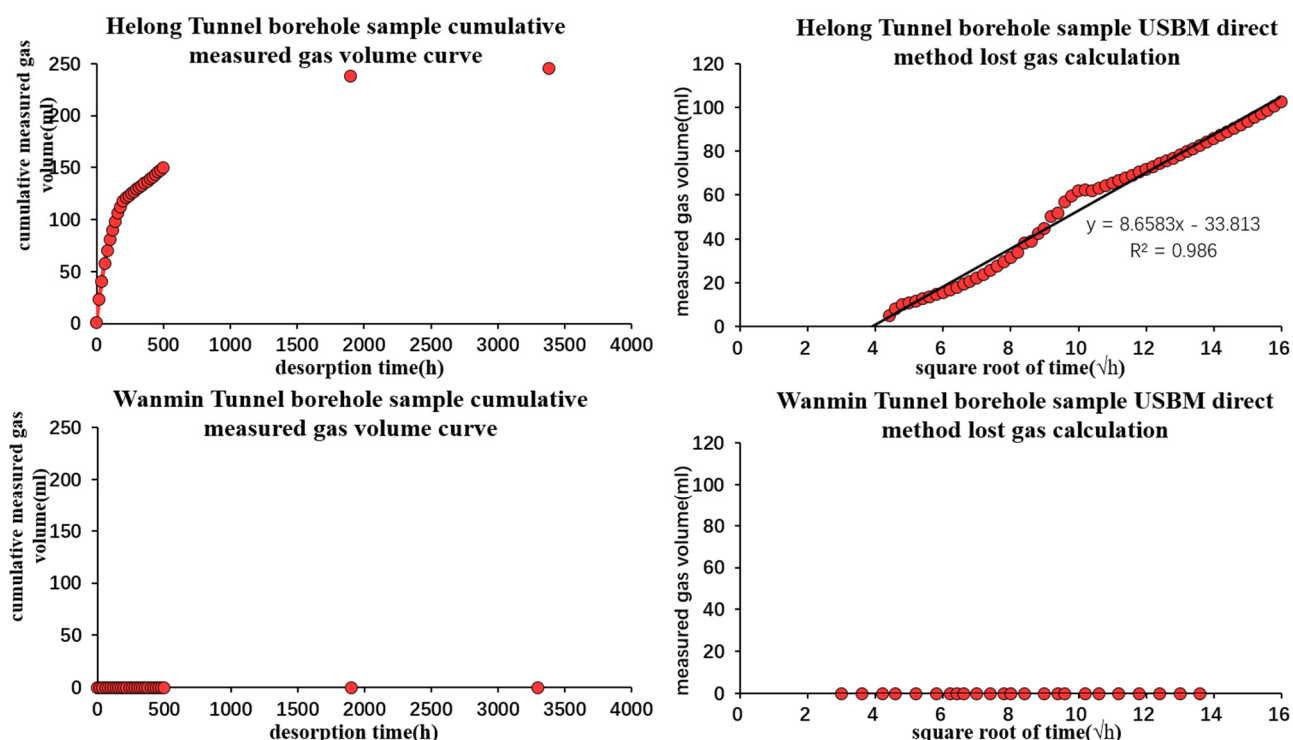


Figure 6. Cumulative gas volume of desorption of tunnel borehole samples along the Sangzhi section of the Zhangnan Expressway and loss calculation curve of the USBM method.

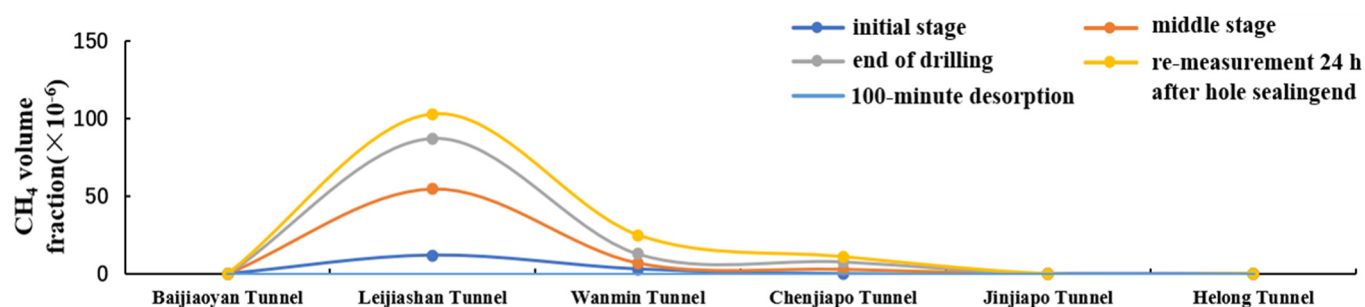


Figure 7. CH₄ gas detection curves under the ventilation conditions inside the tunnel along the Sangzhi section of the Zhangnan Expressway (concentrations below the instrument detection limit are plotted as ND).

The absolute gas emission rate (Q_g) is a key parameter for assessing gas conditions in tunnels and mines. It measures the gas volume emitted per unit of time. The standard units are m³/d or m³/min. The calculation formula is:

$$Q = S \times V \quad (2)$$

$$Q_g = Q \times c/100 \quad (3)$$

Symbol Definitions:

Q_g —absolute gas emission rate, m³/min

S —tunnel face area, m²

V —air velocity, m/min

Q —air volume, m³/min

c —average gas concentration in airflow, %

(Note: Air velocity in the calculation is expressed in m/min. The wind speeds measured in the field were recorded in m/s and converted to m/min using the conversion factor $1 \text{ m/s} = 60 \text{ m/min}$ before substitution into the formula.)

Absolute gas emission rates were calculated for six tunnels (Table 3). According to the “Technical Specifications for Highway Gas Tunnel Design and Construction (JTG/T 3374-2020)”, the tunnels are classified as follows: Leijiashan, Chenjiapo, and Wanmin are low-gas zones ($0 < Q_g < 1.0 \text{ m}^3/\text{min}$); Jinjiapo, Baijiaoyan, and Helong are no-gas zones ($Q_g = 0 \text{ m}^3/\text{min}$).

Table 3. Calculation of absolute gas outflow from tunnels along the Zhangnan Expressway, Sangzhi section.

Tunnel Name	Excavation Face Area/ (m^2)	Air Velocity/ (m/min)	Average Gas Concentration in the Flow/ (%)	Absolute Gas Emission Rate/ (m^3/min)
Leijiashan Tunnel	100	48.0	0.00514	0.24672
Chenjiapo Tunnel	100	39.0	0.00044	0.02112
Jinjiapo Tunnel	100	42.0	ND (<0.0001%)	0
Baijiaoyan Tunnel	100	36.0	ND (<0.0001%)	0
Helong Tunnel	100	37.2	ND (<0.0001%)	0
Wanmin Tunnel	100	49.8	0.00096	0.04608

5. Harmful Gas Accumulation Patterns in Tunnel Site Areas

The primary controls on shale gas content and preservation are tectonic deformation, shale thickness, cap rock lithology, and fault development. When studying gas accumulation near tunnels, consider these key factors for both adsorbed and free gas. First, thickness variation in shale or cap rock allows gas to escape into tunnels. Second, folds and fractures from neotectonic movements provide effective migration pathways. Third, active groundwater flow in shallow burial zones promotes gas dissipation. Finally, the dual-porosity system in shale enables gas movement through both matrix and fractures. It should be noted that the gas-related risk during tunnel construction and operation primarily arises from the release of existing free and adsorbed gas already stored in the shale matrix and fractures, rather than from newly generated hydrocarbons over geological timescales. The two accumulation patterns described below reflect the present-day occurrence and migration characteristics of the already-generated gas. Based on comprehensive research, we summarize two gas accumulation patterns at the tunnel site. These are the self-sourcing composite accumulation pattern with micro-scale migration, and the accumulation pattern of self-generated and self-storage type of water pressure confinement.

5.1. The Self-Sourcing Composite Accumulation Pattern with Micro-Scale Migration

Regional analysis confirms gas concentration in Longmaxi and Qixia Formations. Their upper members feature consistent argillaceous units of dark grey calcareous shales and marlstones. This continuous sequence thickens westward while exhibiting deteriorating reservoir properties eastward. The lower section contains shale, carbonaceous shale, and coal-bearing strata. It also includes banded tight limestone and marl. The mud-shale averages 24.0 m in thickness, providing substantial storage capacity. Gas occurs as free phase in microscopic pores, similar to coalbed methane. Secondary fractures in shale provide excellent migration pathways and storage spaces. Under gravity and buoyancy, free gas separates from mobile water. It migrates through larger pores and fractures, following Darcy’s law (Figure 8). Taking the six key “shale gas” tunnels along the Zhangnan Expressway as an example, the Jinjiapo Tunnel and Wanmin Tunnel are located in the core area of the structural fold belt in the northwestern Hunan region. The strata there have a

steep dip, the core is relatively fractured due to tectonic influences, and groundwater conditions are poor. The shale gas in these tunnel areas is mainly characterized by the self-sourcing composite accumulation pattern with micro-scale migration.

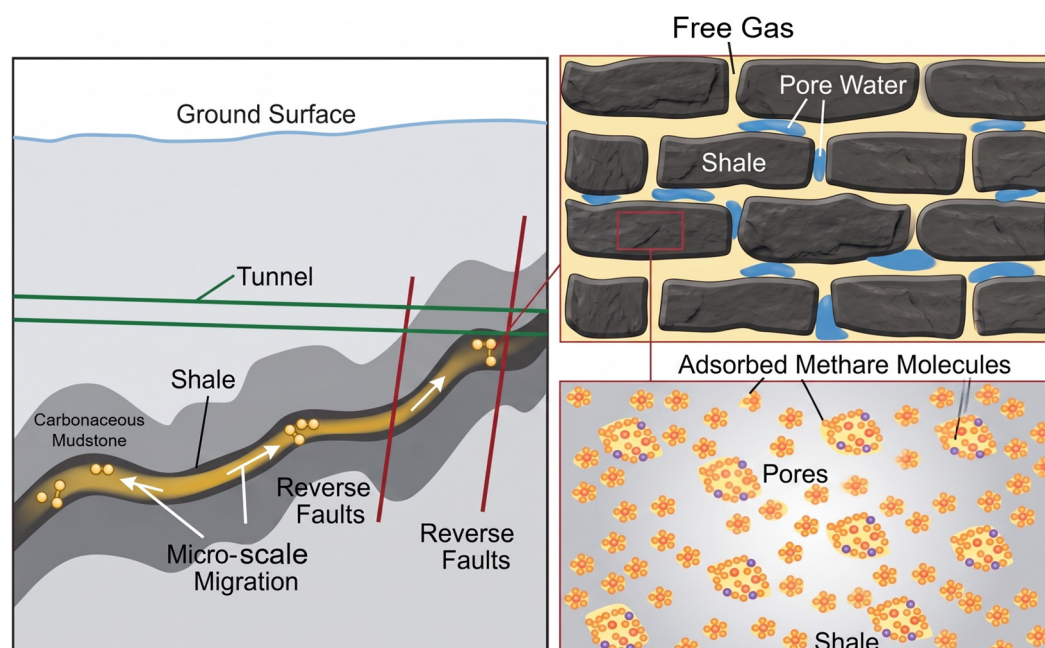


Figure 8. Accumulation pattern of Self-Sourcing Composite with Micro-Scale Migration.

5.2. The Self-Sourcing Accumulation Pattern Under Water Pressure Confinement

Traditional shale gas assessments only consider adsorbed gas. They ignore free and dissolved gas. In the tunnel area, generated gas first accumulates in organic matter micropores. Adsorbed gas is preserved by pressurized groundwater during neotectonic adjustment, enabling accumulation in synclinal cores and structural slopes (Figure 9). These accumulations form local high-pressure gas pockets, creating serious tunnel construction hazards. Taking the six key “shale gas” tunnels along the Zhangnan Expressway as an example, the Baijiaoyan Tunnel, Leijiashan Tunnel, Chenjiapo Tunnel, and Helong Tunnel are located in the structural fold transition zone of northwestern Hunan. The strata in this area have a gentle dip and are well-preserved, and the tunnels are situated below the water table. The shale gas in these tunnel areas is mainly characterized by the accumulation pattern of self-generated and self-storage type of water pressure confinement.

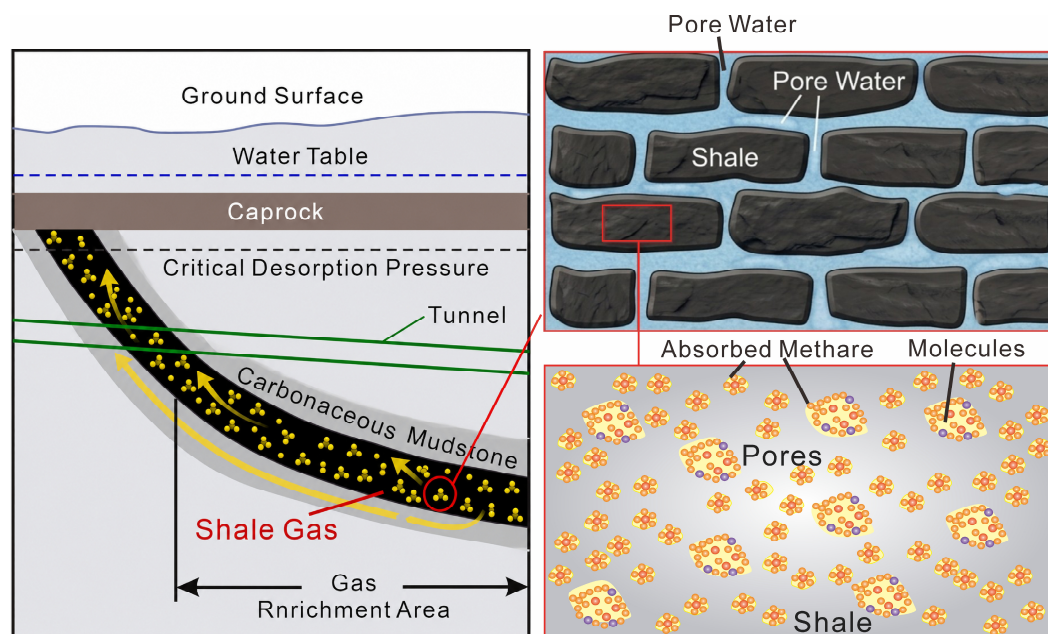


Figure 9. Accumulation pattern of self-generated and self-storage type of water pressure confinement.

6. Conclusions

1. The Sangzhi section of the Zhangnan Expressway is located in northwestern Hunan's Paleozoic marine mud-shale strata. It traverses the Silurian Longmaxi Formation and multiple Permian carbonaceous and sandy shale formations, which are quality source rocks. The reservoir is sandy shale and siltstone, sealed by the overlying Shamao Formation. The Sangzhi anticlinorium provides gas accumulation structures, while the Cili–Zhangjiajie fault system serves as migration pathways.
2. Comprehensive analysis was conducted on samples from six tunnels. The evaluation covered geochemical, reservoir, and mechanical parameters. Combined with bore-hole gas concentration data, results confirm an ultra-low porosity, ultra-low permeability reservoir with modest capacity. The organic matter is predominantly Type III kerogen, exhibiting low to moderate maturity within the early oil window, based on the combined HI–Tmax cross-plot analysis and PI values (mean 0.15), and resulting in low total gas content. The shale formations show high TOC with limited late-stage hydrocarbon generation potential. On the engineering timescale of tunnel construction and operation, the main risk is associated with release of existing free and adsorbed gas rather than future gas generation. Based on calculated absolute gas emission rates, Leijiashan, Chenjiapo, and Wanmin Tunnels are classified as low-gas zones, while Jinjiapo, Bajiaoyan, and Helong Tunnels are no-gas zones.
3. The harmful gas (shale gas) in the Sangzhi section show clear zonal enrichment. This distribution is controlled by structural systems, stratigraphic features, and gas-bearing structures. Considering the configuration between gas reservoirs and tunnel alignment, we define two accumulation pattern. These are self-sourcing composite accumulation with micro-scale migration, and self-sourcing accumulation under water-pressure confinement.
4. The Sangzhi section shows localized harmful gas enrichment. When tunneling through rocks with favorable reservoir properties or near fault zones, we recommend enhanced monitoring and advance geological prediction, maintaining continuous ventilation inside the tunnel, and applying grouting for sealing when necessary to prevent sudden accidents.

In summary, this study fills a research gap concerning harmful gas in tunnels crossing non-coal measured strata in northwestern Hunan. It reveals the zoned enrichment patterns and migration-accumulation mechanisms of shale gas. The results provide a scientific basis for gas hazard assessment, dynamic monitoring, ventilation, and grouting sealing measures when tunnels pass through similar geological settings. The findings have substantial engineering value and practical significance for ensuring construction and operational safety of tunnels and for promoting sustainable development of tunnel construction.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: Author Xiao Quan and Xinhua Tao was employed by the company Sanglong Project Command Center, China Railway Communications Investment Group Co., Ltd., Nanning, China. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

TOC	Total organic carbon
ppm	Parts per million
USBM	United States Bureau of Mines
Porosity	POR
Permeability	PERM
Total Gas	TG
Not Detected	ND

Appendix A

Table A1. Sample inventory and analytical tests performed for all samples used in this study.

Sampling Point	Sample Number	Depth (m)	Lithology	TOC	Tmax	Rock-Eval	Porosity	Permeability	Desorption
Leijiashan Tunnel	LJS-05-1	118.31–118.47	Sandstone	✓	✓	✓	✓	✓	✓
	LJS-05-2	157.42–157.68	Sandstone	✓	✓	✓	✓	✓	✓
	LJS-05-3	130.50–130.70	Sandstone	/	/	/	/	/	✓
	LJS-05-4	172.30–172.50	Sandstone	/	/	/	/	/	✓
Chenjiapo Tunnel	CJP-04-1	91.33–91.47	Limestone	✓	✓	✓	✓	✓	✓
	CJP-04-2	146.37–146.50	Carbonaceous shale	✓	✓	✓	✓	✓	✓
	CJP-04-3	154.70–155.00	Carbonaceous shale	✓	✓	✓	✓	✓	✓
	CJP-04-4	175.10–175.21	Dolomite	✓	✓	✓	✓	✓	✓
	CJP-04-5	80.20–80.40	Limestone	/	/	/	/	/	✓

	CJP-04-6	163.80–164.00	Carbonaceous shale	/	/	/	/	/	✓
Jinjiapo Tunnel	JJP-05-1	140.73–141.00	Limestone	✓	✓	✓	✓	✓	✓
	JJP-05-2	169.04–169.22	Limestone	✓	✓	✓	✓	✓	✓
	JJP-05-3	193.92–194.13	Limestone	✓	✓	✓	✓	✓	✓
	JJP-05-4	115.50–115.70	Limestone	/	/	/	/	/	✓
Baiyanjiao Tunnel	BJY-03-1	123.79–124.00	Limestone	✓	✓	✓	✓	✓	✓
	BJY-03-2	195.35–195.51	Grey-green shale	✓	✓	✓	✓	✓	✓
	BJY-03-3	150.20–150.40	Limestone	/	/	/	/	/	✓
	BJY-03-4	178.60–178.80	Limestone	/	/	/	/	/	✓
Helong Tunnel	HE-05-1	106.83–107.02	Carbonaceous limestone	✓	✓	✓	✓	✓	✓
	HE-05-2	156.40–156.60	Carbonaceous limestone	✓	✓	✓	✓	✓	✓
	HE-05-3	162.90–163.20	Carbonaceous limestone	✓	✓	✓	✓	✓	✓
	HE-05-4	80.50–80.70	Carbonaceous limestone	/	/	/	/	/	✓
	HE-05-5	135.20–135.40	Carbonaceous limestone	/	/	/	/	/	✓
Wanmin Tunnel	WM-04-1	89.40–89.66	Limestone	✓	✓	✓	✓	✓	✓
	WM-04-2	207.35–207.56	Limestone	✓	✓	✓	✓	✓	✓
	WM-04-3	158.40–158.60	Limestone	/	/	/	/	/	✓

✓: Analysis performed on this sample.; /: Analysis not performed (due to limited core volume or sample failure during preparation). Rock-Eval includes S₁, S₂, S₃, HI, OI, PI, and D. TOC: Total Organic Carbon; Tmax: Rock-Eval pyrolysis maximum temperature. Porosity: helium porosimetry; Permeability: gas permeameter steady-state method. Desorption: USBM direct method (lost gas + desorbed gas + residual gas).

Sample count summary:

Total samples listed: 26

Full geochemical characterization (TOC + Tmax + Rock-Eval): 16 samples

Porosity and permeability tests: 13 samples (samples with “/” were not tested due to limited core volume or sample failure)

Desorption tests: 26 samples (all samples)

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