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REVIEW ARTICLE

Gas Tunnels in Non-Coal Strata in China: A Systematic Review of Conceptual Framework, Genetic Typology and Regional Distribution

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Abstract

The expansion of transportation infrastructure into geologically complex mountainous regions of China has increased encounters with gas-bearing non-coal strata during tunnel construction. Unlike coal-measure gas systems, gas occurrences in carbonate, clastic, and metamorphic rocks present distinct challenges due to multi-source origins, structurally controlled accumulation, and abrupt outburst mechanisms. This review examines existing research to establish a conceptual framework for this hazard category. Analysis of gas sources, reservoir characteristics, and geological controls indicates that non-coal gas tunnels require theoretical approaches distinct from coal-gas methodologies. A genetic classification system distinguishes three fundamental types: tectonically migrated, stratum-self-generated, and composite origins. Regional distribution patterns reveal clustering around petroliferous basin margins, particularly the Sichuan Basin and surrounding provinces, governed by the interaction of source rocks, migration pathways, and structural traps. Critical gaps remain in multi-field coupling theory, concealed gas detection technology, and dedicated technical standards. Development of quantitative predictive models and intelligent monitoring systems represents the primary direction for future research.

Keywords: non-coal strata, gas tunnel, genetic classification, regional distribution, structural control, hazard prevention.

1 Introduction

In recent years, China has pushed major transport infrastructure into complex mountain areas, driven by national strategies like building a "transportation powerhouse" and the Belt and Road Initiative [1, 2]. Tunnel projects have grown larger and deeper as a result [3, 4]. At the same time, a particular kind of geological hazard has become more common: gas disasters from non-coal strata. These hazards now pose a serious risk to construction safety [5].

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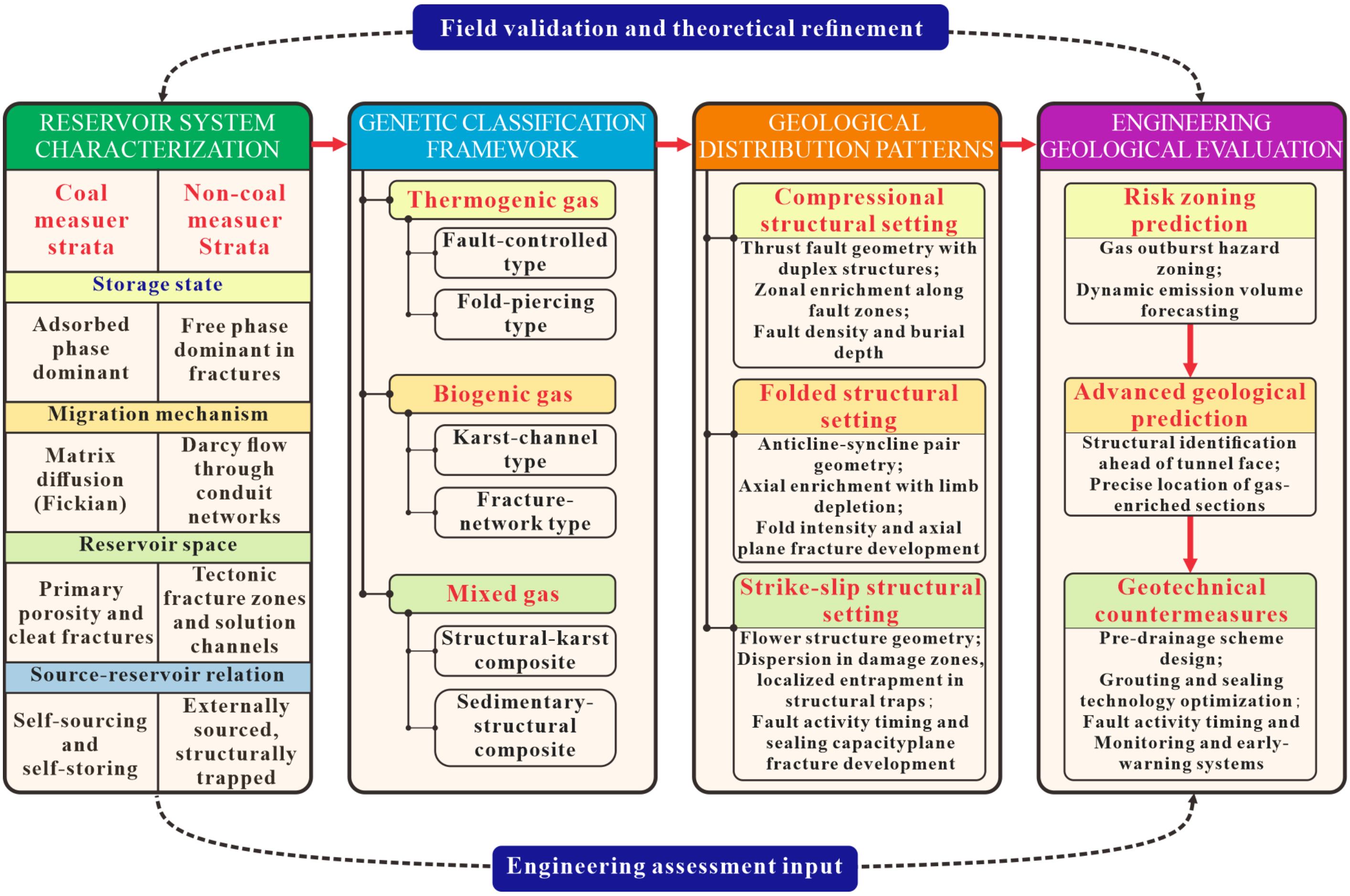

Figure 1. Research framework structure diagram of this work.

Unlike coal mine gas, which comes from coal seams, the gas here sits in non-coal rocks like carbonate and clastic strata [6]. It has a few distinct traits. Gas sources vary. Some migrate from deep oil or gas reservoirs. Others come from the surrounding rock itself. Accumulation is hidden, mostly controlled by fractures and fissures. Outbursts often happen without much warning. These traits make prediction and prevention very difficult [7]. Many real projects have shown how severe these hazards can be. One example is the Xiaojialiang Tunnel on the Lanzhou–Chengdu Railway, which lies in a deep oil and gas field in the Sichuan Basin [8]. Another is the deep buried Chengdu Jiulong Reservoir Tunnel under complex geology. The 2005 gas explosion in the Dongjiashan Tunnel on the Dujiangyan–Wenchuan Expressway was especially bad [9]. That event was a clear warning: we need to treat non-coal strata gas as an independent risk source and set up dedicated research and prevention systems.

These repeated incidents have led to the formal idea of "gas tunnels in non-coal strata." This term refers to tunnels that go through such strata and face serious threats from toxic and flammable gases, mainly hydrocarbons but often with H_2S and CO_2 [10]. Compared to coal measure gas, the main difficulties are the high uncertainty about gas sources and storage spaces, plus strong tectonic control and the random nature of outbursts [11]. Because of these differences, the theories and methods developed for coal mine gas do not work well here. Research on non-coal strata gas tunnels remains scattered across conceptual boundaries, genetic mechanisms, and distribution patterns. This scattering makes it hard to develop effective, integrated risk management strategies.

This review fills the gaps by pulling together dispersed engineering experiences into a coherent framework. We have three objectives, as shown in Figure 1. First, to clarify the conceptual boundaries and essential attributes of non-coal gas tunnels through comparison with coal measure systems. Second, to establish a genetic classification based on gas origins and geological formation mechanisms. Third, to reveal the regional distribution patterns of these tunnels across China and the geological factors that control them.

2 Conceptual Framework and Fundamental Characteristics of Gas Tunnels in Non-Coal Strata

2.1 Conceptual Evolution and Delineation

2.1.1 Core Definition and Essential Attributes

Gas tunnels in non-coal strata are defined as tunnel engineering projects traversing non-coal lithologies (including carbonate, clastic, and metamorphic rocks) that encounter hazardous levels of combustible gases stored within or migrating through these formations [12]. This definition encompasses three critical attributes that distinguish these systems from coal-measure gas (Figure 2).

2.1.2 Historical Evolution of the Concept

The formation of the concept "Gas Tunnels in Non-Coal Strata" has undergone a prolonged process from incidental engineering encounters to systematic understanding. This study delineates its historical evolution into the following four key phases (Figure 3) to clarify its developmental trajectory from a hidden risk to a distinct research discipline.

1. Phase I: Pre-Cognitive Encounter
   During this extended period, there were sporadic records of encounters with gas in non-coal strata during mountain tunnel construction in China [13]. However, constrained by the level of geological understanding and exploration technology, such incidents were often attributed to local geological anomalies or confused with coal mining activities. They were not endowed with independent geological significance. Documentation was fragmented within engineering logs or accident reports, failing to trigger systematic attention. Nevertheless, these earliest practical evidence provided raw material for subsequent cognition.

2. Phase II: Phenomenon Description Phase
   Triggered by major accidents such as the Dongjiashan Tunnel disaster, research focus shifted away from coal mine gas. The term "non-coal hazardous gas tunnel" prevailed, emphasizing its non-coal origin while understanding remained at the level of describing the presence and hazards of the gas [14, 15].

3. Phase III: Concept Independence Phase
   As complex gas issues emerged in projects like the Lan-Yu Railway [16] and deep-buried tunnels in the Sichuan Basin [17], understanding deepened. Scholars, including Wei Youyi, proposed the concept of "non-coalbed-associated gas tunnel" [18]. Its key contribution was clarifying the gas storage space as independent of coal seams and its occurrence primarily in a free state, marking the concept's formal proposal as an independent research subject.

4. Phase IV: Systematic Deepening Phase
   Driven by shale gas geology and unconventional hydrocarbon exploration technology [19, 20], research entered a systematic stage. Exemplified by the works of scholars such as Peidong Su, the focus shifted from "whether gas exists" to "how gas is generated, migrates, accumulates, and causes disasters" [21–23]. "Gas Tunnels in Non-Coal Strata" became the standard term, with its core connotations solidifying around multi-source origins, strong structural control, and complex disaster-causing mechanisms.

Table 1. Multidimensional Analysis of the Core Connotation of "Gas Tunnels in Non-Coal Strata".

Aspect	Core Principle	Key Implications & Manifestations
Non-coal & Multi-source Gas Origin	Gas comes from multiple sources, not coal	Three pathways: deep migrated hydrocarbons, in-situ generation from organic-rich strata, shallow biogenic gas. This gives complex gas composition and multiple hazard modes.
Heterogeneous & Concealed Gas Reservoirs	Gas stored in secondary spaces of non-coal rocks, not in a primary matrix	Storage includes fractures, fault zones, and dissolution pores, often as isolated high-pressure pockets. Discontinuous distribution and lack of predictable marker beds make prediction very difficult.
Strong Structural Control on Gas Dynamics	Geological structures dominate from accumulation to outburst	Structures control the whole path from source to emission. Excavation that hits such structures directly triggers sudden, episodic, random gas influxes.

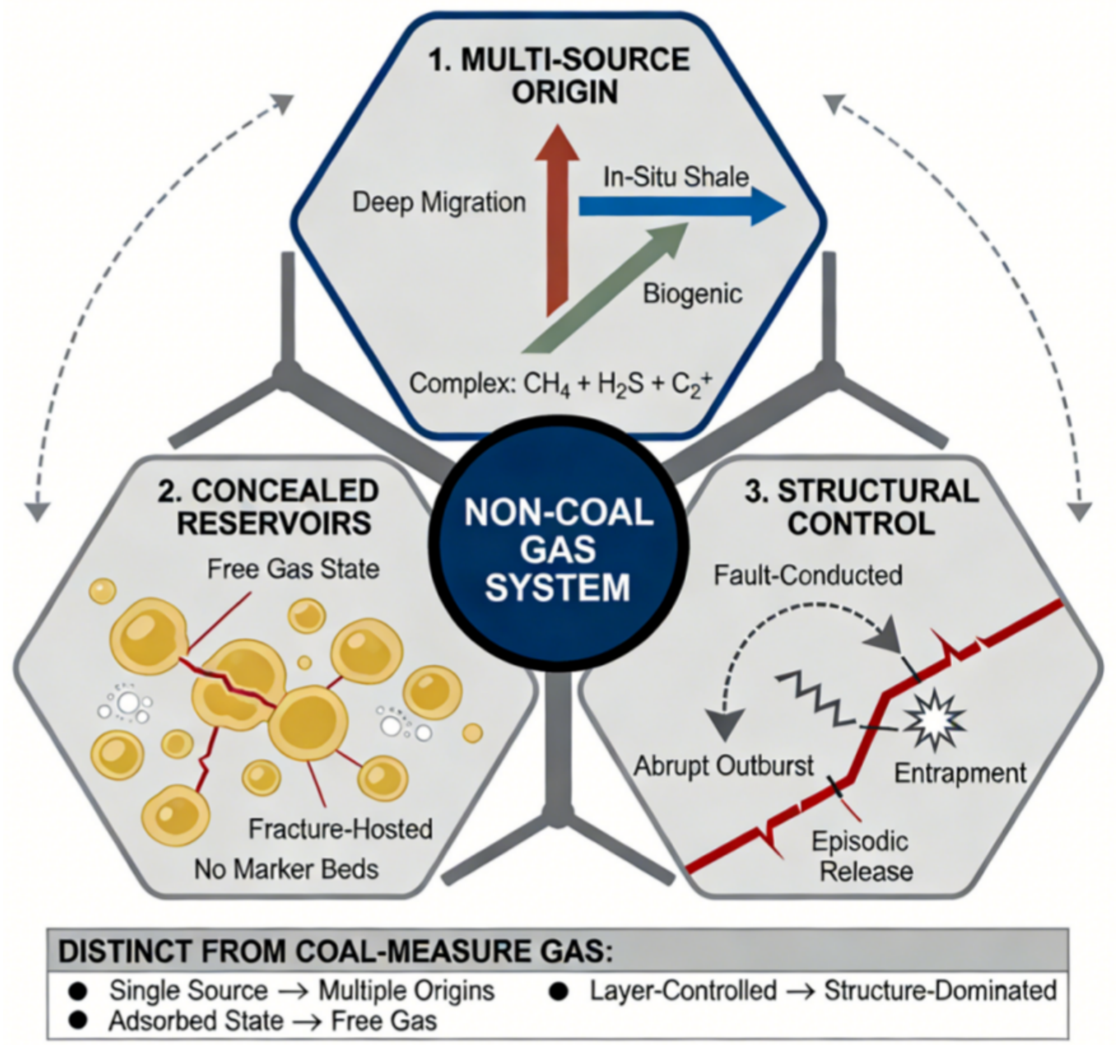

Figure 2. Characteristics of Gas in Tunnels within Non-Coal Strata.

2.1.3 Analysis of Core Connotation

Its connotation can be systematically analyzed through three interrelated dimensions (Table 1).

The multiplicity of sources governs the gas's fundamental properties; the concealment of reservoirs presents the primary detection challenge; and the strong structural control ultimately reveals the underlying hazard mechanisms [24–26]. Together, these dimensions define the essential characteristics that distinguish gas tunnels in non-coal strata from their coal measure counterparts.

2.2 Distinguishing Characteristics

The core connotation analyzed above gives rise to the fundamental differences of gas tunnels in non-coal strata: specifically in gas source, occurrence, and outburst mechanisms. These differences, in turn, lead to fundamental differences in engineering characteristics and prevention/control logic compared to traditional gas tunnels in coal measures [27–30]. To clearly articulate their distinctiveness and justify an independent research framework, the core differences are contrasted in Table 2.

2.3 Delimitation of Scope: Related Concepts and Engineering Boundaries

Having established the fundamental distinctions from coal measure gas tunnels, it is essential to delineate several closely related yet distinct engineering concepts to precisely define the scope of this study.

1. (1) "Gas Tunnels in Non-Coal Strata" vs. "Non-Coal Hazardous Gas Tunnels"

   Relationship: These concepts intersect but differ in emphasis. "Non-coal hazardous gas tunnels" is the broader, superordinate category, encompassing all tunnels threatened by hazardous gases in non-coal strata. The hazards include not only combustible hydrocarbons

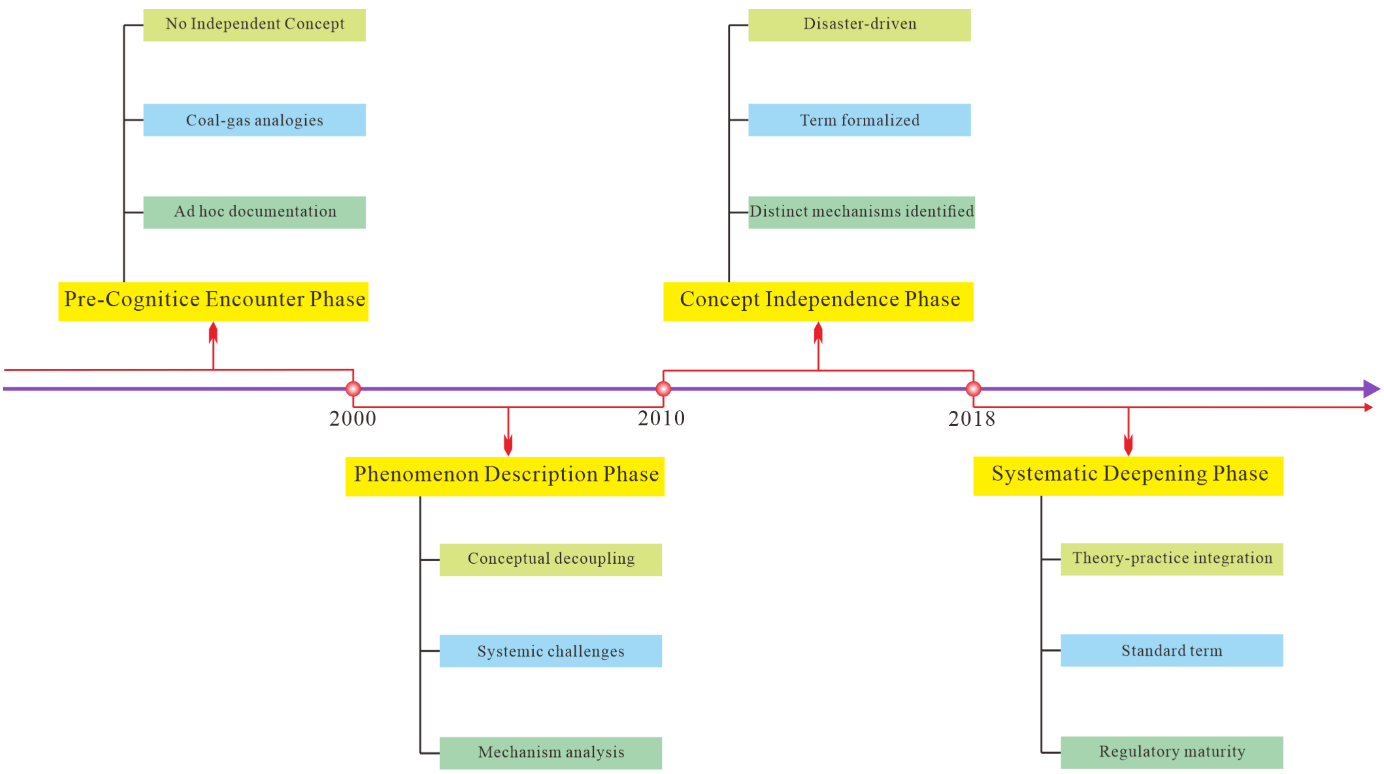

Figure 3. Stages in the Conceptual Evolution of "Gas Tunnels in Non-Coal Strata".

but also gases such as high-concentration CO_2 (asphyxiant), H_2S (highly toxic), and radioactive radon [31, 32].

Scope of This Paper: This paper focuses specifically on "Gas Tunnels in Non-Coal Strata," where the primary risk stems from combustible hydrocarbon mixtures (predominantly CH_4) with explosion hazards. Although H_2S and CO_2 may be present, the discussion centers on the geology, mechanisms, and control of combustible gas hazards. This focus allows for an in-depth examination of the most destructive explosion risks and their unique geological formation conditions.

2. "Gas Tunnels" vs. "Oil/Gas Pipeline Tunnels"

Fundamental Difference in Purpose: These are fundamentally different engineering types. Gas tunnels (for transport, water conservancy, etc.) aim to safely traverse gas-bearing strata, where the gas is an external hazard to be excluded [33]. In contrast, oil/gas pipeline tunnels are dedicated conduits designed for the safe, sealed transport of hydrocarbons, where the gas is the protected internal medium [34].

Divergence in Technical Systems: Consequently, their technical systems diverge. Gas tunnel engineering prioritizes geological prediction, ventilation, monitoring, and explosion-proof design [35–38]. Pipeline tunnel engineering focuses on pipeline integrity, leak detection, internal corrosion protection, and pressure control. Confusing these principles leads to fundamental errors in safety design [39].

3. Relationship with "Rockburst Tunnels" and "High-Pressure Water Inrush Tunnels": A Compound Hazards Perspective

Engineering Relevance: In deep-buried mountain tunnels, gas hazards in non-coal strata rarely occur in isolation. They often coexist and interact with other hazards, such as rockburst (stress-driven) and high-pressure water/mud inrush (fluid-driven), within the same complex geological body [40, 41]. For instance, a fault may act as both a gas conduit and a water pathway, while rockburst can create new fractures for gas release.

Focus and Relevance of this Paper: While focusing on the gas hazard per se, this paper acknowledges its role within compound hazard systems. This systemic perspective is crucial for holistic risk assessment and design. The analysis of gas, particularly its "strong structural control," inherently considers interactions with

Table 2. A Comparison of Characteristics: Gas Tunnels in Non-Coal Strata versus Coal Measures Strata.

Connotative Dimension	Coal Measure Gas Tunnels	Non-Coal Strata Gas Tunnels	Engineering Implications of the Differences
Gas origin	Single source from coal	Multiple sources: deep migrated hydrocarbons, in-situ generation from organic rocks, shallow biogenic gas	Complex hazards (H_2S, heavy hydrocarbons, CO_2). Need better sensors, PPE, and emergency plans
Gas reservoir	Homogeneous; coal seam is a clear marker	Heterogeneous; gas stored in fractures, fault zones, dissolution pores as isolated high-pressure pockets	Hard to predict and detect. No continuous markers. Conventional surveys often fail
Structural control	Mainly controlled by coal seam depth, rank, and structural deformation; distribution relatively predictable along coal seams	Outburst triggered by excavation of specific structures (e.g., faults), not lithology	Random and sudden. Need continuous real-time monitoring and dynamic ventilation across the whole tunnel

in-situ stress and groundwater, thereby laying groundwork for future research on multi-hazard coupling.

Through these clarifications, the research object of this paper is now clearly defined. Gas tunnels in non-coal strata in China represent an independent hazard type in tunnel engineering. Several features stand out. The main risk comes from multi-source combustible hydrocarbons. Gas occurrence is highly concealed. Outbursts are controlled by geological structures. These hazards also often occur together with other geological problems. This clear definition lays a solid foundation for building the classification system and analyzing distribution patterns in the following chapters.

3 A Genetic Typology of Gas Tunnels in Non-Coal Strata

Gas tunnels in non-coal strata vary widely in their features [42]. A scientific classification system is therefore needed to deepen geological understanding and improve risk management. Existing classifications fall short. Some are based on engineering phenomena. Others are adapted from coal measure gas. Neither works well for building reliable predictive models or universal mitigation strategies.

Therefore, this paper introduces a classification framework grounded in gas source as its primary principle. Since the source governs gas composition, occurrence, and enrichment patterns, it forms the logical basis for differentiating fundamental problem types.

This leads to the proposed genetic typology, which distinguishes three basic types: tectonically migrated, stratum-self-generated, and composite genetic, according to the gas's origin and formation mechanism [43]. This typology elucidates the critical pathway from "genetic analysis to characteristic identification to risk assessment," laying a foundation for explaining macroscopic distribution patterns. In practice, the primary types can be subdivided according to specific geological structures or engineering responses to facilitate precise risk identification.

3.1 Tectonically Migrated

3.1.1 *Basic Definition and Genetic Mechanism*

The tectonically migrated type is also called the distant-source replenishment type. Gas here does not come from the surrounding rock near the tunnel. Instead, it originates from deep sources such as ancient hydrocarbon reservoirs, modern gas fields, or deep high-pressure layers [44]. Tectonic forces drive the gas to migrate over long distances through regional faults, fracture networks, and unconformities [45]. The gas then accumulates in shallow geological traps like secondary faults, anticlines, or lithological pinch-outs, forming high-pressure pockets or layers [46]. When tunnel excavation breaks into these gas-bearing structures, the pressure balance is suddenly lost. This triggers rapid and violent gas outbursts or high-volume influxes.

3.1.2 *Geological and Engineering Characteristics*

1. *Exogenous and Replenishable Gas Source:* The gas is externally sourced, independent of the lithology or age of the immediate tunnel surroundings. A continuous supply via tectonic pathways can sustain outbursts, leading to prolonged duration and relatively stable pressure [47].

2. *Strong Structural Control:* The distribution of gas-enriched zones is strictly controlled by geological structures (active faults, folds, and associated fractures). Consequently, precise identification of concealed structures, especially gas-conducting faults, is the cornerstone of risk prediction [48].

3. *Sudden, High-Pressure Outbursts:* Outbursts are typically instantaneous, high-pressure, and high-volume events. Although clustered near structural zones, the exact breakout points on the excavation face are spatially random, allowing minimal warning time [49].

4. *Complex and Hazardous Gas Composition:* Sourced from mature petroleum systems, the gas contains significant concentrations of heavy hydrocarbons (C_2^+) and hydrogen sulfide (H_2S) alongside methane. This results in combined and escalating risks of explosion, poisoning, and corrosion [50].

5. Representative Case Studies:

   Xiaojialiang Tunnel (Lan-Yu Railway): This tunnel traverses the northern Sichuan oil-gas region [51]. The gas originated from deep Triassic Xujiahe Formation reservoirs and migrated upwards via a fault-fracture network, illustrating the classic "distant-source migration" model.

   Huangjialiang Tunnel (Xi-Cheng Railway): While crossing a complex structural zone, it encountered a mixed gas (methane, petroleum gas, and H_2S), demonstrating the compositional complexity and multi-hazard nature typical of this tunnel type [52].

3.2 Stratum-Self-Generated

3.2.1 Definition and Genetic Mechanism

The Stratum-Self-Generated Type (or In-Situ Generated Type) is defined by gas originating from the organic-rich source rocks through which the tunnel passes, such as shale, carbonaceous mudstone, or carbonaceous phyllite [53, 54]. These strata generated hydrocarbons in situ via thermal or biochemical processes. The gas is stored both as adsorbed layers on organic/mineral surfaces and as free gas in micropores and fractures, forming a source-reservoir continuum. Tunnel excavation disrupts this system through stress release and damage, breaking the adsorption-desorption and seepage equilibrium, which leads to gas release ranging from slow desorption to rapid outbursts.

3.2.2 Geological and Engineering Characteristics

1. *Integrated Source-Reservoir Configuration:* The gas is generated, stored, and released within the same rock unit; thus, the tunnel effectively excavates inside a "gas reservoir." [55]. Outbursts result solely from the disruption of the internal gas-rock equilibrium by engineering activities, with no external gas supply.

2. *Control by Lithology and Organic Geochemistry:* Gas abundance is directly governed by the source rock quality: Total Organic Carbon (TOC) content, Kerogen type, and thermal maturity (Ro). Strata with high TOC within the gas window represent the highest risk horizons.

3. *Widespread and Prolonged Emission:* Gas emission is typically areal or zonal across the gas-bearing section, not point-specific. The process is prolonged, beginning with the rapid release of free gas upon excavation, followed by the sustained desorption of adsorbed gas.

4. *High Sensitivity to Engineering Disturbance:* Emission rates are highly sensitive to construction-induced disturbances (e.g., blasting, vibration). In fractured zones, such disturbances can induce stress concentration and fracture propagation, potentially creating local high-pressure zones and triggering outbursts.

5. Representative Case Studies:

   Huangcao Tunnel (Yu-Huai Railway): This tunnel traverses the organic-rich marine shale of the Lower Silurian Longmaxi Formation, serving as a classic example of a shale gas-derived tunnel hazard, illustrating the typical "source-reservoir" configuration [56].

   Zhegushan Tunnel (Wen-Ma Expressway): Crossing Triassic carbonaceous phyllite, studies here detailed gas adsorption-desorption behavior and heterogeneous distribution in low-grade metamorphic rocks, significantly extending the applicable rock range for this tunnel type [57].

3.3 Composite Genetic

3.3.1 Definition and Genetic Mechanism

The Composite Genetic Type denotes gas hazards arising from the interaction of two or more fundamental mechanisms within a single tunnel project, reflecting the complexity of natural gas systems. A predominant form is the "Tectonically Migrated–Stratum-Self-Generated Composite," where a tunnel traverses in-situ gas-generating strata while also being influenced by deep gas sources via regional faults. Other scenarios include the superposition of multiple self-generating source rocks or compounding with thermal processes (e.g., magmatic activity).

3.3.2 *Geological and Engineering Characteristics*

1. *Diverse and Coupled Gas Sources:* The gas originates from multiple, overlapping sources: in-situ generation within surrounding rocks and migrated supply from deep reservoirs. Mixing within shared storage spaces leads to exceptionally complex and variable gas compositions.

2. *Superimposed Geological Controls:* Hazard formation is co-controlled by stratigraphy (source rock quality) and structure (migration pathways and traps). This dual control necessitates integrating disparate geological data for accurate risk zone identification.

3. *Highly Complex and Amplified Hazards:* Outbursts may exhibit hybrid characteristics: the sudden, high-pressure release of migrated gas combined with the prolonged, widespread emission of in-situ gas. This interaction often creates a synergistic risk amplification ("1+1>2"), vastly increasing the difficulty of prediction and mitigation.

4. *Representative Case Study:* The Huayingshan Tunnel in Sichuan is a typical example of the composite genetic type. Certain sections through non-coal strata of the composite genetic type, especially the sections through non-coal strata [58]. This project encountered gas from coal seams and goafs. In some zones, it also had non-coal hydrocarbon gases like natural gas and hydrogen sulfide, plus light oily liquids from deep petroleum systems. The tunnel passes through intense tectonic zones and multiple gas-bearing strata. This led to a coupling of several hazards: coal measure gas, non-coal hydrocarbons, toxic gases, high in-situ stress, and high-pressure water inflows. It was an extreme case, often called facing "five-fold hazards" [59–62]. The Huayingshan Tunnel clearly shows how gas sources mix and mechanisms couple in the composite genetic type.

3.4 Comparative Analysis of Type Characteristics

A comparative summary of the geological characteristics and engineering responses of the three gas tunnel types is presented in Table 3.

4 Regional Distribution Patterns of Gas Tunnels in Non-Coal Strata

Gas tunnels in non-coal strata in China are not random. They cluster in certain regions and specific geological settings. This clustering reflects a spatial match of three factors: regional tectonics, petroliferous basins, and major engineering corridors. This chapter examines the distribution from both geospatial and geological views to identify what controls it.

4.1 Geospatial Distribution: A Four-Tier Density Hierarchy Based on Provincial Units

Documented cases of gas tunnels in non-coal strata across China fall into a four-tier provincial hierarchy, as shown in Table 4. The framework goes from a high-density core with many hazards down to zones of potential or background risk. This gives engineers and planners a practical tool for national-scale risk assessment and infrastructure planning [63–65].

1. *Tier I: The Core Agglomeration Zone*

   This zone is the core area for non-coal gas tunnel

Table 3. Comparison of Characteristics among the Main Genetic Types of Gas Tunnels in Non-Coal Strata in China.

Aspect	Tectonically Migrated Type	Stratum-Self-Generated Type	Composite Genetic Type
Primary Gas Source	Deep oil/gas reservoirs	In-Situ Generation	Mixed
Key Geological Control	Regional deep-seated faults; secondary structures; lithologic traps	Distribution and maturity of organic-rich strata; tectonic fractures	Overlap of faults and organic-rich strata
Main Storage Space	Fault zones; fracture networks; solution cavities	Rock matrix micropores; adsorbed state on matrix; fractures	Combination of multiple storage types
Typical Outburst Characteristics	Sudden; high-pressure; spatially random; potentially steady supply	Sustained; widespread; disturbance-sensitive desorption; local outbursts	Complex and variable; combines sudden high-pressure and sustained emission
Primary Hazards	High-pressure outburst; Explosion; Poisoning	Gas accumulation explosion; local outburst	Composite hazards; high mitigation difficulty
Representative Cases	Xiaojialiang Tunnel (Lan-Yu Railway); Huangjialiang Tunnel (Xi-Cheng Railway)	Huangcao Tunnel (Yu-Huai Railway); Zhegushan Tunnel (Wen-Ma Expressway)	Huayingshan Tunnel, complex sections (Guang-Lin Expressway)

Table 4. A Four-Tier Provincial Hierarchy of Distribution Density for Gas Tunnels in Non-Coal Strata in China.

Tier	Region Name	Encompassing Provinces	Core Characteristics
Tier I	Core Agglomeration Zone	Sichuan, Guizhou, Chongqing	Highest hazard density. Deep gas sources plus structural pathways, karst-shale system, organic-rich shale belts.
Tier II	High-Incidence Zone	Yunnan, Shaanxi, Hubei, Hunan, Shanxi	Many documented hazards. Karst terrains, shale belts, tectonically active margins with non-coal gas conditions.
Tier III	Potential Risk Zone	Gansu, Qinghai, Xinjiang, Tibet	Geological preconditions exist but few verified major cases. Western orogenic belts. Risk may rise with westward infrastructure.
Tier IV	Background Zone	All other provinces	Lacks key gas-inducing factors. No major source rocks or strong neotectonic activity. Only sporadic cases.

hazards in China. It has the highest recorded hazard density and the most complex mix of disaster mechanisms. Three geological features come together here: the hydrocarbon-rich Sichuan Basin, the karst-shale terrains of Guizhou, and the organic-rich shale belts of Chongqing. Together they create a uniquely dangerous environment. Tectonically migrated gas from deep reservoirs, stratum-self-generated gas from shales, and composite hazards often coupled with karst water not only coexist but also interact. This leads to the most severe and challenging outburst events seen in the country.

2. *Tier II: The High-Incidence Zone*

Surrounding the core zone, this tier includes several provinces with many documented cases. Each shows clear, region-specific hazard patterns. In eastern Yunnan, the main risk is a composite of gas and water in karst and tectonically active settings. Southern Shaanxi, western Hubei, and western Hunan are extensions of the Lower Paleozoic shale gas belt. Here, stratum-self-generated hazards dominate. Shanxi is also in this zone. Along the tectonically active western margin of the Ordos Basin, fault systems related to basin-mountain coupling can bring deep non-coal gases, such as from Ordovician carbonates, up into shallow ground layers. This poses a distinct threat to tunnels, different from Shanxi's well-known coal mine gas hazards.

3. *Tier III: The Potential Risk Zone*

This tier covers the large orogenic belts and intermountain basins of western China. Regions in the Tianshan, Qilian, and Himalayan systems have the basic geological conditions for gas hazards. These include Meso-Cenozoic sedimentary strata with hydrocarbon potential and active faults. However, confirmed major tunnel disasters are still rare. The main reason is that deep, long tunnels have historically been few in the most susceptible locations. This low number does not mean there is no risk. On the contrary, as engineering projects move further west, these geological conditions mark the area as a high-stakes potential risk zone. Pre-emptive and careful investigation will be needed.

4. *Tier IV: The Low-Incidence / Background Zone*

Most provinces in eastern, northeastern, and central-southern China fall into this tier. These areas generally lack one or more key factors that cause gas hazards. They may have no extensive non-coal source rocks at the right maturity level. Or they lack strong neotectonic activity to create effective migration pathways. Some are stable cratonic blocks with simple geology. Reported incidents are rare and usually tied to very local geological anomalies. So at the macro-planning scale, these regions represent a background risk level. The chance of encountering widespread, severe non-coal gas hazards here is much lower than in the higher tiers.

4.2 Geological Distribution: Governed by the Source-Migration-Reservoir-Seal System

At the detailed scale of a geological section, the occurrence of gas hazards is governed by the dynamic "Source-Migration-Reservoir-Seal" system (Figure 4). Its effective configuration at shallow depths determines whether gas can locally accumulate to hazardous levels.

1. *Control of the "Source"*

High-risk tunnel sections line up exactly with

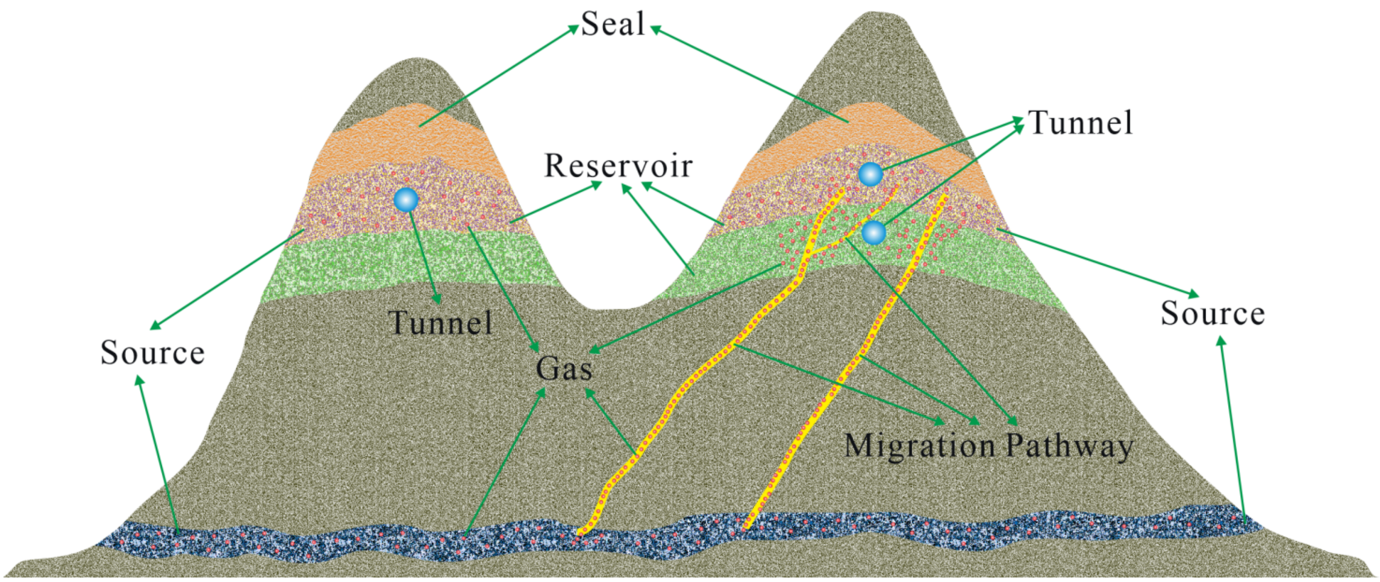

Figure 4. Schematic diagram of the "Source-Migration-Reservoir-Seal" control system.

effective source rocks. Two types matter. One is deep oil or gas reservoirs. These serve as distant sources for tectonic migration. The other is shallow strata with high total organic carbon, such as the Longmaxi Formation shale or carbonaceous phyllite, found along the tunnel alignment. These provide the local material basis for gas generation.

2. *Control of the "Migration Pathway"*

   Regional deep-seated faults are the main gas conduits, along with their associated structures like secondary faults and anticlinal axes. Where the tunnel axis crosses these conduits, the risk is highest for sudden, high-pressure gas outbursts.

3. *Control of the "Reservoir"*

   Gas accumulation needs effective storage spaces close to the tunnel horizon. These reservoirs are usually secondary porosity systems. Examples include fractured sandstone bodies, tectonic breccia zones, or well-developed fracture networks inside competent rock. The size and connectivity of these spaces directly control how much free gas can be stored and later released.

4. *Control of the "Seal"* An effective regional or local seal is needed to form and keep shallow, high-pressure gas pockets. Low-permeability strata work as seals. These include thick mudstone, gypsum-salt layers, or intact phyllite. If a tunnel goes through a geological unit where such a seal sits on top of a porous or fractured reservoir, the risk goes up significantly. The tunnel may then hit sealed, pressurized gas accumulations.

4.3 Engineering Implications of Distribution Patterns

The identified distribution patterns offer critical guidance for the lifecycle management of tunnel projects, informing strategies from planning to construction.

1. *Macro-Route Selection and Proactive Risk Zoning*

   During network planning and feasibility studies, gas risk in non-coal strata should be a primary factor in route evaluation. For lines that go through core agglomeration zones, such as the area around the Sichuan Basin, proactive zoning is essential. Dedicated resources for specialized investigation and mitigation must be included in both budget and schedule.

2. *Investigation and Design*

   Site investigation needs a different approach. Instead of conventional practice, it should combine oil and gas methods with geotechnical work. Key tasks include detailed fault mapping, identifying organic-rich strata, and using geochemical or geophysical techniques to detect shallow gas. The goal is a preliminary look at source, migration, reservoir, and seal conditions along the tunnel alignment.

3. *Risk-Adaptive Warning and Control During Construction*

   Prevention and control plans should differ based on the dominant gas type. In tectonically migrated zones, advanced prediction needs to locate gas-conducting structures and hidden pockets. In stratum-self-generated zones, the focus moves to measuring gas content and how it releases when disturbed. This calls for stronger continuous ventilation and real-time monitoring.

5 From Current Understanding to Future Frontiers

Large-scale construction of complex mountain tunnels in China has pushed research on gas tunnels in non-coal strata forward. What once were scattered records have now grown into a distinct sub-discipline. This chapter reviews the current consensus, points out persistent bottlenecks in theory and technology, and suggests future directions based on the concept, type, and distribution frameworks developed in this study.

5.1 Current Research Consensus

Through years of engineering practice and scientific research, several key consensuses have been formed in this field in China:

1. *Recognition as an Independent Hazard Type*

   Researchers and engineers now agree that gas in non-coal strata differs fundamentally from coal mine gas. The differences lie in gas source, occurrence, outburst mechanisms, and how disasters unfold. Therefore, it must be studied and controlled as a distinct major type of engineering geological hazard.

2. *Establishment of a Genetic Classification Framework*

   Research has moved beyond early descriptive work. A genetic classification based on gas origin is now in place. Two basic types are recognized: tectonically migrated and stratum self generated. Many cases support this scheme. It gives a theoretical basis for understanding these hazards and for applying type-specific prevention and control.

3. *Preliminary Formation of a Comprehensive Prevention and Control System*

   Because gas hazards are hidden and sudden, a technical strategy has taken shape. It centers on four elements. Advanced geological prediction provides guidance. Enhanced ventilation and dilution form the foundation. Real-time monitoring acts as the safeguard. Emergency response serves as backup. This system has been applied, tested, and improved during construction of many high-risk tunnels.

4. *Accumulation of Engineering Knowledge and Experience*

   High-incidence areas like the periphery of the Sichuan Basin have seen many challenging projects. Through these, valuable experience has been gained. It covers specialized investigation, construction ventilation, explosion-proof equipment, and safety management. This experience provides an important reference for future projects.

5.2 Persistent Challenges and Research Gaps

However, a significant gap persists between rapidly advancing engineering practice and the supporting theoretical research and key technologies, manifesting in several critical challenges:

1. *Weak Theoretical Foundations and Unclear Multi-Field Coupling*

   Most research is still macro and phenomenological. We lack dynamic mechanistic models for the full process of gas generation, migration, accumulation, and release in fractured rock. More importantly, there is no solid theoretical framework to describe how key physical fields couple together. These include geological structures, in situ stress, gas pressure, groundwater, and excavation disturbance. This gap makes it very hard to reliably predict outburst volume and pressure dynamics.

2. *Prominent Bottlenecks in Detection and Early-Warning Capabilities*

   Finding hidden gas pockets remains a tough engineering problem worldwide. Current geophysical methods lack the resolution and accuracy needed for small scale accumulations. Advance drilling only gives localized, scattered data points. As a result, accurate spatio-temporal prediction of outbursts is very limited. Early warning systems mostly rely on reactive threshold alarms, which have little predictive power [66].

3. *Severe Lack of Dedicated Standards and Systematic Management*

   Current industry standards mostly come from coal mine gas practice. For non-coal gas, there is a systematic gap in regulations. This includes investigation methods like gas source identification, risk classification, design principles such as ventilation and lining specifications, and specialized construction techniques. As a result, management often relies on adapting existing frameworks and on engineering judgment. There is an urgent need to make the approach more scientific and standardized [67, 68].

4. *Neglected Research on Hazards from Complex Gas Mixtures*

   Most research focuses on methane. We still have critical gaps in understanding the origin, migration, and especially the combined effects of other hazardous components like H_2S, heavy hydrocarbons (C_2^+), and CO_2. These neglected components actually make hazards more complex and severe. The Huayingshan Tunnel is a clear example.

5.3 Emerging Frontiers and Strategic Directions

To fundamentally advance risk prevention and control, future research must pursue breakthroughs along five strategic fronts [69–73]:

1. *Establish Multiscale, Coupled Predictive Theories*

   Gas migration and accumulation happen at different scales, from pore fracture networks up to large geological structures. We need physics based and numerical models that can simulate the full chain coupling among engineering disturbance, rock damage, and gas transport. Such models should help identify precursory signals and critical thresholds for different types of gas outbursts. That would give us a quantitative theoretical basis for risk prediction.

2. *Forge Intelligent Detection and Proactive Early-Warning Capabilities*

   We need to develop high-precision, explosion-proof geophysical and in-situ sensors that work in confined tunnels. Multi-source data such as geology, geophysics, drilling, and real-time monitoring should be integrated. AI or machine learning can then be used to build intelligent models for gas zone identification and dynamic risk forecasting. This would shift the approach from intermittent, contact-based probing to continuous, non-contact, intelligent early warning.

3. *Build Risk-Informed, Resilient Engineering Systems*

   Evolve the safety philosophy from accident prevention to whole-process risk management. Develop adaptive construction methods (e.g., dynamic ventilation, differentiated support) and engineer resilient tunnel structures using high-performance airtight linings and efficient pressure-relief technologies. The objective is to imbue tunnels with intrinsic "engineering resilience" against gas disasters.

4. *Accelerate the Development of Dedicated Technical Standards* The immediate priority is to create the first dedicated technical code. This requires joint efforts from industry, academia, and research. The code should systematically standardize the whole process for non-coal strata: site investigation, risk classification, design principles, and specialized construction. That would end the current reliance on adapted coal gas standards.

5. *Pioneer Research on Complex, Multi-Component Gas Hazards*

   Expand the research framework beyond methane to systematically investigate the origin, behavior, and synergistic hazards of H_2S, heavy hydrocarbons (C_2^+), and CO_2. This must lead to the development of integrated technologies for monitoring, purification, and personnel protection tailored to multi-component gas mixtures.

6 Conclusions

This paper reviews gas tunnels in non-coal strata in China from three angles: concept, type, and distribution. Four main conclusions stand out. First, these tunnels are an independent hazard, distinct from coal measure gas in terms of multi-source gas, concealed storage, and strong structural control. Second, we propose a source-based genetic classification with three types: tectonically migrated, stratum-self-generated, and composite genetic, each with different controls and risk profiles. Third, their distribution follows a four-tier provincial density hierarchy, governed by a source-migration-reservoir-seal system, with clusters in areas like the Sichuan Basin margin and eastern Yunnan-Guizhou Plateau. Fourth, research gaps remain in multi-field coupling, hidden gas detection, and dedicated standards; future work should target intelligent warning, resilient design, and a dedicated technical system. The concept-type-distribution framework answers what these tunnels are, how they differ, and where they occur, supporting early risk assessment and laying a foundation for follow-up studies on mechanisms and mitigation.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

Maolian Yuan is affiliated with the Nuclear Industry Southwest Geotechnical Investigation & Design Institute Co.,Ltd., Chengdu, China. The authors declare that this affiliation had no influence on the study design, data collection, analysis, interpretation, or the decision to publish, and that no other competing interests exist.

AI Use Statement

The authors declare that generative AI was used in the preparation of this manuscript. Specifically, DeepSeek was used for translation and language polishing purposes only. The authors reviewed and edited the content as needed and take full responsibility for the final version of the manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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