

Mechanism of Differential Natural Gas Enrichment on the Northern and Southern Sides of the Lingshui Sag, Qiongdongnan Basin

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Abstract

The natural gas enrichment in the Lingshui Sag of the Qiongdongnan Basin exhibits a prominent spatial pattern characterized as "superior in the south and inferior in the north, dry in the south and mixed in the north." This paper systematically compares the hydrocarbon accumulation conditions on the northern and southern sides to elucidate the mechanisms driving this differential enrichment. Research indicates that the coal-measure source rocks of the Yacheng Formation on the southern side possess tremendous hydrocarbon generation potential. Furthermore, the deep-water gravity flow channel sandstone reservoirs of the Huangliu Formation are large in scale and feature excellent physical properties. Coupled with the development of a highly efficient three-dimensional vertical transport system composed of mud diapirs and associated faults, the southern side possesses a superior foundation for hydrocarbon accumulation. In contrast, the northern side is constrained by multiple unfavorable factors, including low organic matter abundance in source rocks, thin and poor-quality submarine fan reservoirs, weak fault transport connectivity, and a high susceptibility to dispersion, which ultimately limits the scale of natural gas accumulation. The spatial configuration differences in various geological factors—namely generation, storage, and transportation—directly determine the accumulation efficiency and scale of natural gas in this region.

Keywords

Qiongdongnan Basin; Lingshui Sag; Differential Enrichment.

1. Regional Geological Setting

Located in the northern South China Sea, the Qiongdongnan Basin is a Cenozoic rift basin developed upon a Mesozoic basement, generally extending in a northeast-southwest direction [1]. It features a structural framework characterized by "north-south zonation and east-west block division," bounded by the No. 2 fault. The basin covers an area of nearly 80,000 km², with water depths ranging from 80 to 3,000 m; the deep-water area (water depth > 300 m) encompasses approximately 50,000 km². As previously noted, the regional Cenozoic structure of the Qiongdongnan Basin demonstrates a distinct "north-south zonation and east-west block division" pattern [2]. From north to south, it can be divided into four first-order structural units: the Northern Depression, Northern Uplift, Central Depression, and Southern Uplift [3,7]. Each first-order unit is further subdivided into several second-order structural units, primarily including the Ledong Sag, Lingshui Sag, Songnan Sag, Baodao Sag, Changchang Sag, Lingnan Low Uplift, and Songnan Low Uplift [8].

The study area is situated on the northern and southern sides of the Lingshui Sag in the western segment of the Central Depression, Qiongdongnan Basin. Its northern boundary is adjacent to the Lingshui Low Uplift, the southern boundary connects to the Lingnan Low Uplift, the west borders the Ledong Sag, and the east adjoins the Songnan Low Uplift, covering a total area of approximately 4,600 km² (with the study area delineated in Figure 1). The area proximate to the northern Lingshui Low Uplift belongs to the shallow-water zone, while the remainder is situated in a deep-water environment. The overarching structural pattern exhibits characteristics of faulting in the north and overlapping in the south. A central canyon channel has developed in the middle section of the slope belt on the southern side of the Lingshui Sag, generally extending in a northeast direction with a width ranging from 16 to 30 km [9].

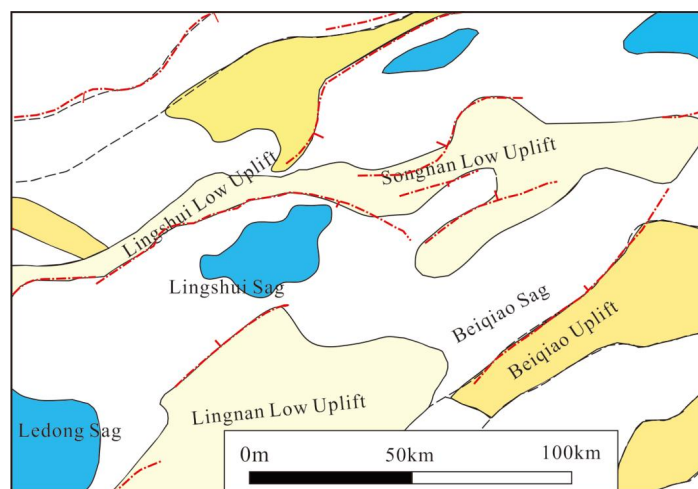


Fig 1. Location map of the study area

The tectonic evolution of this area is characterized by the superimposition of multiple stages and mechanisms, primarily controlled by the seafloor spreading of the South China Sea, plate rifting movements, and the coupling effects of the regional deep structural framework. This tectonic evolution can be broadly categorized into three principal stages:

(1) Syn-rift Stage

Influenced by the intense extension along the northern margin of the South China Sea, the Lingshui Sag underwent severe stretching, forming multiple asymmetrical half-graben structures that constituted the embryonic morphology of the sag; notably, the development of the Lingnan fault governed the structural framework of the sag. Dominated by strong extensional forces, the basin interior developed the coarse-grained alluvial fan deposits of the Lingtou Formation and the fan delta depositional system of the Yacheng Formation. The sedimentary facies are predominantly continental. The Yacheng Formation was deposited in a transitional marine-continental environment, typified by interbedded sandstones and mudstones alongside coal-measure strata, rendering it a critical hydrocarbon-generating interval in later stages. Concurrently, the Lingshui Formation was extensively deposited, laying the groundwork for the subsequent evolution of the depositional systems [10,12].

(2) Thermal Subsidence Stage

Following the Oligocene, the basin transitioned into a depression stage dominated by thermal subsidence. Tectonic activity stabilized, and the Lingshui Sag experienced continuous, basin-wide subsidence. Consequently, the depositional environment underwent a profound transformation, gradually evolving from early continental facies into a deep-water marine environment. During this stage, the Lingshui Formation extensively developed marine fan delta deposits interspersed with carbonate sediments. The Sanya Formation developed shallow-

marine sandstones and mudstones with progressively finer grain sizes, locally exhibiting tidal flat characteristics. By the depositional period of the Meishan Formation, the environment had further transitioned into deep water, forming a deep-water depositional system characterized by turbidite sandstones, submarine fans, and canyon-fill deposits. Reservoir conditions improved significantly, marking a vital period for the development of high-quality reservoirs [13].

(3) Accelerated Subsidence Stage

From the Late Miocene through the Quaternary, influenced by the intense uplift of the Qinghai-Tibet Plateau and the far-field stresses of the Red River fault system, the Lingshui Sag once again underwent rapid subsidence. Renewed tectonic fault activity intensified, further complicating the basin's architecture. The rapid subsidence during this period led to a substantial increase in water depth, plunging the depositional environment fully into a deep-water phase. The rapid deposition of the Huangliu and Yinggehai Formations yielded a deep-water gravity flow depositional system defined by massive deep-water turbidite channels and thick submarine fan sandstones. These depositional systems feature substantial sediment thickness and extensive distribution, providing massive storage capacity. Simultaneously, the thermal maturity of deep source rocks elevated further, generating copious amounts of dry gas, ultimately establishing the Lingshui Sag as a premier natural gas enrichment province.

2. Natural Gas Enrichment Characteristics and Differences

The proven natural gas reservoirs within the study area are primarily hosted in the Meishan, Yinggehai, Huangliu, and Ledong Formations along the periphery of the Lingshui Sag. The scale of these gas reservoirs is intimately linked to their hosting horizons and spatial distribution.

2.1. Distribution Laws of Natural Gas

The distribution patterns of natural gas in the Lingshui Sag and its margins are synergistically controlled by structural features, source rock types, reservoir conditions, and overpressure systems, resulting in stark differences between the northern and southern flanks: Natural gas in the northern Lingshui Low Uplift is predominantly mixed-source wet gas, influenced jointly by Miocene shallow-marine mudstones and Oligocene coal-measure source rocks. Conversely, the southern side (southern slope) is dominated by relatively dry wet gas generated from Oligocene coal-measure source rocks. Natural gas is highly enriched in inversion structural belts, buried hill structures, and submarine fan sand bodies within the central canyon. Fault zones and overpressure release zones act as critical migration pathways. Ultra-shallow gas reservoirs located further south in the deep-water region (e.g., the LS36-1 gas field) represent accumulations supplied by a mixture of near-source biogenic gas and thermogenic gas. There is no evidence supporting the accumulation of overpressured water-soluble gas, a concept that is also presumed to contradict established geological principles.

The spatial distribution of natural gas on the northern and southern sides of the Lingshui Sag is significantly dictated by variations in the spatial configuration of transport systems [1]: Wells LS13-2-1 and LS13-2-2 on the northern slope are situated on the downthrow block of the main F2 fault and structural highs associated with peripheral minor faults; these locations offer superior sand body transport performance, and exploration has confirmed the presence of numerous gas layers. In stark contrast, Wells LS13-2W-1 and LS13-2W-2 are located on the upthrow block of a minor fault, isolated from highly efficient transport conduits; due to migration obstruction, natural gas predominantly occurs as gas-bearing layers or coexisting gas-water layers [14]. The southern side is influenced by the baffling effect of reverse faults and an overpressure-driven mud diapir transport system. Natural gas migrates rapidly vertically along mud diapirs, but the reverse faults sever lateral migration pathways toward the LS33-1

structure on the Songnan Low Uplift, causing natural gas to concentrate within shallow sand bodies on the slope belt. The spatial coupling between fault positioning (upthrow vs. downthrow block) and structural highs directly dictates the degree of reservoir enrichment. Structural highs on the downthrow blocks of faults are more conducive to forming pure gas layers due to high transport efficiency. Meanwhile, although mud diapirs accelerate vertical migration, their lateral diffusion is restricted by fault seals, resulting in localized overpressured gas reservoirs [14,15].

2.2. Genetic Types of Natural Gas

Carbon isotope composition analysis of natural gas from the Meishan Formation in the Lingshui Sag reveals that $\delta^{13}\text{C}_1 < -30\text{‰}$, indicating a typical mature to highly mature organically-derived gas. Concurrently, $\delta^{13}\text{C}_2 > -28\text{‰}$, which signifies typical coal-type gas characteristics. The natural gas in both the Huangliu and Yinggehai Formations within the Lingshui Sag consists of thermogenic coal-type gas. Only a fraction of the gas in the ultra-shallow Ledong Formation is of biogenic origin. A minor portion of the gas in the northern Huangliu Formation falls into the oil-type gas category, reflecting relatively weak mixed-source accumulation signatures.

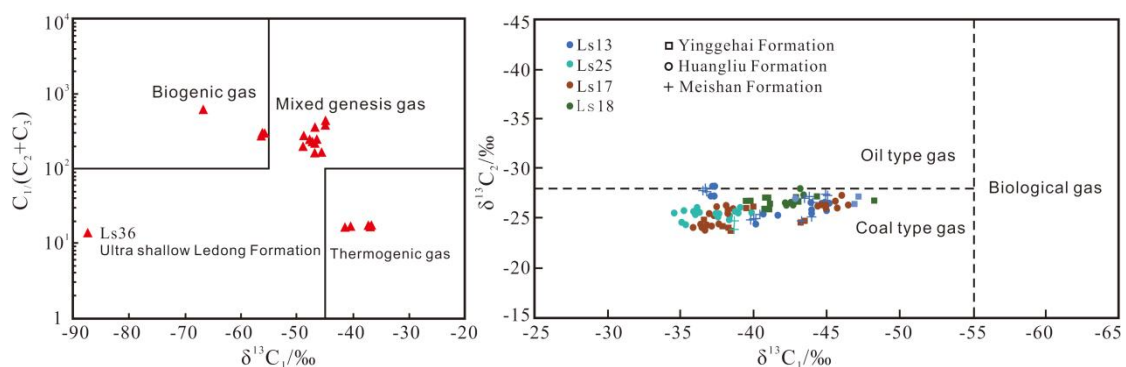


Fig 2. Discrimination diagram of methane-ethane carbon isotopic genetic types of natural gas across different formations in the Lingshui Sag

3. Differential Characteristics of Source Rocks

3.1. Organic Matter Abundance

The organic carbon content of source rocks in the Lingshui Sag varies markedly between the northern and southern sides. The coal-measure source rocks of the Yacheng Formation in the depocenter possess the highest organic matter abundance. The carbonaceous mudstones and coal measures are exceptionally rich in organic matter, with Total Organic Carbon (TOC) values ranging from 9% to 96%, demonstrating immense hydrocarbon-generating potential. The primary source rocks on the southern slope of the Lingshui Sag are coal-measure mudstones of the Yacheng Formation, rich in terrigenous organic matter, capable of generating abundant natural gas alongside a certain volume of light crude oil. Statistical data show that the TOC of mudstone samples from the deep-water Yacheng Formation ranges from 0.25% to 2.4%, averaging approximately 1.3%. In comparison, the organic matter abundance of the Lingshui Formation mudstones is slightly lower, with TOC values between 0.3% and 1.8%, averaging roughly 0.9%. Conversely, drilling results from the northern side reveal low organic matter abundance; the average TOC of the Yacheng Formation source rocks is estimated to be around 1.0%, while that of the Lingshui Formation is estimated to average less than 1.0%.

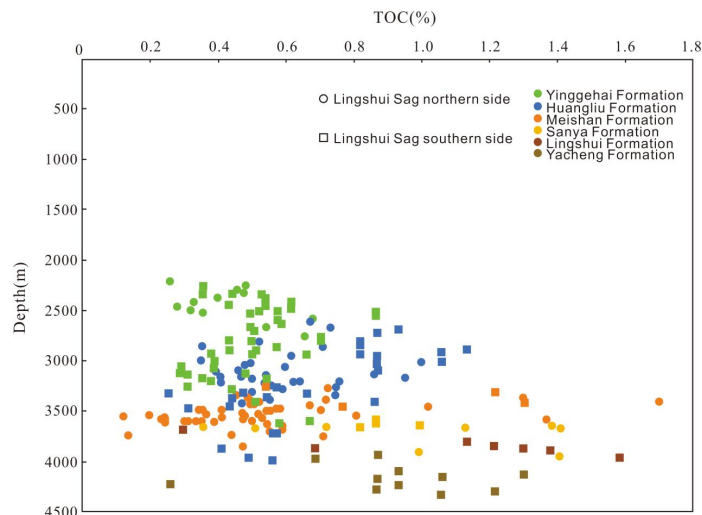


Fig 3. Comparison of organic matter abundance on the northern and southern sides of the Lingshui Sag

3.2. Kerogen Types

The organic matter within the source rocks of the Lingshui Sag is predominantly derived from terrestrial higher plants, and the kerogen is primarily classified as Types II and III. Zhang et al. noted that the Oligocene strata developed three major source rock types: authigenic coal, allochthonous coal, and terrigenous marine source rocks, wherein organic matter derived from terrestrial higher plants accounts for over 50%. Based on the relationship diagram between the Hydrogen Index (HI) and maximum pyrolysis peak temperature (Tmax) derived from previous studies, it is evident that source rocks on the southern side exhibit higher hydrogen indices, containing both Type I and Type II1 kerogen. The source rocks on the northern side are dominated by terrigenous organic matter. However, because their sedimentary facies lean more toward shallow marine to shore-shallow lake environments, they contain a relatively higher proportion of sapropelic components, constituting a mixture of Type II2 and Type III kerogen.

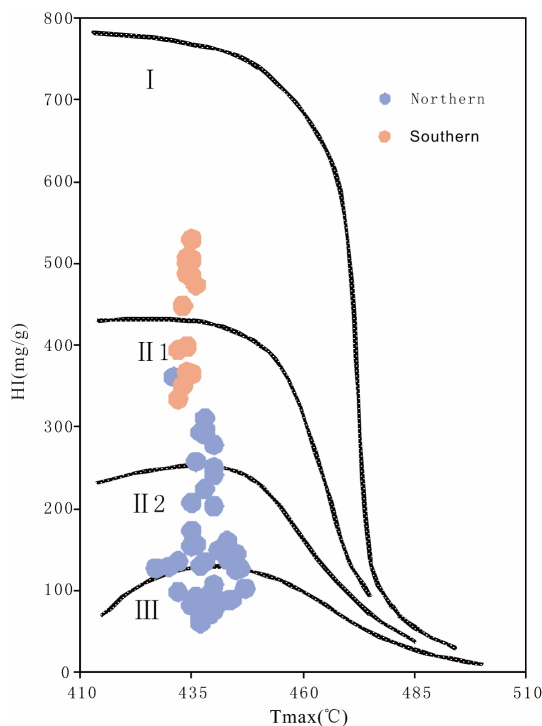


Fig 4. Relationship between Hydrogen Index (HI) and maximum pyrolysis temperature (Tmax) of source rocks on the northern and southern sides of the Lingshui Sag

4. Differential Characteristics of Reservoirs

4.1. Differences in Depositional System Types

The reservoirs on the northern side of the Lingshui Sag primarily belong to the Paleogene Lingshui Formation and the Neogene Meishan Formation, deposited within an assemblage of braided river delta, slope fan, and basin floor fan systems. Proximity to the terrigenous provenance area of the Hainan Uplift provided an abundant and close sediment supply. Since the Early Miocene, deltaic system sediments developed on the shelf margin bypassed via canyons and slope breaks into the deep-water basin, forming a quintessential gravity flow depositional system. For example, LS13-2 is situated within the continental margin slope fan system on the northern slope. During the Meishan Formation epoch, sedimentation was dominated by gravity flows, developing multiple slope fan and basin floor fan sand bodies, which largely exhibit lobe-like or fan-sheet geometries.

Conversely, the reservoir depositional environment on the southern slope is dominated by the Late Miocene Huangliu Formation's axial turbidite system within the central canyon. The southern slope is distal to the terrigenous provenance. However, influenced by the dramatic sea-level fall during the Late Miocene and the subsequent downcutting event that formed the central canyon, a deep-water gravity flow depositional system—characterized by axial canyon transport—was established, forming its distinct reservoirs.

4.2. Differences in Sand Body Distribution

The sand body reservoirs on the northern side are predominantly submarine fan deposits of the Middle Miocene Meishan Formation, comprising both slope fan and basin floor fan sand bodies. In the Lingshui 13-2 block, for example, seismic and drilling data reveal multiple stages of prograding slope fan sands and basin floor fan sandstones; nevertheless, individual sand bodies are small in scale and lack lateral continuity. Studies indicate that the submarine fan sand bodies on the northern slope are heavily constrained by provenance supply and geomorphology, resulting in a lower degree of sand enrichment compared to the southern slope canyon [16].

Based on drilling and seismic data analysis, the southern slope of the Lingshui Sag developed massive axial central canyon channel sand body reservoirs, exhibiting a nearly east-west distribution. The central canyon on the southern slope is filled with multi-stage channel deposits, primarily developing four types of channel sand bodies: canyon axis sands, lateral aggradation sands, natural levee sand bodies, and erosional remnant sands. These possess excellent continuity and large spatial scale. The Huangliu Formation reservoirs in the Lingshui 17-2 well block are composed largely of fine-to-silt sandstones. They are characterized by "diverse sand body types, excellent porosity and permeability, lateral segmented development, vertical superposition, multi-point provenance supply, and multi-stage channel filling." These channel sandstones constitute the high-quality reservoirs of the central canyon [17] and serve as the critical foundation for natural gas enrichment in the Lingshui 17-2 gas field.

4.3. Differences in Reservoir Physical Properties

The primary reservoirs on the northern side are submarine fan sandstones of the Meishan Formation, mainly concentrated within the Lingshui Low Uplift and the adjacent northern slope area. Sediment grains are relatively fine, and reservoir sand bodies are typically thin and poorly continuous. Dominated by interbedded siltstones, fine-grained sandstones, and mudstones, the lithology is highly heterogeneous. The argillaceous content is notably higher than that on the southern slope, heavily degrading reservoir quality. In contrast, the primary reservoirs on the southern slope are early- and late-stage turbidite channel sandstones of the Huangliu Formation, alongside submarine fan sandstones of the second member of the Yinggehai

Formation. The Huangliu Formation sand bodies are distributed in belts along the central canyon channel axis, originating from the intersection of the Lingshui-Ledong Sag and the Lingnan Low Uplift, gradually extending east-northeastward toward the eastern sub-sag of the Lingshui Sag, and ultimately breaching the Songnan Low Uplift. The submarine fan sandstones of the Yinggehai Formation are smaller and sporadically distributed, developing solely at the boundary between the eastern sub-sag and the southern flank of the Songnan Low Uplift, as well as in localized regions northwest of the Lingshui-Ledong Sag and Lingnan Low Uplift.

The pore throat radii of the Meishan Formation reservoirs on the northern side are significantly small, generally falling below 1 μm . This subjects migrating natural gas to intense capillary resistance, severely impeding fluid entry and flow. Conversely, the pore throat radii of the canyon channel sandstones in the Huangliu Formation on the southern slope are markedly superior, typically ranging from 1 to 5 μm , with an average of 4.3 μm .

Porosity data analysis indicates that the porosity on the northern slope is primarily distributed between 15% and 25%, with sample averages at 19.9% and a median of 19.3%. Permeability mainly falls within the 0-10 mD range, averaging 4.27 mD with a median of 0.46 mD. Overall, these are classified as medium-porosity, low-permeability reservoirs. The southern slope reservoirs boast substantially higher porosity, predominantly spanning 25% to 35%, while permeability averages between 100 and 650 mD, classifying them as medium-high porosity and medium-high permeability reservoirs. The conditions for natural gas migration and accumulation are exceptionally favorable. These superior physical properties are a direct consequence of the stronger hydrodynamic depositional environment on the southern slope; the high-energy setting facilitated the accumulation and sorting of coarse-grained sediments, ensuring the robust development and preservation of pore space.

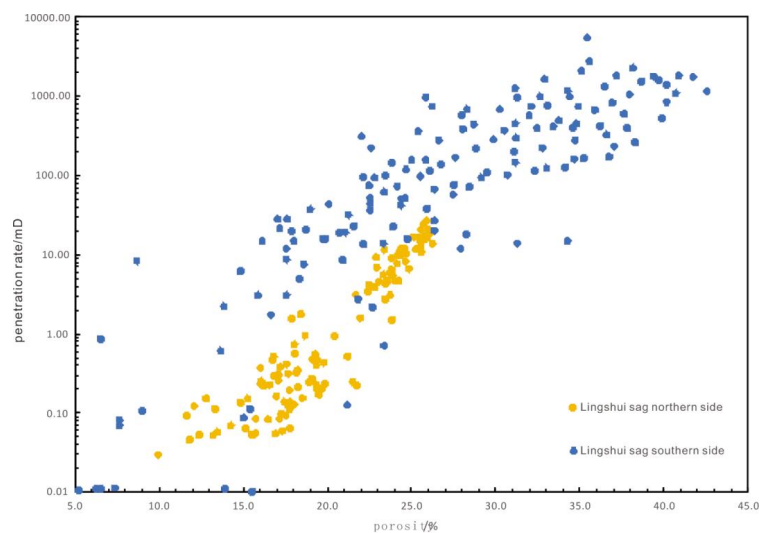


Fig 5. Cross-plot of reservoir porosity and permeability on the northern and southern slopes of the Lingshui Sag

4.4. Differences in Reservoir Microstructure

Submarine fan reservoirs on the northern slope are largely fine-grained feldspathic lithic sandstones or siltstones, demonstrating relatively low compositional and textural maturity [16]. Thin-section petrography reveals that due to substantial burial depths, these rocks have undergone intense diagenetic compaction and cementation. Microscopically, detrital grains primarily exhibit point-line contacts. Quartz grains display irregular marginal dissolution, and severe localized dissolution generates "bay-like" pore geometries containing visible dissolution remnant grains.

In the central canyon on the southern slope, the Huangliu Formation reservoir sandstones are predominantly silty to fine sandstones, displaying moderate sorting and rounding, accompanied by weak cementation. Core thin-section analyses suggest that because of shorter burial durations and potential preservation via abnormal fluid overpressures, primary intergranular pores have not been catastrophically compromised by dissolution or cementation. Pore margins remain distinct and clear. The reservoir space is overwhelmingly dominated by primary intergranular pores, supplemented by intergranular and intragranular dissolution pores, with trace occurrences of moldic and biological cavity pores [18].

5. Differences in Transport Systems

The southern side of the Lingshui Sag is dominated by a composite vertical hydrocarbon transport system forged by massive mud diapir structures and their associated faults. Natural gas generated in the deep Oligocene Yacheng Formation coal-measure source rocks migrates vertically along these diapiric structures and derivative faults, injecting massively into overlying structural traps. These faults not only pierce through multiple reservoir-cap assemblages but also extend deeply, establishing themselves as highly efficient primary conduits for hydrocarbon migration. The presence of these faults significantly elevates the permeability of the reservoir formations, amplifies the vertical and lateral migration efficiency of natural gas, and effectively links deep source rocks to shallow reservoirs. This dynamic allows natural gas to seamlessly accumulate within high-quality shallow sandstone reservoirs. Concurrently, beaded mud-fluid diapir zones are prolific on the southern slope. These diapiric structures generally align along the southern slope strike and frequently occur clustered with faults, forming a "step-like" vertical through-going pathway. This architecture bridges deep, highly mature hydrocarbon-generating depocenters with shallow reservoirs, providing a rapid vertical transport superhighway for natural gas [17].

In the northern region of the Lingshui Sag, transport systems are generally poorly developed. Specifically, the fault network is small in scale, sparse in distribution, and lacks the vertical penetration required to effectively link source rocks with shallow reservoirs, resulting in a precipitous drop in hydrocarbon transport efficiency. Moreover, some faults may compromise the integrity of overlying seals. When fault activity breaches a cap rock, high-pressure deep hydrocarbons migrate upward and escape along the fault plane, occasionally reaching the seabed surface. Deprived of effective trap systems capable of simultaneously transporting and sealing hydrocarbons, migrating fluids on the northern slope suffer severe lateral and vertical dispersion. This prevents natural gas from accumulating stably and continuously within the reservoirs, ultimately stunting the enrichment scale and thwarting massive commercial accumulations on the northern slope.

6. Conclusion

(1) The enrichment of natural gas in the Lingshui Sag manifests a conspicuous distribution pattern: "superior in the south and inferior in the north, dry in the south and mixed in the north." The southern side boasts a high degree of natural gas enrichment, overwhelmingly comprising coal-type gas generated from Oligocene coal-measure source rocks, predominantly accumulating in shallow slope sand bodies and central canyon submarine fans. Natural gas on the northern side mostly exists as gas-bearing strata or coexisting gas-water layers, reflecting a diminished enrichment scale. The gas is primarily mixed-source wet gas, whose accumulation is locally stifled by inadequate transport pathways and traps.

(2) Hydrocarbon generation potential differs radically between the two flanks. The Yacheng Formation coal-measure mudstones on the southern side are rich in organic matter (average TOC ~1.3%, with extremely high localized values). The kerogen is principally Type I and Type

II1, representing a mix of terrigenous and marine organic matter, thereby providing a stellar material foundation for generating abundant natural gas and light crude oil. The northern source rocks suffer from universally low organic matter abundance (average TOC < 1.0%), and the kerogen is mostly a Type II2 and Type III mixture, culminating in fundamentally weaker generation potential.

(3) Reservoir conditions exhibit a sharp contrast: "massive and superior in the south, thin and poor in the north." The primary deep-water gravity flow reservoirs on the southern side are the axial channel sandstones of the Huangliu Formation central canyon. These sand bodies are massive, multi-stage, and boast well-developed primary intergranular porosity, functioning as premium medium-high porosity and medium-high permeability reservoirs. The northern side relies on Meishan Formation submarine fan sand bodies as its primary reservoirs. Constrained by sediment supply and paleogeomorphology, these sand bodies are thin, discontinuous, and argillaceous. Microscopically, they suffer from intense compaction and cementation, resulting in minuscule pore throat radii and relegating them to medium-porosity, low-permeability status.

(4) The connectivity and spatial arrangement of transport systems act as the ultimate arbiters of gas accumulation efficiency. The southern side features massive mud diapir structures and accompanying faults, erecting a "step-like," highly efficient 3D vertical corridor. This allows deep-sourced natural gas to rapidly ascend through multiple stratigraphic layers and converge in shallow reservoirs. The northern fault system is architecturally stunted and lacks penetrative depth, yielding poor transport efficiency. Aggravated by the absence of effectively sealed traps, migrating hydrocarbons are prone to catastrophic dispersion, precluding large-scale accumulation.

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