Potential on joint development of three-gas reservoirs in the Qiongdongnan Basin

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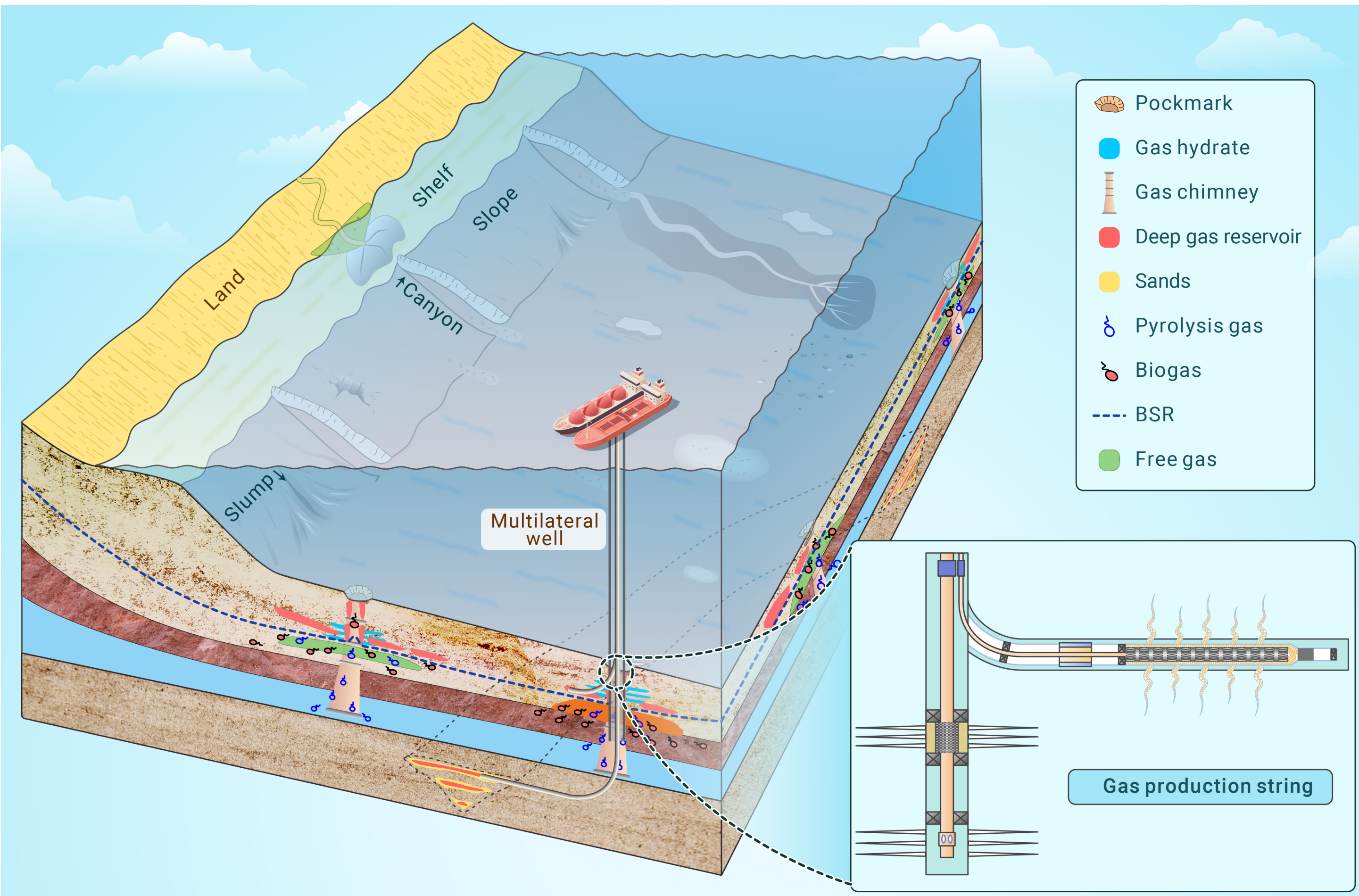
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Gas hydrate, shallow gas and deep gas reservoirs are coexistent in the Qiongdongnan basin.
- Gas chimney controls the spatial distribution of gas hydrates.
- Multilateral well and dual production string are required for three-gas joint development.

REVIEW

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Gas hydrates are typically found in the fine-grained sediments with low abundance and strong heterogeneity in the northern South China Sea. To date, although numerous gas hydrate reservoirs have been discovered, commercial exploitation remains highly challenging. Previous studies show that the Qiongdongnan Basin exhibits coexistence of gas hydrates, shallow gas and deep gas reservoirs. The hydrate-bound gases are a mixture of thermogenic and biogenic gas, mainly sourced from the granite buried hill reservoir, central canyon channel of the Lingshui Depression and the Yacheng Formation. In this study, we described a new development concept termed "Three-gas Joint Development" (TJD), to elucidate the simultaneous exploitation of these three gas reservoirs. Based on the distribution of three-gas reservoirs, three different TJD plans are proposed. If the relative distance between three-gas reservoirs does not exceeds the extension limit, a single production platform is capable of exploiting all three-gas reservoirs. A vertical well is suggested if the deep gas reservoir lies directly below the gas hydrates and shallow gas. Otherwise, multilateral well should be used to exploit different gas reservoirs with various branches in a main wellbore. However, several key issues remain unsolved. Numerical simulation of TJD should be conducted to evaluate interlayer interference and productivity. Efficient sand control and wellbore stability techniques, such as frac-packing and high-performance drilling fluids, are recommended when drilling unconsolidated sediments. Once these key technologies are overcome, TJD can provide a feasible approach for the commercial development of gas hydrates.

INTRODUCTION

The gas hydrates, shallow gas and deep gas reservoir are the main components of the overpressure fluid system in the deep-water basin, and they are often found in different formations.[1-3] Gas hydrates are typically found in the upper sediments within the gas hydrates stability zone, which ranges from 200 m to 300 m below seafloor. Shallow gas is commonly distributed in the unconsolidated sediments underneath the gas hydrates layers.[4] Deep thermal gas reservoirs, on the other hand, are usually located in deep consolidated strata.[5]

Gas hydrate is a crystalline compound formed by natural gas and water under high pressure and low temperature.[6] The basic idea behind utilizing gas hydrates is to allow it to decompose into free gas and water before extracting gas from the formation.[7] There are several techniques available for exploiting gas hydrates, including depressurization, heat injection, CO_2 replacement, chemical reagent injection, solid fluidization, and combined methods.[8-10] Depressurization and heat injection methods have been used in many production projects globally, such as the gas hydrates production tests in the Mackenzie Delta in Canada in 2002, 2007 and 2008.[11] The first marine natural gas hydrates production test was carried out in the eastern Nankai Trough in Japan in 2013.[12,13] In China, two successful marine natural gas hydrates production tests have been carried out.[14,15] The inaugural trial production test of gas hydrates was conducted in 2017 in the Shenhu area in the northern South China Sea by the China Geological Survey. The feasibility of exploiting the fine-grained gas hydrates reservoir was successfully demonstrated. The test employed a vertical well and depressurization method, lasting for 60 days, with an average daily gas production of approximately 5000 m^3.[16] However, this production rate fell significantly below the threshold for commercial production. In response, a second trial production test was conducted in the same area, utilizing a horizontal well to enhance production rates. The average daily gas production rate reached 2.87×10^4 m^3, marking a 5.54-fold increase compared to the initial trial.[17] Despite this improvement, the production rate still fell short of the minimum requirement for economically feasible commercial development. Therefore, relying solely on gas hydrates exploitation presents challenges in achieving commercial viability.

In the Qiongdongnan Basin, some scientists have confirmed the co-existence of gas hydrates, shallow gas and deep gas reservoirs.[18,19] Faults, gas chimneys, and shallow fractures act as efficient pathways for the migration of geofluids from deep formations to shallow layers. Consequently, the areal distribution of these three gas reservoirs overlaps, presenting an opportunity for their joint exploitation. To economically develop gas hydrates resources, some researchers have proposed the simultaneous exploitation of underlying shallow gas alongside gas hydrates in recent years.[20] For instance, a novel concept known as the Three-gas Joint Development (TJD) program has been introduced.[21,22] The TJD program aims to exploit gas hydrates, shallow gas, and deep gas collectively in deep-water basins. However, it is important to note that, TJD remains a conceptual idea lacking detailed discussion, requiring further exploration of its potential in the northern South China Sea.

In this study, we take Qiongdongnan Basin as an example to discuss the potential and planning of TJD. Utilizing the spatial distribution of gas hydrates, shallow gas and deep gas reservoirs, we have constructed a three-dimensional geological model for the three-gas reservoirs. Various development plans have been devised based on the distribution characteristics of three-gas reservoirs. Additionally, we delve into key technologies associated with TJD. This study aims to pave the way for a new approach to the commercial development of marine natural gas hydrates.

RESERVOIR MODEL OF THREE GAS RESERVOIRS

Geological setting

The Qiongdongnan Basin is a Cenozoic extensional rift basin developed on the pre-Paleogene basement in the northern South China Sea.[23-25] The basin is characterized by four structural units: the northern depression belt, the northern uplift belt, the central depression belt, and the southern uplift belt (Figure 1). The formation and evolution of the Qiongdongnan Basin have been significantly influenced by regional tectonic processes, including the South China continental margin rift, the South China Sea spread and Indo–Eurasian plate collision.[26] The sedimentary sequence in the Qiongdongnan Basin arranged from bottom to top comprises Eocene lacustrine deposits, Early Oligocene fluvial-littoral deposits, Late Oligocene neritic deposits, and Miocene to Quaternary bathyal-abyssal deposits.[27,28]

The extensive detachment in the Qiongdongnan Basin results in significant crustal thinning, uplifting of the asthenosphere, and the establishment of a high heat flow background in deep-water regions. This process also leads to substantial and rapid hydrocarbon generation from source rocks. Consequently, the Qiongdongnan Basin is characterized as a high-temperature and high-pressure basin. The basin exhibits widespread development of mud diapirs, gas chimneys, and other fluid activities.[29,30] These fluid leakage channels manifest in diverse forms, scales, and exhibit complex genetic and evolutionary processes. As a result, the Qiongdongnan Basin has become a focal point in current research on fluid leakage systems.[31,32]

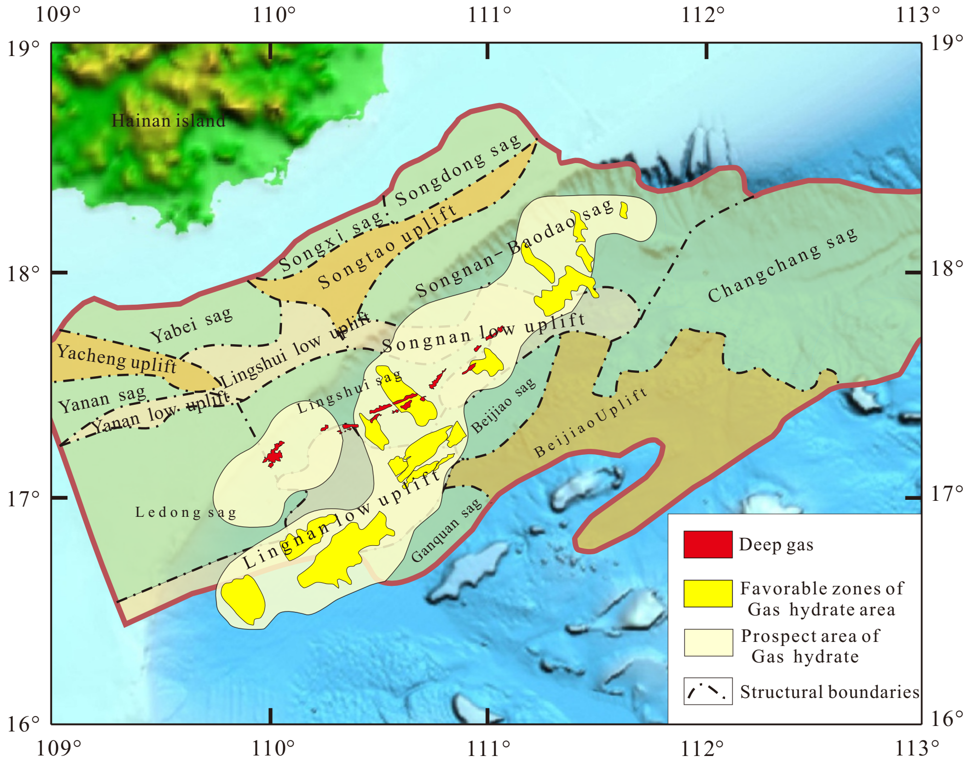

Figure 1. Structural units and distribution of gas hydrates and deep gas reservoirs in the Qiongdongnan Basin.

3D geological model of three gas reservoirs

To facilitate the concurrent exploration of the three gases—gas hydrates, shallow gas, and deep gas reservoirs—in the deep-water basin, it is essential for these resources to coexist. In recent years, extensive geological investigations have been conducted in the Qiongdongnan Basin.[33,34] The outcomes of these studies reveal the widespread presence of various fluid activities, including mud diapirs and gas chimneys. These geological features make the basin an ideal location for exploiting these three gases.

(1) Distribution and geological control factors of gas hydrates reservoirs

The Guangzhou Marine Geological Survey (GMGS) initiated the first gas hydrates drilling expedition in the Songnan Low Uplift in 2018. This drilling endeavor resulted in the discovery of various forms of gas hydrates within fine-grained sediments.[35] Subsequently, in 2019, GMGS conducted gas hydrates drilling in the Lingnan Low Uplift, as reported by He et al.[36] Additionally, in 2021, CNOOC Ltd. drilled eight wells in the Songnan Lower Uplift, situated in close proximity to GMGS-drilled wells.[37] Gas hydrates of both pore filling and matrix support types were identified in the unconsolidated silts and clays. In contrast, gas hydrates samples from the Lingnan Low Uplift were discovered in sandy sediments, where both fracture filled and pore filled hydrates were prevalent. The calculated average effective porosity exceeds 50%, the average gas hydrate saturation ranges from 20% to 52%, and the average permeability surpasses 0.1 mD. Notably, this marks the first discovery of sandy gas hydrates in the Qiongdongnan Basin.

Based on a comprehensive analysis of geophysical, geochemical, and drilling data, it is evident that gas hydrates are extensively distributed across the Qiongdongnan Basin. These deposits primarily manifest in three key areas: the Songnan Low Uplift, the Lingnan Low Uplift, and the Songnan-Baodao sag (Figure 1).[38] The gas hydrates exhibit noticeable variations in thickness and saturation within their layers. They tend to accumulate in pore spaces or fractures, showcasing a spatial consistency with both shallow gas and deep gas reservoirs. The accumulation of leakage-type gas hydrates is influenced by the migration of middle-deep overpressure fluids. The distribution of gas hydrates is primarily determined by the presence of gas chimneys and deep gas reservoirs. This correlation highlights the close relationship among thermogenic gas, deep central canyon sandstone gas reservoirs, buried hill gas reservoir, and Paleogene source rocks.[39,40]

(2) Distribution and geological control factors of shallow gas

Shallow gas has been identified based on seismic imaging and interpretation.[41] These gas deposits can be characterized by gas chimneys or enhance reflections. There are two types of shallow gas in deep-water area based on the geochemical data:[42] (1) Gas-bearing sediments, where methane gas constitutes the primary component (approximately 98%). This methane is predominantly sourced from decomposed shallow organic matter transported.[43] (2) Gas reservoirs formed primarily through the migration and accumulation of hydrocarbons resulting from kerogen decomposition during the formation of deep oil or coal series. A large number of gas chimneys have been discovered beneath the gas hydrates layers, serving as the primary conduits for the release of deep thermogenic gas.

(3) Distribution and geological control factors of deep gas reservoir

Deep gas reservoirs in the Qiongdongnan Basin are mainly distributed in five major structural strata,[44] i.e., buried hill reservoirs above the basin basement (e.g., Yongle area of the Songnan Low Uplift and Yacheng Uplift), fault depression series-developed (fan) delta reservoir, lower (fan) delta reservoir and the upper (fan) delta-seabed fan reservoir in the depression fault system, fault depression system delta-seabed fan reservoir and carbonate reservoir, and delta-turbidite channel-submarine fan reservoir and carbonate reservoir at the continental shelf edge of the depression series. The structural configuration plays a pivotal role in controlling overpressure.[45] The Cenozoic multistage tectonic movements influence the formation and re-regulation of the pore fluid pressure, causing changes in elastic energy and fluid potential differences. The opening and closing of the faults, along with the continuity in the distribution of sand bodies, manifest in varying interface energies due to alterations in pore throat size. This, in turn, leads to fluctuations in fluid potential within the system. The Songnan Low Uplift stands out as a region characterized by relatively weak diagenesis, exhibiting a low potential for interfacial energy. The multistage tectonic movements further control the formation and transformation of topography. These movements result in variations in elevation between the source and surrounding areas, leading to the accumulation of fluid under the gravitational potential energy. Throughout the Cenozoic tectonic movements, the basin system underwent the development of fault-sand bodies, tectonic ridges, and other transport channels, contributing to the establishment of diverse transport system frameworks. These frameworks indirectly shape the spatial configuration of deep gas reservoirs.

(4) Development of shallow fluid migration channels in the Qiongdongnan Basin

Shallow fluid migration channels play a pivotal role in connecting middle-deep gas reservoirs with shallow gas hydrates, bearing significant implications for identifying favorable areas for gas hydrates.[46,47] Within the Qiongdongnan Basin, well-developed migration channels, such as faults, offer the potential for natural gas generated in the deep formation to migrate towards the shallow strata.[48] Based on the interpretation of 3D seismic data, shallow fluid migration channels in the Qiongdongnan Basin mainly include faults, fractures, gas chimneys, and erosion unconformities,[49] as illustrated in Figure 2. Shallow faults of the Quaternary system are mainly distributed along the depression's edge, with some connecting to major deep faults and extending to the seabed—integral gas migration pathways. Gas chimneys in the Qiongdongnan Basin exhibit a clustered distribution pattern, often

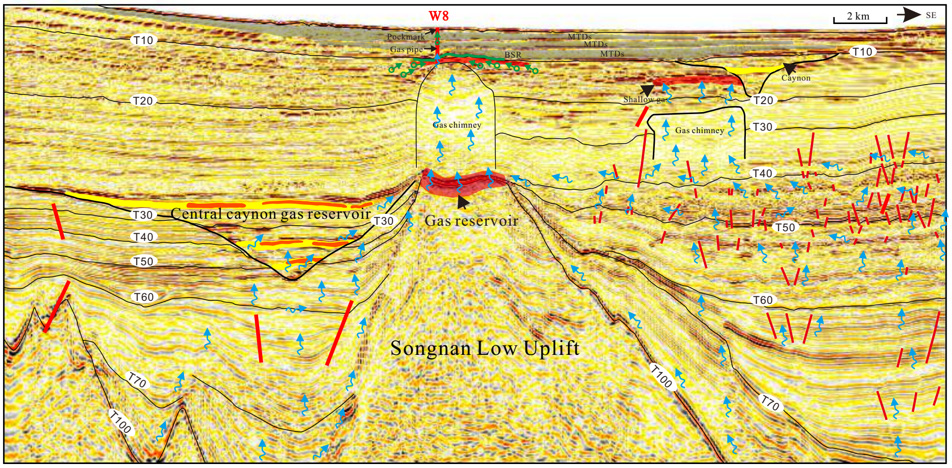

Figure 2. Seismic profile interpretation of fluid migration channels in the Qiongdongnan Basin, near Songnan Low Uplift The seismic profile pass through Well W8. Red Lines indicates the faults or fracture. Pink region represents gas pipe. Blue curved arrows represent the direction of hydrocarbon migration. Red regions represent gas reservoirs. Green line represents bottom simulating reflectors (BSRs). T10 is the boundary between Le I and Le II member of Ledong Formation. T20 is the bottom boundary of Ledong Formation. T30 is the bottom boundary of Yinggehai Formation, T40 is the bottom boundary of Huangliu Formation. T50 is the bottom boundary of Meishan Formation. T60 is the bottom boundary of Sanya Formation. T70 is the bottom boundary of Lingshui Formation. T100 is the base.

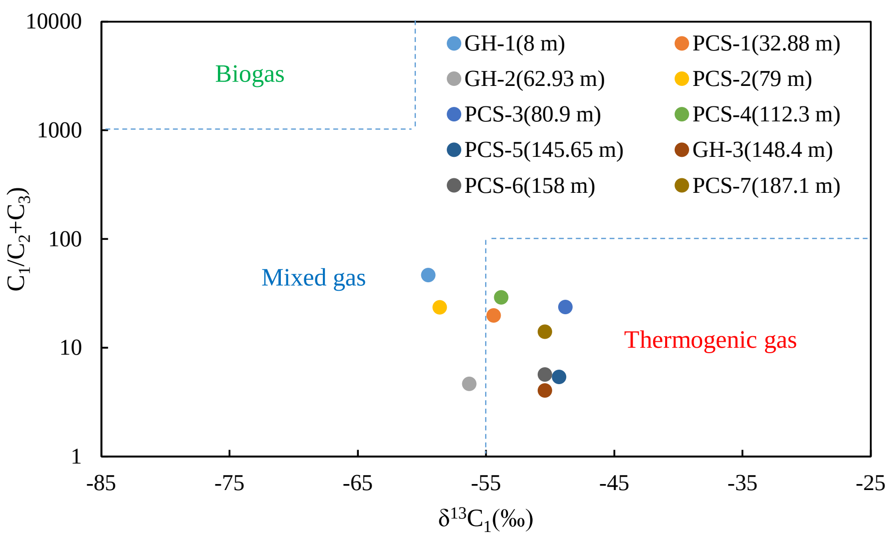

Figure 3. Types of hydrate-bound gases in Well W8 in the Qiongdongnan Basin near Songnan Low Uplift.

appearing circular or elliptical on horizontal sections. On seismic profiles, they often manifest as vertically distributed columns or mushrooms.[50] Coherence analysis allows for the identification of vertical channels, such as faults and cracks, within the gas chimney structure. Some gas chimneys feature fluid pipelines at the top that extend to the seabed, forming pockmarks (Figure 2). This observation suggests active fluid migration within the gas chimney, potentially serving as a source for gas in shallow gas hydrates and cold springs.

(5) Gas origin of gas hydrates

Well W8 is a gas hydrate exploration well on the top of a gas chimney area near the Songnan Low Uplift, whose water depth is about 1750 m. The well depth is 188 m and three potentially gas hydrates-rich intervals were discovered, namely the 60-80 mbsf, 100-120 mbsf, and 150-180 mbsf. Ten hydrate-related gas samples were collected in Well W8.[51] The gas composition data are given in Supplementary Table S1. is The ratio of methane to ethane plus propane $C_1/(C_2+C_3)$ and carbon isotopic compositions of the methane $\delta^{13}C_1$ are used to determine the origin of gas, results are shown in Figure 3.

Natural gas typically contains significant amounts of ethane and propane, with most gas samples also containing heavy hydrocarbons, such as n-butane, isobutane, and isopentane. Figure 3 demonstrates that $C_1/(C_2+C_3)$ is below 100, and the $\delta^{13}C_1$ value is below −45‰ in all samples. These findings suggest that the hydrate-bound gases are a mixture of thermogenic and biogenic gases, indicating the possible coexistence of structure I and structure II gas hydrates. Gas hydrates likely have a close relationship with deep source rocks and gas reservoirs.

In the Songnan Low Uplift, shallow biogenic gas is produced through the decomposition of organic matter in the sediments.[52] It migrates laterally to the reservoir through unconformity surfaces and mass transport deposits (MTDs) interfaces. Deep thermogenic gas originates from the gas source rocks of the Yacheng Formation, buried hill gas reservoirs in the basement of the Songnan Low Uplift, and deep gas reservoirs in the central caynon. This gas migrates through the large fault of the Songnan Low Uplift basement, then ascends to the BSRs through gas chimneys at the top of the Songnan Low Uplift.[53] Additionally, the boundary of the central canyon and polygonal faults may act as channels. Some of the gas enters the gas hydrates stability zone and accumulates in the three phase MTDs above the BSRs.[54] Ultimately, it is preferentially stored in layers with larger particle sizes and fractures, forming a high saturation gas hydrates reservoir. Furthermore, some gas permeates the MTDs and flows upward to the seafloor. The accumulation model of natural gas hydrates in the Songnan Low Uplift is depicted in Figure 4.

Based on gas hydrates drilling results and seismic interpretation, we developed a 3D model of gas hydrates, shallow gas and deep gas reservoir in the Qiongdongnan Basin (see details in Figure 5). The model reveals that gas hydrates, shallow gas and deep gas reservoirs are coexistent. Gas hydrates are distributed above the Songnan Low Uplift, with distinct areas in the west, center, and east (labeled GH-A, GH-B, and GH-C) covering 15.3 km^2, 11.5 km^2, and 6.0 km^2, respectively. Four gas chimney areas (labeled SG-A, SG-B, SG-C and SG-D) are accurately characterized, three situated closely above the Songnan Low Uplift, and one in the Beijiao Depression. Deep gas mainly accumulates in the central canyon and fissured granite buried hill. The buried hill gas reservoir (labeled BHG) is located in the granite buried hill below the Songnan Low Uplift, while the central canyon reservoir (labeled CCG) lies within the Lingshui central canyon. Gas hydrates and gas chimney closely relate to the distribution of deep gas reservoirs. When deep thermogenic gas rise and reach the gas hydrate stability zone, gas hydrate forms in sediment pores and fractures, with free gas accumulating beneath gas hydrate layers.

Due to the spatial correlation among gas hydrates, shallow gas, and deep gas reservoirs, it's possible to exploit all three gases using a single well (Figure 5).

Table 1. Development plans under different spatial distribution and reservoir characteristics of gas hydrates, shallow gas and deep gas reservoir

Development plan			Spatial relation among three gas reservoirs	Gas hydrates reservoir characteristics		
Number of platform	Well pattern	Production string		Saturation	Permeability	Thickness
One	Vertical well	Dual gas production string	Deep gas reservoir is directly below the gas hydrates and shallow gas	High	High	Thick
One	Multilateral horizontal well	Dual gas production string	Deep gas reservoir is directly below or not far from the gas hydrates and shallow gas	The saturation can be lower when using horizontal well instead of vertical well	The permeability can be lower when using horizontal well instead of vertical well	The thickness can be smaller when using horizontal well instead of vertical well
One	Multilateral extended reach well	Dual gas production string	There is a considerable distance between deep gas reservoir and gas hydrates, but the distance should not exceed the extension limit	The saturation can be lower when using horizontal well instead of vertical well	The permeability can be lower when using horizontal well instead of vertical well	The thickness can be smaller when using horizontal well instead of vertical well
More than one	Using vertical well to exploit gas hydrates and shallow gas; Using extended reach well to exploit deep gas reservoir	Single gas production string	The distance between gas hydrates reservoir and deep gas reservoir exceeds the extension limit	High	High	Thick
	Using horizontal well to exploit gas hydrates and shallow gas; Using extended reach well to exploit deep gas reservoir	Single gas production string	The distance between gas hydrates reservoir and deep gas reservoir exceeds the extension limit	The saturation can be lower when using horizontal well instead of vertical well	The permeability can be lower when using horizontal well instead of vertical well	The thickness can be smaller when using horizontal well instead of vertical well

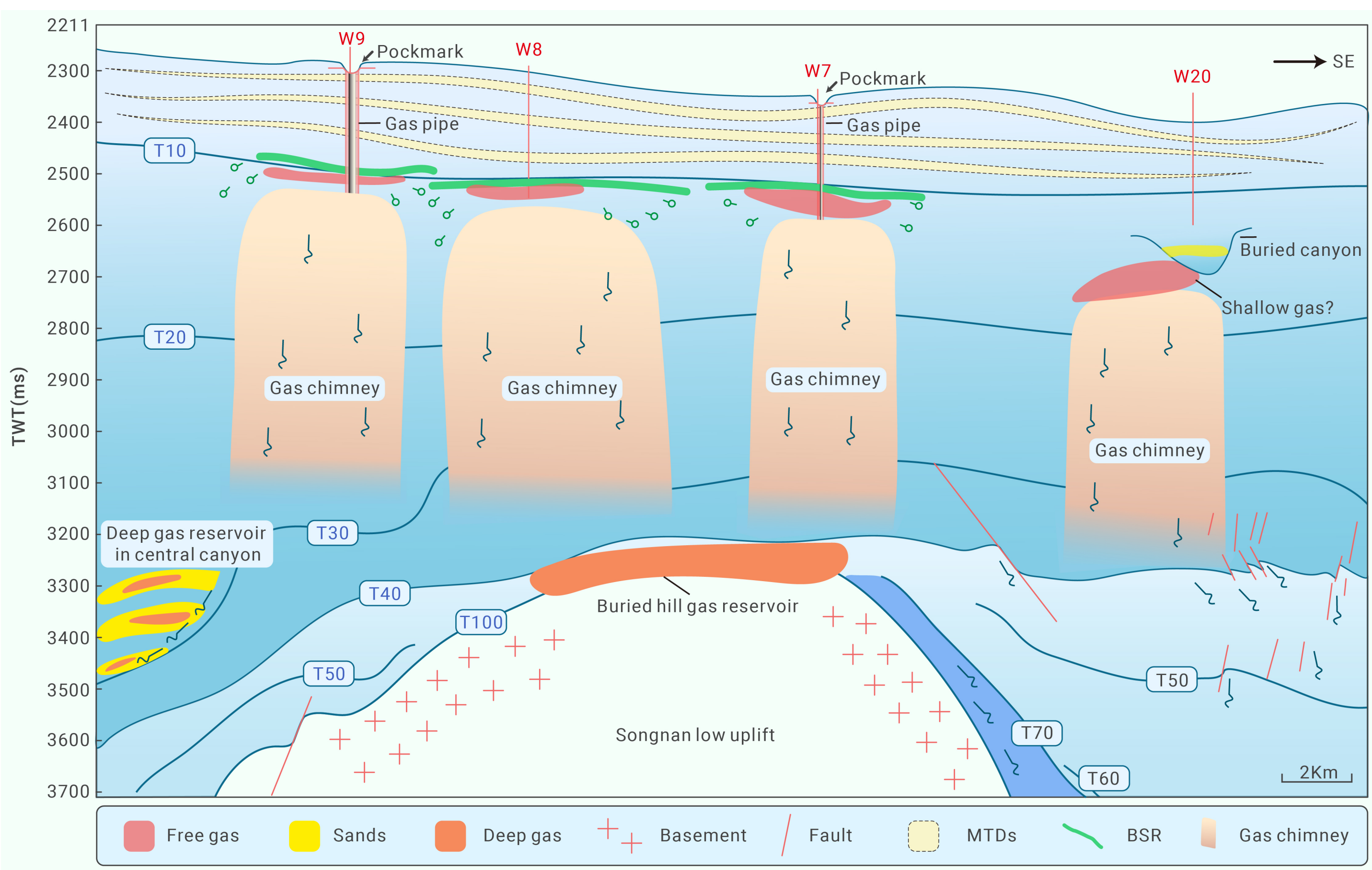

Figure 4. Reservoir accumulation model of natural gas hydrates in the Songnan Low Uplift There are two types of deep gas reservoirs: buried hill gas reservoir and central canyon gas reservoir. The gas migrates to the BSRs through channels, such as the gas chimney at the top of the Songnan Low Uplift.[53]

DESIGN OF JOINT DEVELOPMENT PLAN OF THREE GAS RESERVOIRS

Necessity of joint development of three gas reservoirs

The preceding geological conditions analysis reveals that the shallow gas is distributed beneath the natural gas hydrates reservoir. Conventional deep gas reservoirs, such as central canyon reservoir and Mesozoic buried hill gas reservoir, are located near natural gas hydrates in the Qiongdongnan Basin.[55] This spatial coupling between natural gas hydrates, shallow gas, and deep gas reservoirs creates favorable conditions for their joint development.

To reduce investment costs throughout the entire gas hydrates development process, key technologies and equipment commonly used in deep-

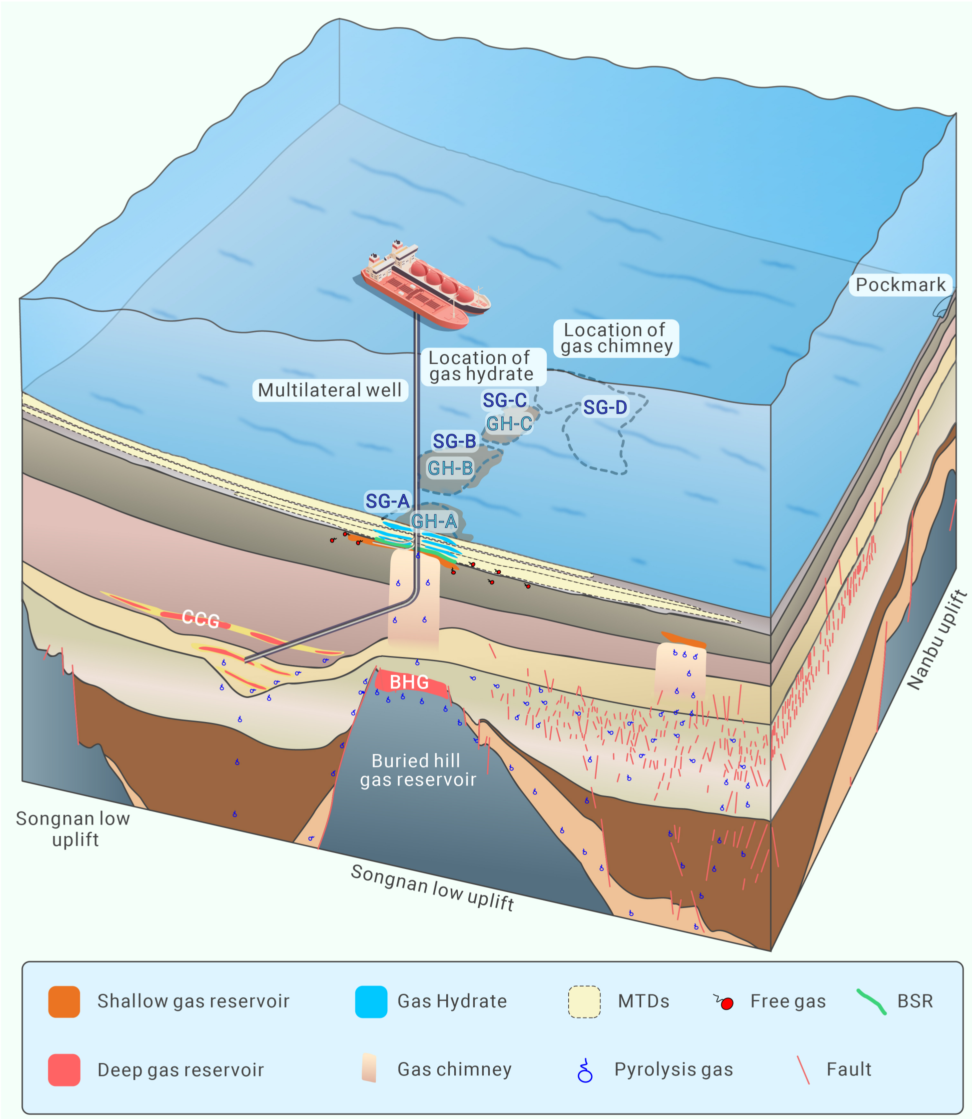

Figure 5. 3D Reservoir model of the gas hydrates, shallow gas and deep gas field in the Songnan Low Uplift of the Qiongdongnan Basin The gas hydrates, shallow gas and deep gas reservoir are coexistent in some zones of the Qiongdongnan Basin, especially in the Songnan Low Uplift. There are two types of deep gas reservoirs: buried hill reservoir (labeled BHG) and central canyon reservoir (labeled CCG). The gases in the buried hill reservoir are accumulated in the fissured granite. The central canyon is in the northwest side of the Songnan Low Uplift whose gases are accumulated in the multistage-channel sands. Three gas chimneys are distributed above the basement of the Songnan Low Uplift very near to the deep gas reservoir (labeled SG-A, SG-B and SG-C, respectively). Another gas chimney is located in Beijiao Depression (labeled SG-D). The shallow gas hydrates reservoirs are formed in the MTDs above the gas chimney (labeled GH-A, GH-B and GH-C, respectively).

water gas can be shared, enabling a "single platform, multiple utilization" approach. This not only enhances the utilization of oil and gas platforms or equipments, but also greatly lowers the development costs of marine gas hydrates.

Joint development plans of three-gas

Spatial distribution of gas hydrates, shallow gas and deep gas reservoir in the Songnan Low Uplift

To draw up the TJD plan, understanding the spatial distribution relationship is essential. Using the Songnan Low Uplift as a case study, we demonstrate how to design a joint development plan for three gases. Relative distances between various gas hydrates, shallow gas, and deep gas reservoirs are provided in Supplementary Table S2.

We can know that gas hydrates, shallow gas and deep gas reservoirs are distributed within an approximately 9.0 km radius area. Gas hydrates areas are closely clustered together. For example, GH-B is only 0.7 km from GH-C. Shallow gas and burial hill deep gas reservoirs lie directly beneath the gas hydrates layers, making them highly suitable for a joint development program. However, the central canyon gas reservoir (CCG) is located farther away from the gas hydrates, indicating the need for a different development plan.

Joint development plans of three-gas

Natural gas hydrates, shallow gas, and deep gas reservoirs exhibit spatial coexistence, but possess distinct spatial configuration relationships. Given constraints such as development costs and drilling complexities, varying natural gas resources necessitate different strategies during the joint development process of the three gases. In this study, we propose different development plans based on spatial distribution laws and reservoir characteristics. Table 1 and Figure 6 outline our proposed development plans under different spatial distributions and reservoir characteristics of gas hydrates, shallow gas and deep gas reservoir.

Various development plans under different conditions are illustrated as follows:

(1) Vertical well with dual gas production string on a single platform

For the case where deep gas reservoir lies directly below the gas hydrates and shallow gas, we recommend utilizing a vertical well on a single platform to exploit three-gas jointly. However, this approach requires the gas hydrates layer to have high saturation and permeability to achieve a high gas production rate, as the discharge area of the vertical well is relatively small. By drilling vertically through the gas hydrates layer, shallow gas, and deep gas reservoir directly, the need for constructing costly new platforms can be eliminated. Moreover, compared to horizontal and multilateral wells, vertical wells can be drilled at a lower cost. Given the great differences in pressure and reservoir characteristics, employing a dual production string is necessary to extract gas from different gas reservoirs. One production string is dedicated to exploiting gas hydrates and shallow gas reservoir, while another one is used for the deep gas reservoir. These two strings operate independently, allowing for different downhole operations in the various gas reservoirs without interference.

(2) Multilateral horizontal well with dual gas production string on a single platform

When the deep gas reservoir lies directly below or in close proximity to the gas hydrates and shallow gas, a multilateral horizontal well approach can effectively exploit all three gases. A multilateral well involves drilling two or more branch wells (secondary wells) into the main wellbore, then drilling a tertiary well from the secondary well, and connecting it back into the main wellbore.[56] In this scenario, it's advisable to drill multiple horizontal wells laterally from the main wellbore at different layers and directions. The main wellbore traverses through both the underlying shallow gas reservoir and deep reservoir, while the multilateral wellbores branch out from the main wellbore to access different targets. Horizontal branch boreholes can expand the contact area between the wellbore and the gas reservoir, leading to a significant increase in gas production rate.[57-59] Compared to conventional vertical well technology, the multilateral well approach allows for the joint development of deep gas, shallow gas and gas hydrates on a smaller scale with a single platform. This approach substantially reduces the number of

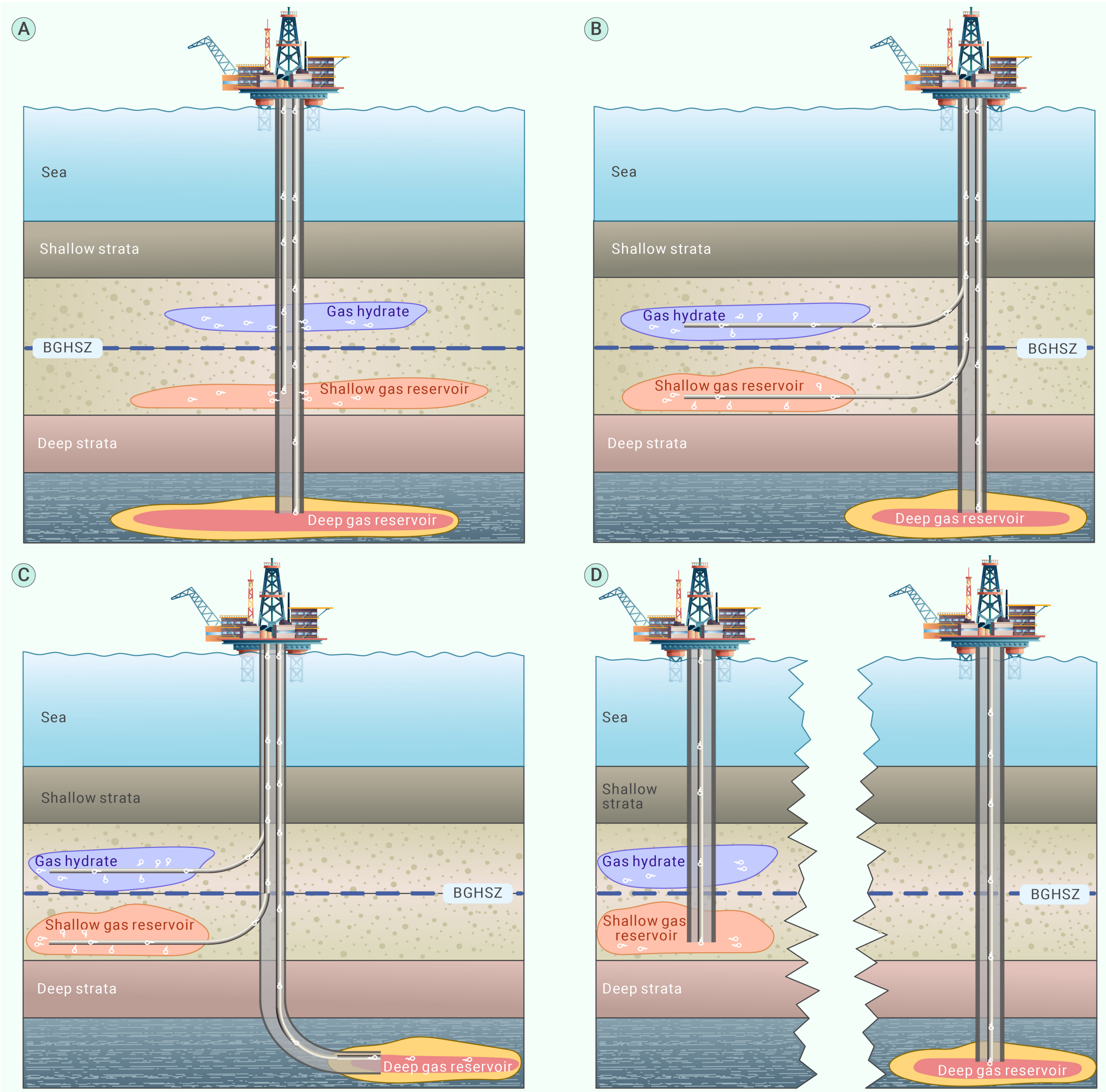

Figure 6. Schematic diagram of TJD under different spatial distribution of gas hydrates, shallow gas and deep gas reservoir (A) Vertical well with dual gas production string; (B) Multilateral horizontal well with dual gas production string; (C) Multilateral extended reach well with dual gas production string; (D) Multiple wells on different platforms.

drilled wells.

(3) Multilateral extended reach well with dual gas production string on a single platform

When the distance between deep gas reservoir and gas hydrates is substantial, it becomes challenging to exploit all three-gas reservoirs simultaneously using a multilateral horizontal well approach. However, if the distance does not exceed the extension limit,[60,61] a multilateral extended reach well can be employed. In this method, horizontal branches are drilled to exploit the shallow gas and gas hydrates, while the main wellbore extends toward the deep zone to exploit the deep gas reservoir. Despite this configuration, a dual production string is still required to extract gas from different gas reservoirs effectively.

(4) Multiple platforms to exploit three-gas

In the South China Sea, the maximum horizontal extension achievable with extended reach drilling is about 8 km.[62] Consequently, when the distance between three-gas reservoirs exceeds 8 km, multiple platforms are required. In such case, one platform can be dedicated to exploiting the gas hydrates reservoir and the underlying shallow gas, while another platform is utilized for the distant deep gas reservoir.

Considering the distribution characteristics of different gas reservoirs in the Songnan Low Uplift, a multi branch well model can be adopted to exploit the three-gas. For the deep gas reservoir in the Mesozoic buried hill, a vertical well with a dual gas production string is suitable. Conversely, for exploiting the deep gas reservoir in the central canyon, a multilateral extended reach well with dual gas production is necessary.

Production casing design of three-gas joint development (TJD)

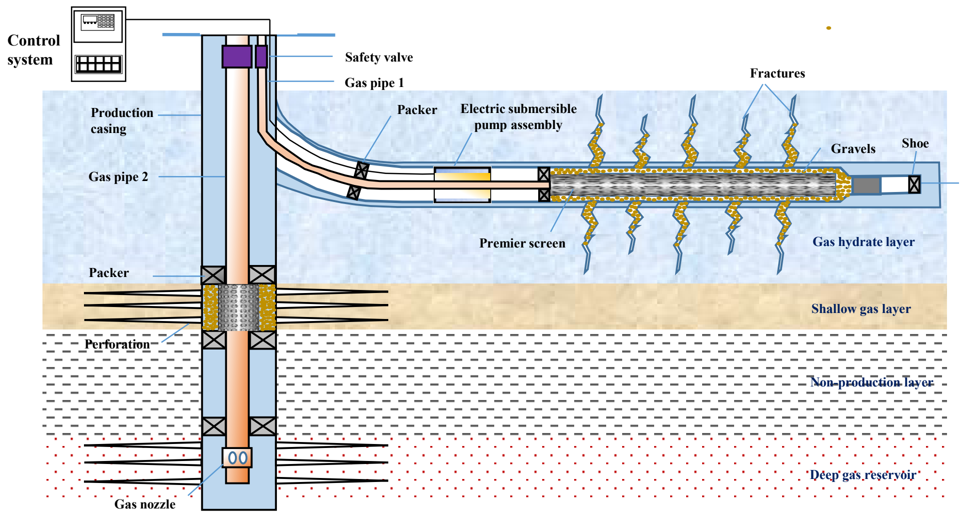

Figure 7. Schematic of production string of the TJD

$$\alpha(t)=\left[\sum_{i=1}^{n}q_{di}(t)-\sum_{i=1}^{n}q_{hi}(t)\right]/\sum_{i=1}^{n}q_{di}(t) \quad (1)$$

where $\alpha(t)$ is the interlayer interference coefficient, t is the production time; q_{di} is the gas production rate from the ith layer when using stratified production method. q_{hi} is the gas production rate from the ith layer.

Due to the significant pressure difference between the deep gas reservoir and shallow gas reservoir, it's recommended to use a dual production string. Additionally, considering the high flow rate of shallow gas, it's preferable to exploit the shallow gas initially before selecting suitable extraction methods for extracting natural gas from the gas hydrate layers. The potential interlayer interference between multiple layers should be thoroughly evaluated by combining indoor experimental testing methods, reservoir engineering techniques, and numerical simulation methods.

Gas in the deep gas reservoir and shallow gas reservoir typically exhibit overpressure, and can be extracted using its own energy. Conversely, gas hydrates, being an ice-like crystalline substance at high pressure and low temperature, require special methods for efficient gas extraction, such as depressurization, thermal stimulation, and gas replacement. Among these methods, depressurization is considered promising. Therefore, different production strings should be used for different reservoirs. For the gas hydrates layer, it is recommended to use an electric submersible pump to decrease the formation pressure by draining gas and water. Additionally, selective zone production can be implemented in vertical wells to extract gas from different gas hydrates layers with varying physical properties (Figure 7). When employing horizontal wells, the entire formation is mined together for simplifying the structure of the production string. However, since the reservoir consists of unconsolidated fined-grained sediments, appropriate sand control measures must be adopted. Fracture-packing is recommended as it not only enhances the permeability near the wellbore but also controls sand production, making it well-suited for low-permeability unconsolidated reservoir. Therefore, it is advisable to use facture-packing sand control method during gas hydrates production. For the shallow gas and deep gas reservoir, the gas production string is relatively simpler, and a flowing well production string can be directly employed (Figure 7). However, since shallow gas is typically accumulated in unconsolidated sediments, sand control completions should also be utilized in the shallow gas layers.

DISCUSSION ON KEY TECHNOLOGIES

Productivity simulation and interlayer interference prevention technology

The joint development of gas hydrates, shallow gas and deep gas reservoirs presents an alternative approach to enhance the economic benefits of gas hydrates development. Some researchers have conducted numerical simulations of gas hydrates development or the joint development of gas hydrates and underlying shallow gas.[63] For example, Wei et al. found that a dual horizontal well could yield 4.1 times more cumulative gas compared to a single vertical well when exploiting gas hydrates and underlying shallow gas together.[22] However, there is a lack of research on productivity simulation for TJD. The physical properties and formation pressure in different gas reservoirs vary significantly, necessitating different development plans for exploiting these gas reservoirs. It is crucial to conduct numerical simulations to verify the feasibility of the design before proceeding to on-site testing.

Indeed, multi-layer gas coproduction offers a promising approach for developing gas hydrates, shallow gas and gas reservoirs simultaneously. However, the differences in properties between layers can result in interlayer interference and reduced gas production efficiency.[64-66] Permeability and initial reservoir pressure are key parameters that should be considered before deciding on the coproduction of multiple layers at different depths, nonetheless, the impact of the combined performance of each layer on gas production has not been thoroughly understood.

Interlayer interference coefficient is commonly used to for evaluating the degree of interlayer interference quantitatively, which can be defined as[67]

Multilateral well drilling technology in unconsolidated formations

There are a number of difficulties during the construction process of this trial production by the multilateral well,[68,69] they are: (1) The formation is unconsolidated, leading to potential collapse and instability of the wellhead and wellbore. (2) The effective bottom hole pressure generated during drilling fluid circulation can easily result in formation fracture and leakage. (3) The formation offers limited support for the inclination of drilling tools. (4) The reservoir's shallow burial depth result in high frictional resistance along the drilling string. Consequently, the safe entry length of the drilling string is restricted. (5) Achieving directional deviation and controlling wellbore trajectory with significant dog legs poses challenges. (6) Running long horizontal sections of casing is challenging.

Wellbore instability poses a significant concern, particularly in horizontal and extended-reach well drilling.[70] Unlike shallow water and land drilling, deepwater areas exhibit lower pressure gradients in the overlying formation, resulting in a narrow safe mud density window between pore pressure and fracture pressure.[71] This situation can lead to formation fractures during well kick control operations and necessitate excessive casing layers when drilling to the designed depth to reach the target layer. To address wellbore collapse, further research is needed on high-performance low-density drilling fluid system design, whipstocking tools, and optimization of drilling parameters. Horizontal well drilling in shallow, soft formations may be achieved by employing appropriate drilling parameters across different well sections and employing various control measures.

Sand control technology

Natural gas hydrates in the South China Sea are commonly found filling the pores of fine-grained sediments.[72] Additionally, , these hydrates are typically situated in shallow layers within deep water regions, which are characterized by unconsolidated, low strength formations. Upon the decomposition of natural gas hydrates, multiphase flow comprising gas, water, and fine particles occurs due to pressure difference. Consequently, the formation may experience significant sand production issues under the influence of in-situ stress and fluid drag forces. For example, in March 2013, Japan utilized openhole gravel packing sand control technology in the gas hydrates test production well AT1-P.[73] However, after 6 days, gravel movement caused substantial sand production, leading to the termination of the test production. This highlights the critical nature of the sand production problem during gas hydrates development.[74] Nevertheless, traditional sand control methods are typically tailored for sandy reservoirs with low mud content, and efficient sand control methods for fine-grained gas hydrates formations remain elusive. Investigating the blocking mechanisms of sand control media in fine-grained gas hydrate reservoirs and establishing a method for optimizing sand control parameters are crucial for the long-term and efficient exploitation of gas hydrates.

CONCLUSION

(1) The investigations reveal that the Qiongdongnan Basin exhibits the spatial coexistence of gas hydrates, shallow gas and deep gas reservoirs. Gas hydrates are predominantly formed in the upper sediments within 200 m below seafloor, with shallow gas occurring beneath gas hydrate layers. Deep gas reservoirs are primarily accumulated in the central canyon and Mesozoic buried hill. This coexistence makes the Qiongdongnan Basin an ideal target area for the joint development of these three gases.

(2) The Songnan Low Uplift features three gas hydrate favorable areas, characterized by thermogenic-biogenic mixed gas.. Thermogenic gas originates from the granite buried hill reservoir in the Songnan Low Uplift, central canyon channel of the Lingshui Depression, and source rock of the Yacheng Formation. Deep natural gas migrates into shallow fine-grained clay silt through gas chimneys and fault channels.

(3) TJD program is primarily determined by the distribution characteristics of gas hydrates, shallow gas and deep gas reservoirs. When the relative distance between these reservoirs does not exceed extension limit, it is recommend to utilize a single production platform to exploit all three gas reservoirs simultaneously, thereby reducing costs. Given that the three gas reservoirs are distributed within an area with a radius of approximately 9.0 km, employing a multi-branch extended-reach well can efficiently exploit all three gases.

(4) Due to great differences in pressure and reservoir characteristics, a dual production string is necessary to extract gas from the various reservoirs. One production string is dedicated to exploit gas hydrates, while another one is utilized for exploiting gas from shallow and deep gas reservoirs.

(5) Key challenges in the joint development of gas hydrates, shallow gas and deep gas reservoirs include interlayer interference prevention technology, multilateral well drilling technology, and sand control technology. Future efforts should focus on further advancements in these technologies to facilitate the commercial development of marine gas hydrates.

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AUTHOR CONTRIBUTIONS

S.G. Wu and J. Sun conceived the research idea and supervised the whole research process. S.G. Wu and J. Sun wrote the manuscript. Q.P. Li provided the 3D seismic data and sequence stratigraphy interpreting results. Y.S. Ma designed the plans of three-gas joint development. S.G. Wu, J. Sun and T. Lüdmann contributed to the 3D seismic interpretation. All authors reviewed the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

The gas components data of Well W08 are given in Supplementary Table S1. The relative distance between gas hydrates, shallow gas and deep gas reservoirs are given in Supplementary Table S2. The raw 3D seismic interpretation data are proprietary and can not be shared at this time.

SUPPLEMENTAL INFORMATION

It can be found online at https://doi.org/10.59717/j.xinn-geo.2024.100065

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