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Research Article

Elements and gas enrichment laws of sweet spots in shale gas reservoir: A case study of the Longmaxi Fm in Changning block, Sichuan Basin☆

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Abstract

Identification of sweet spot is of great significance in confirming shale gas prospects to realize large-scale economic shale gas development. In this paper, geological characteristics of shale gas reservoirs were compared and analyzed based on abundant data of domestic and foreign shale gas reservoirs. Key elements of sweet spots were illustrated, including net thickness of gas shale, total organic carbon (*TOC*) content, types and maturity (R_o) of organic matters, rock matrix and its physical properties (porosity and permeability), and development characteristics of natural fractures. After the data in Changning and Weiyuan blocks, the Sichuan Basin, were analyzed, the geologic laws of shale gas enrichment were summarized based on the economic exploitation characteristics of shale gas and the correlation between the elements. The elements of favorable "sweet spots" of marine shale gas reservoirs in the Changning block and their distribution characteristics were confirmed. Firstly, the quality of gas source rocks is ensured with the continuous thickness of effective gas shale larger than 30 m, $TOC > 2.0\%$ and $R_o = 2.4-3.5\%$. Secondly, the quality of reservoir is ensured with the brittle minerals content being 30−69%, the clay mineral content lower than 30% and a single lamination thickness being 0.1−1.0 m. And thirdly, the porosity is higher than 2.0%, the permeability is larger than 50 nD, gas content is higher than 1.45 m^3/t, and formation is under normal pressure−overpressure system, which ensures the production modes and capacities. Finally, the primary and secondary elements that control the "sweet spots" of shale gas reservoirs were further analyzed and their restrictive relationships with each other were also discussed.

Keywords: Shale gas; Sweet spot; Elements; Gas enrichment laws; Early Silurian; Sichuan Basin; Changning block; Weiyuan block

North America, where shale gas was discovered before the mid-20th century, was the pioneer to recover shale gas. However, no systematic study was conducted and no substantial progress was made in the region until the early 21st century [1]. The shale gas and oil revolution also pushed more and more countries to conduct shale gas research. In recent years, with the expansion of shale gas exploration, the recognition of shale gas has been intensifying and updating especially, in shale gas enrichment law and demand for relevant recovery technologies. For example, the rock types of shale gas reservoirs change from single type to multiple type [2], and the genesis [3] and occurrence phases of shale gas are also multiple. For a special self-generating and self-preserving reservoir, the accumulation conditions are quite important, while the preservation conditions [4] are more important. Shale pore system has a direct influence on the occurrence condition and enrichment mechanism of shale gas. Adsorption and desorption are the two key factors for shale gas occurrence and development. The amount of adsorbed gas substantially decides the enrichment degree of shale gas. These factors that control shale gas enrichment degree and production are called "sweet spots". To achieve a large-scale economic development of shale gas, the elements of "sweet spots" and their interrelations must be identified.

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1. Geological features of shale gas reservoirs and elements of "sweet spots"

1.1. Geological features of shale gas reservoirs

Shale gas usually occurs in shale formations (including shale formation, interlayers and adjacent strata) in free and sorbed states, with source rock and reservoir in the same bed [5−7]. Shale gas reservoirs are characterized by low porosity and low permeability, and show diverse regional distribution, affected by a variety of factors (e.g. structural settings, depositional conditions, types and abundance of organic matter, rock matrix and minerals, fractures, and faults).

Shale gas reservoirs can impossibly provide industrial productivity only depending on their natural conditions, unless artificial stimulation is conducted. Thus, horizontal wells are drilled to fracture the gas-rich well intervals, so the "cocoon-shaped" gas recovery space is formed. Apart from the geological factors for enrichment, structural features of gas supply layers, combination of matrix minerals and other conditions that can be treated are significant.

1.2. Elements of "sweet spots" in shale gas reservoirs

Elements of "sweet spots" in a shale gas reservoir are mainly manifested in three aspects, i.e. hydrocarbon-generating potential, gas-preserving conditions, and recoverability. The former two elements are classified into "geological sweet spots", while the latter one belongs to "engineering sweet spots".

For an unconventional gas reservoir that was accumulated regionally and continuously, good hydrocarbon-generating conditions generally include subsidence center, source rocks with certain thickness and high abundance and good types of organic matters, and evolution of gas window. Good reservoir conditions include a good reservoir-forming pattern of self-generating and self-preserving in favorable storage conditions, presence of natural fractures, uninterrupted gas supply, and continuous accumulation.

Geographic location, burial depth and rock brittleness are key factors and prerequisites for the recovery of shale gas, and elements of "engineering sweet spots".

2. Elements of "sweet spots" in shale gas reservoirs in North America

The successful exploration and development of shale gas and oil in the United States triggered a worldwide petroleum technological revolution. Shale gas and oil are changing the world's supply and demand framework. In this circumstance, many countries have accelerated their exploration and development of shale gas and oil. In North America, shale gas [8−11] was mainly discovered in the Appalachian Basin, the Fort Worth Basin, the San Juan Basin, the Arkoma Basin, and the Texas−Louisiana Salt Basin (Table 1). These basins contain a lot of marine formations in Cambrian, Ordovician and Silurian of Lower Paleozoic, Devonian, Mississippi (Lower Carboniferous) and Pennsylvanian (Upper Carboniferous) of Upper Paleozoic, and Cretaceous of Mesozoic, and a large quantity of organic-rich black shale, with immense shale gas resources.

By the end of 2014, the United States achieved an annual shale gas production of 3740×10^8 m^3. Its spurt development and great success in shale gas and oil also made petroleum geologists further understand the petroleum resources. Based on the parameters of gas shale (Table 1) obtained from the typical high-quality shale plays in the United States, the shale gas industry can obtain valuable references and standards.

2.1. Hydrocarbon-generating potential

Ross et al. [13] found that total organic carbon (*TOC*) was positively correlated with the amount of methane adsorbed [14]. Boyer et al. [15] proposed that shale rocks could become effective source rocks only if the minimum *TOC* of shale should not be less than 2%. Chalmers et al. [16] found that the maximum amount of methane adsorbed corresponding to sapropelic and mixed-type kerogens was larger than that of mixed/humic and humic kerogens. Moreover, the statistics in North America [17] indicate that the thicker shale often corresponds to greater natural gas generating potential and retention volume. The analysis on the relationship between thermal maturity and hydrocarbon yield index [4] shows that the most favorable vitrinite reflectance (R_o) for shale gas generation and enrichment is 1.2−2.7%.

2.2. Accumulation conditions

In shale formations, the presence of fractures and pores effectively controls the enrichment degree of gas reservoirs. Due to low porosity and low permeability of a reservoir, free gas mainly exists in matrix pores and fractures, and the pore surface area of shale is positively correlated with its methane adsorption capability [18]. Shale gas basins under commercial exploitation in North America generally underwent intensive tectonic movements, resulting in the formation of folds and fractures in rock surface. Besides, abundant natural fractures developed in a shale with strong brittleness can provide storage space for free gas, but also provide a favorable condition for desorption of absorbed gas and for the increase of total gas amount [19].

2.3. Recoverability

In the mineral components of several typical shale plays in North America, swelling clay accounts for 25−40%, and silica, carbonate and other minerals account for 60−80%. Under strain, the brittle rocks demonstrate much stronger fracture-forming capacity and are liable to form fracture networks [20]. Temperature and pressure at effective depth are the prerequisites for transformation from kerogen to hydrocarbon. Gas shales in North America are characterized by a wide range of burial depth and thickness (Table 1), and the golden interval thickness for shale gas development is 1000−3000 m [12].

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Table 1
Main parameters of gas shale in shale plays in the USA.

Item	Parameters				
Shale play	Barnett	Haynesville	Marcellus	Woodford	Lewis
Basin	Fort Worth	ETNL salt	Appalachian	Arkoma	San Juan
Lithofacies type	Marine	Marine	Marine	Marine	Marine–Continental transitional
Strata	Mississippi	Jurassic	Devonian	Mississippi	Cretaceous
Enrichment area/km^2	13000	23000	240000	28500	10000
Depth/m	1981–2591	3048–4115	914–2591	1829–3353	914–1829
Effective thickness/m	15–60	61–91	15–61	37–67	61–91
TOC	4.5%	0.5%–4.0%	5.3%–7.8%	1.0%–14.0%	0.5%–2.5%
R_o	1.1%–2.3%	2.2%–3.2%	1.5%–3.0%	1.1%–4.9%	1.6%–1.9%
Total porosity	4.0%–5.0%	8.0%–9.0%	2.0%–10.0%	5.0%–9.0%	3.0%–5.5%
Gas content/(m^3/t)	8.5–9.9	2.8–9.3	1.7–2.8	5.6–8.5	0.4–1.3

Note: Modified according to Curtis [12].

3. Elements of "sweet spots" in shale gas reservoirs in Changning block

Shale gas enrichment in China is controlled by basin types, depositional environment, tectonic settings, lithofacies and other factors. Compared with terraces in North America, the sedimentary basins in China are small and unstable. Relatively complex plate tectonic activities led to diverse basin types and sedimentary modes, corresponding to multiple types of shale gas reservoirs. In addition, organic-rich shales of marine, continental, and marine–continental transitional facies exist in the multiple sedimentary types of basins within China. For example, the marine organic-rich shale is widely distributed in the Lower Paleozoic of the Sichuan Basin and its periphery, and Changning block, located in the Changning–Weiyuan national shale gas demonstration area, is a typical example in the basin.

The Lower Silurian Longmaxi Fm in Changning block is mainly composed of organic-rich black shale, carbonaceous shale, and carbonaceous siliceous shale, which contains graptolites, brachiopods and other fossils, with a thickness of 400–900 m. Many successfully-drilled wells in Changning block and its periphery reveal that shale in the Longmaxi Fm is thick and widely distributed, with high abundance and a good type of organic matters, relatively high thermal maturity, moderate content of brittle mineral components in shale matrix, and presence of diverse types of pores and fractures. So, these outstanding features make the Longmaxi Fm shale favorable for shale gas accumulation [21,22].

3.1. Hydrocarbon-generation elements

The factors that affect gas generation are mainly *TOC*, shale thickness, types and thermal maturity of organic matters. The Lower Silurian shales are the major gas shales in southern China, with generally high *TOC* (0.74–5.98%). In Changning block, *TOC* of favorable reservoir intervals in gas-producing wells is 2.70–3.25% (Fig. 1), and effective thickness is more than 30 m (Fig. 2). According to the analysis results, the gas content per unit of rock positively correlates with *TOC* and shale thickness (possibly, preservation conditions are determined by thickness).

As to the macerals of kerogen, sapropelinite accounts for 71–94%; either vitrinite or inertinite accounts for less than 5% (Fig. 3). The kerogen is mainly of sapropelic type, and partially of sapropelic-prone mixed type, being the favorable type of organic matter. Major shale formations show a large burial depth and have entered an over-mature thermal evolution stage. Accordingly, sufficient conditions are available for the formation of shale gas reservoirs. It can be seen from Fig. 4 that R_o of gas producing interval is mainly 2.1–3.7%.

3.2. Gas-storage elements

Shale reservoirs often have low porosity (less than 10%) and low permeability (10–50 nD). Data of existing wells indicate that reservoir porosity mainly concentrates in 2.78–6.12% and positively correlates with gas content – gas content in shale increases with the increase of porosity (Fig. 5).

Mineral components in shale are also the factors that affect the preservation condition of shale gas. In this block, main mineral components include clay, carbonates, quartz, feldspar and a small amount of pyrite (Fig. 6). In a favorable reservoir interval, the average clay content is 30.51% and the content of brittle minerals is greater than 50%. High shale brittleness

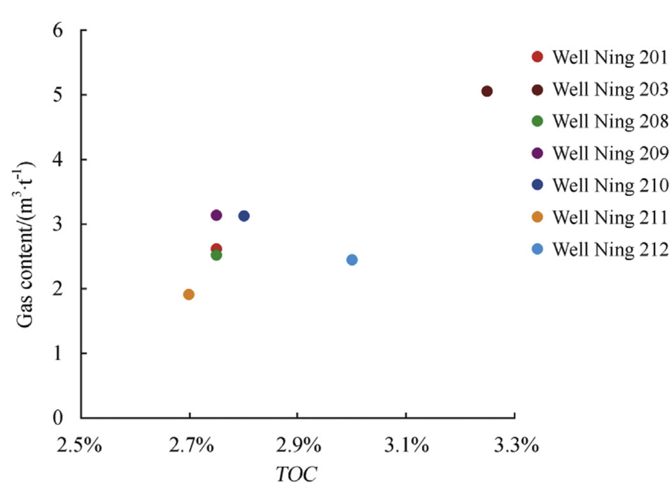

Fig. 1. *TOC* vs. gas content in shale.

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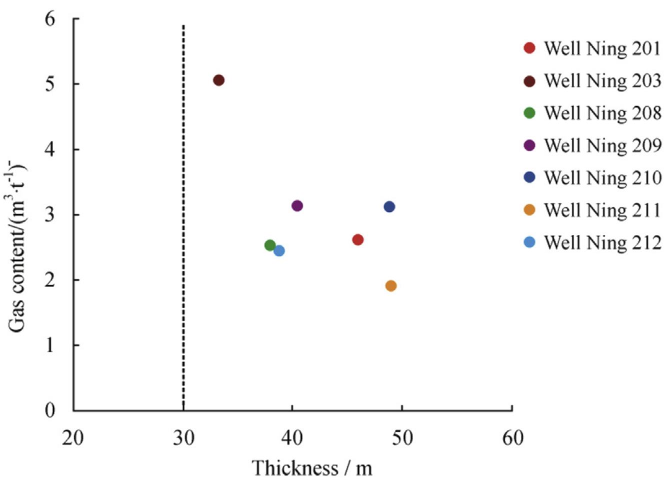

Fig. 2. Shale thickness vs. gas content in shale.

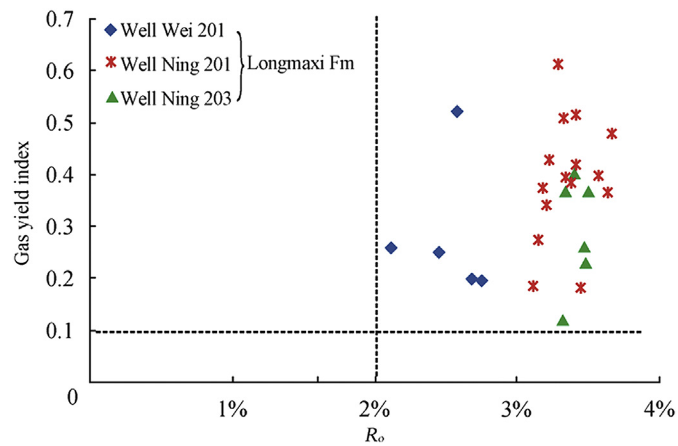

Fig. 4. Thermal maturity vs. gas yield index.

facilitates the formation of natural fractures and induced fractures, thus further enhancing the permeability of shale formation and increasing the reservoir space for oil and gas, so that the gas desorption and migration are promoted to control the accumulation and production of oil and gas.

Exploration results show that, similar to the shale gas fields developed in North America, both Changning and Weiyuan blocks contain excellent fracture systems, especially Changning. The Weiyuan block mostly contains micro-fine closed fractures filled by secondary minerals such as quartz, calcite, and dolomite [23,24].

3.3. Recovery elements

Li Jingxin et al. [25] held that not all high-quality source rocks were economically recoverable, but only those organic-rich shales containing high content of brittle minerals with low Poisson's ratio and high elasticity modulus are the major targets for exploration [26,27]. Therefore, given good hydrocarbon generation and gas storage conditions, engineering "sweet spot" elements will be the key factors that determine shale gas production. Fig. 6 shows that the brittle mineral content in gas producing well is 50—80%, and the shale with high content of brittle minerals is favorable for future recovery by fracturing.

Based on actual data, fractures identified in critical wells in the study area are mainly high-conductivity fractures, high-resistance and fractures induced by drilling. These fractures facilitate the formation and alteration of reservoirs [27], and play a decisive role in the reservoir properties (e.g. storage and seepage) and the ultimate recoverable reserves of reservoirs. Moreover, they provide reference for the subsequent design of engineering programs (e.g. fracturing) [28].

4. Gas enrichment features of "sweet spots" in shale gas reservoirs in Changning block

As of August 2015, the daily shale gas production in Changning block had reached 236 × 10^4 m^3, and the sole proved shale gas reserves had increased to 9200 × 10^8 m^3, indicating abundant natural gas resources in the Longmaxi Fm shales. In view of the unique gas enrichment features of favorable shale intervals in the block and based on the above analysis of "sweet spots" elements, the applicable parameters

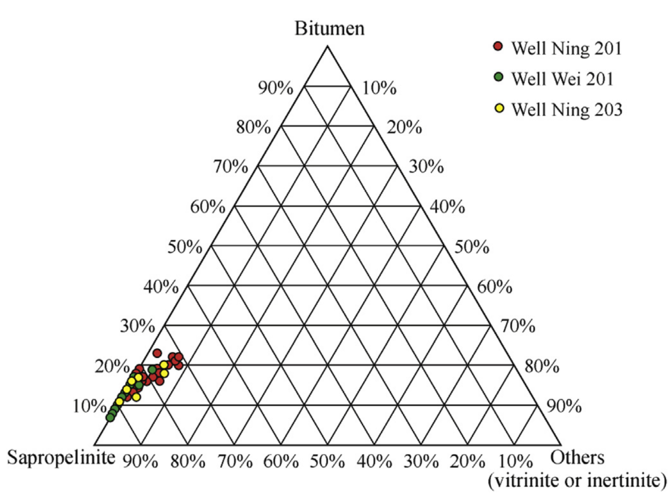

Fig. 3. Triangle of kerogen macerals in different gas-producing wells.

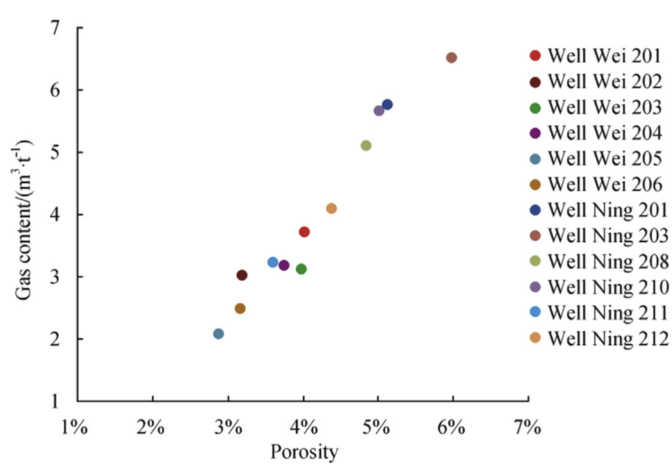

Fig. 5. Porosity vs. gas content in shale.

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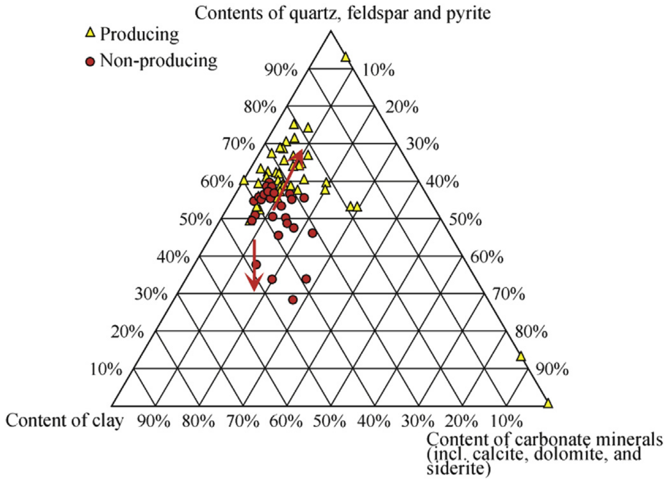

Fig. 6. Triangle of mineral components in gas producing and non-producing wells.

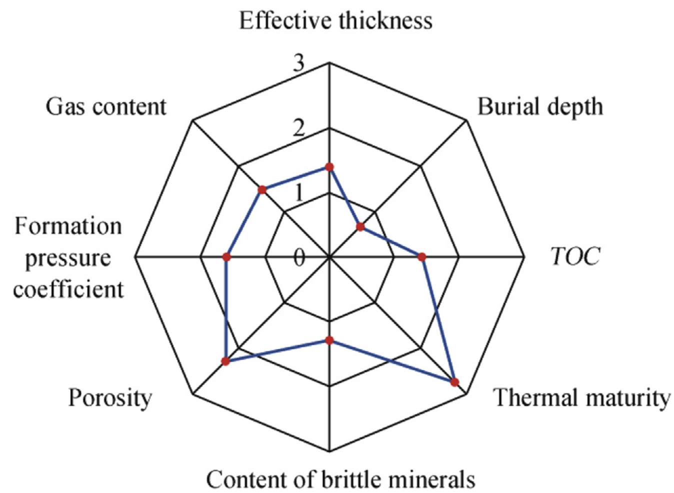

Fig. 7. Feature distribution of evaluation parameters for the Longmaxi Fm shale in Changning block.

that can guide the exploration and development of shale gas were sorted out, namely, R_o: 2.4–3.5%, *TOC*: >2%, effective thickness: 33.4–49.0 m, burial depth: 1285.0–3174.5 m, content of brittle minerals: 30–69%, porosity: 2.0–7.6%, gas content: 1.45–6.50 m^3/t, permeability: >50 nD, water saturation: <45%, Poisson's ratio: 0.10–0.35, Young's modulus: 15–44 GPa, formation pressure coefficient: 1.00–2.03, and interlayer thickness: 0.1–1.0 m.

With the geological evaluation criteria of shale gas in North America and China as a contrast, the essential elements for shale gas accumulation and exploitation in Changning block are determined to be *TOC*, R_o, porosity, effective thickness, gas content, content of brittle minerals, burial depth and fracture development degree. The main factors are R_o and gas saturation, followed by gas content, *TOC* and formation pressure (Fig. 7).

5. Constraints among “sweet spots” elements in shale gas reservoirs

The elements of “sweet spots” in shale gas reservoirs are not isolated, but correlate with each other to a certain extent. For instance, *TOC* is correlative to gas content [29]. The higher the content of brittle minerals in shale is, the higher the fracture development degrees. On the other hand, they demonstrate mutual constraints (Fig. 8).

5.1. Clay and shale brittleness

Clay associates with organic matters. It can also increase the content of adsorbed gas since it has strong adsorption and a very large specific surface area, thereby increasing the total gas content. However, higher clay content often corresponds to lower content of brittle minerals in shale, and such shale is not liable to create fractures under external strain, thereby unfavorable for gas exploitation. Therefore, it is essential to find the premium proportion between clay and brittle minerals to deepen the study on “sweet spots” elements in shale gas reservoirs.

5.2. Porosity and content of brittle minerals

On the one hand, higher content of brittle minerals will reduce the porosity of a reservoir, such as the biogenic siliceous minerals, thereby reducing the amount of free gas [30]. On the other hand, brittle minerals facilitate the formation of fractures in the rock, thereby promoting the shale gas flow. Therefore, higher content of brittle minerals is not always better. Presence of more siliceous and carbonate minerals may block the flow pathway, and reduce the shale porosity, thereby making the storage space of free gas decrease continuously.

Calcite formation usually leads to cementation in cracks, which may further reduce the pores [29]. Therefore, the evaluation of shale gas reservoirs should be conducted to find a balance among clay, water, quartz, and carbonate minerals.

5.3. Fractures and formation pressure

Given higher pressure, the content of adsorbed gas and free gas in shale will increase accordingly, and so will the total volume of gas stored. However, as the pressure rises to a certain level, the increase rate of total gas volume will slow down due to the constrained pores and the specific surface area of minerals. In addition, higher formation pressure and temperature may affect the properties of minerals in formations, which then results in enhanced plasticity, and correspondingly weakens the development of fractures.

Furthermore, the burial depth will also affect the organic matter maturity. Along with the increase of burial depth, the formation temperature rises. For the same type of organic matter, the gas generation features vary in different thermal evolution stages. When the burial depth is too large, the maturity of organic matter will be high, which is not favorable for shale gas preservation.

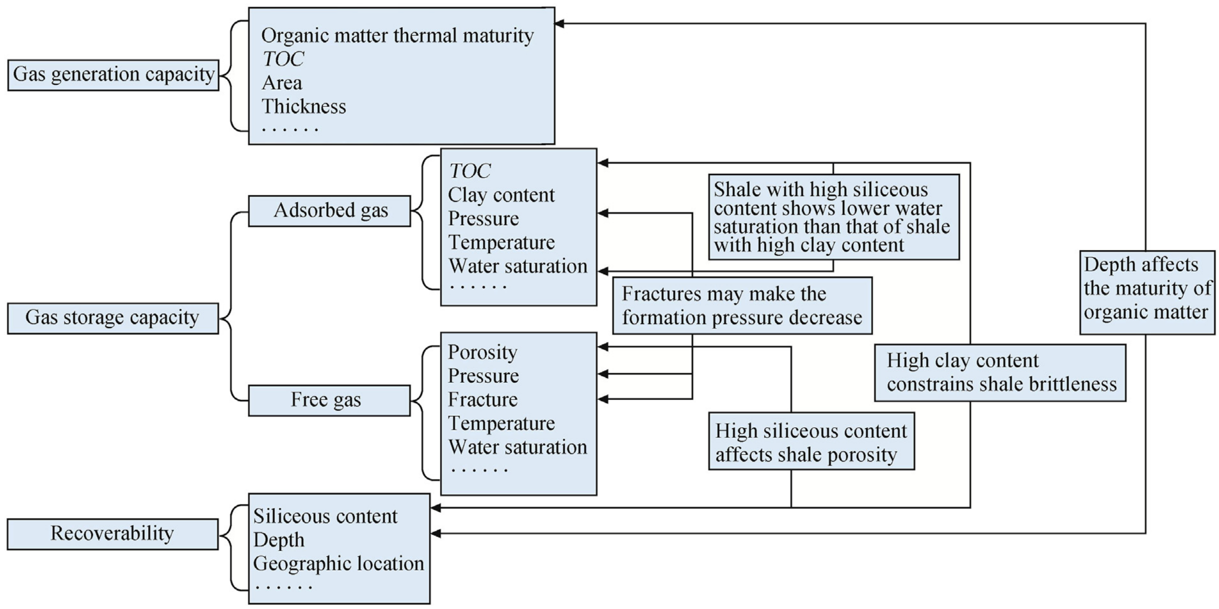

Fig. 8. Constraints among "sweet spots" elements in shale gas reservoirs.

6. Conclusions and recognition

1) Elements of "sweet spots" in shale gas reservoirs mainly include good hydrocarbon generation capacity, favorable accumulation conditions, and favorable engineering stimulation conditions for shale gas recovery.
2) Based on the features of "sweet spots" in shale gas enrichment areas in North America and the geological and geochemical data of favorable shale intervals in the Longmaxi Fm of Changning block, the elements of "sweet spots" in the shale gas reservoirs of the block are determined to be: TOC>2.0%, R_o being 2.4–3.5%, effective thickness >30 m, porosity >2.0%, content of brittle minerals being 30–69%, gas content >2.0 m^3/t, and depth <3500 m, and good development of fractures.
3) The elements of "sweet spots" in shale gas reservoirs correlate with each other, but also demonstrate mutual constraints. Therefore, these elements should be determined on individual basis, but also with consideration to the mutual constraints among them. Thus, the optimum distribution range of these elements can be determined.

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