Resource Potential for Co-Exploration and Joint Exploitation on Unconventional Gas in Coal Measures in China

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Abstract: China has considerable coal resources. Benefiting from the widespread distribution of coal measures and the inter-sedimentary development of coal bed, dark shale, and fine-grained tight sandstone in coal measures, China has a geological environment and material basis favorable for the co-occurrence of a variety of coal gases. With such a huge reservoir of coal gases, including gases such as coal bed methane (CBM), shale gas, tight sandstone gas, and natural gas hydrate, the co-occurrence of two or three of these gases is very common across the country. The per-well production of any individual coal measure gas (*e.g.*, CBM) is generally low when exploited separately. Therefore, it is essential to have more gas explored and produced in one well to raise the per-well production, lower the cost, and thus, increase the economic benefit. Additionally, regarding gas control and treatment, coal measure gas, including CBM and surrounding rock gas (a major source of CBM), should be preliminarily pumped, to significantly reduce the number of coal mine gas accidents and effectively reduce greenhouse gas emissions. More extensive research and further exploration will result in the discovery of more coal measures containing multiple gases, increasing the proven resources of coal measure gas and substantiating the co-exploration and joint exploitation of coal bed gas in China.

Keywords: Co-exploration and joint exploitation, multi-gas concurrent production, resource potential, unconventional gas in coal measures.

1. INTRODUCTION

Along with coal, a variety of energy and mineral resources extensively exist in coal bearing strata. Therefore, it is practical and essential to conduct comprehensive geological research, exploration, and development of coal basins [1]. As China's coal measures are characterized by the following—a long coal-forming period, a wide distribution of coal measures, and a large area of coal accumulating basins [1], as well as inter-sedimentation of coal bed, organic dark shale, and fine-grained compact sandstone a physical foundation has been formed for the sound development of unconventional natural gas in coal measures.

Unconventional gas in coal measures is also called coal gas for short. It consists of all natural gases evolving from hydrocarbon source rocks throughout the entire coal measures through biochemical and physicochemical coalification, including the following four types [1, 2]: (1) shale gas occurring in coal measure shale, (2) coal gas in the coal bed (CBM), (3) tight sandstone gas occurring in coal measure sandstone, and (4) natural gas hydrate in the coal measures.

China has considerable coal measure resources, totaling 36.8 trillion m^3 of CBM resources above 2000 m burial depth [3], corresponding to 36 trillion m^3 of extractable shale gas resources (Energy Information Administration). The amount of shale gas in coal measures, however, is unclear. Yet, the considerable amount of coal resources on the whole is recognized. China has 9.2–13.4 trillion m^3 of extractable tight sandstone gas resources, primarily distributed in the coal measures [4]. To consider the amount of natural gas hydrate in coal measures, only the estimated data for the Muri coalfield of Qinghai is available. This data shows that the amount equals to 300 billion m^3 of natural gas, 16–30 times the geological resources of CBM. China, the country with the third largest frozen area in the world, has up to 2.15 million km^2 of frozen earth area [5], indicating abundant potential resources. As an important part of natural gas in China, the huge reservoir of coal gas contributes to the industrial development of natural gas and helps narrow the large supply-demand gap.

2. SIGNIFICANCE OF MULTI-GAS CO-EXPLORATION AND JOINT EXPLOITATION

China upholds the principle of "Coal First, Comprehensive Exploration & Assessment" in its geological exploration for coal resources and, at the same time, has made efforts to ensure sound exploration and evaluation of other mineral resources that occur with coal [6]. A consensus

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has been reached that unconventional gas in the coal measures should be studied and developed as a system, and multi-gas co-exploration and joint exploitation should be conducted accordingly [1, 2, 7, 8]. China's late start in the co-exploration and joint exploitation of coal gas, however, has hindered its execution.

As coal measures, dark shale and fine-grained tight sandstone feature inter-sedimentation in their formation. As such, it is common to find the co-existence of multiple coal measure gases. The distribution of natural gas hydrate in coal measures is restricted by the perennial cryolithic zones in frigid regions. Therefore, with respect to CBM, shale gas, and tight sandstone gas, two or three of these coal gases generally co-occur in coal basins. Specifically, the Qinshui Basin, Ordos Basin, and Tulufan-Hami Basin hold CBM, shale gas, or tight sandstone gas; the Muri coalfield holds CBM, shale gas, and natural gas hydrate; and the Zhungaer Basin, Guizhou region, and Fuxin Basin hold CBM and shale gas. In these regions, multiple coal measure gases can be jointly explored and produced.

The per-well production of an individual coal measure gas (*e.g.*, CBM) is generally low when exploited separately. Therefore, it is essential to have more gas explored and produced in one single well to raise the per-well production, lower the cost, and thus, increase the economic benefit. A test of coal measure gas concurrent production from 60 wells in the American Piceance Basin shows a 10000 m^3/d average per-well gas output, of which 40% comes from tight sandstone gas in the coal measure strata [9]. In the American Greater Green River Basin, the No. 49-007-22885 well had a per-well gas output as high as 20000 m^3/d through the concurrent production of coal measure gas [10]. In China, the Cai 504 Well in the Cainan Region of Xinjiang outputs up to 7300 m^3/d daily through the concurrent production of Jurassic coal measure gas (CBM, tight sandstone gas) [10].

Additionally, coal measure gas, including CBM and surrounding rock gas (a major source of CBM), should be preliminarily pumped, to significantly reduce the number of coal mine gas accidents and effectively reduce greenhouse gas emission.

3. DISTRIBUTION CHARACTERISTICS OF RESOURCES FOR MULTI-GAS CONCURRENT PRODUCTION

The distribution of coal measure gas is closely related to coal resources. Large geological tectonic belts divide China into five coal accumulation regions: North China, Northwest, South China, Northeast, and Yunnan-Tibet. Ranking the proportion of nationwide coal measure gas accounted for by each region in descending order, North China and the Northwest leads the list, taking up 90.7% of nationwide coal measure gas resources, followed by South China, the Northeast, and Yunnan-Tibet (Table **1**) [11]. The resource potential of these five regions in coal gas are stated below in detail.

3.1. North China

North China is the most important reservoir not only for coal resources but also for coal measures. The coal measure strata mainly consist of the Carboniferous-Permian coal formation, the Middle-Lower coal formation, and the Jurassic coal formation. The Qinshui Basin has coal measure strata in the Carboniferous-Permian formation and the Ordos Basin has coal measure strata in the Carboniferous-Permian and Jurassic formations. There is also a great deal of interest in the co-exploration and joint exploitation investigation of these two basins for coal measure gas in China.

3.1.1. Qinshui Basin

Qinshui Basin, located in the southeast of the Shanxi province, is rich in coal and CBM resources. Many exploration and development investigations have demonstrated the potential of multi-gas co-exploration and joint exploitation in this region, where dark shale, tight sandstone, and coal bed are massively deposited in the coal measure, and abundant CBM, shale gas and tight sandstone gas are found.

The coal beds in most areas of the basin lie above 2000 m of burial depth, and the coal ranks are higher than the coal rank of fat coal . In the southern part, CBM resources exceed 1.5 trillion m^3, including 75.4 billion m^3 of proven reserves, becoming the most important CBM development zone in China [12] Located at Jincheng, south of Qinshui Synclinorium, it occupies an area of about 3260 km^2. The coal-bearing beds here are formed by marine and terrestrial sedimentation of the Carboniferous-Permian system. Its specific formation contributes to thick coal beds and a stable distribution lithologically dominated by shale, siltstone, argillaceous siltstone, silty mud-sandstone, and other fine clastic rocks [11, 13]. The Shanxi Formation #3 coal bed—4–5 m in thickness, 4.25 m average thickness—and the Taiyuan Formation #15 coal bed—1.7–6 m in thickness, 3.75 m average thickness—are commercially exploited for CBM [11], yielding as much as 1.6×10^4 m^3 of per-well daily production and 2000–3000 m^3/d of average stable production [15].

In the Qinshui Basin, the Taiyuan Formation and Shanxi Formation in the northern Shouyang holds 0.52–0.66 m^3/t and 3.78–5.51 m^3/t of shale gas, respectively, while the

Table 1. CBM distribution data from China [11].

Coal Accumulation Regions	North China	Northwest	South China	Northeast	Yunnan-Tibet
Coal accumulation points (qty.)	20	13	23	9	3
Resource amount (trillion m^3)	17.13	7.65	2.15	0.4	0.01
Resource ratio (%)	62.67	27.98	7.85	1.46	0.04

Shanxi Formation in the southern Jincheng holds 0.44–1.69 m^3/t. The shale reserve from the Shanxi Formation in Shouyang is believed to be comparable with the Upper Jurassic Haynesville shale, Upper Devonian Woodford shale, and Fayetteville shale which have been already exploited industrially in America [16, 17]. Although estimated data from the Shanxi Formation in Jincheng and Taiyuan Formation in Shouyang are not very optimistic, they meet the industrial exploitation limit; thus, they are comparable with the Upper Devonian New Albany shale in America [16, 17]. Other data also indicate that 1.0–6.4 m^3/t of adsorbed gas can be obtained through on-site desorption of the overlying-underlying mudstone in the Shanxi Formation #3 coal bed of the Qinshui Basin [18]. To further study the resource potential of Paleozoic shale gas in coal measures and tight sandstone gas within the Qinshui Basin, Qin Yong *et al.* (2014) logged gas data from 17 wells in the southern part of the Qinshui Basin. Results show that, in particular, the Shanxi Formation and Taiyuan Formation are promising for co-exploration and joint exploitation because considerable CBM is found in the coal beds as well as large amounts of shale gas and tight sandstone gas in the Carboniferous-Permian coal measures and overlying strata. The co-occurrence of these three types of gas proves the prospect of co-exploration and joint exploitation in the Shanxi Formation and Taiyuan Formation [7].

3.1.2. Ordos Basin

The Ordos Basin, not only is a second major sedimentary basin in China, but also one of ten major coal-bearing basins in the globe. Ordos Basin has two coal measures of Carboniferous-Permian and Jurassic, with the coal beds characterized by well developed, significant thickness, and considerable coal bed gas. In addition, abundant shale gas and tight sandstone gas are also found in the coal measures. Thus, the Ordos Basin has the potential for multi-gas co-exploration and joint exploitation.

In the basin, the Carboniferous-Permian coal bed with high levels of coal holds gas coal smokeless coal with a large reserve of 2.46–23.25 m^3/t. The Jurassic coal bed with low levels of coal is dominated by long flame coal, with a small reserve of 0.01–6.29%. All coal bed gas resources in the basin amount to 10.72 trillion m^3, accounting for 1/3 of CBM resources nationwide and demonstrating great potential for exploitation and development. Currently, the east edge region has the highest degree of CBM exploitation [19], having 2.4 trillion m^3 of prospective resources [20] and is currently entering the phase of commercial production.

In the Linxing block of the east edge, the CBM, shale gas, and tight sandstone gas have been discovered in the Upper Paleozoic coal measure strata [21, 22]. Coal bed gas is produced from two to three major coal beds on the east edge that present great thickness, more consistent distribution, a “Thick North, Thin South” tendency on the whole, and an overall high gas reserve *e.g.*, 6-14 m^3/t of coal bed gas in the Weibei block, 9.03–20.87 m^3/t in the Linfen block, and 4–14 m^3/t in the Lvliang block [23].

The Upper Paleozoic shale in the region has the following characteristics: 1.72% average organic carbon content, primary type-II and type-III kerogen at the mature to postmature stage, highly mature organic matter, 1.49% average Ro, 1–4% porosity, and 0.02–0.2×10^{-3} μm^2 permeability [24]. The shale in the Shanxi Formation of the Linxing region is characterized by a thickness of 55–130 m, an average organic carbon content of 3.91%, and an Ro value of 1.28–1.60%. The shale from Taiyuan Formation is characterized by a thickness of 50–120 m, an average organic carbon content of 13.94%, and an Ro value of 0.938–1.78% [21]. Massive gas production at the site has already started as it has good resource potential for shale gas.

The tight sandstone at the upper Paleozoic coal measure, with an average porosity of 6.58% and an average permeability of 0.77×10^{-3} μm^2 [25], is classified as low-porosity and low-permeability sandstone, but with great thickness. In Linxing, sandstone from Taiyuan Formation has a thickness of 4.0-40.89 m, but Shanxi Formation sandstone is thicker with a wider distribution range. Coal-measure tight sandstone is developed interactively with shale and the coal bed, and is close to the gas source rock, making it a good prospect.

3.2. Northwest Coal Accumulation Region

Coal beds in the Northwest region have a low degree of evolution but considerable thickness, with CBM characterized by low gas content, theoretically low gas saturation, and high resource abundance [14]. In the region, the Turpan-Hami Basin has favorable geological conditions for the co-exploration and joint exploitation of coal bed gas, shale gas, and tight sandstone gas; the Qinghai Muri Basin coalfield is favorable for the co-occurrence of natural gas hydrate in the coal measures, with CBM and shale gas, and the Zhungaer Basin is favorable for the concurrent production of coal bed gas and shale gas.

3.2.1. Turpan-Hami Basin

The coal-rich Turpan-Hami Basin is located in the east Tianshan Mountain region of the northern portion of Xinjiang. The leading coal bearing layer stands at the Jurassic Badaowan Formation and Xishanyao Formation with shallow and intensive coal beds, with a total 40–181 m in thickness; particularly, the primary coal bed may range from 4–147 m in thickness [26]. Thus, the coal measure strata exhibit favorable geological conditions for the co-occurrence of CBM, shale gas, and tight sandstone gas.

The Jurassic coal rock has a vitrinite reflectance (Ro) of 0.40%–0.83% (mostly less than 0.60%). The coals here exhibit low metamorphism and are mainly brown coal and long flame coal. However, gas coals are extremely rare, and so low-rank CBM has been formed [27, 28]. The adsorbed gas is low in raw coal, *e.g.*, 0.34–2.01 m^3/t at Ha testing well No. 1 and 0.73–3.09 m^3/t at Sha testing well No. 1 [27]. For the CBM content, the entire basin hides 4.77–8.36 m^3/t, a little less than the Qinshui Basin.

However, its thick coal measures reduce the impact of low gas content on the CBM abundance with a size as large as 13.48 trillion m^3 [29]. The following three zones, the Shaer Lake coalfield, Aydingkol Lake slope, and Yue No.1 well, are the most important reservoirs for CBM [27].

The Jurassic Shuixigou group (including Badaowan Formation, Sangong River Formation, and Xishanyao Formation) and the Triassic Xiaoquangou group contain an estimated 5 trillion m^3 of shale gas resources in the shale [30]. The Jurassic Shuixigou group exhibits an interbedding of dark mudstone, coal, and carbonaceous mudstone with a single bed of 20–100 m in thickness. For the shale from Badaowan Formation, the maximum thickness is 200 m with an accumulative thickness of 200–800 m, and the organic carbon content exceeds 1%, with an average organic content of 1.85% and a vitrinite reflectance of 0.5–1.3%. The maturity of organic matter provides the possibility of massive gas production, with its large reserve of brittle minerals. Particularly, the quartz accounts for over 35% and brittle minerals account for over 60%, indicating abnormal gas logging and a gas content of 1–8 m^3/t. The eastern part of Taibei Sag and Hami Sanbao Sag are favorable for the exploration of shale gas [30, 31], while Toksun, Turpan, and Qiquanhu are promising for shale gas in the coal measures [31].

The geological conditions of the Jurassic Shuixigou Group of Turpan-Hami Basin are favorable for forming tight sandstone reservoirs on a large scale, providing a sufficient gas source through the long-term generation and discharge of massive gaseous hydrocarbons from coal measure strata. The gas source also benefits from the accumulation of a tight sandstone reserve through tight interbedding contact between source rocks and reservoir strata. It is favorable to seek tight sandstone gas reservoirs in the southern slope area and the northern piedmont thrust belt area where an excellent allocation condition of source rocks and reservoir strata is exhibited [32]. Currently, about 90% of production strata has a porosity of 2%–10% and a permeability of (0.1–1.0) × 10^{-3} μm^2 [32]. Coal measure tight sandstone is overwhelmingly dominated by hydrocarbon gas, which has a volumetric relative content of almost 65%, and a maximum of over 90%. The gas is primarily composed of 76%–86% methane and 12%–18% C_{2+} heavy hydrocarbon [33] by volumetric relative content.

3.2.2. Qinghai Muri Coalfield

Situated at the upstream of Datong River of Qinghai province, the Muri coalfield has its main coal-bearing strata of the Lower-Middle Jurassic, where mostly sandstone, silt, shale, coal bed, and other fine-grained rocks are hidden. Multiple coal beds have been developed, totaling 10.58–14.58 billion tons of abundant coal resources [5, 34, 35]. The most important characteristics lie in the co-occurrence of natural gas hydrate in the coal measures with CBM and shale gas, providing a good resource potential for multi-gas co-exploration and joint exploitation. For this reason, this area provides much research interest.

The Juhugeng mine area of Muri coalfield holds 5–6 coal beds with great thickness—24.59 m on average—where the metamorphic grade is represented by medium gas coal and coking coal, most of which undergoes plutonic metamorphism, favorable for hydrocarbon gas generation. The equilibrium water is 17.25–24.04 m^3/t by Langmuir volume, indicating a high gas storage capacity [36]. It has a coal-bed gas content of 0.05–5.52 m^3/t, whereas most mine areas have less than 3 m^3/t on average [35, 37]. The Muri coalfield has an estimated 9.144 billion m^3 of total geological resources with an average abundance of 0.96×10^8 m^3/km^2 [5, 36].

China—the country with the third largest frozen land area in the world—has up to 2.15 million km^2 of permafrost. The successful physical coring of natural gas hydrate in the coal measures in the Muri coalfield of Qinghai in recent years makes China the first country to discover natural gas hydrate in the middle-low latitude frozen earth areas. The discovery of “flammable ice” in Qinghai has also demonstrated that China has abundant natural gas hydrate resources in the frozen earth areas, setting an example for exploring “flammable ice” in Great Khingan, Qinghai-Tibet Plateau, Qilian Mountain, and the Tianshan Mountain frozen earth zone [5]. The genesis of hydrocarbon gases of natural gas hydrate in Muri coalfield is mixed gas, it is attributed to those main source rocks lying in coal bed, carbon mudstone, and oil shale in Jurassic coal measures and those secondary source rocks lying in areas like the Carboniferous dark marlstone, Lower Permian dark limestone, and the Upper Triassic dark mudstone [38]. It is estimated that the potential resources of natural gas hydrate from coal type gas sources in the Muri coalfield can be converted to approximately 300 billion m^3 of natural gas, 16–30 times the geological resources of CBM in the region [5].

In the Muri coalfield, source beds, like dark mudstone and oil shale, are well-developed in the Jurassic [39]. Its single shale beds are characterized by considerable thickness in the southeast (more than 45 m) and relative thinness in the northwest (more than 25 m). The pure shale in the coal measures accounts for more than 10% and fine-grained clastic accounts for 31.98%–53.69%, with an average of 40.05%. For the mud shale, the Total Organic Carbon (TOC) reaches 0.52%–86.06% and the maturity Ro is 0.74%–1.85%, realizing the gas generation peak with type II and type III kerogen as the predominant organic matter [40]. In conclusion, there is good resource potential for shale gas.

3.2.3. Zhungaer Basin

Within the Zhungaer Basin—a typical superimposed basin in western China—Fukang Sag is the largest hydrocarbon generation sag, hosting four sets of main source rocks: Carboniferous, Permian, Triassic, and Jurassic [41]. Specifically, the Jurassic holds tremendous low-rank coal bed [42] and shale gas resources, exhibiting good resource potential for the co-exploration and joint exploitation of CBM and shale gas.

In terms of coal rank in Jurassic, long flame coal, non-coking coal, and weakly coking coal prevail over gas coal, followed by less fat coal and brown coal, containing 2–18.81 m^3/t CBM [43]. While drilling in the eastern part of the south edge of Zhungaer Basin, natural gas, mainly composed of methane and carbon dioxide, generally appears in the coal beds of Xishanyao Formation. In coal bed testing of the Cai 17 and Cai 19 well, the first breakthrough was to realize a daily output of 2000-4000 m^3 of natural gas. In the eastern part of the south basin edge, the Dahuangshan coal mine has a high level in gas content, with a daily emission of up to 2000 m^3 of methane-dominated gas. It is estimated that there are about a total of 3.87 trillion m^3 of CBM resources in these areas above 2000 m burial depth [43].

Fukang Sag in Jurassic mainly develops three sets of muddy source rock beds—Badaowan Formation, Sangong River Formation, and Xishanyao Formation—with a maximum accumulated thickness of 950 m. The organic matter abundance of mud shale stands at 1.2%–2.5%. The kerogen type II–III is located in the lower part of the Badaowan Formation but type III in the middle-upper part, and the Ro value of 1.6% presents a middle-high maturation phase, demonstrating the potential of generating shale oil and gas [44]. Additionally, Yongfeng Sag on the south edge of the basin may also have good exploration potential of shale gas [45].

3.3. South China Coal Accumulation Region

The South China accumulation region where the Upper Permian coal bed is mainly targeted, along with coal-rich zones, like Sichuan, Yunnan, and Guizhou, have minable beds of 10–20 m, and local coal-rich centers of more than 20–40 m in thickness. The coal beds have the characteristics of high gas content, high gas saturation, and coal bed gas resource scattering [11]. Particularly in Guizhou, there is good resource potential of co-exploration and joint exploitation on CBM and shale gas.

Guizhou province is famous for its status as having the most abundant coal and CBM resources in the South China, holding 243.6 billion tons of coal resources at above 2000 m buried depth. By the end of 2004, 58.729 billion tons of coal resources had been proven [46, 47]. In Guizhou, 3.06 trillion m^3 of inferred coal bed resources are estimated in Upper Permian minable coal beds, of which 92.57% are distributed in the Liupanshui, Zhina, and Qianbei coalfields [48].

Generally speaking, Guizhou province has the geological characteristics of "One Weak, Two Manys, Three Highs and Four Larges" in terms of coal bed gas, i.e., a slightly weak groundwater dynamic condition of Longtan Formation; many gas control structures and coal beds; high coal bed provided gas content, high resource abundance, and high reservoir pressure and ground stress; large coal bed gas resource, large coal rank change, large coal bed permeability change, and large geological vertical change [47]. Liupanshui has an average gas content of more than 13 m^3/t in most synclines, and more than 18 m^3/t in the Zhina area [49] at a high level, in general.

In Guizhou, geological resources of shale gas totaled 4.55 trillion m^3 in coal measures (Jiusi Formation, Liangshan Formation, and Longtan Formation), accounting for 33.6% of the total across Guizhou. Two models for co-exploration and joint exploitation of coal bed gas and shale gas have been developed—a multi-layer fracturing and multi-layer drainage model and a separate layer fracturing and multi-layer drainage model [48]. In addition, the eastern part of the Liupanshui coalfield and the northern part of the Zhina coalfield are under excellent development condition, making it a perfect place for co-exploration and joint exploitation of the two gases [48].

3.4. Northeast Coal Accumulation Region

The Northeast region is dominated by Lower Cretaceous coal beds, but with few CBM resources and low-level research. At present, Liujia area of Fuxin Basin is found to have the potential for co-exploration and joint exploitation of CBM and shale gas.

In Fuxin Basin, five major minable coal beds are deposited in the Cretaceous Fuxin Formation, mainly representing by Taiping coal bed formation, middle coal bed formation and Sunjiawan coal bed formation, featuring an accumulated thickness of over 100 m [50]. By the end of 2000, there had been 1.232 billion tons of proven coal reserves and 13.691 billion m^3 of estimated CBM resources [51]. Fuxin Formation, with 0.6% coal-based vitrinite reflectance at maximum and low maturity, is at the low-middle metamorphic stage and dominated by long flame coal and gas coal [50].

Based on shale gas research in coal measures of Fuxin Basin, the Northeast Coalfield Geology Bureau has reported huge shale gas resources in coal measures, with 8.734 billion m^3 in the Liujia area alone [52]. The Liujia area is located in the middle of Fuxin Basin. The Fuxin Formation has a CBM content of 1.74–10.14 m^3/t, with 3000–6500 m^3/d per-well production and over 97% of methane in actual output [53]. The Cretaceous Shahai Formation mainly includes black shale, mudstone, and siltstone, mingled with sandstone bed of various granularity, conglomerate, and breccia, and is rich in zeolite. It has a thickness of 500–600 m and a burial depth of 1000–1600 m, making it a productive source for shale gas [52]. As the Great Khingan area in the northern part is mainly characterized by a perennial cryolithic zone, the natural gas hydrate should also be highlighted as unconventional energy.

3.5. Yunnan-Tibet Coal Accumulation Region

In the Yunnan-Tibet coal accumulation region, a complicated geological tectonic background and adverse natural conditions lead to considerable difficulty in carrying out geological exploration. This region tends to be neglected as it has a small reserve of coal resources, leading to a low level of research on coal geology and CBM, and virtually no research on shale gas and tight sandstone gas in coal measures. However, it is necessary to seek more energy resources extensively in the Tibetan region, where the local energy is always priced high due to energy shortages and high inland-to-Tibet transportation costs. Meanwhile, the uplift of Qinghai-Tibet Plateau is very harmful to storing conventional oil and gas. Hence, it is very important to conduct research on unconventional oil and gas, *e.g.*, shale gas [54]. Under the background of local dominated perennial cryolithic zones, natural gas hydrate should also be highlighted as unconventional energy. Research finds that the Nyima Basin, in the middle part of Tibet, is a Tertiary terrestrial basin with an estimated 10–20 billion m^3 of shale gas resources, showing great resource potential [54].

CONCLUSION

(1) As China has a favorable geological setting for the co-occurrence of multiple coal measure gases created by the inter-sedimentation of coal beds, dark shale, and fine-grained tight sandstones in the coal measures, it is common to find co-occurring coal gases, such as CBM, shale gas, tight sandstone gas, and natural gas hydrate. In addition, the discovery of huge resources makes systematic exploration and research a necessity. Specifically, the following co-occurrences of coal gases are evident: CBM, shale gas, and tight sandstone gas in the Qinshui Basin, Ordos Basin, and Tulufan-Hami Basin; CBM, shale gas, and natural gas hydrate in the Muri coalfield; and CBM and shale gas in Zhungaer Basin, Guizhou region and Fuxin Basin. Based on the data above, these regions have potential for the co-exploration and joint exploitation of multiple coal gases.

(2) The per-well production of an individual coal measure gas (*e.g.*, CBM) is generally low when exploited separately. Therefore, it is essential to have more gas explored and produced in one single well to raise the per-well production, lower the cost, and thus, increase the economic benefit. Additionally, regarding gas control and treatment, coal measure gas, including CBM and surrounding rock gas (a major source of CBM), should be preliminarily pumped to significantly reduce the number of the coal mine gas accidents and effectively reduce greenhouse gas emission.

(3) China has considerable coal resources. Benefiting from the widespread distribution of coal measures and the inter-sedimentary deposition of coal beds, dark shale, and fine-grained tight sandstones in the coal measures. It has a geological environment favorable for the co-occurrence of a variety of coal gases, such as coal bed methane (CBM), shale gas, tight sandstone gas, and natural gas hydrate. With such a huge reservoir of coal gases, the co-occurrence of two or three gases is very common. More extensive research and further exploration will result in the discovery of more coal measures containing multiple gases, increasing the proven resources of coal measure gas and substantiating the co-exploration and joint exploitation of coal bed gas in China.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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