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

Jinxian He*,1,2, Xiaoli Zhang1,2, Jinpeng Yan3 and Li Ma1,2

1School of Resources and Geosciences, China University of Mining and Technology, Xuzhou, Jiangsu, 221116, China;  
2Key Laboratory of CBM Resource and Reservoir-Formation Process, China Ministry of Education, Xuzhou, Jiangsu, 221008, China  
3No. 3 Oil Production Plant of North China Branch, Tongchuan, Shanxi,727200, China

Abstract: China has considerable coal resources. By 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 good geological conditions and material basis for co-occurrence of a variety of coal gases. With such huge reservoir of coal gases, the co-occurrence of two or three gases of coal bed methane (CBM), shale gas, tight sandstone gas or natural gas hydrate is very common across the country. The per-well production of individual coal measure gas (e.g. CBM) is generally low when it is exploited separately, therefore it is essential to have more gas explored and produced in one well so as to raise per-well production, lower cost as well as increase economic benefit. Additionally, regarding gas control and treatment, the coal measure gas, including CBM and surrounding rock gas (a major source of CBM) should be preliminarily pumped, so as to significantly cut the coal mine gas accidents and effectively reduce greenhouse gas emission. Contributing to deeper research and further exploration, more and more coal measures holding multiple gases will definitely be explored and the proved resources of coal measure gas will be increased, indicating a prospect for co-exploitation 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

A variety of energy and mineral resources in addition to coal extensively exist in the coal bearing strata. Therefore, it is practical and essential to conduct comprehensive geological research and exploration & development on coal basins [1]. As China’s coal measures is characterized by the followings: long coal-forming period, wide distribution of coal measures and large area of coal accumulating basins [1], as well as inter-sedimentation of coal bed, organic dark shale and fine grained compact sandstone in coal measure, 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 in the whole coal measures through biochemical & physicochemical coalification, including four types as follows [1, 2]: (1) shale gas occurring in the coal measure shale, (2) coal gas in the coal bed (CBM), (3) tight sandstone gas occurring in the coal measure sandstone, and (4) natural gas hydrate in the coal measures.

China has considerable coal measure resources, totaling 36.8 trillion m³ of CBM resources above 2000 m burial depth [3]; 36 trillion m³ of technically-possible shale gas resources (by Energy Information Administration). The amount of shale gas in coal measures however is unclear. And yet it is agreed on the huge amount of coal resources on the whole. China has 9.2-13.4 trillion m³ of technically-possible tight sandstone gas resources which mainly distribute in coal measures [4]. For the amount of natural gas hydrate in coal measures, only the primarily estimated data for Muri coalfield of Qinghai is available. And the data shows the amount equals to 300 billion m³ of natural gas, 16-30 times geological resources of CBM. China, the third major frozen earth country in the world, has up to 2.15 million km² of frozen earth area [5], indicating abundant potential resources. As an important part of natural gases 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 & 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 on other
mineral resources that are inter-growing with coal [6]. Researchers have agreed that unconventional gas in the coal measures should be studied and developed as a system and the multi-gas co-exploitation & joint exploitation should be conducted accordingly [1, 2, 7, 8]. China’s late start in co-explooration & joint exploitation of coal gas however leads to low levels of its research job.

As coal measures, dark shale and fine-grained tight sandstone feature inter-sedimentation in their formation, 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 at frigid regions, therefore two or three coal gases of CBM, shale gas or tight sandstone gas generally co-occur in coal basins. Specifically, Qinshui Basin, Ordos Basin and Tulufan-Hami Basin hold CBM, shale gas or tight sandstone gas; Muri coalfield holds CBM, shale gas or natural gas hydrate; Zhunger 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 individual coal measure gas (e.g. CBM) is generally low when it is exploited separately, therefore it is essential to have more gas explored and produced in one single well so as to raise per-well production, lower cost as well as increase economic benefit. A test of coal measure gas concurrent production on 60 wells in 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 American Greater Green River Basin, No. 49-007-22885 well had per-well gas output up to 20000 m^3/d in the concurrent production of coal measure gas[10]. In China, Cai 504 Well in Caiyuan Region of Xinjiang up to 7300 m^3/d daily in the concurrent production of Jurassic coal measure gas (CBM, tight sandstone gas) [10].

Additionally, the coal measure gas, including CBM and surrounding rock gas (a major source of CBM) should be preliminarily pumped, so as to significantly cut the 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. China can be divided by large geological tectonic belts into five coal accumulation regions, i.e. North China, Northwest, South China, Northeast and Yunnan-Tibet. For coal measure gas, it can rank from high to low as North China and Northwest taking up 90.7% of nationwide resources, South China, 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 measure. The coal measure strata mainly consists of the Carboniferous-Permian coal formation and the Middle-Lower coal formation and the Jurassic coal formation. Qinshui Basin has coal measure strata in Carboniferous-Permian formation; Ordos Basin in Carboniferous-Permian and Jurassic formation. The two basins are also hot for co-explooration & joint exploitation research on coal measure gas in China.

3.1.1. Qinshui Basin

Qinshui Basin, located in the southeast of Shanxi province, is rich in coal and CBM resources. Many exploration & development experiences and respective researches show the potential of multi-gas co-exploration & joint exploitation in this region where dark shake, tight sandstone and coal bed are massively sedimentated in the coal measure, and abundant shale gas and tight sandstone gas are found.

The coal bed in most areas of the basin is above 2000 m of burial depth with fast coal metamorphism and all fat coals. In the south part, The CBM resources exceed 1.5 trillion m^3, including 75.4 billion m^3 of proved reserves, becoming the most important CBM development zone in China [12]. It is situated at Jincheng in the south of Qinshui synclinorium and occupies about 3260 km^2. The coal-bearing bed here is formed by the marine and terrestrial sedimentation of Carboniferous-Permian system. Its specific formation contributes to thick coal beds, stable distribution and lithologically domination of coal bed, shale, siltstone, argillaceous siltstone, silty mud-sandstone and other fine clastic rocks [11, 13]. Shanxi Formation 3# coal bed, 4-5 m in thickness, 4.25 m on average, and Taiyuan Formation 15# coal bed, 1.7-6 m in thickness, 3.75 m on average are commercially exploited for CBM [11], proving up to 1.6×10^6 m^3 of per-well daily production and 2000-3000 m^3/d of average stable production [15].

In Qinshui Basin, Taiyuan Formation and Shanxi Formation in the northern Shouyang respectively hold 0.52-0.66 m^3/t and 3.78-5.51 m^3/t shale gas, while Shanxi Formation in the southern Jincheng holds 0.44-1.69 m^3/t. It is believed that the shale reserve from Shanxi Formation in Shouyang is comparable with the Upper Jurassic Haynesville shale, Upper Devonian Woodford shale and Fayetteville shale which were already exploited industrially in America. Although estimated data from Shanxi Formation in Jincheng

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<th>Coal Accumulation Regions</th>
<th>North China</th>
<th>Northwest</th>
<th>South China</th>
<th>Northeast</th>
<th>Yunnan-Tibet</th>
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<tr>
<td>Coal accumulation points (qt.)</td>
<td>20</td>
<td>13</td>
<td>23</td>
<td>9</td>
<td>3</td>
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<tr>
<td>Resource amount (trillion m^3)</td>
<td>17.13</td>
<td>7.65</td>
<td>2.15</td>
<td>0.4</td>
<td>0.01</td>
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<tr>
<td>Resource ratio (%)</td>
<td>62.67</td>
<td>27.98</td>
<td>7.85</td>
<td>1.46</td>
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Table 1. Data for CBM distribution in China [11].
and Taiyuan Formation in Shouyang are not very optimistic, they meet the industrial exploitation limit, thus it is comparable with Upper Devonian New Albany shale in America [16, 17]. Other data also indicate 1.0-6.4 m$^3$/t adsorbed gas can be obtained through the on-site desorption of overlying-underlying mudstone in Shanxi Formation 3# coal bed of Qinshui Basin [18]. To further learn the resource potential of Paleozoic shale gas in the coal measures and tight sandstone gas within Qinshui Basin, Qin Yong et al. (2014) had made statistics on gas logging information of 17 wells in the southern of Qinshui Basin, and the results show that particularly Shanxi Formation and Taiyuan Formation are promising for co-exploration & joint exploitation because considerable CBM is found in the coal beds as well as large amount of shale gas and tight sandstone gas in Carboniferous-Permian coal measures and overlying strata. The co-occurrence of these three types of gas proves the prospect of co-exploration & joint exploitation for Shanxi Formation and Taiyuan Formation [7].

3.1.2. Ordos Basin

Ordos Basin, not only a second major sedimentary basin in China, but also one of ten coal-bearing basins in the globe, forms two coal measures of Carboniferous-Permian and Jurassic, with the coal beds characterized by good formation, great thickness and considerable coal bed gas. And meanwhile abundant shale gas and tight sandstone gas are also found in coal measures, thus it has the potential for multi-gas co-exploration & joint exploitation.

In the basin, Carboniferous-Permian coal bed with high-level coal holds gas coal - smokeless coal, with huge reserve of 2.46-23.25 m$^3$/t. Ant the Jurassic coal bed with low-level coal is dominated by long flame coal, with small reserve of 0.01-6.29%. All coal bed gas resources there amount to 10.72 trillion m$^3$, taking up 1/3 of nationwide CBM resources, demonstrating a great potential in exploitation & 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 currently enters the phase of commercial production.

In Linxing block of the east edge, the CBM, shale gas and tight sandstone gas are discovered in the Upper Paleozoic coal measure strata [21, 22]. On the east edge exists two to three major coal beds from which the coal bed gas is produced, presenting great thickness, more constant distribution and “Thick North, Thin South” tendency on the whole, as well as an overall high gas reserve, e.g. 6-14 m$^3$/t of coal bed gas in Weibei block, 9.03-20.87 m$^3$/t in Linfen block, 4-14 m$^3$/t in Lvilang block [23].

Upper paleozoic shale there has the features of 1.72% average organic carbon content, primary type-II & type-III kerogen, highly mature organic matters and 1.49% Ro on average, as well as at the mature-postmature stage, 1-4% porosity and 0.02-0.2 × 10$^{-3}$ μm$^2$ permeability [24]. For the shale from Shanxi Formation of Linxing region, 55-130 m in thickness, 3.91% average organic carbon content and 1.28-1.60% Ro. The shale from Taiyuan Formation is characterized by 50-120 m in thickness, 13.94% average organic carbon content and 0.938-1.78% Ro [21]. The massive gas production has already started as it has a good resource potential for shale gas.

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

3.2. Northwest Coal Accumulation Region

Coal beds in Northwest region are low in evolution degree, but great in thickness, with CBM characterized by low gas content, theoretically low gas saturation and high resource abundance [14]. In the region, Turpan-Hami Basin is under geological conditions for the favorable co-exploration & joint exploitation of coal bed gas, shale gas and tight sandstone gas; Qinghai Muri Basin coalfield for the co-occurrence of natural gas hydrate in the coal measures, CBM and shale gas; Zhunger Basin 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 east Tianshan Mountain region of the northern of Xinjiang. The leading coal bearing layer stands at Jurassic Badaowan Formation and Xishanyao Formation with shallow and intensive coal beds, with total 40-181 m in thickness, particularly the main single one may reach up to 4-147 m in thickness [26]. Thus the coal measure strata holds good 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, but gas coals are extremely rare, thus 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 bit lower than that of Qinshui Basin. However its thick coal measures reduce the impact of low gas content on CBM abundance with a size of as large as 13.48 trillion m$^3$ [29]. And the following three zones i.e. Shaer Lake coalfield, Aydingkol Lake slope and Yue No.1 well are the most important reservoirs for CBM [27].

Jurassic Shuixigou group (including Badaowan Formation, Sangong River Formation and Xishanyao Formation) and Triassic Xiahouquangou group contain a total of primarily estimated 5 trillion m$^3$ of shale gas resources in the shale [30]. Jurassic Shuixigou group exhibits the interbedding of dark mudstone, coal and carbonaceous mudstone with single bed being 20-100 m in thickness. For the shale from Badaowan Formation, the maximum thickness hits 200 m with an accumulative 200-800 m. And the organic carbon content is more than 1%, being 1.85% on average at Badaowan Formation with 0.5-1.3% vitrinite reflectance. The maturity of organic matter provides the possibility of massive gas production, as it has huge reserve of brittle minerals. Particularly, the quartz takes up over 35%
and brittle minerals account for over 60%, indicating abnormal gas logging and 1-8 m³/t gas content. 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 promising for shale gas in the coal measures [31].

Jurassic Shuixigou Group of Turpan-Hami Basin is under the geological conditions of forming tight sandstone reservoirs on a large scale, providing a sufficient gas source through the long-term generation and discharge of massive gaseous hydrocarbon from coal measure strata, and favorably accumulating 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 northern piedmont thrust belt area where an excellent allocation condition of source rocks and reservoir strata shows [32]. Currently, about 90% of production strata has 2%-10% of porosity and (0.1-1.0) × 10⁻³ μm² of permeability [32]. Coal measure tight sandstone is overwhelmingly dominated by hydrocarbon gas, which has a volumetric relative content of almost over 65%, and mostly over 90%. The gas is primarily composed of 76% to 86% of methane, and 12%-18% of C₂ heavy hydrocarbon [33] by volumetric relative content.

3.2.2. Qinghai Muri Coalfield

Situated at the upstream of Datong River of Qinghai province, Muri coalfield has its main coal-bearing strata at Lower-Middle Jurassic, where mostly sandstone, silt, shale, coal bed and other fine grained rocks hide. And multiple coal beds have been developed, bringing to a total of 10.58-14.58 billion tons of abundant coal resources [5, 34, 35]. The biggest characteristics lie in the co-occurrence of natural gas hydrate in the coal measures, CBM and shale gas, providing a good resource potential for multi-gas co-exploration & joint exploitation. That’s the reason makes it one of the hot research areas.

The Juhugeng mine area of Muri coalfield holds 5-6 coal beds with great thickness of 24.59 m on averages, where the metamorphic grade is represented by medium gas coal and coking coal, most of which undergoes plutonic metamorphism being favorable to generate hydrocarbon gases. And the equilibrium water is 17.25-24.04 m³/t by Langmuir volume, indicating a high gas storage capacity thereof [36]. It has 0.05-5.52 m³/t of CBN content, while most mine areas have less than 3 m³/t on average [35, 37]. Muri coalfield has a primarily estimated 9.144 billion m³ of total geological resources with the abundance of 0.96 ×10⁸ m³/km² average [5, 36].

China - the third major frozen earth country in the world, has up to 2.15 million km² of permafrost areas in total. The successful physical coring of natural gas hydrate in the coal measures in Muri coalfield of Qinghai in recent years makes China the first country to discover natural gas hydrate in middle-low latitude frozen earth areas. And the discovery of “flammable ice” in Qinghai also has proved the fact 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 Tianshan Mountain frozen earth zone [5]. And why the hydrocarbon gases of natural gas hydrate in Muri coalfield belong to mixed gas but more like coal type 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 Carboniferous dark marlstone, Lower Permian dark limestone, Upper Triassic dark mudstone [38, et al.]. It is primarily estimated that the potential resources of natural gas hydrate from coal type gas sources in Muri coalfield can be converted to approximately 300 billion m³ of natural gas, 16-30 times the geological resources of CBM in the region [5].

In Muri coalfield, such source beds as dark mudstone, oil shale are well developed in Jurassic [39]. Its single shale beds are characterized by being thick in southeast (more than 45 m) and thin in northwest (more than 25 m). The pure shale in the coal measures accounts for more than 10%, fine grained clastic 31.98%-53.69%, with an average of 40.05%. For the mud shale, the organic matter abundance TOC reaches 0.52%-86.06%, the maturity Ro 0.74%-1.85%. realizing the gas generation peak with kerogen type II-III as leading organic matters [40]. To be concluded, there is good resource potential for shale gas.

3.2.3. Zhunger Basin

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

In term of coal rank in Jurassic, long flame coal, non-caking coal and weakly caking coal prevail over gas coal, following by less fat coal and brown coal, containing 2 m³/t-18.81 m³/t CBM [43]. In drilling process, the eastern part of south edge of Zhunger Basin, the natural gas generally appears in the coal beds of Xishanyao Formation, mainly being composed of methane and carbon dioxide. In coal bed testing on Cai 17 well and Cai 19 well, the first breakthrough had been made to realize 2000-4000 m³ daily output of natural gas. In the eastern part of south basin edge, Dahuangshan coal mine has high level in gas content, with a daily emission of up to 2000 m³ of methane-dominated gas. It is estimated that there are about a total of 3.87 trillion m³ 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, i.e. Badaowan Formation, Sangong River Formation and Xishanyao Formation, with great accumulated thickness of 950 m at maximum. And the organic matter abundance of mud shale stands at 1.2%-2.5%. The kerogen type II-III mainly locates in the lower part of Badaowan Formation but 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 a good exploration potential of shale gas [45].

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

Guizhou province is famous for its 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 have been proved [46, 47]. In Guizhou, 3.06 trillion m³ of inferred coal bed resources are estimated in Upper Permian minable coal beds, of which 92.57% are distributed in Liupanshui, Zhipa and Qianbei coalfield [48].

Generally speaking, Guizhou province has the geological characteristics of “One Weak, Two Many, Three Highs and Four Larges” in terms of coal bed gas, i.e. slightly weak groundwater dynamic condition of Longtang Formation; many gas control structures and many coal beds; high coal-bed-provided gas content, high resource abundance, 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 the average gas content of more than 13 m³/t in most synclines, and more than 18 m³/t in Zhipa area [49], at a high level on the whole.

In Guizhou, geological resources of shale gas total 4.55 trillion m³ in coal measures (Jiusi Formation, Liangshan Formation and Longtang Formation), taking up 33.6% of the total across Guizhou. Two models for co-exploration & joint exploitation of coal bed gas and shale gas have been developed, i.e. multi-layer fracturing & multi-layer drainage and separate layer fracturing and multi-layer drainage [48]. In addition, the eastern part of Liupanshui coalfield and the northern part of Zhipa coalfield are under excellent combined development conditions of the two gases, making it a perfect place for co-exploration & joint exploitation of the two gases in Guizhou Province [48].

3.4. Northeast Coal Accumulation Region

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

In Fuxin Basin, five major minable coal beds are sedimentated in Cretaceous Fuxin Formation, mainly representing by Taiying coal bed formation, middle coal bed formation and Sunjianwan 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 proved coal reserves and 13.691 billion m³ of estimated CBM resources [51]. Fuxin Formation, with 0.6% coal-based vitrinite reflectance at maximum and lowly maturity, is at low-middle metamorphic stage and dominated by long flame coal and gas coal [50].

Based on the research on the shale gas in coal measures of Fuxin Basin, it is believed that Northeast Coalfield Geology Bureau has huge shale gas resources in coal measures. And the resources reach as many as 8.734 billion m³ only in Liujia area [52]. Liujia area is located in the middle of Fuxin Basin. The Fuxin Formation has CBM content at 1.74-10.14 m³/t, with3000-6500 m³/d per-well production and over 97% of methane in actual output [53]. Cretaceous Shahai Formation mainly includes black shale, mudstone and siltstone, being mingled with various-granularity sandstone bed and conglomerate & breccia, and is rich in zoolite, 500-600 m in thickness and 1000-1600 m in buried depth, making it a productive source for shale gas [52]. As 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 Yunnan-Tibet coal accumulation region, complicated geological tectonic backgrounds and adverse natural conditions lead to a big difficulty in carrying out geological exploration. And people tend to neglect this region as it has small reserve of coal resources, leading to low-level research on coal geology and CBM, not to say any research on shale gas and tight sandstone gas in coal measures. However it is necessary to seek more energy minerals extensively in Tibet region where local energy is always priced high due to energy shortage and overhigh inland-to-Tibet transportation cost. Meanwhile, the uplift of Qinghai-Tibet Plateau is great harmful to storing conventional oil and gas, thus 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 Nyima Basin, in the middle part of Tibet, is a Tertiary terrestrial basin with estimated 10-20 billion m³ of shale gas resources, showing great resource potential [54].

CONCLUSION

(1) As China has a good material foundation for the co-occurrence of multiple coal measure gases created by the inter-sedimentation of coal bed, dark shale and fine-grained tight sandstone in the coal measure, it is common to find the co-occurrence of CBM, shale gas, tight sandstone gas, natural gas hydrate and the like. And the discovery of huge resources makes it a necessity of systematic exploration and research. Specifically, CBM, shale gas and tight sandstone gas co-occur in Qinshui Basin, Ordos Basin and Tulufan-Hami Basin; CBM, shale gas and natural gas hydrate in Muri coalfield; CBM and shale gas in Zhunger Basin, Guizhou region and Fuxin Basin. Based on the data above, these regions have potential for multiple-gases co-exploration and jointly exploitation.

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

(3) China has considerable coal resources. By benefiting from the widespread distribution of coal measures and the inter-sedimentary development of coal bed, dark shale and fine-grained tight sandstone in the coal measure, it has good geological conditions and material basis for the co-occurrence of a variety of coal gases. With such huge reservoir of coal gases, the co-occurrence of two or three gases of CBM, shale gas, tight sandstone gas or natural gas hydrate is very common. Contributing to deeper research and further exploration, more and more coal measures holding multiple gases will definitely be discovered and the proved resources of coal measure gas will be increased, indicating a prospect for co-exploitation 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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