Acta Geologica Sinica (English Edition), 2021, 95(4): 1346–1356

Coordinated Exploration Model and its Application to Coal and Coal-associated Deposits in Coal Basins of China

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Abstract: China is a top world producer of coal resources with numerous coal-rich basins country-wide that also contain coalbed methane (CBM), an unconventional natural gas resource. Recent exploration of coal and CBM resources has also led to the discovery of rare, precious, and scattered metal minerals, including sandstone-type U and Ga–Ge–Li. High-grade and industrial-value deposits have been discovered in the Ordos, Junggar, and other basins across China during exploration for coal resources. Application of coordinated exploration theories and techniques in multiple energy and coal-associated ore deposits, such as coal and unconventional natural gas in coal, achieves efficient and practical exploration of natural resources. Based on the systematic study of accumulation and occurrence of coal and coal-associated mineral resources in coal basins, the basic idea of coordinated exploration for coal and coal-associated deposits is proposed, and multi-targets and multi-methods based on a coordinated exploration model of coal-associated deposits is developed. Coordinated exploration expands the main exploration objective from coal seams to coal-associated series, extending the exploration target from targeting coal only to coal-associated deposits. Entrance times for exploration are decreased to realize coordinated exploration for coal, unconventional natural gas and syngenetic/associated mineral resources in coal by implementing a 'one-time approach' —one time in and out of a coal seam to minimize disturbance and time needed for extraction. According to the differences of geological background in China's coal basins, four coordinated exploration model types, including co-exploration of coal and coal-associated unconventional natural gas, coal and solid minerals, coal and metal minerals, and coal with water resources are established. Other models discussed include a multi-target coordinated exploration model for the combination of coal, coal-associated gas, solid minerals, and metal minerals accordingly. The exploration techniques of coal and coal-associated resources include regional geological investigation and research and synthetic application of other techniques including seismic surveys, drilling, logging, and geochemical exploration. Particularly, applying the 'multi-purpose drill hole' or reworking coalfield drill holes into parameter wells, adding sample testing and logging wells, determining gas-bearing layers by logging and gas content measurement, jointly measuring multiple logging parameters, sampling, and testing of coal-strata help in the exploration and evaluation of coal resources, coal-associated unconventional natural gas resources, and coal-associated element minerals. Accordingly, a system of integrated Space–Air–Ground exploration techniques for coordinated exploration of coal and coal-associated minerals is established. This includes high-resolution, hyperspectral remote-sensing technique, high-precision geophysical exploration and fast, precise drilling, testing of experimental samples, as well as coordinated exploration and determination methods of multi-target factors, multi-exploration means, multi-parameter configuration and optimization, big data fusions and interpretation techniques. In recent years, the application of this integrated system has brought significant breakthroughs in coal exploration in Inner Mongolia, Xinjiang and other provinces, discovering several large, ten-billion-ton coalfields, such as the Eastern Junggar and Tuha basins, and also in exploration and development of CBM from low-rank coals in Fukang, Xinjiang, discovery the Daying U Deposit in Inner Mongolia, the Junggar Ultralarge Ga Deposit, Lincang, Yunnan, and the Wulantuga, Inner Mongolia, Ge-bearing coal deposits, and the Pingshuo Ultralarge Li–Ge Deposit.

Key words: conventional and unconventional energy resources, transition metals, coal, coal-associated deposits, exploration model

Citation: Wang et al., 2021. Coordinated Exploration Model and its Application to Coal and Coal-associated Deposits in Coal Basins of China. Acta Geologica Sinica (English Edition), 95(4): 1346–1356. DOI: 10.1111/1755-6724.14495

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http://www.geojournals.cn/dzxbcn/ch/index.aspx; https://onlinelibrary.wiley.com/journal/17556724

1 Introduction

China contains some of the most abundant coal resources in the world. Coal is also the primary energy source in China, supplying over 60% of energy throughout the country. According to BP's prediction (https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html), coal continues to supply over 50% of the primary energy through 2035. Although the relative proportion of coal in energy consumption is decreasing continuously, the increase in China's total energy consumption will continue to be vigorous well into the future. The absolute measure of coal consumption will continue increasing, and, in short, the position of coal in China will still be dominant. Previous coal geological exploration activities with resource guarantee were mostly for single minerals and mainly constrained to coal seams in coal-bearing strata, and little information exists on the syngenetic/associated mineral resources in coal basins and coal-bearing resources. Such an exploration model not only misses the deposits in the same structural unit but also may increase the number of times of entrances for repetitive exploration aimed at different mineral species in the same exploration area. This intensifies the disturbance on both the environment and ecology, such as surface and ground water. In recent years, exploration for coal and coalbed methane (CBM) resources, rare, precious, and scattered metal mineral resources including sandstone-type uranium (U) and gallium–germanium–lithium (Ga–Ge–Li) resources with high grades and industrial values have been discovered in the Ordos, Junggar, and several other basins in China. The discovery of mineral resources can fill the gaps in ore prospecting in China. Chinese scholars have made valuable efforts in these aspects of coal and U co-exploration and coal–water co-extraction (Wu et al., 2017; Peng, 2018).

In this study, multi-purpose exploration in coal basins is studied according to the characteristics of the coal and coal-associated resources in coal basins. A coordinated exploration idea, model, and exploration techniques of coal and coal-associated resources are proposed, which provide for the guidance and reference for coordinated exploration of multiple energy minerals and syngenetic/associated metal mineral resources, such as coal and coal-measure natural gas.

2 Characteristics of Coal and Coal-associated Resources in Coal-bearing Basins

2.1 Nine-grid distribution of coal resources in China

The numerous coal-bearing basins and coal resources throughout China are distributed in a nine-grid pattern and controlled by two transverse and two vertical lines. The transverse lines trend west–east and extend from the Tianshan Mountain to the Yinshan Mountain tectonic belts, and from the Kunlun Mountain through the Qinling Mountain to Dabie Mountain tectonic belts. The vertical lines trend north–northeast from the Greater Khingan mountains through the Taihang Mountain–Xuefeng Mountain tectonic belts, and from the Helan Mountain through the Liupan Mountain and the Longmen Mountain tectonic belts (Fig. 1).

Based on this nine-grid division pattern, the coal resources distribution can generally be divided into three regions (Peng et al., 2015) from east to westwards, these are the Eastern, Central, and Western. The Eastern Region consists of three subregions: Northeastern with coal-bearing areas mainly in Liaoning, Jilin and Heilongjiang provinces; Huang–Huai–Hai with coal-bearing areas mainly in Beijing, Tianjin, Hebei, Shandong, Henan, Northern Jiangsu and Northern Anhui; and the Southeastern with coal-bearing areas mainly in Southern Jiangsu, Southern Anhui, Zhejiang, Jiangxi, Fujian, Hunan, Hubei, Guangdong, Guangxi and Hainan. The Central Region consists of three subregions: Eastern Inner Mongolia mainly includes coal-bearing areas in that region; Shanxi–Shannxi–Inner Mongolia (Western Inner Mongolia)–Ningxia has coal-bearing areas mainly in Shanxi, Shannxi, Eastern Gansu, Ningxia, and Western Inner Mongolia; and the Southwestern mainly includes coal-bearing areas in Yunnan, Guizhou, Eastern Sichuan and Chongqing. The Western Region consists of three subregions: Northern Xinjiang that mainly includes coal-bearing areas in Xinjiang to the north of Tianshan; Southern Xinjiang–Gansu–Qinghai includes coal-bearing areas in Qinghai, Gansu (Hexi Corridor) and Southern Xinjiang; and the Tibet mainly with coal-bearing areas in Tibet, Western Yunnan, and Western Sichuan.

The nine-grid distribution pattern not only clearly identifies the accumulation and distribution characteristics of coal basins and coal resources in China but also closely correlates these to regional natural environment characteristics, the local economic development level, and the combined administrative regionalization of China (Tian et al., 2006). Traditionally, virtually the N–S-trending Greater Khingan–Taihang–Xuefeng and Helan–Longmen mountains and the W–E-trending direction of Tianshan–Yinshan and Kunlun–Qingling–Dabie mountains act as the boundaries of terrain, climate, ecological environment and water resources in China. The economic-social development level differs significantly between the nine-grid division lines: the eastern region has a highly developed economy and society, while the central and southern regions are moderately developed; the western and northern regions are underdeveloped in economy. The distribution characteristics of China's coal resources are inversely correlated to the economic and social development level. Depending on the regional and economic differentiation, the coal resources are transported from west to the east and coal in the south is transported to the north across the country.

2.2 Coal resources

Because of the geology, the distribution of coal resources is unbalanced across China. The total coal resources amount to 5.82 trillion tons, retained coal resources amount to 1945.59 billion tons, and predicated resources amount to 3.88 trillion tons (Peng et al., 2015). According to the nine-grid distribution pattern, the coal resources of the eastern, central, and western regions account for 7.9%, 55.6% and 36.5% of the total,

① Northeastern subregion ② Huang–Huai–Hai subregion ③ Southeastern subregion
④ Eastern Inner Mongolia ⑤ Shanxi–Shannxi–Inner Mongolia (Western Inner Mongolia)–Ningxia
⑥ Southwestern subregion ⑦ Northern Xinjiang ⑧ Southern Xinjiang–Gansu–Qinghai
⑨ Tibet subregion

Fig. 1. Schematic map of nine-grid division pattern in coal geology (China basemap after China National Bureau of Surveying and Mapping Geographical Information, CNBSMGI).

respectively. The Shanxi–Shannxi–Inner Mongolia (Western)–Ningxia and the Northern Xinjiang subregions are the main regions for coal resources of China, accounting for 41.4% and 30.8% of the total, respectively (Table 1). Resources are accumulated mainly in the following provinces in descending order of the amount of coal: Xinjiang, Inner Mongolia, Shannxi, Shannxi and Guizhou.

Among retained coal resources in China, 404.04 billion tons have been mined, which accounts for about 20.8% of the known amount. There are still around 1541.56 billion tons that have not been used (79.2%), and, of this unused resource, there are 259.36 billion tons of coal that are currently being explored, 297.19 billion tons have been surveyed in detail, 511.16 billion tons have generally been identified in generic surveys, and 473.84 billion tons are known but have not been surveyed.

2.3 Coal series associated ore deposits

Coal series are sedimentary rock systems composed of coal seams, coal streaks, or organic mud shale that are abundant in organic matter. In recent years, with the improvement of exploration techniques, syngenetic/associated minerals have been commonly reported in these series, and the value of some minerals even exceeds that of the coal resources. Occurrence of multiple types of syngenetic/associated mineral resources is typical of coal and coal series in China, and also opens up a new field for seeking other rare mineral resources. The diversity of these coal-associated mineral resources not only provides specific coordinated targets and objects for green coal geological exploration but also meets the requirement for comprehensive, efficient, and green utilization of coal and coal-associated resources for the construction of an ecological civilization in this new era. Chinese scholars

Table 1 Nine-grid distribution of coal resources in China (Peng et al., 2014)

Region	Subregion	Retained resource (100 Mt)	Predicated resource above 2000 m at depth
Eastern	Northeastern	325.08	324.53
	Huang–Huai–Hai	1604.76	2045.52
	Southeastern	103.29	214.77
Central	Eastern Inner Monglia	3146.47	1272.11
	Shanxi–Shannxi–Inner Mongolia (Western)–Ningxia	10620.24	13528.15
	Southwestern	1116.74	2697.32
Western	Northern Xinjiang	2097.85	15857.84
	Southern Xinjiang–Gansu–Qinghai	419.53	2825.28
	Tibet	21.94	39.24
	Total	19455.90	38804.76

have proposed various classification methods for coal-associated mineral resources (Li et al., 2011; Cao et al., 2016), and, in recent years, research has mainly focused on unconventional natural gas in coal (Cao et al., 2014), which includes CBM, shale gas, sandstone gas, and bulk solid mineral resources such as sandstone-type U deposit, Ga-, Ge- and Li-bearing resources in coal (Table 2).

2.3.1 Unconventional natural gas resources in coal

CBM, as a type of clean, low-carbon, and high-quality energy resource, is widely distributed in coal seams; however, it is also one of the main risk factors of coal mine safety production. Whether from the perspective of safe production and comprehensive utilization of resources or ecological environmental protection, it is necessary to perform coordinated exploration of both coal and CBM. Coal exploration also requires CBM exploration currently, which reflects the core idea of green exploration with efficient use of natural resources. Organic matter source, type and degree of the thermal evolution of sandstone and mud shale in a coal series are closely correlated to coal accumulation and coalification. Gas components are highly consistent and have similar accumulation models as the coal. These gas components are ‘congeneric gases that occur in different layers’ of generalized ‘CBM’ reservoirs (Cao et al., 2017). Wang et al. (2014) used the concept of coal-measure gas, and combined ‘CBM, tight sandstone gas and shale gas in coal-bearing strata’ into ‘coal-measure gas’, and positively advocated the coordinated exploration and development of coal and coal series.

China has abundant coal-measure gas resources. There are 30 trillion m^3 of CBM less than 2000 m below the surface, the majority of which are in Mesozoic strata, mainly distributed in Shanxi–Shannxi–Inner Mongolia (Western)–Ningxia, Northern Xinjiang, Huanghuaihai District, and the Southwest District. The nine basins, which include Ordos, Qinshui, Junggar, Eastern Yunnan and Western Guizhou, and Erlian, contain more than 1 trillion m^3 of CBM resources combined (Center for Strategic Research of Oil and Gas Resources, 2017). Sandstone gas in coal is mainly developed in the Carboniferous–Permian, Triassic and Jurassic coal-bearing formations, and reaches 30.95 trillion m^3 as a preliminary estimate, accounting for 60% of the total natural gas resources in China (Li et al., 2016). Carbonaceous mudstone is the significant shale-gas exploration layer in China, which is widespread in the marine-continental transitional and continental facies. It has high organic matter content and is mostly located in the peak stage of gas formation. Besides, coal-associated limestone gas has been discovered in Shanxi province (Fu et al., 2016) and coal-associated continental natural gas hydrate (NGH) is found in the Muli area, Qinghai province.

2.3.2 Coal-based other solid mineral resources

Coal basins accumulate multiple mineral resources, and many solid mineral resources in coal series have extremely high strategic value. These mainly include oil shale, graphite, kaolinite, bauxite, and refractory clay, which are mainly distributed in Shanxi–Shannxi–Inner Mongolia (Western)–Ningxia, and the Northwestern and Southwestern districts. Oil shale is a significant coal-associated resource and longitudinally interbeds coal seams. Oil shale resources are abundant in the Songliao, Ordos and Junggar basins, with their measured reserves accounting for over 50% of China’s total reserves. Coal-associated sandstone-type U deposits in fluvial-delta sedimentary environments are currently being developed, and the discovery of the world-class Daying U Deposit in Inner Mongolia is the most important uranium deposit in China. Coal-bearing graphite, a new strategic mineral resource, is mostly cryptocrystalline and occurs in clustered ore bodies that are easily developed. The measured graphite reserves of China accounts for 42% of the total world reserves. Kaolinite in coal has 1.67 billion tons of measured global reserves, and China contains 50% of that. The spatial-temporal distribution pattern of coal-associated bauxite and refractory clay are consistent with those of kaolinite and are also distributed mainly in the coal series in China. These mineral resources are widely

Table 2 Statistics of major coal-bearing mineral resources in China

Type	Mineral species	Main Areas	Resource	Percentage of total resources of China (%)	Source
Coal-associated unconventional natural gases	CBM	Shanxi–Shannxi–Inner Mongolia (Western Inner Mongolia) –Ningxia, Northern Xinjiang, Huanghuaihai District, Southwest District	30.05 trillion m^3 of CBM resources (within 2000 m at depth)	/	Center, Oil and Gas, Ministry of National Resources, 2017
	Shale gas	Southwest District, Shanxi–Shannxi–Inner Mongolia (Western Inner Mongolia)–Ningxia	32 trillion m^3 of shale gas resource (within 3000 m at depth)	>20% of the shale gas geological resource of China	Fu et al., 2016
	Tight gas	Shanxi–Shannxi–Inner Mongolia (Western Inner Mongolia)–Ningxia, Northern Xinjiang, Huanghuaihai District, Southwest District	30.95 trillion m^3	~60% of China’s natural gas resource	Li et al., 2016
Coal-associated non-metal minerals	Kaoline	Southeast District, Shanxi–Shannxi–Inner Mongolia (Western Inner Mongolia)–Ningxia	1.67 billion tonnes of measured reserve	above 50% of China’s total kaoline reserve	Zhang et al., 2012
	Refractory clay	Southeast District, Shanxi–Shannxi–Inner Mongolia (Western Inner Mongolia)–Ningxia	4.92 billion tonnes of total resources	/	Cui, 2018
	Bentonite	Northern Xinjiang, Eastern Inner Mongolia, Southeast District, Northeast District	888 Mt tonnes of measured reserve	/	
	Ceyssatite	Northeast District, Southwest District	190 Mt tonnes of measured reserve	71% of total measured reserve	
	Graphite	Northeast District, Southeast District, Shanxi–Shannxi–Inner Mongolia (Western Inner Mongolia)–Ningxia	60 Mt tonnes of resource reserve	/	Cao et al., 2016

distributed, of high-grade and large reserves or have exceptionally high strategic value. They have become a non-negligible resource in the coordinated exploration of coal.

2.3.3 Metal mineral resources in coal series

Metal mineral resources such as Ge, Li, and Ga are distributed throughout coal and coal series, but their concentrations are generally low and occur in element state; thus, they are called element deposits in coal, which are mainly distributed in Shanxi–Shannxi–Inner Mongolia (Western)–Ningxia, eastern Inner Mongolia, northern Xinjiang and the Southwest District (Tang, et al., 2008). CNACG, in a survey of coal and coal-associated mineral resources, discovered 68 element minerals following resource discoveries in coal series. They named the Erlian–Hailaer Ge/Ga, the Tianshan Mountain Ge/Ga, the Yinshan Mountain Ge/Ga/Li, East Taihang Mountain Ge/Ga, Qilian–Qingling Mountain Ge/Ga, the Peripheral Sichuan Basin Ga/Li, the Sichuan–Yunnan–Guizhou Ge, Ga, Li, and the Western Yunnan SanJiang Ge metallogenic belts (Fig. 2).

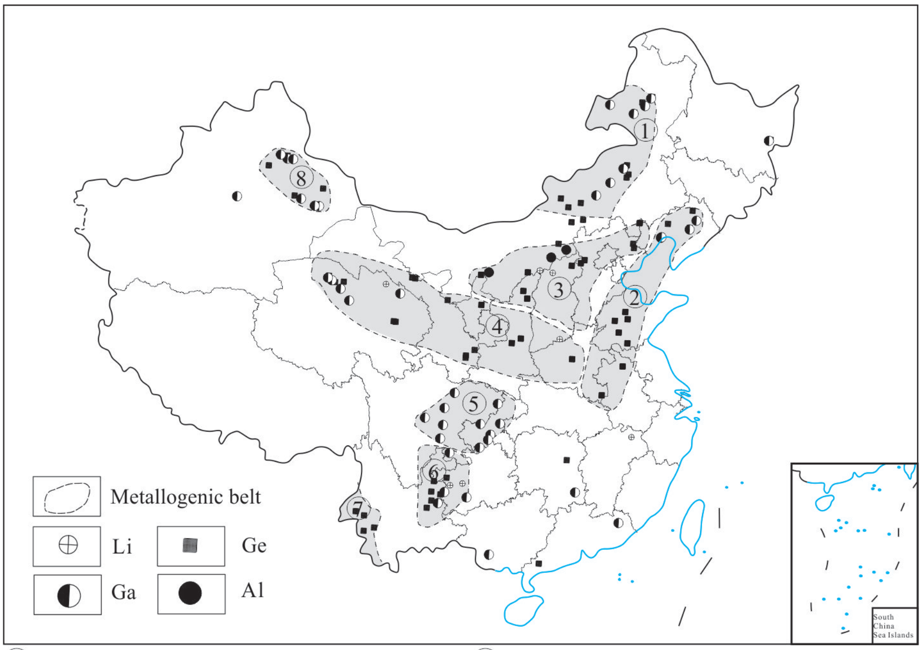
In recent years, an ultra-large Ge-bearing coal deposit was discovered in the Heidaigou Coal Mine, Junggar Basin, with an estimated resource of 63,400 t and an average grade of 44.8 μg/g Ga (Dai et al., 2006). Another ultra-large Ge coal deposit was discovered in the Shengli Coal Field, Xilin Gol League, Inner Mongolia, with 1,600 t containing Ge, holding 30% of the total Ge reserve in China (Liu et al., 2018). The Damoguaihe Formation, Yimin Coal Field, and the Hulunbeier League have a preliminary estimated Ge resource of 4,000 t, making it yet another ultra-large coal-associated Ge deposit following the Shengli Coal Field. The Guanbanwusu Coal Deposit in the Junggar Coal Field has a potential resource up to 13,210 t, providing 28,290 t of Li_2O resource (Cui, 2018).

3 Basic Idea and Model of Coordinated Exploration of Coal and Coal-associated Mineral Deposits

With advances in the theory and research of coal geology and exploration techniques over the past 60 years, ‘coalfield geological exploration’ has gradually developed into ‘precise geological exploration of coal’, and a new integrated exploration system for coal resources in China has been established (Wang, 2013). However, this system is still aimed at coal resources. In recent years, based on a comprehensive exploration technique system and characteristics of variable species and widespread distribution of syngenetic/associated mineral resources in coal-measure strata, the idea of multi-resource coordinated exploration of coal with CBM, coal with U and coal with water has gradually developed (Li et al., 2011; Cao et al., 2016; Qin et al., 2018). Coordinated exploration has further developed based on integrated exploration and expanded from single resource to multi-resource exploration. Coordinated exploration not only emphasizes the comprehensive application of multiple advanced exploration techniques but also focuses on the comprehensive exploration, integrated evaluation, and co-development geological research of multiple energy types and other syngenetic/associated mineral resources in coal-bearing formations.

3.1 Basic conception

The fundamental conception of coal-associated mineral



① Erlian–Hailaer Ge/Ga Metallogenic Belt
② East Taihang Mountain Ge/Ga Metallogenic Belt
③ Yinshan Mountain Ge/Ga/Li Metallogenic Belt
④ Qilian–Qingling Mountain Ge/Ga Metallogenic Belt
⑤ Peripheral Sichuan Basin Ga/Li Metallogenic Belt
⑥ Sichuan–Yunnan–Guizhou Ge, Ga, Li Metallogenic Belt
⑦ Western Yunnan Sanjiang Ge Metallogenic Belt
⑧ Tianshan Mountain Ge/Ga Metallogenic Belt

Fig. 2. Map of distribution of metal element mineral resources in coal of China (China basemap after CNBSMGI).

resource coordinated exploration has expanded the main exploration object from coal seams to coal-associated systems, and the exploration target has extended from just coal to coal and other minerals associated with coal. The exploration techniques have correspondingly developed from simple-target exploration to coordinated application of multi-targets, and multi-methods exploration techniques. Moreover, the entrance times of exploration have decreased so as to coordinate exploration of coal and unconventional natural gas and syngenetic/associated mineral resources in coal measures by a 'one-time' approach (Fig. 3).

3.2 Exploration model

The coordinated exploration of coal and coal-associated mineral resources is aimed at different exploration areas. Before exploration commences, the results from drilling, geophysical exploration, and geochemical exploration data are fully used to determine the full extent of resources. Also, 'geological big data' are commonly used to predict the geologic background, types of mineral resource, resource abundance, and distribution characteristics or even resources of unknown areas to determine the major target mineral species and exploration tasks. This, in turn, also minimizes resource omission and engineering exploration replacement.

According to the temporal-spatial distribution, ore-forming types and environmental constraints of coal-associated multiple mineral resources, appropriate coordinated models are selected. Coordinated exploration types can be divided into dual-target factors, such as coal and gas, coal and water, coal and solid minerals, coal and metal element minerals, and so on; triple-target factors of coal, gas and water; four target factors such as coal, gas, water and solid minerals; and multiple target factors of coal and gas, water and solid mineral, metal element minerals and other geological conditions (Wang et al., 2020). Here, only the coordinated exploration of dual-target factors is described in detail; other types will not be mentioned because they have similar exploration concepts.

3.2.1 Coordinated exploration of coal and unconventional natural gas in coal

Coal-measure gas is an unconventional natural gas generated and accumulated in coal reservoirs. During coal exploration, drilling should also include exploration and evaluation of gas resources. Gas-bearing layers can be determined by gas content testing, strata and gas logging. Replacement of coalfield drill holes by minor coal-measure gas exploratory wells or parameter wells or reworking of drill holes into parameters can not only meet coal series sampling requirements but also can guarantee

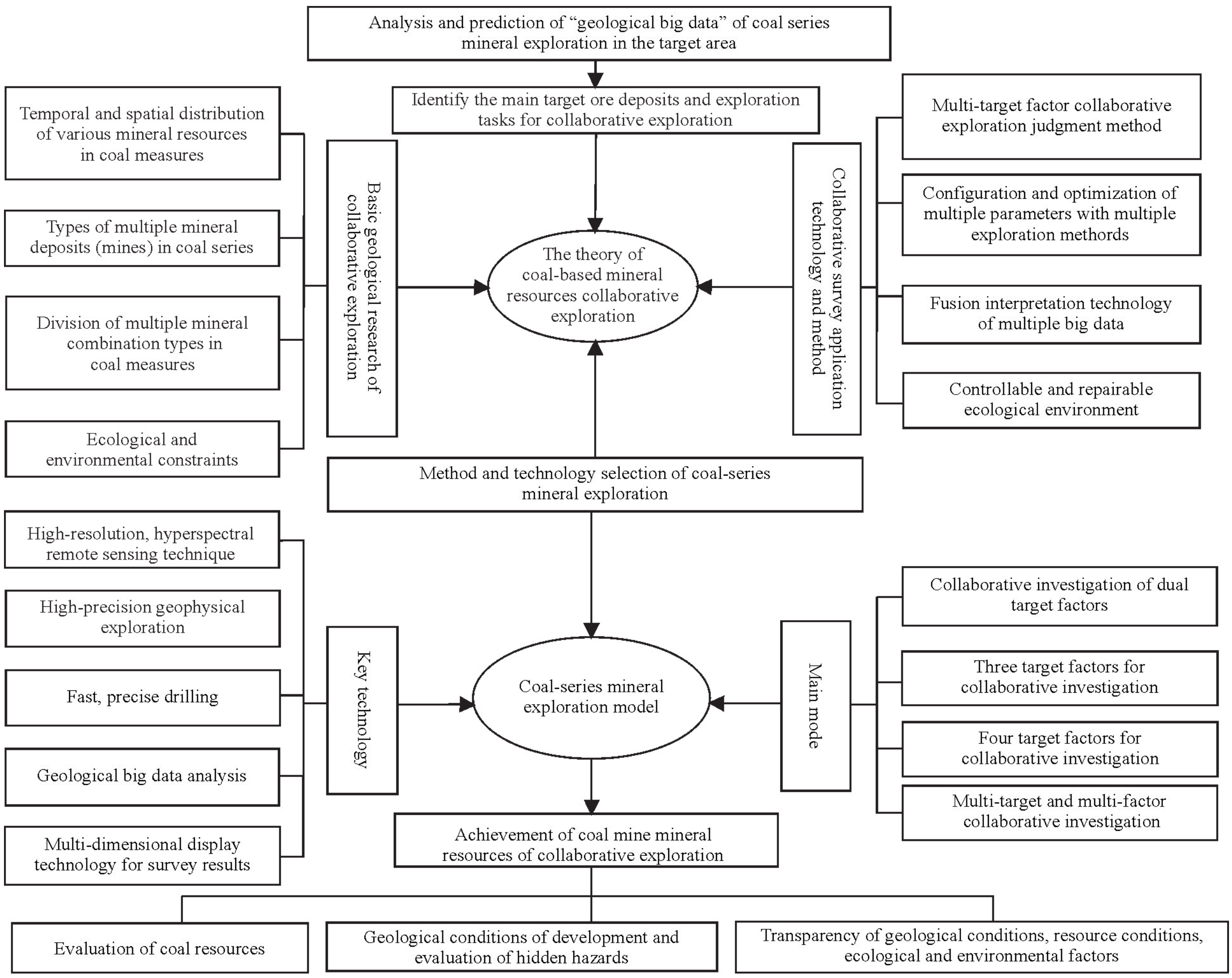


Fig. 3. Coal and coal series-associated deposits exploration system.

coal reserve parameter measurements. For layers with a high gas content, further pilot production can be conducted. In the coal extraction stage, research on the temporal-spatial configuration of coal and coal-measure gas exploration and extraction should first be satisfactorily conducted so as to determine the extraction sequence. Generally, CH_4 should be extracted before mining is done for the safe extraction of coal and then transformation into clean natural resources (Fig. 4).

3.2.2 Coordinated exploration of coal and associated solid mineral resource

Coal-associated solid minerals comprise numerous species. During coal exploration, sample testing and logging content can be enhanced by a 'one hole with multiple purposes' approach. This information combined with regional geological background on the ore deposits, and particularly the comprehensive application of other techniques, such as logging, assay and testing, can enhance the understanding of the occurrence and state of the coal and syngenetic/associated mineral resources in the coal measures. This further enhances coordinated resource exploration. As an example, sedimentary type U deposits are often developed in coalfields in North China and mainly produce coal-associated minerals. The success of the Daying Coal–U mine implementing the co-exploration model is a specific practice of the coordinated exploration concept, which has led to a more coordinated exploration of multiple associated minerals, such as prospecting coal–K and coal–Al (Fig. 5).

3.3 Coordinated exploration of coal and metal mineral resources

Coal contains a variety of elements that show significant prospecting potential. The major elements include Na, Mg, Ca, K, Si, Al, Ti, P, S, plus another 60 trace elements. In the coordinated exploration of coal and element resources, spectrofluorometry and chemical analysis are required in addition to drilling logging, and sample collection. After syngenetic/associated minerals are confirmed, further research into the distribution, grade variation, ore composition, structure texture and occurrence state of the resources are needed. After coal extraction, elemental minerals in crude coal and post-combustion coal ash need to be recovered, extracted and utilized comprehensively (Fig. 6).

3.4 Coordinated exploration of coal and water resources

The hydrogeological conditions of coal deposits in China are complex, and the extraction of coal resources is continuously threatened by water disasters. Surface water systems are closely linked to people's lives, in addition to the state of hydrogeological exploration of the coal deposits during early-stage extraction. Coal mine production should be scientifically and orderly arranged to prevent water disasters at the surface and within the mine. Site-specific water prevention and control of mine shafts

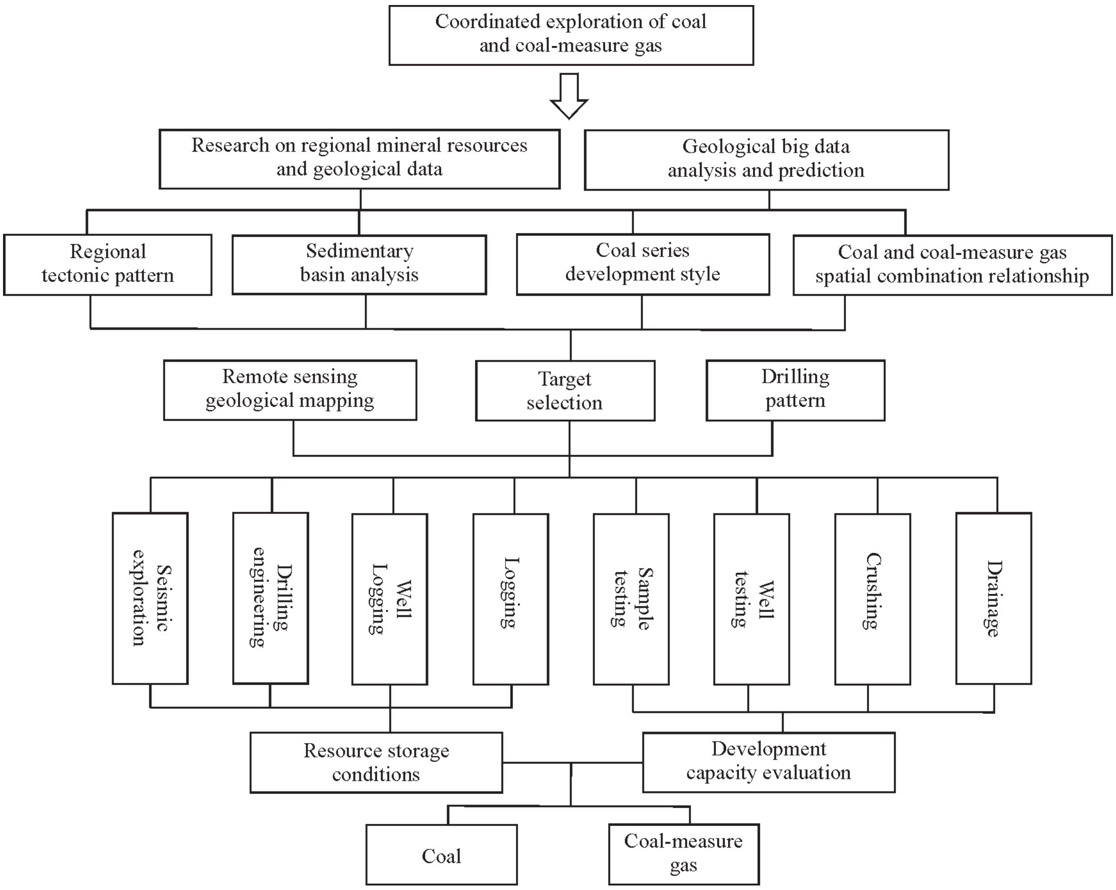


Fig. 4. Coordinated exploration of coal and coal-measure gas.

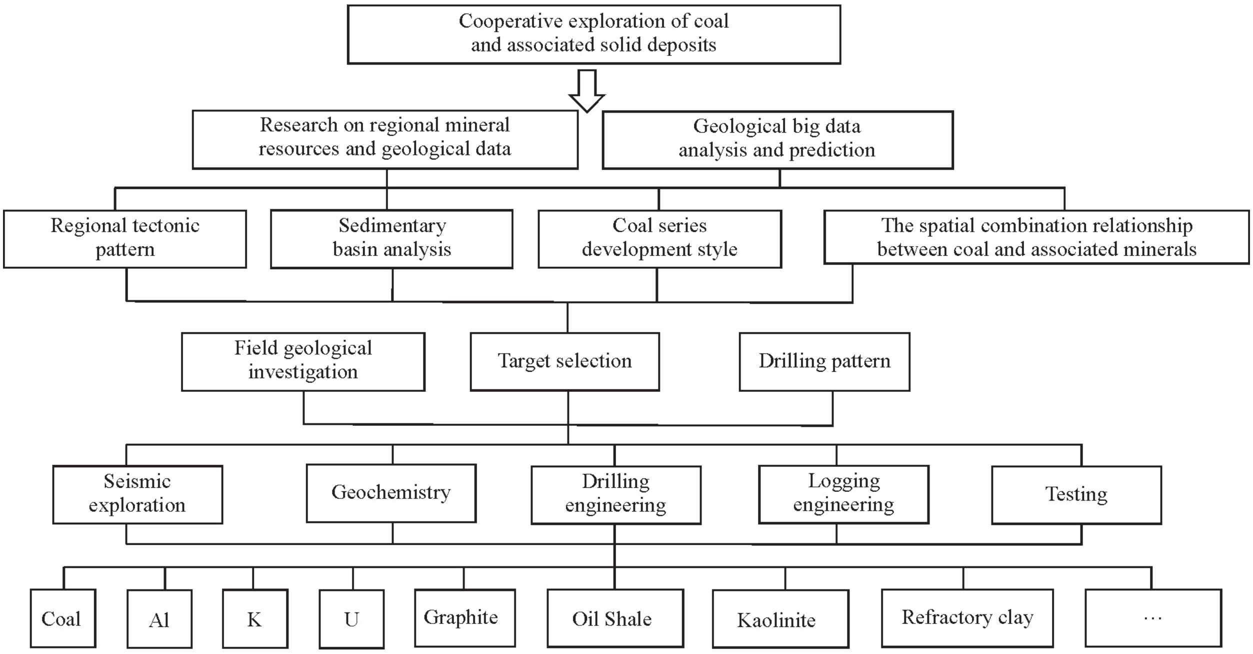


Fig. 5. Cooperative exploration of coal associated solid deposits.

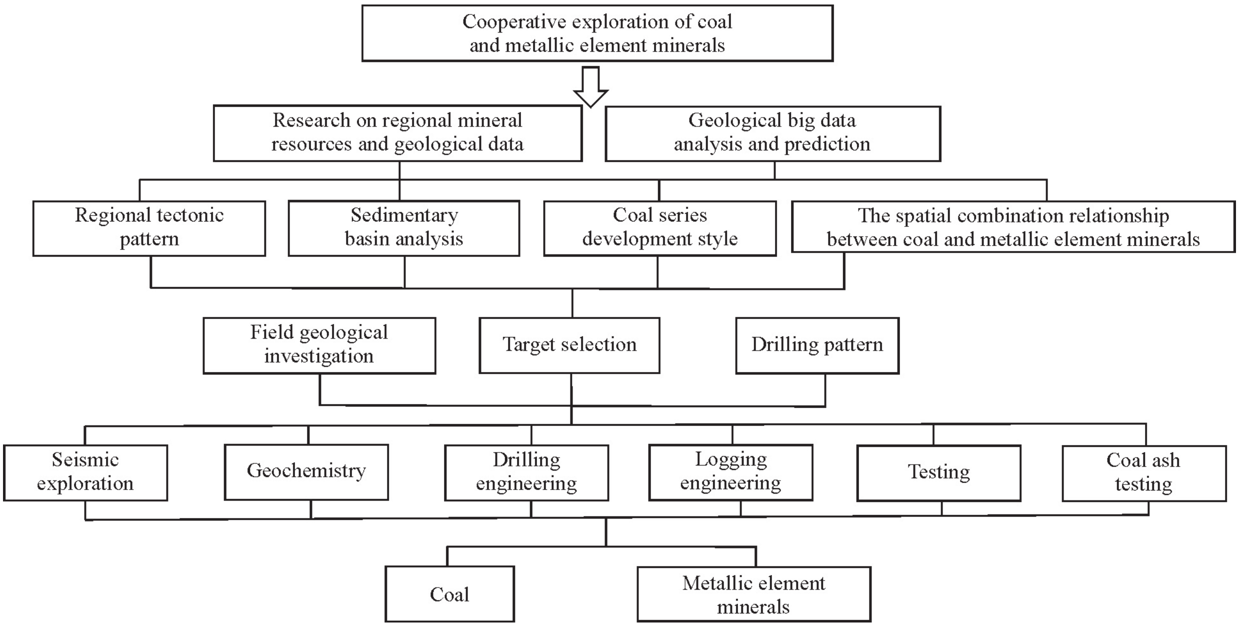


Fig. 6. Cooperative exploration of coal and metallic element minerals.

need to be implemented for optimal prevention. Moreover, protection and full utilization of surface water resources need to be strengthened. In coal deposit areas, surface water resource protection should be strengthened to prevent contamination and depletion. Many ancient lake-bed water-bearing basins and high-porosity sandstone aquifers with water resource development potential are found in extremely arid coal-bearing regions. Of these, the Jurassic aquifer in the Dananhu deposit in Xinjiang has a 439 million m^3 groundwater static reserve, and the Santanghu deposit in Xinjiang is predicted to have a normal mine water discharge of 4.56 million m^3/year (Sun et al., 2017). All of these water resources could be developed in coordination in a coal-water co-extraction method (Fig. 7).

4 Main Technical Measures

The coordinated exploration of coal and coal-associated minerals should apply multiple integrated Space–Air–Ground exploration techniques and mutually verify and comprehensively analyze a region. Furthermore, environmental protection should be paramount with forethought for restoration at every step of exploration, development, and after-extraction to minimize damage to the environment. The essential techniques for coordinated

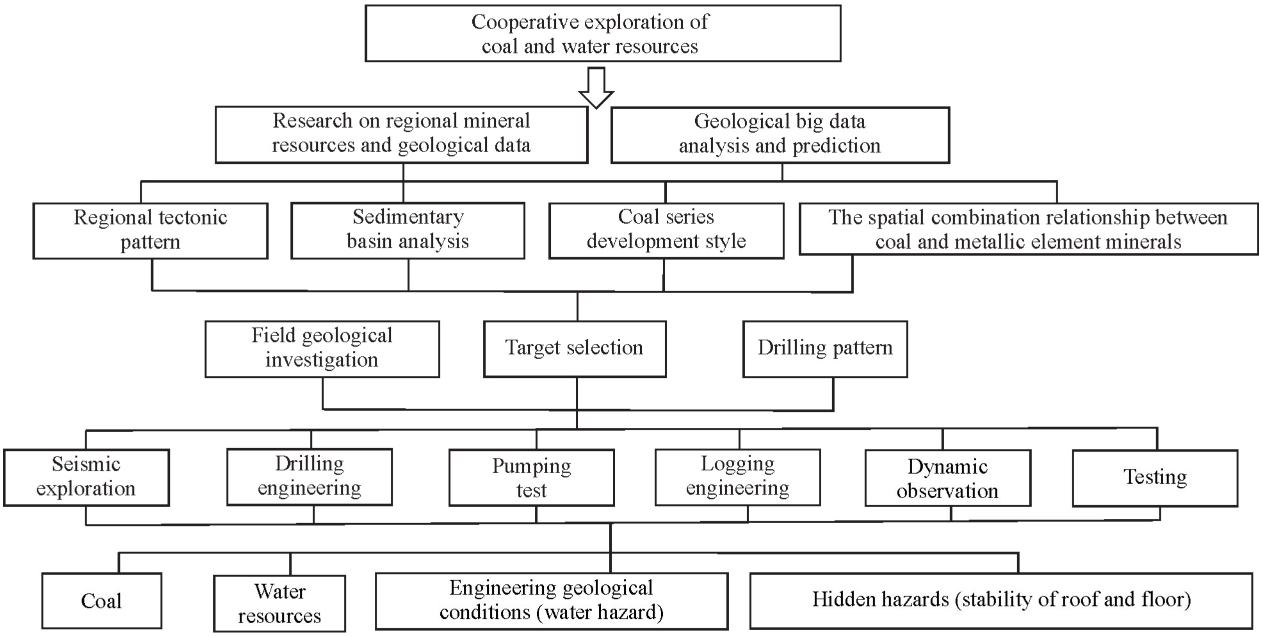


Fig. 7. Cooperative exploration of coal and water resources.

exploration of coal and coal-associated deposits include high-resolution, hyperspectral remote sensing, small-caliber fast, precise drilling, high-precision geophysical exploration, geological big data analysis techniques and multi-dimensional display technology for good survey results. The purpose of all this is to achieve coordinated exploration and determination with multiple-target factors, configuration and optimization of multiple parameters with multiple exploration techniques, and to interpret and display multi-dimensionally the many items of controllable and repairable big data.

Remote sensing receives ground target reflected and scattered external electromagnetic waves or electromagnetic waves emitted by the target itself to obtain target physical parameters using a space sensor (Tan et al., 2012). This technique has been widely applied in mine resource scanning exploration and target optimization, mine environment surveys, and the ecological environment dynamic monitoring. Notably, it plays a crucial role in resource exploration of poor physiographic conditions and inconvenient access, as well as in ecologically vulnerable areas. The main difference between the remote sensing technique and other exploration techniques lies in the former being 'non-contact' exploration and this has facilitated more obvious applications in the Northwestern Region than in the Eastern Region, especially as it is a natural 'green' exploration technique. Remote sensing is passive and does not disturb the environment. In recent years, new techniques such as high-resolution, hyperspectral remote sensing, post-remote sensing, visible light squint and stereoscopy, Differential Interferometry Synthetic Aperture (DISA), and remote sensing platform with multiple remote sensors have all been developed. These techniques provide new data sources and developmental direction for coal prospecting, and can be measured by remote sensing and ecological environment monitoring (Wang, 2017).

Fast, precise drilling using advanced drilling techniques and an organic combination of mechanical parameter optimization, mud configuration, and precise position of target layers minimizes the deviation between actual and designed bore-hole trajectory. Because it is fast and precise, a small-caliber application can further bring superior outcomes in decreasing costs of equipment and drilling and easing environmental impacts, particularly in protection of drill hole formation sections and various aquifers as well as fast, precise positioning of critical layers.

High-precision geophysical exploration techniques mainly include seismic exploration and geophysical logging. Seismic exploration has been proven to be the most effective method for identifying the geological conditions of coal seams, particularly structural controls, complementing advantages with the drilling method. Currently, three-dimensional seismic methods are rapidly developing and have made significant breakthroughs in the explosive pore-forming and excitation process, high-density data collection and special observation system design techniques, tomography statics correction technique, CMP gather correction technique, large-dip-angle prestack depth migration imaging and other vital techniques allowing for advanced imaging of the subsurface (Wang et al., 2017). Geophysical logging and drilling are usually used together and can provide critical technical parameters particularly in the aspects of lithology identification of non-cored sections, lithological combination, coal–rock interface identification, coal quality analysis, physical properties and resource potential evaluation of various gas reservoirs in coal, and accumulation area prediction. The small-caliber logging technique developed from small-caliber drilling can realize equipment integration, micro-miniaturization, electronization and intelligentization, and has been widely applied in multi-mineral, multi-purpose coordinated exploration for coal, CBM, shale gas and even continental NGH, amongst others.

Geological big data analysis is based on the massive amounts of remote sensing, drilling, geophysical exploration, analytical and testing data accumulated by coal resource exploration. These data not only include vital parameters and information about coal but also CBM and even other syngenetic/associated minerals. By establishing an exploration results information base and geological cloud–computing platform, 'geological big data analysis' is conducted to analyze and guide exploration. Currently, the application of such analysis in the coal geological exploration industry is still in its early stages of discovery, and further work is needed before practical and widespread application to the mining industry is optimized (Li et al., 2015).

The main difficulties of multi-dimensional display of exploration results lie in the integration, combination and assimilation of the many types of data (Li et al., 2018). Multi-sourced, multi-resolution and multi-typed geological big data produced by the different technical means (remote sensing imaging, field survey, drilling, geophysical exploration, sample testing, etc.) need to be effectively classified, integrated, connected, processed and utilized, to realize digitalization and multi-dimension exploration results. Resources and ecologic environmental geology results are the core of the multi-dimension display of information in coal geological exploration, correlating diversified information results of other geological carriers, and carefully combining 3-D and dynamic modeling and virtual reality techniques to display that information and finally realize controllable shared informatization and networking.

5 The Effect of Engineering Application

The application of integrated Space–Air–Ground coordinated exploration technique for coal and coal-associated minerals has obtained fruitful results in recent prospecting in China. Significant breakthroughs have been made in coal prospecting and exploration in Xinjiang and Inner Mongolia, where the Daying U Deposit, the Junngar Ultra-large Ga Deposit, the Lincang (Yunnan), the Wulantuga (Inner Mongolia) Ge-bearing coal deposits, and the Pingshuo Ultra-large Li–Ga Deposit have all recently been discovered because of these advances and applications.

Coal and CBM resources in the Northwestern Region, west of Liupan Mountain and north of Kunlun Mountain, account for 40% and 30% of the total resources, respectively; the Northwestern Region is the main base for the westward coal development strategy. CNACG applied the coordinated exploration model there and discovered 26 coal fields, of which eight are appropriate for the construction and development of ultra-large 10 billion t coal fields. Multiple groundwater resource sites have also been discovered in the Santanghu, Dananhu and Kamusite ultra-large mines, which can be developed to meet the requirements of national large-sized coal base construction for precise exploration/detection techniques of high-quality coal and water resources and hidden disaster-caused geological factors. To date, 518×10^8 m^3 of CBM resources were exploited and a CBM-development demonstration plot has produced 3000×10^4 m^3. A coordinated green exploration theory and technique system was established, which is appropriate for coal, gas and water resources of the Northwestern Region with unique geological features. The concepts that are included in this are: 1) ore controlling theory construction of coal basins and coal-associated deposits, 2) optimization combination types of coal, gas, water and accumulation units, 3) optimization of exploration techniques and methods aimed at multiple geological purposes and means, 4) ecological protection and environment monitoring techniques of coal fields (mining areas), and 5) comprehensive evaluation of development conditions and economics. Using this theory in the application, only one entrance for an exploration area was created and the coal–gas–water resources and other syngenetic/associated mineral resources/reserves were exploited simultaneously. Missing resources due to single mineral species exploration and repetitive exploration of different mineral species as well as the impacts of repetitive exploration on the environment were avoided.

6 Conclusions

(1) The basic idea of coordinated exploration of coal and coal-associated minerals was proposed. The multi-target and multi-method process based on the coordinated exploration model of coal-associated minerals was developed. Coordinated exploration expands the main exploration object from just coal seams to coal series and the exploration target from only coal to coal and other minerals in the coal seams and series. The exploration techniques are correspondingly developed from simple-target exploration to coordinated application of multi-target, multi-method exploration techniques. Moreover, the entrance times of exploration decrease to accomplish coordinated exploration of coal and unconventional natural gas and coal-associated mineral resources using a one-time in-and-out of the mine once rather than repetitive mining excursions.

(2) Coordinated exploration of coal and coal-associated mineral resources selects an appropriate coordinated model according to spatial-temporal distribution, ore-forming types and environment constraints. This study proposed four types of coordinate exploration model, i.e., 1) co-exploration of coal and unconventional natural gas in coal, 2) of coal and solid minerals, 3) of coal and metal element minerals, and 4) of coal and water resources, and, accordingly, also developed a multi-purposes exploration model of coal, coal-measure gas, solid minerals and element metal minerals.

(3) Essential techniques for the coordinated exploration include remote sensing, small-caliber, fast, precise drilling, high-precision geophysical exploration and geological big data analysis. These techniques require coordination, mutual verification and comprehensive

analysis. Furthermore, restoration should be conducted after each step rather than only after the final extraction to minimize the total amount of damage to the environment. To realize coordinated exploration and determination of multiple target factors, multiple exploration means and parameters need to be configured, optimized, and interpreted to display the multiple items of big data with multi-dimensions.

Acknowledgements

We are grateful to anonymous reviewers for the valuable and constructive comments on the manuscript. Thanks for assisting of English language by Susan Turner and FANG Xiang.

Manuscript received Feb. 21, 2020
accepted Jul. 23, 2020
associate EIC: FEI Hongcai
edited by Susan TURNER and FANG Xiang

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