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Application Results of 3-D Seismic Exploration Technology in Coal Mines

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Abstract This paper briefly introduces the development and present situation of China's coal seismic exploration. It focuses on analyzing the important functions of 3-D seismic exploration technology in the designing and production of coal mines, and also the results of its application.

Key words: seismic exploration, mining area, structure

1 Introduction

China is a big coal country, having coal reserves ranking third in the world and coal production No. 1 in the world. Coal is the main energy in China and accounts for over 70% in the energy consumption structure of China. At present, coal has an annual production of 1 billion tons, which is widely used in national economy and people's life; 70% of the fuel power, 60% of chemical materials and 80% of civil commodity energy are supplied by coal. In recent decades, as a pioneer of coal industry, coal geological exploration has contributed significantly to coal industry. In the Tenth Five-Year Planning of coal industry in China, it is an important means to strengthen coal geological exploration to quicken the technical reform of coal enterprises, promote industrial updating, implement the strategy of encouraging the coal industry with science and technology and promote technical innovation.

In recent years, with the need for high production and high efficiency of coal mines the requirement for fine geological exploration is getting higher day by day, the seismic exploration of coal mines based on high-resolution seismic exploration technology, has become an efficient measure to determine in detail important geological data of small faults, small folds, caved pillars, mined-out areas, flushing zones and change of coal seams, and a new "bright spot" in coal geological exploration.

With the application and development for years , the mining area seismic exploration technology has played an important role in solving geological problems effecting coal mine production and construction, building high-production and high-efficiency mines and improving economic benefits of the enterprises (Ni, 2000). The seismic exploration of coal mines has set off a new upsurge, which is characterized by the popularization and application of the 3-D seismic exploration technology. Since the mining area high-resolution 3-D seismic exploration was first adopted in Xieqiao, Huainan in 1993, it has been used in varioius mining areas over 15 provinces, such as Shandong, Anhui, Jiangsu, Henan, Hebei, Shanxi and Heilongjiang. According to incomplete statistics, up to October 2001, a total of 150 3-D seismic exploration projects have been accomplished, covering an area of 460 km^2 and physical points of 450,000. Those projects have yielded rich geological results and provided efficient geological guarantee for building high-production and high-efficiency mines with enormous social and economic benefits .

2 Development of 3-D Seismic Exploration Technology in Coal Mines

The conception of 3-D seismic exploration was proposed by a geophysicist named Walton in 1970. In 1975, the 3-D seismic exploration was first applied to oil development and exploration.

Compared with 2-D seismics, the 3-D seismics has a larger data volume, is more accurate and reliable, and thus worths preservation for a long time; has accurate migration and homing with high lateral resolution favorable for researches on complex and small structures; the higher fidelity of the amplitude for seismic reflected waves are favorable for researches on the lithology of the strata; he automation of data interpretation and development of interactive interpretation are favorable for the improvement of data interpretation; therefore, it is more reasonable in economy and technology.

In 1978, the China National Administration of Coal Geology (CNACG, then the Geological Bureau of the Ministry of Coal Industry) organized a seismic team and

relative experts to carry out the first 3-D seismic exploration test in the field of coal geology in the central Yimin Coalfield. Two TYDC-24 analogue seismograph tape recorders with 48-channel reception, 6 multiplicities and a CDP grid of 15×15 m were used for field acquisition. A TQ-16 computer with self-developed software was used for data processing at the Research Institute of Coal Geophysical Exploration (RICGE), actively exploring for the development of 3-D seismic exploration in the field of coal geology.

In 1988, in conducting the project of the Sino-Japanese joint exploration for the Tangkou area, Jining Coalfield, Shandong Province, the first 3-D seismic exploration and production project with an area of 5 km^2 was implemented in the field of coal geology. A SN-338 digital seismograph made in France, with 96-channel reception, 12 folds and a CDP grid of 10 m ×15 m, was used in field acquisition. Data acquisition was carried out by a Japanese company. The main task of the project was to determine faults with throw larger than 10 m and folds with amplitude over 10 m. Compared with 2-D seismic data, the 3-D seismic data have higher resolution, better continuity, high exploration precision and better results, from which experiences in coal mine 3-D seismic exploration were accumulated, thereby laying a good technical foundation.

The 3-D seismic exploration of coal initiated in 1993, which was conducted in the mining area of the Xieqiao Coal Mine, Huainan Bureau of Mining with a great success. In only a few years, the 3-D seismic exploration has been rapidly popularized and applied from the east to the west, from the plains to the mountainous areas, from land to lakes, from state-owned large-scale mines to local coal mines. Its precision and resolution have been greatly improved and accepted by coal enterprises and the society, yielding remarkable geological results and enormous social and economic benefits.

In recent years, great achievements have been made in the researches and application of he mining area 3-D seismic exploration technology.

2.1 Continuous expansion of work scope

In recent years, the mining area 3-D seismic exploration has been conducted from the plains to the mountainous areas, lakes, swamps, urban areas, loess areas, cobble and gravel areas and hilly land.

In 1997, the CNACG and the Yangquan Coal Industry Group jointly carried out first 3-D seismic exploration project in the mountainous area of Wukuang, Yangquan, creating a precedent of 3-D seismic exploration in the coalfield in mountainous areas. Technical breakthroughs were made in data acquisition, processing and interpretation with excellent geological results. Twenty-seven (27) caved pillars were detected, some of which were verified by tunneling and drilling with an accuracy of 80%. Afterwards, 3-D seismic exploration in mountainous areas has been popularized and applied in large mining areas of Shanxi Province, and good data are obtained in some loess areas. Up to the end of October 2001, a total of 16 3-D seismic exploration projects in mountainous areas had been accomplished, covering an area of 25 km^2.

Sino-Japanese joint high-resolution seismic exploration test and researches were carried out on Weishan lake for 5 years. A set of high-resolution seismic exploration technology and equipment catering to conditions of various waters were summarized and improved. In 1997, a 3-D seismic exploration was conducted on the lake of the first mining area, the No. 5 well of the Tengxian Coalfield, with excellent results. Afterwards, 3-D seismic exploration has been carried out on the waters of mining areas in Zhaozhuang and Yanzhou of Shandong Province, and Dadun of Jiangsu Province.

In 1999, a 3-D seismic exploration was carried out in urban buildings area of the first mining area of the Linxi Mine, Kailuan (Group). The advantages of wireless remote sensing seismic instrument were made full use of in data acquisition and grounding coupling problems were solved by laying geophones with the gypsum adhering method on the cement and asphalt roads, obtaining good seismic data.

2.2 Continuous renewal of technology and equipment

In 1995, the China National Administration of Coal Geology invested RMB¥ 9.5 million to import a set of high-resolution 3-D seismic exploration equipment (including 3 sets of SN-388 remote sensing seismic acquisition system made in France, a GEOVECTEURPLUS seismic data processing system made in France and a GEOQUEST seismic interpretation system made in USA), which laid a good equipment foundation for the 3-D seismic exploration. Afterwards, geophysical exploration teams of Shandong Province, Hebei Province, Henan Province, Shanxi Province, Northeast China, Heilongjiang, Hydrogeologcial Bureau and Gansu Province purchased 11 advanced remote sensing digital seismographs with 4500 channels, such as BOX and DS-6 made in USA and SUMMIT made in Germany. Later on, more advanced IMAGE remote sensing system made by the I/O company in USA and 408UL remote sensing system made by the SERCEL in France were introduced.

Since 1999, all the institutions have updated or renewed the original processing and interpretation systems. The SGI ORIGIN2000 parallel computers and SUN ULTRA interpretation workstations were imported. Meanwhile, the seismic processing system and seismic data interpretation system were updated. Thus, they have become geophysical

exploration teams integrating field acquisition, data processing and interpretation.

2.3 Gradual improvement of data acquisition technology

In order to carry out 3-D seismic exploration data acquisition under various conditions and improve the acquisition technology and capability, the geophysical exploration teams, with continuous innovation and efforts, have imported and developed mountain drills and some other special equipment for operation on land and water, and purchased advanced software for acquisition and designing. At present, different acquisition technologies and measures can be applied according to different geological conditions and tasks to obtain ideal results. Meanwhile, they have carried out 3D-3C (three-dimensional and three-component) exploration acquisition.

3-D seismic acquisition was carried out on the lake of the first mining area in the No. 5 well of the Tengxian Coalfield, which have resulted in excellent data, summed up and improved set of technologies, methods and equipment favorable for high-resolution seismic exploration under various water conditions.

A test of target acquisition was made in the Panshan Mine. Key acquisition problems have been tackled for thin coal seams without good reflected waves, and excellent results have been obtained .

3-D seismic acquisition was carried out in the area covered by super-thick magmatic rocks in the No. 2 well field of the Nianzhou Mining Group, Shandong Province, with ideal seismic reflected waves.

In recent years, in cooperation with the China University of Mining (Beijing), the Geophysical Exploration Team, Anhui Bureau of Coal Geology, and the Research Institute of Coal Geophysical Exploration, Huainan Mining Group have finished 3D-3C seismic acquisition in 5 mining areas, pushing forward seismic exploration in the mining areas.

2.4 Gratifying progress in data processing technology

With years of efforts, the full 3-D seismic data processing technology has been developed and improved. Technologies of pre-stack depth migration, 3-D target processing, 3-D seismic static correction in various complicated areas have been introduced and developed. In addition, the RICGE has cooperated with Tsinghua University to develop a 3D-3C processing technology and related software, forming a 3D-3C seismic data processing system.

With the improvement of processing technology and the innovation of processing software, the 3-D data acquired and processed in the past were processed again, especially for target processing, which have resulted in new interpretations with high efficiency. For example, a target processing was carried out for the field data acquired in the No. 2 mining area of the Pansan Coalmine in Huaina in 1995, which stressed the energy and continuity of reflected waves from the Nos. 11–2 coal seams, and improved the interpretation precision of the structures in those coal seams.

2.5 Interpretation means getting richer and interpretation precision and report quality improved day by day

The full 3-D seismic interpretation technology ahs been enriched and developed. The interpretation precision has been enhanced by using the comprehensive interpretation method combining the section, plane and stereo interpretations together, and making full use of the technologies of slice interpretation, seismic attribute interpretation, fault model identification, 3-D visualization, coherent body and variant body fault interpretation (Fig. 1). Moreover, the seismic interpretation has been carried out jointly by personnel specialized in physical exploration, geology and design, and the seismic data were incorporated closely with known geological data, resulting in the improvement of interpretation precision and shortening of interpretation duration.

Some mining bureaus and coal enterprises have carried out a dynamic interpretation of 3-D seismic exploration data, i.e., the designing and geological workers go to the interpretation workstations of the operation unit or coal mine site for interactive interpretation and analysis; make analysis and interpretation again, in combination of the mine's geological data, geological laws and experiences in practice, for the fault structures directly influencing the layout of the working face and the production, to make sure which fault can be mined through, and determine the dimensions of the preserved coal pillar in the fault and the layout direction of the working face, by which the data utilization has been enhanced.

Meanwhile the digitalization technology of geological results from the 3-D seismic exploration has been greatly developed. Computer is used to compile 3-D seismic exploration reports, which results in the improvement of precision and quality of the reports, and is also favorable for dynamic analysis and usage, so that standardization and digitalization of the reports are realized.

3 Roles and Contributions of 3-D Seismics in Building High-production and High-efficiency Mines

3.1 Main geological results and their verification

Up to the end of October 2001, 150 3-D seismic

Table 1 Verification of some 3-D seismic exploration results (faults)

Name of mining area	Number of faults >5 m	Identity	Identity rate (%)	Number of faults 3–5 m	Identity	Identity rate (%)
Huainan	25	23	92	7	5	71
Yongxia	10	8	80	15	9	60
Xinzhuang, Yongcheng	7	6	86	10	7	70
Kailuan mining area	38	27	71	7	4	57
Zaozhuang, Shandong	18	14	78	2	1	50
Feicheng	10	8	80			
Zhengyang, Jixi	5	5	100			
Subtotal	113	93	82	41	26	63

exploration projects had been accomplished, among which a total of 2259 faults had been detected for 60 pairs of production mines with statistic data available. There were found 1431 faults with throw ≥5, 828 faults with throw < 5 m; 95 caved pillars and 4 zones invaded by magmatic rocks.

As to the 50 3-D seismic exploration projects in 6 mining areas of Huainan, Yongcheng etc., bottom contours of 436 coal seams were verified, among which there were 346 with relative errors less than 1.5%, accounting for 79%; 113 faults with throw larger than 5 m were verified, among which there were 93 faults identical or basically identical, accounting for 81%; 41 faults with throw of 3–5m were verified, among which there were 26 faults identical or basically identical, accounting for 63% (Table 1). A 3 m×3 m tunnel was displayed clearly in the 3-D data body (Fig. 2). Five 3-D seismic exploration projects covering an area of 7.5 km^2 were carried out by the Yangquan Bureau of Mining, in which totally 88 caved pillars with the diameter of the long axis larger than 20 m were detected. Nine caved pillars were verified by a correlation between geophysical exploration and mining for 6800 m tunnels and one ground drill in 4 extraction faces with a mining scope of 0.5 km^2, among which 7 were identical or basically identical, accounting for 80%.

3.2 Roles in the construction of modern high-production and high-efficiency mines

3.2.1 Optimizing of the mining area design and reducing the drilling rate of conveying tunnels

A total of 145 faults have been discovered and 36 faults modified in the Kailuan mining area by applying the 3-D seismic exploration, which has improved the exploration degree of the mining area, and provides reliable geological guarantee for the building of high-production and high-efficiency mines. This is not only of guiding significance for the production and optimization of the mining area design, but has also reduced the drilling rate of the conveying tunnels, thereby resulting in the raise of daily yield of the comprehensive mechanized coal mining faces and reduction of blindness in the project operation.

Besides, dynamic data interpretation has been made in the Xieqiao Coal Mine. With the accumulation of data obtained from the production, modification has been made for some structures and boundary depths. Meanwhile, a number of new faults have been interpreted, some small faults denied, the areas with coal seams getting thinner modified and the design of working faces adjusted properly, so that the layout of the comprehensive mechanized mining face is more reasonable, and the per unit area production is thereby enhanced.

3.2.2 Providing geological guarantee for the safe production of mines

3-D seismic exploration has been applied to determine the occurrence of the main mineable coal seams, the position of water-bearing pebble and gravel horizons, the boundary of super-thick crossing-boundary mined-out area of local small coal mines, geological structures and the boundary of Ordovician limestone, which provide geological guarantee for the safe production and high production and high efficiency of the mines, and mitigate losses caused by geological hazards.

3.3 Economic and social benefits

3.3.1 Making a thorough investigation of the geological structure to create enormous policy-making benefits for the construction and production of coal mines

Totally 27 caved pillars and 12 small faults have been interpreted in the 3-D seismic exploration project of the

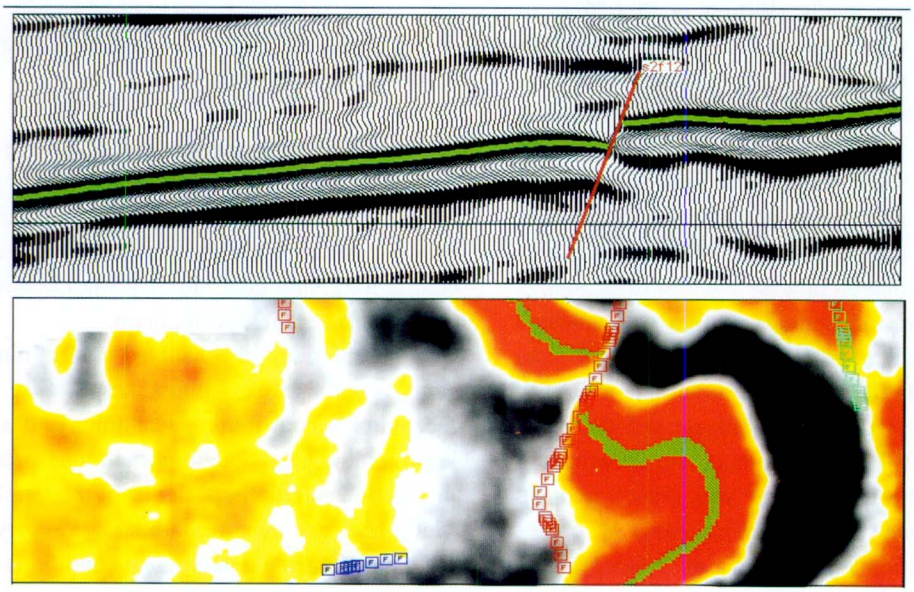

Fig. 1. A small fault on the seismic section and the seismic slice.

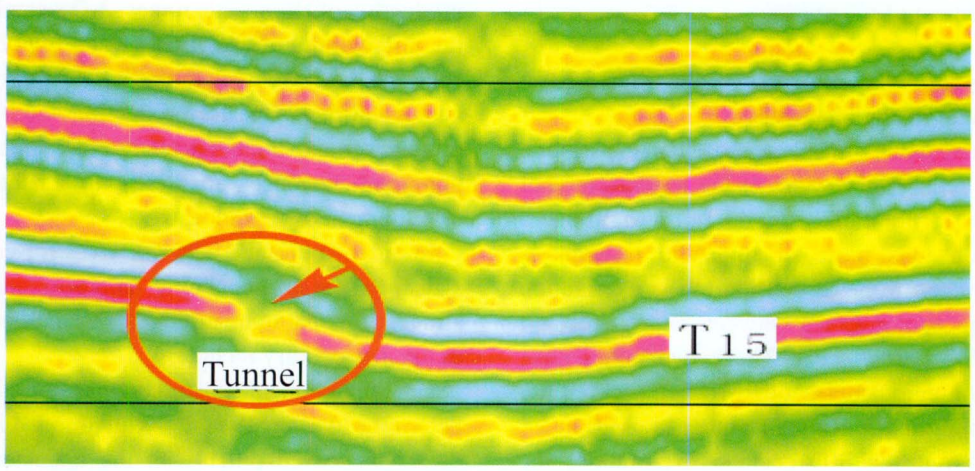

Fig. 2. The coal tunnel on the seismic section.

central mining area in the No. 5 mine of the Yangquan Coal Mine. It is thought, based on an analysis of the above results, that this area has complicated geological conditions unfavorable for arranging a comprehensive mining face while other coal mining methods feature low production, high cost and losses incurred in management. Therefore, a decision was made to give up mining in the central mining area, shorten the production line, reasonably concentrate the production and maintain the production capacity of 1.5 million tons/year. This decision reduced not only invalid investment in the central mining area, but also losses incurred in the No. 5 mine. Meanwhile, disjointing of the mining areas was avoided, and smooth operation and management of the No. 5 mine was guaranteed by shifting the operation site and enhancing exploration of the northwest mining area.

3.3.2 Adjusting and optimizing the layout of mines and mining areas to create enormous economic benefits for the coal mines

The Panxie mining area of the Huainan Bureau of Mining, based on the 3-D seismic exploration, has optimized the design of mine and mining area, extended the strike of working face from 1000–1200 m long to 2000–3000 m long, and can avoid serious geological risks for 8–10 years, which has resulted in direct and indirect economic benefits over RMB¥ 50 million per year. The additional accumulated output value for the past seven years has reached RMB¥ 640.51 million, taxes RMB¥ 83.24 million and profits RMB¥ 109.82 million. A loss of RMB¥ 0.252 billion has been avoided and an addition of 208 million tons of coal resources recovered.

The Kailuan mining area has also adopted the 3-D seismic exploration to adjust and optimize the mine and

mining area plans. As a result, drilling of 20,626 m of tunnel has been saved with a saving of investment of RMB ¥ 41 million for seven mines in the past five years.

Another example, the first mining area of the No. 4 Yangquan Mine was designed to lay in west and east directions at the north boundary of the mining area with the working face mined from south to north. It was discovered, based on the 3-D seismic exploration, that caved pillars were developed and arranged in west and east directions in the area. Therefore, the preliminary design was adjusted and modified. The annual production was adjusted from 1,200,000 tons to 900,000 tons and an investment of RMB¥ 30 million was saved. A major adjustment, with the strike changing from N-S to E-W, was also made for the layout of the working face in the first mining area, which avoided encountering the caved pillar. The meaning of proper reduction in production scale lies in reducing the investment, enhancing investment benefits; and what is more important, it lays a foundation for smooth production and good management of the mines.

3.3.3 Preserving safe coal columns reasonably to raise the utilization ratio of the resources

The Fangezhuang Mine of Kailuan, based on the seismic exploration data, reduced the width of the waterproof coal columns designed for the fault from 43–94 m to 30 m, so that 260 million tons more of mineable reserves is liberated; the Lujiatuo Mine, according to the exploration data, arranged the working face between fault zones and mined out 239,700 tons of coal. Those two mines have yielded direct economic benefits of RMB¥ 162.38 million and the utilization ratio of the mine resources raised.

After carrying out the 3-D seismic exploration, the Huajiahu Coal Mine of the Xinji Energy Company is able to set the safe coal columns accurately, so as to avoid the waste of resources caused by setting oversized coal columns, liberating 41.9 million tons of coal from the coal columns and guaranteeing safe production at the same time.

3.3.4 Choosing tunnel support method reasonably to reduce the cost

In coal mine production, cost of support for drilling tunnel constitutes a major part of mine production cost. Application of 3-D seismic exploration result to predict the distribution of fault structure in front of drilling face and choose pin timbering in the segment where there is no fault or densified pin timbering and anchor cable support in the segment where there is the fault and crack, not only reducing the support cost of the tunnel but also ensuring the safety.

4 Objectives of 3-D Seismic Exploration in the Coal Mining Area

According to the prediction of the experts, up to 2020 and 2050, the coal shall account for 68% and 50% respectively in primary energy of China. Therefore, the need of national economy's sustainable development for coal is long, and coal industry shall continue to go on the way to sustainable development.

In recent years, mechanized coal mining degree of key state-owned coal mine, especially comprehensive mechanized coal mining technology, has been obviously improved, and become important measures to realize high-production and high-efficiency of modern large-scale mine. Since coal geological conditions are very complicated in China, underground geological conditions of the mine need to be determined in detail and known accurately in order to guarantee smooth design, building and safe high-efficiency production of large-scale mines. 3-D seismic exploration in the mining area of coal mine, as an important measure of coal geological exploration, has provided important geological guarantee for production and building of high-production and high-efficiency coal mine, and is one of important technical measures to maintain sustainable development of coal industry.

In order to provide better services for coal industry and satisfy the needs of coal mine enterprise, main objectives of struggle for coal mine mining area 3-D seismic exploration in the new century include:

(1) Improvement of structural exploration precision to determine the small faults with throw bigger than 3 m, detect the caved pillar with the diameter of major axis larger than 10 m and the plane undulation error smaller than 15 m; accurate range control of effect of magmatic rock invasion, mined-out area and ancient river bed on the coal seam; accurate control of sedimentation, flushing-caused losing and thinning area of the coal seam; improvement of the resolution of coal seam group within a distance of 10–15 m.

(2) Carrying out lithological seismic exploration to widen service ranges, determination for the change of macro structure and thickness of the coal seam; providing necessary geological data for the occurrence and mining of coalbed methane; detecting the lithology of top and bottom of the coal seam; determination of water-bearing and waterproof strata at the bottom of the Cenozoic to preserve waterproof coal column for the coal mine, improving upper limit service for coal mining; accurate detecting the boundary of carbonate rock at the bottom of coal formation, division of karst and crack developed zone and water-abundant zone to liberate the mining of lower group of

coal; determination of thin limestone in coal formation strata and its water abundance.

(3) Improving the accuracy of control on coal seam depth and fault to over 90% in 3-D seismic exploration

(4) Popularizing the dynamic interpretation of mining area 3-D seismic exploration results and improving the utilization of 3-D seismic exploration result for the coal mine to solve the geological problems badly in need of being solved and finally improve the payoff of the investment in 3-D seismic exploration.

In recent years, with the continuous progresses made in mining area 3-D seismic exploration technology and improvement of exploration precision, outstanding benefits have been made in building and production of high-production and high-efficiency coal mine. But a great gap has existed between it and the requirement of modern mine for geological data. Researches on fundamental work of "three highs" (high resolution, high fidelity and high signal-to-noise ratio), extra-high resolution and lithology in 3-D seismic exploration shall be enhanced to improve the precision and ability of 3-D seismic exploration to solve geological problems; management and innovation of every technical link in 3-D seismic exploration shall be boosted, since 3-D seismic exploration is a systematical engineering, including the links of design, acquisition, processing and interpretation, and a problem in any link shall affect the whole project. Design shall be stressed, attentions paid to research on acquisition technology, application of pre-stack processing technology popularized, and lithological processing and interpretation undertaken; new and better methods shall be developed continuously for seismic exploration.

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References

China National Administration of Coal Geology, 1993. *Chinese History of Coal Geological Exploration*. Beijing: Press of Coal Industry, 429: 155–175.

China National Administration of Coal Geology, 2001. *A Collection of Papers for Exchange Meeting on Experiences of Seismic Exploration in the Coal Mining Area*. Beijing: Press of China University of Mining, 258.

Ni Bin, 2000. New progress in high-precision and high-resolution seismic exploration technique in coal industry of China. *Acta Geologica Sinica* (English edition), 74(2): 311–315.