Hydrogen sulfide occurrence states in China’s coal seams

Shengbo Yang1,2,3, Haichao Wang1,2,3, Xuehai Fu4, Jijun Tian1,2,3, Fangyu Zhao1,2,3, Ze Wang1,2,3, Pichen Sun1,2,3 and Yuzhao Cao1,2,3

Abstract
The occurrence states of hydrogen sulfide in coal seams are crucial in preventing and controlling hydrogen sulfide emission in coal mines and the safe development of coal bed methane. In this study, the research status of the occurrence states of free-state, adsorbed-state, and water-soluble hydrogen sulfide in coal seams was systematically analyzed. H2S anomaly areas in China’s coal seams are mainly located in the Carboniferous-Permian and Jurassic series of northern, eastern, central, and northwest regions of China. Bacterial sulfate reduction accounts for most of the hydrogen sulfide anomalies of low-rank coal, while thermochemical decomposition thermal desorption spectroscopy and thermochemical sulfate reduction may also result in hydrogen sulfide anomaly in medium- and high-rank coal. In contrast, magmatism-induced hydrogen sulfide anomalies are rarely found. Absorbed-state hydrogen sulfide anomalies are prevailing, while water-soluble and free-state hydrogen sulfide anomalies are relatively scarce. Coal seam’s porosity mainly controls the hydrogen sulfide adsorption, pressure, coalification degree, pore volume, and specific area, while water-soluble hydrogen sulfide is influenced by pressure, sulfate-reducing bacteria, burn, porosity, fractures, water temperature, and hydrodynamic conditions. The fractures in coal seams, their burial depth, coal quality, coal rank, roof, and floor lithology are the main factors controlling the free-state hydrogen sulfide preservation. The absorbed-state hydrogen sulfide in coal seams is mainly mitigated by varying the ventilation mode, increasing the ventilation capacity, spraying alkali fog into the air, and injecting alkali liquid into coal seams for governance.

1Xinjiang Key Laboratory for Geodynamic Processes and Metallogenic Prognosis of Central Asian Orogenic Belt, Xinjiang University, China
2School of Geological and Mining Engineering, Xinjiang University, China
3CBM Engineering Technology Research Center, Xinjiang University, China
4School of Resources and Earth Science, China University of Mining and Technology, Xuzhou, Jiangsu province, China

Corresponding authors:
Haichao Wang, School of Geology and Mining Engineering, Xinjiang University, Room 601 of Building No. 1, No. 1230 of Yan’an Road, Urumqi, Xinjiang Uygur Autonomous Region 830047, China.
Email: wangxiaoshi2111@163.com

Xuehai Fu, Key Laboratory of Coalbed Methane Resource and Reservoir Formation Process, Ministry of Education, South Jiefang Road, Xuzhou, Room 337, Jiangsu Province 221008, China.
Email: fuxuehai@163.com

© The Author(s) 2021
DOI: 10.1177/01445987211033453
journals.sagepub.com/home/eea
Introduction
Hydrogen sulfide (H$_2$S) is one of the most harmful components of coal mine gas. With increased coal mining development scale and depth in recent years, the H$_2$S emission in coal seams has become a serious threat to coal production safety (Lin et al., 2012). On the other hand, mining of high-sulfur coal at increasing burial depths aggravates hazards related to H$_2$S emission (Chou, 2012; Fu et al., 2011; Liu et al., 2012, 2019). In particular, of China, with its prevailing coal-fired power generation, the occurrence state of H$_2$S in coal seams has become very topical.

There exist a variety of occurrence states of H$_2$S in coal seams. Free-state H$_2$S generally exists in coal seams with well-developed fractures, weak hydrodynamic forces, and compact surrounding rocks. The adsorption-state H$_2$S is adsorbed on the inner surface of coal seams’ pores and fractures. Water-soluble H$_2$S is found in coal seam water. In case of water inrush accidents, high-concentration H$_2$S, due to its high solubility, can get into the tunnel with the mine water, triggering secondary disasters and jeopardizing miners’ safety. Tan et al. (2020) conducted an in-depth survey on the causes, distribution, prevention, and control measures of H$_2$S in China’s coal seams, including the H$_2$S harmful impact on the environment and health. Deng et al. (2019a) introduced the prevention and control technology of H$_2$S in coal-bearing strata, airflow in tunnels, and underground water bodies, and analyzed the efficiency of different ventilation systems in the prevention and control of H$_2$S, and systematized the main treatment methods, commonly used alkaline reagents and additives, and the major bottlenecks in this problem’s solution. This survey presents the development history and research results on free-state, adsorbed-state, and water-soluble H$_2$S, which are systematized in terms of distribution characteristics, formation genesis, occurrence state, and development trend of H$_2$S occurrence in China’s coal seams. The present study aims to provide insightful guidance for the prediction and treatment of H$_2$S in coal mines.

Geneses of H$_2$S anomaly in coal seams
Overall, anomalous enrichment of H$_2$S in coal seams can be classified into three states: free-state, adsorbed-state, and water-soluble ones. The formation mechanisms mainly include biogenic formation, thermochemical formation, and magmatism (Berner, 1984; Chambers and Trudinger, 1979; Dai et al., 2002; Zhang et al., 2005). To be specific, the biogenic formation refers to bacterial sulfate reduction (BSR), while the thermochemical formation mainly refers to thermochemical decomposition (thermal desorption spectroscopy (TDS)) and thermochemical sulfate reduction (TSR) (Zhang et al., 2007, 2008).

BSR can be regarded as the main biogenic origin of H$_2$S in coal seams. The occurrence of BSR activity should satisfy the following three basic conditions: availability of organic matter, sulfate, and sulfate-reducing bacteria (SRB) (Huang et al., 2016; Simonton and King, 2013). The anaerobic environment for the occurrence of the reduction is favorable for the storage and aggregation of H$_2$S. Accordingly, BSR or BSR-including mixed causes can mainly account for H$_2$S anomalies in China’s coal seams. The abundance of BSR-induced H$_2$S is generally <3%. Additionally, the formation medium condition should be suitable for the growth and reproduction of SRB (Amrani et al., 2008; Asaoka et al., 2018; Machel, 2001; You et al., 2009). Given this, BSR usually occurs in shallow coal seams.
Thermochemical formation mainly includes TSR and TDS. The former one is the main factor controlling the formation of anomalous H$_2$S enrichment. High temperatures (exceeding 150 °C), sufficient organic matter, and sulfate are three basic conditions required for TSR. Spontaneous combustion of coal rock can directly affect the production of H$_2$S in the TSR process. After being heated or baked to high temperatures, sulfur in the coal rock is partly oxidized to SO$_2$ and partly dissolved in water to form sulfate, providing conditions for TDS and TSR to form H$_2$S. The concentration of TDS-generated H$_2$S is generally <2% (Sośnicka and Lüders, 2020; Vengosh et al., 2014; Zhang, 2007; Zhang et al., 2008).

Magmatic activities melt the rocks in the deep crust, and the generated volatile components, including H$_2$S, enter into the coal seams after degassing separation. Therefore, the content of H$_2$S under magmatism mainly depends on the magma constitutes and gas migration conditions, being very unstable. Furthermore, the formation's H$_2$S can be preserved only under certain reservoir conditions (Wu et al., 2013).

The factors in coal seams that can affect the concentration of H$_2$S include the total sulfur content in the coal, SRB, reservoir pressure, coalification degree, hydrodynamic condition, and the spontaneous combustion of coal rocks. Further identification of genetic types of H$_2$S in coal seams should consider various factors, including coal-forming environment, thermal evolution history of coal rocks, the constituting characteristics of C and S isotopes, and gas components.

According to the National Coal Board coal classification standard (Spears et al., 1999), coal with a total sulfur content exceeding 2.5% is considered a high-sulfur coal. Besides, coals with H$_2$S concentrations exceeding 1000 ppm referred to as high-concentration H$_2$S anomalies. While most coal seams in East China fall into high-sulfur coal classification, high-sulfur Fenghuangshan and Tiexin Coal Mines in North China contain mostly medium- and low-concentration H$_2$S anomalies. In contrast, among the Longtan Coal Mine, Binlang Coal Mine, and Guang’an Coal Mine in Southwest China, the first two mines have high-sulfur coals and high-concentration H$_2$S anomalies, while the latter has medium-concentration one. In general, the H$_2$S concentration in high-sulfur coals significantly exceeds those in medium- and low-sulfur coals, reaching as high as 57.14%.

Noteworthy is that pyrite is one of the common metal minerals in coal seams, and H$_2$S is the basic condition for generating coal seam pyrite. Due to the aggressive chemical properties of H$_2$S, iron ions are susceptible to its action, forming a relatively stable sulfide–pyrite, consuming a large amount of H$_2$S in the gas reservoir. Because the valence of sulfur in pyrite is higher than that of H$_2$S, it shows the sulfur isotope of pyrite. The composition of the sulfur isotope is higher than that of H$_2$S (Zhao et al., 2021a).

Deng (2015) described the two main forms of pyrite produced by consuming H$_2$S in coal as grain-shaped and raspberry-shaped ones:

1. A grain-shaped crystal pyrite is formed by the direct precipitation of H$_2$S into raw pyrite. This occurs in a reducing environment with pH < 6.5, when the coal seam water contains sulfate-reduced saturated water-soluble H$_2$S and Fe$^{2+}$ ions, which concentrations are less than that of FeS.
2. A raspberry-shaped pyrite is formed by evolution of pyrite of complex origin. In the coal seam water environment with pH > 6.5, when the dissolved S$^{2-}$ in the coal-forming environment is relatively abundant, the organic matter can react with SO$_4^{2-}$ to form H$_2$S, and Fe$^{3+}$ is reduced to Fe$^{2+}$. At this time, Fe$^{2+}$ reacts with H$_2$S. The reaction produces FeS, which may continue to undergo several sulfide stages and eventually form a raspberry-shaped pyrite.

Deng (2015) studied the Zhunnan Coalfield and found that the measured sulfur isotope values in the study area were quite low, ranging from $-14.5%e$ to 11.6%e. Among them, the $\delta^{34}S$ value range of
Pyrite in coal was 8.7‰ to 11.6‰, with an average of 10.2‰. The $\delta^{34}$S values of H$_2$S gas in coal seams were negative and ranged from $-14.5$‰ to $-9.4$‰, with an average of $-12.3$‰. The $\delta^{34}$S value in the underground water body of the coal mine was $-0.6$‰, while the $\delta^{34}$S value measured in the crude oil of the regional boundary of Houxia was $14.17$‰. Using the above-mentioned average values of 10.2‰ and $-12.3$‰, the total $\delta^{34}$S value could be assessed as $\delta^{34}$S$_{pyrite} - \delta^{34}$S$_{H_2S} = 10.2 - (-12.3) = 22.5 > 22$‰. Thus, the regional H$_2$S gas generally exhibited the characteristics of BSR genesis.

Wen (2018) conducted an in-depth study of the Huayingshan mining area and reported that most coal fields had H$_2$S content above 2%, being high H$_2$S reservoirs. The sulfur isotope value distribution range was mostly between +10‰ and +15‰. According to the relationship between the content of H$_2$S of different genetic types and the $\delta^{34}$S value, H$_2$S in this region has the characteristics of TSR origin.

**Distribution characteristics of H$_2$S anomaly areas in the coal seams**

From China’s coal mines with proven H$_2$S geneses, a comprehensive analysis of the formation of H$_2$S anomaly coal mines revealed that BSR was the main factor controlling the anomalous enrichment of H$_2$S, among H$_2$S abnormal coal mines, the share of pure BSR-induced ones was 42.31%, while shares of BSR/TSR and BSR/TDS/TSR ones in mixed BSR-related cases were 19.23% and 7.69%, respectively, as shown in Figure 1. It can be observed that the anomalies of free-state H$_2$S and adsorbed-state H$_2$S have coincident formation geneses, namely, BSR, magmatism, TSR, and the mixed BSR/TSR and BSR/TDS/TSR causes. Except for magmatism, the anomaly of watersoluble H$_2$S shows almost the same formation geneses with free-state and adsorbed-state H$_2$S anomalies.

Figure 1. Geneses of hydrogen sulfide (H$_2$S) anomalous enrichment in China’s coal seams.
As shown in Table 1 and Figure 2, H₂S anomaly areas in China’s coal seams are mainly distributed in Inner Mongolia, Hebei, and Shanxi in North China, Shandong in East China, Sichuan and Chongqing in Southwest China, Xinjiang, Shaanxi, and Ningxia in Northwest China, and Henan and Hunan in Central China. H₂S anomaly areas in coal seams are mainly found in Carboniferous-Permian and Jurassic coal series. In terms of anomaly genesis, BSR can primarily account for H₂S anomaly in China, followed by the mixed genesis, while magmatism is rarely found (see Figure 1). As listed in Table 1, BSR genesis is mainly responsible for H₂S anomalies in North and Northwest China. In contrast, H₂S anomalies in East and Southwest China were formed mainly under magmatism and TDS (see Table 1).

In terms of occurrence state, as shown in Table 1, H₂S in China’s anomalously coal seams exists in the adsorbed state; free-state H₂S is relatively common in East and North China, while water-soluble H₂S is scarce. H₂S in free and water-soluble states is rarely found in Southwest China. In contrast, in Northwest China, H₂S anomaly coal seams contain H₂S in the adsorbed, water-soluble, and free states.

H₂S anomalies in China are present in low-, medium-, and high-rank coal seams. However, these coal seams differ in coal type among different regions. Specifically, H₂S anomaly coal seams in East China are mainly composed of gas coal, as shown in Table 1. H₂S anomaly coal seams in Southwest China are mainly composed of fat coal, coking coal, and anthracite, while those in Northwest China are mainly composed of lignite, long flame coal, non-caking coal, gas coal, and gas-fat coal.

Figure 2. Distribution of hydrogen sulfide (H₂S) anomaly areas in China’s coal seams, with account of findings of Tang et al., 2015 and Liu et al., 2019.
Table 1. Distribution characteristics of H₂S anomalous areas in China’s coal mines.

| Region         | Coal mining area                  | H₂S genesis | Occurrence state          | Geological age | Stratum     | Coal rank | Anomalous concentration (ppm) | Total sulfur content (%) | Anomaly concentration scale | References |
|----------------|-----------------------------------|--------------|----------------------------|----------------|-------------|-----------|-------------------------------|----------------------------|--------------------------|------------|
| East China     | Bayi Coal Mine                    | Magmatism    | Free state/adsorbed state  | C              | Taiyuan formation | Gas coal | 1500.00                        | 2.68                        | High         | (Jiao et al., 2013) |
|                | Cuizhuang Coal Mine               | Magmatism    | Free state/adsorbed state  | C              | Taiyuan formation | Gas coal | 3500.00                        | 2.59                        | High         | (Jiao et al., 2013) |
| North China    | Xiqu Coal Mine                    | BSR          | Adsorbed state             | C              | Taiyuan formation | Coking coal | 300.00                         | 1.37                        | Medium       | (Jiao et al., 2013) |
|                | Fenghuangshan Coal Mine           | BSR          | Adsorbed state             | C              | Taiyuan formation | Anthracite | 800.00                         | 3.21                        | Medium       | (Jiao et al., 2013) |
|                | Wuda Coal Mine                    | BSR          | Free state/adsorbed state  | C              | Taiyuan formation | Coking coal | 400.00                         | 2.32                        | Medium       | (Jiao et al., 2013) |
|                | Tiexin Coal Mine                  | BSR/TSR      | Free state/adsorbed state  | C              | Taiyuan formation | Coking coal | 2.00–66.90                    | 2.89–2.91                      | Low          | (Wang, 2014)   |
|                | 1502 Belt Roadway of Wenzhuang Coal Industry | —            | Adsorbed state             | C              | Taiyuan formation | —         | 30.00–35.00                    | —                           | Low          | (Shen, 2017)   |
|                | Jinniu Coal Mine                  | —            | Adsorbed state             | C              | Taiyuan formation | —         | 437.07                         | —                           | Medium       | (Sun et al., 2015) |
|                | Panhe coalbed methane field        | BSR          | Free state/adsorbed state  | C              | Taiyuan formation | Anthracite | 13.01                          | 2.40                        | Low          | (Ye et al., 2011; Lu et al., 2018) |
|                | Huoxi Coalfield                   | TSR          | Adsorbed state             | C-P            | Taiyuan formation/ Shanxi formation | Coking coal/anthracite | 18.00–66.90 | —                           | Low          | (Yuan et al., 2015; Sun et al., 2016) |
| Southwest China| Longtan Coal Mine                 | TDS          | Adsorbed state             | P              | Longtan formation | Coking coal | 1300.00                        | 2.62                        | High         | (Jiao et al., 2013) |
|                | Guang’an Coal Mine                | TDS          | Adsorbed state             | P              | Longtan formation | Coking coal | 35.00                          | 2.74                        | Low          | (Jiao et al., 2013) |
|                | Xinwei Coal Mine                  | TDS          | Free state                 | P              | Xuanwei formation | Anthracite | 500.00                         | 0.50–1.50                      | Medium       | (Rao et al., 2020) |
|                | Binlang Coal Mine                 | —            | Free state/water-soluble   | —              | —           | One-third coke coal | 240.00                         | —                           | Medium       | (Li et al., 2018) |
|                | Huayingshan mining area           | TSR          | Free state/adsorbed state  | P              | Longtan formation | Fat coal/coking coal | 2500.00                      | 3.75                        | High         | (Wen, 2018)   |
|                | Tiechanggou Coal Mine             | BSR/TSR      | Adsorbed state/water-soluble | J              | Xishanyao formation | Lignite | 80.00                          | 0.56                        | Low          | (Jiao et al., 2013) |
|                | Xishan Coal Mine                  | BSR/TDS/TSR  | Free state/adsorbed state/water-soluble | J              | Xishanyao formation | Gas coal | 27.89–789.63                     | 0.69–3.19                      | Medium       | (Fu et al., 2015; Deng et al., 2018) |

(continued)
| Region                     | Coal mining area | H₂S genesis | Occurrence state               | Geological age | Stratum                           | Coal rank                      | Anomalous concentration (ppm) | Total sulfur content (%) | Anomaly concentration scale | References         |
|---------------------------|------------------|--------------|--------------------------------|----------------|----------------------------------|--------------------------------|-------------------------------|--------------------------|--------------------------|------------------------|
| Fukang mining area        | BSR/TDS/TSR      | Free state/ adsorbed state/water-soluble | J                | Badaowan formation/ Xishanyao formation | Long flame coal/gas coal       | 1320.00                       | 0.23–1.05                  | High                     | (Fu et al., 2015)     |
| Xiaozhuang Coal Mine      | BSR              | Adsorbed state | J                | Yan’an Formation                        | Non-caking coal                 | 80.00                         | 0.21–0.88                   | Low                      | (Liu et al., 2016)    |
| Chenghe mining area        | BSR              | Adsorbed state | C-P              | Taiyuan formation/ Shanxi formation      | Lean coal                        | 60.00                         | 2.00–3.00                   | Low                      | (Feng et al., 2016)    |
| Wudong North Coal Mine    | BSR/TSR          | Adsorbed state | J                | Xishanyao formation                     | Lignite                          | 200.00–1000.00                 | 0.35–0.73                   | Medium                   | (Feng et al., 2016)    |
| Jiangou Coal Mine          | BSR              | Free state/ adsorbed state/water-soluble | J                | Xishanyao formation                     | Long flame coal/ non-caking coal| 200.00–350.00                 | 0.40–1.76                   | Medium                   | (Ma et al., 2011; Cheng, 2014) |
| Ningtiaota Coal Mine      | BSR/TSR          | Adsorbed state | J                | Yan’an formation                        | Lignite                          | 5.00–14.00                    | 0.26–0.44                   | Low                      | (Ren et al., 2016)     |
| Yushutian Coal Mine       | BSR/BSR          | Free state/ adsorbed state/water-soluble | J                | Taliqike formation                      | Gas coal, one-third coking coal| 5.00–14.00                    | 0.26–0.44                   | Low                      | (Ren et al., 2016)     |
| Yadian Coal Mine          | BSR              | Free state    | J                | Yan’an formation                        | Long flame coal/gas coal        | 14.00                         | 0.72                         | Low                      | (Liu et al., 2020)     |
| Shuangma Coal Mine        | —                | Free state/ adsorbed state               | J                | Yan’an formation                        | Long flame coal/ non-caking coal| 15.00–60.00                   | —                            | Low                      | (Zhou and Zhou, 2017)  |
| Tingnan Coal Mine         | BSR/TSR          | Free state/ adsorbed state/water-soluble | J                | Yan’an formation                        | Long flame coal                  | 56.00                         | 0.37                        | Low                      | (Jiao et al., 2013)    |
| Shitanjing Coal Mine      | TSR              | Adsorbed state | P                | Shanxi formation                        | Coking coal                      | 50.00                         | 0.41–0.58                   | Low                      | (Zhang et al., 2011)   |
| Fukang No. 1 Mine         | —                | Free state/ adsorbed                      | J                | Badaowan formation                     | —                              | 65.00–73.00                   | —                           | Low                      | (Deng et al., 2019a, 2019b) |

(continued)
| Region                  | Coal mining area | H₂S genesis | Occurrence state | Geological age | Stratum          | Coal rank              | Total sulfur content (%) | Anomalous concentration (ppm) | Anomaly concentration scale | References                |
|------------------------|------------------|--------------|------------------|----------------|------------------|------------------------|--------------------------|-----------------------------|-------------------------------|----------------------------|
| Dongpo Coal Mine       | —                | Adsorbed state | C-P              | —              | Long flame coal/ non-caking coal | 200.00                 | —                        | Medium                       | (Niu and Li, 2015)               |
| A mine in the northeast Binchang mining area | BSR          | Free state/ adsorbed state | J                 | Yan’an formation | Weakly caking coal | 160.00                 | 0.24–3.75                | Medium                       | (Liu et al., 2017)               |
| Cuijagou Coal Mine     | BSR              | Adsorbed state | J                 | Yan’an formation | Taiyuan formation/ Shanxi formation | 8.50                   | —                        | Low                          | (Liu, 2020)                   |
| Shanyang Coal Mine     | —                | Adsorbed state/ water-soluble | C-P              | Taiyuan formation/ Shanxi formation | —                    | 12.00                   | —                        | Low                          | (Song et al., 2016)             |
| Changcheng No. 1 Mine  | —                | Free state/ adsorbed state | —                | —              | —                | 1220.00                 | —                        | High                         | (Song et al., 2014)             |

—: No valid data are available; H₂S: hydrogen sulfide; BSR: bacterial sulfate reduction; TDS: thermal desorption spectroscopy; TSR: thermochemical sulfate reduction; C: Carboniferous; C-P: Carboniferous-Permian; P: Permian; J: Jurassic.
Based on the concentration of H$_2$S in coal gas, H$_2$S anomalies can be subdivided into high-concentration (>1000 ppm), medium-concentration (100–1000 ppm), and low-concentration (6.6–100 ppm) ones. Most of China’s H$_2$S abnormal coal seams are medium- and low-concentration ones, while high-concentration H$_2$S anomalies are scarce. The H$_2$S anomaly concentration scale is related to H$_2$S genesis. As shown in Table 1, the H$_2$S anomaly concentration scale in coal seams nationwide is dominated by medium- and low-concentration anomalies, while high-concentration ones are relatively rare. The abnormal concentration scale is related to the origin of H$_2$S. The total sulfur content and abnormal concentration scale of H$_2$S related to BSR and TSR are lower, while those related to magmatism are generally higher. In general, the total sulfur content and abnormal concentration scales in high-rank coals are generally higher than those in middle- and low-rank ones, and the total sulfur content and H$_2$S concentration exhibit a pronounced positive correlation (Figure 3). For example, in North China, anthracite coals generally have higher total sulfur content and abnormal concentration scale coking coals, with several exceptions. The first one is the Fenghuangshan Coal Mine: although its total sulfur content is as high as 3.21%, its abnormal concentration scale is only moderately abnormal, not reaching a high-concentration anomaly level. The second one is the Xinwei Coal Mine, although its coal rank is anthracite, its total sulfur content is not high. The medium-rank coal (including fat coal and coking coal), with high total sulfur content and anomaly concentration, prevails in Southwest China (Zhao et al., 2021b). Coal seams in Northwest China mainly contain low- and medium-rank coals, including lignite, long flame coal, non-caking coal, gas coal, and gas-fat coal, with low and medium total sulfur content and anomaly concentration.

![Figure 3](image.png)

**Figure 3.** The relationship between total sulfur content in coal and hydrogen sulfide (H$_2$S) concentration.
Free-state H$_2$S occurrence

Free-state H$_2$S is generally found in coal seams with well-developed fractures and weak hydrodynamic conditions. Besides, coal seam roofs and floors, as the overlying rocks, are compact in lithology. Numerous researchers have revealed dependencies between tectonic activities, burial depth, coal quality, and free-state H$_2$S via field measurements and numerical simulations. Gas-collecting bags are commonly used to collect coal bed methane (CBM) samples with free-state H$_2$S. After being separated by the chromatographic column, H$_2$S is combusted in the reaction kettle. The combustion products react with ozone, and the amplification reaction produces chemiluminescence, which is detected by a photomultiplier. Accordingly, the content of H$_2$S in a CBM sample can be analyzed in the data analysis module. This method is quite expensive and involves potentially harmful oxidizing agents, such as ozone (Cheng et al., 2013).

By performing in-situ measurements and numerical simulations on the content of H$_2$S in coal seams, Fu et al. (2015) revealed the effects of burial depth and coal quality on H$_2$S in coal seams of the Xishan Coal Mine, Xinjiang, China. They reported that the H$_2$S content was in negative correlation with the contents of CBM, CH$_4$, CO$_2$, and N$_2$. Besides, the content of H$_2$S was also in negative correlation with moisture (Figure 4(a)) and ash yield (Figure 4(b)), and in positive correlation with the content of volatile yield (Figure 4(c)) and total sulfur (Figure 4(d)). However, no obvious correlation between the H$_2$S content and the coal seam burial depth was detected (Figure 4(e)). Besides, they analyzed the genesis of the H$_2$S anomaly and reported that the coal seam partly absorbed the generated H$_2$S under magmatism of diabase at the late Yanshan Orogeny in the No. 3 Coal Seam of the Bayi Coal Mine in Zaozhuang, China. The remaining free-state H$_2$S was distributed in pores and fractures of coal seams. Thus, anomaly enrichment areas of free-state H$_2$S were formed on the west side of the dry rock wall with no water or faults (Song et al., 2016).

![Figure 4](image_url)

**Figure 4.** Measured H$_2$S content versus water content (a), ash content (b), volatile matter yield (c), total sulfur content (d), and burial depth (e) in the Xinjiang Xishan Coal Mine (Liu, 2014).
Free-state H$_2$S diffusion to the coal mining tunnels is quite high; therefore, minimizing the concentration of free-state H$_2$S in tunnels is vital to ensure miners’ safety. Safe and convenient passive protective ways of reducing H$_2$S hazards in mining tunnels imply more effective ventilation methods, increased exhaust air rate, spraying alkaline fog into the air for neutralization, and wearing anti-H$_2$S masks. For example, in the +469 m B$_3$+6 fully mechanized caving face on the east wing in the Wudong Coal Mine’s western region (Gao, 2020), the mined-out area and the coal seam were above and below the working face, respectively. The measured concentration of H$_2$S in the advanced detection hole reached 14,300 ppm. H$_2$S in a free state would inevitably enter the tunnel’s return flow during the working face’s recovery process. The concentration of H$_2$S was abnormally high (~60 ppm) at the back of the working face. H$_2$S in the adsorbed state could be further desorbed into a free-state one during the coal drawing process, increasing the latter’s concentration and jeopardizing underground workers’ safety. The tunnel was ventilated with a 754.8 m$^3$/min ventilation capacity to mitigate this problem, which dropped the concentration of H$_2$S in the working face below 28 ppm. Besides, workers were obliged to wear anti-H$_2$S masks for more effective personal protection. Another example is the Baozigou Mine in Gansu Jingchuan County, which is a low-concentration H$_2$S anomaly coal mine (Jia et al., 2018). Before the treatment, the concentration of H$_2$S in the working face was 90 ppm, which far exceeded the safety limit of 6.6 ppm. Some protective measures, such as spraying the alkaline liquid and improving the ventilation condition, were recommended to reduce the concentration of H$_2$S to below 6.6 ppm. On the one hand, to avoid the appearance of large-vortex core regions in the working face, the air cylinder could be shifted by 3 m from the working face to ensure the migration of H$_2$S toward the sidewall of the tunnel with the airflow rather than being taken to the vortex region. On the other hand, three high-pressure nozzles that were originally installed for absorbing free-state H$_2$S and dust gushed from the drum during the coal cutting process could be removed, and six single high-pressure alkaline-liquid-sprayers should be reinstalled around the heading machine. As an optimal solution, two nozzles were set on the bottom of the cutting drum of the heading machine 5° toward the inside of the connecting rod, while two more nozzles were set on both sides of the front part of the heading machine at a spraying angle of 30° and 45°, respectively. The front nozzles absorbed the free-state H$_2$S desorbed from the crushed coal near the absorbing air cylinder and H$_2$S and dust in the convolutional airflow on the air return side, while the rear nozzles further purified the escaped H$_2$S and dust. After adopting the above measures, the concentration of free-state H$_2$S at a distance of 5 m from the heading machine’s driving on the air intake side was reduced below 6.6 ppm. In particular, the concentration of free-state H$_2$S on the air return side was reduced below 6.1 ppm, which satisfied the above safety requirements.

**H$_2$S in the adsorbed state**

The adsorbed-state H$_2$S is the main occurrence form of H$_2$S in coal seams. At present, the H$_2$S accumulation process is extensively explored via isothermal adsorption parallel tests, contrastive analysis, generalized gray-scale correlation analysis, and quantum chemical analysis.

Fu et al. (2011, 2015) conducted the H$_2$S isothermal adsorption parallel tests under equilibrium water conditions, which revealed that the Langmuir curve could describe the H$_2$S adsorption pattern by coal rock, i.e., the isothermal curve consisted of (i) rapid adsorption, (ii) relatively slow adsorption, and (iii) equilibrium adsorption stages, as shown in Figure 5. Moreover, the distribution of coal mines with abnormally high H$_2$S concentration was controlled by tectonic structures (Meng and Li, 2018; Shen et al., 2018; Wang et al., 2018). For instance, the Fukang Coal Mine, located in the Mesozoic folded belt of the Bogeda Mountain between the Fukang
and Yaomoshan Fractures, had H$_2$S anomaly coal seams, mainly distributed in the protruded cambered part of the thrust nappe and well-developed tectonic coal regions. Similarly, the Choumeigou Mine, the Xinlong Mine, the Jinlong Mine, and the Kanglong Mine with H$_2$S anomaly were located in the protruded cambered part in the middle thrust nappe, which were closed inverted anticline structures. The coal seams with high-concentration H$_2$S anomaly were crushed, and gas escaping during the coal seam lifting process provided space for later adsorption of H$_2$S. The coal seams were confined by the Nanchi steel reservoir fault, the Choumeigou reverse fault, the Ganhezi reverse fault, the Wugonggou fault, and the Xiaolongkou reverse fault. Accordingly, the late-adsorbed H$_2$S was confined, which led to anomalous enrichment of absorbed-state H$_2$S in the coal seams.

Some scholars also carried out mercury injection tests and isothermal adsorption tests under equilibrium water conditions and analyzed the adsorption rules of H$_2$S by coal at different ranks (He et al., 2015; Xue et al., 2016, 2017). It was found that pressure and coal rank were the main factors influencing the H$_2$S-adsorbing capacity of coal. As shown in Figure 6, coal’s H$_2$S-adsorbing capacity increased with pressure and the degree of coal metamorphism. Besides, H$_2$S adsorption by coal also depended on the pore distribution characteristics of the coal sample. A larger number of micro- and transition pores contributed to the adsorption of H$_2$S by coal, while medium and large pores were unfavorable for the adsorption (Cheng et al., 2017; Guo et al., 2007; Luo et al., 2014).

Lin et al. (2017) and Zhang (2018) analyzed the effects of coal seam’s thermal evolution temperature, adsorption characteristics, pore characteristics, total sulfur content, and the reducibility index on anomalous H$_2$S enrichment. They elaborated a method of quantitative determination of

![Figure 5. Isothermal adsorption curve of hydrogen sulfide (H$_2$S) by coal at 30 °C: rapid adsorption, slow adsorption, and equilibrium stages (He et al., 2015).](image)
the generalized relation degree of various factors. The effect of the studied factors on anomalous 
H2S enrichment was ranked in the decreasing order as follows: the reducibility index, the 
content of total sulfur, the adsorption constant, evolitional thermal temperature, the Brunauer–
Emmett–Teller (BET) specific surface area, and the burial depth. Further analysis revealed that 
large fractional dimensions, more complex pores, uneven surface, high looseness degree, large spe-
cific area, and large adsorption constant promoted the adsorption of H2S in coal seams, causing 
high-concentration anomaly of adsorbed-state H2S. Besides, it was found that the adsorption of 
H2S positively correlated with the content of total sulfur, so that the latter could be used for 
roughly evaluating the adsorbing capability of H2S in the research area.

Liang et al. (2016) analyzed the adsorbed H2S characteristics of coal surfaces via quantum chem-
ical analysis. They established the molecular model of H2S-containing coal surface in Tiexin, 
Shanxi, to assess the adsorption energy of H2S and CH4 by coal surface molecules (Bertoncini 
et al., 2000; Yang et al., 2002). It was found that under the co-existence condition of H2S and 
CH4, the adsorption energy values of H2S and CH4 by coal were 2.230 and 94.861 kJ/mol, respec-
tively. Therefore, the coal seam’s adsorption of CH4 exceeded that of H2S, so that the former 
process inhibited the latter one. Through calculation, the adsorption energy of the mixed gas 
exceeded the sum of the individual adsorption energy values of the single gas with the same 
numbers and kinds, suggesting that coal’s adsorption capability of the H2S/CH4 mixed gas far 
exceeded the adsorption of a single gas. Therefore, H2S promoted the adsorption of CH4 by the 
coal seam.

Based on the occurrence characteristics of adsorbed-stated H2S in the coal seam, some active 
measures such as advanced detection, coal seam pressure-difference pre-drainage H2S, and

Figure 6. Maximum reflectivity of the vitrinite versus hydrogen sulfide (H2S) adsorption by coal (He et al., 
2015).
spraying alkaline liquid for the neutralization of \( \text{H}_2\text{S} \) can be applied. Since active prevention and treatment should always consider the coal seams’ occurrence condition and the mining technologies, they are expensive and problematic. The Gaojiabao Coal Mine was used as a case study by several researchers (Dai et al., 2002; Wu et al., 2016; Xu, 2020); the concentration of \( \text{H}_2\text{S} \) in the No. 4 coal seam was \( \sim 50 \text{ ppm} \). The adsorbed-state \( \text{H}_2\text{S} \) in coal seams could be easily disturbed and spread into the air. The recommended measures for controlling the adsorbed-state \( \text{H}_2\text{S} \) in the coal seams were reduced to drilling the coal seam surface for advanced detection of \( \text{H}_2\text{S} \) before mining, followed by the injection of alkaline liquid in the \( \text{H}_2\text{S} \) anomaly regions of the coal seam for the neutralization of \( \text{H}_2\text{S} \). Moreover, to enhance the treatment performance, the corresponding alkaline injection amount could be assessed by the distribution characteristics of \( \text{H}_2\text{S} \) content in the coal seams (Zhang et al., 2020). Given the neutralization capability, treatment efficiency, cost, and equipment structure, \( \text{NaHCO}_3 \) was a lucrative alkali-injection solute. The analysis of physical properties of coal seams in the Gaojiabao Coal Mine, operation safety, the requirement on drilling equipment, and the final hole sealing difficulty and degree revealed that a drilling hole with a 65 mm diameter provided the optimal solution. When the overall drilling length exceeded the coal seam width, the overflow induced by excessive alkaline liquid amount could be effectively avoided. Based on the working face length, the drilling depth was set at 80 m. Before injecting the alkaline liquid, the airflow’s \( \text{H}_2\text{S} \) concentrations in the working face and the air return ways reached 30 and 40 ppm, respectively. After the injection of alkaline liquid, they were reduced to 11 and 22 ppm, i.e., by 60% and 50%, respectively, which implied a good governance effect.

**Water-soluble \( \text{H}_2\text{S} \)**

Liu (2014) pointed out that the burned areas in the coal mines at the southeast margin of the Junggar Basin included well-developed fractures: the surface water seeped through burnt rocks forming underground water storage units. Under the spontaneous combustion of coal seams, the sulfur in the coal was partly oxidized to \( \text{SO}_2 \); the latter was dissolved in water, forming sulfate ions, which were then decomposed to produce \( \text{H}_2\text{S} \) under TDS and TSR mechanisms. The generated \( \text{H}_2\text{S} \) gas could be dissolved in the coal seams of burnt rocks or driven away by the underground water, thereby forming water-soluble anomalous \( \text{H}_2\text{S} \) enrichment areas in the regions with poorly developed burnt rocks or favorable water-resisting layers (Cai et al., 2009; Su et al., 2017). Deng et al. (2017, 2018, 2020) analyzed mineral (underground) water characteristics at the southeast margin of the Junggar Basin and \( \text{H}_2\text{S} \) genesis. They revealed the co-existence of large content of \( \text{H}_2\text{S} \) with water in the coal seams. Moreover, the \( \text{H}_2\text{S} \) content positively correlated with the \( \text{CO} \) content and pressure value. No correlation between the \( \text{H}_2\text{S} \) content and the coal seam burial depth was detected, as shown in Figures 7 and 8.

Generally, \( \text{CH}_4 \) in water has a form of a water-soluble gas with quite stable properties. When water is abundant in SRB, the latter can use \( \text{CH}_4 \) in water as a sulfate for reductive dissolution of a hydrogen donor, producing \( \text{H}_2\text{S} \) under dissimilation and promoting the reaction between \( \text{CO}_2 \) in water and soluble \( \text{Ca}^{2+} \) ions to form calcium carbonate crystals. BSR reaction is a kind of exothermic reaction. High temperature can suppress the forward reaction; therefore, the decline in water temperature is favorable for the production of \( \text{H}_2\text{S} \), and simultaneously more \( \text{CH}_4 \) can be consumed (Song et al., 2017). Consider a particular case: the southern margin of the Junggar Basin contained coal with a great amount of carbonate, sulfate, and abundant organic matter. The No. 4 spring showed declining temperature year by year, leading to constant consumption of \( \text{CH}_4 \) and increasing \( \text{H}_2\text{S} \) and \( \text{CO}_2 \) contents. Moreover, the content of positive \( \text{Ca}^{2+} \) ions in confined water at deep coal mines dropped, and burn-in regional coal rocks mostly occurred in the
shallow part. A limited amount of H$_2$S was produced under TDS and TSR. These hydrochemical characteristics strongly indicated that active BSR action was the principal cause of the anomaly concentration of water-soluble H$_2$S in this region (Deng et al., 2018).

Water-soluble H$_2$S can generally be governed via sealing, dredging drainage, and spraying lime powder into the water gushing port. The following analysis was performed by taking the Huayingshan Mine and the Xishan Coal Mine in Urumqi as examples. On account of the karst landscape and complexly developed underground rivers, the maximum water inflow in the Huayingshan Mine reached up to 200,000 m$^3$/h (Lei et al., 2011). Moreover, H$_2$S escaped from fractures and could be dissolved in water. The aquifer in coal seams was close to the coal seam, triggering

Figure 7. Hydrogen sulfide (H$_2$S) and CH$_4$ contents versus drilling hole depth in Xinjiang Xishan Coal Mine (Deng et al., 2018).
water inrush accidents and bringing a great threat to safety production. Some sealing and dredging drainage measures were recommended to prevent the potential hazard caused by the prevention of water-soluble H$_2$S. Multi-component composite grouts (including barite powder, bentonite, and sodium carboxymethyl cellulose binder) were the most lucrative for sealing pores and fractures in the coal seams, isolating water, and achieve the goal of sealing water-soluble H$_2$S. Next, water-soluble H$_2$S could be dredged and discharged to the specified positions, and lime or alkaline liquid would be sprayed for neutralization. Insofar as the Xishan Coal Mine had a moderate water inrush of about 924.43 m$^3$/h and high content of H$_2$S in the water of 38 ppm (Fu et al., 2015), it was recommended that lime or alkaline liquid should be periodically sprayed into water gushing port for prevention. The tunnel should also maintain regular water discharge to prevent gas dissolution in water and reduce the hazard risks.

**Prospects**

Due to the limitations of available experimental and calculation techniques, the main research efforts have been focused on the occurrence state of adsorbed-state H$_2$S in coal seams. However, the occurrence states of free-state and water-soluble H$_2$S are also topical, insofar as free-state and water-soluble H$_2$S is more inclined to rush and leak, causing enormous potential safety hazards to safety production. Scholars can improve the sampling techniques and the current methods and explore innovative theories in the future to reduce the potential risks. Firstly, the sampling schemes of free-state and water-soluble H$_2$S can be enhanced in terms of occurrence to explore more targeted sampling techniques. Secondly, the existing dissolved quantity measurement methods should be refined. For example, physical extraction or reactive precipitation method can be
considered for enhancing measurement accuracy. Thirdly, some portable devices for non-contact rapid on-site measurement and the analysis of H$_2$S content of collected water and gas samples should be developed to acquire first-hand information at the site under the premise of ensuring personnel safety. Fourthly, the physical properties of coal seams on the storage and migration of H$_2$S-containing coal-water should be investigated in depth. Fifthly, the effects of hydrodynamic and fire-burning conditions on acidic gas generation and storage mechanism should be clarified. Finally, the difference in sulfur utilization capability of different ranks of coals by SRB under the same hydrodynamic conditions should be examined in detail. However, most available active or passive H$_2$S prevention techniques can only be regarded as local prevention measures. There is still a large gap between safety in a coal mine and high-efficiency mining. In future studies aiming to establish comprehensive and efficient H$_2$S prevention techniques, more fundamental research efforts should be made to develop economical, safe, and high-efficiency H$_2$S absorbents for particular site conditions.

**Conclusions**

1. High-concentration H$_2$S coal seams in China’s coal seams are mainly found in the Carboniferous, Permian, and Jurassic series, located in Xinjiang, Shandon, Hebei, Henan, Shanxi, Hunan, Sichuan, Shannxi, Ningxia, and Inner Mongolia. BSR genesis plays a dominant role in H$_2$S anomalies (mainly medium- and low-concentration H$_2$S anomalies). H$_2$S anomaly mainly exists in adsorbed states, while H$_2$S anomalies in water-soluble and free states are relatively scarce.

2. Free-state H$_2$S generally exists in the coal seams with developed fractures and weak hydrodynamic conditions. Both roofs and floors, as the overlying layers, show compact lithological characteristics. The burial depth and coal quality can significantly affect the enrichment of free-state H$_2$S in coal seams.

3. The Langmuir curves adequately describe the adsorption characteristics of adsorbed-state H$_2$S. The maximum adsorption capacity of H$_2$S by the coal seams positively correlates with the number of transition pores and micropores, being negatively correlated with the number of medium and large pores. In terms of the effects on anomaly enrichment of adsorbed-state H$_2$S, the reducibility index ranks the first, followed by total sulfur content, the adsorption constant, the thermal evolution temperature, the BET specific area, and the burial depth.

4. In coal seams, the reduction of water temperature can promote BSR reaction for the production of H$_2$S, and the coal fire area in the shallow seam is conductive to TDS or TSR reaction. Anomaly enrichment areas of water-soluble H$_2$S are easily formed in the regions with poorly developed burnt rocks or favorable water-resisting layers.

5. Some measures can be adopted for the prevention of H$_2$S in coal mines. In terms of free-state H$_2$S, such measures include: changing the ventilation mode to a more effective one, increasing the exhaust air rate, spraying alkaline fog into the air for neutralization, and wearing anti-H$_2$S masks to reduce the hazard. In terms of adsorbed-state H$_2$S, the most effective would be the advanced detection, pressure-difference pre-pumping H$_2$S, and spraying alkaline liquid for neutralization. In terms of water-soluble H$_2$S, the above measures can be reduced to sealing, dredging, and spraying lime powder at the water gushing port for governance.

6. More research efforts should be focused on free-state and water-soluble H$_2$S, the improvement of sampling techniques, experimental methods, and the development of relevant innovative theories to reduce the H$_2$S-related safety risks.
Declaration of conflicting interests
The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study was sponsored by the National Natural Science Foundation of China (grant nos. 41902171 and U1903303), the Natural Science Foundation of Xinjiang Uygur Autonomous Region (2018D01C050), the Scientific Research Program of the Higher Education Institution of Xinjiang (XJEDU2018Y014), and the 2017 PhD Research Startup Foundation of Xinjiang University (BS180256).

ORCID iD
Haichao Wang https://orcid.org/0000-0001-7830-6139

References
Amrani A, Zhang TW, Ma QS, et al. (2008) The role of labile sulfur compounds in thermochemical sulfate reduction. Geochimica et Cosmochimica Acta 72(12): 2960–2972.
Asaoka S, Jadoom WA, Ishidu T, et al. (2018) Removal of hydrogen sulfide with granulated coal ash under aerobic and anaerobic conditions. Journal of Environmental Chemical Engineering 6(4): 4665–4670.
Berner RA (1984) Sedimentary pyrite formation: An update. Geochimica et Cosmochimica Acta 48(4): 605–615.
Bertoncini C, Odetti H and Bottani EJ (2000) Computer simulation of phenol physisorption on graphite. Langmuir 16(19): 7457–7463.
Cai CF, Li KK, Anlai M, et al. (2009) Distinguishing Cambrian from Upper Ordovician source rocks: Evidence from sulfur isotopes and biomarkers in the Tarim basin. Organic Geochemistry 40(7): 755–768.
Chambers LA and Trudinger PA (1979) Microbiological fractionation of stable sulfur isotopes: A review and critique. Geomicrobiology Journal 1(3): 249–293.
Cheng QH, Liang W, Wei ZJ, et al. (2013) A method and device for detecting sulfide content in coalbed methane. China Patent: CN103175825A.
Cheng YP, Jiang HN, Zhang XL, et al. (2017) Effects of coal rank on physicochemical properties of coal and on methane adsorption. International Journal of Coal Science & Technology 4(9): 129–146.
Cheng YX (2014) Comprehensive control for H2S abnormal emission in B1+2 coal seam of Jiangou mine east wing. Safety in Coal Mines 45: 135–137 (in Chinese with English abstract).
Chou CL (2012) Sulfur in coals: A review of geochemistry and origins. International Journal of Coal Geology 100: 1–13.
Dai SF, Ren DY, Tang YG, et al. (2002) Distribution, isotopic variation and origin of sulfur in coals in the Wuda coalfield, Inner Mongolia, China. International Journal of Coal Geology 51(4): 237–250.
Deng QG (2015) The study of genesis modes and enrichment control factors of hydrogen sulfide in Jurassic coal seam within the midst of southern margin of Junggar Basin. PhD Thesis, Henan Polytechnic University, China (in Chinese with English abstract).
Deng QG, Liu MJ, Cui XF, et al. (2017) A study of hydrogen sulfide genesis in coal mine of southeastern margin of Junggar basin. Earth Science Frontier 24(05): 395–401 (in Chinese with English abstract).
Deng QG, Wen JJ, Liu MJ, et al. (2018) Study on the formation of hydrogen sulfide in coal mines of southeastern margin of Junggar Basin based on the characteristics of spring (well) water. Journal of Henan Polytechnic University (Natural Science) 37(01): 8–14 (in Chinese with English abstract).
Deng QG, Yin JP, Wu XF, et al. (2019a) Research advances of prevention and control of hydrogen sulfide in coal mines. The Scientific World Journal 2019: 1–15.
Deng QG, Zhang T, Zhao FJ, et al. (2020) The influence of hydrogeology to generation of hydrogen sulfide of low-rank coal in the southeast margin of Junggar basin, China. Geofluids 2020: 1–10.

Deng Z, Chen ZW, Wang J, et al. (2019b) Technology of comprehensive hydrogen sulfide control technology in driving face of outburst coal seam. China Energy and Environmental Protection 41(2): 58–61 (in Chinese with English abstract).

Feng H, Chen T, Li T, et al. (2016) Analysis of genetic types and horizons of hydrogen sulfide gas in Chenghe mining area. In: 2016 academic annual meeting of Shaanxi coal society, Urumqi, Xinjiang, China, p. 4.

Fu XH, He Y, Liu XH, et al. (2015) In-situ coal seam gas H2S content influencing factors and genetic analysis in Xishan minefield, Urumqi, Xinjiang. Coal Geology of China 27(01): 28–30 (in Chinese with English abstract).

Fu XH, Liu AH, Wang KX, et al. (2011) Prevention and origin of exceptional deleterious gas compositions in coal mine. Procedia Engineering 26: 424–430.

Gao XH (2020) Study on the occurrence law and prevention technology of hydrogen sulfide in coal seam of Wudong mine. Master Thesis, China Coal Research Institute, China (in Chinese with English abstract).

Guo J, Luo Y, Lua AC, et al. (2007) Adsorption of hydrogen sulphide (H2S) by activated carbons derived from oil-palm shell. Carbon 45(2): 330–336.

He Y, Fu XH and Lu L (2015) Influencing factors of different coal ranks on H2S adsorption. Safety in Coal Mines 46(11): 149–151 (in Chinese with English abstract).

Huang LK, Wu YL, Fan KX, et al. (2016) Formation and transport mechanism of hydrogen sulfide in coal seam. Materials Science Forum 863: 149–153.

Jia NJ, Jia BS, Wang HD, et al. (2018) Study on distribution law and prevent and control technology of hydrogen sulfide in fully-mechanized driving face. Coal Science and Technology 46(12): 158–163 (in Chinese with English abstract).

Jiao CL, Fu XH, Ge YY, et al. (2013) Distribution characteristics of H2S anomaly area of coal mine gas in China. Journal of Heilongjiang Institute of Science & Technology 23(04): 375–377 (in Chinese with English abstract).

Lei CG, Cao SH and Guo P (2011) Mine water disaster prevention and control method under complicated geological conditions in Huayingshan mine. Coal Science and Technology 39(3): 104–107 (in Chinese with English abstract).

Li GR, Tang F and Li H (2018) Practice of controlling high concentration gas and water inrush disaster in Binlang coal mine. Modern Mining 34(10): 248–250.

Liang B, Qu R, Ji SW, et al. (2016) Quantum chemistry on analysis of characteristics of coal surface adsorption of H2S. Journal of Liaoning Technical University (Natural Science) 35(11): 1193–1197 (in Chinese with English abstract).

Lin H, Wei W, Wang YN, et al. (2012) Study on the rapid removal of H2S in underground coal mines. Journal of China Coal Society 37(12): 2065–2069.

Lin HF, Zhang JF, Li SG, et al. (2017) Generalized grey relational analysis on main controlling factors for abnormal enrichment of hydrogen sulfide in coal mine. Journal of Safety Science and Technology 13(06): 27–33 (in Chinese with English abstract).

Liu DJ, Wang Q, Wu J, et al. (2019) A review of sorbents for high-temperature hydrogen sulfide removal from hot coal gas. Environmental Chemistry Letters 17(1): 259–276.

Liu H (2020) Hydrogen sulfide adsorption characteristics and treatment of sulfur-bearing coal seam. Master Thesis, Xi’an University of Science and Technology, China (in Chinese with English abstract).

Liu HB, He WY and Bo J (2020) H2S occurrence conditions and genetic types of low rank bituminous coal in Binchang mining area. Coal Geology & Exploration 48: 26–33 (in Chinese with English abstract).

Liu HB, Kang WA, Yin RS, et al. (2017) Genetic types and prevention measures of H2S anomaly in low rank coal mining area. Coal Technology 36(10): 95–98 (in Chinese with English abstract).

Liu JB, Zan JC, Ma XH, et al. (2016) Research on H2S gushing characteristics and control technology in Xiaozhuang coal mine. Energy Technology and Management 41(04): 98–100.

Liu MJ, Deng QG, Zhao FJ, et al. (2012) Origin of hydrogen sulfide in coal seams in China. Safety Science 50(4): 668–673.
Liu XH (2014) Analysis of geological control factors H2S abnormal mine in Fukang mine. Master Thesis, Xinjiang University, China (in Chinese with English abstract).
Lu GJ, Wang L, Hu QP, et al. (2018) Qinnan Panhe coalbed methane field 15# coal development key problem analysis. *China Petroleum and Chemical Standard and Quality* 38(12): 140–142.
Luo JJ, Liu YE, Sun WJ, et al. (2014) Influence of structural parameters on methane adsorption over activated carbon: Evaluation by using D–A model. *Fuel* 123(may 1): 241–247.
Ma LJ, Cui HQ and Jia XL (2011) Study on geology rules of coal mine methane in Jiangou coal mine. *China Coalbed Methane* 8(01): 14–18 (in Chinese with English abstract).
Machel HG (2001) Bacterial and thermochemical sulfate reduction in diagenetic settings – old and new insights. *Sedimentary Geology* 140(1): 143–175.
Meng Y and Li ZP (2018) Experimental comparisons of gas adsorption, sorption induced strain, diffusivity and permeability for low and high rank coals. *Fuel* 234(DEC. 15): 914–923.
Niu WQ and Li XB (2015) Analysis on prevention technology of hydrogen sulfide gas in fully mechanized mining face. *Shaanxi Coal* 34(02): 119–121 (in Chinese with English abstract).
Su J, Wang Y, Wang XM, et al. (2017) Impact of formation water on the generation of H2S in condensate reservoirs: A case study from the deep Ordovician in the Tazhong Uplift of the Tarim basin, NW China. *Petroleum Science* 14(3): 507–519.
Sun Y, Ning DY, Zhang DP, et al. (2015) Component analysis of irritant gases in Jinniu mine. *Safety in Coal Mines* 46(08): 185–187 (in Chinese with English abstract).
Tan B, Shao ZZ, Wei HY, et al. (2020) Status of research on hydrogen sulphide gas in Chinese mines. *Environmental Science and Pollution Research* 27(3): 2502–2521.
Tang YG, He X, Cheng AG, et al. (2015) Occurrence and sedimentary control of sulfur in coals of China. *Journal of China Coal Society* 40(09): 1977–1988 (in Chinese with English abstract).
Vengosh A, Jackson RB, Warner N, et al. (2014) A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental Science & Technology* 2014(48): 8334–8348.
Wang BY, Qin Y, Shen J, et al. (2018) Pore structure characteristics of low- and medium-rank coals and their differential adsorption and desorption effects. *Journal of Petroleum Science & Engineering* 165: 1–12.

Wang YF (2014) Research and engineering application of hydrogen sulfide treatment by injecting lye into coal seam in Tiexin coal mine. PhD Thesis, Liaoning Technical University, China (in Chinese with English abstract).

Wen JJ (2018) The study of genesis modes and enrichment control factors of hydrogen sulfide in Huayingshan coal mining area. Master Thesis, Henan Polytechnic University, China (in Chinese with English abstract).

Wu XQ, Dai JX, Liao FR, et al. (2013) Origin and source of CO2 in natural gas from the eastern Sichuan basin. *Science China Earth Science* 56(008): 1308–1317.

Wu YL, Liu JJ and Fan KX (2016) Study on release mechanism and control technology of hydrogen sulfide gas in coal mine. *Journal of Residuals Science and Technology* 13(4): S73–S83.

Xu YQ (2020) Study on the distribution law of hydrogen sulfide in coalmine and the treatment technology in different areas. Master Thesis, Xi’an University of Science and Technology, China (in Chinese with English abstract).

Xue JZ, Fu XH, Fan CJ, et al. (2016) Adsorption and adsorption model of H2S in different coal ranks. *Coal Geology & Exploration* 44(06): 75–78 (in Chinese with English abstract).

Ye JP, Wu JG, Fang C, et al. (2011) Regional geological and reservoir characteristics of the Panhe CBM gas field in the southern Qinshui basin and their influences on CBM gas production capacity. *Natural Gas Industry* 31(05): 16–20 (in Chinese with English abstract).

Zhang JF (2018) Study on hydrogen sulfide chemical genetic types and control techniques in low sulfur coal seam. Master Thesis, Xi’an University of Science and Technology, China (in Chinese with English abstract).

Zhang SC, Zhu GY, Liang YB, et al. (2005) Geochemical characteristics of the Zhaolanzhuang sour gas accumulation and thermochemical sulfate reduction in the Jixian Sag of Bohai Bay basin. *Organic Geochemistry* 36(12): 1717–1730.

Zhang SJ, Tian SC, Liu WY, et al. (2011) On causes of mine hydrogen sulfide and comprehensive control technology. *Shaanxi Coal* 30(05): 77–79 (in Chinese with English abstract).

Zhang TW, Amrani A, Ellis GS, et al. (2008) Experimental investigation on thermochemical sulfate reduction by H2S initiation. *Geochimica et Cosmochimica Acta* 72: 3518–3530.

Zhang TW, Ellis GS, Wang KS, et al. (2007) Effect of hydrocarbon type on thermochemical sulfate reduction. *Organic Geochemistry* 38(6): 897–910.

Zhao QJ, Qin SJ, Zhao CL, et al. (2021a) Origin and geological implications of super high sulfur-containing polycyclic aromatic compounds in high-sulfur coal. *Gondwana Research* 96: 219–231.

Zhao QJ, Qin SJ, Zhao CL, et al. (2021b) Data on the sulfur-containing polycyclic aromatic compounds of high-sulfur coal of SW China. *Data in Brief* 37: 107218.

Zhou D and Zhou XJ (2017) Initial analysis and prevention technology of H2S gas source in Shuangma Coal Mine. *Shenhua Science and Technology* 15(09): 25–28 (in Chinese with English abstract).