TECHNICAL ARTICLE

The Water Resisting Properties of the Top Portion of the Ordovician Limestone Aquifer in the North China Coalfield

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Abstract

Coal mining in North China is widely threatened by underlying Ordovician karstic limestone groundwater. This study focused on the top portion of the Ordovician limestone and its water resisting properties at a mine in North China, where the total thickness of the Ordovician limestone ranges between 300 and 1600 m. A packer pump test showed the average permeability coefficient for the top portion of the limestone to be 0.57×10^{-3} m/day; laboratory tests showed that the strength of this segment was 175 Mpa. Meanwhile, the water pressure was 0 Mpa for the top 40 m of the aquifer, and only 6.7×10^{-3} Mpa for the top 41–46 m; it increased considerably between 46 and 55 m, to an average value of 0.47 Mpa, and remained stable after 55 m, with a water pressure of 0.71 Mpa. The top of the Ordovician limestone was therefore divided into weathered, transition, and karst fracture zones. Each zone has different hydrogeological characteristics (water pressure, permeability, and drilling fluid leakage). The thickness of the weathered zone was determined to be ≈ 20–70 m in most of the study area. Overall, the water resistance of the top portion of the Ordovician strata allows it to be treated as an aquifuge, preventing Ordovician groundwater from flowing into the mining face.

Keywords Mine water disaster · Water pressure · Permeability coefficient · Vertical zonation · Weathered zone

Introduction

Coal resources are abundant within the Permo-Carboniferous systems in North China, but the coal mining is widely threatened by underlying Ordovician karstic limestone groundwater (Wang et al. 2019). The Middle Ordovician limestone is a highly heterogeneous aquifer with well-developed karst fissures, high-water pressure, and abundant water (Li et al. 2019; Sun et al. 2017), making it major threat to safe mining. For example, on March 1, 2010, Ordovician limestone groundwater rushed into the working face through a karstic collapse column at the Luotuoshan coal mine, with a maximum water inflow of 60,036 m³/h, causing 32 deaths (Zhou 2017).

Until recently, the entire Ordovician limestone was regarded as an aquifer, with the water pressure at greater mining depths increasing the risk of a water inrush, making coal resources within the lower coal seams unexploitable without major grouting efforts to reinforce the water-resistance of the Ordovician limestone (Chen and Zhang 2001; Philipp et al. 1999; Orndorff et al. 2001). However, grouting the entire Ordovician limestone with clay-cement or fly ash–cement grout is very expensive. So, further study of the hydrogeological conditions of the Ordovician limestone and its water-resisting performance was necessary.

The intensity of karstification in Ordovician limestone varies significantly with depth. Wang (1992) studied the vertical zonation of karst voids below a riverbed and divided the dam foundation into three zones: a shallow, intense karst zone; a middle, moderately weak karst zone; and a lower slightly weak karst zone. Gu (1999) divided the karst below a buried hill in the Lu'an area into a vertical seepage karst zone, horizontal underflow karst zone, and a transitional zone. Chen (2000) described the karst zones as shallow

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karst, middle karst, and deep karst cave zones. Meanwhile, there has been much research on the hydrogeology of the top layer of the Ordovician limestone. Dong and Liu (2009) used different detection methods to investigate this top layer and analyzed the genesis of this section in the Lu'an coal mining area. Wang et al. (2009) determined the water-resisting properties of this top layer by theoretical analysis and experimental study. Bai et al. (2010) studied the characteristics of seepage and fault evolution history in the top layer of Ordovician limestone and concluded that it contained a carbonate aquiclude that was more than 60 m thick. Based on drilling fluid leakage and geophysical detection methods, Zhang et al. (2014) explained the characteristics of karst fissures and relative water abundance of this same layer. Liu and Wang (2015), Miao and Bai (2011), and Wang et al. (2019) have also carried out research on the water-resistance of the Ordovician limestone's top layer in North China.

Although much research has been done on the Ordovician limestone, the detailed partitioning of the top of the Ordovician limestone in North China was not clear enough to be used to prevent and control mine water disasters. Laboratory tests of rock samples had been used to understand the water resistance of the top layer of Ordovician limestone in North China (Sun et al. 2020), but few field hydrological tests had been conducted. In this study, a field investigation, in-situ hydrological tests, and laboratory testing of rock samples were used to understand: (1) the characteristics of karst development of the Ordovician limestone in North China; (2) the vertical zonation of water-bearing and water-resisting properties in a typical coal mine, and (3) the vertical zonation of the water-bearing and resisting properties of the top layer of Ordovician limestone. Determining the characteristics and water-resisting properties of the top of the Ordovician limestone could provide large benefits to safe mining in North China.

Study Area

The North China coalfield formed during the Carboniferous-Permian time period. It spans a vast area (≈ 1.1 million km^2), from the Qinling mountains in the south to the Yinshan mountains in the north, and from the Bohai and Huanghai Sea in the east to the Helan Mountains in the west, covering Shanxi, Hebei, Shandong, Henan, Anhui, Jiangsu, and Shaanxi provinces. The Upper Ordovician, Silurian, Devonian, and Lower Carboniferous are generally missing; the Carboniferous-Permian strata directly overlie the very thick Middle Ordovician limestone. The main strata under the coal seam floor mainly include the: interbedded limestone and mudstone of the Taiyuan Formation, aluminaceous mudstone of the Benxi Formation, and limestone strata of the Ordovician Fengfeng and Majiagou Formations
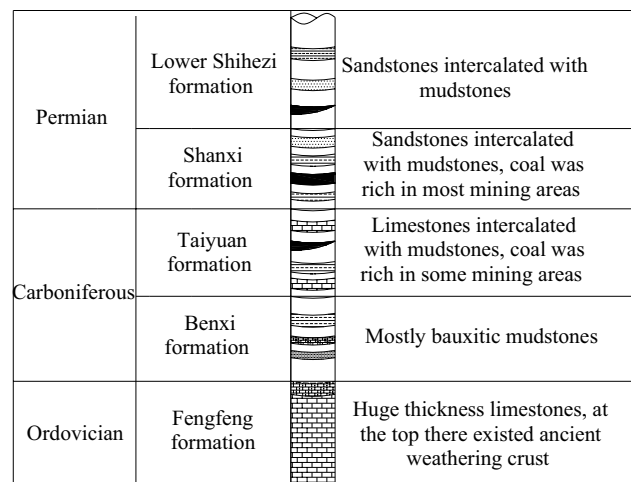

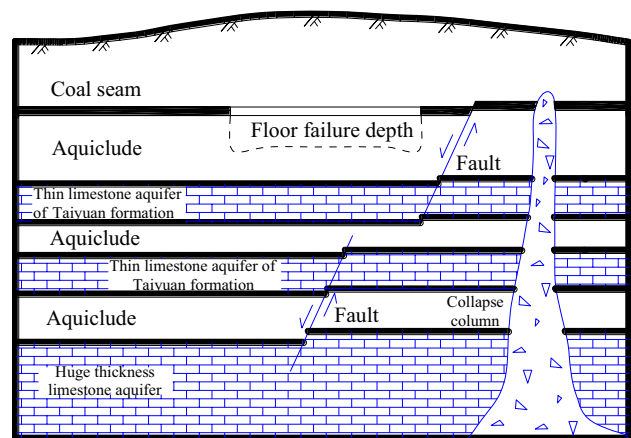**Fig. 1** Typical stratum column in the North China coal field

Fig. 2 Water-filling pattern of the coal seam floor in the North China coal field

(Fig. 1). According to the stratigraphic structure of the study area, the rock under the coal seam would be destroyed and would form the floor failure zone after coal seam stopping. The fracture zone would directly conduct water from the floor aquifers where the aquiclude was thin. At the same time, the potential faults, collapse columns, and other vertical water-flowing channels could also easily communicate water from the limestone aquifer to the coal seam, resulting in water inrush accidents (Fig. 2). In fact, the top layer of the Ordovician limestone has some dissolution holes and karst fissures because of the weathering and erosion that occurred for nearly 100 million years after the Caledonian tectonic movement. Fortunately, the karst holes and fissures were filled by extremely low permeability materials such as clay due to factors such as paleotopography, paleogeomorphology, paleoclimatology, and paleohydrology, and then compacted by the gravity loads of the overlying strata.

Therefore, the top layer of the carbonate aquifer has water-resistant properties (Wu et al. 2014).

Meanwhile, the Chengzhuang coal mine (35°34′11″–35°39′50″N, 112°36′06″–112°43′49″E), located in Jincheng city, Shanxi province, with an annual coal production level of up to 8 million t and an area of 74 km² was selected as a typical experimental site for the North China coalfield. The mean annual precipitation is 595 mm and the potential evapotranspiration is 1010 mm. More than 70% of the precipitation occurs from June to September. The thin layers of limestone (Taiyuan formation, C_3) and thick limestone strata (Fengfeng and Majiagou formation, O_2) underlying the no. 3 coal seam were the main aquifers, and those aquifers badly affected the safe production of coal. Quantities of mine water inflow ranged from 305 to 510 m³ per hour. It's worth noting that 118 faults and 185 karst collapse columns were found (Li et al. 2015) during the construction and operation of the coal mine.

Materials and Methods

A regional scale in-site investigation and data collection were carried out in 15 typical coal mines of six large mining areas in North China. Photographs were taken of the top of Ordovician Limestone for these different coal mining areas. A total of 153 boreholes, 84 geological and hydrogeological data sets, and 37 sets of technical reports were collected. For the typical coal mine (the Chengzhuang coal mine) in-situ packer pump tests and rock sample tests were used to understand the water-resistant properties of the top layer of the Ordovician limestone. The no. 5 underground borehole was drilled in the Chengzhuang coal mine roadway; the depth of the borehole was 428 m and the final horizon of the borehole was the Middle Ordovician limestone. The borehole entered the top of the Ordovician limestone at a depth of 130.5 m. The amount of drilling mud was viewed in real time during

drilling. Meanwhile, the packer pump test was conducted for no water pressure, and then again when the water pressure was more than 0. According to the Chinese industry standard "DL/T 5213–2005 Code of pumping test in borehole for hydropower and water conservancy engineering", when the permeability of rocks is relatively small, the following formula can be used to calculate the permeability of rocks:

$$K = \frac{Q}{2\pi HL}\ln\frac{L}{r}$$

where: K is the permeability coefficient of rocks (m/day); Q is the pump-in flow (m³/day); H = the water head of the tested interval (m); L is the length of the tested interval (m); and r is the borehole radius (m). The American rock mechanics test system MTS815 Flex Test GT was used to test the different rock samples. This system had the capabilities to test aspects such as uniaxial and triaxial compression, pore water pressure and seepage pressure, and indirect and direct tension. Three lithological sample types (sandstone, mudstone, and the top of the Ordovician limestone) were collected from the borehole. Before the test, the rock specimens were standardized to a size of 50 mm in diameter and 100 mm in height (Fig. 3). The strength and permeability of rocks were tested under different confining pressures, axial pressures, and seepage pressures.

Results and Discussion

The Characteristic of Ordovician Limestone in the North China Coalfield

A contour map of the total thickness of the Ordovician strata in the North China coalfield was drawn (Fig. 4). The total thickness of the Ordovician ranged between 300 and 1600 m in most of the study area. The characteristics of the

Fig. 3 Device of Packer test device and rock specimen photographs for the sandstone, mudstone, and limestone
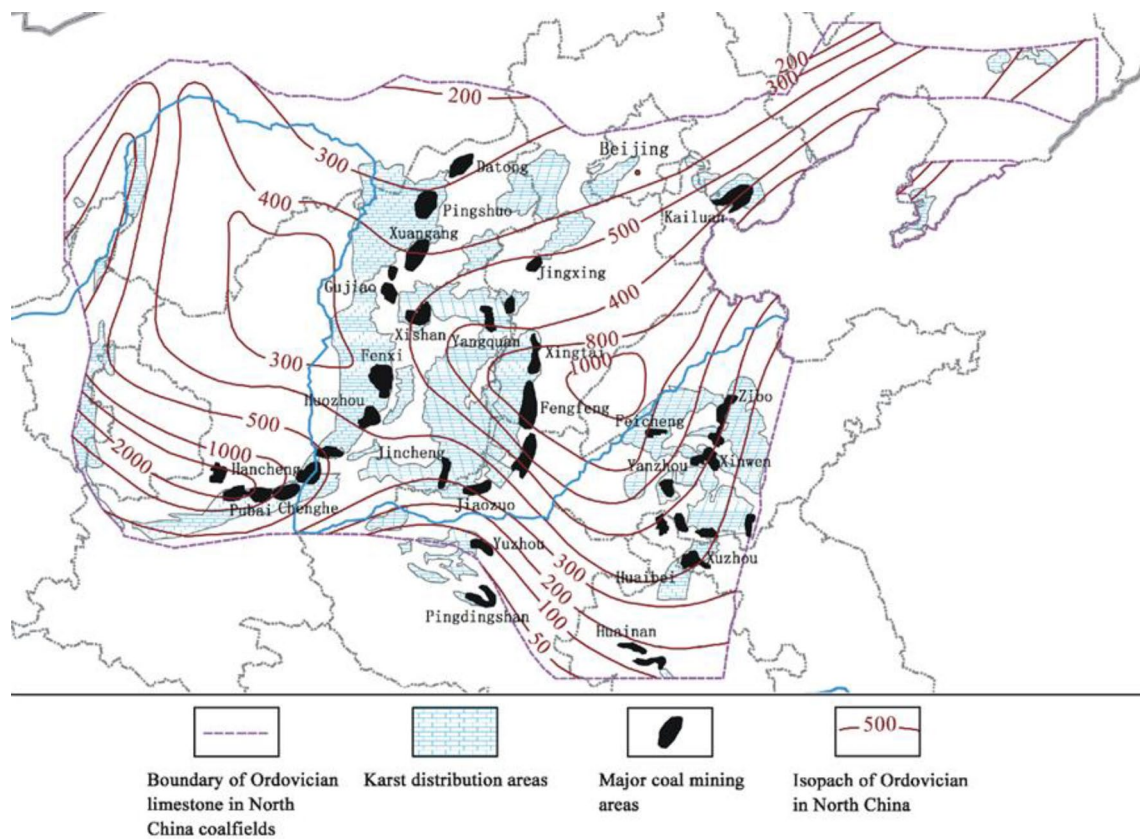
Fig. 4 Contour map of the total thickness for the Ordovician strata in the North China coalfield

limestone in the Feicheng, Xingtai, and Fengfeng Formations is approximately similar, representing relatively stable shallow sea environments. However, the sedimentary characteristics of the Ordovician strata in Helanshan and Pingliang in western North China were different; there, the total thickness might range up to 1800 m. Therefore, most coal mines in the study had the potential threat of Ordovician limestone water disasters.

As the thick, widely distributed Middle Ordovician limestone was the major water-inrush recharge source in the study area, the Middle Ordovician limestone was considered the important target strata for prevention and control of water disasters. The contour map of the thickness for middle Ordovician strata is shown in Fig. 5. Generally speaking, the average thickness of the Middle Ordovician limestone was 300–500 m in the study area. The Middle Ordovician is 640–784 m thick on the line of Shijiazhuang, Jingxing, and Yangquan, and gradually thins to the south and north. And it is up to 800–850 m thick between Zibo and Xinwen, and also gradually thins to the south and north, which can be seen from the strata histogram (Fig. 6) of the Ordovician from the north to the south (Kailuan–Xingtai–Fengfeng–Jiaozuo) and from the west to the east (Chengcheng–Hancheng–Jincheng–Fengfeng–Zibo).

Permeability Coefficient Based on a Packer Pump Test

A packer pump test was conducted in the Chengzhuang coal mine. Figure 7 shows the permeability coefficient variability for the top 40 m of the Ordovician limestone. The average permeability coefficient was 0.57×10^{-3} m/day, with a maximum of 0.70×10^{-3} m/day and a minimum of 0.34×10^{-3} m/day. In addition, there was little consumption of drilling mud and the water pressure was 0. This indicted that the top 40 m of Ordovician limestone in Chengzhuang coal mine contained little groundwater, and was water resistant. Figure 8 shows the water pressure variability for the next 20 m. The average water pressure for the next 6 m of the limestone section (41–46 m) was only 6.7×10^{-3} Mpa. The water pressure increased considerably between 46 and 55 m, with an average value of 0.47 Mpa, and then stabilized after 55 m with a high value of 0.71 Mpa.

Based on the field investigation, pump test, and engineering practices, the Ordovician limestone aquifer was divided vertically into a: weathered zone, transition zone, and karst fracture zone (Fig. 9). The weathered zone is the portion of the limestone that had been exposed to erosion
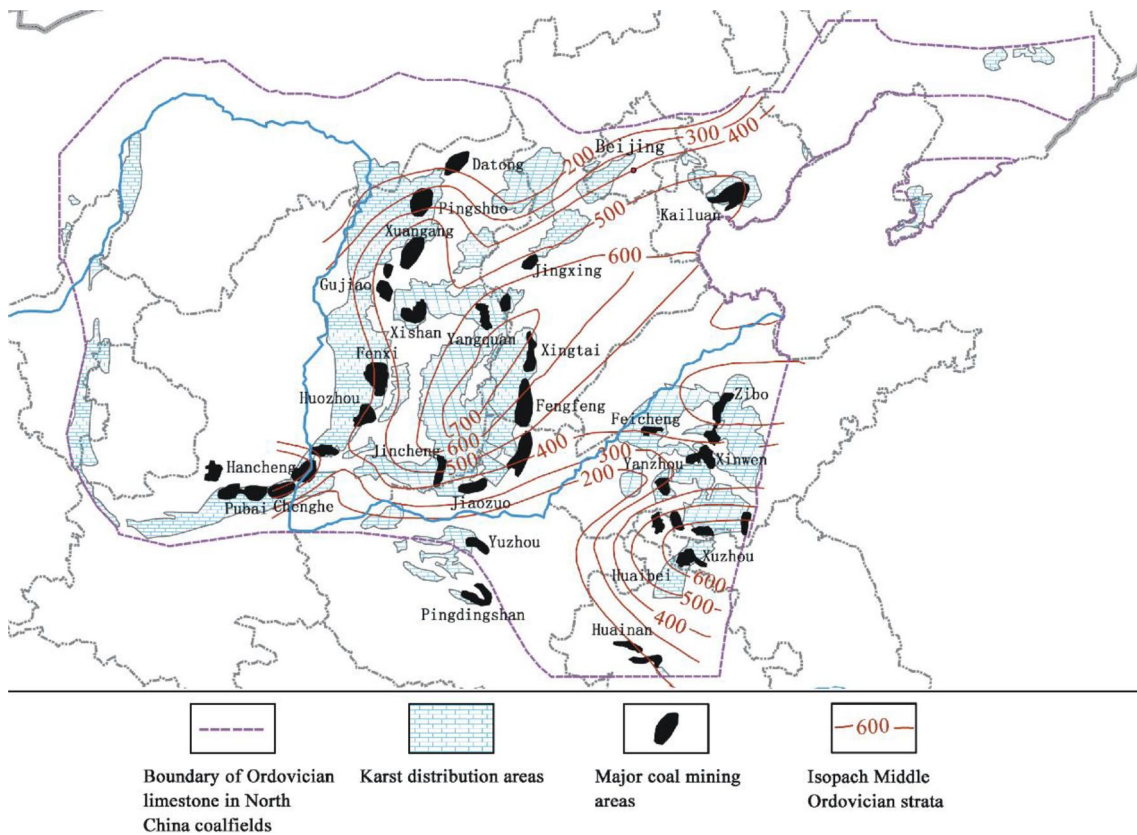
Fig. 5 Contour map of the thickness for the Middle Ordovician strata in the North China coalfield
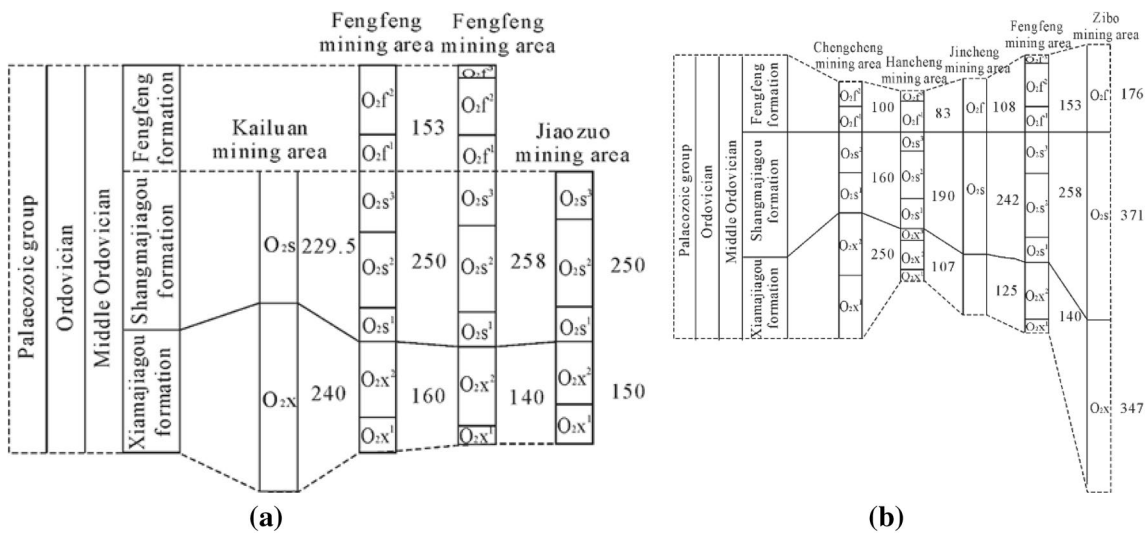

Fig. 6 Stratigraphic column of the Middle Ordovician, from north to south and from west to east, in the North China coalfield

and dissolution on and near the Earth's surface, forming an uneven surface with jagged fractures. During the 100 million years after the Caledonian tectonic movement, the karst void spaces were filled with the materials such as clay and sub-clay, which greatly improved the layer's water resistance and strength.
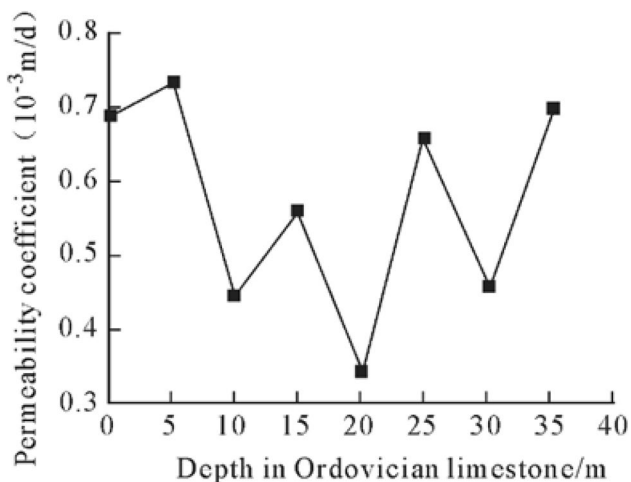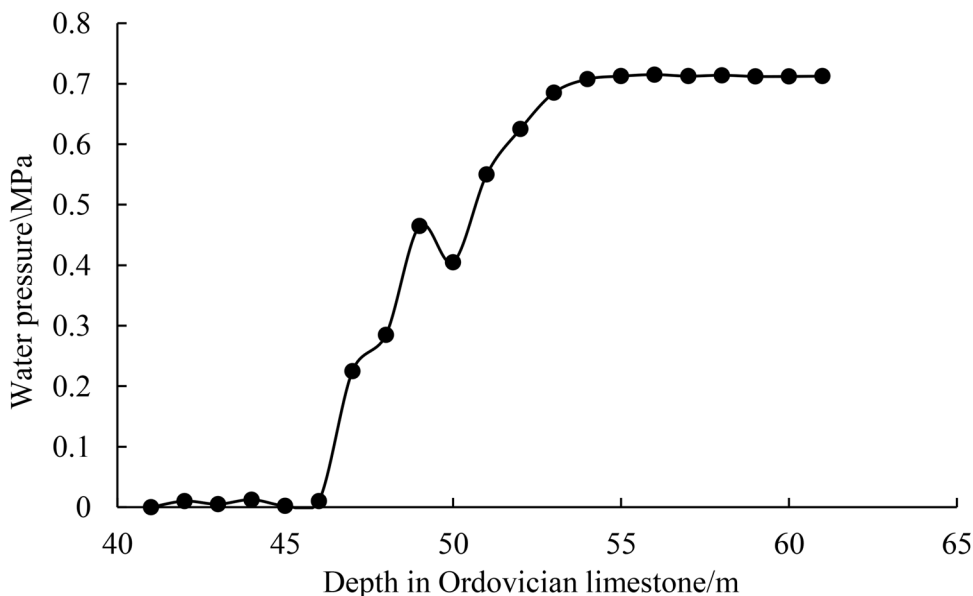
Fig. 7 Variation of permeability coefficient with depth for the Ordovician limestone

The transition zone, located below the weathered zone, represents rock that has been weakened from below by Ordovician groundwater. The water pressure in the upper interface of the transition zone was zero, while the water pressure in the lower interface of was equal to that of the karst fracture zone; the water pressure increased with depth.

The karst fracture zone represents the portion of Ordovician limestone that was not influenced by weathering and filling, though dissolution has developed the fractures and formed a high void ratio. The dissolved fissures extend spatially, forming a network with hydraulic connectivity and a major water storage space. Drilling fluid leakage and permeability in this zone were large and stable.

Significantly, considering all of the mines, the vertical weathering and degree of infilling of the Ordovician limestone was found to decrease gradually from top to bottom, but the partitions were not always at the same depth due to differing sedimentary environments and tectonic movements: some areas only have two zones, and or even only one, the karst fracture zone.

Strength and Permeability Based on Laboratory Tests

To consider the top of middle Ordovician limestone as an aquifuge, two conditions must be met. First, it should have certain water resisting properties; second, it should have the strength to resist the high-pressure Ordovician limestone water. Rock samples were collected from the Benxi formation mudstone, Taiyuan formation siltstone, and the weathered Ordovician zone in the Chengzhuang mine to test their mechanical strength and permeability, relative to their potential role as an aquifuge. The compressive strengths were tested at a confining pressure of 10 Mpa, as described and outlined in Fig. 10. The triaxial compressive strength of the top layer of the Ordovician limestone was 175 Mpa, slightly less than the sandstone (189.2 Mpa), but much higher than the mudstone (85.2 Mpa). Figure 11 shows the relationship between the triaxial compressive strength of the Ordovician top layer and confining pressure. As the confining pressure was increased from 5 to 20 Mpa, the compressive strength of the limestone rapidly increased from 120.98 to 283.52 MPa.

Figure 12 shows the permeability of the limestone, sandstone, and mudstone at a confining pressure of 10 Mpa. The permeability coefficient of the limestone was 1.44E-5 m/day, which was greater than the siltstone
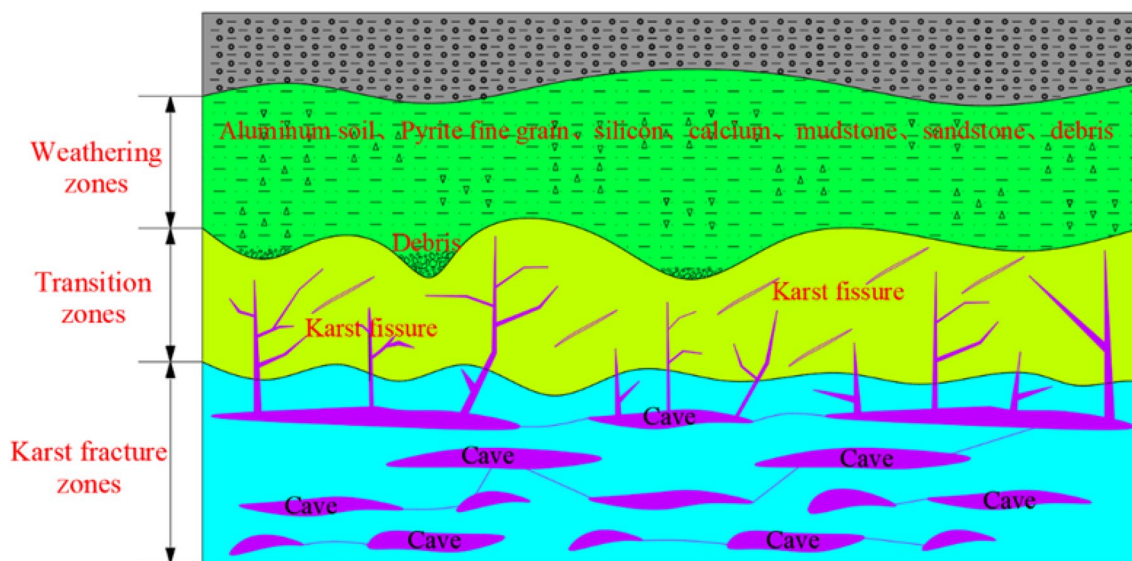
Fig. 8 Variation of water pressure with the depth for the Ordovician limestone

Fig. 9 The vertical partitions for the Ordovician limestone aquifer
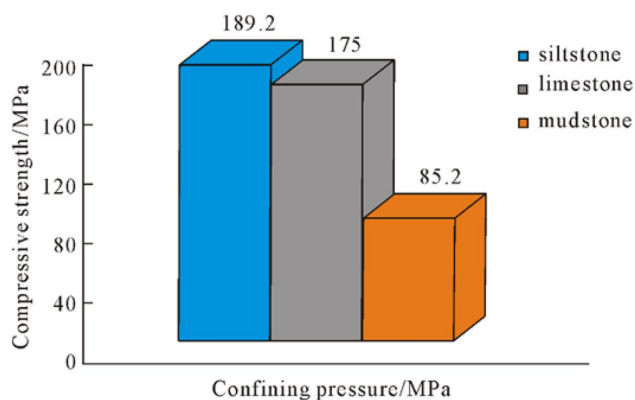
Fig. 10 Comparison of compressive strength of different rock samples under confining pressure of 10 MPa

Fig. 11 Relationship between triaxial compressive strength of limestone and the confining pressure

(5.65E−6 m/day) and mudstone (6.65E−7). The range of permeabilities for the limestone encountered in environmental geosciences and rock mechanics tends to vary from values: $\approx 10^{-14}$ m^2 to $\approx 10^{-15}$ m^2 (Selvadurai et al. 2016; Selvadurai and Głowacki 2008). However, the range of permeabilities for the top of the Ordovician limestone in the study area was usually less than $\approx 10^{-17}$ m^2 (supplemental Table S-1). Standards from the China's Ministry of Water Resources (2008) were used to assess the permeability of the rock. Although the permeability of the limestone was higher than the siltstone and mudstone, the limestone is still classified as micro-permeable based on the classification of rock permeability based on China's standards (Supplemental Table S-2).

In addition, since the permeability coefficient of the limestone rapidly decreased from 7.22E−5 to 9.51E−7 m/day as
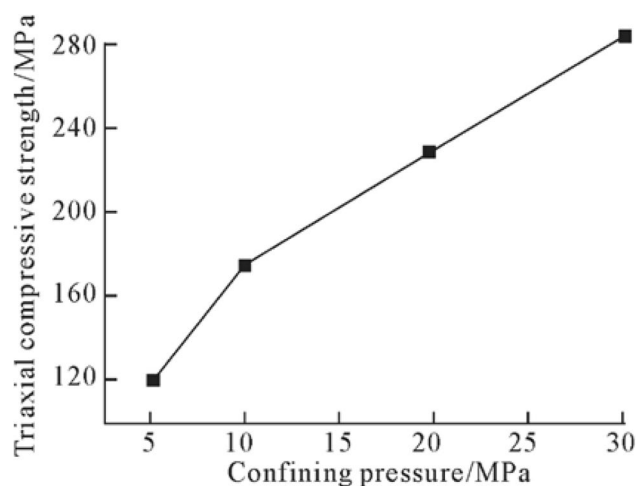
the compressive strength was increased from 5 to 30 Mpa (Fig. 13). Since the confining pressure is closely related to the depth of strata (Zhao et al. 2017), it could be inferred that the water resisting properties of the weathered zone would be further enhanced at greater burial depth.

Applying the Water Resisting Properties of the Weathered Zone.

To further analyze the regional water resistance of the weathered zone, rock strength and permeability data were collected from the literature for typical coal mines in North China (Table 1). The weathered limestone had compressive strengths of 53.2–107.58 Mpa, tensile strengths of 4.49–15.2 Mpa, and permeability coefficients of 0.835–40.51 × 10^{-7} m/

Fig. 12 Comparison of permeability of different rock samples under a confining pressure of 10 MPa
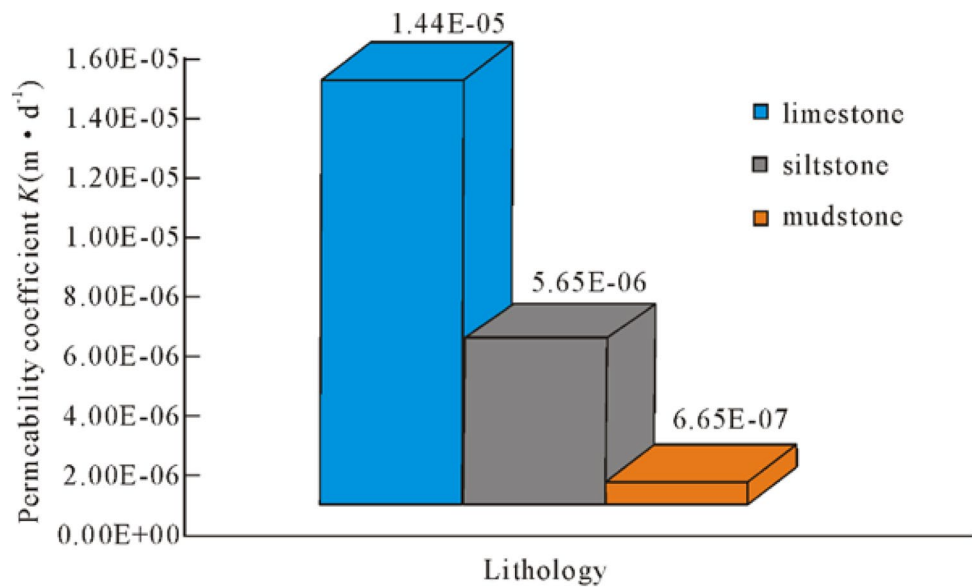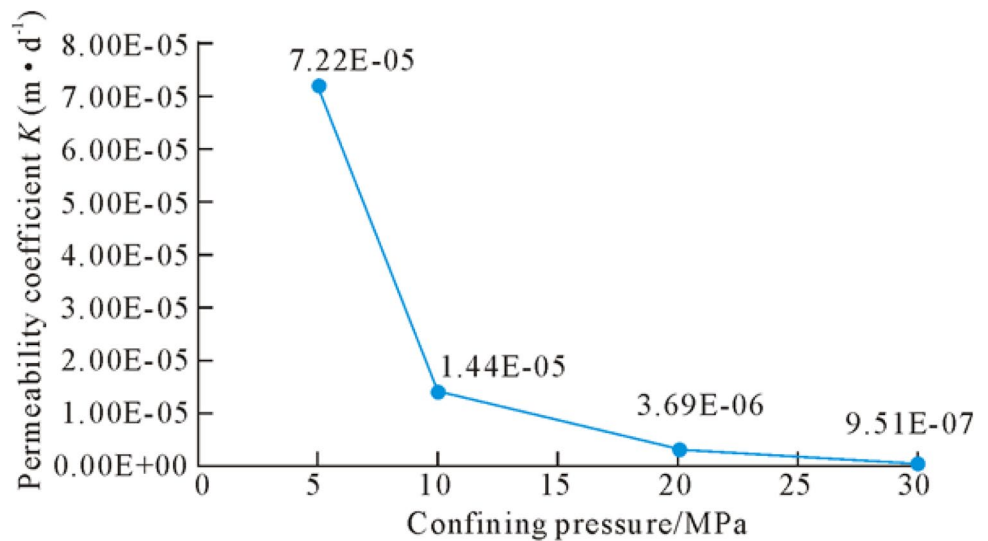

Fig. 13 Relationship between the permeability coefficient of the limestone and the confining pressure

day; the sandstone had compressive strengths of 43.32–108.35 Mpa, tensile strengths of 2.70 ~ 12.6 Mpa, and permeability coefficients of 13.41–22.81×10^{-7} m/day; while the mudstone had compressive strength of 14.77 ~ 51.62Mpa, tensile strength of 1.06–7.6Mpa, permeability coefficient of 0.049–2.11×10^{-7} m/day. Thus, the water resisting properties of the weathered limestone were slightly less than the Benxi mudstone, and similar to the Taiyuan siltstone. The thickness contour map for the weathered zone in the study area (Fig. 14) shows that the weathered zone ranges from ≈ 20–70 m in the study area, and the weathered zone can be used as an aquifuge for the prevention and control of mine water disasters (Dong et al. 2009; Dong et al. 2019; Wu et al. 2014).

In practical terms, the water inrush coefficient was defined as the ratio of the hydrostatic pressure of the Ordovician limestone aquifer to the thickness of the aquicludes. According to China's requirements, the water inrush coefficient should generally not exceed 0.06 MPa/m (Liu et al. 2020). If not, the coal seam should only be exploited once the thickness of the aquicludes had been increased by grouting before exploitation (Mou et al. 2020). This would waste lots of cement and make the cost of mining too high. Figure 15 shows the contour

Table 1 Results of rock strength and permeability in different coal mines

Lithology	Coal mines	Compressive strength (MPa)	Tensile strength (MPa)	Permeability coefficient (10^{-7} m/d)
Limestone of weathered zone	Panxi mine	54.49	12.77	–
	Daizhuang mine	53.2	9.84	–
	Geting mine	–	–	0.835
	Liyan mine,	79.71	15.2	–
	Baodian mine,	–	–	40.51
	Yangcun mine	107.58	4.49	–
	Nantun mine	–	–	11.3859
	Xinglongzhuang mine	–	–	22.571
	Summarize	53.2–107.58	4.49–15.2	0.835–40.51
Sandstone of Taiyuan Formation	Panxi mine	43.32	5.89	–
	Fuyi mine	82.37	8.75	–
	Liyan mine	47.32	12.6	–
	Baodian mine	–	–	22.81
	Yangcun mine	108.35	2.70	–
	Nantun mine	–	–	13.41
	Xinglongzhuang mine	–	–	20.42
	Summarize	43.32–108.35	2.70–12.6	13.41–2.81
Mudstone of Benxi Formation	Daizhuang mine	25.7	4.54	
	Getting mine			0.1259
	Fuyi mine	14.77	2.87	
	Liyan mine	51.62	7.6	
	Baodian mine			2.11
	Yangcun mine	28.3	1.06	
	Nantun mine			1.812
	Xinglongzhuang mine			0.049
	Summarize	14.77–51.62	1.06–7.6	0.049–2.11

of the water inrush coefficient for 3105 mining face without considering the weathered zone as an aquifuge; the water inrush coefficient exceeded 0.06 in most of the area (Fig. 16). However, when the water resistance of the weathered zone was considered, the water inrush coefficient was less than 0.06 in all areas of 3105 mining face, which allowed it to be successfully exploited without grouting the limestone aquifer.

Summary and Conclusions

1. Based on field investigations in six large mining areas of the North China coalfields, the total thickness of the Ordovician strata was about 300–1600 m, the average thickness of the middle Ordovician limestone was 300–500 m, and the weathered zone was about 20–70 m thick in the study area.
2. The average permeability coefficient for the top 40 m of the Ordovician limestone was 0.57×10^{-3} m/day, and the water pressure was 0 MPa for the top 40 m. The water pressure exceeded 0 MPa below this, though the average water pressure for depths of 41–46 m was still only 6.7×10^{-3} Mpa. It increased considerably for depths between 46 and 55 m, with an average value of 0.47 Mpa. The water pressure stabilized after 55 m, with a high value of 0.71 Mpa. Based on the field investigation, the Ordovician limestone was vertically divided into three zones: a weathered zone, a transition zone, and a karst fracture zone.
3. Laboratory test showed that the strength of the top layer of the Ordovician limestone was 175 Mpa, slightly less than the sandstone (189.2 Mpa), but much higher than the mudstone (85.2 Mpa). The permeability coefficient of the weathered limestone was 1.44E–5 m/day. While this was greater than the siltstone (5.65E-6 m/d) and mudstone (6.65E–7 m/day), the limestone is still classified as very micro-permeable rock. Meanwhile, the strength linearly increased with confining pressure while permeability decreased.
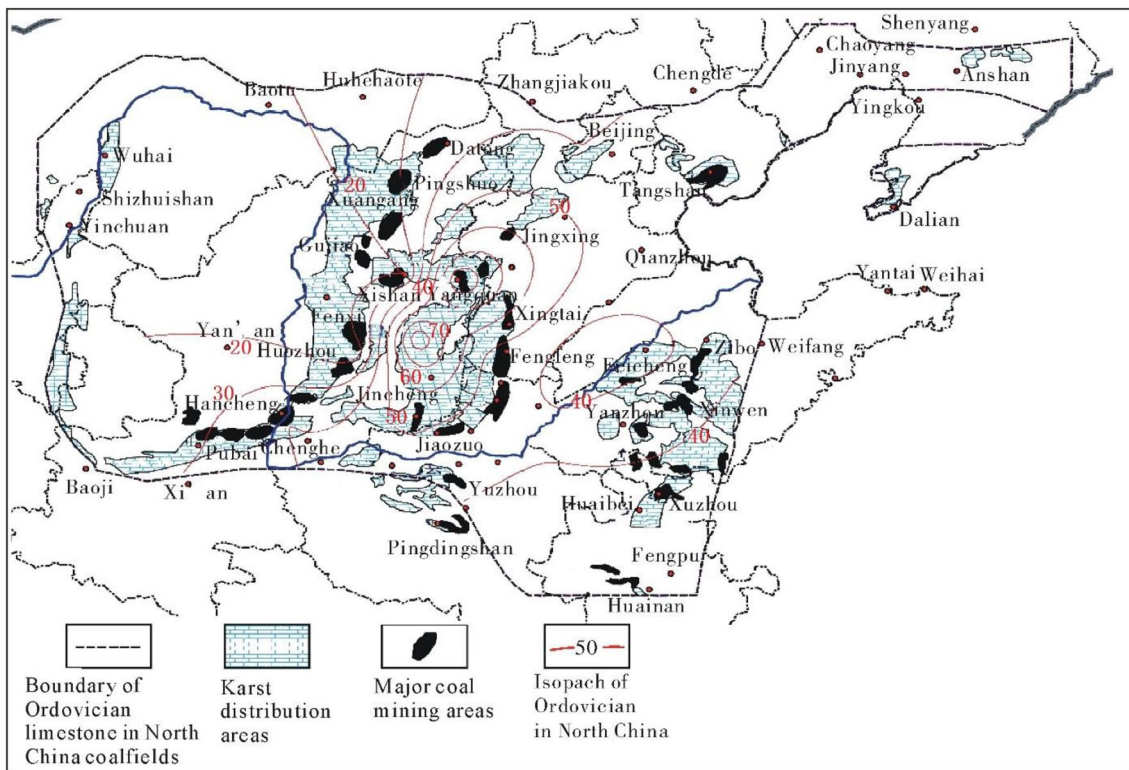4. The water-resisting properties of the weathered zone are widely distributed over the North China coal-

Fig. 14 Contour map of the thickness of the weathered zone in the North China coalfields
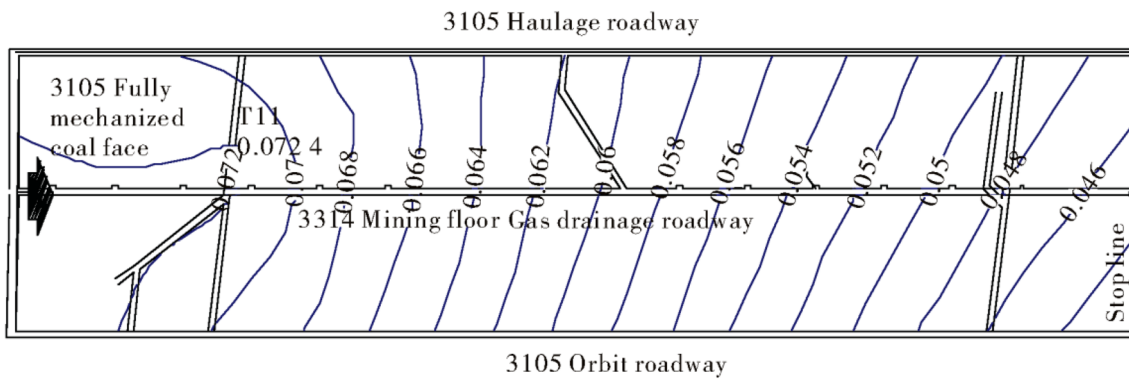

Fig. 15 Contour map of the water inrush coefficient without considering the weathered zone

fields, and it has been considered as an aquiclude for prevention and control of mine water disasters. The water inrush coefficient greatly exceeds 0.06 when the weathered layer is not considered an aquiclude, which means that the coal seam should only have been exploited once the thickness of aquicludes had been increased by grouting. However, when the water resisting properties of weathered zone were considered, the water inrush coefficient was less than 0.06, which allowed this mining face to be exploited successfully without grouting of the Ordovician limestone aquifer.
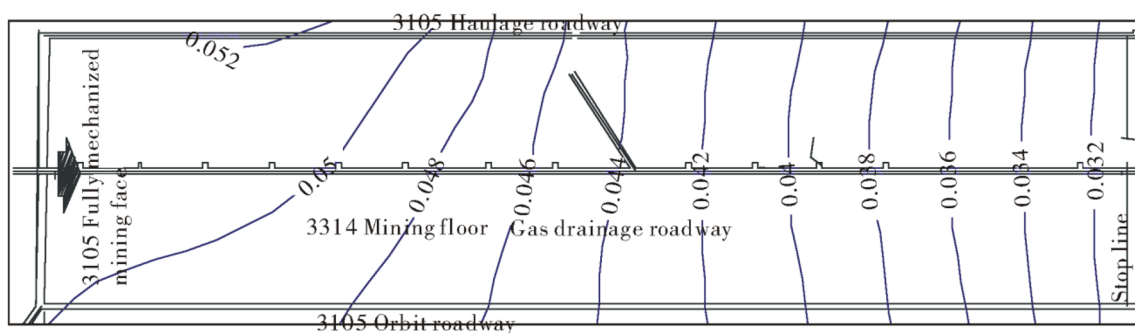
Fig. 16 Contour map of the water inrush coefficient with consideration of the weathered zone

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