Characterization of water bursting and discharge into underground mines with multilayered groundwater flow systems in the North China coal basin

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Abstract A conceptual framework for characterization of water bursting and discharge into underground mines with multilayered groundwater flow systems is presented, based on the features of the site conditions and analyses of the water bursting and mine inundation events of the North China coal basin. Comprehensive analyses of the hydrogeological conditions for establishment of the three-dimensional groundwater flow systems of the North China coal basin revealed different vertical hydraulic connection paths or channels. These connections include karst collapse columns, fault or fracture zones, buried weathering zones, and fracture networks in aquitards, within the multilayered groundwater flow systems. Also examined, was the effect of the primary features of the flow system and those different connection paths on water bursting and discharge into the underground coal mines. It was demonstrated that appropriately identifying and adequately understanding the three-dimensional multilayered groundwater flow systems and those various vertical hydraulic connection mechanisms are critical for appropriately preventing water bursting hazards and predicting water discharge into underground mines. A valuable guideline is presented on characterization of water bursting and discharge into underground mines with multilayered groundwater flow systems.

Résumé Se presenta un marco conceptual para la de caracterización de la despresurización y descarga de agua a minas subterráneas con sistemas de acuíferos de múltiples niveles, el cual se basa en las condiciones del sitio, análisis de la despresurización de agua e inundaciones de minas en la cuenca de carbón del norte de la China.

Un análisis comprehensivo de las condiciones hidrogeológicas para el establecimiento de los sistemas de flujo de agua de tri-dimensionales en la cuenca de carbón del norte de la China ha revelado diferentes canales hidráulicos verticales. Estas conexiones incluyen columnas de karst colapsadas, fallas o zonas de fracturas, zonas de regalita hundida y redes de fracturas en zonas de poca permeabilidad dentro de los sistemas de flujo de múltiples niveles.

También se investigó el efecto de los rasgos primarios del sistema de flujo y los diferentes canales conectivos sobre la despresurización y descarga de agua a minas subterráneas. Se demostró que el entendimiento e identificación adecuada de los sistemas de acuíferos de múltiples niveles en tres dimensiones es crítico para prevenir apropiadamente la despresurización y descarga de agua a minas subterráneas. Se presentan lineamientos valiosos en relación con la despresurización y descarga de agua a minas subterráneas en sistemas de flujo de múltiple nivel.

Resumen Un cadre de travail conceptuel pour la caractérisation du jaillissement et de la vidange des eaux dans les mines à plusieurs niveaux d'écoulement est présenté, basé sur les conditions et l'analyse sur site du jaillissement des eaux et des inondations dans les bassins charbonneux du Nord de la Chine. L'analyse compréhensive des conditions hydrogéologiques des systèmes d'écoulement tridimensionnel de ces bassins, révèle des trajets ou des chenaux qui sont autant de connections hydrauliques verticales. Ces connections comprennent des effondrement karstiques en colonne, des zones de fractures et de failles, des zones d'altération, des réseaux de fractures dans les aquitards, dans le système hydrogéologique multicouche. L'influence des caractéristiques primaires du système d'écoulement et de ces différentes connections sur le jaillissement et la vidange dans les mines, est également examiné. Il a été démontré que l'identification appropriée et la compréhension adéquate du système d'écoulement souterrain multicouche et tridimensionnel, et des mécanismes variés de connection hydraulique verticale est critiquée pour prévenir de manière appropriée les risques de jaillissement et de vidange dans les mines. Des guidelines valorisables sont présentées, pour

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la caractérisation du jaillissement et de la vidange dans de tels systèmes.

Keywords Mines · North China coal basin · Water bursting · Groundwater flow · Hydraulic connection paths

Introduction

The North China coal basin, in which approximately 70% of all the identified coal resources in China are deposited, tectonically is part of the Zhongchao Paraplatform (Gao and Lin 1985). It is located between the Yinshan-Yanshan Mountains in the north and the Qinling-Dabieshan Mountains in the south. The coal basin is also bounded on the west by the Liupanshan Mountains and on the east by the Bohai Sea (Figs. 1 and 2). The area of the coal basin is about 1,664,000 km^2, roughly 1,600 by 1,040 km.

The coal deposits in the coal basin were mainly formed in the Carboniferous to Permian periods, during which the basin alternated between oceanic and continental depositional environments (Han and Yang 1984). Coal layers in the basin are often interbedded with thin-bedded limestone or thick-bedded sandstone aquifers. The coal layers were deposited over an extremely thick Middle Ordovician carbonate formation that forms a large aquifer, called "O_2 aquifer." Those interbedded aquifers and that large O_2 aquifer, the voids of which consist of primary porosity, fractures, and karst structures, are considered to be the major water sources discharging into the mine pits in the basin. When groundwater discharge through certain flow paths from one or more aquifers (called "water discharge aquifers") into a mine pit exceeds the drainage capacity designed for the mine pit, water will gradually invade the mine pit and ultimately submerge the pit. A sudden, catastrophic increase of water discharge from water discharge aquifers into underground coal mines, a phenomenon known as "water bursting," is a critical hydrogeological subject for mining safety and is a complicated and challenging research topic in mining hydrogeology. This water bursting problem predominantly occurs on the footwall of mined coal layers in the coal basin. The problem is compounded by insufficient drainage capability resulting from inappropriate mining pit design due to inadequate understanding of the site hydrogeologic conditions. Primary hydraulic characteristics of water bursting consist of high groundwater head, large amounts of water discharge, and frequent occurrence. It is likely that the problem will be more serious with the deeper mining levels.

A number of investigations have been conducted on the hydraulic behaviors of rock masses and water discharge features (Coldewey and Semrau 1994; Zhang and Zhang 1997), on the mechanisms and prediction approaches of water bursting (Li 1994; Wu and Jin 1995; Wu et al. 2004), and on the modeling approaches for water discharge predictions (Wang 1995; Wang and Zhang 1995; Wang and Tian 1991). However, the effect of attributes of the multilayered, three-dimensional groundwater flow systems and vertical

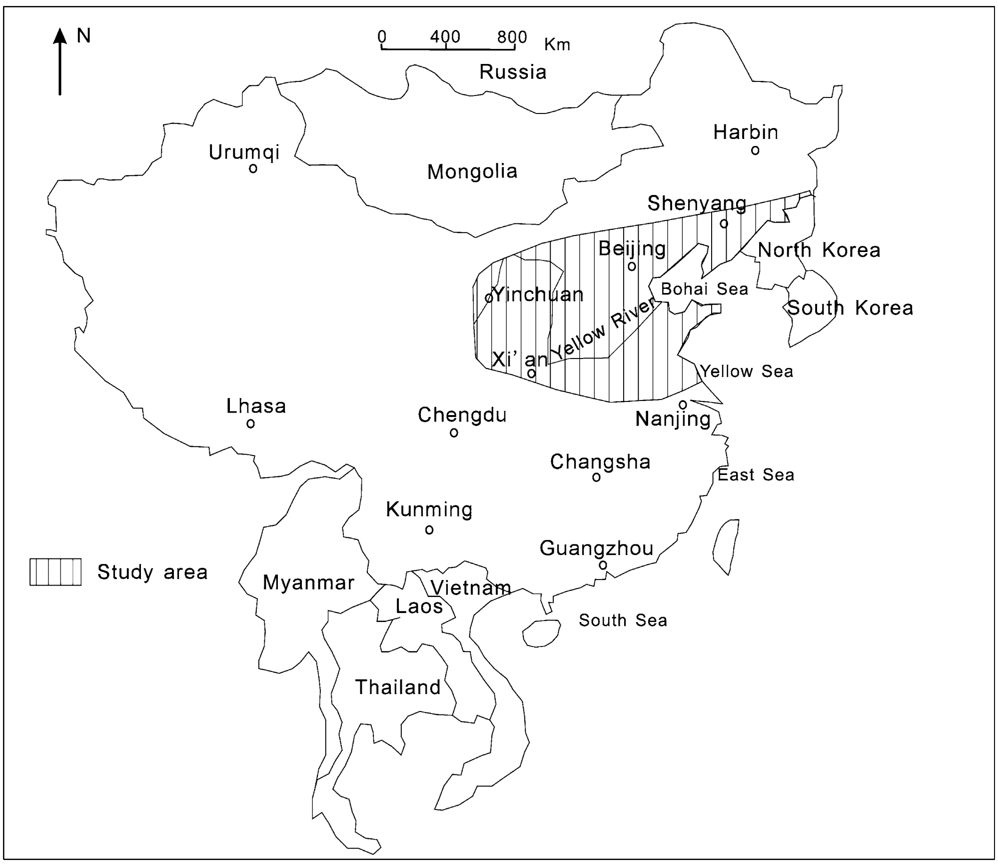

Fig. 1 Location of the North China coal basin

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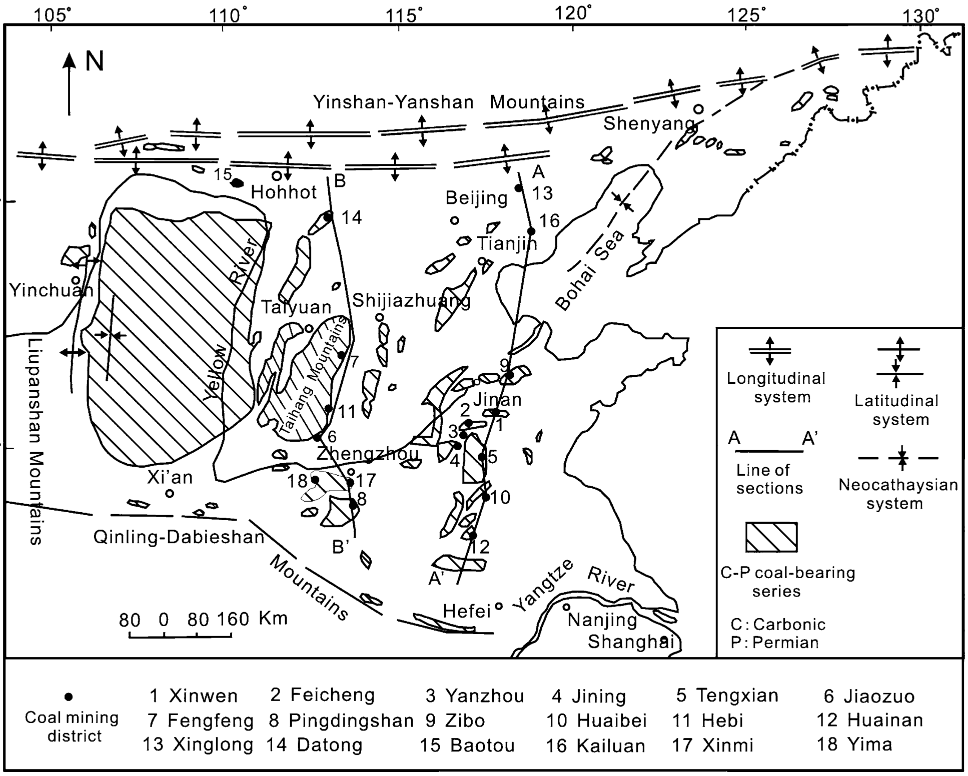

Fig. 2 Map showing the coal mine districts of the North China coal basin

hydraulic connection paths on water bursting and discharge into underground coal mines have not been addressed sufficiently. It has been observed that the features of water bursting hazardous events can be correlated to the types of the vertical hydraulic connection channels (Wu and Jin 1995). The hazardous events could be caused by inadequate understanding of the vertical hydraulic connection channels and by mining practices that do not appropriately take them into account. In order to further address the problem in the North China coal basin, a conceptual framework for characterization of water bursting and discharge into underground mines with multilayered groundwater flow systems is presented, based on the features of the site conditions and analyses of the water bursting and mine inundation events of the North China coal basin. The objectives of this study are to: (1) present the primary features of the multilayered groundwater flow systems in the coal basin; (2) categorize and understand different types of vertical hydraulic connection paths or channels within the multilayered groundwater flow systems of the coal basin; (3) examine the effect of the flow systems with different connection paths on water bursting and discharge into underground coal mines; and (4) present general implications of these findings to characterization of water bursting and discharge into any other underground mines with multilayered groundwater flow systems.

Multilayered groundwater flow systems

In the coal basin there exist vertically and hydraulically connected multilayered aquifer systems with different void structures featured by pores, fractures, and karst voids. Hydraulic connections exist among aquifer layers through different types of vertical hydraulic connection paths or channels. The following summarize the features of the three major groups of water discharge aquifers.

Aquifer groups in coal-bearing rock series

As mentioned previously, the coal-bearing rock strata in the coal basin were mainly deposited from the Carboniferous to Permian periods. The strata deposited in the Permian period were formed primarily under continental depositional environments when the sea had begun to recede at the end of the Carboniferous period. Mudstone, sandstone, and shale were major lithologic types deposited in the Permian period. The sandstone layers interbedded with mudstone and shale beds support the main aquifers in this period. Water discharge from the sandstone aquifers in underground coal mines is quite limited, due to low permeability and interbedded impermeable units. Major water discharge aquifers in the coal-bearing rock series were deposited in the Carboniferous period. The Carboniferous system consists of the Taiyuan and Bengxi rock groups. This study focuses on the Taiyuan coal-bearing rock series, since the deposit thickness of the Bengxi group is very small, even absent in some coal mines in the basin (Liu et al. 1979).

Taiyuan group in the southern and middle parts of the coal basin

The strata formed in the Carboniferous period were deposited in a marine environment. They are discordantly

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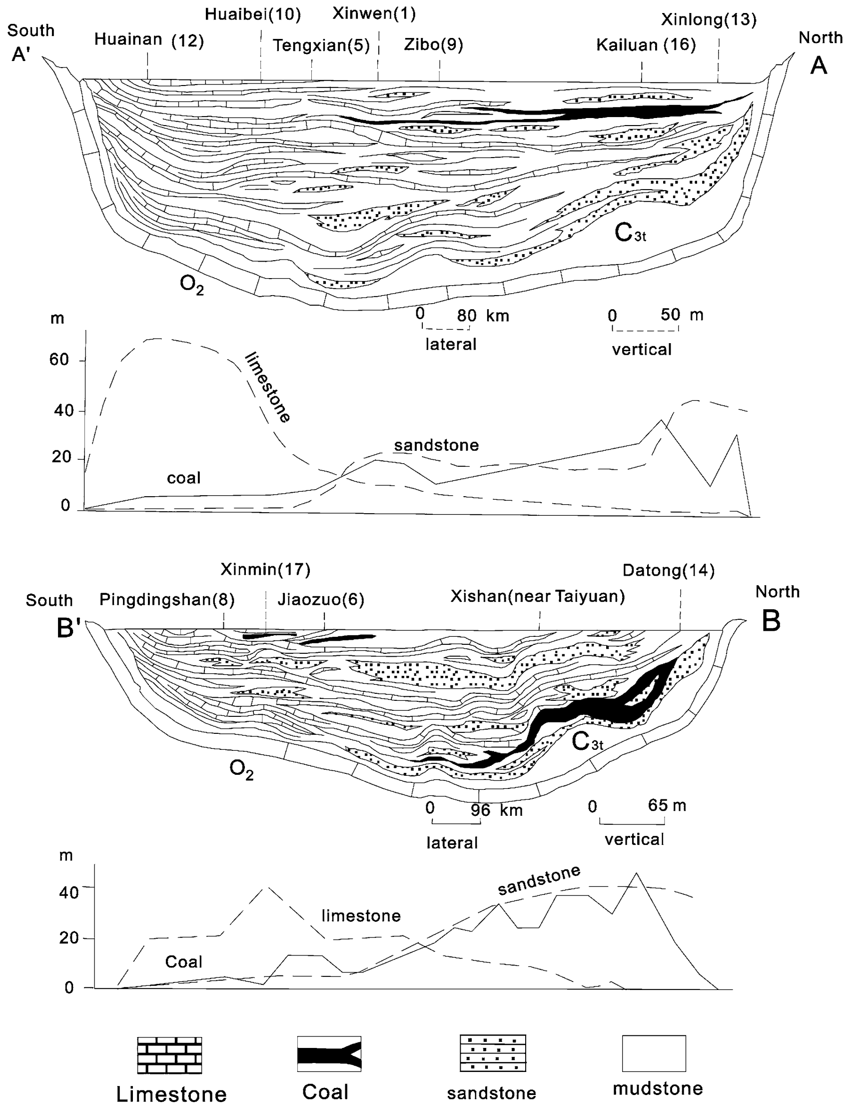

Fig. 3 Diagrammatic sections across the North China coal basin, showing general shape of the basin, and the relation and distribution of the main rock types in Taiyuan group in the upper Carboniferous system, also showing the distribution and total thickness of coal, limestone, and sandstone along lines of the cross sections (location of the sections shown in Fig. 2; modified from Han and Yang 1984)

A-A' Cross section from the Yinshan-Yanshan Mountains southward across the eastern part of the basin to near Hefei
B-B' Cross section from the Yinshan-Yanshan Mountains southward across the center of the basin to the southern part

underlain by the extremely thick-bedded carbonate rock formation deposited in the Middle-Ordovician period (O_2 aquifer). There exist 11 thin-bedded and confined carbonate rock aquifers in the Taiyuan Group in the basin. Those aquifers are sequentially named L1 through L11 from the bottom to the top (Gao and Lin 1985; Wu and Jin 1995). Some of the aquifers could be absent in a specific region, which results in the varied number of those aquifers ranging from 3 to 11 in different districts. The composite depositional thickness of these aquifers is about 10–40 m. However, contributions from specific aquifers provide unique influences on water discharge from aquifers into underground coal mines at different regions or districts of the basin. For example, the fourth karst limestone aquifer L4 influences the Xinwen and Feicheng coal mine districts (Fig. 2) while only the tenth limestone aquifer L10 discharges in the Yanzhou, Jining and Tengxian coal mine districts (Fig. 2). Additionally, the L2 and the L8 limestone aquifers influence considerably water discharge features and events in the Jiaozuo coal mine district (Figs. 2 and 3).

The thin-bedded limestone aquifers are often relatively isolated hydraulically occurring in size-limited blocks by faulting. Water discharge features from these aquifers into the underground coal mines, therefore, depend primarily on hydraulic connectivity with the relatively thick O_2 aquifer or the overlying permeable shallow porous aquifers. If the hydraulic connections are limited, the water discharge from those thin-bedded limestone aquifers mostly comes from the depletion of groundwater storage resources, and there are no serious threats of water bursting to coal mining operations. Otherwise, the thin-bedded limestone aquifers have a large potential to result in water bursting hazards. In other

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words, if the hydraulic connection is extensive, water discharge into the mining pits can be significantly increased. The extent of the hydraulic connection with the O_2 aquifer depends essentially on the thickness and lithologic characteristics of the impermeable beds between the thin-bedded limestone aquifers and the O_2 aquifer, and on their various vertical hydraulic connection paths. In the Jiaozuo, Fengfeng and Pingdingshan coal mine districts (Fig. 2), for example, L2 is the major water discharge aquifer. It is located only 25–40 m above the O_2 aquifer and there is relatively large vertical recharge from the comparatively thicker O_2 aquifer. This recharge results in more complex water discharge conditions from L2 into the underground coal mines. The average flow rate from the water discharge aquifer into the underground coal mines per unit water head drawdown of the aquifer (average water discharge rate per unit drawdown) is over 11,000 $cm^3/s/m$. However, the vertical recharge from the thick aquifer is relatively small in the Zibo, Feicheng, and Huaibei coal mine districts (Fig. 2) since deposit thickness of the impermeable bed between them is larger (35–60 m). As a result, the average flow rate per unit drawdown for water head of the aquifer in these districts is only about 5,000 $cm^3/s/m$. The hydraulic connection with the overlying unconsolidated porous aquifers depends mainly on the thickness of the aquitard underlying the porous aquifers and on the depth and extent of the weathering zones of the thin-bedded limestone aquifers.

The degree of karst development in the thin-bedded limestone aquifers in different coal mine districts varies considerably due to conditions such as extent of outcrop exposure, burial, rock structure, and groundwater recharge from different sources such as the other aquifers and precipitation. It is commonly observed (Wu and Jin 1995), however, that the extent of karst development decreases with the buried depth of the limestone aquifers.

The Jiaozuo coal mine district is located at a hinge point of eastern and southern foothills of the well-known Taihang Mountains (Fig. 2). Well-developed karst features in the underground limestone beds of this area resulted from favorable rock structures, friable strata, and sufficient groundwater recharge. According to the available data obtained from more than 95 exploratory boreholes in the district, different sizes of karst void spaces exist. They vary from small honeycomb-like openings to karst caves with diameters of 0.1–5 m. More than 50% of total exploratory boreholes penetrated karst caves with diameters of 0.2–5 m. These extremely developed karst features are seldom observed in the other mine districts in the coal basin of North China. This is considered to be a major cause of the frequent water bursting events in the Jiaozuo coal mine district (Fig. 2).

There are five thin-bedded limestone layers in the Fengfeng coal mine district (Fig. 2) with only two of them being major water discharge aquifers. One of the two major water discharge aquifers is about 4 m thick; the other is 7 m in thickness. Based on a statistical study from drilling cores taken from exploratory boreholes in the district (Gao and Lin 1985) the karst phenomena are mainly developed between elevations −100 m and +100 m above sea level. Most of the karst spaces consist of dissolved openings and small karst caves with diameters of only about 0.02–0.1 m. It is obvious, therefore, that there are differences in degree of the karst development between the Fengfeng and Jiaozuo coal mine districts.

Furthermore, there are over eight thin-bedded limestone layers deposited in the Hebi, Huainan, Xinwen, Zibo, and Pingdingshan coal mine districts (Fig. 2). Since geological structure and groundwater recharge conditions in the districts are not favorable for karst development, large karst caves in the drilling cores of exploratory boreholes are seldom observed. Water discharge rate per unit drawdown from those aquifers into the underground coal mines of those districts could be only about 30–1,000 $cm^3/s/m$ according to the analysis of the pumping test data which were collected as part of this study.

The sandstone deposit thickness in the Taiyuan group in the coal-bearing rock series in the southern and middle parts of the basin (as showed in Fig. 3) is inversely proportional to the thickness of the thin-bedded limestone. There are almost no sandstone aquifers in the most southern parts of the basin, such as the Huainan and Huaibei coal mine districts (Fig. 2). The number of fractured sandstone aquifers increase gradually towards the north of the basin.

Taiyuan group in the northern part of the coal basin

In contrast to lithological features in the southern and middle parts of the basin, the number of layers and deposit thickness of the thin limestone beds deposited in the Taiyuan Group in the basin's northern part decrease. The thick-bedded fractured sandstone layers constitute the major water discharge aquifers in the group. Particularly in the northern areas from Beijing, such as the Xinlong, Datong, Baotou, and Kailuan coal mine districts (Fig. 2), there are almost no limestone deposits. There are 2–3 major sandstone aquifers that interbed with coal layers in the group. Thickness of each layer is about 40–60 m. Hydraulic conductivities of these aquifers are generally smaller than those of the thin-bedded limestone aquifers. Groundwater head gradients of the sandstone aquifers are relatively steep whereas water capacities within them are relatively small. In this situation, if mining excavations intersect with vertical permeable channels such as fault zones that link hydraulically only with the underlying sandstone aquifers, serious water bursting could not happen. However, if the intersected vertical channels, particularly preferential pathways, connect hydraulically with not only the sandstone aquifers, but also the very thick O_2 aquifer, it is quite possible that a water bursting hazardous event can occur which, in turn, could even result in inundation. This happened, for example, in the Fangezhuang mine in the Kailuan (16, in Fig. 2) coal mine district in 1984, in which the maximum flow rate discharged to the mine reached up to 2,053 m^3/min. Water bursting in this mine also resulted in inundation of two adjacent underground coal mines, the Linxi and Lujiatuo mines in the Kailuan district at the same time (Fig. 2). Two thick sandstone aquifers in the Fangezhuang coal mine have

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been identified (Wu and Jin 1995). Thickness for each of the two aquifers is about 50 m. These aquifers are both underlain by the O_2 aquifer. Distance measured from the bottom of the top sandstone aquifer to the top of the O_2 aquifer is about 170 m.

To sum up, water bursting in the northern part of the basin bears the characteristic of less frequent, apparently random occurrences but with larger water discharge rates, attributed in part to the specific hydrogeological conditions mentioned above. For example, only four water bursting events with inundation have occurred in the underground mines of the Kailuan coal mine district since 1950; however, each of them was attributable to the underlain O_2 aquifer. The water discharge rates of those water bursting events were considerably large ranging from 52.7 to 2,053 m^3/min.

The carbonate rock aquifer in the Middle Ordovician system (O_2)

The carbonate rock in the Middle Ordovician system (O_2) is considered as a base aquifer (O_2 aquifer) for the whole coal-bearing rock series. This aquifer stores a large amount of water and accepts a considerable recharge from precipitation as a result of its large thickness, relatively well-developed fracture and karst features, and wide distribution of outcrop areas. Results from the multiple boreholes pumping tests in the aquifer (Wu and Jin 1995) have shown that karstified fractures are well developed and well connected hydraulically.

The thickness of the aquifer varies greatly in different coal mine districts, averaging about 500 m. The aquifer is thicker in the central part and thinner at the northern and southern parts of the basin. The aquifer thickness in the Xinmi and Yima coal mine districts (Fig. 2), for example, is only about 40–230 m. It is completely absent in the Pingdingshan coal mine district of the coal basin (Fig. 2), where the whole coal-bearing rock series is directly underlain by the Lower Ordovician system or the Cambrian system.

The very thick O_2 aquifer actually is a complicated multilayered aquifer system. It can be generally divided into three groups according to its depositional cycle. Each group may be further subdivided again into two aquifers. A relatively less permeable breccia carbonate aquifer is identified at the lower part of each group while the upper part of each group consists of a highly permeable aquifer of karstified pure limestone.

Dissolved grooves are the common karst features in the outcrop areas of the carbonate rock. Development of directional textures in the karst voids is mainly controlled by the strikes of surface fractures. Karsts and fractures are major repositories for water and form seepage pathways for groundwater in the aquifer. Different fracture sets cut into each other and form a karst fracture network. It is necessary for a karst fractured network to be superimposed by locally developed large karst spaces, such as karst caves, to account for inhomogeneity, anisotropy and complicated groundwater dynamics conditions in the aquifer. The fracture network in the aquifer, however, is considered to be a dominant characteristic of the groundwater seepage system.

It is well known that inhomogeneity and anisotropy of a carbonate aquifer can be attributable to karst development whose attributes, in turn, determine groundwater seepage that affects further karst development. This implies that seepage subdomains with different features can be divided from the whole groundwater seepage field. Seepage subdomains can be generally classified into strong, weak, and normal seepage subdomains. Generally, a strong seepage subdomain is present in a form of a narrow zone. Creation of a strong seepage zone is generally related to a large karst spring. Karst development of physical scales and dimensions is directly proportional to spring water discharge rate.

The following summarizes the general hydrogeological characteristics of strong seepage zones in the North China coal basin:

1. A strong seepage zone correlates with the karst belts of carbonate rock in a contact plane between a karst formation and a nonkarst formation. The contact plane between the carbonate rock in the Middle-Ordovician system and the coal-bearing rock series in Permian-Carboniferous systems is an example of this case. More examples include the axial plane of a structural fold, fractured zones, and the percolation recharge belt of rivers.
2. Geologic media in the strong seepage zone commonly contain karst-fracture networks with higher void ratio, especially in the middle of, and upstream of the zone. However, the groundwater movement within the zone generally still follows Darcy's law based on analyses of the field hydrogeologic data.
3. The zone is usually a water-abundant zone, and water discharge rates per unit drawdown into underground mines located with the seepage zone is often larger than discharge rates in other types of subdomains.
4. Groundwater head within the strong seepage zone is often lower than that outside the zone forming a hydraulic trough valley. The longitudinal groundwater head gradient along the zone is relatively less steep. Dynamic state of groundwater within the zone has a quicker response than that in other types of subdomains.
5. Natural groundwater quality within the zone is also much better than that in the other subdomains.
6. Water bursting events occur more frequently along with larger water discharge rates into the underground coal mines located in the strong seepage zone.

The shallow porous aquifer group in the Quaternary system

In most parts of the basin, the shallow porous aquifer group in the Quaternary system is often underlain discordantly by the coal-bearing rock series of the thick Middle Ordovician carbonate rocks. This results in a specific hydrogeological condition. Several hundred meters of the deposits in

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the Quaternary system have been found in the east part of the basin such as the Kailuan, Huainan, and Huaibei coal mine districts (Fig. 2). Therefore, it is critical to investigate whether an aquitard exists and how its thickness is distributed beneath the shallow porous aquifer group. In the Donghuantuo coal mine of the Kailuan district, for example, there exists only a thin aquitard at the bottom of the shallow porous aquifer group in the areas of the buried outcrops of the various types of bedrock. As a result, the shallow porous aquifer group is located rather close to the aquifers in the coal-bearing rock series as well as the O_2 aquifer in those areas. This stratigraphic configuration is favorable for groundwater recharge from the shallow porous aquifer to the various bedrock aquifers, and could also result in frequent water bursting events in the underground mines.

Vertical hydraulic connection paths, and their effect on water bursting and discharge into underground coal mines

In the North China coal basin in the presently mined coal layers, direct water discharge aquifers could be either the thin-bedded limestone layers or the thick-bedded sandstone layers. These aquifers are generally found to be of weak discharge capacity in a normal situation, although there exist slight differences of water discharge capability between them. However, if these direct water discharge aquifers connect hydraulically with the underlain O_2 aquifer or with the overlying shallow porous aquifers, they will bear a stronger water discharge capacity, and can seriously threaten the safe mining of the coal beds. Therefore, the vertical permeable paths or channels, which result in recharge to the aquifers of the coal-bearing rock series and provide the hydraulic connections for the whole aquifer system of the coal basin, are very important factors in investigating water bursting and predicting water discharge into the underground coal mines (Wu et al. 1992).

Basic vertical connection paths

There are four basic different types of vertical connection paths or channels identified in the coal basin. Each of them represents one mechanism of hydraulic connection between the different aquifers within the groundwater flow systems. These mechanisms reflect water discharge processes from the ultimate groundwater sources to direct water discharge aquifers of the coal-bearing rock series. Based on analyses, undertaken as part of this study, of several hundred serious water bursting and inundation hazardous events that happened in the underground mines of the coal basin (Wu and Jin 1995), it was found that almost all of the hazardous events were related to the various types of vertical hydraulic connection channels, and were caused by inadequate understanding of the different kinds of water discharge mechanisms. It is obvious, therefore, that systematically comprehensive studies on the water discharge mechanisms are critical. These studies should include classifications of the mechanisms, quantitative simulation and assessment of hydraulic attributes, and investigation of distribution and shape for each channel.

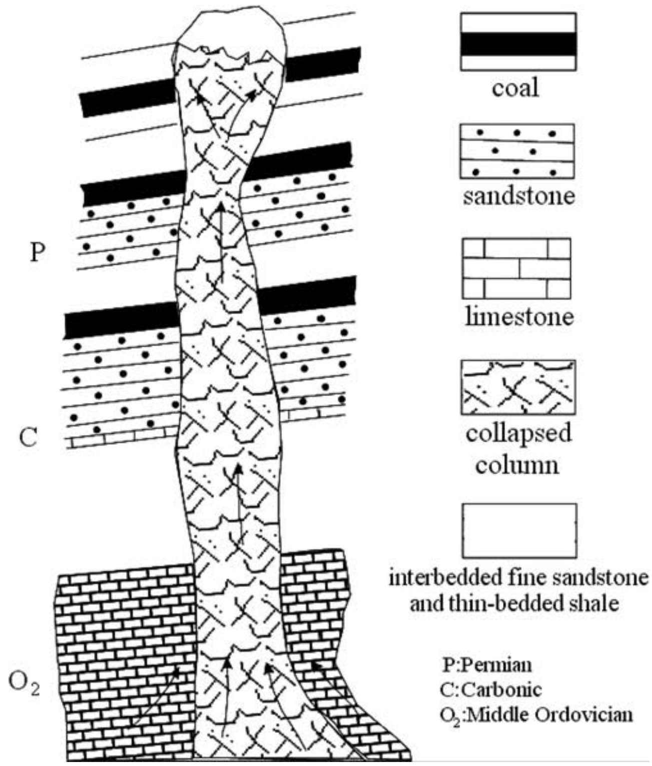

Fig. 4 Cross section of a representative karst collapse column in the North China coal basin, showing relation to adjacent beds and principal direction of groundwater flow (*arrows*)

With regard to hydraulic features, the four fundamental types of hydraulic connection paths, to which different water bursting and discharge mechanisms may be attributable differently, are discussed.

Karst collapse columns

Different sizes of underground karst caves exist in the O_2 aquifer. Over the long term, the weight of overlying rocks, land surface buildings, and other surface loads can collapse these karst caves, which then fill with collapsed heterogeneous lithological brecciform rocks, forming the karst collapse columns (Fig. 4).

Land surface manifestations of the karst collapse columns are relatively obvious in exposed areas of the O_2 aquifer. The strata inside the collapse column are often disordered; however, in the periphery of the column, the strata often have inclination towards the center of the column. The column shape, in cross-section view, looks generally like a taper while it exhibits an ellipse in a plan view. The heights of the columns vary considerably. The heights depend primarily on the original dimensions of the early collapse karst caves formed within the O_2 aquifer. The larger the karst cave, the higher the column. Ranges of heights of the karst columns in the coal basin are approximately from

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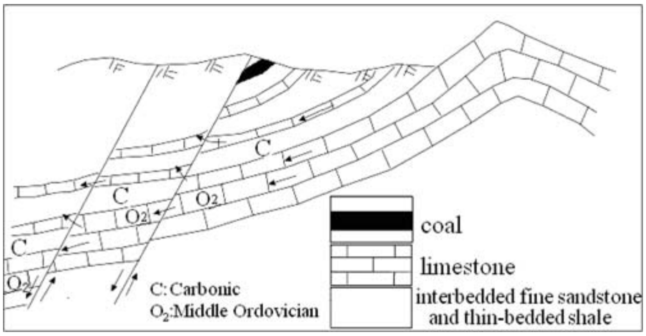

Fig. 5 Cross section showing possible relations of the Middle Ordovician limestone aquifer and limestone aquifers in the coal series due to normal faulting (*arrows* show possible directions of groundwater flow)

100 to 900 m. In addition, the rocks inside the column are generally fractured and heaped up.

The karst collapse columns are mainly distributed in the eastern and southern piedmonts of the Taihang mountains. For example, there are karst collapse columns that were formed several decades ago in the Jingxin coal mine district near to Shijiazhuang city. Moreover, they have been detected in most underground coal mines in the Fengfeng district. More than 100 of the detected karst collapse columns are clustered in a zone with a width of about 1–2 km in the northwest of the Fenfeng coal mine district. The maximum diameter observed in the columns in the Fenfeng coal mine is about 580 m.

Most of the karst collapse columns found in the underground mines are dry whereas some of them such as a karst collapse column in the Fangezhuang coal mine of the Kailuan coal mine district (Fig. 2), are water-abundant and permeable. This permeable column precipitated in 1984, which resulted in one of the most serious water bursting hazardous events in China's mining history (Wu and Jin 1995). The maximum inflow rate into the mine pit during water bursting reached 2,053 m^3/min. It has been found that the karst collapse columns identified in the basin exhibit considerably different hydraulic behaviors. For example, some of them are permeable inside the columns while some are impermeable inside the columns with permeable peripheries due to the influences of highly developed fracture zones caused by the collapse of the rock columns. Additionally, there is another situation where the column is partially permeable.

Many factors control distribution of the columns such as the development of the old karst caves, and the geological structure which is considered to be one of the most important controlling factors for the distribution of the karst collapse columns. It should be noted, however, that it is very difficult at present to find out exactly the development patterns of old karst caves. All karst collapse columns in the Fangezhuang coal mine in the Kailuan district, for example, are distributed in accordance with the axis of the Tantuo syncline, a small scale geological structure formed after the coal-bearing rock series had deposited (Wu and Jin 1995). Moreover, the strong seepage zone is usually believed to be another controlling factor for the column distribution.

Fault or fracture zones

As mentioned previously, the North China coal basin, from a geotectonic viewpoint, belongs to the Zhongchao Paraplatform. Major forms of geologic structures in the coal basin are faults and gentle folds produced due to the relatively weak geotectonic events. The permeable faults are generally located in the areas with high density of faults, fault end convergences, or intersections between faults with different extending directions. A dislocation of rock blocks in the two sides of permeable normal faults break integrity and continuity of both aquifers and impermeable beds. It not only reduces the distances between two neighboring aquifers located separately in the two sides of the faulted blocks of faults, but also decreases significantly the water-resistant capability of the impermeable beds, i.e., increases considerably permeability of the aquitards (Fig. 5). Most of the faults have the potential to serve as hydraulic connection channels, since they often intersect with the thick O_2 aquifer.

There are two different connection configurations of a fault or fracture zone between the O_2 aquifer and an aquifer of the coal-bearing rock series that are separated by the fault or fracture. One way is indirect connection between them. Groundwater flows from a higher head aquifer, passing through part of the fault, then to a lower head aquifer. The fault functions like a "bridge" for connection of groundwater between the two aquifers. The other way is a direct connection between them when the two aquifers are in direct contact. Groundwater flows directly from one side with higher head, passing through the fault, then to the other side with lower head. It is obvious that the latter should generally offer a much stronger hydraulic connection between them than the former (Fig. 5).

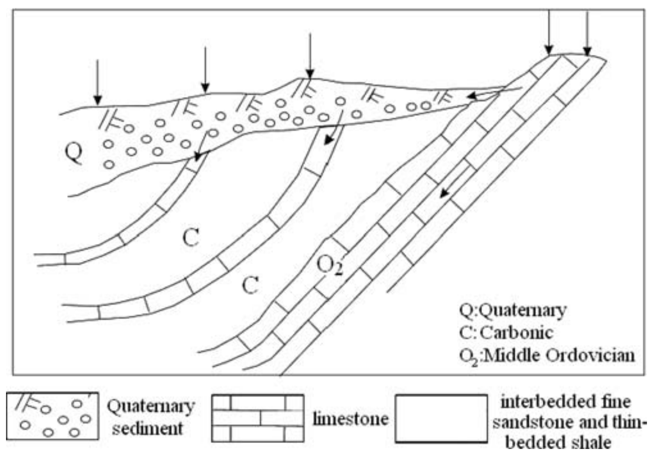

Fig. 6 Cross section showing near-surface relation of the Middle Ordovician limestone aquifer and limestone beds in the coal series beneath Quaternary deposits (*arrows* show directions of groundwater flow)

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Buried weathering zones

The unconsolidated porous deposits in most of the underground coal mines of the basin are often underlain discordantly by the thin-bedded limestone or the thick-bedded sandstone aquifers in the coal-bearing rock series and the O_2 aquifer (Fig. 6). Groundwater connection between the unconsolidated porous aquifer and the bedrock aquifers in the buried weathering zone depends essentially on the following two factors. One is permeability of the weathering zone of the bedrock, and the other is the thickness of the aquitard between the two aquifers.

Weathering could be favorable for permeability of the bedrocks, while the permeability would decrease with depth of the weathering zone. Weathering extent and depth are primarily related to bedrock lithology and original fractures developed in bedrocks. Mudstone, for example, is usually easily weathered; however, its weathering depth is often shallow as a result of its high plasticity and limited number of original fractures. Since the depositional environments of the unconsolidated porous media in the coal basin are diverse, almost all types of unconsolidated continental deposits are observed such as alluvium, fluvial, lacustrine, eluvium, talus, and glacial deposits. Depositional structures of the unconsolidated porous aquifers, therefore, vary significantly. There are generally 2–5 unconsolidated porous aquifers in the coal basin in the Quaternary system of this area. Recharge from precipitation could be a direct source for the shallowest unconfined porous aquifer; however, it has little effect on the lower confined porous aquifers. In some underground coal mines in the coal basin, there exists a relatively thick clay layer distributed underneath the lowest unconsolidated porous aquifer. Thus, it is obvious that little or very weak vertical hydraulic connection between the unconsolidated porous and the bedrock aquifers in the buried weathering zone is expected, no matter how permeable the weathering zone of the bedrock aquifers is. On the other hand, in some other underground coal mines of the basin, the clay deposit is very thin, or completely absent. In this situation, if permeability of the weathering zone of the bedrock aquifers is considerable, groundwater in the O_2 aquifer due to its highest head would first recharge to the unconsolidated porous aquifers through leakage area or permeable windows. Groundwater in the lowest unconsolidated porous aquifer then directly recharges the thin-bedded limestone or the thick-bedded sandstone aquifers in a similar manner. It should be pointed out that the aquifers in the coal-bearing rock series bear a lower water head since they have been generally drained for mining in order to sustain a lower water pressure and to prevent water bursting hazards. The unconsolidated porous aquifer, therefore, functions like a bridge to connect hydraulically between the aquifers in the coal-bearing rock series and the Middle Ordovician system.

Fracture networks in aquitards

As mentioned formerly, in the northern part of the coal basin, the thick-bedded sandstone aquifers are major water discharge aquifers in the coal-bearing rock series. The impermeable beds between those aquifers consist of fine sandstone, siltstone and mudstone. Brittle impermeable beds, such as the fine sandstone and siltstone, could release stress in the form of fracturing under the action of geotectonic forces. This makes the impermeable beds develop a large number of mini-fractures, form the three-dimensional fracture network, and enhance permeability of aquitards. Groundwater may then flow through the aquitards via the fracture network from the higher head aquifer to the lower head one (Fig. 7).

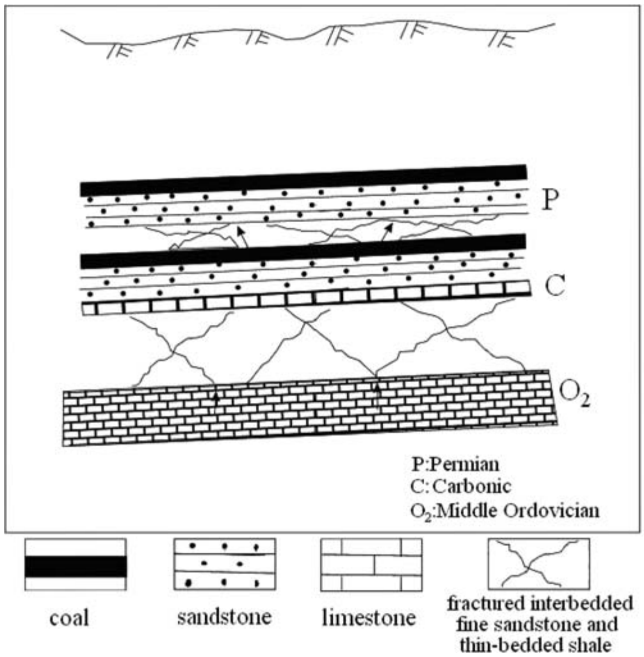

Fig. 7 Cross section showing shear fracture pattern in aquitard beds of the coal series (*arrows* show direction of groundwater flow)

The Donghuantuo coal mine of the Kailuan district is situated in the convergent tilting part of the Chezhoushan syncline that was formed as an important large scale and regional geological structure after the coal-bearing rock series had deposited (Wu and Jin 1995). The northwest limb of the syncline is steep; however, its southeast limb is flat, indicating an asymmetric geotectonic compressive tectonic regime. It is obvious that the rate and distance of interlayer movement in the northwest limb are considered to be larger than ones in the southeast. Therefore, symmetric shear fractures should be formed under a couple force of parallel-bedded plane. The existence of a fracture network has been verified by a large amount of survey boreholes and excavation engineering exposures in the coal mine.

Discussion

The processes of groundwater flow into mine pits through both the buried weathering zone and the fracture network in aquitards are generally gradual and not paroxysmal. Hazardous extents created by these two basic types of water bursting mechanisms, therefore, are normally not quite

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Table 1 Classification of hydrogeologic environments based on vertical hydraulic connection paths in the North China coal basin

Basic type	Combinations of two types	Combinations among three types	Combinations among four types
Karst collapse column (A)			
Fault or fracture zone (B)	AB	ABC	ABCD
Buried weathering zone (C)	AC		
Fault or fracture zone (B)			
Buried weathering zone (C)	BC	BCD	
Fracture network in aquitard (D)	BD		
Buried weathering zone (C)			
Fracture network in aquitard (D)	CD	CDA	
Karst collapse column (A)	CA (=AC)		
Fracture network in aquitard (D)			
Karst collapse column (A)	DA (uncommon)	DAB	
Fault or fracture zone (B)	DB (=BD)		

The hybrid hydraulic connection paths are expressed by the letters without regard to order (for example, AB=BA)

serious. However, groundwater movement along the karst collapse columns and the fault or fracture zones is often considered as turbulent flow. Hydraulic conditions of groundwater flow within them are extremely complicated. These two mechanisms could easily induce very serious water bursting hazards, because they could rapidly initialize and sustain a large water discharge into underground mines (Neuzil 1981).

Correctly understanding difference between groundwater flow features in porous and fractured geologic media is critical for prediction of water bursting and discharge intensity into underground coal mines pertaining to fractures in aquifers or aquitards. Recent research results and field applications indicated that the continuum approach in fluid flow investigations is generally applied to porous geological media, but has limited applicability to fractured rocks (Panda and Kulatilake 1999a,b; Wang et al. 2002). It may be erroneous to implement a continuum assumption in describing the fluid flow in fractured rocks at small or even large field scales. Basically, two practical approaches called discrete fracture fluid flow approach and equivalent continuum approach (Wang et al. 2001, 2002) could be considered for groundwater flow investigations in fractured rocks in large field scales pertaining to water bursting and discharge into underground coal mines. It should be pointed out that it is necessary to obtain fracture information, available from fracture measures from rock outcrops, tunnel walls, borehole fracture geophysical investigations, etc. (Kulatilake et al. 2003) in order to identify the statistical homogeneous regions for fractured rocks, obtain fracture geometry parameters, build the fracture network model, and characterize hydraulic properties for fractured rocks with regard to water bursting and discharge into underground coal mines.

Essentially, the aquifers of each of the three-dimensional, multilayered groundwater flow systems vertically are hydraulically connected together through various types of the vertical flow paths or channels. This is considered as a major hydrogeological feature and foundation for establishing three-dimensional hydrogeological conceptual models for the basin (Wu et al. 1991).

Hybrid types of vertical connection paths

Above-mentioned hydraulic connection paths or channels constitute the four basic types of vertical hydraulic connection ways that build different water bursting and discharge features and mechanisms. Each of those four paths or channels allows a hydraulic connection to a major recharge source for the thin limestone aquifers or the thick sandstone aquifers of the coal-bearing rock series. It is possible, however, to encounter any combinations of those basic types in mining sites (Table 1).

Table 1 shows the different combinations from the four basic types of the vertical hydraulic connection pathways. AB is a hybrid hydraulic connection path containing the karst collapse columns and the fault or fracture zones. The two basic types of paths occur mainly in deep parts of underground coal mines. Vertical permeability of the columns and the faults generally is relatively large. Since the distribution scales of the columns and the faults are usually quite limited, they are often neglected during prospecting and excavation of underground coal mines. This combination of the two paths, therefore, is considered to be a possible cause of serious water bursting hazards, if any mining excavation engineering intercepts with them.

AC is a hybrid hydraulic connection path involving the karst collapse columns and the buried weathering zones. In contrast to AB, this type of path occurs generally in the shallow part of underground coal mines and is relatively common in the North China coal basin. Measures to prevent water bursting include intercepting groundwater flow in the shallow part of underground coal mines and blocking the flow in the deep part of underground coal mines utilizing grouting techniques. The hydrogeological characteristics and water discharge features in Fangezhuang coal mine

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in the Kailuan district are attributable to this combination type.

BC is a hybrid hydraulic connection path involving the fault zone mechanism and the buried weathering zone mechanism. This type is one of the most common situations in the coal basin. The same measures as AC could be taken to prevent water bursting. This combination type was reported, as an example, in the Jiulishan coal mine in the Jiaozuo district (Wu 1994).

BD is a hybrid hydraulic connection path mixing the fault zones and the fracture networks in aquitards. It is commonly observed in the middle part of the basin.

CD is a hybrid hydraulic connection path involving the fracture networks in aquitards and the buried weathering zones. It is generally observed in the northern part of the basin. The hydrogeological characteristics and water discharge features in the Donghuantuo coal mine of the Kailuan (16) district represent this combination type.

The hybrid hydraulic connection paths DA, ABC, BCD, CDA, DAB, and ABCD have seldom been observed in the basin.

Summary and conclusions

It has been significantly revealed from this study that the features of water bursting hazardous events and water discharge into underground mines are correlated to the hydrogeologic environment, especially with regard to types and attributes of the vertical hydraulic connection channels. Moreover, the hazardous events could be caused by inadequate understanding of the types and attributes of the vertical hydraulic connection channels and by inappropriate mining practices where the attributes of the vertical hydraulic connection channels have not been sufficiently taken into account. Therefore, the comprehensive analyses, classification of the vertical hydraulic connection channels, and other findings presented in this paper will significantly enhance understanding of characterization of water bursting and discharge into underground mines with multilayered groundwater flow systems. As a result, this paper provides a valuable guideline on identification of appropriate solutions for these type of problems.

The following summarize the specific findings from this study, most of which may have general implications for characterization of water bursting and discharge into underground coal mines with multilayered groundwater flow systems. *First*, the multilayered porous, fractured, and karstified aquifers are hydraulically connected together vertically through different types of vertical hydraulic connection paths and form the integrated three-dimensional groundwater flow systems. This is a critical hydrogeological feature for the North China coal basin. This feature resulted in the special corresponding characteristics and phenomena of water bursting and discharge into underground coal mines, which could not be previously explained without this understanding. *Second*, the direct water discharge aquifers consist primarily of the limestone aquifers in the coal-bearing rock series formed in the upper Carboniferous period in the southern and the middle parts of the coal basin whereas the direct water discharge aquifers are the sandstone aquifers in the northern part of the basin. The O_2 aquifer provides an intense water source to recharge those aquifers in the coal-bearing rock series through various hydraulic connection paths, which leads to serious concerns on severe water bursting hazards and mining safety. *Third*, the four fundamental types of hydraulic connection paths between different aquifers have been identified in the North China coal basin. These paths include karst collapse columns, fault or fracture zones, buried weathering zones, and fracture networks in aquitards. From this classification of the basic path elements, some other hybrid hydraulic connection paths have also been recognized in the basin. Different water bursting and discharge mechanisms may be attributable diversely to one or more of those fundamental types of hydraulic connection paths. *Finally*, appropriately identifying and adequately understanding the three-dimensional multilayered groundwater flow systems and the various vertical hydraulic connection mechanisms are critical for sufficiently preventing water bursting hazards and acceptably predicting water discharge into underground mines not only for the North China coal basin but also for any other regions with similar hydrogeologic structures.

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